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When do mantle plumes destroy diamonds?

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ABSTRACT

Mantle plumes are hot buoyant upwellings that rise from Earth's core–mantle-boundary to its surface where they can produce large igneous provinces (LIPs) and volcanic tracks, such as the Siberian Traps and the Hawaiian Emperor chain, respectively. We show that flattened mantle plume heads, which can have radii of >1200 km in the uppermost mantle, can heat the overlying lithospheric mantle to temperatures above the diamond stability field. As a consequence, they can destroy diamonds within the roots of Archean cratons, the principal source of diamonds in kimberlites. We quantitatively demonstrate that there is a 'sour spot' for this effect that occurs when lithospheric thicknesses are 165–185 km and the plume has a temperature of >150 °C above background mantle. Our model explains why the kimberlites associated with the 370 Ma Yakutsk–Vilyui plume in the Siberian craton are diamondiferous whilst those associated with the younger 250 Ma Siberian Traps plume are barren. We also show that the time required to restore the pre-plume thermal structure of the lithosphere is ca. 75–120 Myr, and that destroyed diamonds may regrow once the plume's thermal effect dissipates. The 1100 Ma Kyle Lake and adjacent 180–150 Ma Attawapiskat kimberlites in the southern Superior craton exemplify this, where the older kimberlites are associated with a narrower diamond window (<30 km) in comparison with the ca. 85 km diamond window of the younger Attawapiskat field.

1. Introduction

1.1. Kimberlite and mantle plumes

Kimberlites are CO_2 rich, alkaline ultramafic magmas that are rapidly transported through the lithosphere as dykes. They are emplaced explosively at the surface as volcanic diatreme pipes and represent Earth's principal source of diamonds. They are predominantly located in Archean cratons and the Paleoproterozoic mobile belts that surround them (Mitchell, 1995; Haggerty, 1999; Gurney et al., 2010; Chalapathi Rao and Lehmann, 2011). Reconstructed eruption sites for the majority of Phanerozoic kimberlites and Large Igneous Provinces (LIPs) lie above two Large Low Shear-wave Velocity Provinces (LLSVPs) that have been imaged by seismic tomography in the deep mantle beneath the African and Pacific regions (Torsvik et al., 2010; Davies et al., 2015a). Although the thermo-chemical structure of LLSVPs remains debated (see Davies et al., 2015b and Garnero et al., 2016, for discussion), it is generally agreed that they represent regions of anomalously hot mantle and, consequently, will spawn upwelling mantle plumes that rise towards Earth's surface and melt beneath the lithosphere (Campbell, 2001; Arndt, 2003).

A number of kimberlite clusters are spatially and temporally associated with mantle plume-generated LIPs (Ernst and Jowitt, 2013). Important examples include kimberlites associated with the 65 Ma Deccan (Chalapathi Rao and Lehmann, 2011), 290 Ma Tarim (Zhang et al., 2013), 90 Ma Madagascar (Ernst and Jowitt, 2013), and ca. 370 Ma Yakutsk–Vilyui LIPs (Kiselev et al., 2012). There are also kimberlites that exhibit a distinct age progression over large distances and, therefore, are thought to be associated with mantle plume tails (Heaman and Kjarsgaard, 2000; Heaman et al., 2004; Chu et al., 2013). However, other kimberlite fields (e.g. ca. 50 Myr kimberlites of the Slave craton) are not linked with any known plume heads or tails. Furthermore, the effect of multiple large-scale igneous events on cool and deep cratonic roots, the major source of diamonds within kimberlites (Gurney et al., 2010), remains unclear.

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1.2. Link between age and diamond window

Diamonds in kimberlites occur as xenocrysts that were extracted from the lithospheric root of ancient cratons. As a consequence, whether a kimberlite is diamondiferous or not is dependent on the thermal structure and composition of the subcontinental lithosphere. In order for a root to contain diamonds it must contain carbon, and the pressure must be high enough and the temperature low enough for this root to be in the diamond stability field (Gurney et al., 2005; Kerrich et al., 2005; Stachel and Luth, 2015). The deep cool roots needed for diamond stability are characteristic of ancient Archean cratons. As a consequence, ancient lithospheric roots are the key target areas for diamond exploration (Cliffford, 1966; Artemieva, 2011).

Helmstaedt and Gurney (1995) introduced the concept that processes can be either friendly or unfriendly to cratonic root diamond prospectivity, with unfriendly processes, such as the impingement of a mantle plume or the delamination of part of the lithospheric mantle root, raising the thermal gradient in the root and potentially destroying its diamonds. An excellent example of these “unfriendly” processes is the diamond-destroying effect of the 1270 Ma Mackenzie plume on the lithospheric root of the northern Slave craton, North America (Gurney et al., 2010; Helmstaedt and Gurney, 1995). Read et al. (2004) and Grütter (2009) provide further examples where the thermal disturbance (and/or erosion) of cratonic roots has affected the diamond potential post-dating kimberlite events.

