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### A-type Granites of the Permian Emeishan Large Igneous Province (SW China): Implications for the Formation of the Giant Magmatic Oxide Deposits

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#### Abstract

The Permian (~260 Ma) Emeishan (峨眉山) large igneous province of SW China contains three nearly identical gabbro-granitoid complexes — the Taihe (太白), Baima (白馬) and Panzhihua (攀枝花) complexes in which their layered gabbroic intrusions host large magmatic Fe-Ti oxide deposits and are coeval with peralkaline, A-type granitic plutons. Primitive mantle-normalized incompatible element plots show corresponding reciprocal patterns between the mafic and silicic rocks. The chondrite-normalized rare earth element (REE) patterns show europium (Eu) anomalies ( $Eu/Eu^*$ ; defined as the deviation of normalized europium concentration in a sample relative to the expected concentration which is calculated by interpolation between normalized concentrations of the

neighboring elements, samarium (Sm) and gadolinium (Gd)) changing from positive ( $Eu/Eu^* = >1.5$ ) in the gabbroic intrusions to negative ( $Eu/Eu^* = < 1$ ) in silicic rocks. Whole rock initial epsilon neodymium isotope ( $\epsilon Nd_{(T)}$ ) values of the gabbroic intrusion ( $\epsilon Nd_{(T)} = +1.0$  to  $+4.0$ ) are similar to those of the enclaves ( $\epsilon Nd_{(T)} = +1.0$  to  $3.0$ ) and granitoids ( $\epsilon Nd_{(T)} = +1.5$  to  $+3.5$ ) whereas the zircon initial epsilon hafnium isotope ( $\epsilon Hf_{(T)}$ ) values of the gabbros ( $\epsilon Hf_{(T)} \approx +8.1$ ) are indistinguishable from those of the granitoids ( $\epsilon Hf_{(T)} \approx +9.2$ ), suggesting the parental magmas for all intrusions and rock types originated from the same mantle source. Geochemical modeling indicates that the gabbros and granites can be generated by shallow (~1 Kbar) fractional crystallization of a common parental magma similar to high-Ti Emeishan flood basalt. The compositional jump from mafic to silicic is attributed to the crystallization of Fe-Ti oxide minerals.

#### Introduction

The Late Permian (~260 Ma) Emeishan large igneous province (ELIP) of southwestern China is located near the western margin of the Late Archean to Early Proterozoic Yangtze Block. The ELIP covers an area of  $\sim 0.3 \times 10^6$  km<sup>2</sup> and consists mostly of flood basalts but there are ultramafic and silicic volcanic rocks, silicic plutons and layered mafic-ultramafic intrusions some of which host giant iron (Fe)–titanium(Ti)–vanadium(V) oxide deposits and/or nickel (Ni)–copper (Cu)–platinum

group element (PGE) sulphide deposits (Ali et al, 2005; Shellnutt, 2014). There are at least five oxide-bearing layered ultramafic-mafic complexes which are concentrated within the west-central part of the ELIP known as the Panxi region (Fig. 1). The layered complexes can be divided into two main groups: 1) ultramafic to mafic and 2) mafic. The ultramafic-mafic intrusions consist of a lower olivine- and pyroxene-rich peridotite unit which grades into a plagioclase-bearing upper gabbroic unit whereas the mafic layered intrusions uniformly consist of gabbro with varying proportions of olivine, clinopyroxene, plagioclase and titanomagnetite (Ti magnetite). The primary difference between the two layered intrusions is the type and style of mineralization. The mafic-ultramafic intrusions have PGE-rich horizons in their lower parts and Fe-Ti-oxide deposits in their upper parts. In contrast the mafic intrusions strictly have Fe-Ti oxide deposits in their lower parts (Pang et al, 2010). Another difference between the two types of layered intrusions is that the mafic intrusions are spatially and temporally associated with alkaline A-type granitoids whereas the ultramafic-mafic intrusions are not. The petrogenetic relationship between the mafic intrusions and the alkaline granitic intrusions is a contentious issue and is focused on whether or not the mafic and silicic units form coherent complexes (Shellnutt et al, 2011a; Zhong et al, 2011). Additionally the formation of the Fe-Ti oxide deposits within the mafic intrusions are considered to be derived by a number of processes such as: silicate liquid immiscibility, fractional crystallization or oxygen fugacity ( $fO_2$ ) fluxing by carbonate country rock assimilation (Zhou et al, 2005, 2013; Ganino et al, 2008; Pang et al, 2008a, b; Zhang et al, 2009; Shellnutt et al, 2011a; Zhong et al, 2011; Song et al, 2013). This paper is a summary of the work conducted as a Ph.D. thesis and presents the salient points on the petrological

