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A new laboratory method to assess post-depositional heating in sedimentary basins

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Summary

Apatite (U-Th-Sm)/He (AHe) analysis is a low-temperature thermochronometer that records cooling through the 50–80°C temperature window (Wolf et al., 1998). AHe analysis has been recognized as a novel method in petroleum exploration as it provides the magnitude of paleotemperature and timing of maximum heating and subsequent cooling in sedimentary basins (Peyton & Carrapa, 2013; Schneider & Issler, 2019). However, the system is not widely used because conventional AHe analysis uses the whole-grain technique that has strict grain requirements for size, shape, and purity, and is costly and time-consuming. This limits the use of AHe dating to study sedimentary rocks, where tens to hundreds of grains need to be analyzed per sample.

The extraction of helium from apatite by laser-ablation (LA-AHe) offers a solution to these limitations (Horne et al., 2016; Pickering et al., 2020). It uses mounted and polished apatite grains, and only a small portion in the core of the grain is analyzed. This innovative technology opens the door to analyze large numbers of grains per sample at high cost and time efficiency – which is particularly powerful for analyzing basin strata. It also minimizes sampling bias caused by the strict selection criteria of the whole-grain method. Besides attaining an AHe age, geochemical characterization and the U-Pb age can also be acquired from the same grain. Thus, the LA-AHe method not only increases sample throughput but also allows multi-method analysis on individual grains to obtain geologically important information about sediment provenance and basin evolution.

We predicted that LA-AHe data are well-suited to determine if a detrital sample has been thermally reset, partially reset or not reset: an apatite is termed reset if it has lost all its radiogenic helium by thermal diffusion (>80°C), partially reset if only part of the helium was lost within the temperature sensitivity window (50–80°C), and unreset if it effectively retained all helium below ca. 50°C. This evaluation is crucial for estimating the maximum and minimum burial temperatures, but often impossible to achieve with whole-grain AHe data from only ~10 grains per sample. The development of the LA-AHe method thus has practical implications for both scientific research and resource exploration (e.g., Peyton & Carrapa, 2013; Schneider & Issler, 2019).

To test this method, we carried out LA-AHe dating on five Cretaceous to Paleocene sandstones from the deformed and undeformed sections of the Alberta Foreland Basin. These samples experienced different degrees of post-depositional burial and heating between 40 and 200°C, established by conventional apatite and zircon (U-Th)/He (ZHe) dating and apatite fission-track (AFT) analysis.

We analyzed 126 grains per sample in the same time span as the conventional method analyzes ~22 grains. This large dataset allowed for statistical analysis. In addition, we characterized the mineral trace chemistry and measured the U-Pb ages. We used this additional

information for provenance analysis and in identifying the influence of hydrothermal fluid flow, which can play a critical role in basin heating.

Method / Workflow

Our workflow builds on the novel LA-AHe dating procedure that was developed at the Geo- and Thermochronology Lab at the University of Calgary (Pickering et al., 2020). For this approach, we first separated apatite grains from 3-5 kg sandstone samples using standard mineral separation techniques including jaw crusher, disk mill, water table, magnetic and heavy liquid separation. The grains were mounted in Teflon and polished to about 20 µm depth.

We loaded the sample mount into an ultra-high vacuum cell along with AHe age reference materials. A RESOchron™ 193nm excimer laser-ablation system was used for helium extraction at ~10^{-7} Torr. We transferred the extracted gas sample into an Alphachron noble gas mass spectrometer and determined the ^{4}He content. After helium analysis, the ablation-pit volume was measured using a ZeScope optical interferometer. We then re-ablated the apatite with the same laser-ablation system and measured the concentration of U, Th, Sm, Pb, REEs, and other trace elements using an Agilent 7700 quadrupole mass spectrometer. The data output was then reduced using Iolite version 2.5. From the final results, we calculated the AHe and U-Pb ages. These were then filtered manually, excluding data with high uncertainty (>30% for AHe age and >25% for U-Pb age).

Results, Observations, Conclusions

We dated a total of 405 and 415 for LA-AHe and U-Pb age, respectively. Our data show different degrees of resetting, determined from the ratio of grains that pre- and post-date deposition. It shows a generally decreasing degree of resetting upsection. All but one grain in the stratigraphically lowest sample in our dataset, the Albian Beaver Mines Formation are younger than deposition and indicate full reset (Fig. 1). This agrees with existing data obtained from whole-grain AHe analysis. Independent confirmation comes from zircon (U-Th)/He (ZHe) data, indicating that the formation likely experienced temperatures exceeding 130–200°C prior to Eocene cooling (Fig.1). In contrast, only 44% of grains from the stratigraphic uppermost sample, the Paleocene upper Paskapoo Formation, are younger than deposition. This indicates partially reset that did not lose all pre-depositional helium (Fig.1). Previous whole-grain ages AHe suggest full reset of the sample, likely due to the limited number of grain analyzed and grain-selection bias. We infer from the LA-AHe data that post-depositional temperature of the upper Paskapoo Formation was relatively low, somewhere within the temperature sensitivity window of the AHe system (50–80°C) or cooler.

