Surface-wave tomography of the Emeishan large igneous province (China): Magma storage system, hidden hotspot track, and its impact on the Capitanian mass extinction

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ABSTRACT
Large igneous provinces (LIPs) are commonly associated with mass extinctions. However, the precise relations between LIPs and their impacts on biodiversity is enigmatic, given that they can be asynchronous. It has been proposed that the environmental impacts are primarily related to sill emplacement. Therefore, the structure of LIPs' magma storage system is critical because it dictates the occurrence and timing of mass extinction. We use surface-wave tomography to image the lithosphere under the Permain Emeishan large igneous province (ELIP) in southwestern China. We find a northeast-trending zone of high shear-wave velocity (Vs) and negative radial anisotropy (Vsv < Vsh; v and h are vertically and horizontally polarized S waves, respectively) in the crust and lithosphere. We rule out the possibilities of riftting or orogenesis to explain these seismic characteristics and interpret the seismic anomaly as a mafic-ultramafic, dike-dominated magma storage system of the ELIP. We further propose that the anomaly represents a hidden hotspot track that was emplaced before the ELIP eruption. A zone of higher velocity but less-negative radial anisotropy, on the hotspot track but to the northeast of the eruption center in the Panxi region, reflects an elevated proportion of sills emplaced at the incipient stage of the ELIP. Liberation of poisonous gases by the early sill intrusions explains why the mid-Capitanian global biota crisis preceded the peak ELIP eruption by 2–3 m.y.

INTRODUCTION
Large igneous provinces (LIPs) are characterized by rapid emplacement of primarily mafic magma in the lithosphere and volcanic eruptions forming plateau basalts in an area >10⁵ km² (Bryan and Ernst, 2008). Many LIPs have been associated with abrupt environmental catastrophes and mass-extinction events (Sobolev et al., 2011; Ernst, 2014). While LIP-related extinctions generally occurred during or shortly after the major volcanic phase of the corresponding LIPs (Bond and Wignall, 2014), some preceded the major phase, leaving the exact relationship between LIPs and mass extinctions enigmatic. It has been proposed that the structure of magma storage systems of LIPs, particularly sill intrusions, is a key to understanding this relation (Svensen et al., 2009). Modern hotspots, such as Yellowstone (northwestern United States), display the magma storage system of active LIPs (Jiang et al., 2018). However, they do not provide a direct constraint on the timing of mass extinction. Ancient LIPs, by contrast, potentially preserve a complete record and thus offer an opportunity for studying their structures and assessing the environmental impacts. We studied the seismic structure of the Emeishan large igneous province (ELIP) in southwestern China using a new surface-wave tomography model. The ELIP is, so far, the only candidate for having caused the global biota crisis in the mid-Capitanian (ca. 262 Ma) (Wignall et al., 2009; Bond et al., 2020), which preceded the major volcanic activity of the ELIP (260–257 Ma) (Shellnutt et al., 2012). We attempt to characterize the ELIP’s magma storage system and explain the unusual asynchrony.

GEOLOGICAL BACKGROUND
The ELIP is located in the western Yangtze craton of the South China block (Figs. 1A and 1B). It comprises mainly tholeitic continental flood basalts with a lesser amount of picrites, lamproites, gabbros, pyroxenites, and other lithologies (e.g., Chung and Jahn, 1995; Xu et al., 2004). These rocks were mainly derived from the sublithospheric mantle (Chung and Jahn, 1995; Xu et al., 2004; Zhou et al., 2005). The southwestern corner of the ELIP is offset left-laterally by the Cenozoic Ailao Shan-Red River shear zone and is poorly exposed. The larger, better-preserved northeastern part, covering at least ~3 × 10⁶ km², is divided into three concentric zones (inner, intermediate, and outer) that represent a decrease in flood basalt thickness outward (He et al., 2003; Xu et al., 2004). Before the ELIP eruption, the Maokou Formation that was deposited on the Yangtze carbonate platform underwent denudation and karstification (He et al., 2003; Xiao et al., 2016). The denudation began in the northeastern Sichuan Basin and propagated southwestward in the middle to late Guadalupian (Hu et al., 2012). A map of the remnant thickness of the Maokou Formation shows a northeast-trending zone of anomalously thin strata extending from the Sichuan Basin to the ELIP center (Fig. 1C).

