Lithos 204 (2014) 1–3

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

Preface

Permian large igneous provinces: Characteristics, mineralization and paleo-environment effects

The Permian is an important period in the history of the earth, characterized by the emplacement of at least four large igneous provinces (LIPs) (Emeishan, Tarim, Siberian, and to a lesser extent the Panjal). It is of great importance to understand the origin of these LIPs and to provide constraints on the dynamics of Earth' interior. World-class Ni–Cu-(PGE) sulfide deposits and Fe–Ti–V oxide deposits are hosted in the mafic–ultramafic intrusions of these Permian LIPs, such as the Norilsk intrusion in the Siberian Traps and the Panzhihua intrusion in the Emeishan LIP. A number of major global events occurred almost simultaneously during the late Paleozoic (Isozaki, 2009), including the double mass extinctions at Permian–Triassic Boundary (PTB) and Guadalupian–Lopingian Boundary (GLB), ocean superanoxia, sharp C and Sr isotopic excursions, sea-level drop and the Illawara geomagnetic reversal. In particular, the double mass extinctions at PTB and GLB are coincident with the Siberian Traps and the Emeishan LIP, respectively, indicating that the large-scale volcanism may have triggered the mass extinctions. It seems that many sub-systems of the Earth are intimately linked during this particular period, ranging from the core–mantle boundary, lithosphere, atmosphere, hydrosphere and biosphere. This has tentatively been interpreted as the consequences of a Permian superplume activity (Isozaki, 2009; Xu et al., 2013).

Over the past decade, as a result of some major research projects in China on these LIPs, multi-disciplinary investigations have been carried out on the origin of Permian LIPs, mineralization systems associated with mantle plumes, and paleoclimatic reconstructions and their implications for the Permian mass-extinctions. This special issue includes the recent research in these areas.

1. Age, composition and evolution of Permian large igneous provinces

1.1. The Emeishan LIP

Various investigations have been carried out in identifying an ancient mantle plume in the formation of the Emeishan LIP (Xu et al., 2007). However, the age of the Emeishan lavas remains poorly constrained because the extrusive rocks are thermally overprinted and represent an open system unsuitable for ^{40}Ar/^{39}Ar geochronology. The age of the Emeishan LIP has been constrained mainly by Secondary Ion Mass Spectrometer (SIMS) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) U–Pb techniques for the zircons from mafic and felsic intrusions, however accurate age constraints for the lavas have hitherto not been available. Zhong et al. (2014) precisely dated the age of the felsic ignimbrite at the uppermost part of the Emeishan lava succession using high-resolution chemical abrasion-thermal ionization mass spectrometry (CA-TIMS) zircon U–Pb techniques and obtained a weighted mean ^{206}Pb/^{238}U age of 259.1 ± 0.5 Ma, which is interpreted as the termination age of the Emeishan flood basalts.

In an attempt to trace the geological records left by mantle plumes, Deng et al. (2014) investigated the residual gravity anomaly in South China in conjunction with deep seismic sounding profiles and deep seismic reflection surveys. Their results show that the residual gravity anomaly and density anomaly of the inner zone of the Emeishan LIP are $+150$ mGal and $+0.06$ g/cm^3 respectively, and that these decrease gradually with distance from the inner zone. The positive residual gravity and the corresponding high density can be attributed to mafic/ultramafic rocks and cooled surrounding rocks generated by large scale magmatic intrusion, thereby providing further evidence for the formation of the Emeishan LIP by an upwelling of a mantle plume.

