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Geodynamics of kimberlites on a cooling Earth: Clues to plate tectonic evolution and deep volatile cycles

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A B S T R A C T

Kimberlite magmatism has occurred in cratonic regions on every continent. The global age distribution suggests that this form of mantle melting has been more prominent after 1.2 Ga, and notably between 250–50 Ma, than during early Earth history before 2 Ga (i.e., the Paleoproterozoic and Archean). Although preservation bias has been discussed as a possible reason for the skewed kimberlite age distribution, new treatment of an updated global database suggests that the apparent secular evolution of kimberlite and related CO_2-rich ultramafic magmatism is genuine and probably coupled to lowering temperatures of Earth's upper mantle through time.

Incipient melting near the CO_2- and H_2O-bearing peridotite solidus at >200 km depth (1100–1400 °C) is the petrologically most feasible process that can produce high-MgO carbonated silicate melts with enriched trace element concentrations akin to kimberlites. These conditions occur within the convecting asthenospheric mantle directly beneath thick continental lithosphere. In this transient upper mantle source region, variable CHO volatile mixtures control melting of peridotite in the absence of heat anomalies so that low-degree carbonated silicate melts may be permanently present at ambient mantle temperatures below 1400 °C. However, extraction of low-volume melts to Earth's surface requires tectonic triggers. Abrupt changes in the speed and direction of plate motions, such as typified by the dynamics of supercontinent cycles, can be effective in the creation of lithospheric pathways aiding kimberlite magma ascent.

Provided that CO_2- and H_2O-fluxed deep cratonic keels, which formed parts of larger drifting tectonic plates, existed by 3 Ga or even before, kimberlite volcanism could have been frequent during the Archean. However, we argue that frequent kimberlite magmatism had to await establishment of an incipient melting regime beneath the maturing continents, which only became significant after secular mantle cooling to below 1400 °C during post-Archean times, probably sometime shortly after 2 Ga. At around this time kimberlites replace komatiites as the hallmark mantle-derived magmatic feature of continental shields worldwide.

The remarkable Mesozoic–Cenozoic 'kimberlite bloom' between 250–50 Ma may represent the ideal circumstance under which the relatively cool and volatile-fluxed cratonic roots of the Pangea supercontinent underwent significant tectonic disturbance. This created more than 60% of world's known kimberlites in a combination of redox- and decompression-related low-degree partial melting. Less than 2% of world's known kimberlites formed after 50 Ma, and the tectonic settings of rare 'young' kimberlites from eastern Africa and western North America demonstrate that far-field stresses on cratonic lithosphere enforced by either continental rifting or cold subduction play a crucial role in enabling kimberlite magma transfer to Earth's surface.

1. Rationale

Plate tectonics and magmatism are consequences of heat loss from a planet's interior. Earth was significantly hotter in the distant

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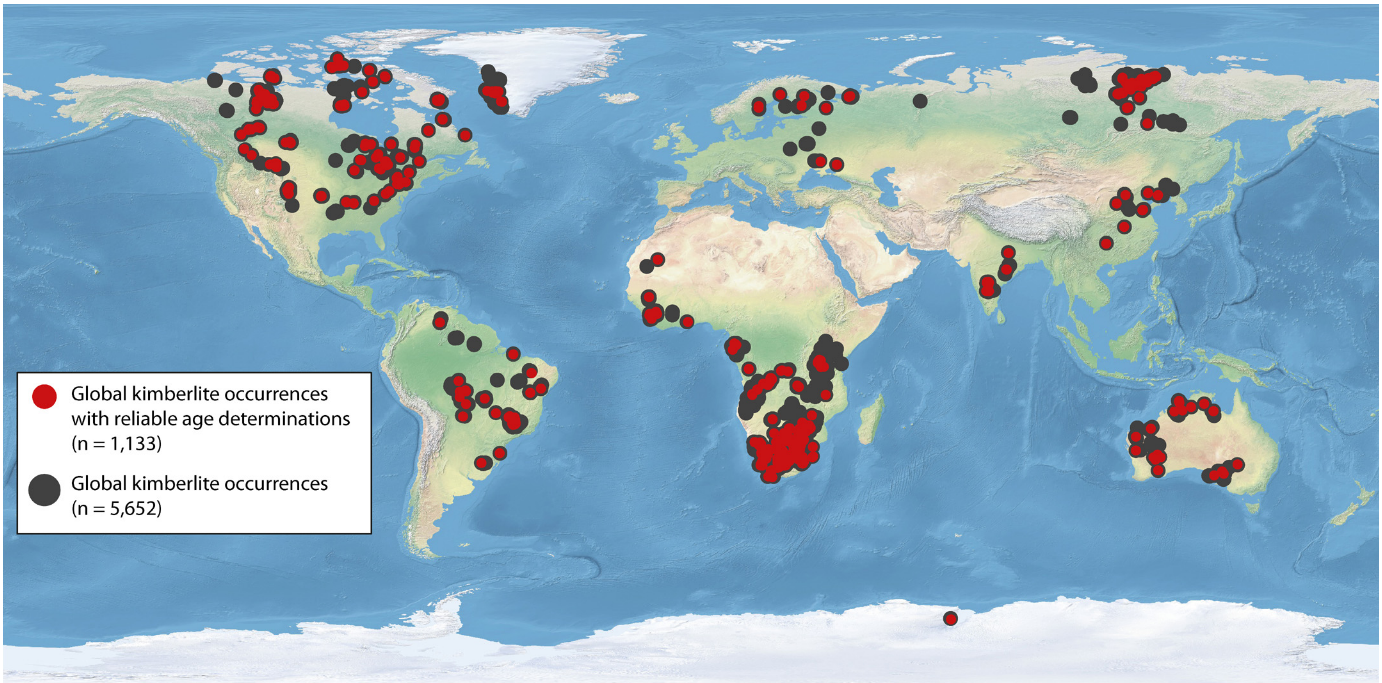

