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Trends and rhythms in carbonatites and kimberlites reflect thermo-tectonic evolution of Earth

Shuang-Liang Liu[1,2], Lin Ma[2,3], Xinyu Zou[1], Linru Fang[4], Ben Qin[2,3], Aleksey E. Melnik[5], Uwe Kirscher[6,7], Kui-Feng Yang[1,2], Hong-Rui Fan[1,2]* and Ross N. Mitchell[2,5]*

[1]Key Laboratory of Mineral Resources, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[2]College of Earth and Planetary Science, University of Chinese Academy of Sciences, Beijing 100049, China
[3]Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[4]Institut de Physique du Globe de Paris, Université de Paris, CNRS, 1 Rue Jussieu, Paris F-75005, France
[5]Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[6]Department of Geosciences, University of Tübingen, Tübingen 72076, Germany
[7]Earth Dynamics Research Group, The Institute for Geoscience Research (TIGeR), School of Earth and Planetary Sciences, Curtin University, Perth, WA 6102, Australia

ABSTRACT

Earth's thermo-tectonic evolution determines the way the planet's interior and surface interact and shows temporal changes in both trends and periodic rhythms. By sampling the subcontinental lithospheric mantle that represents the interface between the convecting mantle and the crust, carbonatite and kimberlite should be ideal rock types for documenting this evolution. The first-order secular rise of kimberlites over time has been noted by researchers, but there is much debate over how to interpret this trend, and their second-order variability has received less attention. We compiled a comprehensive global carbonatite database and compared it with an existing kimberlite one. We find that the numbers of carbonatites and kimberlites have similar increasing secular trends, with accelerated growth after ca. 1 Ga, and show the same periodic rhythms that have been synchronized to the supercontinent cycle since ca. 2.1 Ga. We link these trends and rhythms to the long-term change of Earth and the supercontinent cycle, both of which have altered the temperature of, and the subduction-recycled volatile flux into, the subcontinental lithosphere. Such consistent records in carbonatite and kimberlite behavior provide critical evidence for the synchronous thermo-tectonic evolution of the entire subcontinental lithosphere.

INTRODUCTION

Earth's thermal and tectonic histories are intertwined, and their combined evolution, which determines the way the planet's interior interacts with the surface, has evolved over Earth's history. This evolution is manifest not only in secular changes in terms of mantle temperature, crustal structure, and dominant rock and mineralization type (Goldfarb et al., 2010; Herzberg et al., 2010; Palin et al., 2020), but also in recurring continental assembly and breakup of the supercontinent cycle (Mitchell et al., 2021). Finding geologic records that exhibit both first-order secular trends and second-order periodic rhythms (El Dien et al., 2019) is thus crucial to our understanding of how Earth has evolved.

The subcontinental lithospheric mantle (SCLM) represents the interface between the convecting mantle and the crust and is thus sensitive to both deep thermal and shallow tectonic changes. The SCLM facilitates the petrogenesis of distinct rock types, notably carbonatites and kimberlites (Bell and Simonetti, 2010; Pearson et al., 2019). Carbonatite consists of >50 vol% primary (i.e., magmatic) carbonate minerals (Le Maitre, 2002), and its parental magmas are believed to have originated at a depth of 90–150 km (Hammouda and Keshav, 2015). Kimberlite, on the other hand, is a hybrid potassic ultramafic igneous rock with high volatile contents of primarily CO_2 and H_2O, and is the only magma known to sample Earth's mantle at depths of >150 km (Edgar and Charbonneau, 1993). Both distinctive magmas are related to low-degree partial melting of fertile peridotites in the SCLM, are volatile-enriched, and ascend quickly. Therefore, the spatiotemporal distributions of these two distinct, but related, rock types should reflect both the trends and periodic rhythms of Earth's thermo-tectonic evolution.

Much focus has been given to explaining the secular increase of kimberlites over time. One school of thought is that the increasing trend reflects the addition of H_2O and CO_2 to the mantle by the initiation of deep subduction (Stern et al., 2016), while other researchers think this long-term rise reflects secular mantle cooling (Tappe et al., 2018). A similar secular increase has been suggested for carbonatites (Woolley and Kjarsgaard, 2008), although less attention has been given to its interpretation. Likewise, the meaning behind the secular rise could also be reflected, but on shorter time scales, by potential periodic rhythms within this secular trend, which have received less scrutiny (Tappe et al., 2018). We compiled a comprehensive global carbonatite database through Earth's history and compared it with the kimberlite record. We explore both the secular trends and periodic rhythms of these two unique SCLM-related rock types to provide new insights into the thermo-tectonic evolution of Earth.

