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World-Class Fe-Ti-V Oxide Deposits Formed in Feeder Conduits by Removing Cotectic Silicates

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Abstract

Extremely thick Fe-Ti-V oxide layers are hosted in mafic-ultramafic intrusions of the Emeishan large igneous province (LIP) in the Pan-Xi district of southwest China, accounting for a quarter of the world's Ti and V resource. It is unclear why these small intrusions contain such huge ore reserves that form world-class Fe-Ti-V oxide deposits. We find that the Hongge intrusion contains 35% Fe-Ti-V oxides, which is twice the typical content in mafic-ultramafic intrusions worldwide and the experimentally determined cotectic proportion in natural ferrobasaltic magma systems. The V content is almost constant in titanomagnetite across the entire Hongge intrusion in the Emeishan LIP, indicating a small (10–20%) proportion of cotectic Fe-Ti-V oxide during fractional crystallization. The bulk composition of the intrusion indicates an open magma system at the time of its formation. Clinopyroxene phenocrysts from overlying basalts contain Fe-Ti-V oxide inclusions, indicating that the phenocrysts crystallized at depth from magma saturated in Fe-Ti-V oxide and were then transported to the surface. We suggest that these intrusions were feeder conduits to the overlying basalts, where the silicates were cotectic with Fe-Ti-V oxides which were then extracted from the underlying intrusion as phenocrysts. Such a fundamental process is key to increase the proportion of oxide minerals in the residual assemblage, thereby upgrading the barren oxide-bearing rocks to world-class Fe-Ti-V oxide deposits in the small intrusions of the Emeishan LIP. A similar process might have occurred in LIPs elsewhere, meaning that intrusions formed as conduit-like open systems to the basalts in LIPs are good exploration targets for giant high-grade Fe-Ti-V oxide deposits.

Introduction

Vanadium and Ti have been listed as critical mineral resources by many countries in recent years (e.g., Schulz et al., 2017). Magmatic Fe-Ti-V oxide deposits are the world's most important resources for Ti and V, and they are genetically associated with mafic-ultramafic intrusions. China holds ~24 and ~47% of global Ti and V reserves, respectively (U.S. Geological Survey, 2019). About 90% of China's Ti reserves and 63% of its V reserves (Song et al., 2018) occur as magmatic Fe-Ti-V oxide deposits hosted by several adjacent mafic-ultramafic intrusions in the Panzhihua-Xichang (Pan-Xi) district of southwest China (Fig. 1). The mineralized intrusions are part of the Emeishan large igneous province (LIP) and are genetically associated with the Emeishan mantle plume (Chung and Jahn, 1995; Xu et al., 2001; Zhong et al., 2002; Zhou et al., 2002). The most remarkable feature of these deposits is the huge ore reserves in the relatively small mafic-ultramafic intrusions compared with other typical large mafic-ultramafic intrusions (Pang et al., 2010; Bai et al., 2012).

Mafic-ultramafic layered intrusions commonly contain thin layers of massive Fe-Ti-V oxides (e.g., a total of 20-m thick in the Bushveld Complex; Tegner et al., 2006), and most of the lithologic zones in such intrusions contain <20% Fe-Ti-V oxides, as reported for the Bushveld Complex (Ashwal et al., 2005; Yuan et al., 2017) and the Skaergaard intrusion (Tegner et al., 2009; Thy et al., 2009). In the Pan-Xi area, intrusions that are 1- to 2-km thick contain stratified massive orebodies (>50% Fe-Ti-V oxides) that are 60- to 100-m thick (Pang et al., 2010). These intrusions also contain thick (on the order of 100s of meters) layers of disseminated ore (20–50% Fe-Ti-V oxides). The presence of extremely thick, massive, and disseminated ore means that most of the lithologic zones are economically viable; consequently, this area is the largest Ti and V ore district in the world.

There are two types of layered intrusions based on compositional differences. The layered mafic intrusions include Panzhihua, Taihe, and Baima intrusions. The layered mafic-ultramafic intrusions include Hongge and Xinjie intrusions. It has been suggested that these intrusions, the coeval syenites, and A-type granites represent the crystallized cumulates and residual melt of basaltic parent magmas (Shellnutt et al., 2009, 2010). Isotopic variability in these intrusions (Zhong et al., 2003; Zhou et al., 2005; Shellnutt et al., 2011) suggests that crustal material was involved in these intrusions via crustal assimilation or source contamination. However, a uniform feature of thick ore layers in these intrusions indicates that a common process was involved in the metallogenesis regardless of compositional differences between these intrusions. The genesis of Fe-Ti oxide in these intrusions is highly debatable. Models include the following: (1) early crystallization of Fe-Ti-V oxide from a relatively normal basaltic parental magma by oxidation or hydration through contamination (Ganino et al., 2008; Howarth and Prevec, 2013; Luan et al., 2014); (2) cotectic crystallization from basaltic magma followed by the setting and sorting process (Pang et al., 2008a; Shellnutt et al., 2011; Bai et al., 2012; Zhang et al., 2012; Song et al., 2013); and (3) the consequence of silicate liquid immiscibility (Zhou et al., 2005; Liu et al., 2016; Wang et al., 2018). However, silicate liquid immiscibility and fractionation crystallization are the common processes involved in the formation of mafic-ultramafic layered intrusions regardless of Fe-Ti oxide mineralization potential (e.g., the Bushveld Complex and

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Skaergaard intrusion). Thus, an especially effective enrichment mechanism other than these processes is required to explain how such thick Fe-Ti-V oxide layers were generated in these intrusions. In this study, we investigated a 1,200-m-thick stratigraphic section of the Hongge intrusion (the largest deposit in Pan-Xi area; Yao et al., 1993) and coeval basalts to identify the mechanism of Fe-Ti-V oxide enrichment in these intrusions. Our results have important implications for giant, high-grade Fe-Ti-V oxide exploration in regions with similar geology.

