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Detecting the extent of ca. 1.1 Ga Midcontinent Rift plume heating using U-Pb thermochronology of the lower crust

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ABSTRACT

The occurrence of mantle plumes in the geologic past is hypothesized to be marked by voluminous basaltic volcanism and topographic and gravitational anomalies. Missing from these identifying characteristics is a direct measurement of the elevated mantle temperatures associated with an upwelling channel from the deep mantle. To assess the extent of plume heating in the 1.1 Ga Midcontinent Rift System (North America), we present U-Pb thermochronologic evidence for a ca. 1.1 Ga sublithosphere heat source near Attawapiskat, Canada, >600 km from the inferred plume center. Apatite and rutile U-Pb cooling dates from middle to lower crustal xenoliths exhumed in the Jurassic Victor kimberlite record a thermal history >2.5 b.y. in duration. Shallow amphibolite and gabbro yield Archean to Paleoproterozoic dates with high U-Pb discordance, consistent with middle crust cooling prior to 1.1 Ga. Deeper garnet-bearing samples yield younger dates with low U-Pb discordance. Replicating these data with models reveals a thermal history in which the extent of heating corresponds with sample depth, an observation consistent with heating from below. Thermochronologic data are best fit by model simulations in which the Attawapiskat lithosphere experienced a ca. 1.1 Ga heating event triggered by partial lithosphere removal and mantle temperatures >200 °C in excess of that of ambient mantle, consistent with a model of ~100 m.y. plume head residence beneath the Attawapiskat region.

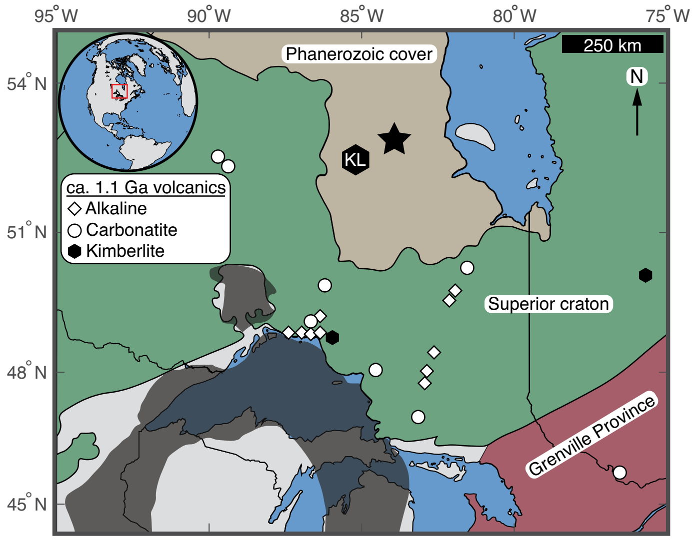

Figure 1. Map of Midcontinent Rift (shaded) and nearby volcanics dated within 100 m.y. of Midcontinent Rift volcanism (adapted from Heaman et al., 2004; Ernst and Bell, 2010; Smit et al., 2014b). Jurassic Attawapiskat kimberlite field (star) includes Victor kimberlite (52.82°N, 83.88°W), and Kyle Lake kimberlite field is labeled "KL."

INTRODUCTION

The Midcontinent Rift (MCR), or Keweenawan Rift, of North America is an ~2000-km-long failed continental rift structure centered at the southern extent of the Superior Province (Fig. 1). MCR flood basalts erupted over a span of 24 m.y. between 1108 and 1084 Ma (Davis and Green, 1997; Fairchild et al., 2017). Mantle plume heating has been invoked as the driver of the MCR and Keweenawan large igneous province for a variety of reasons. The large volume of igneous rock and isotopic signatures of MCR volcanics support an enriched mantle source (Nicholson and Shirey, 1990). Geophysical and geochemical models indicate elevated mantle potential temperatures of >1500 °C (Hutchinson et al., 1990). The coincidence of a radial drainage pattern and a negative gravitational anomaly centered about the Lake Superior Basin has been interpreted as the result of magmatic addition and underplating related to a mantle plume (Allen et al., 1992). Away from the inferred plume center, ca. 1.1 Ga alkali basalts and carbonatite eruptions are proposed to be small partial melts triggered by plume heating (Fig. 1; Ernst and Bell, 2010). Seismic tomography of the surrounding region combined with mantle xenolith geochemistry place the chemically depleted Archean chemical boundary layer to a contemporary depth of ~125 km, underlain by a thermal boundary layer consisting of conductively cooled, though less depleted and possibly younger, lithospheric mantle reaching ~200 km in depth (Yuan and Romanowicz, 2010). Such a mantle lithosphere structure is consistent with the regrowth of a thermal boundary layer following basal lithosphere erosion by a plume head.