CITATION: Liu, Y., et al., 2021, Surface-wave tomography of the Emeishan large igneous province (China): Magma storage system, hidden hotspot track, and its impact on the Capitanian mass extinction: Geology, v. 49, p. 1032–1037, https://doi.org/10.1130/G49055.1
Paleomagnetic studies show an equatorial paleolatitude for the ELIP at the peak eruption time and an overall clockwise rotation of ~27° of the South China block since 260 Ma (Huang et al., 2018). Magmatic underplating occurred at the Moho depth in the inner zone of the ELIP, as evidenced by high density, high seismic velocity, high ratios of compressional to shear-wave velocity (Vp/Vs), and thickened crust (Chen et al., 2015). A pronounced northeast-trending positive residual gravity anomaly extends from the ELIP center to the Sichuan Basin and has been attributed to ELIP intrusions (Deng et al., 2014).

METHOD AND RESULTS

We developed a radially anisotropic shear-wave velocity model of the lithosphere under the ELIP region from Rayleigh wave and Love wave phase velocity at periods of 8–167 s (see Supplemental Material). Rayleigh and Love waves are primarily sensitive to vertically (Vsv) and horizontally (Vsh) polarized shear-wave velocities, respectively. Radial anisotropy, defined as 100% × (Vsh – Vsv)/Vs, where Vs is the Voigt average of Vsh and Vsv, exploits the variations between the two waves by assuming hexagonal anisotropy with a vertical symmetry axis (Babuska and Cara, 1991). Radial anisotropy may be induced by lattice preferred orientation of minerals such as mica, olivine, and pyroxene (Silver and Chan, 1991; Shapiro et al., 2004) or by shape preferred orientation of structures such as fractures, foliation, and magma (Silver and Chan, 1988; Emmermann and Lauterjung, 1997).

Our shear-wave velocity model (Figs. 2 and 3; Figs. S12–S14 in Supplemental Material) shows high velocity at 15–220 km depths beneath the Yangtze craton east of the Xianshuihe-Xiaojiang fault and a low-velocity zone in the crust of the southeastern Tibetan Plateau. These results agree with those of previous studies: high-velocity anomaly dominates the Yangtze craton due to the cold and thick cratonic lithosphere, and the low-velocity zone is related to the thickened, partially molten Tibetan crust (Huang et al., 2010).

Radial anisotropy results show lateral and vertical variations in the crust and mantle lithosphere (Figs. 2 and 3; Fig. S15). Positive radial anisotropy (Vsh > Vsv) is found in the mid- and lower crust (depths of 15 km to the Moho) under the southeastern Tibetan Plateau, which has been interpreted as a result of the subhorizontal alignment of mica due to ductile deformation induced by the India-Asia collision (Shapiro et al., 2004). Another zone of positive radial anisotropy is located around the southern Xianshuihe-Xiaojiang fault. It is associated with low shear-wave velocities. We explain this as a result of subhorizontal ductile deformation in the middle and lower crust due to the lateral expansion of the Tibetan Plateau. In the lithospheric mantle below 80 km, positive radial anisotropy exists ubiquitously. Similar positive radial anisotropy is present in other cratons (Nettles and Dziewoń ski, 2008). This largely results from the lattice preferred orientation of olivine in horizontal planes.

The most intriguing phenomenon is a northeast-trending coherent zone of negative radial anisotropy (Vsv > Vsh) paired with high shear-wave velocity under the inner and intermediate zones of the ELIP (Figs. 2 and 3). It appears as a broad zone in the shallow crust (0–15 km) and can be traced down to ~80 km depth. Such a zone of reduced radial anisotropy is still detectable down to 120 km depth (Fig. 2; Fig. S15). The amplitude of the negative radial anisotropy is mostly ~2%, but is as strong as ~4% in the lower crust under the Sichuan Basin. A similar body of negative radial anisotropy was imaged, but not interpreted, at 20–35 km depths by Huang et al. (2010). Another study (Xie et al., 2013) found a narrow zone of negative anisotropy in the middle and upper crust under eastern Tibet and ascribed it to faults and cracks.

DISCUSSION

Geological Interpretation

We focus on the northeast-trending zone of high velocity and negative radial anisotropy.
in this study. Negative radial anisotropy in the lithosphere is commonly explained by subvertical alignment of mineral crystals such as mica and olivine, macroscopic structures such as faults and shear zones, or partial melts (Shapiro et al., 2004; Xie et al., 2013).