relationship between the gabbroic and granitic rocks of the Fe-Ti-oxide bearing layered intrusions from the Panxi region of Sichuan, China.

## Geological background

The Panxi (攀西) region, between the cities of Panzhihua and Xi Chang (西昌), of southern Sichuan province is an important area within the ELIP because plutonic and hypabyssal rocks are exposed including the Baima, Hongge (和格), Panzhihua, Taihe and Xinjie (新街) mafic-ultramafic intrusions which host world-class orthomagmatic Fe-Ti-V oxide deposits. There are also numerous spatially and temporally associated granitic plutons, which range in composition from peraluminous to metaluminous to peralkaline (Shellnutt and Zhou 2007; Shellnutt et al, 2011b). The Panzhihua, Baima and Taihe gabbros are chemically evolved and spatially associated with peralkaline granitic rocks, whereas the Hongge and Xinjie intrusions are predominantly ultramafic suggesting that there are petrogenetic differences between the two types of intrusions (Zhang et al, 2009; Tao et al, 2010). Samples for this study were collected from the gabbroic units and granitic units of the Panzhihua, Baima and Taihe intrusions (Fig. 1).

## Cogenetic link between the gabbroic and granitic rocks

The ages of the gabbros and granites are identical within error and indicate they were emplaced at the same time (Table 1). Major element trends show a compositional evolution from the cumulate gabbros to the granites (Fig. 2). However, there is a distinct silica ( $SiO_2$ ) gap between the gabbros and the most

primitive enclave compositions which ranges from ~50 wt% to ~60 wt%. The primitive mantle-normalized incompatible multi-element patterns of the gabbros and granitic rocks are antithetical (Fig. 3). On the primitive mantle normalized multi-element plot, uranium to cerium (Ce) and neodymium (Nd) to samarium (Sm) show low abundances in the gabbros and high in the granitoids, whereas barium (Ba), Ti and strontium (Sr) are enriched in the gabbros, and depleted in the granitoids. The chondrite-normalized REE patterns also show the same relationship with respect to the Eu-anomalies. The reciprocal Eu-anomalies in the gabbros and granites likely reflect the accumulation and fractionation of plagioclase. The low Sr ( $\leq 300$  part per million (ppm)) and Eu/Eu\* ( $\text{Eu}/\text{Eu}^* < 1$ ) values of the granitic rocks and enclaves indicate that a significant amount of plagioclase fractionated from the parental magma.

It is inferred from the  $\epsilon\text{Nd}_{(T)}$ , zircon  $\epsilon\text{Hf}_{(T)}$ , and initial strontium isotope ( $I_{\text{Sr}}$ ) values that the magma source characteristics of the gabbro-granitoid complexes are very similar (Table 1). The  $\epsilon\text{Nd}_{(T)}$  values of clinopyroxene separates ( $\epsilon\text{Nd}_{(T)} = +1.1$  to  $+3.2$ ) from the Panzhihua gabbros overlap with the whole-rock  $\epsilon\text{Nd}_{(T)}$  values of the Baima ( $\epsilon\text{Nd}_{(T)} = +1.6$  to  $+4.2$ ) and Taihe gabbros ( $\epsilon\text{Nd}_{(T)} = +2.5$  to  $+3.3$ ) and granitoids (Panzhihua  $\epsilon\text{Nd}_{(T)} = +2.2$  to  $+2.9$ ; Baima  $\epsilon\text{Nd}_{(T)} = +2.5$  to  $+3.2$ ; Taihe  $\epsilon\text{Nd}_{(T)} = +1.0$  to  $+2.0$ ) suggesting that they originated from the same source (Shellnutt et al, 2009a, b, 2010; Zhang et al, 2009). The available zircon  $\epsilon\text{Hf}_{(T)}$  values from the Baima syenite ( $\epsilon\text{Hf}_{(T)} = 8.7 \pm 0.4$ ), Taihe granite ( $\epsilon\text{Hf}_{(T)} = 9.2 \pm 1.0$ ) and gabbro ( $\epsilon\text{Hf}_{(T)} = 8.1 \pm 0.8$ ) are within the same range. The  $I_{\text{Sr}}$  values of some of the peralkaline rocks are a little more difficult to interpret because they are very low ( $< 0.700$ ), that may be due to Sr loss and Rb gain by deuteric alteration. However, the  $I_{\text{Sr}}$  values of the