The aforementioned lines of evidence support a plume heat source for MCR volcanism, yet the nature of the plume-lithosphere interaction is not well understood. Swanson-Hysell et al. (2014) reconciled plate velocities >20 cm/yr with 24 m.y. of MCR volcanism by invoking an upside-down drainage model (Sleep, 1997) whereby crustal thinning drives pooling and protracted residence of hot plume material beneath the Midcontinent Rift. We present evidence for heating of the basal lithosphere, a predicted hallmark of plume impingement, at ca. 1.1 Ga beneath the Attawapiskat region, 600 km north of the Midcontinent Rift.

Kimberlites in the Attawapiskat region of northern Ontario, Canada, contain crustal (amphibolite, gabbro, granulite) and mantle xenoliths that provide a glimpse into the ancient lithosphere conditions at this location

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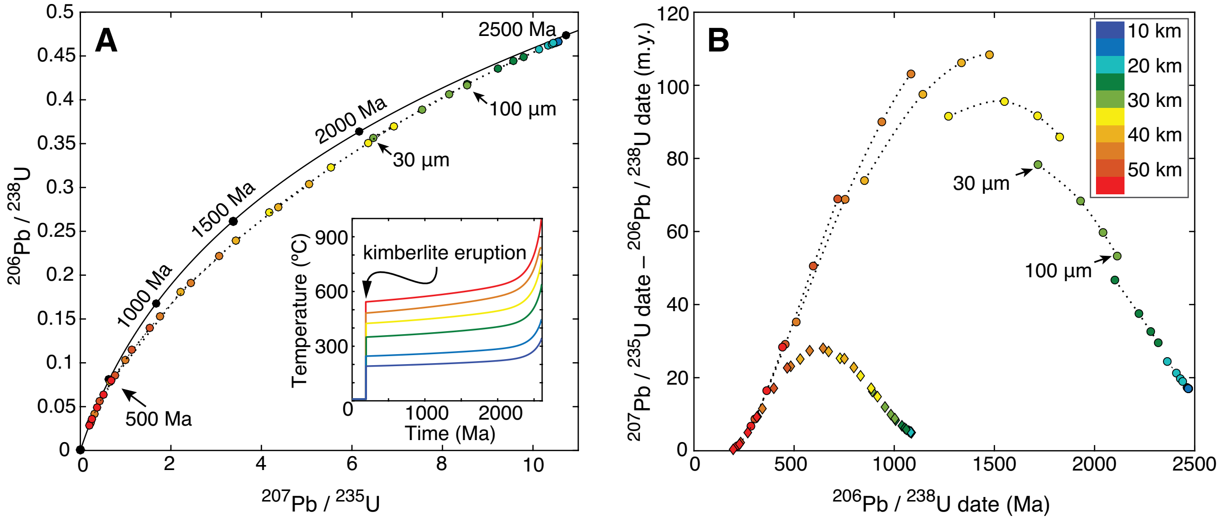

Figure 2. Model rutile U-Pb data for simulated time-temperature histories of unperturbed crustal column. A: Concordia plot presents results for thermal history of continuous cooling from 2500 Ma to a 170 Ma kimberlite eruption. Inset shows corresponding time-temperature histories. Colors denote crustal depth. Dotted curves represent interpolations among multiple crystal sizes, shown in microns, from each depth. B: Difference between $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ dates against $^{206}Pb/^{238}U$ date for model results of continuous cooling since 2.5 Ga (circles) and 1.1 Ga (diamonds).