Geologic Setting

The ~260 Ma Emeishan LIP consists of volcanic sequences (picrites, flood basalts, rhyolitic/trachytic flows), and spatially and temporally associated mafic-felsic intrusive rocks (Chung and Jahn, 1995; Xu et al., 2001; Zhou et al., 2002). The Emeishan basalts have been divided into high-Ti (TiO_2 >2.5%, Ti/Y >500) and low-Ti (TiO_2 <2.5%, Ti/Y <500) series that were derived from different mantle sources (Xu et al., 2001; Xiao et al., 2004). The Pan-Xi district is located in the inner zone of the Emeishan LIP, where mafic-ultramafic intrusions (including the Hongge, Panzhihua, Baima, Taihe, and Xinjie intrusions) occur along N-S-trending faults (Fig. 1). These intrusions generally have thicknesses of 1 to 2 km and cover an area of 13 to 60 km^2, making them similar in size to the rift-related mafic-ultramafic intrusions such as the Koillismaa mafic layered intrusion in northeastern Finland (Karinen et al., 2015), but much smaller than other well-known mafic-ultramafic in-

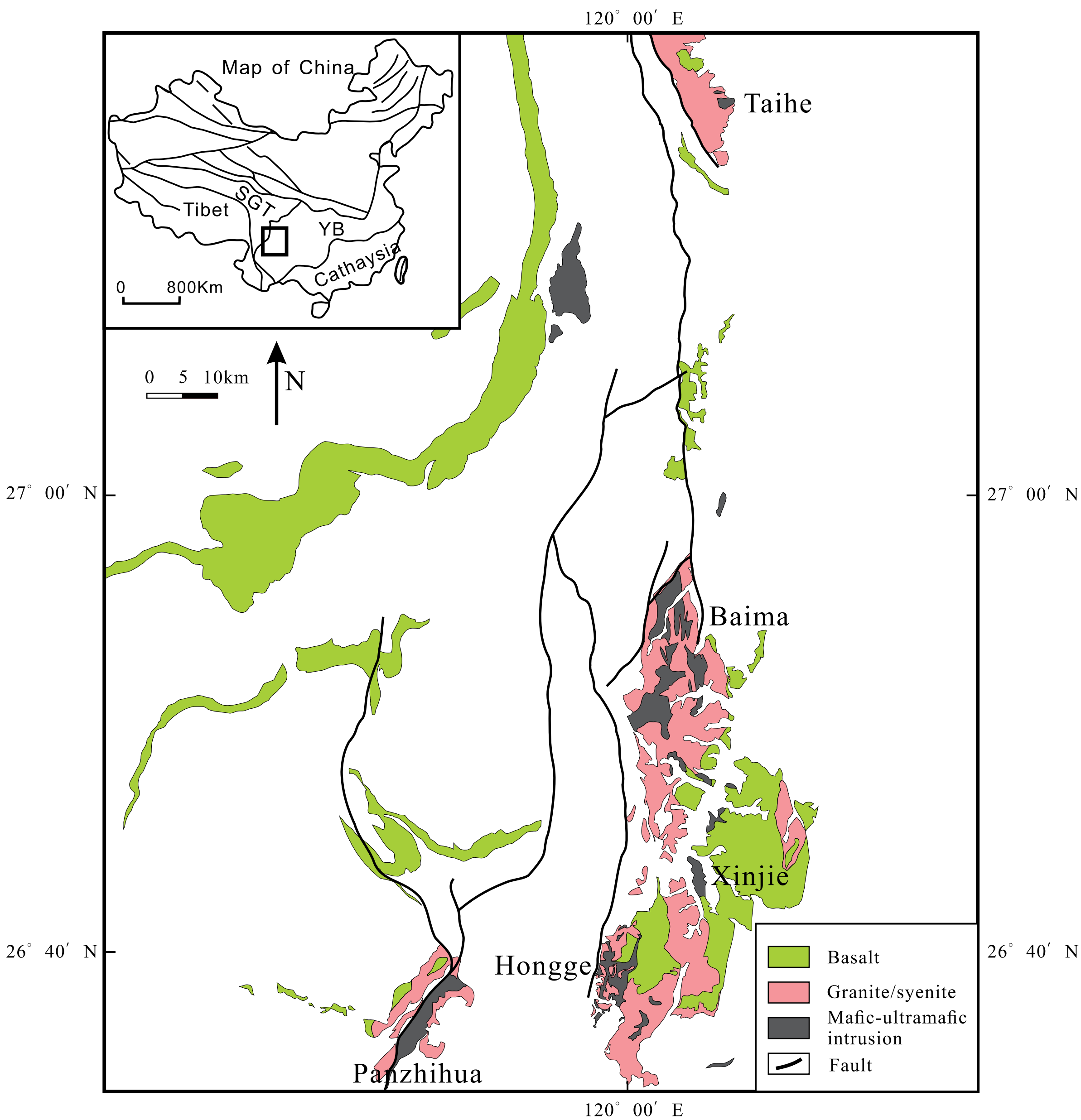

Fig. 1. Distribution of mafic-ultramafic layered intrusions hosting world-class Fe-Ti-V oxide deposits and coeval felsic plutons and continental flood basalts in the Pan-Xi district of the Emeishan large igneous province, South China. SGT = Songpan-Ganze terrane, YB = Yangtze block.

trusions such as the Bushveld Complex (Tegner et al., 2006), Stillwater Complex (McCallum, 1996), and Kiglapait intrusion (Morse, 1979). World-class magmatic Fe-Ti-V oxide deposits were discovered in these intrusions in the early 1970s. These deposits have total proven reserves of 7,209 million tons (Mt) Fe_2O_3, ~559 Mt TiO_2, and 17.4 Mt V_2O_5 (Song et al., 2018). Commonly, felsic plutons and flood basalts are spatially and temporally associated with these mafic-ultramafic intrusions (Fig. 1). However, the majority of the flood basalts in this area have been eroded as a result of uplift. Sporadically distributed basalts include the Longzhoushan basalts that crop out close to the Hongge and Xinjie intrusions and the Ertan basalts that crop out close to the Panzhihua intrusion. It is generally believed that the parental magmas for all of the ore-bearing intrusions are comparable to the coeval high-Ti basalts (Pang et al., 2008a; Bai et al., 2012, 2019; Shellnutt and Pang, 2012; Song et al., 2013; Luan et al., 2014).

The 16-km-long, 3- to 6-km-wide, and 1.5-km-thick sill-like Hongge intrusion is exposed over an area of ~60 km^2 (Fig. 2a). It hosts the largest magmatic Fe-Ti-V oxide deposit in the district that contains 4,572 Mt of oxide ores with 1.83 × 10^9 t Fe, 1.96 × 10^8 Ti, and 1.45 × 10^7 t V (Ma et al., 2003). The Hongge intrusion and the Proterozoic metamorphosed sedimentary-volcanic rocks and dolomitic limestones of the Sinian Dengying Formation. The overlying subvolcanic mafic rocks to the northeast of the intrusion are distributed gradually into the Emeishan basalts at the top of this rock unit. Temporally and spatially associated Late Permian alkaline syenites make up 29 vol % of the intrusion (Pan-Xi Geological Team, 1987). This intrusion can be divided into a marginal series at the base that mainly consists of quench-textured, fine-grained (olivine) gabbros and an overlying layered series that mainly consists of coarse-grained cumulates. The layered series can be further divided into two cyclic units (Units I and II; Fig. 2b) based on the appearance or disappearance of cumulus minerals. Four types of rocks have been recognized in each unit from the base upward: olivine-clinopyroxenites, Fe-Ti oxide-rich clinopyroxenites, massive Fe-Ti oxide ore layers, and apatite-rich gabbros. The general crystallization order in each unit is as follows: olivine + clinopyroxene + Fe-Ti oxides→clinopyroxene + Fe-Ti oxides→clinopyroxene + plagioclase + Fe-Ti oxides + apatite.