Panzhihua gabbro ( $I_{\text{Sr}} = 0.70434$  to  $0.70510$ ) and syenodiorite ( $I_{\text{Sr}} = 0.70346$  to  $0.70427$ ), Baima gabbro ( $I_{\text{Sr}} = 0.70469$  to  $0.70518$ ) and Taihe gabbro ( $I_{\text{Sr}} = 0.70504$  to  $0.70505$ ) are similar.

The mineral and whole-rock compositions of the Panzhihua and Taihe granites are very similar but differ from those of the Baima syenites. The same may be true for the layered gabbroic rocks. Overall, the Baima gabbro appears to contain more olivine and has higher bulk MgO when compared to the gabbroic rocks of the Panzhihua and Taihe complexes. The mineralogy of the granitic rocks indicates that the relative oxidation states of the granitic plutons was likely different. The Baima syenites contain quartz, titanite, magnetite and Mg-rich ferrichterite ( $\text{Fe}^{2+}$  amphibole), which indicates  $f\text{O}_2$  at the fayalite–magnetite–quartz (FMQ) buffer  $\geq 0$  (Wones, 1989). In comparison, the Panzhihua and Taihe granites contain Fe-rich ferrichterite and aenigmatite, which are indicative of reducing conditions ( $f\text{O}_2 = \text{FMQ} < 0$ ).

The relative emplacement depth is difficult to estimate for the Baima and Taihe plutons because the geological relationships do not indicate how close to the surface they intruded. However the Panzhihua granitic pluton intruded subaerial Emeishan basalts and likely served as a magma reservoir for compositionally similar trachytes, indicating a shallow emplacement depth (Shellnutt and Jahn, 2010). Based on the geological relationships of the Panzhihua granite, the inferred depth of emplacement for the other complexes is also likely to be shallow ( $\leq 1$  Kbar) (Pang et al, 2010).

On the basis of their temporal and petrogenetic similarities, a three stage model outlining the possible genesis of the Panxi gabbro-granitoid complexes is proposed. Firstly, a mafic magma resembling high-Ti basalt from the ELIP was

injected into Paleozoic sedimentary rocks of the Yangtze Block at ~260 Ma (Fig. 4a). During and after emplacement, the magma crystallized olivine, plagioclase and clinopyroxene, which controls the evolution of Ni, cobalt (Co), chromium (Cr), scandium (Sc), Eu, Ba, and Sr within the melt. Internal differentiation (e.g. magma convection) may have contributed to the redistribution of earlier formed minerals (Fig. 4b). Secondly, fractionation of olivine, plagioclase and clinopyroxene, likely increased  $fO_2$  in the magma and led to en masse crystallization of oxide minerals. The removal of plagioclase from the parental magma likely caused a 'plagioclase effect', which resulted in the depletion of Al and enrichment of Na+K in the residual magma. In addition, the crystallization of oxide minerals was likely responsible for the SiO<sub>2</sub> gap between the two units. As crystallization continued,  $fO_2$  decreased producing an ilmenite dominated upper gabbro near the boundary with the syenitic unit. The silicic residual liquid partitioned the REEs, niobium (Nb), tantalum (Ta), zirconium (Zr), Hf, thorium (Th) and U and migrated to the top of the magma chamber (Fig. 4c). Finally, the solidification of the gabbroic unit formed a lower cumulate zone, an oxide ore zone containing partially resorbed cumulate crystals of olivine, plagioclase and clinopyroxene and syenitic layers, an olivine gabbroic zone with intermittent oxide-rich layers, and an ilmenite-dominated upper gabbroic zone with a noticeable amount of apatite (Fig. 4d).

