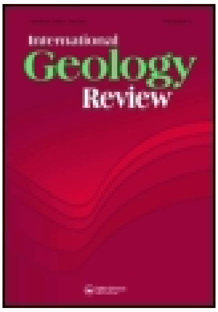


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# Review of the Link between the Hongge Layered Intrusion and Emeishan Flood Basalts, Southwest China

H. Zhong [a] , R.-Z. Hu [a] , A. H. Wilson [b] & W.-G. Zhu [a]
[a] Institute of Geochemistry, Chinese Academy of Sciences
[b] University of Natal
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# Review of the Link between the Hongge Layered Intrusion and Emeishan Flood Basalts, Southwest China

H. ZHONG,[1] R.-Z. HU,
*Institute of Geochemistry, Chinese Academy of Sciences, 73 Guanshui Road, Guiyang 550002, P. R. China*

A. H. WILSON,
*School of Geological and Computer Sciences, University of Natal, Durban 4041, South Africa*

AND W.-G. ZHU
*Institute of Geochemistry, Chinese Academy of Sciences, 73 Guanshui Road, Guiyang 550002, P. R. China*



## Abstract

Generation of the Late Permian Emeishan large igneous province has recently been attributed to the ascent of a mantle plume head. The Hongge layered intrusion, hosting a giant Fe-Ti-V deposit and Ni-Cu-PGE mineralization, is contemporaneous and chemically correlated with high-Ti type Emeishan flood basalts in the Pan-Xi area, southwestern China. Basalts within the lower part of the lava sequence (HT3) were strongly contaminated by material mainly from the middle to upper crust, whereas overlying basalts (HT2) were contaminated by a gabbroic layer near the crust-mantle boundary. In contrast, the magma parental to the Hongge intrusion assimilated appreciable amounts of a plagioclase-rich lower-crustal end-member. The Hongge intrusion may have acted as an open-system conduit through which the lavas erupted. Equilibration of Fe-Ti oxides and immiscible sulfide liquids with successive batches of magma produced the giant Fe-Ti-V deposit, and a gradual increase in the Ni, Cu, and PGE contents of later differentiates.

## Introduction

SEVERAL GIANT FE-TI-V deposits are hosted in layered ultramafic/mafic intrusions in the Pan-Xi area, Sichuan Province, southwestern China (Fig. 1). The intrusions occur along the western margin of the Yangtze block adjacent to N-S–trending, deep faults. Several research groups have suggested that the intrusions represent intrusive equivalents of the Permian Emeishan flood basalts (e.g., Zhang et al., 1988; Xu et al., 2001; Zhou et al., 2002b; Zhong et al., 2003). The intrusions are of particular interest because Ni, Cu, and platinum-group-element (PGE) mineralization has been recognized recently in the Hongge and Xinjie intrusions (Luo, 1981; PXGT, 1987; Liang et al., 1998; Zhang et al., 1998; Zhong et al., 2002, 2004).

Continental flood basalts (CFB) represent major magmatic events, and some are associated with large Ni-Cu-(PGE) sulfide deposits, such as the Noril'sk deposits in the Siberian Traps, Russia; the Duluth Complex in the Keweenawan mid-continent rift, United States; and the Insizwa deposit in the Karoo, South Africa (e.g., Naldrett et al., 1992; Lightfoot and Hawkesworth, 1997). However, the link between layered intrusions and the Emeishan CFB in the Pan-Xi area is poorly constrained, which is critical for the estimation of Ni, Cu, and PGE potentials of the associated intrusions. The major unknowns are as follows: (1) temporal and spatial relationships between the intrusions and basalts (Zhou, 1982; Liu et al., 1985; Yuan et al., 1985; Zhang et al., 1999; Zhou et al., 2002b); (2) tectonic constraints on formation of the Emeishan large igneous province (Cong, 1988; Zhang et al., 1988; Luo et al., 1990; Chung and Jahn, 1995; Lu, 1996; Dmitriev and Bogatikov, 1996; Chung et al., 1998; Xu et al., 2001); and (3) sources of magmas parental to the intrusions and petrogenetic models of Fe-Ti-V deposit and Ni-Cu-PGE mineralization (Li and Mao, 1982; Zhou, 1982; Liu and Xu, 1983; PXGT, 1987; Lu et al., 1988; Zhong et al., 2002, 2003, 2004).

In this paper, correlation between the Hongge intrusion and the Emeishan basalts in the Pan-Xi area, as well as available geological, chemical, and isotopic data and genetic models for the Hongge intrusion and its giant Fe-Ti-V deposit and Ni-Cu-PGE mineralization, are reviewed. Our purpose is

[1]Email: pgezhong@hotmail.com

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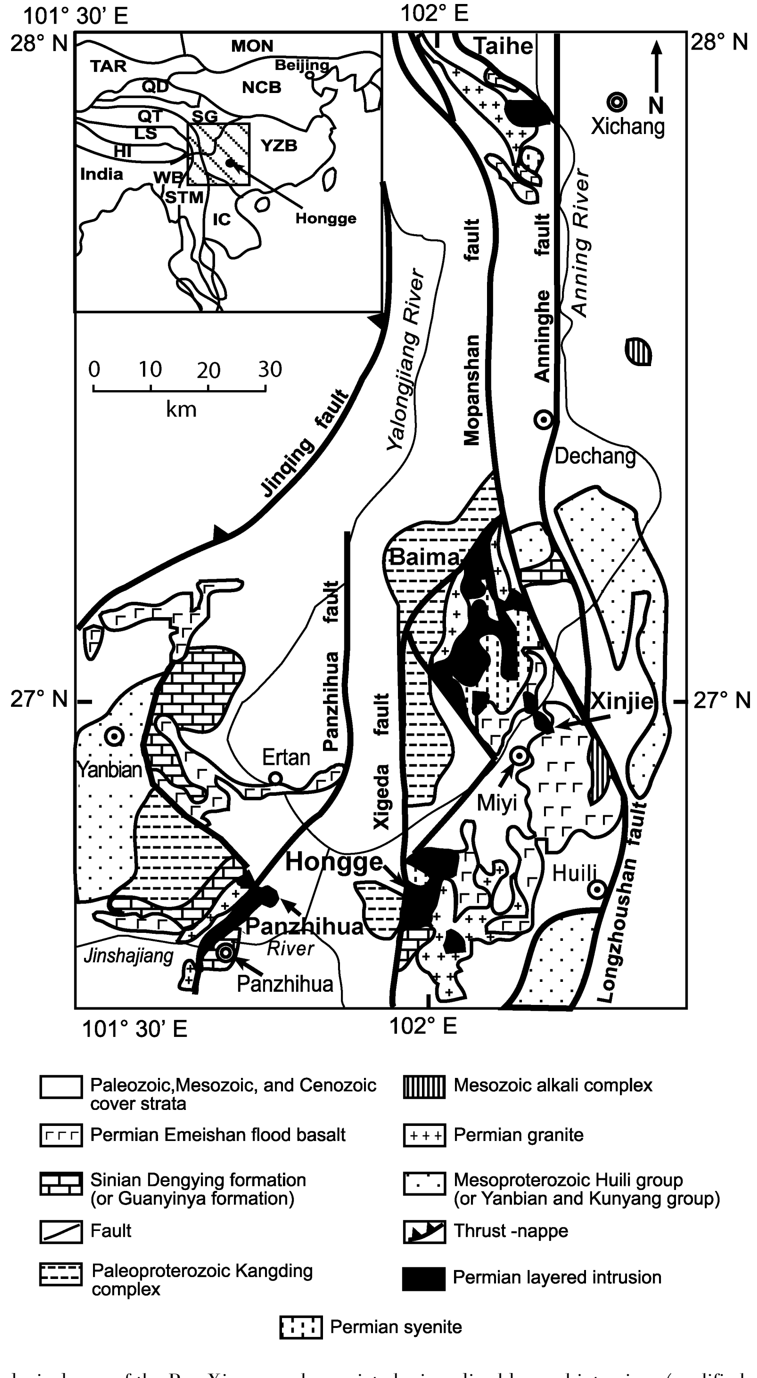


