GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G45210.1

Manuscript received 29 May 2018
Revised manuscript received 30 August 2018
Manuscript accepted 9 September 2018

Published online 25 September 2018

A temporal and causal link between ca. 1380 Ma large igneous provinces and black shales: Implications for the Mesoproterozoic time scale and paleoenvironment

Shuan-Hong Zhang[1]*, Richard E. Ernst[2,3], Jun-Ling Pei[1], Yue Zhao[1], Mei-Fu Zhou[4], and Guo-Hui Hu[1]

[1]Institute of Geomechanics, Chinese Academy of Geological Sciences, MLR Key Laboratory of Paleomagnetism and Tectonic Reconstruction, Beijing 100081, China
[2]Department of Earth Sciences, Carleton University, Ottawa, Ontario K1S 5B6, Canada
[3]Faculty of Geology and Geography, Tomsk State University, Tomsk 634050, Russia
[4]Department of Earth Sciences, The University of Hong Kong, Hong Kong, China

ABSTRACT

Phanerozoic large igneous provinces (LIPs) have a significant influence on global climate changes and mass extinction events (MEEs). Most of the Global Boundary Stratotype Section and Points in the Phanerozoic international chronostratigraphic scale are coeval with LIPs and are marked in the sedimentary record by global-scale MEEs and/or by ocean anoxic events represented by black shales. However, due to limited knowledge on atmospheric oxygen concentrations, ocean redox conditions, and early fossils during the Meso-Neoproterozoic Eras prior to the Ediacaran period, little is known on the climate and environmental effects of LIPs during this period of a billion years, the so-called "Boring Billion" (1.8–0.8 Ga). Here we provide geochronological and geological evidence for a temporal and genetic link between the intense ca. 1380 Ma LIP activity (found on many crustal blocks) and coeval black shales in the Nuna (Columbia) supercontinent. We further propose that the ca. 1380 Ma LIPs and black shales widely distributed in the Nuna supercontinent represent a global-scale geological event and provide a robust natural marker for the Calymmian-Ectasian boundary at 1383 Ma. Further investigation of the temporal and genetic link between the LIPs and black shales at other times can contribute to understanding the variations in atmospheric oxygen concentrations and ocean redox conditions during the Boring Billion, during which virtually nothing of Earth's climate and MEEs is known.

INTRODUCTION

Large igneous provinces (LIPs) represent large-volume, short-duration (or pulsed) mafic igneous events of intraplate character throughout Earth's history (e.g., Coffin and Eldholm, 1994; Bryan and Ernst, 2008). They can have a significant global climatic effect and are usually linked to global environmental catastrophes and mass extinction events (MEEs) (e.g., Courtillot, 1999; Wignall, 2001).

In the Phanerozoic Eon, LIPs can be correlated with major ocean anoxic events (OAEs) and MEEs, and these correlative geological events have been used as natural markers of Global Boundary Stratotype Section and Points (GSSPs) in the sedimentary record (Percival et al., 2015). For example, the Frasnian-Famennian (372.2 Ma), the Permian-Triassic (252.2 Ma), and the Pliensbachian-Toarcian (182.7 Ma) boundaries are temporally correlated with global LIPs, OAEs, and MEEs (e.g., Percival et al., 2015; Ernst and Youbi, 2017).

Subdivisions of the Phanerozoic and the base of the Ediacaran in the international chronostratigraphic scale are each defined by a basal GSSP, whereas the other Precambrian periods are formally subdivided by assigned absolute age due to lack of constraints from global geologic events (Ogg et al., 2016). In the Phanerozoic Eon LIPs, OAEs (represented by black shales) and associated MEEs define many of the boundaries in the Phanerozoic chronostratigraphic scale (Courtillot, 1999). Although MEEs have not yet been identified from the Meso-Neoproterozoic period, global LIPs and black shales during this period are common in many continental blocks. Therefore, the global LIPs and coeval black shales can be used as potential GSSPs in the Meso-Neoproterozoic chronostratigraphic scale. In this paper, we discuss the temporal relationship between the widespread ca. 1.38 Ga LIPs and black shales recently identified from many continental blocks in the Nuna supercontinent, its implications for paleoenvironments, and how it provides a natural definition for the Calymmian-Ectasian boundary.

