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# Timing of Ti-magnetite crystallisation and silicate disequilibrium in the Panzhihua mafic layered intrusion: Implications for ore-forming processes

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ABSTRACT

The ±260 Ma Panzhihua mafic layered intrusion is one of a suite of intrusions related to the Emeishan Large Igneous Province (ELIP), SW China. The Panzhihua intrusion hosts a large (±60 m thick) Fe–Ti oxide ore body at the base of the intrusion. This study provides new constraints on the genesis of Fe–Ti oxide ore layers at the Panzhihua intrusion using: geochemistry, petrography, and modeling of parent magma crystallisation with variation in $fO_2$ and $H_2O$ content.

Whole-rock major element geochemical trends are controlled by the modal abundance of Fe–Ti oxides (Ti-magnetite and ilmenite). The lower ±270 m of the intrusion is clearly dominated by a Ti-magnetite accumulation trend whereas above this level the geochemical variation is consistent with a Ti-magnetite and ilmenite accumulation trend. This suggests that the lower ±270 m of the intrusion crystallised at higher $fO_2$ conditions relative to that above ±270 m. Detailed petrographic analysis of exsolution microtextures of the Ti-magnetite from within ore layers and gabbroic host rocks also indicates a relative increase in $fO_2$ within the ore rocks. Modeling of Panzhihua parent magma shows that Ti-magnetite crystallises late for dry (<0.5 wt.%) starting compositions and early for wet (>1.5 wt.% $H_2O$) compositions. This corresponds to a distinct variation in plagioclase crystallisation temperature, which decreases with increasing $H_2O$ content of the parent magma. The initial plagioclase composition varies from $An_{55}$ for a dry magma up to $An_{73}$ for a magma containing 3 wt.% $H_2O$. The average plagioclase composition for the Panzhihua intrusion is $An_{58}$, indicating an initial magma with low $H_2O$ content. Textures within the Fe–Ti oxide ore rocks clearly indicate that Ti-magnetite crystallised after the silicate phases (plag. + cpx.) and disequilibrium textures indicate that the Fe–Ti oxide ores were not in equilibrium with the enclosed silicates.

We present a model for Fe–Ti oxide ore formation in an open system by multiple replenishments of magma with variable $H_2O$ contents, Ti-magnetite crystal load and volume. Intruding $H_2O$- and crystal-rich magmas effectively thermo-chemically erode previously formed gabbroic cumulates forming the footwall and incorporates previously crystallised silicate grains. These grains are consumed by the magma due to the high $H_2O$ content and higher temperature resulting in the association of consumed silicate primocrysts enclosed in Fe–Ti oxide ore layers.



## 1. Introduction

The Panzhihua layered mafic intrusion hosts a large Fe–Ti–V ore deposit in the form of a massive Fe–Ti oxide ore layer at the base of the intrusion, which has been successfully mined for the last three decades. The intrusion has only relatively recently been the subject of detailed study (e.g., Ganino et al., 2008; Pang et al., 2009; Zhou et al., 2005), given the excellent exposures of the intrusion and the unusually thick Fe–Ti oxide layers present within the intrusion. Several models have been proposed for the formation of the Fe–Ti oxide ore layers, which include: 1) Early crystallisation of Fe–Ti oxides from a parent magma with 1.5 wt.% $H_2O$ and oxide accumulation through crystal settling at the base of the intrusion (Pang et al., 2008a, 2008b); 2) An increase in magma $fO_2$ related to $CO_2$-degassing of the footwall carbonates, resulting in the accumulation of Fe–Ti oxides (Ganino et al., 2008) and 3) Formation of a dense Fe-rich immiscible liquid from a ferrogabbroic parent magma, which sinks toward the base of the intrusion (Zhou et al., 2005). However, relatively little work has been done on the main ore layer itself. We present whole-rock major element geochemical data as well as a detailed petrographic account of the Fe–Ti oxide ore layers from the Jianshan block of the Panzhihua intrusion, including microstructural evidence for silicate disequilibrium within the ore layers, which must be accounted for in any model for the formation of the Fe–Ti oxide layers. Furthermore we model a Panzhihua parent magma in order to further constrain the timing of crystallisation of the Fe–Ti oxides within the ore layers.

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## 2. Geological setting of the Panzhihua intrusion

The Panzhihua intrusion (Fig. 1) is one of numerous layered intrusions related to the ~260 Ma Emeishan Large Igneous Province (ELIP), south west China. The ELIP consists of a large volume ($0.3 \times 10^6$ $km^3$; Xu et al., 2001) of flood basalts and numerous related intrusions. The flood basalts have been divided into high-Ti and low-Ti suites, which have distinct mantle sources (Xiao et al., 2004). The related intrusions are also divided into Fe–Ti–V oxide bearing layered mafic intrusions and Ni–Cu–PGE sulphide bearing ultramafic-mafic intrusions. The Panzhihua intrusion is a large Fe–Ti–V oxide bearing mafic intrusion. Detailed presentation of the regional geological setting has been given by Zhou et al. (2005) and is not repeated here. The Panzhihua intrusion is generally believed to form as an open system style magma chamber with at least three major injections of magma, indicated by reversals in mineral compositions (Pang et al., 2009).