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*E-mails: fanhr@mail.iggcas.ac.cn; ross.mitchell@mail.iggcas.ac.cn

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METHODS

With the compilation provided by Woolley and Kjarsgaard (2008) as a strong basis (527 carbonatites with detailed information), we present an updated carbonatite database that includes 594 occurrences along with 355 reliable age data (Table S1 in the Supplemental Material[1]). The workflow details of the filtering protocols for updating age data can be found in Figure S1. The kimberlite database (Tappe et al., 2018) includes, of 5652 total kimberlite occurrences, 1133 with quality age constraints. Statistical analysis was performed using Acycle (Li et al., 2019; https://acycle.org/) and Matlab (https://www.mathworks.com/products/matlab.html). Methods are detailed in the Supplemental Material.

RESULTS

Figure 1 shows the spatial distribution of carbonatites and kimberlites with reliable ages. Carbonatites and kimberlites are found on every continent and occur mainly in Precambrian shields and preferentially along cratonic margins. This spatial correlation is thought to reflect the fact that (1) thick lithosphere is needed for the melting depths required for both carbonatite and kimberlite, and (2) the over-thickened central part of a craton provides fewer chances for magma to rise to the surface. Most carbonatites are sourced in the rigid parts of the continental lithosphere, but some are found within orogens. These "orogenic" carbonatites may be related to continental collision (Xu et al., 2018). Those carbonatites that are significantly younger than the host orogeny appear to have exploited an older tectonic boundary (Ranta et al., 2018).

We present the age records of carbonatites and kimberlites with their associated distribution curves (Fig. 2). Both carbonatite and kimberlite occurrence data sets range from ca. 3 Ga to the present day over multiple orders of magnitude in amplitude, such that both distribution curves can be characterized well by power-law growth curves ($r^2 = 0.94$ and 0.84, respectively). In addition to exhibiting secular nonlinear increases, both carbonatite and kimberlite magmatism show cyclic behavior. We detrended each distribution curve by fitting the first-order trend and subtracting it to see the second-order residuals, and then performed statistical analysis. We find that both data sets show alternating peaks and troughs and that their fluctuations are similar (lead-lag of <80 m.y.; Fig. S4) from 2.1 to 0 Ga, but different from 3.0 to 2.1 Ga (Fig. 3A). Spectral analysis of carbonatites yields the strongest periodic signal at ~584 m.y. with a secondary peak at ~800 m.y., and the kimberlites have the strongest periodic signal at ~514 m.y. with a secondary peak at ~327 m.y. (>95% confidence; Figs. 3B and 3C). The 500–800 m.y. bandwidth is reminiscent of the supercontinent cycle, and the shorter period matches the 200–350 m.y. Wilson cycle (Mitchell et al., 2019). Sensitivity tests conducted to assess the influence of bin size on these results confirm their robustness when bin sizes do not over-smooth the data (Figs. S3 and S4).

To further explore the meaning of these rhythms, we compared them to the detrended MgO content of plume basalts (Fig. 3; Figs. S4, and S5), which is a proxy for mantle potential temperature (El Dien et al., 2019). Strikingly, the fluctuations in carbonatite and kimberlite are inversely related to ΔMgO from 2.1 to 0.2 Ga, and most obviously starting at 1.2 Ga. The weak kimberlite fluctuations from 2.1 to 1.2 Ga, although broadly consistent with carbonatite and the inverse of ΔMgO, add uncertainty to the results from that period. When bin sizes are varied, unstable relationships during 200–0 Ma imply that dramatic fluctuations exist on short timescales (Fig. S4). If we focus on this most recent interval at higher resolution (10 m.y. bin size), the fluctuation of these carbonate-bearing rocks still roughly corresponds to colder ΔMgO (Fig. S5). Furthermore, major peaks in the two rock types are broadly consistent with the reorganization phases of the supercontinent cycle.

