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Formation of the Late Permian Panzhihua plutonic-hypabyssal-volcanic igneous complex: Implications for the genesis of Fe–Ti oxide deposits and A-type granites of SW China

J.G. Shellnutt *, B.-M. Jahn

Academia Sinica, Institute of Earth Science, 128 Academia Road Sec. 2, Nankang Taipei 11529, Taiwan

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ABSTRACT

The Late Permian (260 Ma) Emeishan large igneous province of SW China contains numerous magmatic Fe–Ti oxide deposits. The Fe–Ti oxide deposits occur in the lower parts of evolved layered gabbroic intrusions which are spatially and temporally associated with A-type granitic rocks. The 260 Ma Panzhihua layered gabbroic intrusion hosts one of the largest magmatic Fe–Ti oxide deposits in China and is coeval with a peralkaline A-type granitic pluton. The granite has intruded the overlying Emeishan flood basalts and fed at least one dyke which erupted onto the surface producing columnar jointed trachytes. The presence of syenodiorite between the layered gabbro and granite is evidence for compositional evolution from mafic to intermediate to felsic rocks. The syenodiorites have intermediate to felsic composition with $SiO_2 = 61$ to 65 wt.%, $MgO = 0.27$ to 0.6 wt.% and $CaO = 1.0$ to 2.5 wt.% as compared to the granite $SiO_2 = 65$ to 72 wt.%, $MgO = 0.1$ to 0.4 wt.%, $CaO = <1.0$ wt.%. Primitive-mantle-normalized incompatible element plots show corresponding reciprocal patterns between the mafic and felsic rocks. The chondrite-normalized REE patterns show Eu anomalies changing from >1($Eu/Eu^* = 1.1$ to 2.6) in the gabbroic intrusion, to <1 in the syenodiorite ($Eu/Eu^* = 0.75$ to 0.83), granites and trachytes ($Eu/Eu^* = 0.55$–0.87). Previously published $\varepsilon Nd_{(T)}$ values from clinopyroxenes ($\varepsilon Nd_{(T)} = +1.1$ to $+3.2$) of the gabbroic intrusion match the whole-rock values of the syenodiorite ($\varepsilon Nd_{(T)} = +2.1$ to $+2.5$), granite and trachyte ($\varepsilon Nd_{(T)} = +2.2$ to $+2.9$), suggesting that all rock types originated from the same mantle source. MELTS and trace element modeling confirm that all rock types can be generated by fractional crystallization of high-Ti Emeishan basalt. The jump in SiO_2 from the gabbro to the syenodiorite is attributed to the en masse crystallization of the Fe–Ti oxides. The geological and geochemical data indicate that fractional crystallization of a common parental magma produced the layered gabbroic intrusion and Fe–Ti oxide deposit, the syenodiorite, granites and trachyte of the Panzhihua region, which thus form a genetically related plutonic-hypabyssal-volcanic complex. Other granite–gabbro complexes in the region likely formed in a similar manner.
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1. Introduction

Layered mafic–ultramafic intrusions are some of the most complex magmatic systems in the world. The examination of layered intrusions has contributed significantly in advancing modern igneous petrology because they preserve physiochemical processes within magma chambers (Wager and Brown, 1968; Cawthorn, 1996). The interest in layered intrusions is not solely based on their geologic features because many of them contain substantial deposits of precious metals. Some layered intrusions host deposits of Ni, Cu and platinum group elements (PGE) within sulphide minerals, whereas others contain Cr, Fe, Ti and V within oxide minerals (Irvine, 1977; Eales and Cawthorn, 1996; Lee, 1996; Zhou et al., 2008). The formation of Fe–Ti oxide deposits within layered intrusions is not completely understood and many models have been proposed to explain their origin such as fractional crystallization, magma mingling, silicate liquid immiscibility, separate magma systems, and periodic changes in fO_2 (Philpotts, 1967; Kolker, 1982; Reynolds, 1985; Harney and von Gruenewadt, 1995; Duchesne, 1999; Higgins, 2005; Shellnutt et al., 2009).