The exposed section of the Panzhihua intrusion is ±19 km long and 1500–3000 m thick and consists of a layered series of gabbroic rocks. The lower contact is intrusive into carbonate rocks of the Late Neoproterozoic Dengying Formation, which have undergone contact metamorphism to marbles (Ganino et al., 2008). Pang et al. (2009) showed that the intrusion formed in an open system by several pulses of magma, which are marked by distinct reversals in the mineral compositions. The Panzhihua intrusion has been affected by post-emplacement shearing, which has resulted in minor displacement of several distinct blocks (Fig. 1). The mining activity is currently concentrated in the northern Zujiabaobao, Lanjiahuoshan and Jianshan blocks. Samples collected for the current study are from the Jianshan block. A distinct marginal zone (MGZ) is observed in contact with the footwall rocks. The MGZ (0–40 m) is fine-grained and consists of a variety of rock types including dominantly amphibole microgabbro with lesser olivine microclinopyroxenite, microclinopyroxenite and pegmatoids (e.g., Pang et al., 2009). The amphibole content increases toward the footwall contact and rocks composed essentially only of amphibole are present immediately adjacent to the footwall (Pang et al., 2009). The Panzhihua intrusion has been stratigraphically divided into five zones from the base upward (Fig. 2) (Pang et al., 2009): MGZ, Lower Zone (LZ), Middle Zone A (MZa), Middle Zone B (MZb) and the Upper Zone (UZ). The LZ (0–110 m) is comprised of massive melagabbros and contains Fe–Ti oxide ore layers. The MZa (±300 m)

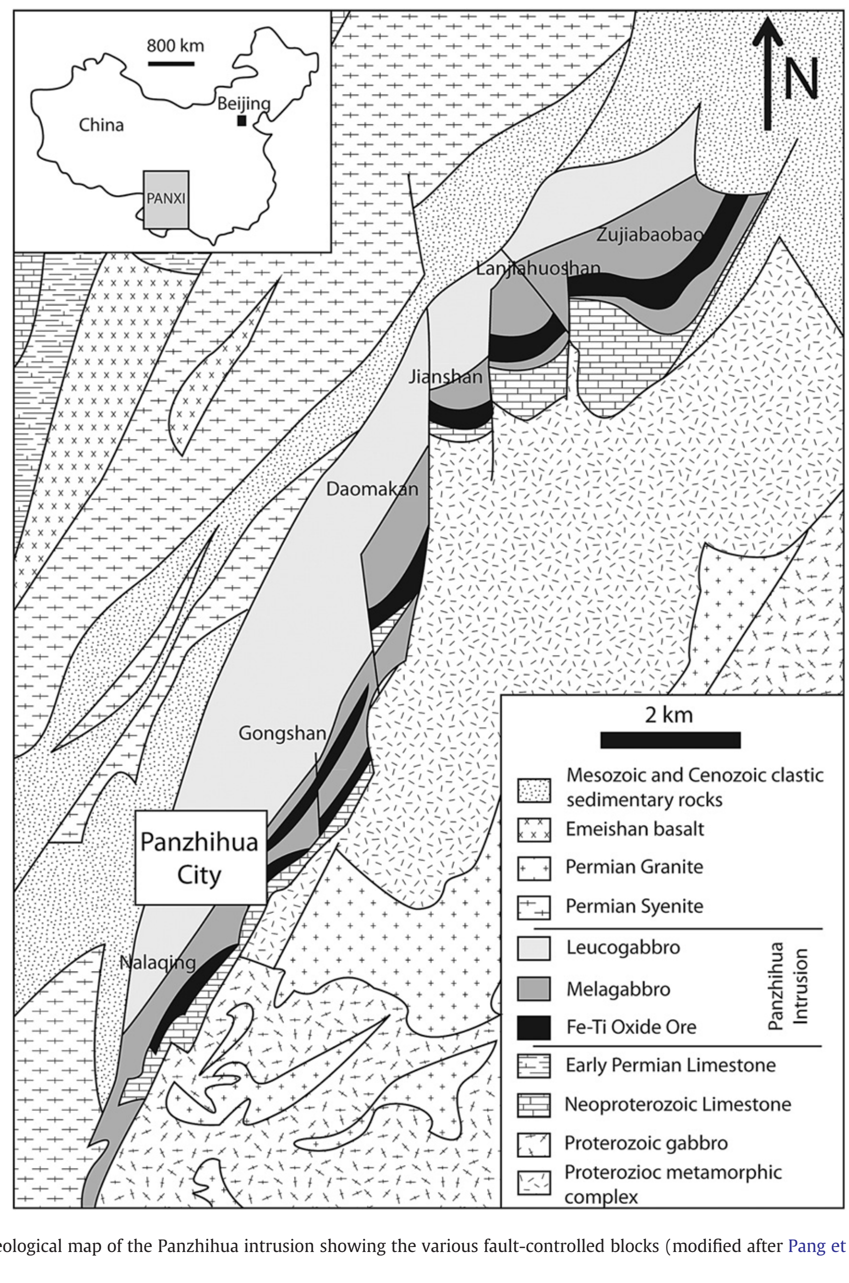


**Fig. 1.** Geological map of the Panzhihua intrusion showing the various fault-controlled blocks (modified after Pang et al., 2009).