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Focus paper

The Emeishan large igneous province: A synthesis

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A R T I C L E I N F O

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A B S T R A C T

The late Permian Emeishan large igneous province (ELIP) covers $\sim 0.3 \times 10^6$ km^2 of the western margin of the Yangtze Block and Tibetan Plateau with displaced, correlative units in northern Vietnam (Song Da zone). The ELIP is of particular interest because it contains numerous world-class base metal deposits and is contemporaneous with the late Capitanian ($\sim$260 Ma) mass extinction. The flood basalts are the signature feature of the ELIP but there are also ultramafic and silicic volcanic rocks and layered mafic-ultramafic and silicic plutonic rocks exposed. The ELIP is divided into three nearly concentric zones (i.e. inner, middle and outer) which correspond to progressively thicker crust from the inner to the outer zone. The eruptive age of the ELIP is constrained by geological, paleomagnetic and geochronological evidence to an interval of $\leq$3 Ma. The presence of picritic rocks and thick piles of flood basalts testifies to high temperature thermal regime however there is uncertainty as to whether these magmas were derived from the subcontinental lithospheric mantle or sub-lithospheric mantle (i.e. asthenosphere or mantle plume) sources or both. The range of Sr ($I_{Sr} \approx$ 0.7040–0.7132), Nd ($\varepsilon_{Nd}(t) \approx -14$ to $+8$), Pb ($^{206}Pb/^{204}Pb_1 \approx$ 17.9–20.6) and Os ($\gamma_{Os} \approx -5$ to $+11$) isotope values of the ultramafic and mafic rocks does not permit a conclusive answer to ultimate source origin of the primitive rocks but it is clear that some rocks were affected by crustal contamination and the presence of near-depleted isotope compositions suggests that there is a sub-lithospheric mantle component in the system. The silicic rocks are derived by basaltic magmas/rocks through fractional crystallization or partial melting, crustal melting or by interactions between mafic and crustal melts. The formation of the Fe-Ti-V oxide-ore deposits is probably due to a combination of fractional crystallization of Ti-rich basalt and fluxing of CO_2-rich fluids whereas the Ni-Cu-(PGE) deposits are related to crystallization and crustal contamination of mafic or ultramafic magmas with subsequent segregation of a sulphide-rich portion. The ELIP is considered to be a mantle plume-derived LIP however the primary evidence for such a model is less convincing (e.g. uplift and geochemistry) and is far more complicated than previously suggested but is likely to be derived from a relatively short-lived, plume-like upwelling of mantle-derived magmas. The emplacement of the ELIP may have adversely affected the short-term environmental conditions and contributed to the decline in biota during the late Capitanian.

1. Introduction

The study of mafic continental large igneous provinces (LIPs) requires the application of a broad range of disciplines within the earth and biological sciences to explain the physical transfer of material from the mantle to the crust and its effect on the biosphere. In the broadest sense continental mafic LIPs are large (i.e. $>0.5 \times 10^5$ km^2) spatially contiguous regions of the continental crust which host temporally and petrogenetically associated igneous rocks predominated by mafic compositions (Sheth, 2007a). The formation of LIPs is debated as some are considered to be derived by deep-seated diapiric upwellings of high temperature magmas (i.e. mantle plume) whereas others are considered to be derived by relatively shallow mantle melting associated with tensile stress in the overriding lithosphere (Jerram and Widdowson, 2005; Campbell, 2007; Saunders et al., 2007; Bryan and Ernst, 2008; Foulger, 2010). Regardless of their formation, LIPs are

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either directly or indirectly a consequence of plate tectonics and the cooling of the Earth (Wilson, 1963; Morgan, 1971, 1972; White and McKenzie, 1989, 1995; Coffin and Eldholm, 1994; Ernst and Buchan, 2003).

The emplacement and eruption of LIP magmas are often coincident with mass extinctions as four of the major (i.e. Cretaceous–Paleogene, Triassic–Jurassic, middle Permian and Permian–Triassic) mass extinctions are contemporaneous with the formation of the Deccan Traps, Central Atlantic Magmatic Province, Emeishan large igneous province and the Siberia Traps (Raup and Sepkoski, 1982; Rampino and Stothers, 1988; Courtillot et al., 1999; Wignall, 2001, 2005; Courtillot and Renne, 2003; White and Saunders, 2005; Wignall et al., 2009). The emission of particulate and gasses (i.e. SO_2 and CO_2) from the erupting lavas as well as country rock degassing may be sufficient to induce climate change, cause a reduction in sunlight and inhibit photosynthesis and/or induce acid rain (Wignall, 2001; Ganino and Arndt, 2009). However not all LIPs are coincident with biotic crises and therefore the relationship may not be clear-cut (Courtillot and Renne, 2003; Shellnutt et al., 2011a). Although LIPs may contribute to ecosystem collapse they are also important sites for economic deposits of precious and base metals (Pirajno, 2000; Borisenko et al., 2006; Ernst, 2007; Zhang et al., 2008a, b). In many cases the ore deposits are orthomagmatic (i.e. layered intrusions, volcanogenic massive sulphide) but due to the large volume of hot magmas passing through the crust it is possible to form a variety of types including skarns and hydrothermal copper and gold.