FIG. 1. Geological map of the Pan-Xi area and associated mineralized layered intrusions (modified after Liu et al., 1985). Insert illustrates distributions of major terranes in China, in which the shaded area indicates the distribution of the Emeishan basalts (modified after Chung and Jahn, 1995). Abbreviations: NCB = North China block; YZB = Yangtze block; SG = Songpan-Ganze accretionary complex; QT = Qiangtang; LS = Lhasa; HI = Himalayan; TAR= Tarim; MON = Mongolia; QD = Qaidam; WB = West Burma; STM = Shan-Thai-Malay; IC = Indochina.

to evaluate the relationship between the intrusive and extrusive rocks, and to develop a scenario for igneous events that led to formation of Fe-Ti-V and Ni-Cu-PGE mineralization. This in turn may have implications for further exploration in other associated intrusions in the Pan-Xi area.

## Regional Geology

The Emeishan large igneous province (LIP) is exposed over a large part of southwestern China from the eastern margin of the Tibetan Plateau to the western margin of the Yangtze block (Fig. 1). The Pan-Xi area is located in the central part of the Emeishan LIP, which consists of N-S–trending, fault-controlled, massive flood basalts, numerous associated mafic/ultramafic intrusions, and late-stage granites and syenites. The thickness of the Emeishan basalts adjacent to regional faults is much larger than those of the other regions. The basement of the Yangtze block is mainly composed of high-grade metamorphic rocks of Archean to Mesoproterozoic ages, overlain by a thick sequence (>9 km) of Sinian (610–850 Ma) to Permian strata consisting of clastic, carbonate, and meta-volcanic rocks (SBGMR, 1991).

The Emeishan basalts unconformably overlie the Upper Permian Maokou Formation, which consists of limestones corresponding to the Capitanian/Kazanian stage, and are covered by sandstone of the Upper Permian Xuanwei Formation. The lack of thick sedimentary piles or paleosols within the volcanic sections implies a short eruption period of the entire sequence. This is consistent with the overall duration of the flood event, which was less than 2 m.y. based on several magnetostratigraphic studies (Huang and Opdyke, 1998; Ali et al., 2002). Thick flows and tuffs of trachyte rhyolite form an important member in the upper sequence of the Emeishan LIP (Huang, 1986; Chung and Jahn, 1995). This volcanism may have produced the Permian–Triassic boundary clay and ash beds widespread in South China, as documented by a SHRIMP zircon U-Pb age of 251.2 ± 3.4 Ma (Claoué-Long et al., 1991). However, an age of 259 ± 3 Ma has recently been determined by SHRIMP dating of zircon from the Emeishan basalt–related Xinjie gabbros, providing a temporal link between the Emeishan traps and the end-Guadalupian extinction (Zhou et al., 2002b). The age of the gabbro is also in agreement with geological relationships (e.g., SBGMR, 1991; Yin et al., 1992; Thompson et al., 2001).

The mafic/ultramafic intrusions described here are exposed along a 200 km–long belt, which is controlled by regional N-S–trending faults in the Pan-Xi area (Fig. 1). The mafic-type of intrusion consists of layered gabbro, with minor olivine-bearing gabbro, troctolite, and anorthosite, although small amounts of ultramafic rocks occur in the lower portion of the igneous bodies (e.g., Panzhihua, Baima, and Taihe). In contrast, the mafic/ultramafic complexes (e.g., Hongge, Xinjie) consist mainly of clinopyroxene-bearing peridotite, olivine-bearing clinopyroxenite, clinopyroxenite, and gabbro. The most important Fe-Ti-V deposits within the Hongge and Taihe intrusions are hosted in their middle parts, whereas those within the Panzhihua and Baima intrusions are located in their lower parts (Yao et al., 1993). Vanadium-titanium-magnetite ores occur mainly at the tops of the lowermost cyclic units of the Xinjie intrusion (Luo, 1981). The major PGE mineralization occurs in the lower parts of the mafic/ultramafic complexes, such as the Hongge intrusion and the Xinjie intrusion (Luo, 1981; PXGT, 1981, 1987; Zhang et al., 1998; Liang et al., 1998; Zhong et al., 2002, 2004).

Abundant Sinian granites and Neoproterozoic arc plutonic-metamorphic assemblages (760–860 Ma) along the western and northern margins of the Yangtze block are interpreted to be the result of subduction of Rodinian oceanic lithosphere beneath the Yangtze block (Zhou et al., 2002a). The Yangtze block was then subjected to late Variscan-Indosinian (280–230 Ma) rifting (Cong, 1988), which is responsible for the formation of Emeishan LIP. This region was further deformed during the Himalayan orogeny, a collisional event between India and Eurasia (Yin and Harrison, 2000). However, the extensive Upper Permian Emeishan LIP is now believed to have resulted from mantle plume activity, as suggested by several recent geological and geochemical studies (e.g., Chung and Jahn, 1995; Lu, 1996; Chung et al., 1998; Xu et al., 2001), rather being related to stable cratonic rifting (e.g., Luo et al., 1990; Dmitriev and Bogatikov, 1996).