DISCUSSION

Our results show that both the carbonatite and kimberlite age-frequency distributions can be deconvolved into two similar signals: a power-law growth trend, and periodic rhythms (Figs. 2 and 3). Although such a trend increasing in recent times and the apparent episodicity may be artifacts of various forms of bias (Brown and Valentine, 2013; Ault et al., 2015), we suggest they closely approximate the true rock records. First, being of economic interest, these rocks are highly sought. Carbonatites are known from

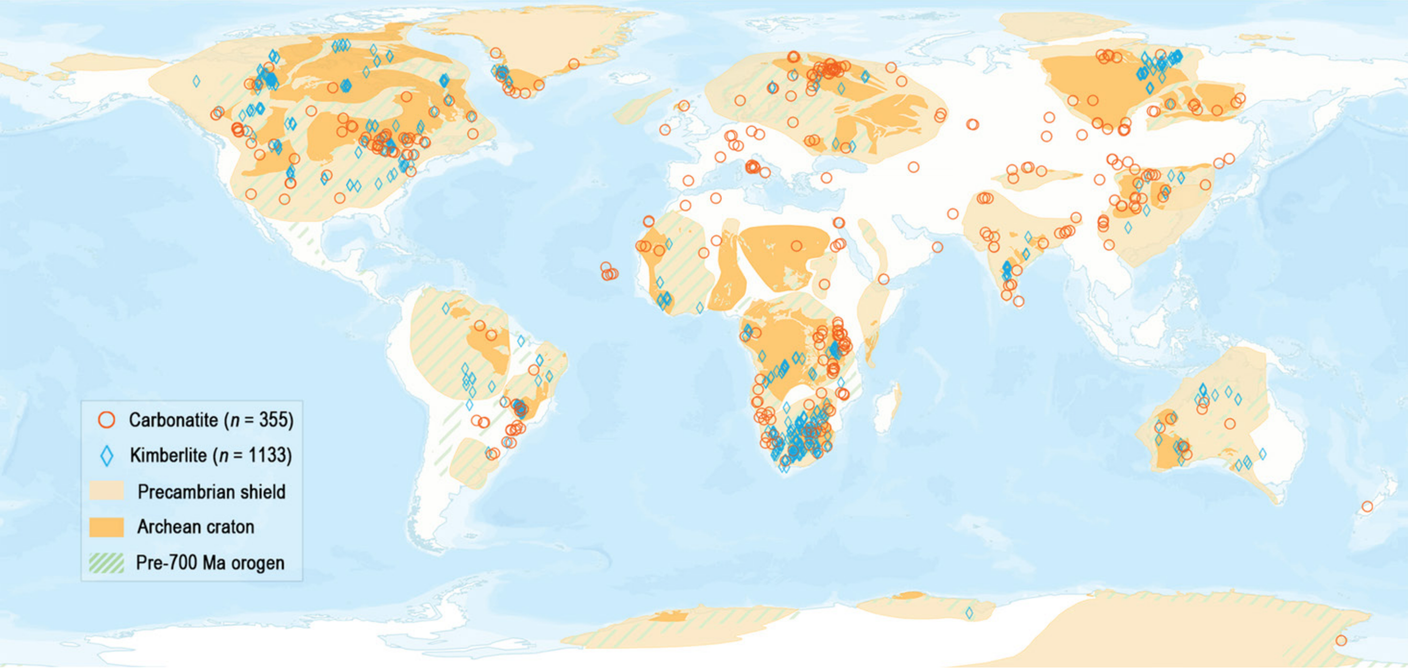

Figure 1. Global geologic map showing the distribution of carbonatites and kimberlites with reliable ages. All carbonatites and kimberlites are shown in Figure S2 (see footnote 1) for comparison. Kimberlite data are from Tappe et al. (2018).

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[1] Supplemental Material. Methods, Figures S1–S7, Table S1, and references. Please visit https://doi.org/10.1130/GEOL.S.21397176 to access the supplemental material, and contact editing@geosociety.org with any questions.

