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Kimberlite apatite (U-Th)/He thermochronology of the Canadian Arctic: what fraction of kimberlites were eroded?

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Motivation

It is increasingly recognized that cratonic regions such as the Canadian Shield have undergone burial and erosion episodes for which little sedimentary evidence remains. However, the influences of far-field tectonics, heterogeneous lithospheric architecture, and deep mantle-processes on the magnitudes, timescales, and spatial extents of burial and erosion remain elusive. The Canadian Arctic offers an excellent opportunity to examine these questions because it is underlain by the Archean Slave and Rae cratonic nuclei along with Proterozoic cratonic lithosphere that is heterogeneous in age, thickness, thermal structure, and composition. While the cratons themselves were not significantly modified during the Phanerozoic, the surrounding regions have all undergone a far more complex Phanerozoic history— including at least three major orogenic events, several episodes of rifting, and at least one large igneous province magmatic event. In addition, this region has experienced several hundred kimberlite eruptions throughout the late Neoproterozoic-Phanerozoic (<625 Ma), presenting a unique opportunity to evaluate the relationship between surface uplift and kimberlite magmatism.

Here, we use low-temperature apatite (U-Th)/He thermochronology (AHe) on kimberlites to investigate the Phanerozoic burial and erosion history of the Canadian Arctic. AHe thermochronology is used to explore a wide variety of surface processes that occur in the uppermost ~4 km of the crust. AHe is based on the radioactive decay of U, Th, and Sm to ^{4}He. The retention of ^{4}He in the apatite crystal lattice is temperature dependent. At temperatures above ~90°C, He diffuses out of the apatite crystal lattice, between 90-30°C He is partially retained, and below 30°C He is fully retained in the apatite (Figure 1). Unlike a U-Pb date, an AHe "date" is not always indicative of an "event" since the amount of He retained in the crystal lattice is a function of the entire history of burial and erosion experienced by that crystal. Therefore, if an AHe date is younger than the known emplacement age of the kimberlite, then that kimberlitic apatite has experienced some He loss, due to either burial and subsequent erosion, or emplacement at depth and erosion to present-day exposure levels. If AHe dates overlap with the emplacement age of the kimberlite, this indicates no He loss from the apatite and thus no significant heating due to burial (to temperatures >30 °C) and no substantial cooling due to erosion (from temperatures >30 °C) since the emplacement of the kimberlite. AHe thermochronology is therefore an ideal tool for studying the magnitudes, timescales, and spatial extents of burial and erosion.

Kimberlites are a unique target for AHe thermochronology because they record information about both the deep lithosphere and the surface history, which allows us to directly tie the surface history to the lithospheric architecture and history of kimberlite magmatism. Hence, we are targeting kimberlites for three main reasons: 1) they contain direct information about the lithospheric architecture at the time of eruption owing to the mantle xenolith suites that they contain, 2) they record information about the surface history from their crustal (sedimentary-dominated) xenolith suites, and 3) AHe dating of kimberlites facilitates a "higher resolution" look at the post-emplacement thermal history associated with burial and erosion events.

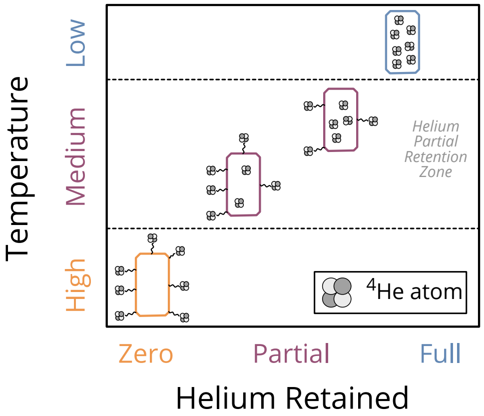

Figure 1. A schematic representation of apatite (U-Th)/He thermochronology. At high temperatures, helium diffuses fully out of the crystal. As the crystal cools, helium begins to be partially retained in the crystal, and at cooler temperatures is fully retained in the crystal. Modified after Flowers et al., 2022.

Mantle xenoliths contained in kimberlites provide direct constraints on the thickness, composition, and thermal structure of the lithosphere at the time of eruption. Mantle xenolith studies across the Slave craton and farther north suggest a general trend of lithosphere that is thinner northward, from SE Slave (>220-250 km) towards Victoria Island (~200 km), and up through Somerset Island (~165 km) (Kopylova and Caro, 2004; Liu et al., 2018; Mather et al., 2011).

Sedimentary xenoliths entrained in kimberlites and preserved in the Western Canadian Sedimentary Basin indicate a protracted history of sedimentation and erosion throughout the Phanerozoic. Widespread Paleozoic burial across the shield is documented by an outlier of Ordovician limestone in the Thelon Basin (Rae craton) and early-middle Paleozoic carbonate and marine xenoliths found in Paleozoic-Jurassic kimberlites across the Slave craton (e.g., Cookenboo et al., 1998). Later sedimentation is evidenced by Cretaceous and Eocene terrestrial and marine sediments found in the kimberlites of the Lac de Gras region.