## Hongge Layered Intrusion

### *Local geology and petrography*

The Hongge layered intrusion crops out over an area of about 60 km$^2$; it intruded dolomitic limestones of the Sinian Dengying Formation and granitic gneisses of the Precambrian Kangding Complex. The Dengying Formation has been meta-

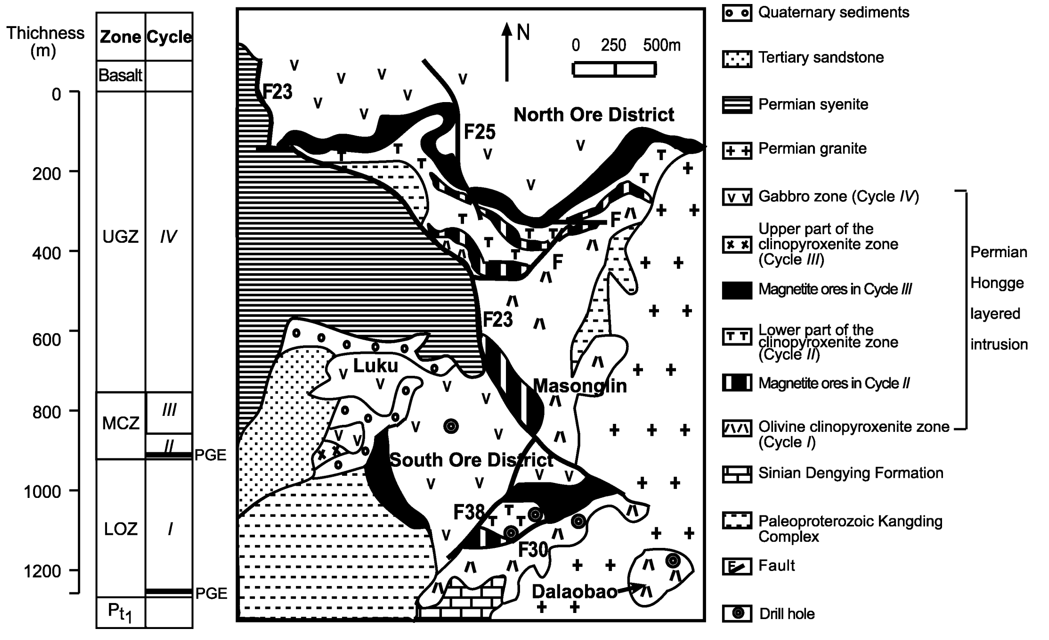


FIG. 2. Stratigraphy (modified after PXGT, 1987) and simplified geological map of the Hongge layered intrusion (modified after Yao et al., 1993). Abbreviations: UGZ = upper gabbro zone; MCZ = middle clinopyroxenite zone; LOZ = lower olivine clinopyroxenite zone. Legend: I-IV = Cycles I-IV; $Pt_1$ = Early Proterozoic rocks; dark bands at base of sections II and I in the "Cycle" column indicate PGE-enriched layers.

morphosed to marble in places adjacent to the intrusion (Zhang et al., 1999). The intrusion is related to the nearly N-S–striking Xigeda fault, and Emeishan basalts are closely controlled by the regional Longzhoushan and Xigeda faults (Fig. 1). The Emeishan basalts are present to the northeast of the Hongge intrusion, and together with the later body were intruded by Permian granites and syenites (Figs. 1 and 2).

Geochronological studies (K-Ar and Rb-Sr dating) on the Hongge intrusion have yielded ages ranging from 310 to 566 Ma (Yuan et al., 1985; PXGT, 1987; Cong, 1988). The wide spread in ages may reflect post-eruption alteration or assimilation of older continental crust. New Sm-Nd ages of 283 ± 38 Ma for whole rocks and 261 ± 45 Ma for minerals from the Hongge intrusion were recently reported (Zhang et al., 1999). However, these ages are still questionable, due to large uncertainties. A precise SHRIMP U/Pb dating on zircon from the similar Xinjie intrusion in the area yielded a crystallization age of 259 ± 3 Ma (Zhou et al., 2002b), within error of the Sm-Nd ages. Thus, it may imply that the Hongge intrusion was almost contemporaneous with or shortly predated the Emeishan basalts, of which the latter were suggested to erupt at the end of Guadalupian (ca. 256–259 Ma) (Lu, 1996; Courtillot et al., 1999; Zhou et al., 2002b; Ali et al., 2002).

Igneous layering is well developed in the Hongge intrusion and consists of three zones: the lower olivine-clinopyroxenite zone (LOZ), middle clinopyroxenite zone (MCZ), and upper gabbro zone (UGZ). The LOZ and UGZ are delineated by single compositional cyclic units but the MCZ is dominated by two compositional cyclic units (Fig. 2). The detailed petrography of the Hongge intrusion has been studied by Zhong et al. (2002). The LOZ consists of cumulus olivine, magnetite and minor chromite, and intercumulus clinopyroxene and hornblende within its lower part. The upper part of the LOZ comprises cumulus olivine and clinopyroxene, intercumulus titanomagnetite, ilmenite and hornblende, and minor plagioclase. In contrast, the MCZ comprises lherzolite and olivine clinopyroxenite at the bottom and clinopyroxenite at the top. The UGZ consists of medium-grained to pegmatoidal gabbro and clinopyroxenite with minor lherzolite and anorthosite, within which the cumulus plagioclase content increases upward.

*General character of the Fe-Ti-V deposit and Ni-Cu-PGE mineralization*

Mafic/ultramafic intrusions in the Pan-Xi area are well known in China for hosting numerous Fe-Ti-V deposits and Ni-Cu-PGE mineralization, of which the Panzhihua, Hongge, Taihe, and Baima intrusive complexes contain giant Fe-Ti-V deposits (Fig. 1; Table 1). The Hongge Fe-Ti-V deposit is the second largest economic concentration of iron and titanium of this type in China, after the Panzhihua deposit in this area. It is also the largest in terms of contained vanadium reserve (Yao et al., 1993; Table 1). Extensive exploration carried out from 1966 to 1980 suggested that the Hongge intrusion contains about $1.83 \times 10^9$ t $FeO_T$, $1.96 \times 10^8$ t $TiO_2$ and $1.45 \times 10^7$ t $V_2O_5$, and with ore grading 27.04 wt% $FeO_T$ (total Fe), 10.57 wt% $TiO_2$ and 0.24 wt% $V_2O_5$ (Yao et al., 1993; Table 1). The MCZ and UGZ host layers of disseminated V- and Ti-rich magnetite that are 14 to 84 m thick and 300 to 1700 m long, of which those in the MCZ form the most important deposits (Fig. 2; PXGT, 1987; Yao et al., 1993; Zhong et al., 2002).