Thick, massive Fe-Ti-V oxide layers containing >50% Fe-Ti-V oxides and appreciable amounts of silicates (Figs. 2b, 3a, Table A1) have a total thickness of >100 m. They occur mainly within the clinopyroxenite zone, which accounts for the major reserve in this deposit. The titanomagnetite intergrows with ilmenite to form a massive granular texture in the ores. The other lithologic zones contain 20 to 50% Fe-Ti-V oxides as disseminated ore. Clinopyroxenes from both the massive and disseminated ores commonly contain abundant euhedral to rounded Fe-Ti oxide inclusions or partial inclusions (Fig. 3a, b). All lithologic zones have ratios of titanomagnetite to ilmenite that range from almost pure titanomagnetite to 3:1, with an average of 4:1. Subsolidus exsolution textures in the titanomagnetite are well developed both in the massive and disseminated ores, which are mainly characterized by the ilmenite lamellae in the host magnetite.

Syenites and I-type granites cover the gabbro zone and are overlain by the Emeishan flood basalts. The syenites have zircon U-Pb age and Sr-Nd-Hf isotope compositions that are similar to the Hongge layered series (Wang et al., 2015), suggesting that the syenites and Hongge intrusion were generated by fractional crystallization of a common parental magma. In contrast, the I-type granites originated from the partial melting of the mid-upper crustal associated with the underplating of plume-derived magmas (Zhong et al., 2007). Thick Emeishan high-Ti basalts (>3,000 m; Mei et al., 2013) to the west of the Hongge intrusion are mainly composed of (olivine) pyroxene-phyric, amygdaloidal basalts (Fig. 3c) interbedded with massive plagioclase-phyric basalts (Zhong et al., 2006). Clinopyroxene phenocrysts in the basalts contain inclusions of Fe-Ti-V oxides (Fig. 3d, e).

Methods and Results

In total, 164 samples were collected at 5- to 10-m intervals from a 1,200-m drill core that intersected the entire known vertical stratigraphy of the Hongge intrusion. Whole-rock major and trace element concentrations were determined using X-ray fluorescence spectrometry and inductively coupled plasma-mass spectrometry, respectively. Titanomagnetite compositions were analyzed by laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) at the State Key Laboratory of Ore Deposit Geochemistry, Institute of Geochemistry, Chinese Academy of Sciences, following the analytical protocol and data reduction methods of Gao et al. (2013) and Huang et al. (2013). Reference materials (BCR-2G and ML3B-G) were analyzed to monitor data quality. The offline data processing was performed using a program called ICP-MS Data Cal of Liu et al. (2008). The precision of the LA-ICP-MS data is better than 10% for most elements (Fig. A1).

Most of the samples contain Fe_2O_{3total}, TiO_2, and V contents above the cutoff grade (Fig. A2), suggesting the occurrence of thick layers of economic ore in the intrusion that contains high contents of Fe-Ti-V oxides. The composition of titanomagnetite crystals varies from that of near-primary titanomagnetite crystalized from basaltic magma (Pang et al., 2008b) to that of near-pure magnetite following the subsolidus exsolution of ilmenite (Fig. A3). V contents of titanomagnetite range from 3,500 to 6,500 ppm in the entire stratigraphic section, which is much less variable than in the Bushveld complex (Fig. 4a, b). In addition, V contents in titanomagnetite show a positive correlation with Fe_2O_{3total} contents (Fig. 4a), indicating that the variation in V content was controlled mainly by the subsolidus exsolution of ilmenite. This means that the primary titanomagnetite before oxyexsolution would have had a narrower range of V content than that measured, which in turn suggests that the partition coefficient of V for the bulk fractionating assemblages is close to unity during fractional crystallization. In contrast, there is no correlation between V and Fe_2O_{3total} in magnetites of the Bushveld Complex (Fig. 4a). This, together with the upward decreasing of V contents in magnetites (Fig. 5b), implies a higher partition coefficient of V during magnetite crystallization in the Bushveld Complex. The difference in the partition coefficient of V between these two intrusions may be caused by different oxygen fugacities of them since the partition coefficient of V is a function of oxygen fugacity (Toplis and Corgne, 2002). Cr contents in titanomagnetite decrease upward, with an abrupt increase in some stratigraphic

