THE GEOLOGICAL SOCIETY
OF AMERICA®

Kimberlites and the start of plate tectonics

R.J. Stern[1], M.I. Leybourne[2], and Tatsuki Tsujimori[3,4]
[1]Department of Geoscience, University of Texas at Dallas, Richardson, Texas 75080, USA
[2]Mineral Exploration Research Centre, Department of Earth Sciences, Laurentian University, Sudbury, Ontario P3E 2C6, Canada
[3]Center for Northeast Asian Studies, Tohoku University, 41 Kawauchi, Aoba-ku, Sendai, Miyagi 980-8576, Japan
[4]Department of Earth Science, Tohoku University, Sendai, 6-3 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi 980-8578, Japan

ABSTRACT

We want to know when plate tectonics began and will consider any important Earth feature that shows significant temporal evolution. Kimberlites, the primary source of diamonds, are rare igneous features. We analyze their distribution throughout Earth history; most are young (~95% are younger than 0.75 Ga), but rare examples are found as far back as the Archean (older than 2.5 Ga). Although there are differing explanations for this age asymmetry (lack of preservation, lack of exposure, fewer mantle plumes, or lack of old thick lithosphere in the Archean and Proterozoic), we suggest that kimberlite eruptions are a consequence of modern-style plate tectonics, in particular subduction of hydrated oceanic crust and sediments deep into the mantle. This recycling since the onset of modern-style plate tectonics ca. 1 Ga has massively increased mantle CO_2 and H_2O contents, leading to the rapid and explosive ascent of diamond-bearing kimberlite magmas. The age distribution of kimberlites, combined with other large-scale tectonic indicators that are prevalent only in the past ~1 Ga (blueschists, glaucophane-bearing eclogites; coesite- or diamond-bearing ultrahigh-pressure metamorphic rocks; lawsonite-bearing metamorphic rocks; and jadeitites), indicates that plate tectonics, as observed today, has only operated for <25% of Earth history.

INTRODUCTION

Understanding when and how plate tectonics (PT) began is an important focus of geoscientific research, and resolving this controversy will not be easy. Korenaga (2013) summarized 10 estimates for this beginning; these encompass most of Earth history, from before 4.2 Ga to ca. 0.85 Ga. To resolve this debate, we need to consider any potentially useful line of evidence that promises to provide new insights and place independent constraints on when this critical transition occurred. Here we consider how the unusual and valuable rock type kimberlite (KBL) may be an important new line of evidence in this exploration.

KBLs are potassic, volatile-rich ultramafic rocks with high contents of both compatible (e.g., Ni, Cr) and incompatible elements (Ti, P, light rare earth elements). They erupt explosively as diatremes through the overlying continental lithosphere en route to the surface. KBLs represent lithospheric "aneurysms" that release fluid overpressure in the upper mantle. These instabilities are due to high concentrations of a mixed CO_2-H_2O fluid.

KBLs are uncommon and would be a petrologic curiosity except that they contain some of the deepest mantle fragments (xenoliths, xenocrysts) and diamonds and thus are intensely scrutinized by both industry and academic geoscientists. Here we explore the implications of the KBL record through time, showing that, although these eruptions have occurred since the Neoarchean, the frequency of such eruptions has greatly increased recently. We explain this as reflecting a massive increase in water flux to the mantle beneath the lithosphere due to the onset of continuous deep subduction in the past 1 Ga. The greatly increased flux of water and CO_2 led to greatly increased fluid pressure at the base of thick cratonic lithosphere. Our exploration, motivated by the PT origins controversy, may incidentally provide new insights into the origin and significance of these important and interesting rocks.

KIMBERLITES

KBL magmas are end members of a complex petrologic continuum that encompasses lamproites, carbonatites, and a wide range of silica-undersaturated alkaline silicate magmas (Sparks, 2013). This magma stem is united by four broad petrogenetic similarities: (1) an important role for CO_2 as a volatile phase, (2) formation by melting at elevated pressures, (3) low degrees of melting, and (4) formation at intraplate and rift tectonic settings. This continuum also forms on the silica-undersaturated side of an important peridotite thermal divide (Milholland and Presnall, 1998).