Fig. 1. World map showing the global distribution of kimberlites (grey dots; $n = 5{,}652$). Occurrences that have quality age information in the public domain are indicated with red dots ($n = 1{,}133$; Supplementary file A). The frequency distribution of kimberlite ages displayed in Fig. 2a and discussed in the main text is based on this updated global database. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

past and has been cooling for most of its history (Korenaga, 2008; Davies, 2009; Michaut et al., 2009; Ganne and Feng, 2017). The effects of an early hotter Earth on the intensity of mantle convection, volcanism, and volatile element cycling continue to be debated, because they had critical influence on the formation of a life-supporting atmosphere (Lyons et al., 2014; Gaillard et al., 2015; Duncan and Dasgupta, 2017). One of the strongest lines of evidence for the secular cooling of Earth is the changing composition of mantle-derived melts through time. Archean basalts are typically more MgO-rich compared with their modern analogs due to higher degrees of partial melting at higher mantle potential temperatures (Herzberg et al., 2010; Keller and Schoene, 2012; Ganne and Feng, 2017). The hottest magmas on Earth, komatiites, are largely restricted to the Archean and Paleoproterozoic (Arndt, 2003), demonstrating that mantle temperatures were up to 400 °C higher than today (Herzberg et al., 2010; Sobolev et al., 2016). Conversely, some igneous rock types appear to have formed more frequently during the latter half of Earth history. The temporal distribution of global kimberlites and associated carbonatites is strikingly skewed toward the more recent Earth history. Although this pattern may be influenced by preservation (Veizer et al., 1992; Brown and Valentine, 2013; Ault et al., 2015), it is equally plausible that deep mantle melting under volatile-rich conditions (e.g., kimberlite melt formation) was more common during the Mesozoic–Cenozoic and rare during the Precambrian (Tappe et al., 2014). Several explanations have been provided to explain the 'delayed' appearance of global kimberlite and carbonatite magmatism. Among these models are an increasing oxidation state (Foley, 2011) and volatile content (Stern et al., 2016) of Earth's upper mantle through time, primarily owed to enhanced post-Archean subduction recycling. In contrast, secular mantle cooling has largely been ignored, or downgraded (Stern et al., 2016) in models that seek to explain the skewed age distribution of kimberlites and carbonatites. Here we discuss evidence from petrology and geochronology suggesting that the cooling of Earth's upper mantle, in tandem with supercontinent cyclicity, exerted a strong control on the temporal evolution of kimberlites and related CO_2-rich ultramafic magmas of deep origin.

2. Approach and results

2.1. Constraints from an updated global kimberlite age database

We have compiled a high-quality geochronology database for bona fide kimberlites[1] to better understand their global magma emplacement patterns (Supplementary file A). The database contains published age information for 1,133 kimberlite localities, which represents approximately 20% of the known kimberlite occurrences worldwide (Fig. 1). Although quality age information is not available for every occurrence, our database contains entries for each major kimberlite cluster from every continent without over-representing economic clusters that host diamond mines and are therefore more intensively studied (Fig. 1). Thus, our database provides the currently most comprehensive and most scrutinized account of the temporal distribution of global kimberlite magmatism.

Fig. 2 shows the temporal distribution of global kimberlite occurrences (those with available age dates) in the form of a frequency distribution with a bin size of 25 Myr. Kimberlite magmatism occurred episodically since ca. 2.85 Ga (cf., de Wit et al., 2016), and the overall frequency increases significantly toward the Cretaceous–Paleocene. Periods of pronounced kimberlite magmatism occurred between 1200–1075 Ma (9.4%), 600–500 Ma (7.4%), 400–350 Ma (5%), and 250–50 Ma (62.5%; Fig. 3a). The total number of known kimberlite clusters that formed during these relatively short time windows accounts for approximately 84% of global kimberlite volcanism. In contrast, the past 50 Myr are characterized by a relatively low frequency of kimberlite volcanism, accounting for less than 2% of global kimberlite clusters (Figs. 2a, 3b). However, the ca. 12,000 yr old Igwisi Hills volcanoes on the

[1] Unless stated otherwise, all subsequent use of the term 'kimberlite' refers to Group-1 kimberlite.