## Conclusions

The important conclusions from the work compiled from the Panxi gabbro-granitoid complexes are: 1) some peralkaline, silica-saturated, A-type granitoids are derived by shallow level fractional crystallization of mafic magmas under oxidizing or

reducing conditions, 2) the formation of 'Panxi-type' massive oxide deposits do not appear to require assimilation of crustal material or magmatic fluids to enrich the evolving liquid in metals, 3) 'Panxi-type' deposits may be common within continental LIPs provided that geochemically more-fertile, oceanic island basalt (OIB)-like lavas are present and 4) silica saturated peralkaline granitic rocks may be used as indicators for magmatic Fe-Ti oxide deposits.

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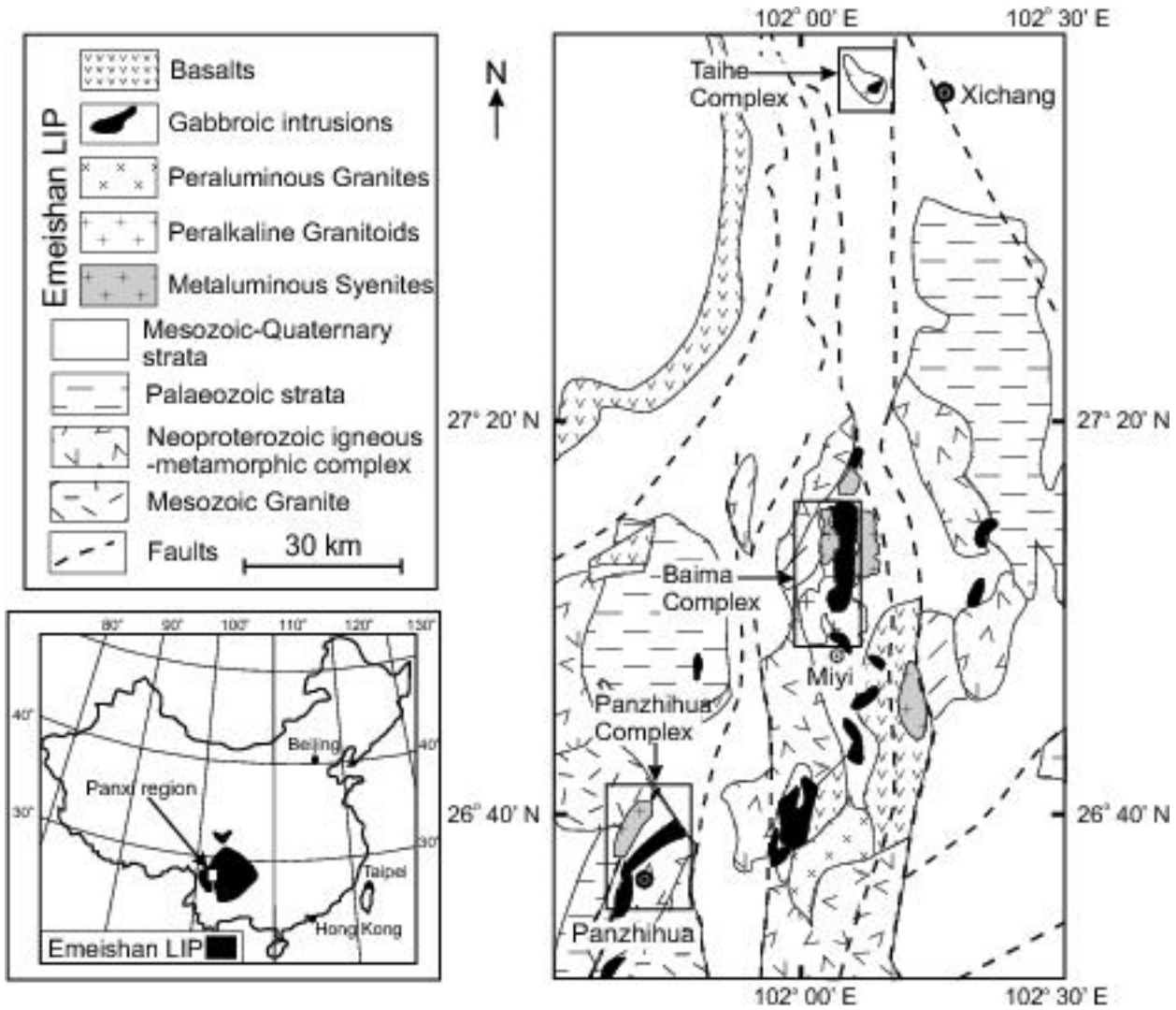