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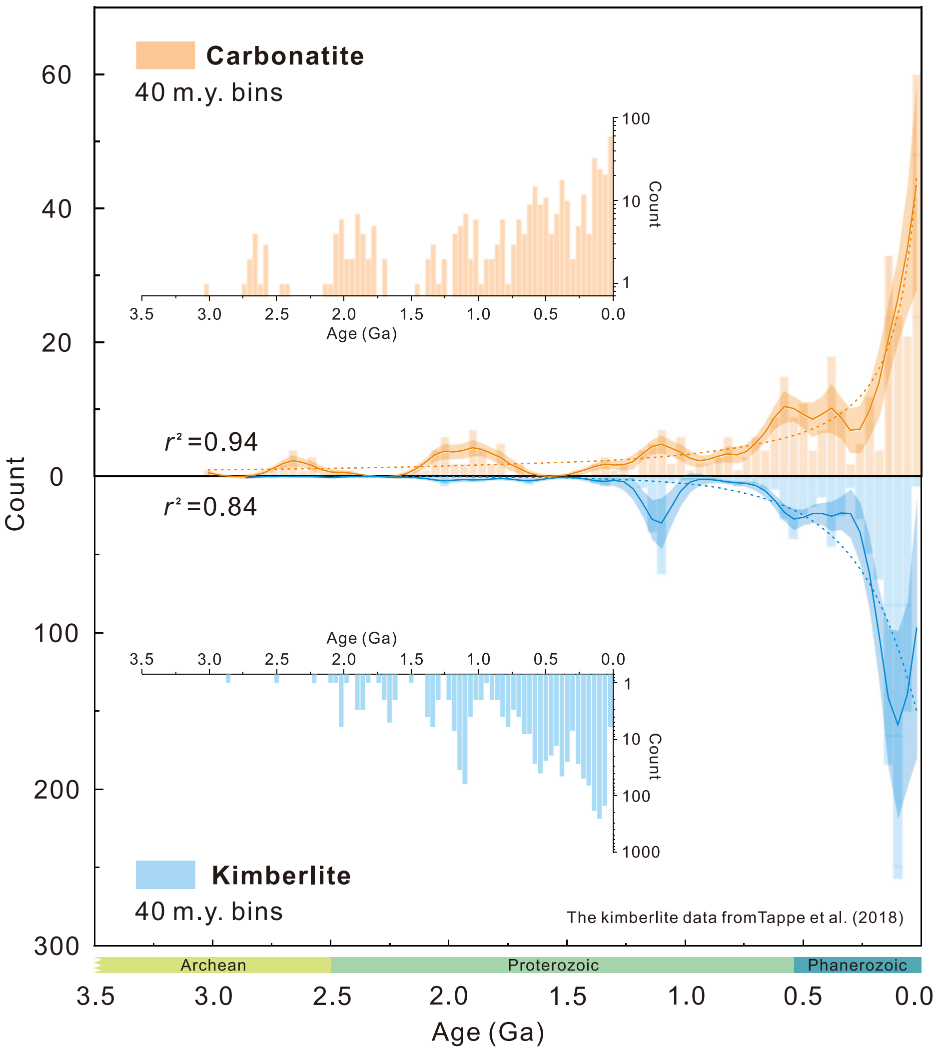

Figure 2. Age-frequency distribution of carbonatites and kimberlites. The estimated age-distribution curves (solid lines; 1σ confidence intervals) were calculated using a locally estimated scatterplot and bootstrap method. The fitting power functions (dashed lines) were evaluated by r^2. Insets are logarithmic scales.

every craton and geological period, and they spatially overlap with reported kimberlites that are 10 times more abundant (Fig. 1). These facts suggest that any discovery or investigative bias is insignificant. Second, even when accounting for preservation after normalizing by crustal surface ages over time, kimberlites, known for their pinching and swelling extrusive pipes that could be sensitive to surface erosion, still exhibit an increasing abundance since 1.2 Ga (Fig. S6). Carbonatites, which are mostly plutonic, should be better preserved. Furthermore, these rocks show the same signals even if the count is limited to occurrences in Archean cratons or Precambrian orogens, which are less affected by crustal recycling by subduction than younger, more peripheral continental margins (Fig. S7). We therefore conclude that these records are mostly genuine and not artifacts of preservation bias. Taken as largely reliable, these rock records, containing both first-order trends and second-order rhythms, complement each other and can be linked to the thermo-tectonic evolution of Earth. In this respect, subduction and mantle temperature are two criteria that are thought to be the leading factors in controlling carbonatite and kimberlite records through time.