To interpret this anomaly, we first consider three regional tectonic events: Cenozoic Tibetan orogenesis (Shapiro et al., 2004), Permian rifting (Cong, 1988), and Neoproterozoic rifting (Li et al., 1999). Faulting and/or fracturing caused by any of these events would have resulted in low, rather than high, seismic velocities in the craton. Neither the Xianshuihe-Xiaojiang fault nor the Ailao Shan–Red River shear zone is parallel to the observed northeast-trending anomaly, which does not favor the Cenozoic orogenesis interpretation. While the Panxi rift was active in Permian, a hypothetical northeastern extension of the failed rift triggered by the ELIP is unlikely because it would predict northeastward expansion of denudation starting from the end-Guadalupian; this is in conflict with the observation that denudation initiated in the mid-Guadalupian and propagated southward (Hu et al., 2012). A Neoproterozoic rift cannot explain the Permian volcanism or denudation, either. Because of the lack of geologic support, we favor an alternative explanation for the seismic anomaly.

We propose an interpretation that connects the seismic anomaly with the shape preferred orientation of magma systems (Fig. 4A). The magma storage system of a LIP consists of a network of dikes, sills, laccoliths, and magma chambers by which magma is transported through and stored within the lithosphere (Ernst et al., 2019). The geometry of such a system can be simplified into two end members in the scope of seismic radial anisotropy: vertical dikes and horizontal sills. The thickness of a single dike or sill is usually below the detection limit of seismic waves; in groups, however, they can be seismically detectable (Backus, 1962).

For a transversely isotropic medium of mafic to felsic composition with a vertical or horizontal symmetry (Eshelby, 1957), the presence of dikes and sills of mafic-ultramafic composition can effectively alter the bulk elastic properties of the medium (Fig. 4A). The bulk Vs and radial anisotropy of a medium with a dike-dominated system both decrease at the time of intrusion; after the magma solidifies and cools, Vs increases and the radial anisotropy remains depleted. For a sill-dominated system, Vs decreases first then increases after cooling, while the radial anisotropy remains elevated.

The observed body of negative radial anisotropy and high Vs (such as anomalies “a” and “c” in Fig. 3) can thus be interpreted as the solidified magma storage system of the ELIP that is dominated by sub-seismic-scale, densely spaced mafic-ultramafic dikes. Extensive dike swarms of the ELIP are observed on the surface (Li et al., 2015; Fig. S19). This is consistent with our interpretation for the subsurface. Anomaly “b” (Fig. 3) is characterized by thicker crust, higher Vs, and less-negative radial anisotropy than anomalies “a” and “c”, indicating a greater amount of intrusion with a higher fraction of sills there.
Tectonic and Environmental Implications

We place the South China block in a plate reconstruction framework (Fig. 4B). Paleomagnetic studies show that the South China block was moving northward continuously from 300 to 260 Ma and has experienced an overall ~27° clockwise rotation since then (Huang et al., 2018). Assuming a stationary Emeishan hotspot, the predicted hotspot track should have aligned north-south in the middle Permian; i.e., northeast-southwest at present. Another prediction would be the southwestward propagation of denudation via dynamic topography. Indeed, the seismic anomaly trends northeast (Fig. 2; Fig. S15) and overlaps the positive residual gravity anomaly (Deng et al., 2014) and the thinned zone of the Maokou Formation (Fig. 1C). Therefore, we infer that this 700-km-long anomaly represents the Emeishan hotspot track that was emplaced before the ELIP eruption and is concealed in the Yangtze craton.

Lithospheric thickness variations affect the route of magma transport and storage and the location of major eruptions. A schematic section A–A’ (Fig. 4C) illustrates the various magma systems through time (Figs. 4C and 4D). While the northern half of the hotspot track has no radiogenic age constraint yet, from the denudation record (Hu et al., 2012) and plate reconstruction (Huang et al., 2018), we infer that a mantle upflow reached the base of the thick crust under the Sichuan Basin in the mid-Guadalupian. It caused gentle uplift of the surface, leading to denudation and karstification of the Maokou carbonate rocks.