Figure 1. Simplified geological map of the Panxi region showing the distribution of the Late Permian gabbro-granitoid complexes of the Emeishan large igneous province.

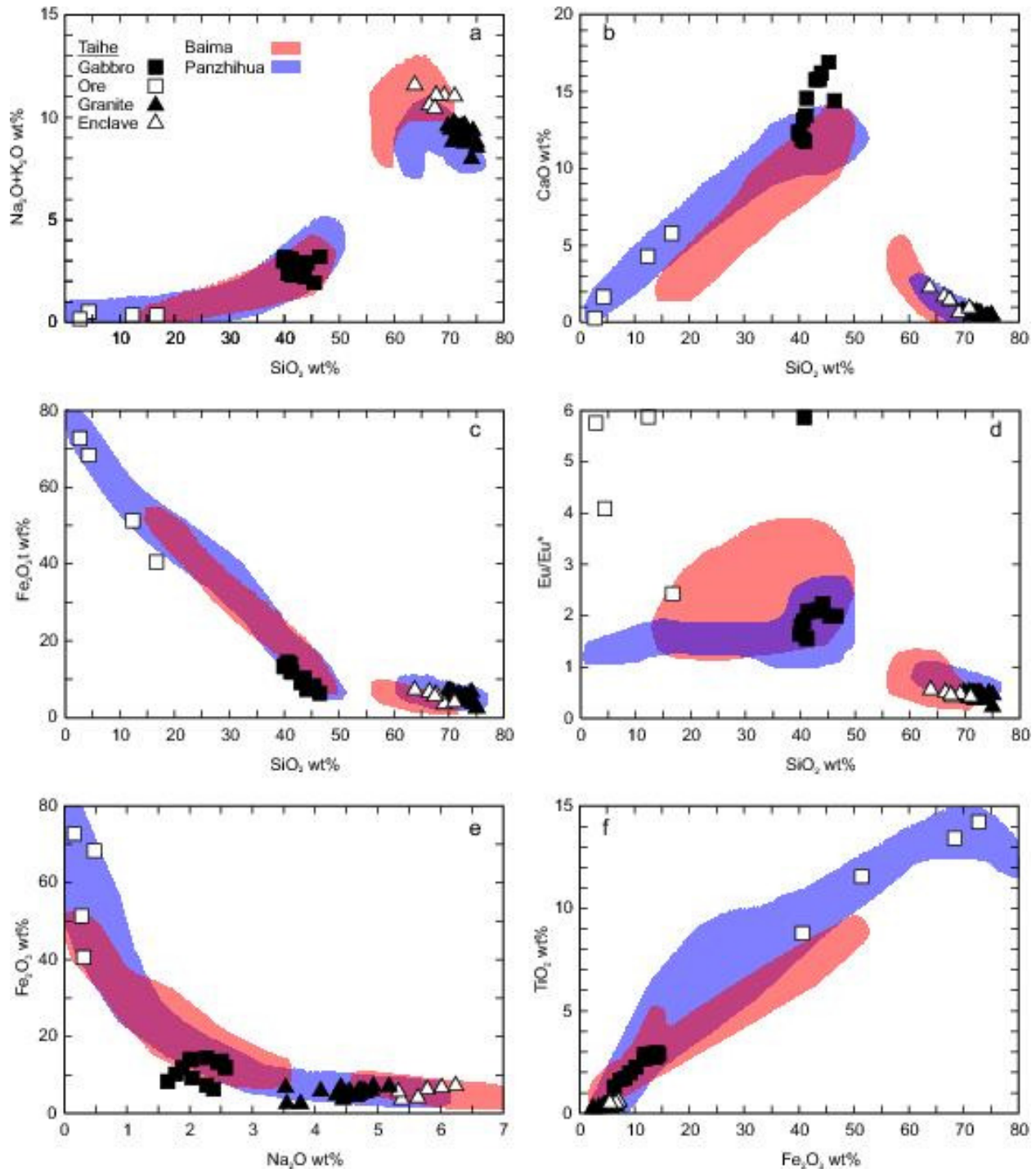