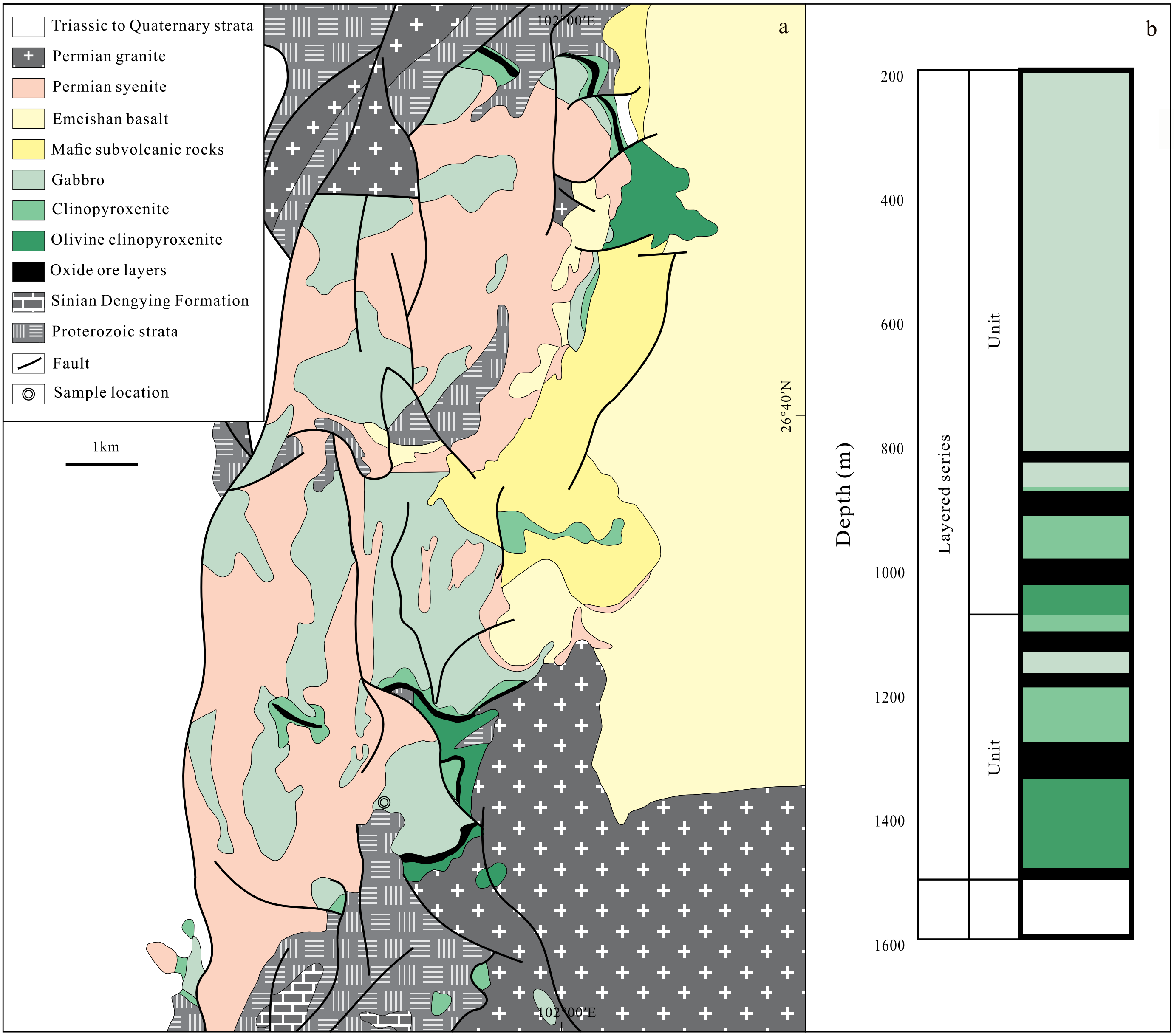

Fig. 2. (a) Geologic map showing the distribution of major rock types in the Hongge intrusion (modified after Pan-Xi Geological Team, 1987). (b) Composite stratigraphic column of the Hongge mafic-ultramafic intrusion.

levels, suggesting the in situ fractional crystallization of Fe-Ti-V oxides and periodic magma recharging (Fig. A4). Whole-rock V contents show a positive correlation with Fe_2O_{3total} contents (Fig. 4b), further confirming that the V content is relatively constant in all the samples. However, such a correlation does not exist in the Bushveld Complex (Fig. 4b).

Discussion

Proportion of Fe-Ti oxide during crystallization

The strong enrichment of Fe-Ti-V oxides in the Hongge intrusion in the Pan-Xi area is highlighted by the high FeO_{total} and TiO_2 contents in bulk compositions of the cumulate rocks (Table 1). Most of the rocks (132 of 164 samples) from the Hongge intrusion contain 20 to 90% Fe-Ti-V oxides (Fig. 5a). The weighted average Fe-Ti-V oxide content of the entire Hongge intrusion is 35%. The euhedral Fe-Ti oxide inclusions in clinopyroxene (Fig. 3a) suggest that the Fe-Ti-V oxides were crystallized together with clinopyroxene from the magma, rather than immiscible Fe-Ti-V–rich liquid (Pang et al., 2008a). This interpretation is further supported by the upward decrease in magnetite Cr contents (Fig. A4) and the positive correlation between the Cr contents of magnetite and associated clinopyroxene within each unit (Bai et al., 2012). Howarth et al. (2013) suggested that the Fe-Ti oxides were crystallized within a deep magma chamber and then transported to their current position as crystal-rich slurries. It is questionable how such a high proportion of dense, coarse-