(Fig. 1). The Kyle Lake kimberlites erupted coincidently with rifting (ca. 1075 Ma), while the Attawapiskat kimberlites, including the Victor kimberlite, are Jurassic in age (ca. 170 Ma; U-Pb perovskite; Heaman et al., 2004; Fig. 1). The thermal conditions of the Superior Province mantle lithosphere are recorded by the pressure and temperature conditions of silicate minerals and the nitrogen aggregation states of diamonds entrained within both kimberlite families. The observation that thermally mature diamonds exhumed in the Proterozoic were replaced by a less-heated diamond population in the Jurassic suggests that the region experienced a major regional heating event that raised the geothermal gradient of the entire lithosphere, exceeding the temperature of the diamond stability field, and then resumed cooling and diamond growth prior to Jurassic kimberlite eruption (Smit et al., 2014b), with diamond stability reestablished by ca. 720 Ma (Aulbach et al., 2017). These data, however, neither constrain the time scales of reheating more precisely than between ca. 720 and ca. 1100 Ma nor permit testing of possible sublithosphere heat sources.

Uranium-lead (U-Pb) thermochronometers record thermal histories between 400 and 800 °C due to the temperature-dependent diffusion of radiogenic Pb in U-bearing accessory phases like apatite and rutile. However, the production of radiogenic ^{206}Pb relative to ^{207}Pb varies with time as a result of the difference in the half-lives of ^{238}U and ^{235}U. The resulting Pb-isotopic evolution can be captured by U-Pb thermochronometers and is unique to the time scales of cooling. The effects of Pb production and loss on the U-Pb isotopic evolution of U-bearing accessory phases have been described with a lithosphere-scale thermal model coupled to a model that forward calculates U-Pb cooling dates for a tested thermal history (Blackburn et al., 2012). For a generalized crustal section beginning cooling at 2.5 Ga, model rutile U-Pb dates span from 2.5 Ga, recorded by the shallowest samples, to the time of kimberlite eruption, recorded by the deepest samples which were too hot to retain radiogenic Pb prior to cooling at the surface (Fig. 2A). Superimposed on this depth-age relationship is the length-scale effect of diffusion, whereby the age difference between large and small crystals inversely relates to cooling rate (Fig. 2). Middle to lower crustal samples may experience a long duration within a mineral's Pb partial retention zone (PRZ), resulting in U-Pb discordance that scales with the time and duration of PRZ residence (Blackburn et al., 2011, 2012). The degree of discordance may be characterized by plotting the difference between $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ dates (hereafter referred to as ΔU-Pb) against the more precise $^{206}Pb/^{238}U$ date (Fig. 2B). Two crustal sections that cool following initially high geothermal gradients at 1.1 Ga and 2.5 Ga yield thermochronologic U-Pb data that occupy distinct areas in ΔU-Pb versus $^{206}Pb/^{238}U$ date space due to the retention of Pb isotopic compositions produced at different time scales (Fig. 2B). In general, high ΔU-Pb values are a hallmark of ancient prolonged cooling histories.

We apply U-Pb thermochronology to xenoliths from the Victor kimberlite (North pipe) to assess the thermal history of the lower crust in the Attawapiskat region. We utilize the existing model framework to explore how forward-modeled U-Pb data respond to simulations of single end-member scenarios of basal lithosphere heating and thinning as well as scenarios that hybridize the end-member conditions. Comparing modeled and measured data, we show that Attawapiskat xenoliths record conductive heating from below, as predicted by a plume model, and thus map a minimum northward extent of heating associated with the MCR and suspected plume head. Notably these U-Pb thermochronologic data provide a direct measurement of plume heating without relying on mantle chemical models. Such a measurement has hitherto been lacking and that lack has consequently been utilized by detractors of the plume hypothesis (e.g., Anderson and Natland, 2005).