Figure 2. Major element plots of the gabbros, granites and enclaves from the Panzhihua, Baima and Taihe complexes.



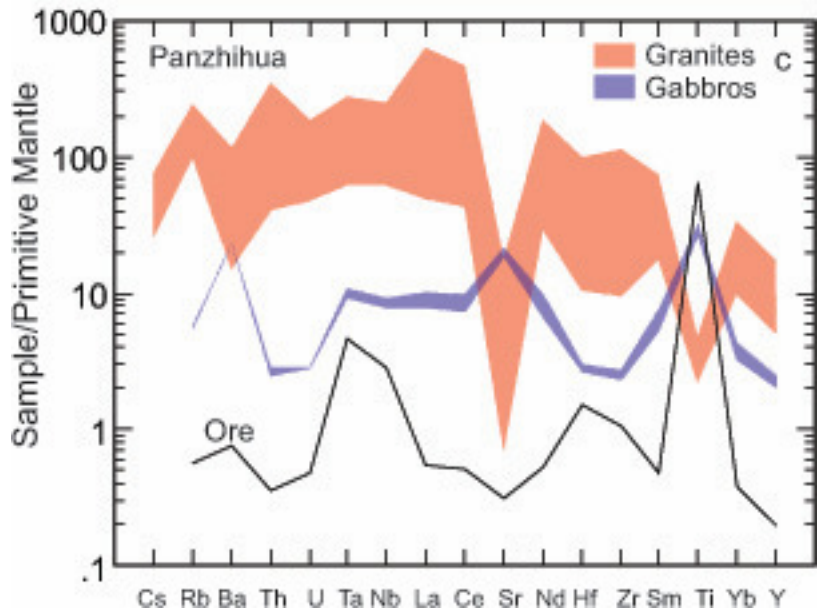
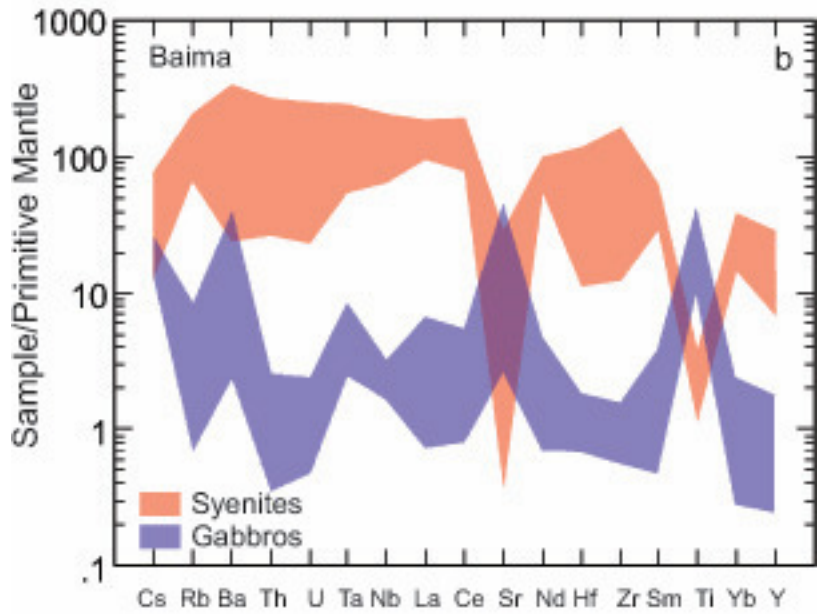
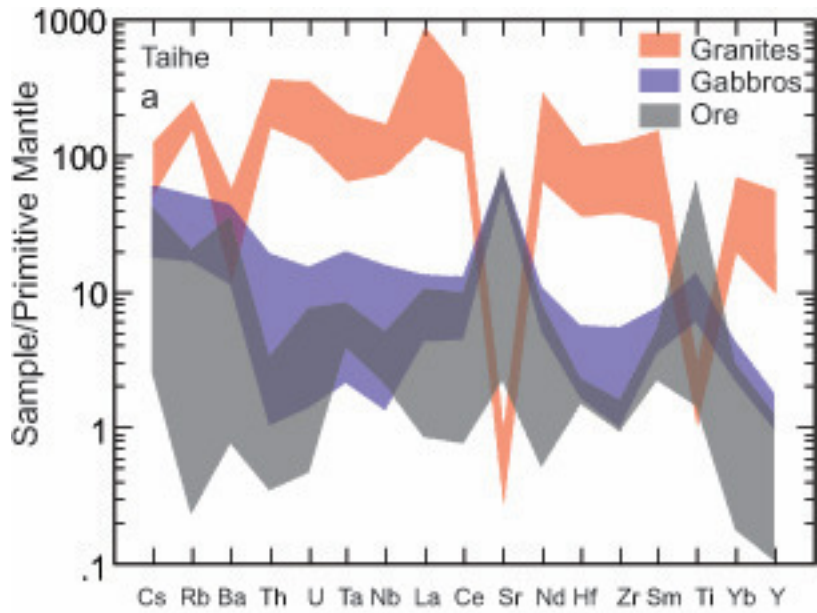