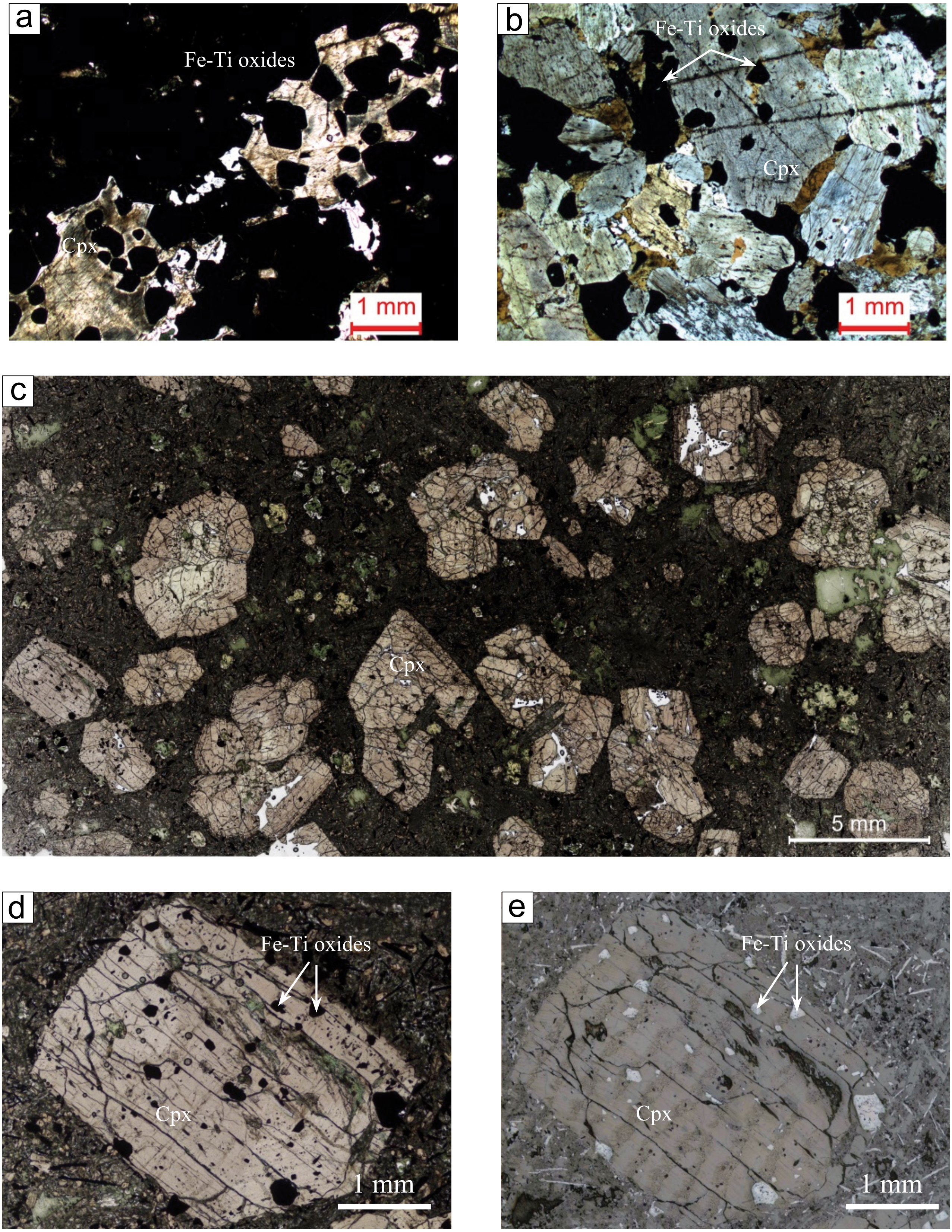

Fig. 3. (a) Massive ore with clinopyroxene (Cpx) containing inclusions or partial inclusions of Fe-Ti-V oxides; (b) disseminated ore with clinopyroxene containing inclusions of Fe-Ti-V oxides, and (c) Overview of the overlying clinopyroxene-bearing phyric-basalts. (d-e) Clinopyroxene phenocrysts containing inclusions of Fe-Ti-V oxides in the overlying basalts, (d) plane-polarized light, and (e) cross-polarized light.

Table 1. The Mass-Balance Calculation for the Hongge Fe-Ti-V Oxide Mineralized Intrusion

	Hongge bulk-composition	Basalt	Syenite	Plag	Cpx	Ol	Fe-Ti oxide	Phenocryst-mixture	70% bulk + 30% syenite	50% bulk + 50% phenocryst	70% j + 30% syenite	Bulk-20% Fe-Ti oxides	70% l +30% syenite
	a	b	c	d	e	f	g	h	i	j	k	l	m
SiO_2	31.48	48.25	62.97	51.87	50.81	40.06		50.34	40.93	40.91	47.53	39.35	46.44
TiO_2	9.07	3.54	0.61	0.06	1.88		23	1.26	6.53	5.16	3.80	5.59	4.09
Al_2O_3	8.61	12.53	17.53	29.87	3.78		2.6	10.56	11.29	9.58	11.97	10.11	12.34
Fe_2O_3	27.17	12.92	4.13	0.2	6.53	17.16	71	5.57	20.26	16.37	12.70	16.21	12.59
MgO	8.25	7.87	0.69	0	13.95	41.47	3.4	12.11	5.98	10.18	7.33	9.46	6.83
CaO	12.2	10.96	1.11	12.76	22.32			18.18	8.87	15.19	10.96	15.25	11.01
Na_2O	0.91	2.11	8.37	4.12	0.44			1.40	3.15	1.16	3.32	1.14	3.31
K_2O	0.7	1.28	3.13	0.03	0			0.01	1.43	0.35	1.19	0.88	1.55
Zr	55	283	815						283	27.50	264	68.8	292

Notes: a = Bulk composition of cumulate rocks from drill core ZK11420 of Hongge intrusion (n =164); b = Emeishan basalt coeval to the Hongge intrusion (Qi et al., 2008); c = syenite coeval to the Hongge intrusion; d-g = typical mineral composition of the Hongge intrusion (Bai, 2012; Bai et al., 2012); h = mixture of olivine, chalcopyrite, and plagioclase with the ratios similar in the intrusion (0.07:0.66:0.27)

Abbreviations: Cpx = clinopyroxene, Ol = olivine, Plag = plagioclase

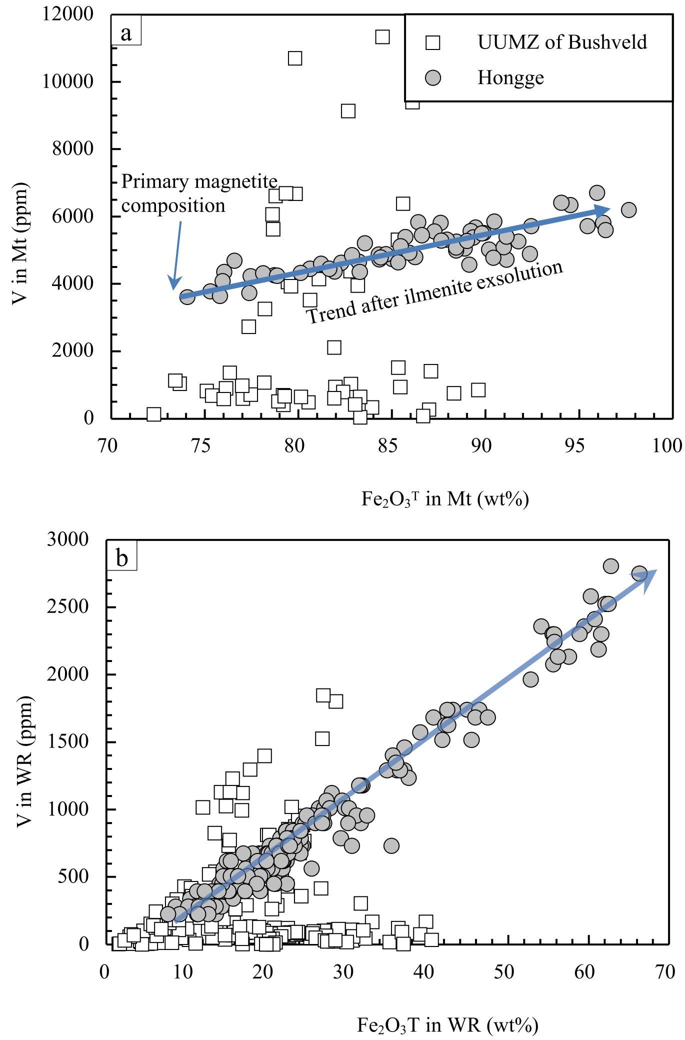

Fig. 4. Vanadium content in (a) titanomagnetite and in (b) whole rocks (WR) of the Hongge intrusion and the Upper zone of Bushveld Complex (Yuan et al., 2017; Fischer, 2018). UUMZ = Upper Main zone and Upper zone.

grained Fe-Ti-V oxides could be so effectively transported to a shallow level. Moreover, the regular decrease in the Cr contents of titanomagnetites (Fig. A4) suggests that the titanomagnetite crystallized from the magma in situ rather than being transported as slurries from the deep magma chamber.