As the South China block drifted northward, melts started to form and infiltrate the craton, mainly as dikes. They did not find an “easy way” out until a thinner lithosphere was above the mantle upflow. In the upper crust, the Xiangjiang normal fault and the Panxi rift were (re)activated before and during the onset of the ELIP (Cong, 1988; He et al., 2003). On the surface, the denudation zone expanded southward with respect to the north-drifting South China block.

Magma underplating (Chen et al., 2015) must have started at anomaly “b” (Fig. 4C) by 263 Ma (Zhou et al., 2005), causing abundant intrusions with a higher proportion of sills in the Panxi region. Emplacement of laterally extensive sills tends to take place in mechanical layers (Kavanagh et al., 2006) such as crust-mantle interface, near the brittle-ductile transition, and within sedimentary basins. Sills efficiently store magma over large areas. When emplaced in a shallow basin, they can liberate large volumes of greenhouse gases and mercury that may trigger catastrophic environmental change (Svensen et al., 2009). Indeed, above “b”, the 263 Ma Panzhihua layered mafic intrusions intruded and metamorphosed the Dengying dolomitic limestone in the shallow crust (Zhou et al., 2005), which could have caused degassing that led to the mid-Capitanian biota crisis.

As the South China block kept moving northward, the major eruption occurred at 260–257 Ma near the cratonic margin, associated with domal uplift and dike swarm intrusions (He et al., 2003; Shellnutt et al., 2012; Li et al., 2015). The release of volatiles and mercury peaked, causing the end-Guadalupian mass extinction (Huang et al., 2019). After solidification, the 700-km-long magma storage system of the ELIP left a frozen-in seismic anisotropy and became a stiff body in the western Yangtze craton, which shaped the geometry of the Cenozoic Himalayan-Tibetan orogen (Xu et al., 2021).

CONCLUSIONS

Our study used surface-wave tomography to characterize the structure of the magma storage system of the ELIP, discovered the concealed Emeishan hotspot track, and established a connection among hotspot volcanism, plate motion, and a biodiversity crisis. Similar studies can be conducted for other LIPs, which may enable future models to evaluate the environmental impacts in a more quantitative way.

ACKNOWLEDGMENTS

Seismic data were collected by the Massachusetts Institute of Technology (USA) and the Chengdu Institute of Geology and Mineral Resources (China) seismic network and archived at the Incorporated Research Institutions for Seismology (IRIS, https://www.iris.edu). L. Li is supported by the National Natural Science Foundation of China (grants 41804043 and 41874102) and the Second Tibetan Plateau Scientific Expedition and Research Program (STEP) (grant 2019QZKK0701). Y. Liu thanks the Governor’s University Research Initiative Fund from the State of Texas. Zheng-Xiang Li and Richard Ernst and an anonymous reviewer offered constructive reviews. We are grateful to John Suppe, Jiaxuan Li, Bo Wan, Xiaofeng Liang, and Jianye Chen for their help. This is Los Alamos National Laboratory contribution LA-UR-21-22878.

REFERENCES CITED

Babuska, V., and Cara, M., 1991, Seismic Anisotropy in the Earth: Dordrecht, Netherlands, Kluwer, Modern Approaches in Geophysics, v. 10, 219 p., https://doi.org/10.1007/978-94-011-3600-6.

Backus, G.E., 1962, Long-wave elastic anisotropy produced by horizontal layering: Journal of Geophysical Research, v. 67, p. 4427–4440, https://doi.org/10.1029/JZ067i011p04427.

Bond, D.P.G., and Wignall, P.B., 2014, Large igneous provinces and mass extinctions: An update, in Keller, G., and Kerr, A.C., eds, Volcanism, Impacts, and Mass Extinctions: Causes and Effects: Geological Society of America Special Paper 505, p. 29–55, https://doi.org/10.1130/2014.2505(02).

Bond, D.P.G., Wignall, P.B., and Grasby, S.E., 2020, The Capitanian (Guadalupian, Middle Permian) mass extinction in NW Pangaea (Borup Fiord, Arctic Canada): A global crisis driven by volcanism and anoxia: Geological Society of America Bulletin, v. 132, p. 931–942, https://doi.org/10.1130/B35281.1.

Bryan, S.E., and Ernst, R.E., 2008, Revised definition of large igneous provinces (LIPs): Earth and Planetary Science Reviews, v. 86, p. 175–202, https://doi.org/10.1016/j.epsc.2007.08.008.