KBLs contain abundant phlogopite and carbonate, indicating that they formed from a magma that was rich in H_2O and CO_2 and poor in SiO_2. Primary H_2O and CO_2 contents are difficult to constrain because these rocks alter easily. The best direct estimate of KBL fluid composition comes from aphanitic samples of the Jericho KBL, northwest Canada, which contains 12–19 wt% CO_2 and 5.3–7.5 wt% H_2O (Price et al., 2000).

Diamond-bearing KBL magmas must have been generated deeper than the low-pressure stability limit of diamonds (>140 km) in order to pluck them from their lithospheric source and carry them to the surface. Researchers agree that KBL melts are generated by low-degree melting of carbonate-bearing garnet lherzolite involving abundant H_2O and CO_2 in or near the thick, cool, metasomatized roots of continents (Tainton and McKenzie, 1994), consistent with KBL isotopic compositions (Nowell et al., 2004).

Clifford's Rule (Clifford, 1966) teaches the importance of cratons for finding diamonds and KBLs. KBLs erupt through cratons, presumably because these have lithospheres thick enough to concentrate volatiles to pressures (>6 GPa) capable of blasting through it. The interiors of continents are cored by cratons, regions of crustal basement that have not been deformed for >~1 Ga (Lee et al., 2011). The great strength of cratons is because they are underlain by thick mantle lithosphere composed of highly melt-depleted peridotites. In spite of the intimate relationship between KBLs and cratons and the fact that cratons have existed for 2.5–3.0 Ga, KBLs are a much more recent phenomena. We examine the evidence for this conclusion in the following.

AGE DISTRIBUTION OF KIMBERLITES AND ITS SIGNIFICANCE

The age distribution of KBLs was summarized by Faure (2006; his spreadsheet can be found at https://consorem.uqac.ca/kimberlite/world_kimberlites_and_lamproites_consorem_database_v2010.xls). Approximately 95% of dated KBLs are younger than 750 Ma; the vast majority are Mesozoic and younger (Fig. 1). This global summary is mirrored in age distributions for the great KBL provinces of the world. For example, ~80% of North American KBLs are younger than 200 Ma (Heaman et al., 2004); a similar record is seen for South Africa KBLs (Jelsma et al., 2009).

Is the age distribution of Faure (2006) a reasonable approximation of reality or an artifact

GEOLOGY, October 2016; v. 44; no. 10; p. 799–802 | doi:10.1130/G38024.1 | Published online 17 August 2016

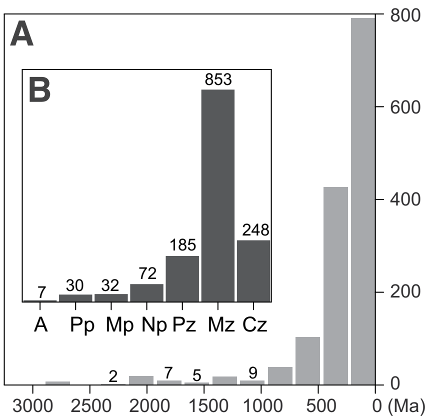

Figure 1. Histogram of kimberlite ages based on the compilation of Faure (2006). A: Ages binned each 500 Ma. B: Ages binned by geologic eons. A—Archean; Pp—Paleoproterozoic; Mp—Mesoproterozoic; Np—Neoproterozoic; Pz—Paleozoic; Mz—Mesozoic; Cz—Cenozoic. Note the great increase in kimberlites in Neoproterozoic and later time (after 750 Ma).

of preservation or exposure? Specifically, why are there are so few pre-Neoproterozoic KBLs? Some scientists think that the age distribution (Fig. 1) is not representative of what really happened, and others think it is. Skeptics think that there are many more old KBLs that are hidden beneath younger deposits or have been eroded (Brown and Valentine, 2013). However, many cratons have undergone little erosion since they stabilized ca. 2.5 Ga; the abundance of Archean and Paleoproterozoic greenstone belts demonstrates that erosion of this crust is generally modest, so the preponderance of KBLs of similar age, if they exist, should be found by diligent explorationists.

The second group of scientists recognizes that the age distribution (Fig. 1) may be somewhat biased but concludes that it usefully approximates KBL eruption frequency through time. We subscribe to this interpretation, for the reasons outlined in the previous paragraph. In this case, how can the increase in KBL eruptions in recent Earth history be explained? We can consider four main groups of explanations: whole Earth focused, plume focused, lithosphere focused, and volatile focused. Whole Earth explanations identify the cooling of the Earth as responsible, resulting in more low-degree melts with time. There is general agreement that mantle potential temperature has decreased by 150–250 °C since the Archean (Herzberg et al., 2010). Examination of the distribution through time of nephelinites, phonolites, and alkali basalts (data from GEOROC; georoc.mpch-mainz.gwdg.de/) shows that these are abundant only in the last part of Earth history. The abundance of KBLs may have a similar explanation, although this does not explain why they are so enriched in volatiles.