THE ca. 1380 Ma LARGE IGNEOUS PROVINCES (LIPs)

The ca. 1380 Ma LIPs have been identified from many continental blocks including Baltica, Laurentia, Siberia, Amazonia, Kalahari, Congo, West Africa, and East Antarctica (Fig. 1; Ernst, 2014; see summary and full referencing in Table DR1 in the GSA Data Repository[1]). The Mashak LIP is located in the eastern margin of the Baltica craton and is made up of plutonic, volcanic (Mashak Formation), and subvolcanic (numerous diabase dike and sill swarms) rocks of bimodal composition with zircon and baddeleyite U-Pb ages of 1391 ± 2 Ma to 1369 ± 13 Ma. The Hart River–Salmon River Arch LIP is located in western margin of Laurentia and is composed mainly of Hart River mafic sills and dikes with a zircon U-Pb age of 1382 ± 4 Ma, and of Salmon River Arch diabase sills and minor granite, quartz diorite, quartz monzonite, and leucosome with zircon U-Pb ages of 1386 ± 2 Ma to 1370 ± 2 Ma and new precise ages 1382.2 ± 0.4 Ma and 1382.1 ± 0.4 Ma. The Midsommersø–Zig-Zag Dal LIP in eastern North Greenland consists of Midsommersø diabase (conformable sills, dikes, and inclined sheets, with a baddeleyite U-Pb age of 1382 ± 2 Ma) and minor granophyric intrusions and Zig-Zag Dal flood basalts covering

*E-mail: tozhangshuanhong@163.com
CITATION: Zhang, S.-H., et al., 2018, A temporal and causal link between ca. 1380 Ma large igneous provinces and black shales: Implications for the Mesoproterozoic time scale and paleoenvironment: Geology, v. 46, p. 963–966, https://doi.org/10.1130/G45210.1

[1]GSA Data Repository item 2018367, Figures DR1–DR5 and Tables DR1–DR2, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

an area of >10,000 km² and with a maximum thickness of ~1350 m. In southern Laurentia there is a widespread 1390–1340 Ma silicic LIP. The Chieress LIP in the Anabar shield in the northern Siberia craton consists mainly of diabase dikes with a baddeleyite U-Pb age of 1384 ± 2 Ma, and can be extended into the Taimyr block as the Severobyrrang sills with ages of 1345 ± 35 Ma and 1365 ± 11 Ma. The Kunene-Kibaran LIP in the Congo craton is composed of the Lake Victoria giant semicircular diabase dike swarm (Sm-Nd isochron ages of 1368 ± 41 Ma and 1374 ± 42 Ma), associated layered intrusions, and coeval felsic magmatism on the eastern side of the craton. On the western side of the Congo craton there are the Kunene anorthosite, granite, and mafic-ultramafic layered intrusions and sills (zircon and baddeleyite U-Pb ages of 1385 ± 25 Ma to 1365 ± 2 Ma). The Pilanesberg LIP in the Kalahari craton is composed mainly of diabase dikes with zircon and titanite U-Pb ages of 1395 ± 10 Ma to 1374 ± 10 Ma. Diabase dike swarms of ca. 1380 Ma have also been identified from other cratons including West Africa, Amazonia, and East Antarctica.