There are two ways the unusually high proportions of Fe-Ti-V oxides could be produced in the Hongge intrusion: (1) 35% Fe-Ti-V oxide together with other silicates directly crystallized from the parental magma, and (2) a lower cotectic proportion of Fe-Ti-V oxides could have crystallized from the magma and then upgraded the whole intrusion to the present contents. The proportions of various cotectic solid phases that crystallize from natural ferrobasaltic magma have been determined in previous experimental studies (Thy and Lofgren, 1994; Toplis and Carroll, 1995; Botcharnikov et al., 2008). The results indicate that modal Fe-Ti-V oxides commonly make up <20% of total solid phases during fractional crystallization. The bulk Fe-Ti-V oxide contents in the cumulate rocks of the Bushveld Complex (Yuan et al., 2017), Koillismaa mafic layered intrusion (Karinen et al., 2015), and the Skaer-

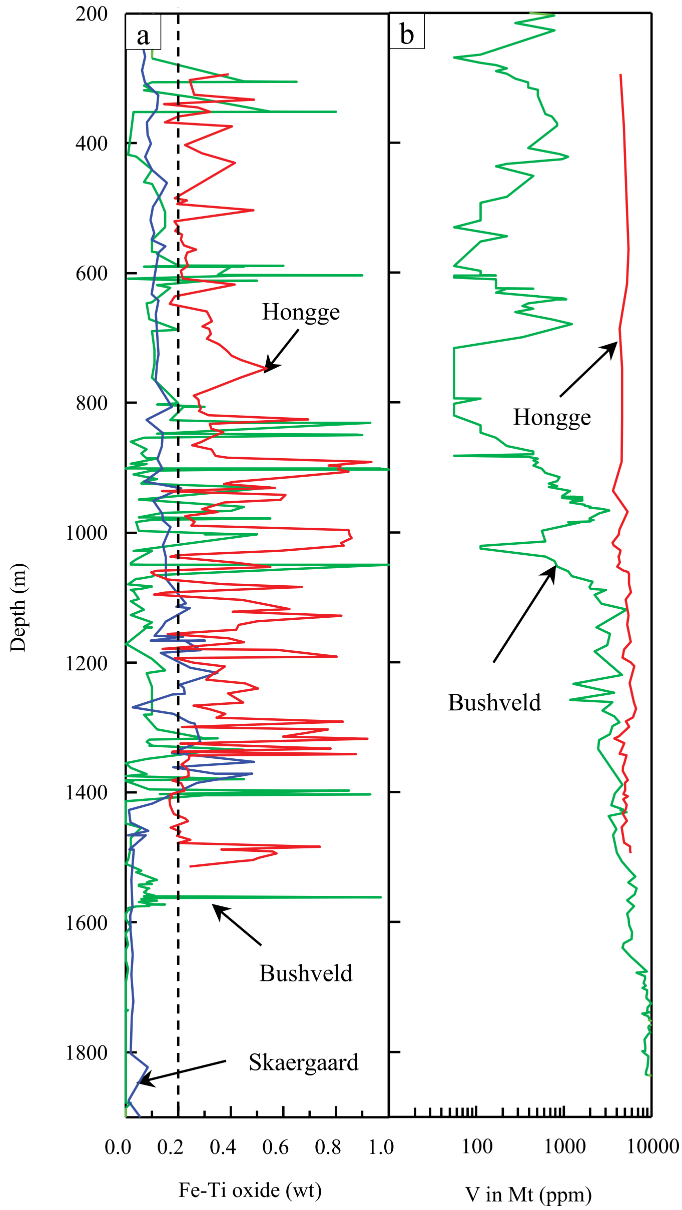

Fig. 5. Content of (a) Fe-Ti-V oxides in rocks and (b) V in titanomagnetite throughout the Hongge intrusion and the Upper zone of the Bushveld Complex (Ashwal et al., 2005; Tegner et al., 2006), and the Skaergaard intrusion (Thy et al., 2009).

gaard intrusion (Tegner et al., 2009; Thy et al., 2009) after Fe-Ti-V oxide saturation are generally below 20% (Fig. 5a), which is consistent with the experimental results. However, the weighted average Fe-Ti-V oxide content of the Hongge intrusion (35%) is twice the experimentally determined cotectic content in natural ferrobasaltic magma systems, as well as twice the content in typical mafic-ultramafic intrusions worldwide (Fig. 5a).

Although the exact composition of the parental magma of the Hongge intrusion is still debatable, it is generally believed that the parental magma had normal basaltic compositions, similar to the coeval Emeishan high-Ti basalts (Pang et al., 2008a; Bai et al., 2012; Luan et al., 2014). Could the basaltic parental magma crystallize as high as 35% Fe-Ti-V oxides? The crystallization of such a large amount of Fe-Ti-V oxides (titanomagnetite/ilmenite = 4:1) from the parental magma would have resulted in a rapid drop in the contents of compatible elements (e.g., Cr and V) in the magma and titanomagnetite. For example, the V content in titanomagnetite from the upper zone of the Bushveld Complex decreases from >10,000 ppm at the base to <100 ppm at the top of each cycle (Fig. 5b) (Tegner et al., 2006). However, the primary titanomagnetites in the Hongge intrusion have relatively constant V contents (~3,500 ppm; Fig. 4a) throughout the entire stratigraphy. Thus, the absence of a reduction in V content toward the top of the stratigraphy indicates that the bulk partition coefficient of the fractionating assemblages was close to unity during fractional crystallization.

The average V content of high-Ti basaltic magmas and ilmenite in the Emeishan LIP is ~370 and ~580 ppm (GEOROC database), suggesting a partition coefficient of ~9 and 1.5 for V in titanomagnetite and ilmenite. Thus, the crystallization of 35% of Fe-Ti-V oxides would have resulted in a rapid drop in the V content of the titanomagnetite with magma differentiation (Fig. 6). Further calculations show that the V content would increase and decrease with magma differentiation at the proportion of 10 and 20% Fe-Ti-V oxide crystallization, respectively. As a result, a constant V content in titanomagnetite requires a cotectic Fe-Ti-V oxides content of 10 to 20%, similar to the experimental determined cotectic content in natural ferrobasaltic magma systems. Various processes (e.g., settling and sorting) in a closed magma chamber can redistribute Fe-Ti-V oxides but cannot raise the bulk content of such minerals in the intrusion. Consequently, the unusually high proportion of oxides in these intrusions requires an effective enrichment mechanism during crystallization and solidification.

Open magma chamber system

If a magma chamber remains a closed system, the bulk composition of cumulate rocks in the intrusion should be equal to the parental magma. The bulk compositions of cumulate rocks from the mineralized intrusions in the Pan-Xi area are much more mafic (e.g., higher in MgO, Fe_2O_{3total}, and TiO_2, and lower in SiO_2) than their proposed parental magmas (e.g., coeval Emeishan basalt, Table 1). This compositional inconsistency suggests an open magma system where not all the magma/mineral involved in the formation of these intrusions was retained. The intrusions have much lower bulk abundances of Zr (55 ppm, Table 1) than the coeval Emeishan basalts (283 ppm, Qi et al., 2008), suggesting a melt with Zr content higher than the coeval basalts was extracted from the Hongge magma chamber.