Plume-focused interpretations relate KBLs to mantle plume activity (Haggerty, 1994; Torsvik et al., 2010). This explanation is not supported by the geologic record, which shows that the plume record as revealed by large igneous provinces and large dike swarms is semicontinuous at least from ca. 3.0 Ga, with no obvious increase with time (Ernst and Buchan, 2002).

Lithosphere-focused explanations consider that KBLs require thick cratonic lithosphere, and that this did not exist until relatively late in Earth history. This position is difficult to defend because it appears that cratons as represented by supercontinent assemblages formed early and that the oldest cratons have the thickest lithospheres (Artemieva and Mooney, 2002; Rey and Coltice, 2008).

The fourth explanation focuses on the role of volatiles in KBL formation, implying a relatively recent increase in the concentration of $H_2O + CO_2$ in the sublithospheric mantle as responsible. This is an interesting suggestion that could explain the age histogram, especially in tandem with Earth cooling, but what process could be responsible for such an increase in $H_2O + CO_2$ in the mantle? The onset of PT and deep subduction could be responsible, as discussed further here.

PLATE TECTONICS AND DEEP SUBDUCTION

PT is a unique style of silicate planet convection, whereby rigid shells of lithosphere slide over weaker mantle asthenosphere and sink to great depths in the mantle. It is the sinking of oceanic lithosphere in subduction zones that powers plate motions. Although subduction zones are not part of the formal definition of PT, we now know that convergent plate margins are surficial expressions of subduction zones where oceanic lithosphere sinks deep into the mantle (Stern, 2002). Subducted lithospheric slabs may stagnate just above the 670 km discontinuity or may sink through it, carrying tremendous amounts of H_2O and CO_2 (Hacker, 2008). The two concepts, PT and deep subduction, are equivalent, so evidence for deep subduction is also evidence for PT. There are surely other ways of delivering such volatiles to the deep mantle than by subduction. There is no question that water- and carbonate-rich surface materials have been recycled deep into the mantle throughout Earth history (Harrison, 2009), but this may have been accomplished by convective styles other than PT and subduction, for example, by heat-pipe tectonics (Moore and Webb, 2013) and delamination (Bédard 2006). These mechanisms are capable of delivering some surface volatiles to sublithospheric depths, but the volumes delivered by subduction to mantle depths below that sampled by arc magmas (~2 × 10^{13} mol/yr; Parai and Mukhopadhyay, 2012) are much greater.

DEEP SUBDUCTION AND KIMBERLITES

The remaining interpretation for the observed age distribution of KBLs is that the concentrations of volatiles in the upper mantle delivered to the base of the lithosphere beneath cratons increased tremendously in the latter part of Earth history. In this interpretation, the great problem is where did the fluids come from to rupture the lithosphere and allow KBL to erupt? As noted here, the only solid Earth processes that are capable of delivering large amounts of H_2O and CO_2 to the mantle beneath the lithosphere are PT and subduction. Water and carbonate in subducting slabs is sequestered in sediments, oceanic crust, and upper mantle, and these volatiles are released continuously as the slab descends. Hacker (2008) calculated that, at present, 8.4 × 10^{17} kg/Ma of water (~0.06% of the ocean each Ma) is subducted beneath 4 GPa (~135 km deep), although other estimates are significantly lower (Parai and Mukhopadhyay, 2012). Subduction zones and the water that these transport to depth have been linked to some KBLs, specifically an ~4000-km-long north-south–trending corridor of Cretaceous to Eocene KBL magmatism in northwest Canada that Heaman et al. (2004) interpreted to reflect subduction of the Kula-Farallon plate.