The late Permian Emeishan large igneous province (ELIP) is relatively small compared to the Siberian Traps or Central Atlantic Magmatic Province but is the focus of a tremendous amount of geological, geochemical, paleomagnetic, geochronological and biostratigraphic research during the past three decades. In spite of its stature as a 'smaller' large igneous province, the ELIP is an important geological feature of SW China not only because it hosts a number of world-class orthomagmatic Fe-Ti-V oxide deposits and series of smaller economically important Ni-Cu-(PGE) sulphide deposits but also the eruption of the Emeishan flood basalts is contemporaneous with the late Capitanian–early Wuchiapingian mass extinction (i.e. end-Guadalupian) indicating that there may be a link between the two (Zhou et al., 2002a; Zhang et al., 2006a, b; Ganino and Arndt, 2009; Sun et al., 2010; Shellnutt et al., 2012a). Beyond the flood basalts, economic and biogeological importance, the ELIP contains a diverse set of igneous rocks including cumulate mafic-ultramafic layered intrusions, picrites and the full spectrum of volcanic and plutonic silicic rocks (i.e. andesites, trachytes, rhyolites, syenites, granites). The fact that the magmatic plumbing system of the ELIP is well exposed at the surface is relatively special because the plutonic-hypabyssal rocks are not often observed within continental mafic LIPs thus providing a nearly complete account of its development. The bulk of the geological and petrological research, including evidence of structural doming of the crust and high temperature picritic lavas, suggests that the ELIP was formed by a mantle plume. Consequently it is considered to be one of the best examples of a mantle plume-derived LIP and can be used as a benchmark for comparison with other continental mafic LIPs (Campbell, 2005).

The numerous studies have produced a general understanding on the formation of the ELIP but recently many of the old views are giving way to new ideas which challenge the conventional orthodoxy. Specifically that the ELIP shows evidence for doming of the crust or that it was derived by a mantle plume is questioned as well as the ongoing debate regarding the formation of the flood basalts and oxide-ore deposits (Song et al., 2001, 2004, 2008a; Xu et al., 2001, 2004; He et al., 2003; Zhou et al., 2005; Ganino et al., 2008; Utskins-Peate and Bryan, 2008; Sun et al., 2010; Shellnutt and Jahn, 2011; Shellnutt et al., 2011b; Zhong et al., 2011a; Kamenetsky et al., 2012). The objective of this paper is to provide an overview of the major features and issues regarding the formation of the ELIP. The paper is divided into seven parts which focus on a specific topic. The first part discusses the basic geological background of the ELIP including its context within the geology of China. The second part discusses the age and duration ELIP including the uncertainties between geochronological techniques and interpretations. The third part discusses the formation of the non-mineralized magmatic rocks. The fourth part focuses on the structural features, i.e. evidence for a fossil plume head and crust doming, and the effect that magmatism may have had on the late middle Permian ecosystem. The metallogenesis of the ELIP is the focus of the fifth part, specifically the formation of the Ni-Cu-(PGE) sulphide and the Fe-Ti-V oxide deposits as well as some thoughts on the potential formation of rare earth element (REE) deposits. The sixth section attempts to bring all of the information together outlined in the previous sections and provide a synthesis of the ELIP. The final section discusses future research directions and opinions of ELIP-related topics.

2. Geological background

China is composed of three major Precambrian blocks and smaller terranes which have been amalgamating since ~1850 Ma or earlier (Fig. 1). In the east, the Archean North China Block (NCB) also known as the Sino-Korean Craton is bounded to the North by the Central Asia Orogenic Belt (CAOB), a Proterozoic to Paleozoic fold and thrust belt, and to the South by the middle Triassic Central Orogenic Belt (Qinling-Dabie Orogenic Belt). To the west of the NCB and the north of the Tibetan Plateau is the Tarim Block which is a Paleoproterozoic stable craton. Southeast of the Tibetan Plateau is the South China Block, a composite craton of the Yangtze Block and the Cathaysia Block (Fig. 1).

The NCB consists of two major Archean continental fragments surrounded by Paleoproterozoic orogenic belts (Zhao et al., 2005, 2006). From the late Paleoproterozoic to the Paleozoic shallow marine carbonates were deposited on many parts of the NCB. During this time, the southern margin was a site of volcanic arc accretion and granitic magmatism (1400–1000 Ma). During the Neoproterozoic extensive rift basins were formed along the northern and southern margins of the NCB (Wang and Mo, 1995; Li, 1998).

To the south of the Central Orogenic Belt is the South China Block (SCB) which comprises the Archean–Proterozoic Yangtze Block to the northwest and the Paleo-Mesoproterozoic Cathaysia Block to the southeast (Wang and Mo, 1995; Chen and Jahn, 1998). These two blocks are in contact along the Jiangshan-Shaoxing fault zone and likely collided during the late Mesoproterozoic (~1000 Ma) although this is debated (Hsu et al., 1990; Chen and Jahn, 1998). To the immediate west of the SCB is the Tibetan Plateau. The Tibetan Plateau consists of four distinct terranes, the Lhasa, Qiangtang, Yidun and Songpan-Ganze, a late Triassic–early Jurassic thrust sequence composed of 10 km thick marine sediments (Bruguier et al., 1997; Yan et al., 2003). Many of these terranes were accreted during the Paleozoic to Mesozoic and were deformed during the India-Eurasia collision (Wang and Mo, 1995; Yin and Harrison, 2000).

Southwestern China comprises the western margin of the Yangtze Block to the east and the eastern most part of the Tibetan Plateau to the west (Fig. 1). The Yangtze Block consists of Meso-Proterozoic granitic gneisses and metasedimentry rocks which have been intruded by Neoproterozoic (~800 Ma) granites and mafic rocks (Zhou et al., 2002b; Zhao and Zhou, 2007). The Neoproterozoic granites are overlain by a series of marine and