In terms of petrogenesis, the formation of these carbonate-bearing rocks requires a pre-enrichment of carbon and other volatiles in the SCLM. The carbon in their source region does not have to be entirely derived from subducted crust, but subduction inevitably contributes to it because the primordial mantle carbon alone is not enough to have continued providing carbonaceous rock since ca. 3 Ga (Dasgupta, 2013). This is corroborated by chemical studies that show their sources exhibit recycled signatures (Shirey and Richardson, 2011; Amsellem et al., 2020). Indeed, evidence that subduction facilitated the generation of these rocks is reflected not only by their secular rise, corresponding to the increased volatile influxes along with Earth transitioning into a deep subduction regime after 1.0 Ga (Stern et al., 2016), but also by the coincidence of their peaks with the reorganization phase of each supercontinent cycle, which usually has greater subduction flux/length and cratonic motion speeds (Cao et al., 2017; Müller et al., 2022; Roberts et al., 2022; Fig. 3A). The consistency does not mean these rocks must be directly tied to a contemporaneous subduction zone, given the various forms and time scales of carbon transport in the mantle (Sun and Dasgupta, 2019; Farsang et al., 2021). It is more likely the result of the increasing volatile influx of SCLM resulting from ascending magma channels induced by increased subduction rates, and favorable physicochemical conditions in the SCLM (Fig. 4). Thus, subduction plays a critical role in the interpretation of carbonatite and kimberlite occurrences.

Both carbonatites and kimberlites form from low-degree partial melting of carbonated peridotite at 1000–1100 °C, 3–8 GPa, and 1100–1400 °C, 6–10 GPa, respectively. The high mantle adiabat in the Archean (1500–1600 °C; Herzberg et al., 2010) would have produced a major melting regime along the dry peridotite solidus, promoting extensive MgO-rich basaltic to komatiitic magmatism (Tappe et al., 2018). In contrast, subsequent mantle cooling would have benefitted carbonatite and kimberlite magmatism. Well-documented secular mantle cooling indicates fairly constant mantle heat flow, implying cooling of the SCLM over time (Lenardic and Kaula, 1995; Herzberg et al., 2010) and is consistent with the trends of carbonatite and kimberlite. However, a heterogeneous mantle cooling history has also been proposed based on surface heat loss observations and thermal modeling (Rolf et al., 2012; Karlsen et al., 2021), where aggregated continents can cause heating of the underlying mantle of up to 100 °C. Otherwise, there is no significant warming, and subcontinental mantle can be colder than suboceanic mantle. This situation is consistent with the second-order rhythms of the two rock records, which are inversely related to the ΔMgO of basalts since ca. 2.1 Ga (Fig. 3A). This means the two rock types are more likely to occur during the cycle when the subcontinental mantle is relatively cold, which corresponds to the reorganization phase of the supercontinent cycle.

We investigated the apparent dependence of these SCLM-related rocks on both subduction and mantle cooling. On the one hand, subduction is possible even in the Archean, with a mantle potential temperature (T_p) 170–200 °C higher than at present. However, under such conditions, slabs would experience a hotter (87–100 °C, half of ΔT_p) thermal profile than the hottest modern subduction zone (Cascadia), thus potentially stripping almost all crustal carbon off the downgoing plate at shallow (e.g., sub-arc) depths (Sizova et al., 2010; Dasgupta, 2013). In contrast, modern colder temperatures have