Given the ability of subduction to deliver H_2O and CO_2 deep into the mantle, it is worth considering the possibility that the increased abundance of KBLs in the past 1 Ga reflects the massive injection of H_2O and CO_2 into the mantle after PT and deep subduction began (Fig. 2). In this interpretation, there was no PT and no deep subduction before ca. 1 Ga. The flux of water to the mantle was low, mostly delivered by delamination and lithospheric drips, so fluid pressure at the top of asthenosphere was mostly low and the buildup of volatiles needed for KBL eruptions rarely occurred (Fig. 2A). After ca. 1 Ga, PT and deep subduction began delivering much more water to the mantle at depths greater than the base of the cratonic lithosphere, ~250 km. Evidence that deeply subducted water currently rises back into the overlying mantle includes a persistent low S-velocity anomaly in the upper mantle (van der Lee et al., 2008). Water and carbon dioxide released from the slab infiltrated and permeated upward, perhaps interacting with carbonated peridotite mantle, generating abundant H_2O-CO_2 fluids and eventually becoming trapped at the base of the continental lithosphere, increasing fluid pressure there (Fig. 2B). Eventually the build-up of fluid pressure broke to the surface as a KBL eruption; in regions of thinner lithosphere the mixed fluid phase may enhance generation of other low-degree mantle melts, which also seem to have erupted more abundantly in recent Earth history.

It must be acknowledged that, even if the general hypothesis is correct, there are many unanswered questions. Do both H_2O and CO_2

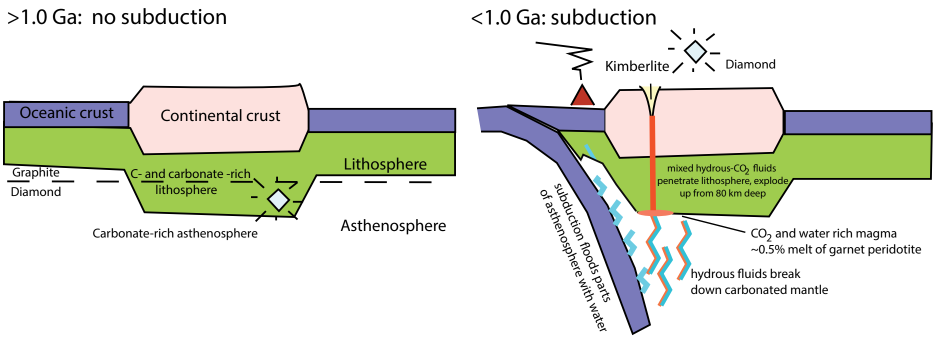

Figure 2. Simple explanation of why abundance of kimberlites increased ca. 750 Ma. A: Before ca. 1 Ga, no plate tectonics and no deep subduction exist. The flux of water to the mantle is low so fluid pressure at the top of the asthenosphere is low. B: After ca. 1 Ga, plate tectonics and deep subduction deliver water to the deep mantle. Upward-infiltrating water interacts with carbonated peridotite mantle, generating abundant H_2O-CO_2 fluids and increasing fluid pressure at the top of the asthenosphere. Eventually build-up of fluid pressure breaks to the surface as a kimberlite eruption.

in KBLs have the same origin? Are both derived from deeply subducted slabs, or does this mixed phase reflect destabilization of preexisting mantle carbonate by water rising from subducted slabs (as shown in Fig. 2B)? How long after PT and deep subduction began did it take for fluids to be subducted to depth, be released from the slab and rise through the mantle to the base of the continental lithosphere and reach concentrations sufficient to cause a KBL eruption? Although this is an unknown, it likely requires time spans of hundreds of millions of years. For example, it would take a minimum of ~100 Ma for the Farallon slab at a nominal rate of 50 mm/yr to move 5000 km and reach a position 660 km beneath the U.S. east coast. The time it would take for fluids to move from the subducted slab through the mantle and concentrate in sufficient quantities to break through the lithosphere could also be tens to hundreds of millions of years.

COMPARISON WITH OTHER PLATE TECTONIC INDICATORS

If we seriously consider KBLs as a PT indicator, then the conclusion that PT and deep subduction began within the past 1 Ga must be consistent with other lines of evidence. There is a wide diversity of opinion on this point, and most think that it was sometime in the Archean (Korenaga, 2013). If this quasi-consensus is correct, then our conclusions based on the KBL age distribution must be wrong. However, if the recent increase of KBL activity is related to the beginning of PT activity and massive increase in fluid budget of sublithospheric mantle due to the onset of deep subduction, there should be confirmation from the geologic record. We argue here that, although there is clear evidence of deep recycling very early in Earth history and that Earth was tectonically and magmatically very active throughout the Precambrian, most of the large-scale (the size of terranes) PT indicators first appeared in the Neoproterozoic (Fig. 3).