More than 90 mineral types in the Hongge intrusion have been found in previous studies, including major Fe, Ti, and Cr oxides and silicates, and minor sulfides, arsenides, antimonides, and phosphates (Liu et al., 1974; Li and Mao, 1982; PXGT, 1987; Lu et al., 1988). In summary, the ore minerals are composed of predominant titanomagnetite and ilmenite, and subordinate titanochromite, chrome-spinel, and candite. The gangue minerals mainly consist of clinopyroxene, olivine, titanohornblende and plagioclase, with subordinate brown biotite. Secondary hornblende, biotite, talc, serpentine, epidote, saulpitite, and chlorite reflect post-magmatic hydrothermal activity (Fig. 3). The ore textures are typically poikilitic, mosaic, and sideronitic upward in a cyclic unit (Lu et al., 1988); major features are disseminated, taxitic, banded, flaggy, and flowage structures (PXGT, 1987; Yao et al., 1993).

The PGE-enriched horizons in the lower parts of the LOZ and MCZ are associated with Cu- and Ni-rich sulfides, which locally form as much as 1 vol% of the rock immediately below a thick magnetite horizon (Fig. 2; PXGT, 1987; Zhong et al., 2002). The average total PGE concentration in the enriched horizon within the LOZ is 0.354 ppm, and that within the MCZ is 0.533 ppm (Liang et al., 1998). These horizons are also anomalous in Ni, Cr, and Cu (Fig. 3; PXGT, 1987). The most common sulfides are pyrrhotite, pentlandite, pyrite, chalcopyrite, and cubanite, 90% of which is pyrrhotite. Sperrylites, vincentites, and $(Ru,Os)S_2$ are the most common platinum-group minerals (PGMs) in the PGE-enriched horizons, which are characteristically enclosed in Fe-, Ni-, and Cu-bearing sulfides (Liang et al., 1998).

*Geochemistry of the Hongge intrusion*

Most of the rocks in the Hongge intrusion exhibit high $TiO_2$ contents (Zhong et al., 2002). As shown in Figure 4, Mg# and MgO for the Hongge intrusion correlate positively with $SiO_2$, whereas they correlate negatively with $TiO_2$. Both Ni and Cr show positive correlations with MgO (Figs. 5A and 5B). The ultramafic portions (HG1, including LOZ and MCZ in Fig. 2) of the Hongge intrusion exhibit significantly positive Nb-Ta and obviously negative Th-U and Sr anomalies, as well as strongly positive Ti anomalies. The mafic portions (HG2, referred to as the UGZ in Fig. 2) develop remarkable Th-U and Nb-Ta depletions, and Sr and Ti enrichments (Fig. 6) (Zhong et al., 2003). In Figure 7, the initial Sr isotopic compositions of the Hongge intrusion show a restricted range of slightly enriched source(s), whereas the initial Nd isotopic compositions exhibit a relatively wide range of slightly enriched to depleted source(s) (Zhong et al., 2003; unpubl. data). The isotopic data implies either complex sources or variable contamination. The following general variations accompany the increase in $(Th/Ta)_N$ (normalized to primitive mantle of Sun and McDonough, 1989) in the Hongge intrusion: (1) increase in $(La/Sm)_N$, $(La/Nb)_N$, and $(La/Ta)_N$ (Figs. 8A–8C); and (2) a reduction in $\varepsilon_{Nd}$ (Fig. 7B). In addition, there is a negative correlation between Nb/Y and Zr/Y (Fig. 8D). Notably, two samples extremely enriched in plagioclase have significantly higher $(La/Sm)_N$, $(La/Nb)_N$, $(La/Ta)_N$, and Zr/Y values. PGE data of the Hongge intrusion indicate that rocks from the LOZ have Pd/Ir ratios (1.8–22.3) lower than those of the MCZ (3.6–83). The Pd/Ir ratios increase progressively upward in each cyclic unit and the Cu/Pd ratios at the bottom of each cyclic unit are close to that of the mantle and increase upwards (Zhong et al., 2002).

## Emeishan Basalts in the Pan-Xi Area

The Emeishan basalts outcrop over an area exceeding 250,000–500,000 km$^2$ and their thickness varies from a few hundred meters in the eastern parts to somewhat localized highs up to 5 km in the

TABLE 1. Geological and Geochemical Characteristics of Giant Fe-Ti-V Deposits in the Pan-Xi Area

| Deposit | Host rock | Covered area and thickness | Mean grade, % | Reserve, t | Grade of byproduct, % | Main metal minerals | Main gangue minerals | Main sulfide minerals |
|---|---|---|---|---|---|---|---|---|
| Panzhihua | Gabbro | 38 $km^2$<br>712–2570 m | TFe 33.23<br>$TiO_2$ 11.68<br>$V_2O_5$ 0.30 | TFe $2.05 \times 10^9$<br>$TiO_2$ $2.37 \times 10^8$<br>$V_2O_5$ $6.01 \times 10^6$ | $Cr_2O_3$ 0.13<br>Co 0.0203<br>Cu 0.04 | V-Ti magnetite, ilmenite | Titanaugite, labrador-feldspar | Pyrrhotite, chalcopyrite, pyrite, pentlandite |
| Hongge | Gabbro, clinopyroxenite, olivine clinopyroxenite | 60 $km^2$<br>>1700 m | TFe 27.04<br>$TiO_2$ 10.57<br>$V_2O_5$ 0.24 | TFe $1.83 \times 10^9$<br>$TiO_2$ $1.96 \times 10^8$<br>$V_2O_5$ $1.45 \times 10^7$ | $Cr_2O_3$ 0.31<br>Ni 0.06<br>Cu 0.03<br>ΣPGE 0.354 ~0.533 g/t | V-Ti magnetite, ilmenite | Titanaugite, diopside, olivine, titanohorn-blende, basic plagioclase | Pyrrhotite, pentlandite, pyrite, chalcopyrite, cubanite |
| Taihe | Gabbro | 13 $km^2$<br>1213–1913 m | TFe 30.31<br>$TiO_2$ 11.76<br>$V_2O_5$ 0.27 | TFe $1.78 \times 10^9$<br>$TiO_2$ $2.00 \times 10^8$<br>$V_2O_5$ $5.18 \times 10^6$ | Co 0.011<br>Cu 0.02 | Titanomagnetite, ilmenite | Titanaugite, basic plagioclase | Pyrrhotite, pyrite |
| Baima | Plagioclase peridotite, plagioclase-bearing olivine clinopyroxenite, troctolite, olivine gabbro | 50 $km^2$<br>up to 3989 m | TFe 25.51<br>$TiO_2$ 6.55<br>$V_2O_5$ 0.21 | TFe $1.15 \times 10^9$<br>$TiO_2$ $4.48 \times 10^7$<br>$V_2O_5$ $2.85 \times 10^6$ | Co 0.015<br>Ni 0.023<br>Cu 0.033 | Titanomagnetite, ilmenite | Titanaugite, basic plagioclase, olivine, hornblende, biotite | Pyrrhotite, chalcopyrite, pyrite, cobalt pyrite, pentlandite, cubanite |

*Sources*: Summarized mainly after Li and Mao, 1982; PXGT, 1987; Yao et al., 1993; and Liang et al., 1998.