1.2. The Tarim LIP

The Early Permian magmatism in the Tarim LIP (NW China) comprises diamondiferous kimberlite, lamprophyre, flood basalts, Fe–Ti oxide-bearing, layered mafic–ultramafic intrusions, bi-modal dyke swarms, syenitic-A-type granitic complexes, and rhyolite and pyroclastic rocks. The extent of this intraplate magmatism exceeds 250,000 km^2, making it comparable to LIPs elsewhere. Xu et al. (2014) outlined three main episodes of magmatism in the Tarim LIP, ~300 Ma kimberlite, ~290 Ma flood basalts and ~280 Ma mafic–ultramafic and felsic plutons and dyke swarms. The ~290 Ma magmatism is widespread across the Tarim LIP, whereas ~300 Ma and ~280 Ma magmatism is sporadically distributed on the margin of the LIP. A plume incubation model is proposed to account for the temporo-spatial distribution of the Tarim LIP (Xu et al., 2014); the ~300 Ma kimberlite may have been derived from metasomatized sub-continental lithospheric mantle (SCLM), whereas the ~290 Ma flood basalts were likely formed from the mixing of the plume-derived melts with the SCLM-derived melts during ascent. The ~280 Ma intrusive bodies may have been derived from the convecting mantle.

Li et al. (2014a) identified a regional unconformity between Carboniferous and Permian, and showed that the erosion degree of Carboniferous strata is highest in the Northern Tarim region and decreases gradually to the south. The early Permian pre-eruption deposit displays a similar pattern. They concluded that both the late Carboniferous and early Permian sedimentary records indicate a crustal uplift event at ~300 Ma, likely triggered by a mantle plume.

http://dx.doi.org/10.1016/j.lithos.2014.06.003

The $\varepsilon_{Hf}(t)$ values (-6.8 to $+1.4$) of the early Permian (ca. 290 Ma) zircons from the Keping basalts are generally lower than those of the host basalts (-2.8 to $+2.1$), and distinctly different from that of intrusions (-0.3 to $+7.1$) and the zircons from the intrusions ($+4.9$ to $+8.8$) elsewhere in the Tarim LIP. These zircons are interpreted as the xenocrysts from the in situ sedimentary rocks due to crustal contamination and may be originally derived from unrevealed igneous plutons in the Tarim LIP or other coeval plutons in adjacent regions (Li et al., 2014b).

In order to understand the behavior of crust above a mantle plume, Liu et al. (2014) studied two types of silicic volcanics in the Tarim LIP. The low Nb–Ta type rhyolites, which are associated with the ~290 Ma flood basalts have low $\varepsilon_{Nd}(t)$ (-7.7 to -5.6) and $\varepsilon_{Hf}(t)$ values (-5.2 to -0.8), and high zircon $\delta^{18}O$ values (8.1 to 9.6‰), consistent with a derivation from continental crust. In contrast, the high Nb–Ta type rhyolites and their plutonic equivalents are associated with the ~280 Ma episode of Tarim magmatism and have OIB-like trace element ratios, high $\varepsilon_{Nd}(t)$ (-3.4 to $+1.3$) and $\varepsilon_{Hf}(t)$ values (0.7–8.2). These two types of rhyolite may explain the various extents of thermal and mass exchange between mantle-derived basaltic magma and crustal material above the Tarim mantle plume.

Chen et al. (2014a) identified the geometry and emplacement mode of the mafic dikes, sills and flood basalts of the Tarim LIP in the Keping area using multiple-source high-resolution remote sensing images together with structural analyses and paleomagnetic results. This work confirms that the flood basalts of the Tarim LIP may have extended to the Keping Uplift so that the areal extent of the Tarim LIP could be enlarged by ~12,000 km^2 compared with originally reported ~250,000 km^2.