Figure 3 compares three different types of PT indicators: mantle fluids, seafloor spreading, and products of subduction zone metamorphism. KBL abundance monitors mantle fluid concentrations (Fig. 3A). Ophiolites are direct indicators of seafloor spreading and PT. A few ca. 1.9 Ga ophiolites are known, possibly indicating an abortive phase of Paleoproterozoic proto-PT, but abundant ophiolites began to appear ca. 1.0 Ga (Fig. 3B). Four different and direct indicators of uniquely cool subduction zone thermal environments are all metamorphic rocks, not easily removed by erosion (Fig. 3C). Blueschists are fragments of oceanic crust and sediments metamorphosed 30–60 km deep under unusually cool conditions only found in subduction zones. Ultrahigh-pressure metamorphic rocks contain metamorphic coesite or diamond and require subduction of continental crust to at least 100 km deep. Lawsonite formation requires high-pressure, high-temperature metamorphic conditions, typically blueschist and low-temperature eclogite facies. The oldest lawsonite-bearing rocks are latest Neoproterozoic, implying that sufficiently cold subduction zone thermal structures for lawsonite formation did not exist until then (Tsujimori and Ernst, 2014). Jadeitite formation requires hydrous fluid precipitation or the interaction of fluid and subduction zone metamorphic rocks at high pressures and high temperatures within the forearc mantle wedge.

Taken together, the geologic record of large-scale petrotectonic indicators supports the hypothesis that the recent increase in KBLs reflects the beginning of PT and sustained deep subduction in Neoproterozoic time.

CONCLUSIONS

We summarized evidence that the high volatile contents of KBLs reflect addition of water and carbon dioxide to the mantle by deep subduction and showed how the KBL record can be used to help constrain when sustained deep subduction first began. It is a low-fidelity record because of the long time needed between the start of deep subduction and increased KBL eruption frequency. Recognition that the modern episode of PT and deep subduction began in the Neoproterozoic opens the door to considering magmatic and tectonic styles of the pre-PT era, an exciting research topic that we are only starting to consider. It may also provide some new

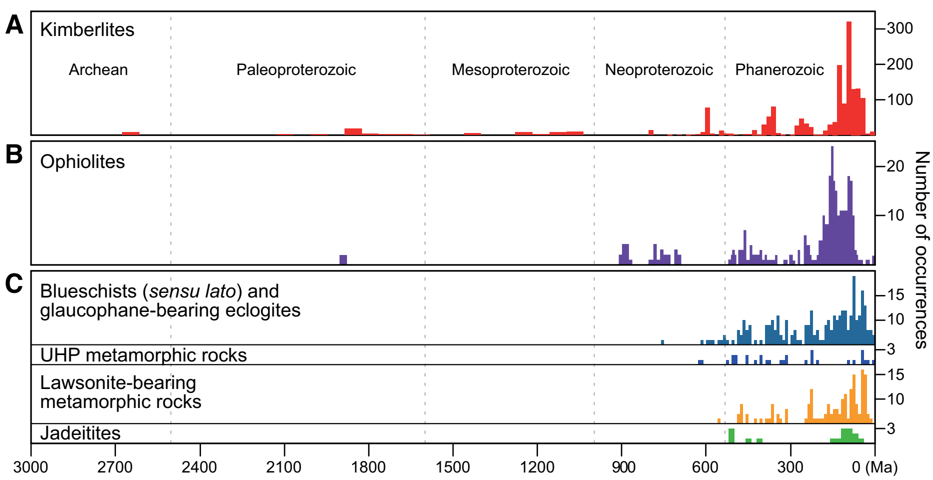

Figure 3. Age histograms for distinctive plate tectonic and subduction indicators for the past 3 Ga of Earth history (modified after Stern et al., 2013). A: Mantle volatile indicators, from kimberlite age distribution of Figure 1. B: Seafloor-spreading indicator of ophiolites. Age distribution of ophiolites is from Dilek (2003) for those until 1040 Ma, plus minor Paleoproterozoic ophiolites. C: Subduction zone indicators are all distinctive metamorphic rocks, i.e., blueschists and glaucophane-bearing eclogites, coesite- or diamond-bearing ultrahigh-pressure (UHP) metamorphic rocks, lawsonite-bearing metamorphic rocks, and jadeitites. The ages of blueschists are from Tsujimori and Ernst (2014), those of UHP metamorphic belts are from Liou et al. (2014), those of lawsonite-bearing metamorphic rocks are from Tsujimori and Ernst (2014), and those of jadeitites are from Harlow et al. (2015).

insights on the causes of the Neoproterozoic climate crisis summarized as snowball Earth and on the Cambrian evolutionary explosion.