Results

We have targeted a suite of kimberlites for AHe dating from the Lac de Gras and Coronation Gulf areas across the central and northern Slave craton, as well as from Parry Peninsula, Victoria Island, and Somerset Island in the surrounding areas of Paleoproterozoic lithosphere and northernmost Rae craton (Figure 2). These regions are underlain by cratonic lithosphere of variable age, thickness, and composition. The Slave craton retains no preserved Phanerozoic sedimentary cover, but our other study areas all preserve variable amounts of Paleozoic-Mesozoic sedimentary rocks.

Despite northern Canadian kimberlites having much lower phosphorous, and therefore lower apatite contents than kimberlites typical of the Kaapvaal craton, we acquired AHe data for several kimberlite clusters of varying emplacement age in the Slave craton. Kimberlites from the Coronation Gulf region — the Thrift (534.2 ± 2.8 Ma), Hydra (601.6 ± 18.8 Ma), and Anuri (613.0 ± 6 Ma) pipes—all have post-eruption AHe dates, indicating some amount of post-emplacement burial and erosion. In the central Slave craton, the Eddie kimberlite (321 ± 3 Ma) also yields AHe dates younger than emplacement, in contrast to the younger Roger (58.7 ± 5.4 Ma) kimberlite that has an AHe date that overlaps with emplacement, suggesting no significant burial or erosion since the Eocene. The Jericho (173.1 ± 1.3 Ma) and Muskox (172.1 ± 2.4 Ma) kimberlites of the northwest Slave craton also have AHe dates that overlap with emplacement, indicating no significant burial or erosion since the middle Jurassic.

Parry Peninsula and Victoria Island, to the west and north of the Slave craton, respectively, are underlain by a diamondiferous Paleoproterozoic mantle root and both maintain sedimentary cover of the Interior

Platform (Liu et al., 2018). The Darnley Bay kimberlite (~275 Ma) in the Parry Peninsula region, as well as the Snowy Owl kimberlite (271.2 ± 2.6 Ma) on Victoria Island ~550 km east of Darnley Bay, both yield post-emplacement AHe dates, indicating some degree of post-eruption burial and/or erosion in these areas.

On Somerset Island (Rae craton), ~1000 km northeast of Coronation Gulf, the Jos (97.5 ± 1.4 Ma) and Tunraq (97.1 ± 1.1 Ma) kimberlites both have AHe dates that overlap with emplacement. These results indicate no substantial burial or erosion since the mid-Cretaceous.

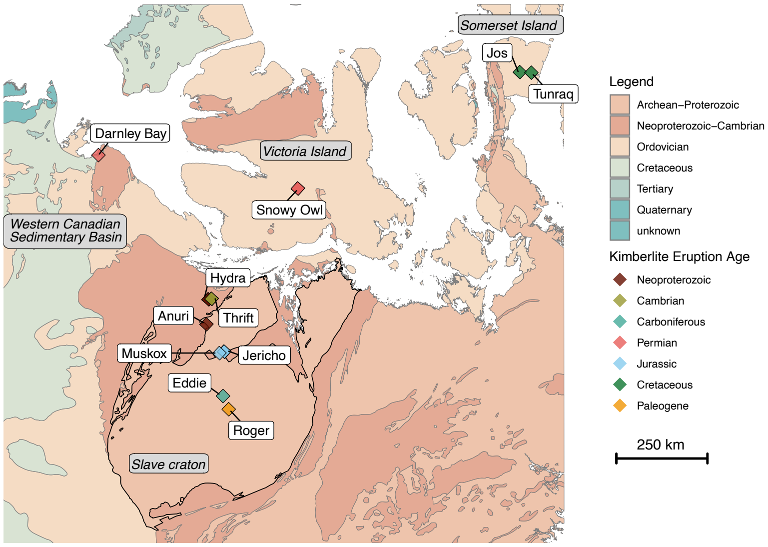

Figure 2. Map of kimberlite sample locations for which apatite (U-Th)/He data were acquired.

In order to scrutinize the degree to which preservation bias impacts the kimberlite record, the true vertical extents of kimberlite pipes must be considered. Current estimates for the depth of the tapering portions kimberlite pipes range between 1 and 3 km based on extrapolation of drill core logs and exposures of kimberlite dikes and sills. AHe thermochronology offers a means of constraining the magnitudes of burial and erosion of exposed basement, such as in the Slave craton where no Phanerozoic sedimentary cover is preserved, but where diamondiferous kimberlites emplaced into a > 3 km thick package of sediments might have been subsequently denuded. Such information may help locate yet-undiscovered detrital diamond deposits.

In addition to the issues of vertical extent and preservation bias, we can use our dataset to explore a variety of questions relating to the influence of the heterogenous lithospheric architecture on the burial and erosion history, the likely tectonic or geodynamic causes of burial and erosion, and the surface expressions of kimberlite magmatism.

References

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