The influence of the Tarim plume activity is recorded in high-temperature granulites (Li et al., 2014c) and in mantle-derived spinel peridotite and spinel plagioclase pyroxenite xenoliths hosted in Cenozoic (~20 Ma) alkali basalts in the Xikeer area, west Tarim (Chen et al., 2014b). Li et al. (2014c) reported the discovery of the ultra-high-temperature (UHT) pelitic granulite in the Altai orogenic belt. They recognized two mineral assemblages of high-Al orthopyroxene + sillimanite + quartz and low-Zn spinel + quartz, and constrain an anti-clockwise P–T path using pseudo-sections and the y(opx) isopleths. They interpreted the anti-clockwise P–T path to be related to an extensional event due to the sinistral strike-slip along the Irtysh suture zone after the subduction and slab detachment between the Kazakhstan–Junggar plate and Siberian plate. The Re–Os isotopic systematics of the Xikeer peridotites and pyroxenites yield an apparent isochron of ~290 Ma, virtually identical to the age of Tarim flood basalts. The Xikeer xenolith suite may have been initially formed by melt extraction from the convecting mantle and, shortly after, was refertilized by Tarim mantle plume melts during the Early Permian (Chen et al., 2014b).

It was unclear how far the magmas of the early Permian Tarim plume extend in the Central Asian Orogenic Belt (CAOB). Zhang et al. (2014a) documented the zircon U–Pb ages and Hf isotopic compositions, whole-rock and mineral geochemistry for the Permian gabbroic intrusions in the southern margin of the Altai orogenic belt. Together with the observations in the field and lithology, they consider that the gabbroic intrusions in this region are also part of the Tarim LIP. They also evaluated the Ni–Cu mineralization potential of these intrusions.

Gao et al. (2014) presented petrological, geochronological, and geochemical data for I-type and A-type granites from West Junggar, which were emplaced at 348–319 Ma and 321–290 Ma, respectively. They interpreted the early Carboniferous I-type granites the products of re melting of trapped oceanic crust due to underplated mantle wedge-derived basaltic magma. The high positive $\varepsilon_{Nd}(t)$ values and high Zr-saturation temperatures of the A-type granitoids may be genetically related to a mantle plume or a regional-scale mantle upwelling in the CAOB.

Dan et al. (2014) characterized the Early Permian (ca. 280 Ma) granitoids in the Alxa Block. Using zircon U–Pb age and Hf–O isotopic, and whole-rock geochemical and Sr–Nd isotopic data, these authors are able to quantify the relative contribution of the crust and mantle to this silicic province. Given that these magmatic rocks have no spatial or temporal zonation, they suggest that the ca. 280 Ma Tarim mantle plume in NW China may have triggered the magmatic flare-up of the Alxa silicic igneous province.

1.3. Panjal Trap

The Early Permian (~290 Ma) Panjal Traps in northern India represent a significant eruption of magmas during the opening of the Neotethys ocean. Similar to the observations made in LIPs elsewhere (e.g., Karoo, Deccan, Parana, Emeishan), Shellnutt et al. (2014) identify two main rock types: OIB-like high-Ti ($TiO_2 > 2.0$ wt.%) and low-Ti ($TiO_2 < 1.8$ wt.%). They propose that the volcanism in the Panjal Traps is likely to be due to partial melting of the SCLM within a passive extensional setting related to the rifting of Cimmeria from Gondwana.

2. Mineralization system associated with Permian large igneous provinces

Crustal contamination has been considered as a key factor in generating the giant Noril'sk Ni–Cu-(PGE) sulfide deposit, however the nature of contaminant remains poorly characterized. Malitch et al. (2014) presents the Cu and S isotopic compositions of the sulfides in the economic deposits, subeconomic deposits and non-economic occurrences in the Noril'sk Province in Russia. They consider that the restricted range of $\delta^{65}Cu$ values of the sulfides may represent the primary signature of the ores. The variation of the $\delta^{34}S$ values among the different types of the ores is attributed to the sulfur fractionation in deep-seated magma chambers rather than at shallow levels or the present emplacement sites.

The origin of the giant Fe–Ti oxide-bearing layered intrusions in the Emeishan LIP has been debated in the recent years. Xing et al. (2014) presented more evidence for a silicate immiscibility model. They documented the major and trace element variations along an apatite-rich rock profile, above the major ore bodies of the Panzhihua layered intrusion in the Emeishan LIP. They noted a few compositional reversals in the column and interpreted them as double-diffusive convection that occurred in the P- and Si-rich melt and magma mixing between the stratified magma layers. They proposed a model to explain that the Panzhihua intrusion may have formed due to the immiscibility of ferrobasaltic magmas in a large convection cell at high temperatures and to explain why the apatite-rich MZb is above the major Fe–Ti oxide layers in the Panzhihua intrusion.