Chen, Y., et al., 2015, Magma underplating and crustal growth in the Emeishan Large Igneous Province, SW China, revealed by a passive seismic experiment: Earth and Planetary
Chung, S.L., and Jahn, B.M., 1995, Plume-lithosphere interaction in generation of the Emeishan flood basalts at the Permian-Triassic boundary: Geology, v. 23, p. 889–892, https://doi.org/10.1130/0091-7613(1995)023<0889:PLIIGO>2.3.CO;2.

Cong, B.L., 1988, Formation and Evolution of the Panxi Rift: Beijing, China Science Publishing House, 424 p.

Deng, Y., Zhang, Z., Mooney, W., Badal, J., Fan, W., and Zhong, Q., 2014, Mantle origin of the Emeishan large igneous province (South China) from the analysis of residual gravity anomalies: Lithos, v. 204, p. 4–13, https://doi.org/10.1016/j.lithos.2014.02.008.

Emmermann, R., and Lauterjung, J., 1997, The German Continental Deep Drilling Program KTB: Overview and major results: Journal of Geophysical Research, v. 102, p. 18,179–18,201, https://doi.org/10.1029/96JB03945.

Ernst, R.E., 2014, Large Igneous Provinces: Cambridge, UK, Cambridge University Press, 653 p., https://doi.org/10.1017/CBO9781139025300.

Ernst, R.E., Liikane, D.A., Jowitt, S.M., Buchan, K.L., and Blanchard, J.A., 2019, A new plumbing system framework for mantle plume-related continental Large Igneous Provinces and their mafic-ultramafic intrusions: Journal of Volcanology and Geothermal Research, v. 384, p. 75–84, https://doi.org/10.1016/j.jvolgeores.2019.07.007.

Eshelby, J.D., 1957, The determination of the elastic field of an ellipsoidal inclusion, and related problems: Proceedings of the Royal Society: Series A, v. 241, p. 376–396, https://doi.org/10.1098/rspa.1957.0131.

He, B., Xu, Y.-G., Chung, S.-L., Xiao, L., and Wang, Y., 2003, Sedimentary evidence for a rapid, kilometer-scale crustal doming prior to the eruption
of the Emeishan flood basalts: Earth and Planetary Science Letters, v. 213, p. 391–405, https://doi.org/10.1016/S0012-821X(03)00323-6.

Hu, M., Hu, Z., Wei, G., Yang, W., and Liu, M., 2012, Sequence lithofacies paleogeography and reservoir potential of the Maokou formation in Sichuan Basin: Petroleum Exploration and Development, v. 39, p. 51–61, https://doi.org/10.1016/S1876-3804(12)60014-7.

Huang, B., Yan, Y., Piper, J.D.A., Zhang, D., Yi, Z., Yu, S., and Zhou, T., 2018, Paleomagnetic constraints on the paleogeography of the East Asian blocks during Late Paleozoic and Early Mesozoic times: Earth-Science Reviews, v. 186, p. 8–36, https://doi.org/10.1016/j.earscirev.2018.02.004.

Huang, H., Yao, H., and van der Hilst, R.D., 2010, Radial anisotropy in the crust of SE Tibet and SW China from ambient noise interferometry: Geophysical Research Letters, v. 37, L21310, https://doi.org/10.1029/2010GL044981.

Huang, Y., Chen, Z.-Q., Wignall, P.B., Grasby, S.E., Zhao, L., Wang, X., and Kaiho, K., 2019, Biotic responses to volatile volcanism and environmental stresses over the Guadalupian-Lopingian (Permain) transition: Geology, v. 47, p. 175–178, https://doi.org/10.1130/G45283.1.

Jiang, C., Schmandt, B., Farrell, J., Lin, F.-C., and Huang, Y., 2010, Linking mantle and propagation in layered elastic media: Earth and Planetary Science Letters, v. 245, p. 799–813, https://doi.org/10.1016/j.epsl.2006.03.025.

Li, H., Zhang, Z., Ernst, R., Lü, L., Santosh, M., Zhang, D., and Cheng, Z., 2015, Giant radiating mafic dyke swarm of the Emeishan Large Igneous Province: Identifying the mantle plume centre: Terra Nova, v. 27, p. 247–257, https://doi.org/10.1111/ter.12154.

