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Apatite geochemistry of the Taihe layered intrusion, SW China: Implications for the magmatic differentiation and the origin of apatite-rich Fe-Ti oxide ores

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ABSTRACT

The Taihe intrusion is one of the layered intrusions situated in the central zone of the Emeishan Large Igneous Province (ELIP), SW China. The cyclic units in the Middle Zone of the intrusion are composed of apatite-magnetite clinopyroxenite at the base and gabbro at the top. The apatite-rich oxide ores contain 6–12 modal% apatite and 20–50 modal% Fe-Ti oxides evidently distinguished from the coeval intrusions in which apatite-rich rocks are poor in Fe-Ti oxides. Most of apatites of the Taihe Middle and Upper Zones are fluorapatite, although four samples show slightly high Cl content in apatite suggesting that they crystallize from a hydrous parental magma. Compared to the apatite from the gabbro of the Panzhihua intrusion, situated 100 km to the south of the Taihe intrusion, the apatite of the Taihe rocks is richer in Sr and depleted in HREE relative to LREE. The calculated magma in equilibrium with apatite of the Taihe Middle and Upper Zones also shows weakly negative Sr anomalies in primitive mantle normalized trace element diagrams. These features indicate that the apatite of the Taihe Middle and Upper Zones crystallizes after clinopyroxene and before plagioclase. The apatite of the Taihe Middle and Upper Zones shows weakly negative Eu anomalies suggesting a high oxygen fugacity condition. The high iron and titanium contents in the oxidizing magma result in crystallization of Fe-Ti oxides. Crystallization of abundant Fe-Ti oxides and clinopyroxenes lowers the solubility of phosphorus and elevates SiO_2 concentration in the magma triggering the saturation of apatite. The positive correlations of Sr, V, total REE contents and Ce/Yb ratio in apatite with cumulus clinopyroxene demonstrate approximately compositional equilibrium between these phases suggesting they crystallized from the same ferrobasaltic magma. Early crystallization and accumulation of Fe-Ti oxide together with apatite produced the apatite-rich oxide ores at the base of the cyclic units of the Taihe Middle Zone.

1. Introduction

Magmatic apatite-rich Fe-Ti oxide ores are commonly associated with mafic layered intrusions or Proterozoic anorthosite complexes (Eales and Cawthorn, 1996; Ashwal, 2010; McLelland et al., 2010; Cawthorn, 2015). The Fe-Ti oxide ores varying in apatite modal content occur generally in the upper part of the layered intrusions, such as the Bushveld Complex and the Sept Iles intrusion (Von Gruenewaldt, 1993; Higgins and Doig, 1981). The Fe-Ti-P ore deposits associated with anorthosites occur generally as veins and lenses and cut enclosing rocks (Kolker, 1982; Dymek and Owens, 2001). The origin of these Fe-Ti-P ores is highly debated. Gravitational settling and sorting of crystals from ferrobasaltic magma have been proposed by a number of authors for their formation (Duchesne, 1999; Dymek and Owens, 2001). Nevertheless, some authors argued that the dense ores resulted from immiscible Fe-Ti-P melt segregated from mafic magma (Lister, 1966; Kolker, 1982; Naslund, 1983; Reynolds, 1985).

In the central zone of the Emeishan Large Igneous Province (ELIP), several large layered intrusions, such as Panzhihua, Baima, Xinjie and Hongge, host thick layers of Fe-Ti oxide ores, in which apatite is rare (<1 modal%). The formation of the Fe-Ti oxide layers are attributed to early crystallization and gravitational accumulation of Fe-Ti oxides from Fe-Ti-enriched magmas, which are produced by fractional crystallization of high-Ti picritic magma at depths (Pang et al., 2008a, 2009; Ganino et al., 2008, 2013; Zhang et al., 2009; Bai et al., 2012; Zhang et al., 2012; Song et al., 2013; Howarth et al., 2013; Howarth and Prevec, 2013). These thick Fe-Ti oxide layers are also thought to have crystallized from a dense immiscible Fe-rich melt (Zhou et al., 2005, 2013; Shellnutt et al., 2010; Wang and Zhou, 2013; Dong et al., 2013; Xing et al., 2014). A fluid dynamic model was also proposed to explain the origin of these oxide deposits (Hou et al., 2012; Luo et al., 2014;