ACKNOWLEDGMENTS

The late Don Anderson suggested that Stern look into the kimberlite record as a possible indicator of when plate tectonics began. Lyall Harris is gratefully acknowledged for bringing our attention to the kimberlite age compilation of Faure (2006), without which this work would not have been possible. We are grateful for constructive reviews from Brad Hacker and two anonymous reviewers. This research was supported by Tohoku University (Japan) in part by the MEXT/JSPS (Ministry of Education, Culture, Sports, Science and Technology–Japan Society for the Promotion of Science) KAKENHI (Grants-in-Aid for Scientific Research) 15H05212 and 26610163 to Tsujimori.

REFERENCES CITED

Artemieva, I.M., and Mooney, W.D., 2002, On the relations between cratonic lithosphere thickness, plate motions, and basal drag: Tectonophysics, v. 358, p. 211–231, doi:10.1016/S0040-1951(02)00425-0.

Bédard, J.H., 2006, A catalytic delamination-driven model for coupled genesis of Archaean crust and sub-continental lithospheric mantle: Geochimica et Cosmochimica Acta, v. 70, p. 1188–1214, doi:10.1016/j.gca.2005.11.008.

Brown, R.J., and Valentine, G.A., 2013, Physical characteristics of kimberlite and basaltic intraplate volcanism and implications of a biased kimberlite record: Geological Society of America Bulletin, v. 125, p. 1224–1238, doi:10.1130/B30749.1.

Clifford, T.N., 1966, Tectono-metallogenic units and metallogenic provinces of Africa: Earth and Planetary Science Letters, v. 1, p. 421–434, doi:10.1016/0012-821X(66)90039-2.

Dilek, Y., 2003, Ophiolite pulses, mantle plumes and orogeny, in Dilek, Y., and Robinson, P.T., eds., Ophiolites in Earth history: Geological Society of London Special Publication 218, p. 9–19, doi:10.1144/GSL.SP.2003.218.01.02.

Ernst, R.E., and Buchan, K.L., 2002, Maximum size and distribution in time and space of mantle plumes: Evidence from large igneous provinces: Journal of Geodynamics, v. 34, p. 309–342, doi:10.1016/S0264-3707(02)00025-X.

Faure, S., 2006, World Kimberlites CONSOREM Database Version 2006–2: Quebec, Canada, Consortium de Recherche en Exploration Minérale CONSOREM, Université du Québec à Montréal, https://consorem.uqac.ca/kimberlite/world_kimberlites_and_lamproites_consorem_database_v2010.xls.

Hacker, B.R., 2008, H_2O subduction beyond arcs: Geochemistry, Geophysics, Geosystems, v. 9, Q03001, doi:10.1029/2007GC001707.

Haggerty, S.E., 1994, Superkimberlites, a geodynamic window to the Earth's core: Earth and Planetary Science Letters, v. 122, p. 57–69, doi:10.1016/0012-821X(94)90051-5.

Harlow, G.E., Tsujimori, T., and Sorensen, S.S., 2015, Jadeitites and plate tectonics: Annual Review of Earth and Planetary Sciences, v. 43, p. 105–138, doi:10.1146/annurev-earth-060614-105215.

Harrison, T.M., 2009, The Hadean crust: Evidence form > 4Ga zircons: Annual Review of Earth and Planetary Sciences, v. 37, p. 479–505, doi:10.1146/annurev.earth.031208.100151.

Heaman, L., Kjarsgaard, B.A., and Creaser, R.A., 2004, The temporal evolution of North American kimberlites: Lithos, v. 76, p. 377–397, doi:10.1016/j.lithos.2004.03.047.

Herzberg, C., Condie, K., and Korenaga, J., 2010, Thermal history of the Earth and its petrological expression: Earth and Planetary Science Letters, v. 292, p. 79–88, doi:10.1016/j.epsl.2010.01.022.