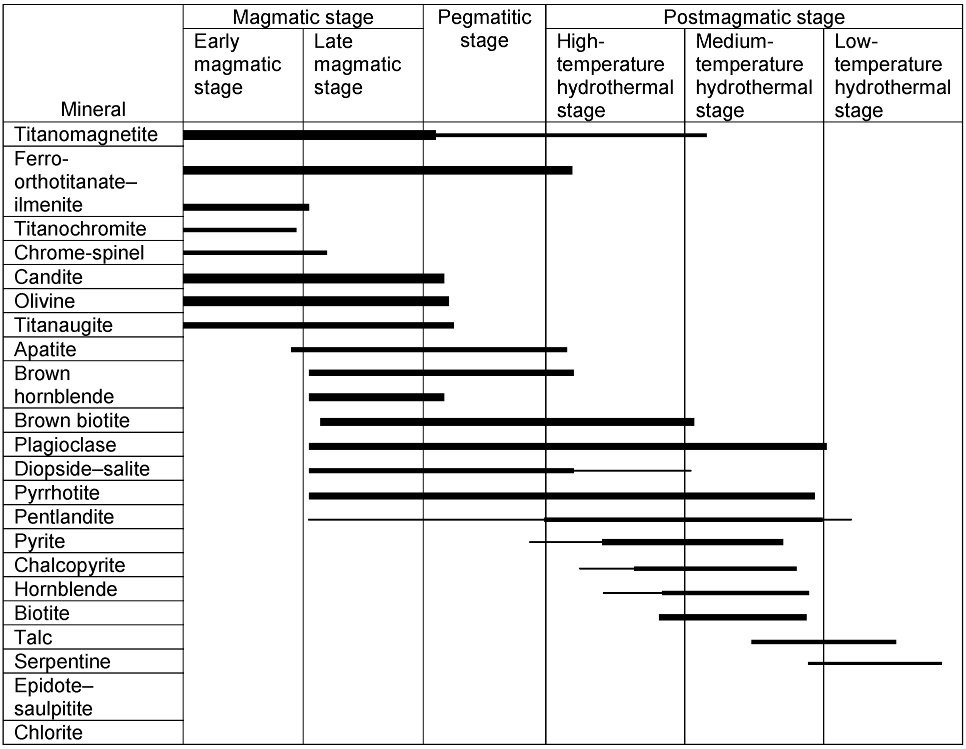


FIG. 3. Paragenesis of main ore and gangue minerals from the Hongge intrusion, according to Liu et al. (1974), Li and Mao (1982), Pan-Xi Geological Team (PXGT, 1987), and Lu et al. (1988).

west, typically in the 1–2 km range (SBGMR, 1991; Huang and Opdyke, 1998). In the west, the Emeishan lavas show a remarkable diversity of rock types including picrite, basalt, basaltic andesite, rhyolite-trachyte, and basaltic pyroclastics. Furthermore, trachyte and rhyolite tuffs occur in the upper volcanic sequence (Huang, 1986; Chung et al., 1998). In contrast, lavas emplaced in the eastern part of the Emeishan LIP are uniformly tholeiitic-alkali basalts, characterized by rather high $TiO_2$ (3.6–5%) and low MgO (<6%) contents. The Emeishan basalts can be divided into high-Ti and low-Ti types by Ti/Y ratios, of which the low-Ti basalts (Ti/Y $\leq$ 500) are confined to the lower volcanic successions in the western part of the province, whereas the high-Ti lavas (Ti/Y>500) predominate in the upper succession in nearly the entire region (Xu et al., 2001).

Interaction of a plume head with the lithosphere is suggested to be responsible for generation of the Emeishan LIP (Xu et al., 2001). This short-lived (<2 m.y.), massive igneous event required a large thermal anomaly within the mantle (Richards et al., 1989; Campbell and Griffiths, 1990), which is highlighted by the REE inversion results (Xu et al., 2001). The plume/lithosphere interaction should also generate uplift and stretching prior to, or concurrent with, volcanism (e.g., Hill et al., 1992). This is consistent with large-scale uplift and decompression in the Dongwu movement (~260 Ma) in South China, followed by massive basaltic magma extrusion (Zhang et al., 1988; Lu, 1996).

In this paper, we focus on the Emeishan basalts in the Pan-Xi area (e.g., basalts in Miyi and Ertan), equivalent to the central part of the Emeishan LIP. Most of them are characterized by high titanium contents (Song et al., 2001; Xu et al., 2001; Mei et al., 2003), similar to HT3 and HT2 Emeishan basalts as identified by Xu et al. (2001). HT2 Emeishan basalts overlie HT3 Emeishan basalts within the Ertan sequence (Xu et al., 2001).

Mg# and MgO for the basalts negatively correlate with $SiO_2$ and $TiO_2$ (Fig. 4). Positive correlations