To constrain the time scale of the emplacement of layered intrusions in the Emeishan LIP, Cheng et al. (2014) analyzed plagioclase megacrysts in the gabbros of the lower zone of the Panzhihua intrusion and presented the major and trace elements and in situ Sr isotopic compositions of the plagioclase magacrysts. Together with the textural relationship and crystal size distribution, they concluded that the emplacement and crystallization of the Panzhihua intrusion may have taken place in a short time, maybe thousands of years.

3. Paleo-environmental changes across the GLB and PTB and their relevance to mass extinction

The-end-Permian mass extinction is the most severe biotic crisis during the Phanerozoic. However, its cause, or causes, yet remain unclear. Numerous scenarios have been proposed, including asteroid impact, Siberian flood basalt volcanism, marine anoxia and euxinia, sea-level change and methane release. To understand the cause(s) of the end-Permian mass extinction, a high-resolution timescale is essential. Conodonts are one of the best fossil groups for establishing high-resolution biostratigraphic framework. However, the previous studies indicate that different approaches produced very different frameworks. Yuan et al. (2014) provides a new high-resolution conodont framework from the Meishan section in South China with a sample-population approach. They also established an integrative high-resolution framework including high-precision geochronologic ages (Burgess et al., 2014; Shen et al., 2011) and high-resolution chemostratigraphy (Cao et al., 2009; Shen et al., 2013) which provides a precise calibration for the largest mass extinction. Previously, numerous micropherules with various origins from asteroid impact and volcanism were reported from the PTB beds in South China. Zhang et al. (2014b) analyzed 60 samples from 12 intensively-studied PTB sections and some soil samples nearby the studied sections. Their investigation indicates that the abundant microspherules with mosaic or dot shape crystals on rounded surface from the boundary beds are mostly modern industrial fly ashes and only the rounded quartz and the particles containing extremely high SO_2 and TiO_2 are possibly of volcanic origin.

On the basis of the U–Pb ages and Hf–O isotopes of the zircons from the volcanic ashes in the five PTB sections in South China, He et al. (2014) suggested that the zircon grains have a crustal-derived origin, and therefore proposed that the PTB mass extinction may be related to the Paleo-Tethys continental arc magmatism in the Kunlun area, rather than to the Siberian Traps. They speculated that the ignimbrite flare-up related to rapid plate subduction during the final assemblage of the Pangea super-continent may have eventually triggered the collapse of ecosystem and ultimately mass extinction at the end of Permian.

Acknowledgments

Most of the contributions to this special issue were supported by the Ministry of Science and Technology of China (2011CB808900). We would like to thank all the authors for their contributions and all the referees whose reviews of the manuscripts have helped to improve this volume. We are particularly grateful to the Editor-in-chief, Dr. Andrew Kerr who read everything of this volume, and journal manager, Ms. Rohini Shivaram, for providing guidance in the review and publication processes of this special issue.

References

Burgess, S.D., Bowring, S.A., Shen, S.Z., 2014. High-precision timeline for Earth's most severe extinction. Proceedings of the National Academy of Sciences 111, 3316–3321.

Cao, C.Q., Love, G.D., Hays, L.E., Wang, W., Shen, S.Z., Summons, R.E., 2009. Biogeochemical evidence for euxinic oceans and ecological disturbance presaging the end-Permian mass extinction event. Earth and Planetary Science Letters 281, 188–201.

Chen, N.H., Dong, J.J., Yang, S.F., Cheng, J.Y., Li, Z.L., Ni, N.N., 2014a. Restoration of geometry and emplacement mode of the Permian mafic dyke swarms in Keping and its adjacent areas of the Tarim Block, NW China. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.05.020.