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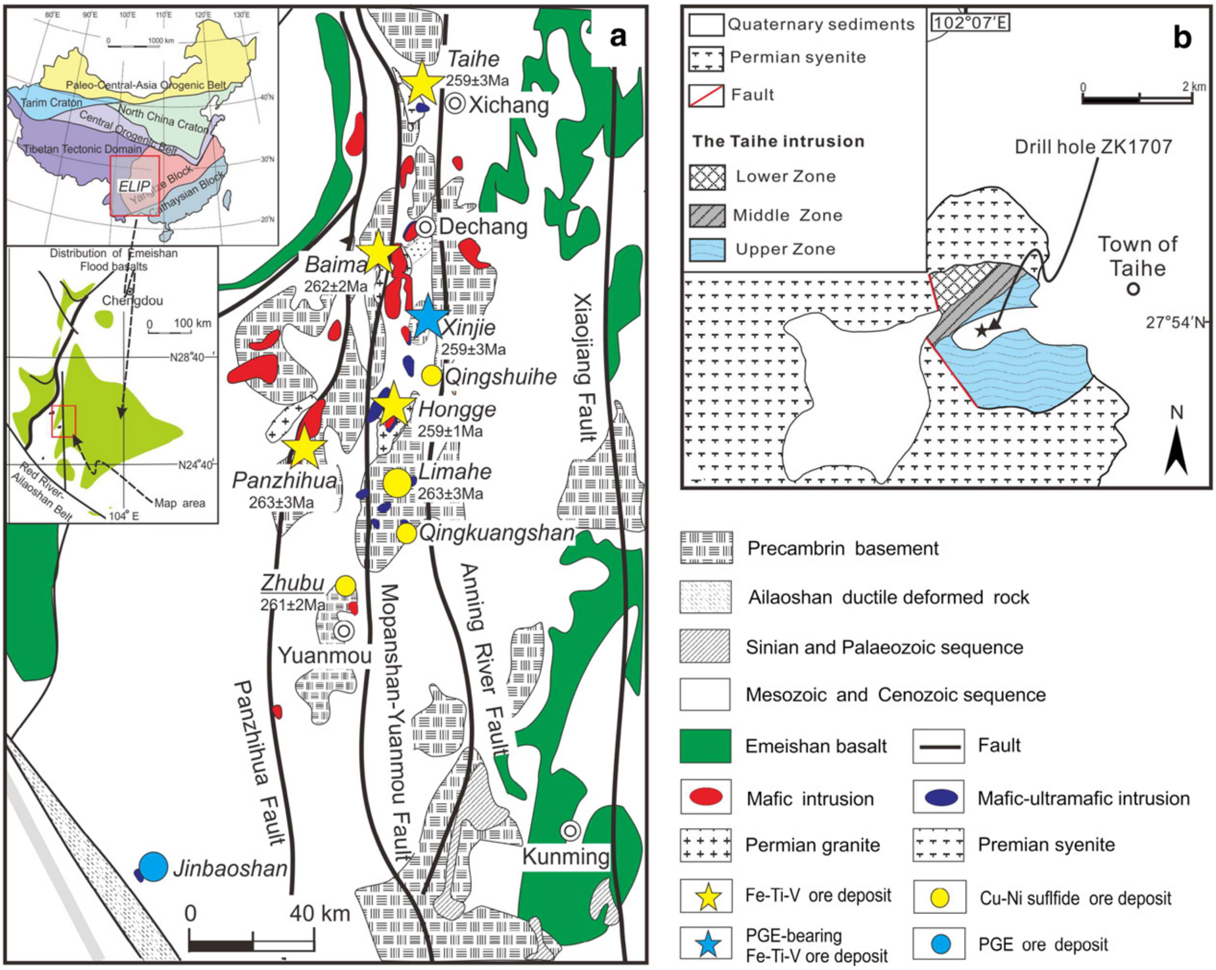

Fig. 1. (a) Regional geological map of the central Emeishan large igneous province (ELIP), showing the distribution of layered mafic-ultramafic intrusions hosting Fe-Ti oxide ore deposits (modified after Song et al., 2009). (b) Simplified geological map of the Taihe intrusion.