METHODS AND RESULTS

Measured Thermochronologic Data

Crustal xenoliths of various lithologies from the Victor North kimberlite (Fig. 1) were selected in order to examine material from a range of possible depths. The xenoliths studied here exhibit lithologies corresponding to depths between 20 and 50 km for a generalized crustal section, where garnet may be used as a mineral stratigraphic marker associated with depths >30 km (Jagoutz and Schmidt, 2012). Measurements of single- and multi-crystal rutile and apatite U-Pb isotope dilution–thermal ionization mass spectrometry (ID-TIMS) dates were conducted following the methods summarized in Appendix DR1 of the GSA Data Repository[1].

[1]GSA Data Repository item 2018333, expanded laboratory, numerical, and statistical methodologies, and results of model sensitivity tests, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

Rutile and apatite U-Pb data for nine Victor xenoliths of a range of lithologies are presented in Figure 3. Combined rutile and apatite U-Pb data in ΔU-Pb space reveal a bifurcated topology spanning intercepts (ΔU-Pb = 0 m.y.) of >2500 Ma and 160 Ma. Rutile from four of five garnet-bearing samples (likely from depths >30 km) exhibit $^{206}Pb/^{238}U$ dates from ca. 160 to ca. 1100 Ma and relatively low degrees of discordance (ΔU-Pb < 20 m.y.) for higher-precision (high radiogenic Pb) measurements. Rutile from gabbros and biotite-bearing granulites reveal older cooling dates (1150–1350 Ma) and values of ΔU-Pb >75 m.y. Apatite analyses from non–garnet-bearing amphibolite and gabbro xenoliths (likely from depths <30 km) exhibit $^{206}Pb/^{238}U$ ages ranging from ca. 1270 to 2500 Ma with an arcing array of ΔU-Pb values.

Modeled Thermochronologic Data

Numerical models predict how U-Pb thermochronometers in a crustal column respond to 1.1 Ga heating (Fig. 4). The unperturbed history (black curve in Fig. 4) is characterized by a single arc through ΔU-Pb space. An increasingly pronounced bifurcated topology develops with heating intensity and associated Pb loss. Shallow samples yield older dates and high ΔU-Pb values, the latter of which correlate with reheating intensity (peaks to the right, Fig. 4). Deeper samples are fully reset and contain little to no Pb produced prior to 1.1 Ga, resulting in ΔU-Pb curves that are nearly identical to the data predicted for unperturbed cooling beginning at 1.1 Ga (Figs. 2B, 4). Numerical modeling methods and sensitivity tests are available in Appendices DR2 and DR3.

DATA INTERPRETATION AND CONCLUSIONS

The topology of measured U-Pb thermochronologic data for rutile and apatite from Victor kimberlite xenoliths preclude a history of continuous cooling (Fig. 3). Rather, the bifurcated topology describes a history of cooling and reheating, most consistent with a scenario of cooling beginning prior to 2500 Ma, a 1100 Ma reheating event characterized by a substantial increase in the geothermal gradient (>50 mW/m^2; Fig. 4), and the ≥160 Ma eruption of the Victor kimberlite. This sequence agrees with models of Superior Province amalgamation (e.g., Langford and Morin, 1976), the timing of MCR magmatism (Davis and Green, 1997), and ca. 170 Ma Attawapiskat kimberlite eruptions (Heaman et al., 2004).

Local magmatism at sub- or intracrustal depths does not offer a compelling explanation for the heating experienced by the Victor xenoliths. Despite widespread magmatism occurring 600 km to the south in the Midcontinent Rift, there is no evidence for Mesoproterozoic magmatism of significant magnitude or duration occurring in the Attawapiskat region related to the rift (Fig. 1) nor Grenvillian convergence (e.g., Rivers, 1997). Simulations of crustal igneous sources of variable size and temperature require intrusion sizes >25 km and temperatures >1200 °C to reproduce measured data (Appendix DR4). Although the scenario cannot be ruled out absolutely, the presence of a >25-km-thick intrusion beneath the Attawapiskat region is contradicted by independent geologic and geophysical evidence: zircon U-Pb dates from Victor xenoliths limit crustal igneous activity to before 2.2 Ga (Landis, 2016), Pb compositions of sample 14-VK-02 support an Archean origin for this deepest-residing xenolith (Appendix DR1), and combined seismic and gravity data limit the extent of significant magmatic underplating to within <100 km of the MCR center (Hutchinson et al., 1990). The only contemporaneous magmatism in the Attawapiskat region is the Kyle Lake kimberlites (Fig. 1; Heaman et al., 2004), yet kimberlites are associated with crustal transit times that, even at mantle temperatures (1400 °C), are predicted to remove negligible Pb (<0.1%) from rutile or apatite (Blackburn et al., 2011).