In many cases anorogenic granitic rocks of A-type affinity are associated with layered intrusions (Bonin, 2007). A-type granitic rocks are mildly alkaline with high Fe/Mg and K/Na ratios, high K_2O wt.%, low CaO and Al_2O_3 wt.% contents and rich in incompatible elements, rare earth elements (REE), Zr, Nb and Ta, but poor in Co, Sc, Cr, Ni, Ba, Sr and Eu (Loiselle and Wones, 1979; Bonin, 2007). Much like the formation of Fe–Ti oxide deposits there are many models which can explain the genesis of A-type granites including: 1) differentiation (i.e. partial melting or fractional crystallization) of basaltic magmas (Loiselle and Wones, 1979; Frost and Frost, 1997; Bonin, 2007), 2) melting of deep crustal sources previously depleted in H_2O (Loiselle and Wones, 1979;

* Corresponding author: Tel.: +886 2 2783 9910x618; fax: +886 2 2783 9871.
E-mail address: jgshelln@earth.sinica.edu.tw (J.G. Shellnutt).

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Collins et al., 1982; Clemens et al., 1986; Whalen et al., 1987), 3) partial melting of charnockitic lower crust (Landenberger and Collins, 1996), 4) low degrees of partial melting of I-type granites (King et al., 1997), and 5) dehydration melting of calc-alkaline or amphibole-bearing tonalite (Creaser et al., 1991; Skjerlie and Johnston, 1992).

Within the Late Permian (~260 Ma) Emeishan large igneous province (ELIP) of Southeast Asia are numerous layered gabbroic intrusions which host world class Fe–Ti oxide deposits. In every case the Fe–Ti oxide bearing gabbroic intrusions are spatially and temporally associated with A-type granitic plutons (Shellnutt and Zhou, 2007; Shellnutt et al., 2009). The Panzhihua layered gabbroic intrusion is one of the largest Fe–Ti oxide deposits in China with ore reserves of over 1300 million tons (Zhou et al., 2005; Pang et al., 2008a,b, 2009; Zhang et al., 2009). The origins of the Panzhihua intrusion, oxide deposit and A-type granite are debated. Zhou et al. (2005) have suggested that evolved Ti-rich mafic magmas underwent immiscible separation which produced the cumulate gabbro and oxide ores separately whereas others suggest that fractional crystallization of a Fe-rich mafic (i.e. ferrogabbro or Ti-rich ferrobasalt) parent produced the ore deposits and gabbro (Ganino et al., 2008; Pang et al., 2008a; Zhang et al., 2009). There have been no direct attempts to link the layered gabbroic intrusion and the peralkaline granite which are considered to be mutually exclusive intrusions (Xu et al., 2008; Zhong et al., 2009).

Located between the Panzhihua layered gabbroic intrusion and the A-type granite is an intermediate unit of syenodiorite. The location and composition of the syenodiorite suggest that it could represent a 'missing compositional link' between the gabbroic and granitic rocks of Panzhihua. Here we present new major and trace element data and whole-rock radiogenic Sr–Nd isotopic data from the syenodioritic and trachytic rocks in Panzhihua in order to assess their relationship to the Panzhihua layered gabbroic intrusion and A-type granitic rocks and to determine if all rock types (e.g. gabbro, syenodiorite, granite and trachyte) represent a genetically related plutonic-hypabyssal-volcanic complex.

2. Geologic setting

2.1. Emeishan large igneous province

Southwestern China comprises the western margin of the Yangtze Block to the east and the easternmost part of the Tibetan Plateau to the west. The Yangtze Block consists of Mesoproterozoic granitic gneisses and metasedimentary rocks, which have been intruded by the Kangdian (~800 Ma) granites (Zhou et al., 2002b). The Neoproterozoic granites are overlain by a series of marine and terrestrial strata from the late Neoproterozoic (~600 Ma) to the Late Permian (Yan et al., 2003).