Based on mass-balance modeling, it has long been proposed that a significant volume of residual felsic magma had escaped from the Bushveld magma chamber at the end of magma differentiation to form the part of the Rooiberg Group lava sequence or the Rashoop Granophyre (Cawthorn and Walraven, 1998; Vantongeren et al., 2010; Mathez et al., 2013). The evolved part of some mafic-ultramafic intrusions could have also been missed by tectonic truncation (e.g., Karinen et al., 2015). In the Pan-Xi area, coeval A-type granites and syenites are thought to be the residual melt of mafic-ultramafic intrusions (Shellnutt et al., 2009; Shellnutt

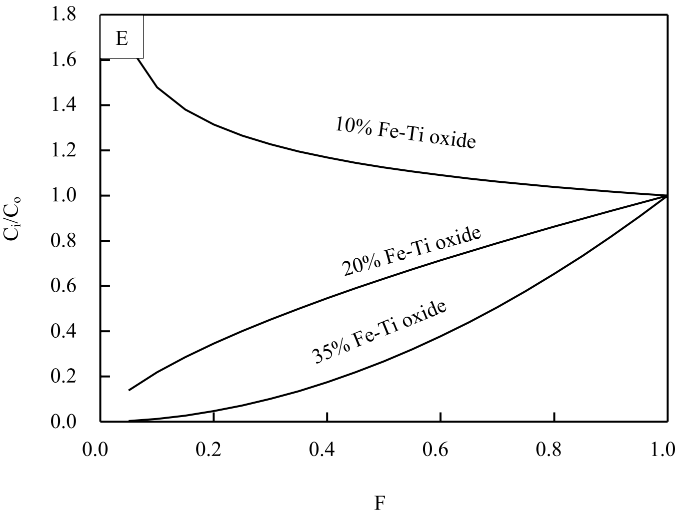

Fig. 6. Calculated depletion of V in the residual melt with variable proportions of Fe-Ti-V oxides (titanomagnetite/ilmenite = 4:1) fractional crystallization from the magma using Rayleigh fractionation with V partition coefficient of 9 and 1.5 for titanomagnetite and ilmenite (see text). C_i = instantaneous V content in the residual melt, C_o = V content in initial melt, F = a fraction of melt.

and Jahn, 2010). The syenites coeval with the Hongge intrusion has zircon age and Sr-Nd-Hf isotope composition similar to the layered series of the Hongge intrusion (Luan et al., 2014; Wang et al., 2015). This is consistent with the interpretation that the syenites and the Hongge intrusion were generated by fractional crystallization of a common parental magma. Fractional crystallization of the parental magma of the Hongge intrusion was simulated using Rhyolite-MELTS software (Gualda et al., 2012) at a f_{O_2} of FMQ and a pressure of 3 kbar. The results suggest that the Hongge syenites can be generated after 70 to 80% fractional crystallization of basaltic magma. A similar proportion (~30%) of the residual felsic melt is estimated from the bulk Zr content of Emeishan basalts (260 ppm) and Hongge syenites (~800 ppm). Assuming a closed system where a basaltic parent magma (e.g., 45–50% SiO_2) produced both the oxide-rich ultramafic intrusions and the syenites, recombining the two compositions in the proportions appropriate for their original derivation cannot reproduce the proposed original basaltic magma composition (column i in Table 1). Moreover, such mixing would produce a melt with low SiO_2, high Fe_2O_{3total}, and high TiO_2 contents relative to natural basaltic magma (Table 1). Even if an unreasonably high proportion of syenite (e.g., >50%) is added to the bulk composition to balance the low SiO_2, high Fe_2O_{3Total}, and high TiO_2 contents, the mixing composition is still distinct from basaltic magma due to their low MgO, low CaO contents, and high incompatible elements such as Zr (>430 ppm). The above mass-balance calculation indicates components other than syenitic magmas also escaped from the Hongge magma chamber. More importantly, the escape of pure residual felsic residual melt or other melt would not change the cotectic proportion of Fe-Ti-V oxides in the earlier-crystallized assemblage. In contrast, removing cotectic silicates out of the magma chamber is possibly an effective way to increase the proportion of Fe-Ti-V oxides.

Genetic model and exploration implications

In addition to syenites, the Emeishan basalts, containing clinopyroxene, plagioclase, and olivine phenocrysts, are temporally and spatially related to the Hongge mafic-ultramafic intrusion (Zhong et al., 2006). The clinopyroxene phenocrysts from the basalts contain abundant inclusions of Fe-Ti-V oxides (Fig. 3d, e), suggesting that the phenocrysts were crystallized together with Fe-Ti-V oxides in a magma chamber from basaltic magma and were then carried to the surface by the basaltic magma. The absence of coarse-grained Fe-Ti-V oxide phenocrysts in these basalts indicates that the cotectic Fe-Ti-V oxides were retained in a magma chamber due to their high densities. The basalts located near the mafic-ultramafic intrusions in the Pan-Xi area have much lower Fe_2O_{3total} contents than those outside the Pan-Xi area (Bai et al., 2012), which is consistent with the interpretation that Fe-Ti-V oxides were removed from these basalts in a magma chamber before ascending to the surface and being erupted. Similar inclusions of Fe-Ti-V oxides in clinopyroxenes are widely observed in ore rocks of the Hongge intrusion (Fig. 3a, b). We therefore suggest that the silicate phenocrysts in the overlying basalt were derived from the magma chambers of these intrusions that contain Fe-Ti-V oxide mineralization. These mineralized intrusions acted as feeder conduits, from which some of the liquid escaped to form the overlying basalts (Fig. 7). The separation of basaltic magma from coarse-grained Fe-Ti oxides was induced by density contrast between Fe-Ti oxides and basaltic magma. Ascending basaltic magma transported abundant clinopyroxene, plagioclase, and olivine crystals from the fractionating assemblage due to their low density (2.7–3.5 g/cm^3), resulting in the enrichment of Fe-Ti-V oxides of high density (4.7–5.2 g/cm^3) in the residual solid cumulates (Fig. 7). Such an enrichment process would have upgraded the barren oxide-bearing rocks to world-class Fe-Ti-V oxide deposits in the Emeishan LIP. The Hongge intrusion was overlain by subvolcanic mafic rocks in the northwest of the intrusion (Fig. 2). These subvolcanic mafic rocks are then distributed gradually into basalts at the top of this rock unit. The variation of rock types from cumulate rocks, subvolcanic rocks to volcanic rocks upward, is consistent with the conduit system in the upper crust. The Hongge and other deposits are mainly exposed along with a series of large, N-S–dipping deep faults in the western Emeishan LIP (Fig. 1). These faults formed during the Mesoproterozoic and were reactivated by the upwelling Emeishan mantle plume during the Late Permian (Pan-Xi Geological Team, 1987; Liu, 1988; Chen, 2010), suggesting that these faults had acted as open-system conduits for the transport of magmas.