Chen, M.M., Tian, W., Suzuki, Tejada, K., M.-L.-G, Liu, F.-L., Senda, R., Wei, C.J., Chen, B., Chu, Z.Y., 2014b. Peridotite and pyroxenite xenoliths from Tarim, NW China: evidences for melt depletion and mantle refertilization in the mantle source region of the Tarim flood basalt. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.01.005.

Cheng, L.L., Zeng, L., Ren, Z.Y., Wang, Y., Luo, Z.H., 2014. Time scale of emplacement of the Panzhihua gabbroic layered intrusion recorded in giant plagioclase at Sichuan Province, SW China. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.02.017.

Dan, W., Li, X.H., Wang, Q., Tang, G.J., Liu, Y., 2014. An Early Permian (ca. 280 Ma) silicic igneous province in the Alxa Block, NW China: a magmatic flare-up triggered by a mantle-plume? Lithos. http://dx.doi.org/10.1016/j.lithos.2014.01.018.

Deng, Y., Zhang, Z., Zhang, Z.J., Mooney, W., Badal, J., Fan, W.M., Zhong, Q., 2014. Mantle origin of the Emeishan large igneous province (South China) from the analysis of residual gravity anomalies. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.02.008.

Gao, R., Xiao, L., Pirajno, F., Wang, G., He, X.X., Yang, G., Yan, S., 2014. Carboniferous-Permian extensive magmatism in the West Junggar, Xinjiang, northwestern China: its geochemistry, geochronology, and petrogenesis. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.05.028.

He, B., Zhong, Y.T., Xu, Y.G., Li, X.H., 2014. Permo-Triassic mass extinction: Siberian Traps or an ignimbrite flare-up? Lithos. http://dx.doi.org/10.1016/j.lithos.2014.05.011.

Isozaki, Y., 2009. Illawarra Reversal: the fingerprint of a superplume that triggered Pangean breakup and the end-Guadalupian (Permian) mass extinction. Gondwana Research 15, 421–432.

Li, Y.Q., Li, Z.L., Yu, X., Santosh, M., Langmuir, C.H., Yang, S.F., Chen, H.L., Tang, Z.L., Song, B., Zou, S.Y., 2014a. Origin of zircons from the Traim flood basalts. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.05.021.

Li, Z.L., Yang, X.Q., Li, Y.Q., Santosh, M., Chen, H.L., Xiao, W.J., 2014b. Late Paleozoic tectono-metamorphic evolution of the Altai segment of the Central Asian Orogenic Belt: constraints from metamorphic P–T pseudosection and zircon U–Pb dating of ultra-high-temperature granulite. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.05.022.

Li, D.X., Yang, S.F., Chen, H.L., Cheng, X.G., Li, Kang, Jin, X.L., Li, Z.L., Li, Y.Q., Zou, S.Y., 2014c. Late Carboniferous crustal uplift of the Tarim plate and its constraint on the evolution of Early Permian Tarim Large Igneous Province. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.05.023.

Liu, H.Q., Xu, Y.G., Tain, W., Zhong, Y.T., Mundil, R., Li, X.H., Yang, Y.H., Luo, Z.Y., Shangguan, S.M., 2014. Origin of two types of rhyolites from Tarim Large Igneous Province: consequences of plume incubation and melting. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.02.007.

Malitch, K.N., Latypov, R.M., Badanina, I.Y., Sluzhenikin, S.F., 2014. Insights into ore genesis of Ni–Cu–PGE sulfide deposits of the Noril'sk Province (Russia): evidence from copper and sulfur isotopes. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.05.014.

Shellnutt, J.G., Bhat, G.M., Wang, K.L., Brookfield, M.E., Jahn, B.M., Dostal, J., 2014. Petrogenesis of the flood basalts from the Early Permian Panjal Traps, Kashmir, India: geochemical evidence for shallow melting of the mantle. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.01.008.

