Carbonatites and Global Tectonics
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Supplementary Methods

Digital plate tectonic reconstructions using GPlates (www.gplates.org) were used to reconstruct the carbonatite occurrences presented in this paper. The carbonatite occurrences at present-day were assigned Plate IDs using GPlates and reconstructed through time – with the age of eruption that considers the entire uncertainty range of that age. The plate tectonic reconstruction of Müller et al. (2019) covers the Mesozoic and Cenozoic, and was extended to the Devonian by linking to the Young et al. (2018) reconstruction.

This 410 to 0 Ma digital plate reconstruction includes a full topological network of plate boundaries, that enables the numerical interrogation of the model at the carbonatite emplacement locations (such as distance to particular plate boundary types, and so on). In addition, the Müller et al. (2019) plate motion model is the first global model to include deformation of the continental lithosphere. Our analysis is restricted for the last 410 Ma, as that time range incorporates the only GPlates plate reconstruction that has both rigid (entire timeframe) and deforming (240 to 0 Ma) plate topologies. This enables the interrogation of the plate kinematics, as well as the rifting regions, which is not possible with other models that lack these features. Only carbonatites with age-constraints were included in the analysis.

We extract only actively deforming rift areas from the plate reconstructions through time, since the initial breakup of Pangea at 240 Ma. The evolution of the paleo-rift settings is constrained by the area of present-day stretched continental crust (area between unstretched continental crust and the continent-ocean boundaries). The onset of rifting is determined from syn-rift sedimentation and faulting, while the cessation of rifting is typically inferred from the onset of seafloor spreading. Tectonic subsidence curves from well data on the passive margins provides a key constraint for the evolution (timing and magnitude) of rifting, and the rifts considered here are described in Müller et al. (2019). The geometries of plume products (Johansson et al., 2018), elevated regions (Cao et al., 2017) (410 to 3 Ma), and cratons (Artemieva, 2006) were also reconstructed in 1 Myr intervals. Although cratonic keels may have been eroded and modified over geological time, we assume that the edges of the cratons have remained largely unchanged. Considering the geodynamic complexity of LLSVPs, for this study we made a simplifying assumption of LLSVP stability, and followed the present-day −0.7% dln V₃ contour from Davies et al. (2015).
At each 1 Myr timestep, a spherical (great-circle) distance grid from rifts, plume products, mountains, craton edges, and LLSVPs was computed using Generic Mapping Tools 6.2 (Wessel et al., 2019). Any carbonatite occurrence is then placed on these distance grids, and the distance between the carbonatite and each setting (rift, mountain, etc.) is extracted in the reconstructed co-ordinates. As this is a simple spatial interrogation, the analysis is agnostic of the causative mechanism for carbonatite emplacement, and instead only reveals the distance from the major geological settings that were investigated in this study.

The time series for each geological setting (e.g., rifts) was grouped and presented in a simple box-and-whisker plot (Fig. 4), enabling a comparison of spatial associations between the geological settings. The analysis does not discriminate correlation and causation between the tectonic setting and the carbonatite occurrence, and the wide range of tectonic settings associated with carbonatites is best highlighted with present-day east Africa (Fig. S1). Future work will focus on extending the plate tectonic reconstructions and analysis back in time, as well as increasing the level of detail captured in the rifting and mountain-building histories.

A simple sensitivity analysis was performed by generating synthetic carbonatites at each timestep (Fig. S2). At each reconstruction time, the number of “actual” carbonatites was counted, and an equivalent number of synthetic carbonatites were randomly seeded. In one test, synthetic carbonatites could be generated anywhere in the world (continental or oceanic lithosphere), while in another test synthetic carbonatites were confined to continental lithosphere. The comparison to continental lithosphere is more meaningful, considering that carbonatite eruption is biased towards continental lithosphere (see main text). To ensure that the synthetic carbonatites were not spatially seeded in a biased manner (namely, closer to the poles) when using a cartesian geographic range (-180/180°E and -90/90°N), a dense spherical (rather than cartesian) equidistant mesh of points was first constructed – and points were randomly selected from this unbiased mesh. For continental lithosphere, these mesh points were first selected using the reconstructed outlines of continental lithosphere, and then random points selected from that pool. The pooled distances in each geological setting were then compared using histogram and box-and-whisker distributions (Fig. S3).

Perhaps not surprisingly, the craton results were most robust and convincing – in other words, the actual reconstructed carbonatites clustered much more closely with the craton edges than the synthetic case. In the LLSVP, rifts, and LIPs analyses – more than 50% of the carbonatites erupt closer to these geological settings than the synthetic cases. The carbonatite association with orogens is not as convincing, as the synthetic randomised points yield a generally similar distribution. However, this simple analysis does not rule out these geological settings for hosting
carbonatites. Instead, it highlights the need for additional work to untangle the drivers and dominating mechanisms for generating carbonatite magmatism. One obvious further refinement of our analysis, considering that almost all carbonatite eruptions are confined to continental lithosphere, only LIPs that erupted on continental crust should be considered. Our simple sensitivity analysis here (Fig. S3) indicates that carbonatites are likely more strongly associated to erupting LIPs than randomly distributed synthetic points, suggesting that the inclusion of oceanic LIPs obscured that relationship in our global comparison (Fig. 4 in main text).

**Figure S1.** Map of carbonatite occurrences (green circles, with age labels, this study) in north-east Africa, highlighting spatial associations with craton edges (thick orange lines) (Artemieva, 2006), active structures (largely related to rifting, in yellow) (Styron and Pagani, 2020), recent volcanism from the Global Volcanism Program (red triangles) (Venzke, 2013), alkaline rocks (maroon circles) (Humphreys-Williams & Woolley, submitted), and ANSS seismicity with magnitude greater than 5.5 (pink points) (U.S. Geological Survey, 2017). Some clusters of carbonatites seem to be (spatially) associated with recent volcanism (e.g., 1), alkaline volcanism (e.g., 2), a mix of rift-related structures, seismicity, and volcanism (e.g., 3 and 4), intraplate seismicity (e.g., 5), and rift-flanks (e.g., 6) – highlighting the range of tectonic settings that can be associated with carbonatites, even in a single region.
Figure S2. A sensitivity analysis was performed to compare a synthetic global distribution (top), synthetic continental distribution (middle), and the actual reconstructed carbonatites (bottom). At each reconstruction time (between 410 and 0 Ma), the “actual” number of carbonatites was counted, and an equivalent number of random synthetic points were generated globally or just confined to the continents. An animation of each scenario is provided in the supplement for comparison, and a histogram and box plot comparison is provided in Fig. S3.
Figure S3. The distance of reconstructed carbonatites in different geological settings (green) is compared to synthetic (random) equivalents for a global (blue) and continental (orange) distribution.

REFERENCES


Young, A., Flament, N., Maloney, K., Williams, S., Matthews, K., Zahrivic, S., and Müller, R. D., 2018, Global kinematics of tectonic plates and subduction zones since the late Paleozoic Era: Geoscience Frontiers.