This model can be roughly examined by performing a mass balance calculation (Table 1). The compositions of olivine, clinopyroxene, and plagioclase from the Hongge intrusion are used to represent the composition of silicate phenocrysts transferred to the surface. The mixing composition of the escaping phenocrysts is calculated using the ratios similar to the Hongge intrusion. If the parental magmas of the Hongge intrusion crystallized 10 to 20% cotectic Fe-Ti-V oxides, the amounts of magmas should be doubled to meet the observed abundance in the intrusion. Removal of 50% silicates could just double the Fe-Ti-V oxides contents in the remaining cumulates. Thus, 50% of the escaping phenocrysts were added back to the bulk composition of the Hongge intrusion and

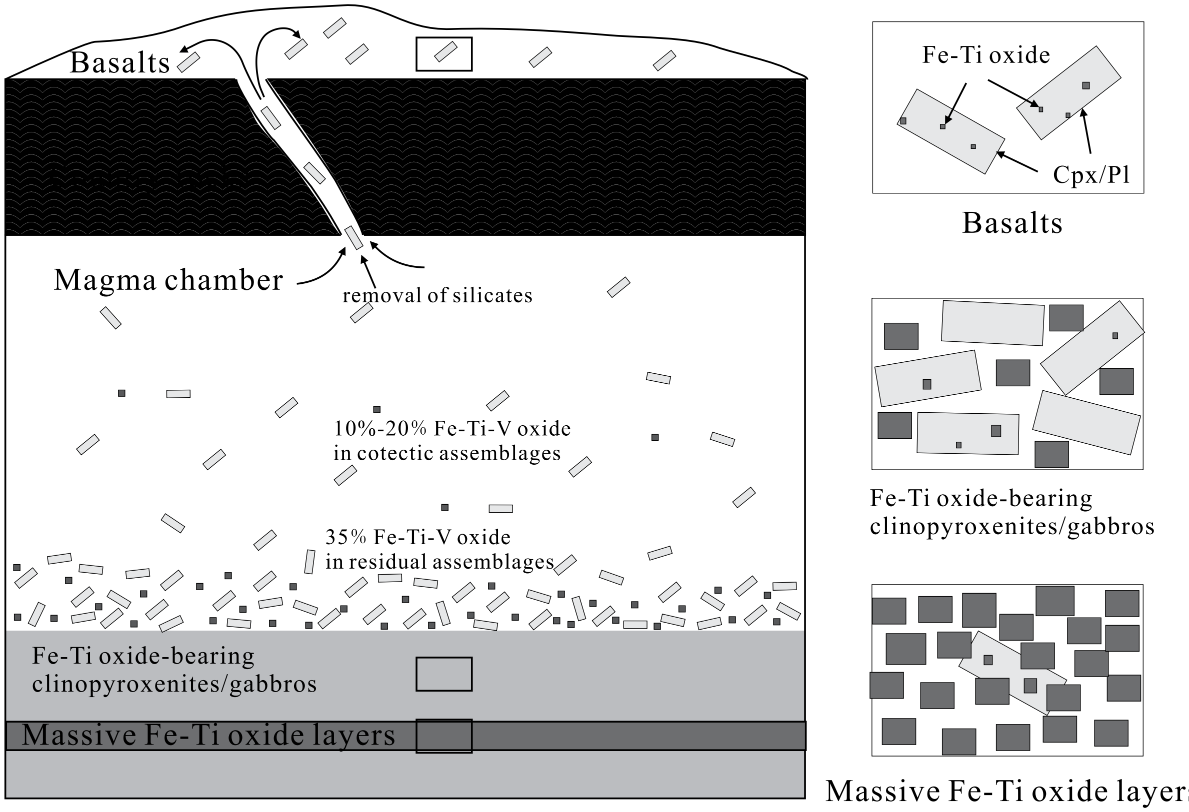

Fig. 7. Schematic model of Fe-Ti-V oxides enrichment in a fractionating assemblage by the removal of cotectic silicates from the magma chamber. See text for discussion.

then mixed with 30% of residual felsic magma resembling coeval syenites. The calculated final composition (column k in Table 1) is well matched to the composition of the coeval Emeishan basalts. Uncertainty may occur in this mass balance calculation because the actual proportion of silicate phenocrysts is not well constrained. As a result, the reverse model was used for the mass balance calculation. A total of 20% of the Fe-Ti oxides were extracted from the bulk composition to reconstruct the primary cotectic composition of mineral assemblage during crystallization and then mixed with 30% syenites. Similarly, the calculated magma composition (column m in Table 1) is still similar to the coeval Emeishan high-Ti basalts. The modeling results demonstrate that it is possible to generate enriched Fe-Ti-V oxides in feeder conduits by the removal of cotectic silicates.

The Hongge deposit provides a good example of Fe-Ti-V oxide enrichment in a small intrusion associated with a large igneous province. The similar enrichment features of Fe-Ti-V oxides in other mafic-ultramafic intrusions in the Pan-Xi region indicate that a common process was involved in the formation of these world-class Fe-Ti-V oxide deposits within the Emeishan LIP. We suggest that similar enrichment processes may have occurred in LIPs elsewhere. We therefore suggest that intrusions that form as open feeder-like systems to overlying basalts in LIPs are good exploration targets for giant, high-grade Fe-Ti-V oxide deposits. In contrast, thick layers of Fe-Ti-V oxides are unlikely to form in a closed magma system (e.g., the Skaergaard intrusion) or large magma chambers (e.g., Bushveld Complex) where there is no significant loss of cotectic silicates to peripheral coeval lavas.

Conclusions

The Hongge mafic-ultramafic intrusion in the Pan-Xi area of Emeishan LIP contains an unusually high proportion of Fe-Ti-V oxides (average of 35%) in the cumulate rocks. Titanomagnetite compositions reveal that the cotectic proportion of Fe-Ti-V oxides is much lower than those in the cumulates. Geochemical compositions indicate these intrusions were formed in open magma systems where some magmas/minerals escaped out of these intrusions. Phenocrysts in the overlying basalts contain abundant inclusions of Fe-Ti-V oxides that are broadly similar to the features in the underlying intrusion. We propose that these mineralized intrusions were feeder conduits to the overlying basalts. The phenocrysts were removed from these intrusions, resulting in significant enrichment of Fe-Ti-V oxides in the residual fractionating assemblages. Such an enrichment process plays a fundamental role in the formation of these world-class deposits in relatively small intrusions. A similar process might have occurred in other conduit-like mafic-ultramafic intrusions elsewhere associated with LIPs, and thus are good exploration targets for giant high-grade Fe-Ti-V oxide deposits.

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