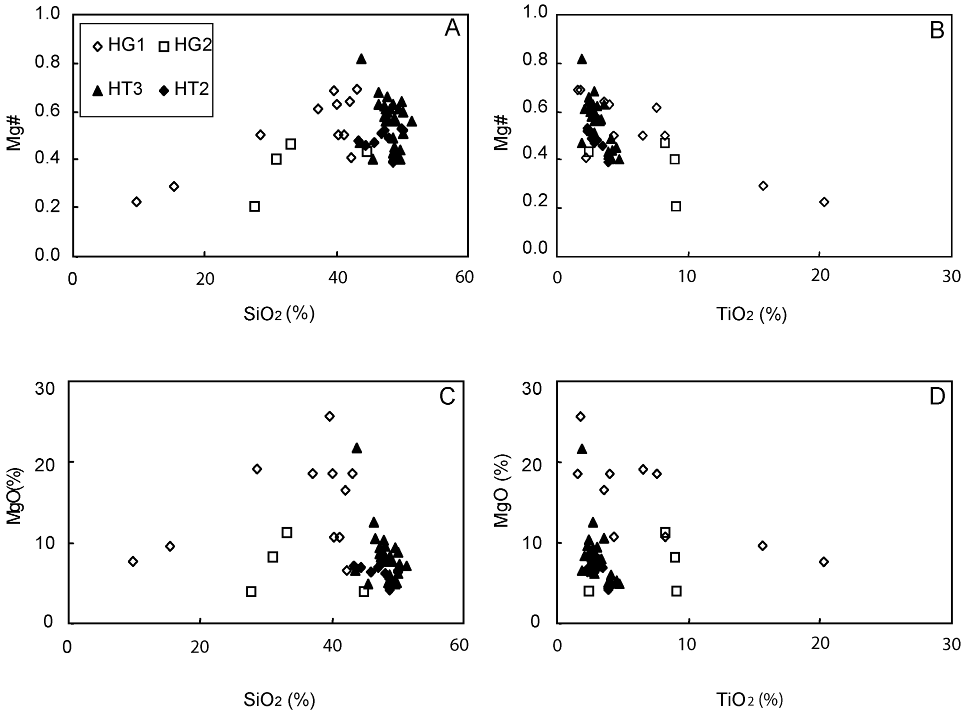


FIG. 4. Variations of $SiO_2$, and $TiO_2$ vs. Mg# and MgO for the Hongge intrusion and Emeishan basalts in the Pan-Xi area. Legend: HG1 = ultramafic portions of the Hongge intrusion (including Cycles I-III); HG2 = mafic portions of the intrusion (including Cycle IV); HT3, HT2 = high-Ti type 3, 2 Emeishan basalts. Data for HG1 are from Zhong et al. (2002); HG2 from unpublished data of H. Zhong; HT3 including data from Xu et al. (2001; HT3 basalts), Song et al. (2001; samples from Ertan), and Mei et al. (2003; samples from Cycles I, IV); HT2 including HT2 basalts and EM-95, 97, 98 of Xu et al. (2001).

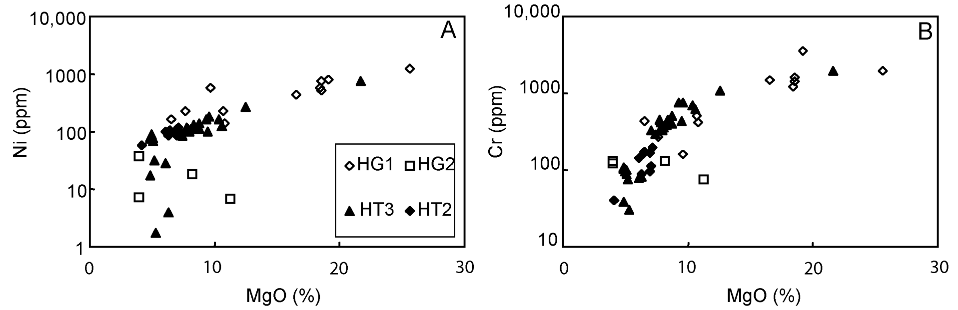


FIG. 5. Variations of Ni, and Cr vs. MgO for the Hongge intrusion and the Emeishan basalts. Symbols and data sources are the same as those in Figure 4.

between both Ni and Cr versus MgO are shown in Figures 5A–5B. HT2 basalts have obviously negative Th-U and Sr anomalies and slight Ti enrichments, whereas HT3 basalts are characterized by higher contents of incompatible trace elements, slight Nb-Ta, significant Sr depletions, and slight Ti enrichments (Fig. 6; Song et al., 2001; Xu et al., 2001; Mei et al., 2003). As summarized in Figures 7 and 8, HT3 basalts located at the bottom of the volcanic sequence exhibit enriched Sr-Nd isotopic

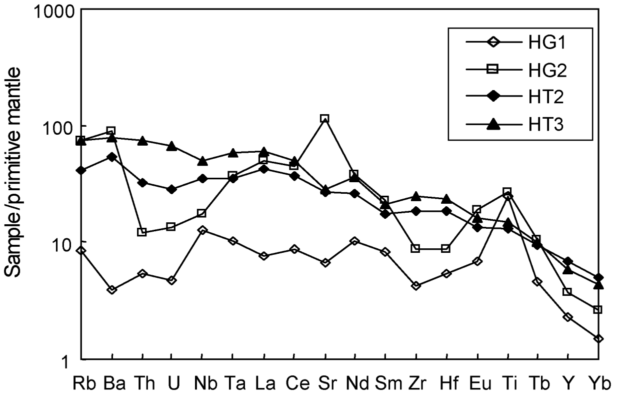


FIG. 6. Primitive mantle–normalized average trace-element concentrations for the Hongge intrusion and Emeishan basalts. Normalizing values are from Sun and McDonough (1989). Symbols are the same as those in Figure 4. La, Ce, Sm, Nd, Eu, Tb, Yb, and Ti contents for HG1 are from Zhong et al. (2002); Rb, Sr, Ba, Nb, Ta, Zr, Hf, and Y concentrations for HG1 are from Zhong et al. (2003); Th and U contents for HG1 and HG2 and the other contents for HG2 are from unpublished data of H. Zhong. Data for Emeishan basalts are from the same source as those in Figure 4.

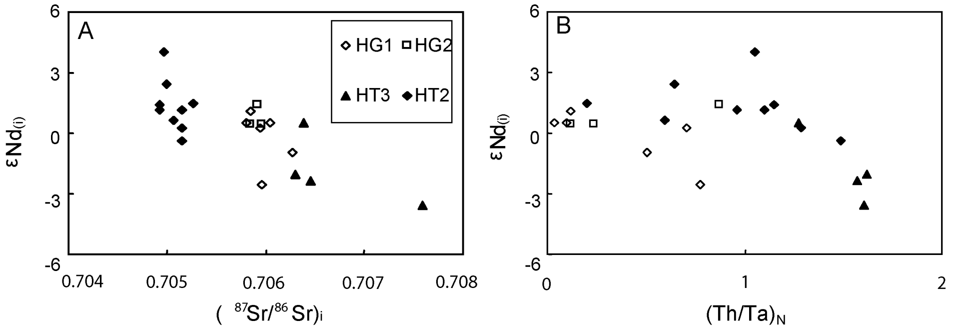


FIG. 7. Plot of $\varepsilon_{Nd}$(i) vs. $(^{87}Sr/^{86}Sr)_i$ (t = 259 Ma), and $(Th/Ta)_N$ for the Hongge intrusion and the Emeishan basalts. Normalizing values are from Sun and McDonough (1989). Symbols are the same as those in Figure 4. Isotopic data for HG1 are from Zhong et al. (2003), HG2 from Hu (2001), HT3 from HT3 basalts of Xu et al. (2001), and HT2 from HT2 basalts and EM-95, 97, 98 of Xu et al. (2001). Trace element data are from the same source as those in Figure 6.