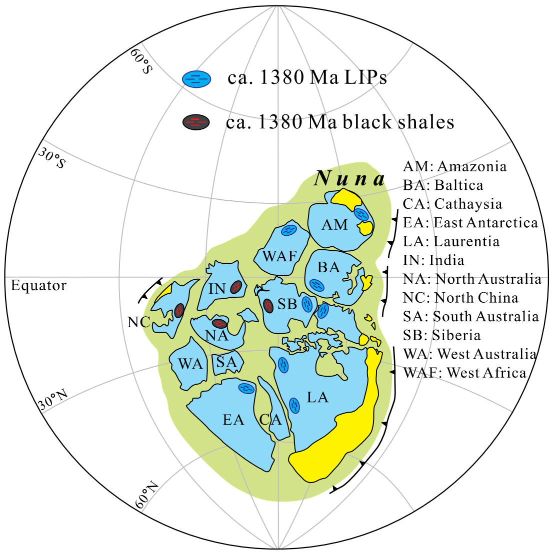

Figure 1. Distribution of ca. 1380 Ma large igneous provinces (LIPs) and black shales in paleogeographic reconstruction map of Nuna supercontinent (after Zhang et al., 2012).

THE ca. 1380 Ma BLACK SHALES

The ca. 1380 Ma black shales have been confirmed from at least two cratons, the North China and North Australian cratons (Figs. 1 and 2). The Xiamaling Formation (XF) in the Yanliao rift zone in the northern North China craton (NCC) consists mainly of shale and mudstone and was deposited in a tectonically quiet marine basin. Black shales, which are ~100–300 m in thickness, are very common at the middle part of the formation. Tuff and K-bentonite beds with thermal ionization mass spectrometry (TIMS) and sensitive high-resolution ion microprobe (SHRIMP) zircon U-Pb ages of 1384 ± 1 Ma to 1366 ± 9 Ma are very common within the black shales of the formation (middle part) with a peak age of 1384 Ma and a weighted mean age of 1383 ± 2 Ma (Table DR2; Figs. 2A–2C and 3; Fig. DR1 in the Data Repository), indicating deposition of the black shales at ca. 1380 Ma.

The Velkerri Formation of Roper Group in the McArthur Basin in the North Australian craton is up to 900 m thick and consists predominantly of organic-rich black shales (100–300 m thick) with subordinate