Shen, S.Z., Crowley, J.L., Wang, Y., Bowring, S.A., Erwin, D.H., Sadler, P.M., Cao, C., Rothman, D.H., Henderson, C.M., Ramezani, J., Zhang, H., Shen, Y., Wang, X.D., Wang, W., Mu, L., Li, W.Z., Tang, Y.G., Liu, X.L., Liu, L.J., Zeng, Y., Jiang, Y.F., Jin, Y.G., 2011. Calibrating the end-Permian mass extinction. Science 334, 1367–1372.

Shen, S.Z., Cao, C.Q., Zhang, H., Bowring, S.A., Henderson, C.M., Payne, J.L., Davydov, V.I., Chen, B., Yuan, D.X., Zhang, Y.C., Wang, W., Zheng, Q.F., 2013. High-resolution δ^{13}Ccarb chemostratigraphy from latest Guadalupian through earliest Triassic in South China and Iran. Earth and Planetary Science Letters 375, 156–165.

Xing, C.M., Wang, C.Y., Li, C.Y., 2014. Trace element compositions of apatite from the middle zone of the Panzhihua layered intrusion, SW China: insights into the differentiation of a P- and Si-rich melt. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.02.009.

Xu, Y.G., He, B., Huang, X.L., Luo, Z.Y., Chung, S.L., Xiao, L., Zhu, D., Shao, H., Xu, J.F., Fan, W.M., Wang, Y.J., 2007. Testing plume hypothesis in the Emeishan large igneous province. Episodes 30, 32–42.

Xu, Y.G., He, B., Luo, Z.Y., Liu, H.Q., 2013. Study on mantle plume and large igneous provinces in China: an overview and perspectives. Bulletin of Mineralogy, Petrology and Geochemistry 32, 25–39 (in Chinese with English abstract).

Xu, Y.G., Wei, X., Luo, Z.Y., Liu, H.Q., Cao, J., 2014. The Early Permian Tarim Large Igneous Province: main characteristics and a plume incubation model. Lithos 214. http://dx.doi.org/10.1016/j.lithos.2014.02.015.

Yuan, D.X., Shen, S.Z., Henderson, C.M., Chen, J., Zhang, H., Feng, H.Z., 2014. Revised conodont-based integrated high-resolution timescale for the Changhsingian Stage and end-Permian extinction interval at the Meishan sections, South China. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.03.026.

Zhang, C.L., Zou, H.B., Yao, C.Y., Dong, Y.G., 2014a. Origin of the Permian mafic–ultramafic intrusions in the southern margin of the Altai Orogen: a possible link to the Permian Tarim mantle plume? Lithos. http://dx.doi.org/10.1016/j.lithos.2014.05.019.

Zhang, H., Shen, S.Z., Cao, C.Q., Zheng, Q.-F., 2014b. Origins of microspherules from the Permian–Triassic boundary event layers in South China. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.02.018.

Zhong, Y.T., He, B., Mundil, R., Xu, Y.G., 2014. CA-TIMS zircon U–Pb dating of felsic ignimbrite from the Binchuan section: implications for the termination age of Emeishan large igneous province. Lithos. http://dx.doi.org/10.1016/j.lithos.2014.03.005.

Yi-Gang Xu*
State Key Laboratory of Isotope Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, 510640 Guangzhou, PR China
*Corresponding author. Tel.: +86 20 85290109; fax: +86 20 85290130.
E-mail address: yigangxu@gig.ac.cn.

Christina Yan Wang
CAS Key Laboratory of Mineralogy and Metallogeny, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, 510640 Guangzhou, PR China

Shuzhong Shen
State Key Laboratory of Paleobiology and Stratigraphy, Nanjing Institute of Geology and Palaeontology, Chinese Academy of Sciences, Nanjing 210008, PR China

24 May 2014