There are also temporal variations in terms of the diamond potential of multiple generations of kimberlites within a single region or area. For example, the first pulse of spatially overlapping generations of kimberlites in an area is generally thought to be the most prospective for diamonds. One example of this is Gurney et al. (2010), who noted that ca. 200 to 110 Ma Mesozoic Group II kimberlites in the Kaapvaal craton are more consistently diamondiferous than later ca. 100 to 85 Ma megacryst-bearing Group I kimberlites. One further example is the highly diamondiferous 234 Ma kimberlite dykes of the Churchill kimberlite province, near Rankin Inlet, Nunavut, Canada, which are succeeded by weakly diamondiferous to barren 228 to 170 Ma kimberlite pipes (Gurney et al., 2010). Hypotheses that explain these temporal variations in diamond potential from higher for earlier events to lower for later events include: (i) the fact that kimberlite magmatism appears to be a mantle root-unfriendly event, suggesting that whatever triggered the kimberlite magmatism may have a deleterious effect on lithospheric root diamond potential (e.g. Gurney et al., 2010); (ii) later kimberlites may pass through the lithospheric roots of cratons that have had diamonds extracted by previous kimberlites (Gurney et al., 2010). However, in this case, the small size of individual kimberlites means that the early kimberlites would deplete only a small volume of the lithosphere, so this second effect is likely to be localized. (iii) Earlier kimberlite events are less likely to tap cratonic roots that have undergone delamination and the removal of diamondiferous lithosphere as part of the plate tectonic cycle, making these early kimberlites more likely to be diamondiferous than later kimberlites that pass through the same region (Helmstaedt and Gurney, 1995; Griffin et al., 1999, 2005); and (iv) a thermal pulse from a mantle plume can heat all, or part of, the overlying lithospheric cratonic root to a temperature that exceeds the threshold required for diamond stability (Helmstaedt and Gurney, 1995; Ernst and Jowitt, 2013).

The purpose of this study is to quantify the latter effect by modeling the thermal influence of a mantle plume head arriving beneath a thick lithospheric root and assessing its ability to destroy the diamond window within the overlying lithosphere. We also model the time taken for the lithosphere to cool to a temperature that allows the destroyed diamonds to recrystallize, following removal of the plume head. We apply our model to the Siberian and Superior cratons and generalize our conclusions so that they can be used to predict the likelihood of diamond destruction on other Archean cratons.

Table 1
Parameters relevant to transient geotherm calculations.

Parameter	Value	Unit
Continental crust thickness	35	km
Initial lithospheric thickness	150–200	km
Heat production rate: upper crust (17.5 km thick)	0.8×10^{-6}	$\mathrm{W\,m^{-3}}$
Heat production rate: lower crust (17.5 km thick)	0.2×10^{-6}	$\mathrm{W\,m^{-3}}$
Thermal diffusivity, κ	1.0×10^{-6}	$\mathrm{m^2\,s^{-1}}$
Density, ρ	3300	$\mathrm{kg\,m^{-3}}$
Specific heat capacity, C_p	1250	$\mathrm{J\,kg^{-1}\,°C^{-1}}$
Surface temperature, T_S	0	°C
Mantle temperature, T_M	1400	°C
Plume excess temperature, (ΔT_P)	100–300	°C

2. Methodology

2.1. Parameters of model

We calculate the thermal effect of a hot plume head of thickness 200 km arriving and flattening beneath a thick region of continental lithosphere. A range of lithospheric thicknesses from 150–200 km are examined, with plume excess temperatures ranging from 100 to 300 °C above ambient mantle, consistent with estimates from petrology (e.g. Herzberg and Gazel, 2009). The upward propagation of temperature from the plume head is modeled to access the lithospheric depth range over which temperature exceeds that of the diamond–graphite transition. The position and slope of the diamond–graphite transition in P–T space is taken from Day (2012).

2.2. Geotherm calculations

Time-dependent geotherms are derived by solving the following one-dimensional diffusion equation with a (radioactive) heat source term:

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2} + \frac{A}{\rho C_p}$$

Here, T is temperature, t is time, κ is thermal diffusivity, A is radiogenic heat production rate, ρ is density and C_p is heat capacity. For the results presented in Fig. 1, this equation is solved with constant temperature boundary conditions of T_S at the surface and T_M (initial conditions) or $T = T_M + T_P$ (following the arrival of a plume) at the base. We assume a depth-dependent distribution of radiogenic heat production within the 35 km thick continental crust, specified as 0.8×10^{-6} W/m^3 and 0.2×10^{-6} W/m^3 in the upper and lower 17.5 km of the continental crust, respectively (similar to estimates of the modern continental crust, Rudnick and Fountain, 1995) with negligible radiogenic heat production in the mantle. Key parameters are listed in Table 1, with calculations building on those presented in Campbell and Davies (2017) and performed using the Fluidity computational modeling framework (e.g. Davies et al., 2011; Kramer et al., 2012).

Calculations assume that the arrival and flattening of a plume head is instantaneous at a range of depths (160, 170, 180 or 190 km), and represents a step-wise increase in temperature at the base of the lithosphere. In reality, the plume head would have a temperature gradient across it. Furthermore, a rising plume would gradually thin the overlying lithosphere through small-scale convection (e.g. Moore et al., 1999; Burov and Gerya, 2014) and