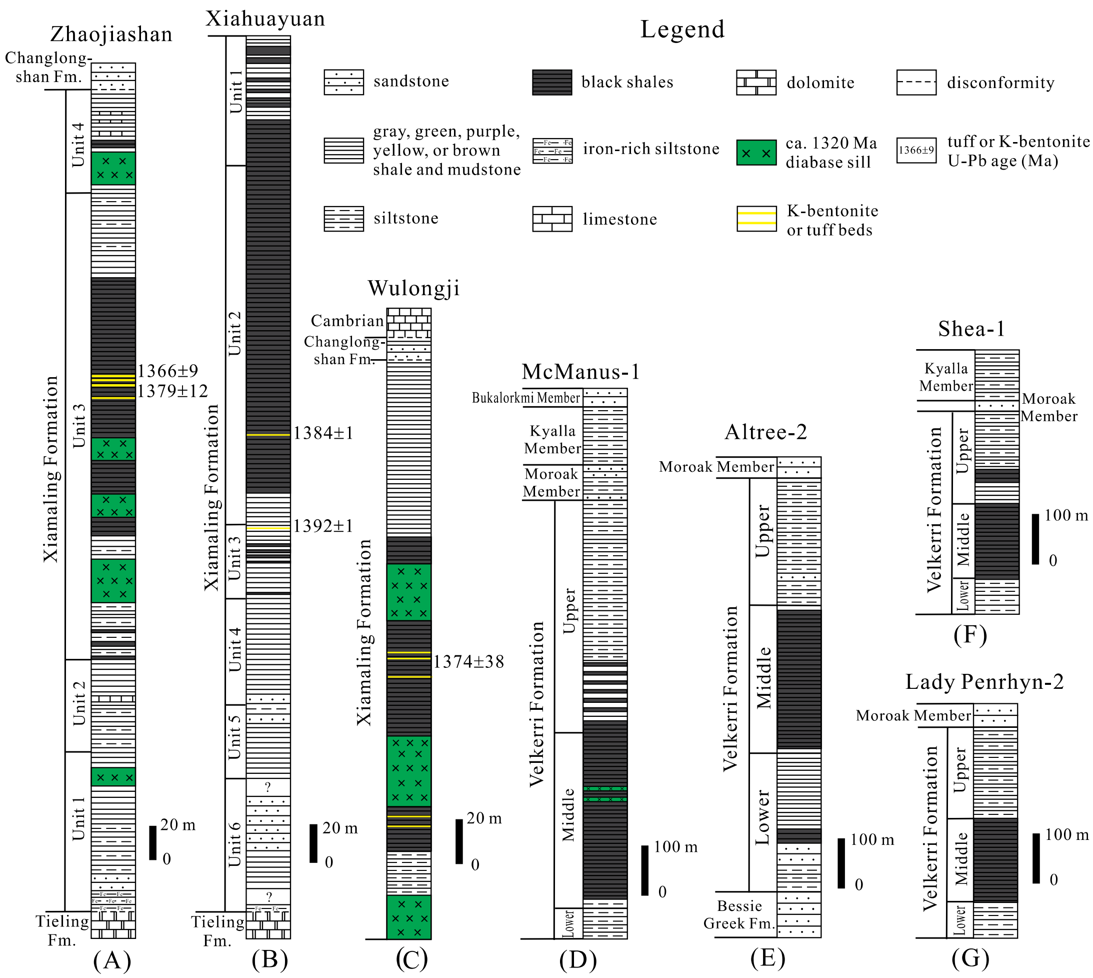

Figure 2. Representative stratigraphic columns of black shales in Xiamaling Formation in North China craton (A–C) and Velkerri Formation in North Australian craton (D–G) (modified after Warren et al., 1998 [columns D–G]; Fan, 2015 [column A]; Wang et al., 2017 [column B]; Zhang et al., 2017 [column C]).

organic-poor glauconitic siltstones and fine-grained sandstones (Figs. 2D–2G; Warren et al., 1998). A Re-Os isochron age of 1361 ± 21 Ma has been obtained for the black shales from the uppermost part of the middle Velkerri Formation (Kendall et al., 2009), which is similar to zircon U-Pb ages of the tuff beds from the uppermost part of the black shales within the XF in the NCC. It was recently proposed that North China and North Australian cratons were reconstructed at this time through the matching of 1320 Ma Yanliao and Derim Derim LIP magmatism (Zhang et al., 2017), suggesting that the similar ca. 1380 Ma black shales of the two cratons were part of a shared sedimentary basin.

In addition to the robust North China and northern Australia examples, black shales with approximately the same ca. 1380 Ma ages may also exist in Mesoproterozoic sequences on other crustal blocks including the western Siberia (Dzhelindukon and Vedreshev Formations; Fig. DR2), India (Bijaigarh Shale of the Kaimur Formation; Fig. DR3; black shales from the Srisailam Formation), and São Francisco (Serra do Garrote Formation of the Vazante Group, São Francisco basin) cratons (Fig. DR4). However, the deposition ages of these black shales are still poorly constrained.

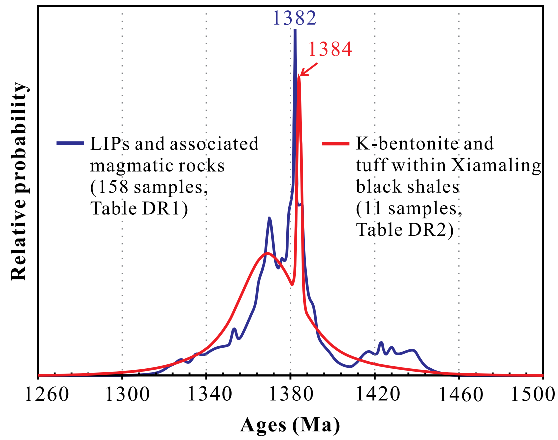

Figure 3. Comparisons of ages of ca. 1380 Ma large igneous provinces (LIPs) and those of tuff beds with black shales in middle part of Xiamaling Formation (North China craton) in probability density plot. See Data Repository (see footnote 1) for Tables DR1 and DR2.