signatures (Xu et al., 2001), elevated $(Th/Ta)_N$, $(La/Sm)_N$, $(La/Nb)_N$, $(La/Ta)_N$, Nb/Y, and Zr/Y. In contrast, HT2 basalts are characterized by relatively low $(Th/Ta)_N$, $(La/Sm)_N$, $(La/Nb)_N$, $(La/Ta)_N$, Nb/Y, and Zr/Y, and depleted Sr-Nd isotope signatures. The average PGE concentrations of 14 Emeishan basalts are 7.71 ppb Pt, 5.48 ppb Pd, 0.39 ppb Os, 0.07 ppb Ir, 0.49 ppb Ru, 0.25 ppb Rh, and 1.62 ppb Au (Zhang and Li, 1998; Fig. 9). The average Pd/Ir (78.5) and (Pt+Pd)/(Os+Ir+Ru) (13.96) ratios are much higher that those of the primitive mantle (Barnes et al., 1988).

## Discussion

### *Link between the Hongge intrusion and the Emeishan basalts*

It has long been suggested that the layered intrusions in the Pan-Xi area were derived from differentiated basaltic magma parental to the Emeishan basalts (e.g., Mei, 1973; Liu et al., 1985; PXGT, 1987; Zhang et al., 1999). However, the nature of the parental magma of the Hongge intrusion is poorly understood, mainly due to lack of comparative

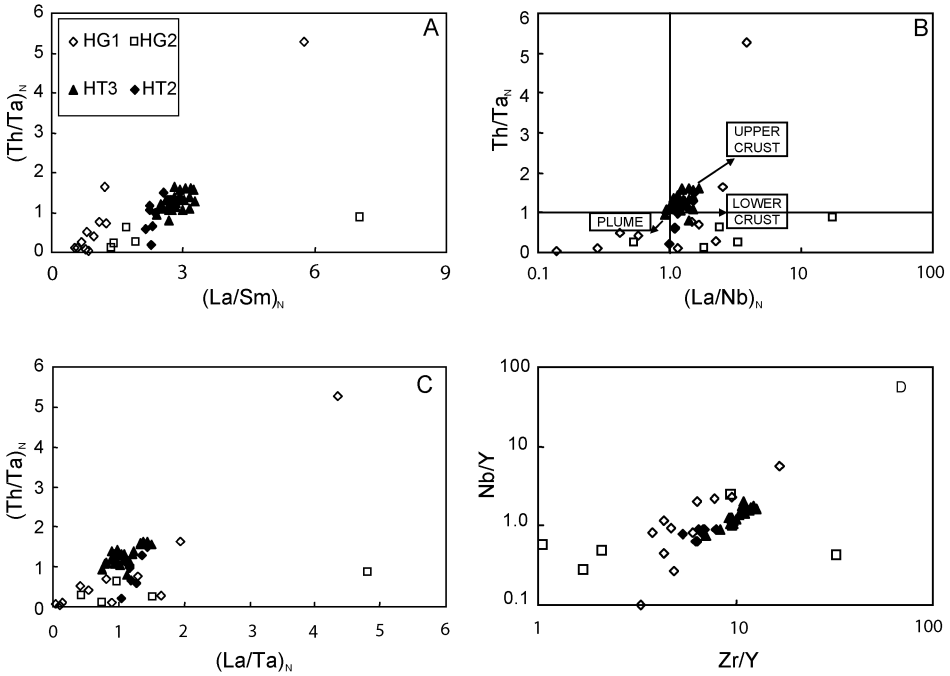


FIG. 8. (A-C) Variations of $(Th/Ta)_N$ vs. $(La/Sm)_N$, $(La/Nb)_N$, and $(La/Ta)_N$ for the Hongge intrusion and Emeishan basalts; (D) variations of Nb/Y vs. Zr/Y for the Hongge intrusion and the Emeishan basalts. Normalizing values are from Sun and McDonough (1989). Continental crust estimates from Rudnick and Fountain (1995). Symbols are the same as those in Figure 4. Data are from the same source as those in Figure 6.

studies on geochmical links between the intrusion and associated basalts.

Most of the Emeishan basalts in the Pan-Xi area are characterized by high $TiO_2$ contents, and those in the Hongge intrusion are even higher (Figs. 4B and 4D), which implies the high-Ti contents of their original magmas. The positive correlations between Ni and Cr versus MgO (Figs. 5A–5B) suggest that the Ni tended to concentrate in the olivine, whereas the Cr content was mainly dependent on pyroxene (particularly clinopyroxene).

Crustal contamination has significantly modified the compositions of mantle-derived magmas in many areas, and differences between continental flood basalts (CFB) and oceanic basalts have been attributed to different crustal contamination processes acting on plume-related magmas (e.g., Arndt et al., 1993; Wooden et al., 1993; Lightfoot et al., 1993; Lightfoot and Hawkesworth, 1997). Incompatible trace element ratios have the advantage of minimizing the effects of fractional crystallization, partial melting, and other magmatic processes, and thus should approximately represent source compositions or, in the case of mixed magmas, should represent mixtures of end-member source ratios. Accordingly, the $(Th/Ta)_N$ (e.g., Wooden et al., 1993; Arndt et al., 2003) and $(La/Sm)_N$ (e. g., Lightfoot et al., 1993; Lightfoot and Hawkesworth, 1997) ratios have been regarded as the indexes of crustal contamination. As shown in Figures 7 and 8, most of the HT3 Emeishan basalts exhibit elevated $(Th/Ta)_N$, $(La/Sm)_N$, $(La/Nb)_N$, and $(La/Ta)_N$, much higher than those of the primitive mantle (Sun and McDonough, 1989), suggesting that the parental magmas may be strongly influenced by crustal material (especially those from the middle to upper crust). This interpretation is highlighted by the enriched Sr-Nd isotopic compositions of HT3 basalts (data from Xu et al., 2001). In contrast, the slightly depleted Sr-Nd isotope signatures of HT2 Emeishan basalts are likely comparable to deeper asthenopheric mantle-plume–generated lavas similar to oceanic island basalts (Xu et al., 2001). However, the presence of continental components in HT2 basalts is still evident in terms of corresponding $(Th/Ta)_N$ and $(La/Sm)_N$, yet they are slightly lower than those of HT3