Li, Z.X., Li, X.H., Kinny, P.D., and Wang, J., 1999, The breakup of Rodinia: Did it start with a mantle plume beneath South China?: Earth and Planetary Science Letters, v. 173, p. 171–181, https://doi.org/10.1016/S0012-821X(99)00240-X.

Nettles, M., and Drzewiński, A.M., 2008, Radially anisotropic shear velocity structure of the upper mantle globally and beneath North America: Journal of Geophysical Research, v. 113, B02303, https://doi.org/10.1029/2006JB004819.

Shapiro, N.M., Ritzwoller, M.H., Molnar, P., and Levin, V., 2004, Thinning and flow of Tibetan crust constrained by seismic anisotropy: Science, v. 305, p. 233–236, https://doi.org/10.1126/science.1098276.

Shellnutt, J.G., Denysyszyn, S.W., and Mundil, R., 2012, Precise age determination of mafic and felsic intrusive rocks from the Permian Emeishan flood-basalt province: Geology, v. 40, p. 765–768, https://doi.org/10.1130/G32680.1.

Silver, P.G., and Chan, W.W., 1988, Implications for continental structure and evolution from seismic anisotropy: Nature, v. 335, p. 34–39, https://doi.org/10.1038/335034a0.

Silver, P.G., and Chan, W.W., 1991, Implications for continental structure and evolution from seismic anisotropy: Jounal of Geophysical Research, v. 96, p. 16,429–16,454, https://doi.org/10.1029/91JB00899.

Sobolev, S.V., Sobolev, A.V., Kuzmin, D.V., Krivolutskaya, N.A., Petrurinn, A.G., Arndt, N.T., Radko, V.A., and Vasiliev, Y.R., 2011, Linking mantle plumes, large igneous provinces and environmental catastrophes: Nature, v. 477, p. 312–316, https://doi.org/10.1038/nature10385.

Svensen, H., Planke, S., Polozov, A.G., Schmidtauer, N., Corfu, F., Podladchikov, Y.Y., and Jamtveit, B., 2009, Siberian gas venting and the end-Permain environmental crisis: Earth and Planetary Science Letters, v. 277, p. 490–500, https://doi.org/10.1016/j.epsl.2008.11.015.

Wignall, P.B., et al., 2009, Volcanism, mass extinction, and carbon isotope fluctuations in the Middle Permian of China: Science, v. 324, p. 1179–1182, https://doi.org/10.1126/science.1171956.

Xiao, D., Tan, X., Xi, A., Liu, H., Shan, S., Xia, J., Cheng, Y., and Lian, C., 2016, An inland facies-controlled eogenetic karst of the carbonate reservoir in the Middle Permian Maokou Formation, southern Sichuan Basin, SW China: Marine and Petroleum Geology, v. 72, p. 218–233, https://doi.org/10.1016/j.marpetgeo.2016.02.001.

Xie, J., Ritzwoller, M.H., Shen, W., Yang, Y., Zheng, Y., and Zhou, L., 2013, Crustal radial anisotropy across eastern Tibet and the western Yangtze craton: Journal of Geophysical Research: Solid Earth, v. 118, p. 4226–4252, https://doi.org/10.1002/jgre.50296.

Xu, X., Zuza, A.V., Yin, A., Lin, X., Chen, H., and Yang, S., 2021, Permian plume-strengthened Tarim lithosphere controls the Cenozoic deformation pattern of the Himalayan-Tibetan orogen: Geology, v. 49, p. 96–100, https://doi.org/10.1130/G47961.1.

Xu, Y.-G., He, B., Chang, S.-L., Menzies, M.A., and Frey, F.A., 2004, Geologic, geochemical, and geophysical consequences of plume involvement in the Emeishan flood-basalt province: Geology, v. 32, p. 917–920, https://doi.org/10.1130/G20602.1.

Zhou, M.-F., Robinson, P.T., Lesher, C.M., Keays, R.R., Zhang, C.-J., and Malpas, J., 2005, Geochemistry, petrogenesis and metallogenesis of the Panzhihua gabbroic layered intrusion and associated Fe-Ti-V oxide deposits, Sichuan Province, SW China: Journal of Petrology, v. 46, p. 2253–2280, https://doi.org/10.1093/petrology/egi054.

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