DISCUSSION

A Temporal Link between the ca. 1380 Ma LIPs and Black Shales

Correlations between global black shales, OAEs, and LIPs in Meso-Neoproterozoic period are not well established due to poor age constraints. Another consideration is the background oxygen level during this period. Black shales must mark a transition from higher levels of oxygen to lower levels in deep marine basins. However, there is limited knowledge on atmospheric oxygen concentrations, ocean redox conditions, and early fossils during this period (Lyons et al., 2014; Planavsky et al., 2014), although recent data are suggesting elevated oxygen levels (Mukherjee and Large, 2016; Zhang et al., 2016, 2018; Wang et al., 2017). Geochemical results on the XF (unit 3 in Fig. 2B) indicate that there was sufficient (>4% of present-day levels) atmospheric oxygen for animals prior to the evolution of animals themselves at ca. 1400 Ma (Zhang et al., 2016). Recent geochemical results on the Gaoyuzhuang Formation in the NCC suggest a progressive deep-water oxygenation event beginning at ca. 1570 Ma and demonstrates that oxygenation of the Mesoproterozoic environment was far more dynamic and intense than previously envisaged (Zhang et al., 2018), which contrasts with the persistent low-oxygen conditions commonly advocated for this period (Lyons et al., 2014; Planavsky et al., 2014). The presence of sufficient atmospheric oxygen concentrations during much of the Mesoproterozoic Era is supported by a recent discovery of decimeter-scale multicellular eukaryotes from the 1560 Ma Gaoyuzhuang Formation in the NCC (Zhu et al., 2016) and the large triploblastic metazoans from the 1600 Ma Chorhat Sandstone in central India (Seilacher et al., 1998; Rasmussen et al., 2002).

As noted above, contemporaneous deposition of the ca. 1380 Ma black shales in several different cratons in the Nuna supercontinent indicates a global-scale OAE and a change from oxygen-bearing conditions prior to ca. 1380 Ma. Recent geochronological results on Mesoproterozoic LIPs, black shales, and paleogeographic reconstructions allow us to establish a temporal link between the ca. 1380 Ma LIPs and black shales, and to suggest that the LIPs were the cause of the change from oxygen-bearing conditions to oxygen-poor conditions in the ocean. Evidence to support this link includes the following:

1. As presented above, the ca. 1380 Ma LIPs are widely distributed in the Baltica, Laurentia, Siberia, Amazonia, Kalahari, Congo–São Francisco, West Africa, and East Antarctica cratons, and contemporaneous black shales have been identified from the North China, North Australian, Siberia, India, and São Francisco cratons, indicating that these are approximately coeval global-scale magmatic and sedimentary processes.

2. In particular, K-bentonite and thin tuff beds, which were generated through explosive felsic to intermediate volcanism and can be transported for hundreds of kilometers in the air before deposition, are very commonly observed within black shales of the XF in the North China craton (Fig. DR1) and have a zircon U-Pb peak age of 1384 Ma which matches that of the LIPs and their associated felsic to intermediate igneous rocks (Fig. 3).

3. Most of the cratons with ca. 1380 Ma LIPs were connected or near neighbors to those with ca. 1380 Ma black shales in the paleogeographic reconstruction maps of the Nuna supercontinent (Fig. 1; Fig. DR5), indicating possible deposition of these black shales in regional extensive, shared sedimentary basins (especially apparent in Fig. 1 and Fig. DR5B).

Therefore, we propose that the ca. 1380 Ma black shales widely distributed in the North China, North Australian, and possibly other cratons represent a global OAE during the Mesoproterozoic period at ca. 1380 Ma related to environmental effects of ca. 1380 Ma LIP events.

Using the ca. 1380 Ma LIPs and Black Shales as a Natural Marker for the Calymmian-Ectasian Boundary

The Calymmian-Ectasian boundary in the international chronostratigraphic scale has been assigned a round-number age of 1400 Ma (Ogg et al., 2016), and both time periods are broadly correlated with the expansion of platform covers. However, the age of this transition is not based on constraints from global geologic events (Ogg et al., 2016). There have been proposals for defining more natural boundaries in the Precambrian chronostratigraphic scale based on major geological transitions including, in some cases, the role of LIPs (e.g., Bleeker, 2004; Su, 2014), and Ernst and Youbi (2017) have emphasized the potential role of LIPs in defining the majority of the Precambrian stratigraphic boundaries.