The lower crustal thermochronologic results require a significant heat source: at a maximum lower crustal temperature of 1100 °C (solidus), a 250 k.y. holding time is required to match data trends. Yet, the presence of thermally immature diamonds in Jurassic kimberlites indicates that the entirety of the Attawapiskat lithosphere, not just the crust, was heated (Smit et al., 2014b). Further, the measured data suggest a correlation between sample depth and degree of reheating, whereby deeper-residing samples of higher metamorphic grade exhibit younger dates, reflecting more pronounced resetting of the Pb isotopic system. The correlation is consistent with a scenario of long-term heating from below, through intact lithosphere mapped by mantle xenolith pressure-temperature data to a depth of 180 km at ca. 1.1 Ga (Smit et al., 2014a).

Possible end-member sublithosphere heat sources include (1) increased asthenosphere temperature or (2) removal of mantle lithosphere and replacement by asthenosphere at ambient mantle temperatures (1400 °C). Our numerical thermal model simulates both end members and their hybridized conditions for a 100 m.y. heating event starting at 1135 Ma.

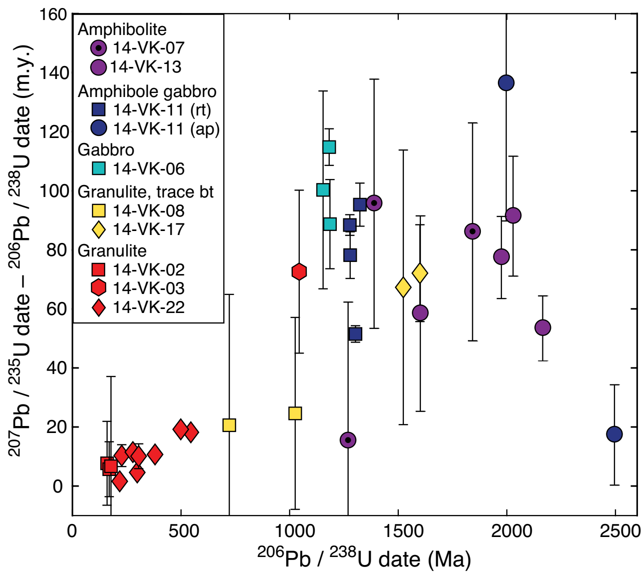

Figure 3. Measured U-Pb data plotted as difference between $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ dates versus $^{206}Pb/^{238}U$ date (±2σ) for single- and multi-grain rutile (rt; polygons) and apatite (ap; circles) fractions from Victor kimberlite xenoliths (North America). bt—biotite.

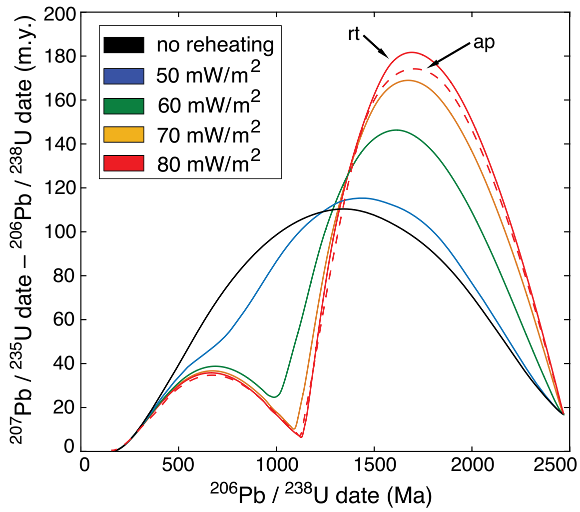

Figure 4. Model rutile (rt) and apatite (ap) U-Pb data plotted as difference between $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ dates versus $^{206}Pb/^{238}U$ date from simulated time-temperature histories of cooling since 2.5 Ga and reheating at 1.1 Ga for a single grain size (50 µm radius) at closely spaced depths. Reheating is accomplished by raising geotherm to designated surface flux (color) and holding for 10 m.y.