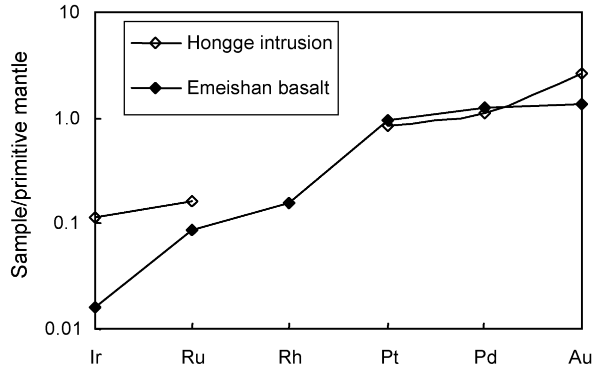


FIG. 9. Primitive mantle-normalized distribution patterns of average PGE, and Au concentrations for the Hongge intrusion and the Emeishan basalts. Normalizing values are from Barnes et al. (1988). Data for the Hongge intrusion are from Zhong et al. (2002) and for Emeishan basalts from Zhang and Li (1998).



basalts. Xu et al. (2001) invoked a gabbroic layer near the crust-mantle boundary to explain the U-Th depletions of HT2 basalts.

The slightly enriched to depleted Sr-Nd isotopic compositions of the Hongge intrusion possibly reflect the influence of continental lithospheric material (Zhong et al., 2003). Although isotopic signatures can be attributed solely to a simple mixing between HT3 and HT2 basalts, major and trace element characteristics (Figs. 4-8) for the Hongge intrusion differ obviously from those for the HT3 and HT2 basalts. They may be related to different processes of contamination and fractionation. Most of the samples in the Hongge intrusion have $(Th/Ta)_N < 1$, but highly variable $(La/Nb)_N$ (0.07–3.33) and $(La/Ta)_N$ (0.03–1.94), except for two samples highly enriched in plagioclase. Some estimates of average lower crust composition have $(Th/Ta)_N$ ~1, with $(La/Nb)_N > 1$ (e.g., Rudnick and Fountain, 1995; Fig. 8B). Thus, the incorporation of appreciable amounts of lower continental crust (i.e., a gabboric layer) in the generation of the Hongge intrusion is highlighted by the significant U-Th depletions (Fig. 6).

### *Implications for mineralization*

The Hongge Fe-V-Ti deposit was interpreted as the product of gravitational differentiation in a completely closed magma chamber (Liu and Xu, 1983; PXGT, 1987) or *in situ* crystallization accompanied by new pulses of magmas in an open-system magma chamber (Li and Mao, 1982; Liu et al., 1985; Lu et al., 1988). On geological grounds, a completely closed magma is unlikely to exist. Although zonation is an important feature of magma chambers, tapping and replenishment are also essential processes (Brügmann et al., 1993). In combination of the previous studies, a magma mixing model has recently been invoked to explain the Fe-Ti-V and Ni-Cu-PGE mineralization on the basis of PGE, trace-element, and Sr-Nd isotopic characteristics (Zhong et al., 2002, 2003). The dynamic model suggests that the Fe-Ti-V mineralization and evolution of the Hongge intrusion are controlled by open-system magmatic activity, characterized by continuous, simultaneous replenishment, assimilation, and crystallization.

As discussed above, the Hongge intrusion is located proximal to the Xigeda fault (Fig.1), through which the lavas were erupted, and therefore may have had the opportunity to become chonoliths as envisaged for the Noril'sk systems (Naldrett et al., 1992; Lightfoot and Hawkesworth, 1997). Wall or floor rocks are likely to have been assimilated at the base of the intrusion, and the resulting increase in $SiO_2$ could have caused sulfide saturation (Zhong et al., 2003). Consequently, the initial magma equilibrated with sulfide and was scavenged of Ni, Cu, and PGE to produce the Ni-, Cu-, and PGE-poor rocks in the upper part of Cycle I (Zhong et al., 2002). Shortly after this, magma at the top of the chamber broke through to the surface to erupt as HT3 Emeishan basalts, which represent the most contaminated compositions by the upper crust. A new batch of depleted magma thereafter traveled through the chonolith and erupted at the surface as the HT2 Emeishan basalts.

The above proposal is supported by similar distribution patterns of average PGE concentrations for Emeishan basalts and the Hongge intrusion (Fig. 9). As a result of continuous mixing of residual and replenishing magma, sulfide and Fe-Ti oxide liquids equilibrated with quite large amount of magma, and subsequent batches of magma further equilibrated with the sulfides and Fe-Ti oxides as they passed through the chonolith enroute to the surface. Each of these sulfide liquids was formed with a higher R-factor (i.e., mass ratio of the sulfide and silicate liquids; Campbell and Naldrett, 1979) than that of the initial sulfides in the Hongge intrusion, because the replenishment process increased the capacity of the magmas to dissolve sulfur (Brügmann et al., 1993), iron, and titanium. This mechanism explains formation of the giant Hongge Fe-V-Ti deposit and Ni-Cu-PGE mineralization, and accounts for the continuous upward increase in siderophile-element abundances of Cycles II and III (Zhong et al., 2002).

## Summary

This paper offers a progress report on a number of studies carried out on the giant Hongge Fe-Ti-V deposit and Ni-Cu-PGE mineralization, and magmatic evolution of the Hongge intrusion, as well as the causal relationship between the intrusion and the Emeishan flood basalts. The main points of this discussion may be highlighted as follows.

1. The distribution of the Hongge intrusion is linked broadly to the location of the maximum thickness of comagmatic lavas, and associated with the nearly N-S–trending Xigeda fault. The fault appears to have acted as an open-system conduit for the magmas, and as locus for the intrusion. The Hongge intrusion can be correlated chemically with units in the associated Emeishan basalts sequence.

2. Although the Hongge intrusion and the Emeishan basalts share a number of common features, significant differences in terms of trace elements and Sr-Nd isotopic compositions are due to different processes of contamination and fractionation. HT3 Emeishan basalts within the lowermost parts of the volcanic sequence were significantly contaminated by crustal material (mainly the middle to upper crust). In contrast, generation of HT2 Emeishan basalts is attributed to contamination of plume-derived magmas by melts derived from a gabbroic layer near the crust-mantle boundary. The magma parental to the Hongge intrusion was probably contaminated by appreciable amounts of lower continental crust (i.e., a gabboric layer), significantly greater than those of HT2 basalts.

3. The mixing of magmas with different compositions, originating from variable contamination, is responsible not only for generation of sulfide-rich layers, but also for magnetite layers in the Hongge intrusion. Formation of the giant Fe-Ti-V deposit and a gradual increase in the Ni, Cu, and PGE contents of the later differentiates are attributed to equilibration of the Fe-Ti oxide and immiscible sulfide liquids with successive batches of magma.

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