As stated above, many boundaries in the Phanerozoic chronostratigraphic scale are defined by coeval LIPs, OAEs, and MEEs (Percival et al., 2015; Ernst and Youbi, 2017). Because the origin and evolution of early animals during the Meso-Neoproterozoic period prior to the Ediacaran are poorly constrained, little is known regarding any MEEs that occurred during this period. Temporal and causal linking of the ca. 1380 Ma LIPs and black shales in the Nuna supercontinent indicate that these global-scale events may represent a reliable natural marker for the Calymmian-Ectasian boundary, and their peak age of 1383 Ma can be proposed as a boundary age for the above boundary. Furthermore, the XF in the North China craton and the Velkerri Formation in the North Australian craton are proposed as reliable global stratotype sections for the Calymmian-Ectasian boundary, with the exact boundary location to be defined in future studies.

Implications for Meso-Neoproterozoic International Divisions of Geologic Time and the Paleoenvironment of the Ocean-Atmosphere System

Other correlations of LIPs with black shales and OAEs (beside that at ca. 1380 Ma) could be expected in the Precambrian, especially following cessation of banded iron formation deposition at ca. 1800 Ma (Klein, 2005) which suggested increasing levels of atmospheric oxygen (Canfield, 2005) and mild oxygenation of marine basins (Holland, 2006).

The period of 1800–800 Ma has been termed as the "Boring Billion." This time interval corresponds to five periods including the Statherian, Calymmian, Ectasian, Stenian, and Tonian with "round-number" boundary ages of 1600, 1400, 1200, and 1000 Ma, respectively (Ogg et al., 2016). The above boundary ages delineate 200-m.y.-long intervals and generally lack constraints by global geological events, but LIP events have been proposed to be correlated with each (Ernst and Youbi, 2017). Coincident LIPs and black shale deposition in large craton basins are common on most continents (e.g., Craig et al., 2013; Ernst, 2014). For other LIPs formed during the Boring Billion, more precise dating of black shales is required to identify other matches between LIPs and black shales. Further investigation of the temporal and genetic link between the LIPs and black shales during the Meso-Neoproterozoic period can contribute to understanding the variations in atmospheric oxygen concentrations and ocean redox conditions during the Boring Billion, during which virtually nothing of Earth's climate and MEEs is known.

CONCLUSIONS

Large igneous provinces of ca. 1380 Ma are widely distributed in the Baltica, Laurentia, Siberia, Amazonia, Kalahari, Congo–São Francisco, West Africa, and East Antarctica cratons, and contemporaneous black shales have been identified from the North China and North Australian cratons. Geochronological and geological results suggest a temporal and causal link between the ca. 1380 Ma LIPs and black shales in the Nuna supercontinent. They represent a global-scale geological event during the Mesoproterozoic Era, and their age is a good candidate for a boundary age (1383 Ma) of the Calymmian-Ectasian in the international chronostratigraphic scale. The results also suggest that additional OAEs related to global-scale LIPs may have occurred during the Boring Billion, during which virtually nothing of Earth's climate and MEEs is known, suggesting relatively high atmospheric oxygen concentrations and suboxic or mildly oxygenated marine basins interrupted by transient oceanic anoxia engendered by LIPs during this period.

ACKNOWLEDGMENTS

This research was financially supported by the National Natural Science Foundation of China (grants 41725011, 41572204) and the Chinese Academy of Geological Sciences fundamental research fund (grant YYWF201718). REE was partially supported by Russian Federation megagrant 14.Y26.31.0012. We thank Ross Large, Andrey Bekker, and an anonymous reviewer for helpful reviews.

REFERENCES CITED

Bleeker, W., 2004, Towards a 'natural' time scale for the Precambrian—A proposal: Lethaia, v. 37, p. 219–222, https://doi.org/10.1080/00241160410006456.