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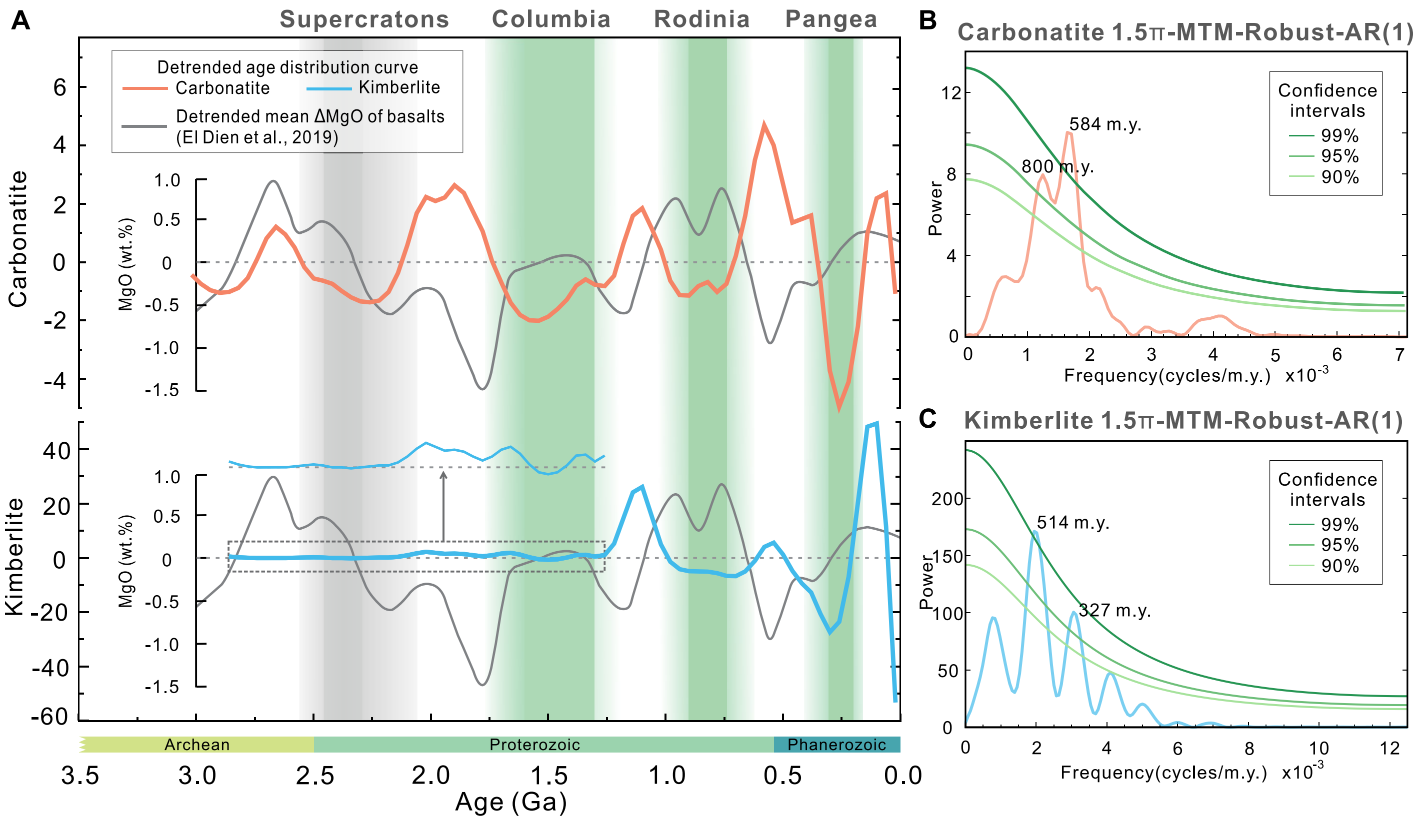

Figure 3. (A) Detrended carbonatite and kimberlite age-distribution curves compared to the detrended global mean ΔMgO of plume basalts and the supercontinent cycle. The supercontinents and their reorganization are shown as green and white bars, respectively, with uncertain Archean supercratons in gray. The kimberlite curve from 3.0 Ga to 1.2 Ga is amplified. (B,C) Multi-taper method (MTM) power spectra of carbonatite and kimberlite curves in Figure 3A.