Jelsma, H., Barnett, W., Richards, S., and Lister, G., 2009, Tectonic setting of kimberlites: Lithos, v. 112, p. 155–165, doi:10.1016/j.lithos.2009.06.030.

Korenaga, J., 2013, Initiation and evolution of plate tectonics on Earth: Theories and observations: Annual Review of Earth and Planetary Sciences, v. 41, p. 117–151, doi:10.1146/annurev-earth-050212-124208.

Lee, C.-T.A., Luffli, P., and Chin, E.J., 2011, Building and destroying continental mantle: Annual Review of Earth and Planetary Sciences, v. 39, p. 59–90, doi:10.1146/annurev-earth-040610-133505.

Liou, J.G., Tsujimori, T., Yang, J.S., Zhang, R.Y., and Ernst, W.G., 2014, Recycling of crustal materials through study of ultrahigh-pressure minerals in collisional orogens, ophiolites, and mantle xenoliths: A review: Journal of Asian Earth Sciences, v. 96, p. 386–420, doi:10.1016/j.jseaes.2014.09.011.

Moore, W.B., and Webb, A.A.G., 2013, Heat-pipe Earth: Nature, v. 501, p. 501–505, doi:10.1038/nature12473.

Milholland, C.S., and Presnall, D.C., 1998, Liquidus phase relations in the CaO-MgO-Al_2O_3-SiO_2 system at 3.0 GPa: The aluminous pyroxene thermal divide and high-pressure fractionation of picritic and komatiitic magmas: Journal of Petrology, v. 39, p. 3–27, doi:10.1093/petroj/39.1.3.

Nowell, G.M., Pearson, D.G., Bell, D.R., Carlson, R.W., Smith, C.B., Kempton, P.D., and Noble, S.R., 2004, Hf isotope systematics of kimberlites and their megacrysts: New constraints on their source regions: Journal of Petrology, v. 45, p. 1583–1612, doi:10.1093/petrology/egh024.

Parai, R., and Mukhopadhyay, S., 2012, How large is the subducted water flux? New constraints on mantle regassing rates: Earth and Planetary Science Letters, v. 317–318, p. 396–406, doi:10.1016/j.epsl.2011.11.024.

Price, S.E., Russell, J.K., and Kopylova, M.C., 2000, Primitive magma from the Jericho Pipe NWT, Canada: Constraints on primary kimberlite melt chemistry: Journal of Petrology, v. 41, p. 789–808, doi:10.1093/petrology/41.6.789.

Rey, P.F., and Coltice, N., 2008, Neoarchean lithospheric strengthening and the coupling of Earth's geochemical reservoirs: Geology, v. 36, p. 635–638, doi:10.1130/G25031A.1;.

Sparks, R.S.J., 2013, Kimberlite volcanism: Annual Review of Earth and Planetary Sciences, v. 41, p. 497–528, doi:10.1146/annurev-earth-042711-105252.

Stern, R.J., 2002, Subduction zones: Reviews of Geophysics, v. 40, p. 1012, doi:10.1029/2001RG000108.

Stern, R.J., Tsujimori, T., Harlow, G.E., and Groat, L.A., 2013, Plate tectonic gemstones: Geology, v. 41, p. 723–726, doi:10.1130/G34204.1.

Tainton, K.M., and McKenzie, D., 1994, The generation of kimberlites, lamproites, and their source rocks: Journal of Petrology, v. 35, p. 787–817, doi:10.1093/petrology/35.3.787.

Torsvik, T., Burke, K., Steinberger, B., Webb, S.J., and Ashwal, L.D., 2010, Diamonds sampled by plumes from the core-mantle boundary: Nature, v. 466, p. 352–355, doi:10.1038/nature09216.

Tsujimori, T., and Ernst, W.G., 2014, Lawsonite blueschists and lawsonite eclogites as proxies for paleo-subduction zone processes: A review: Journal of Metamorphic Geology, v. 32, p. 437–454, doi:10.1111/jmg.12057.

van der Lee, S., Regenauer-Lieb, K., and Yuen, D.A., 2008, The role of water in connecting past and future episodes of subduction: Earth and Planetary Science Letters, v. 273, p. 15–27, doi:10.1016/j.epsl.2008.04.041.

Manuscript received 24 April 2016
Revised manuscript received 10 July 2016
Manuscript accepted 11 July 2016

Printed in USA