Bryan, S.E., and Ernst, R.E., 2008, Revised definition of Large Igneous Provinces (LIPs): Earth-Science Reviews, v. 86, p. 175–202 https://doi.org/10.1016/j.earscirev.2007.08.008.

Canfield, D.E., 2005, The early history of atmospheric oxygen: Homage to Robert A. Garrels: Annual Review of Earth and Planetary Sciences, v. 33, p. 1–36, https://doi.org/10.1146/annurev.earth.33.092203.122711.

Coffin, M.F., and Eldholm, O., 1994, Large igneous provinces: Crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, p. 1–36, https://doi.org/10.1029/93RG02508.

Courtillot, V., 1999, Evolutionary Catastrophes: The Science of Mass Extinction: Cambridge, UK, Cambridge University Press, 173 p.

Craig, J., Biffi, U., Galimberti, R.F., Ghori, K.A.R., Gorter, J.D., Hakhoo, N., Le Heron, D.P., Thurow, J., and Vecoli, M., 2013, The palaeobiology and geochemistry of Precambrian hydrocarbon source rocks: Marine and Petroleum Geology, v. 40, p. 1–47, https://doi.org/10.1016/j.marpetgeo.2012.09.011.

Ernst, R.E., 2014, Large Igneous Provinces: Cambridge, UK, Cambridge University Press, 653 p.

Ernst, R.E., and Youbi, N., 2017, How Large Igneous Provinces affect global climate, sometimes cause mass extinctions, and represent natural markers in the geological record: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 478, p. 30–52, https://doi.org/10.1016/j.palaeo.2017.03.014.

Fan, W.B., 2015, Geological features and research progress of the Mesoproterozoic Xiamaling Formation in the North China Craton: A review after nearly one hundred years of study: Dizhi Lunping, v. 61, p. 1347–1406, in Chinese with English abstract.

Holland, H.D., 2006, The oxygenation of the atmosphere and oceans: Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences, v. 361, p. 903–915, https://doi.org/10.1098/rstb.2006.1838.

Kendall, B., Creaser, R.A., Gordon, G.W., and Anbar, A.D., 2009, Re-Os and Mo isotope systematics of black shales from the Middle Proterozoic Velkerri and Wollogorang Formations, McArthur Basin, northern Australia: Geochimica et Cosmochimica Acta, v. 73, p. 2534–2558, https://doi.org/10.1016/j.gca.2009.02.013.

Klein, C., 2005, Some Precambrian banded iron formations (BIFs) from around the world: Their age, geologic setting, mineralogy, geochemistry, and origin: The American Mineralogist, v. 90, p. 1473–1499, https://doi.org/10.2138/am.2005.1871.

Lyons, T.W., Reinhard, C.T., and Planavsky, N.J., 2014, The rise of oxygen in Earth's early ocean and atmosphere: Nature, v. 506, p. 307–315, https://doi.org/10.1038/nature13068.

Mukherjee, I., and Large, R.R., 2016, Pyrite trace element chemistry of the Velkerri Formation, Roper Group, McArthur Basin: Evidence for atmospheric oxygenation during the Boring Billion: Precambrian Research, v. 281, p. 13–26, https://doi.org/10.1016/j.precamres.2016.05.003.

Ogg, J.G., Ogg, G.M., and Gradstein, F.M., 2016, A Concise Geologic Time Scale: Amsterdam, Elsevier, 234 p.

Percival, L.M.E., Witt, M.L.I., Mather, T.A., Hermoso, M., Jenkyns, H.C., Hesselbo, S.P., Al-Suwaidi, A.H., Storm, M.S., Xu, W., and Ruhl, M., 2015, Globally enhanced mercury deposition during the end-Pliensbachian extinction and Toarcian OAE: A link to the Karoo–Ferrar Large Igneous Province: Earth and Planetary Science Letters, v. 428, p. 267–280, https://doi.org/10.1016/j.epsl.2015.06.064.