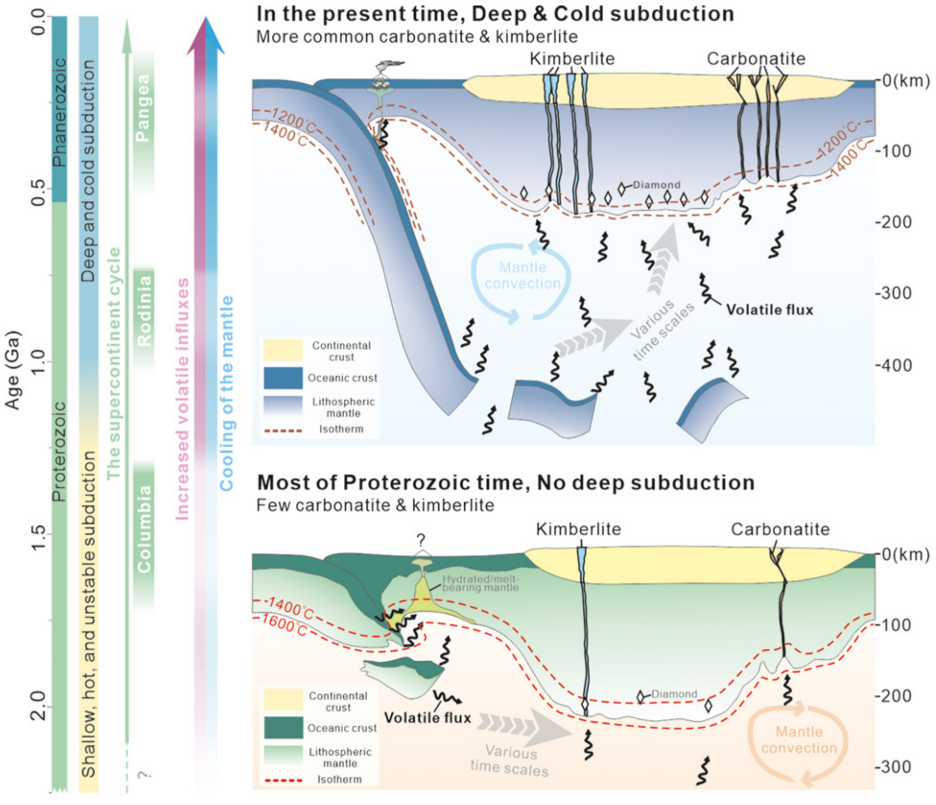

Figure 4. Model of the thermo-tectonic evolution of Earth accounts for the observed trends and rhythms in the occurrences of carbonatites and kimberlites from 2 Ga to the present day.

led to stronger plates, transforming once shallow underthrusting into deep subduction and introducing increasing volatile contents ($\sim$75% for carbon) through deeper cycling (Plank and Manning, 2019). Thus, a corollary of mantle cooling is that deep subduction is promoted and volatiles have more of a chance to migrate and be stored in cold, rigid, thick, and refractory cratonic lithosphere through redox freezing and melting associated with mantle convection (Sun and Dasgupta, 2019).

On the other hand, subduction in turn affects mantle cooling. The onset of plate tectonics would have changed the early Earth's geodynamic mode of cooling (e.g., heat-pipe and/or squishy lid models; Moore and Webb, 2013; Rozel et al., 2017), thereby increasing cooling efficiency through subduction of cold slabs. In addition, more widespread subduction over time would have increased the core-mantle boundary heat flux by slabs cooling the core, thereby generating hot thermal anomalies or mantle plumes (Li, 2020) that transferred core heat through the entire mantle to the surface. Hence, a feedback exists by which subduction can promote mantle cooling, which in turn causes subduction to become more common because a cooling Earth has a more rigid lithosphere that promotes plate-like behavior. In this way, the two processes are coupled, both in terms of the long-term change

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and supercontinent cycles, and thus form a positive feedback loop that could explain the power laws and rhythms of the two rock records.

During the Archean and most of Proterozoic time, without deep subduction to deliver volatiles and to cool the mantle, carbonatites and kimberlites were rare (Fig. 4). But, as the feedback between subduction and mantle cooling proceeded, more volatiles were delivered into a cooler mantle, and carbonatites and kimberlites became progressively more common, especially after ca. 1 Ga. Thus, both tectonics (i.e., subduction) and the thermal state of the mantle (i.e., cooling) have influenced carbonatite and kimberlite magmatism through time. Not only are tectonic and thermal boundary conditions both important for the formation of carbonatites and kimberlites, they are also consistent with one another and arguably mechanistically linked. The two rock records therefore provide a critical link in our understanding of the thermo-tectonic evolution of Earth.

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