Figure 3. Concentrations of incompatible elements in granitic and gabbroic rocks of the (a) Taihe complex, (b) Baima complex and (c) Panzhihua complex normalized to primitive mantle (value of Sun and McDonough (1989)). Shown from left to right are: cesium (Cs), rubidium (Rb), barium (Ba), thorium (Th), uranium (U), tantalum (Ta), niobium (Nb), lanthanum (La), Cerium (Ce), strontium (Sr), neodymium (Nd), hafnium (Hf), zirconium (Zr), samarium (Sm), titanium (Ti), terbium (Tb), and yttrium (Y).

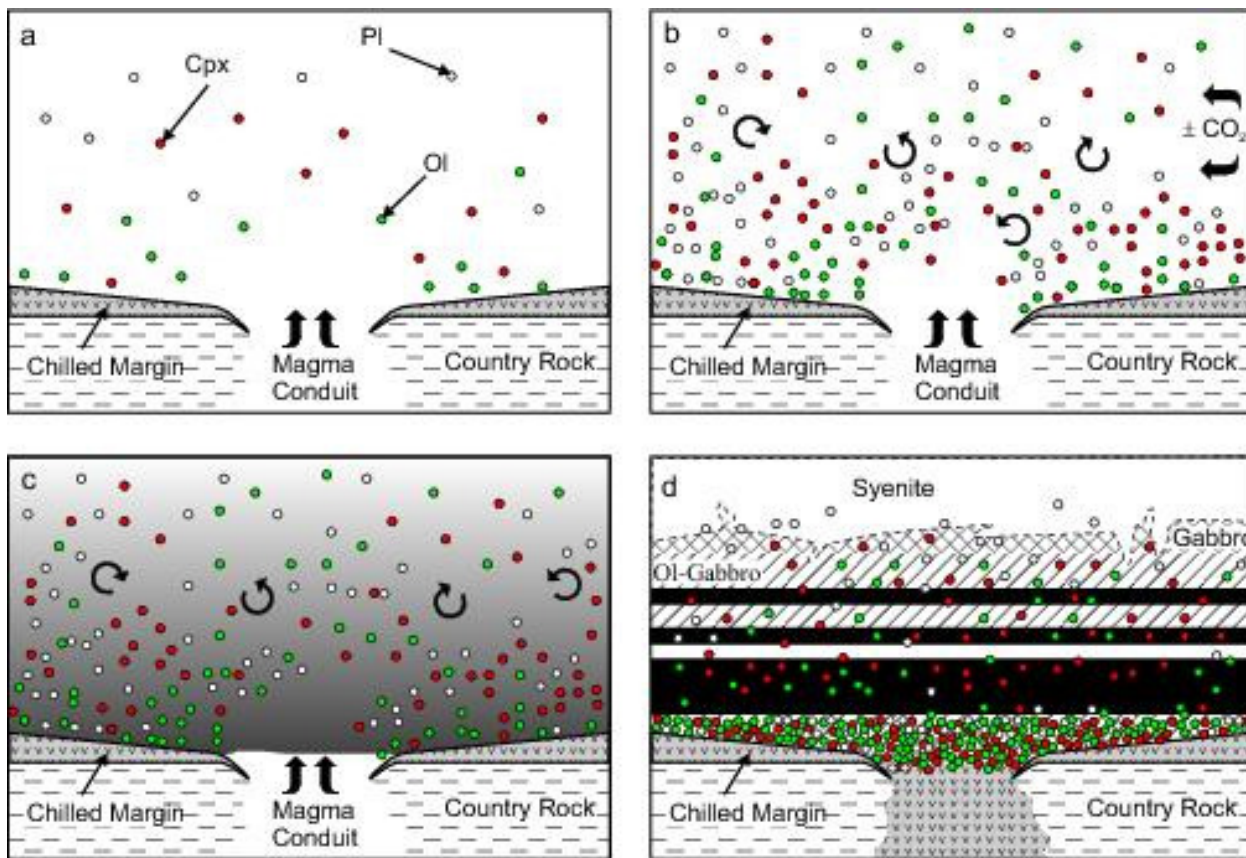


Figure 4. Proposed petrogenetic model of the formation of the Panxi gabbro-granite complexes. (a) Emplacement of a basaltic parental magma with an initial amount of suspended crystals. (b) Settling and *in situ* crystallization of cumulate olivine, plagioclase and clinopyroxene. It is possible that carbon dioxide (CO<sub>2</sub>) influx from the wall rocks occurred. (c) After a period of fractionation, a lighter alkali-rich (white) residual magma migrates to the top of the magma chamber. At this point the magma chamber is likely