Planavsky, N.J., Reinhard, C.T., Wang, X., Thomson, D., McGoldrick, P., Rainbird, R.H., Johnson, T., Fischer, W.W., and Lyons, T.W., 2014, Low Mid-Proterozoic atmospheric oxygen levels and the delayed rise of animals: Science, v. 346, p. 635–638, https://doi.org/10.1126/science.1258410.

Rasmussen, B., Bose, P.K., Sarkar, S., Banerjee, S., Fletcher, I.R., and McNaughton, N.J., 2002, 1.6 Ga U-Pb zircon ages for the Chorhat Sandstone, lower Vindhyan, India: Possible implications for early evolution of animals: Geology, v. 30, p. 103–106, https://doi.org/10.1130/0091-7613(2002)030<0103:GUPZAF>2.0.CO;2.

Seilacher, A., Bose, P.K., and Pflüger, F., 1998, Triploblastic animals more than 1 billion years ago: Trace fossil evidence from India: Science, v. 282, p. 80–83, https://doi.org/10.1126/science.282.5386.80.

Su, W., 2014, A review of the revised Precambrian Time Scale (GTS2012) and the research of the Mesoproterozoic chronostratigraphy of China: Earth Science Frontiers, v. 21, p. 119–138, in Chinese with English abstract, https://doi.org/10.13745/j.esf.2014.02.010.

Wang, X., Zhang, S., Wang, H., Bjerrum, C.J., Hammarlund, E.U., Haxen, E.R., Su, J., Wang, Y., and Canfield, D.E., 2017, Oxygen, climate and the chemical evolution of a 1400 million year old tropical marine setting: American Journal of Science, v. 317, p. 861–900, https://doi.org/10.2475/08.2017.01.

Warren, J.K., George, S.C., Hamilton, P.J., and Tingate, P., 1998, Proterozoic source rocks: Sedimentology and organic characteristics of the Velkerri Formation, Northern Territory, Australia: American Association of Petroleum Geologists Bulletin, v. 82, p. 442–463.

Wignall, P.B., 2001, Large igneous provinces and mass extinctions: Earth-Science Reviews, v. 53, p. 1–33, https://doi.org/10.1016/S0012-8252(00)00037-4.

Zhang, K., Zhu, X., Wood, R.A., Shi, Y., Gao, Z., and Poulton, S.W., 2018, Oxygenation of the Mesoproterozoic ocean and the evolution of complex eukaryotes: Nature Geoscience, v. 11, p. 345–350, https://doi.org/10.1038/s41561-018-0111-y.

Zhang, S., Li, Z.-X., Evans, D.A.D., Wu, H., Li, H., and Dong, J., 2012, Pre-Rodinia supercontinent Nuna shaping up: A global synthesis with new paleomagnetic results from North China: Earth and Planetary Science Letters, v. 353–354, p. 145–155, https://doi.org/10.1016/j.epsl.2012.07.034.

Zhang, S., Wang, X., Wang, H., Bjerrum, C.J., Hammarlund, E.U., Costa, M.M., Connelly, J.N., Zhang, B., Su, J., and Canfield, D.E., 2016, Sufficient oxygen for animal respiration 1,400 million years ago: Proceedings of the National Academy of Sciences of the United States of America, v. 113, p. 1731–1736, https://doi.org/10.1073/pnas.1523449113.

Zhang, S.-H., Zhao, Y., Li, X.-H., Ernst, R.E., and Yang, Z.-Y., 2017, The 1.33–1.30 Ga Yanliao large igneous province in the North China Craton: Implications for reconstruction of the Nuna (Columbia) supercontinent, and specifically with the North Australian Craton: Earth and Planetary Science Letters, v. 465, p. 112–125, https://doi.org/10.1016/j.epsl.2017.02.034.

Zhu, S., Zhu, M., Knoll, A.H., Yin, Z., Zhao, F., Sun, S., Qu, Y., Shi, M., and Liu, H., 2016, Decimetre-scale multicellular eukaryotes from the 1.56-billion-year-old Gaoyuzhuang Formation in North China: Nature Communications, v. 7, 11500, https://doi.org/10.1038/ncomms11500.

Printed in USA