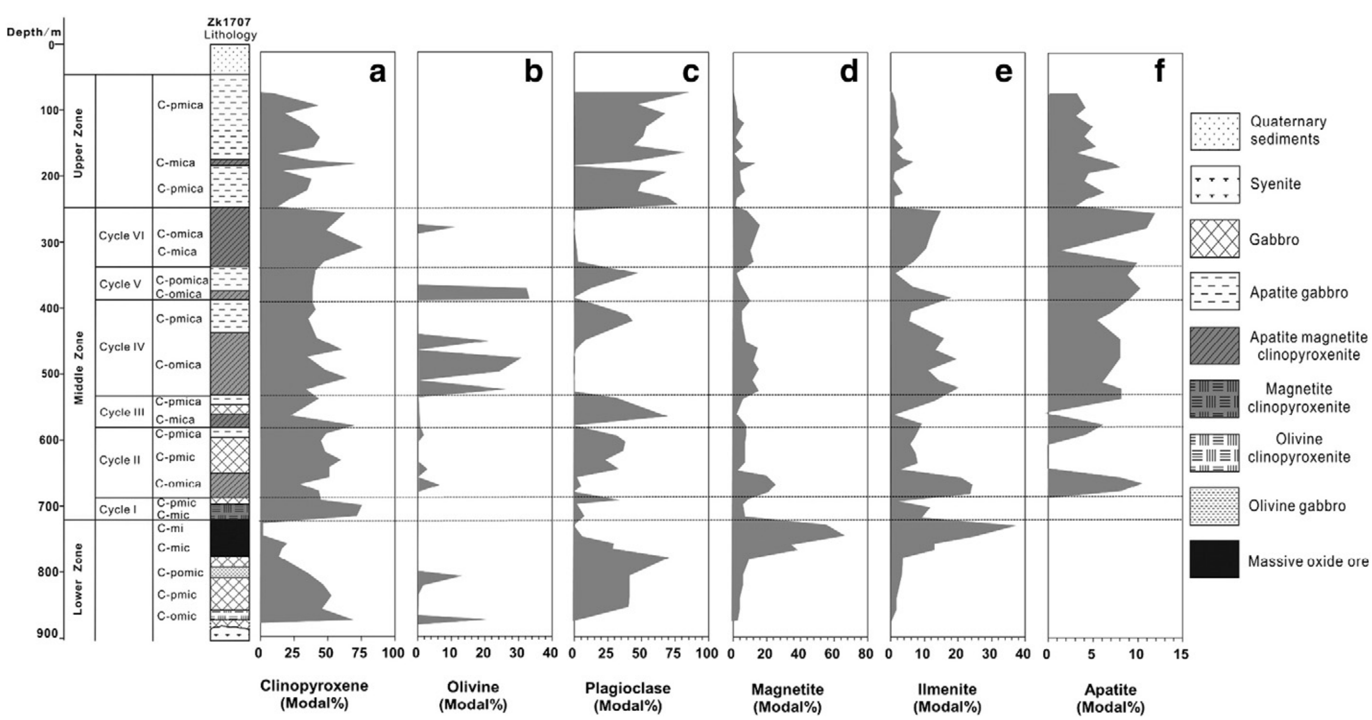

Fig. 2. Lithostratigraphic column from drill core ZK1707 from the Taihe intrusion. C = cumulus; m = magnetite; i = ilmenite; o = olivine; c = clinopyroxene; p = plagioclase; a = apatite.