oxygenated and crystallizes massive amounts of magnetite (black) in the lower part of the magma chamber while the syenite forms in the upper part of the magma chamber. (d) Solidification and stratification of the Baima Igneous Complex (BIC) gabbroic unit into four zones and formation of the syenitic unit.

Table 1. Summary of ages, europium anomaly (Eu/Eu\*) values and strontium (Sr)–neodymium (Nd)–hafnium (Hf) isotopes of the Emeishan gabbro-granitoid complexes

Intrusion	Panzhihua		Baima		Taihe	
	Gabbro	Granite	Gabbro	Syenite	Gabbro	Granite
Age (Ma)	263 ± 3 Ma		261 ± 2 Ma	259 ± 5 Ma	261 ± 2 Ma	264 ± 3 Ma
Eu/Eu*	0.8 to 5.6	0.6 to 0.9	1.5 to 3.6	0.4 to 1.0	1.5 to 5.9	0.2 to 0.5
εNd <sub>(T)</sub>	+1.1 to +3.2	+2.2 to +2.9	+1.6 to +4.2	+2.5 to +3.2	+2.5 to +3.3	+1.0 to +2.0
εHf <sub>(T)</sub>				+8.7 ± 0.4	+8.1 ± 0.8	+9.2 ± 1.0
I <sub>Sr</sub>	0.7043 - 0.7051	0.7035 - 0.7043	0.7045 - 0.7052		0.7050 - 0.7051	

Uranium-lead ages ( $^{238}\text{U}/^{206}\text{Pb}$ ) and Hf isotopes are determined from *in situ* zircon analyses. Sr and Nd isotopes are from whole rock analysis