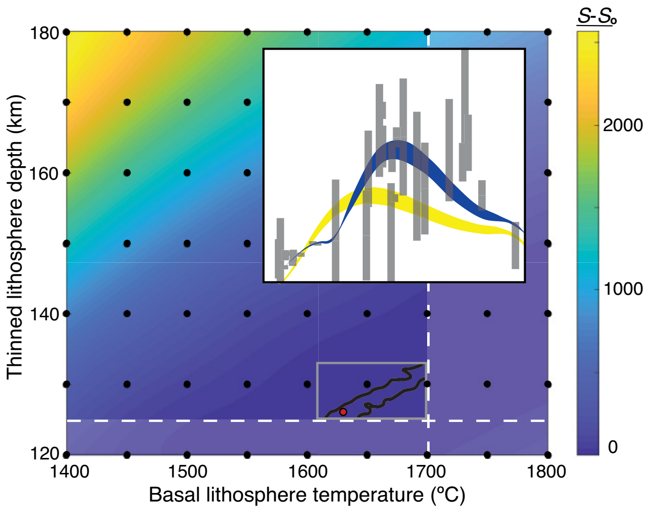

Figure 5. Results of Pearson chi-squared (χ^2) tests comparing measured and modeled data for range of simulated conditions of lithosphere thinning depth and basal temperature. Colored contour values are calculated from simulated model conditions (black dots) and represent difference between sum of χ^2 values for given model condition (*S*) and the minimum χ^2 summation (S_o, red circle). Black contours demarcate conditions producing *S* values within 1σ of S_o from higher-resolution suite of simulations (bounded by gray box). Dashed white lines indicate permissible minimum depth and maximum temperature. Inset shows measured U-Pb data (gray) with model rutile U-Pb data ranges (25–150 μm grain radii) for the best-fit model (blue) and unperturbed condition (1400 °C, 180 km; yellow). Inset axes are the same as those in Figure 3.

Similar results are found for heating onsets between 1000 and 1200 Ma, while heating events beyond this time frame yield poor agreement between measured and model data (Appendix DR3). Model U-Pb results for each scenario compared to measured data with a Pearson χ^2 test are presented in Figure 5 as the deviation from the best-fit scenario. Simulations of lithosphere thinning with no increase in mantle temperature require removal to <125 km depths to reproduce measured data. This scenario conflicts with depleted compositions and Re-Os dates of mantle xenoliths that place Archean lithosphere to depths of at least 125 km through the Jurassic (Smit et al., 2014a). A model of only mantle reheating with intact lithosphere to 180 km requires basal temperatures ≥600 °C in excess of that of the ambient mantle, vastly exceeding projected temperatures for plumes sourced from the core-mantle boundary (e.g., Albers and Christensen, 1996). The black contours in Figure 5 identify a suite of hybrid model conditions that best replicate the measured U-Pb data within the known lithosphere architecture. The conditions are characterized by mantle temperatures >1600 °C and lithosphere removal to depths <135 km. Collectively, the model and measured data evidence that the Superior Province crust was heated at 1.1 Ga, triggered by partial lithosphere removal and mantle temperatures >200 °C in excess of that of ambient mantle. Such a heating history is consistent with a spatially extensive plume head extending at least as far north as the Attawapiskat region and residing on time scales of ~100 m.y. Plume impingement was accompanied by widespread shallowing of the lithosphere thermal boundary layer beneath the Superior Province (Yuan and Romanowicz, 2010) that rethickened by conductive cooling to ~200 km at the time of Victor kimberlite eruption in the Jurassic (Smit et al., 2014b).

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