The Late Permian (~260 Ma) Emeishan large igneous province (ELIP) covers an area of $\sim 0.3 \times 10^6$ km^2 near the western margin of the Yangtze Block and is fragmented and wedge shaped (Chung and Jahn, 1995; Chung et al., 1998; Zhou et al., 2002a) (Fig. 1). The Red River and Longmenshan–Jinhe fault zones, active during the Indo-Eurasian collision, mark the western boundary of the ELIP and are partially responsible for exhuming plutonic rocks (Chung et al., 1997). The volcanic rocks include picrites, basaltic andesites and basalts which are subdivided into high- and low-Ti groups (Xu et al., 2001; Xiao et al., 2004). The basaltic sequences range in thickness from 1.0

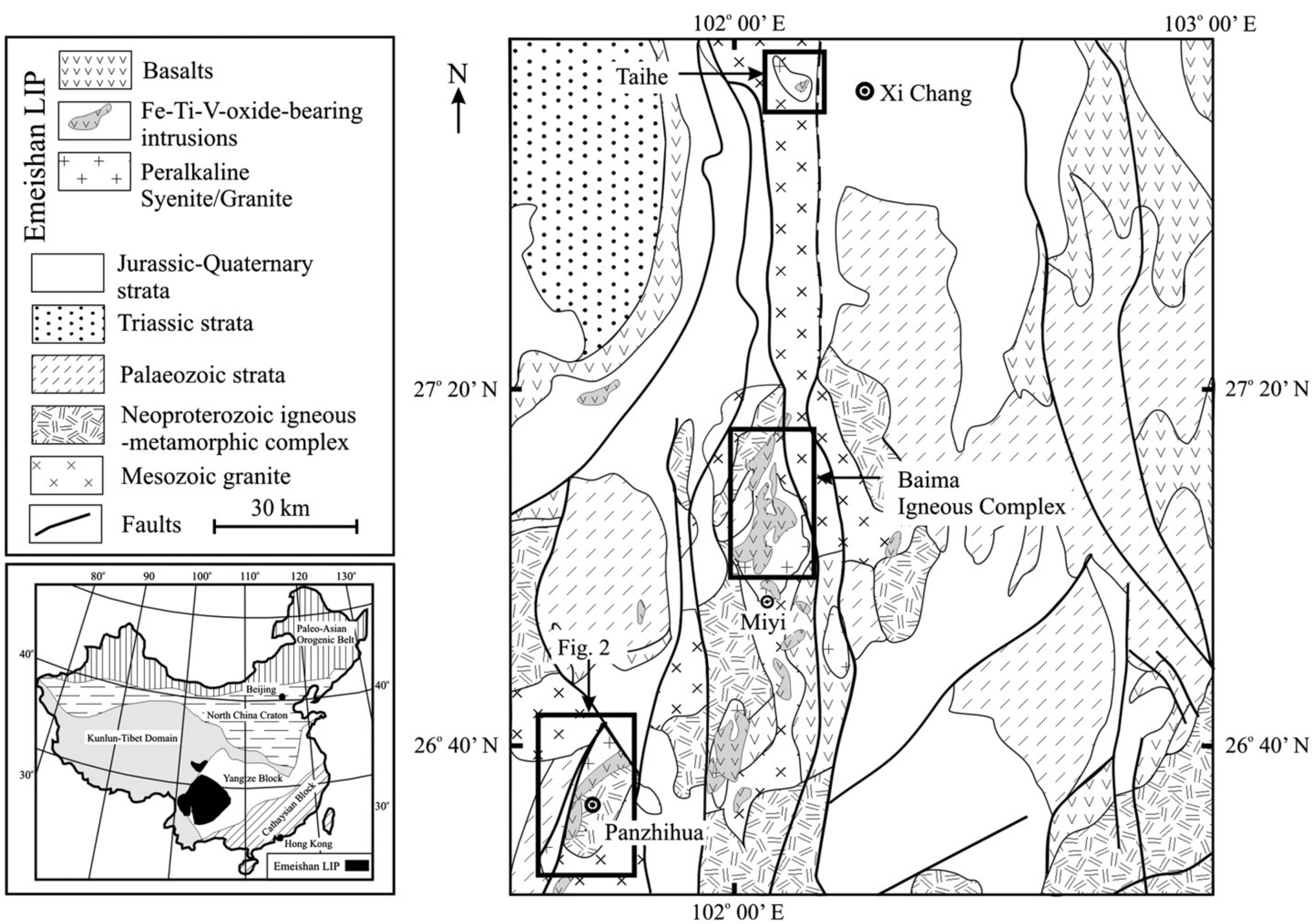

Fig. 1. Simplified regional geological map of the Panzhihua-Xi Chang region of the Emeishan large igneous province.

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