We used the apatite geochemistry and U-Pb ages to determine the sediment provenance and to test if hydrothermal heating affected the formation. All samples have at least one major U-Pb age mode centered at ~100–125 Ma. In addition, the samples from the Paleogene lower Paskapoo and Albian Beaver Mines formation show an older age mode centered at ~200 and Campanian lower Brazeau Formation shows a second age mode at ~150 Ma (Fig. 1). The younger age mode indicates a shared source provenance between all the samples, while older age modes point to evolving sediment routing system or source exposure and erosion.

We used the geochemical data for source lithotype identification using the classification scheme of O'Sullivan et al. (2020). The majority of apatite in all samples were sourced from mafic or I-type felsic igneous rocks or derived sediments, followed by high-grade, and low- to medium-grade metamorphic rocks. Combined with the U-Pb ages, we identified five major potential sources. These sources are distinct from each other from a combination of U-Pb ages (older

versus younger ages), lithotypes (mafic and I-type felsic versus metamorphic), Th/U content, and Cl content (high versus low).

In summary, the LA-AHe method provided a major improvement compared to the conventional AHe method. Hundreds of grains can be analyzed for multiple analysis on the same grains. This high-n approach captures the full age distributions, which can be used to evaluate the degree of thermal resetting post-deposition and to identify sediment source regions. The thermochronological data can then be used to approximate the temperature and potentially the timing of cooling of the formation.

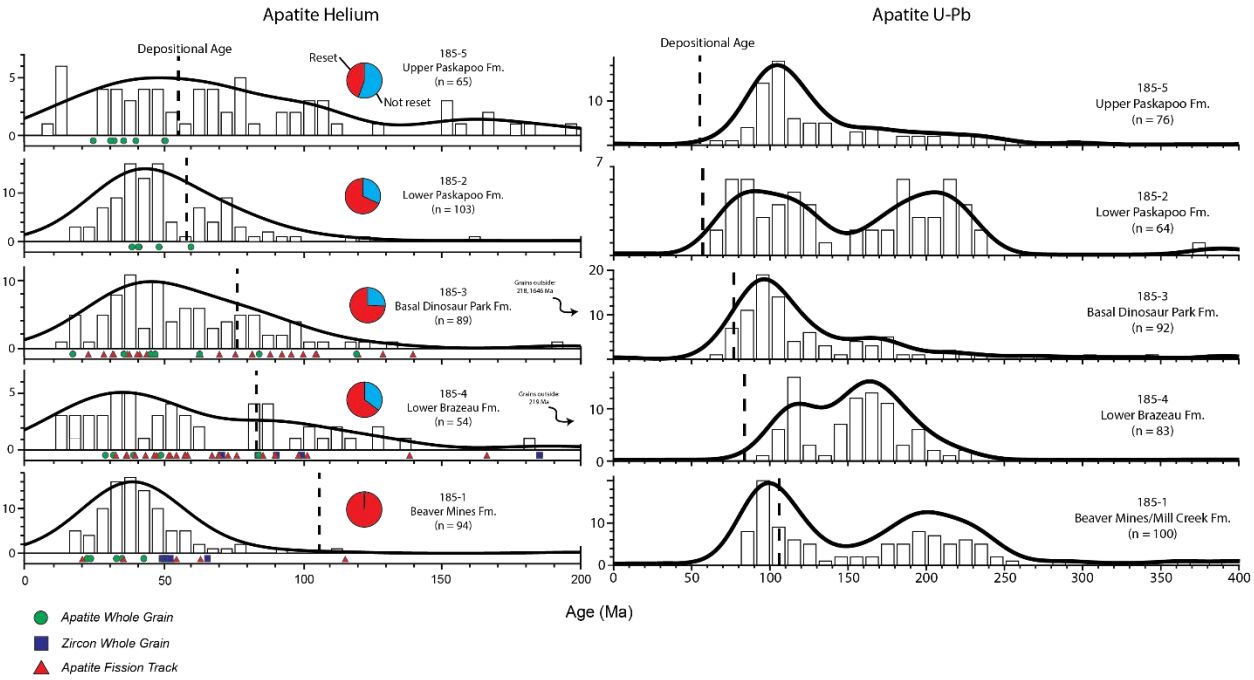


Figure 1: Kernel density estimates (KDE) for apatite (U-Th-Sm)/He (AHe) and U-Pb ages. Different symbols under the AHe KDE represent single grain ages obtained from different thermochronological methods.

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