Preliminary characterization of the Mesozoic–Cenozoic exhumation history of Hall Peninsula, Baffin Island, Nunavut, based on apatite and zircon (U-Th)/He thermochronology

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Abstract

The thermochronometric data from the southeastern half of Hall Peninsula will provide a means of establishing the spatial and temporal patterns of rock cooling as the rocks were brought to the surface through tectonic and erosional processes. The ^{4}He concentrations in apatite (n = 130) and zircon (n = 35) grains from 26 samples reveal a strong sensitivity to radiation damage, which suggests a record of slow exhumation. After adjusting the He ages for the effects of radiation damage, two models will be used to interpret the cooling history. A widely used thermal modelling program used to simulate potential time-temperature (t-T) paths for various thermochronometers (HeFTy) will provide a means of establishing constraints for the cooling history of each sample. A three-dimensional thermokinematic finite-element modelling code (Pecube) will also be used to determine the t-T history of the rocks on Hall Peninsula, and test how regional tectonism and long-term climate changes were responsible for spatial and temporal variations in the cooling rates.

Résumé

Les données thermochronométriques recueillies dans la moitié sud-est de la péninsule Hall serviront à établir les profils spatiaux et temporels du refroidissement des roches, à mesure que ces dernières ont été entraînées vers la surface par les processus associés à la tectonique et à l'érosion. Les concentrations en ^{4}He dans les grains d'apatite (n = 130) et de zircon (n = 35) provenant de 26 échantillons accusent une forte sensibilité aux effets du rayonnement, phénomène qui semble indiquer que l'exhumation s'est faite sur une longue période de temps. Après avoir ajusté les âges du He pour compenser les effets du rayonnement, on aura recours à deux modèles afin d'interpréter le parcours des conditions de refroidissement des roches. Un logiciel de modélisation thermique à utilisation fort répandue (HeFTy), qui simule les trajets temps-température (t-T) possibles pour divers thermochronomètres, servira à préciser les contraintes propres aux conditions de refroidissement de chaque échantillon. En outre, un code de modélisation thermocinétique par éléments finis en trois dimensions (Pecube) servira à établir le parcours t-T des roches de la péninsule Hall et à vérifier à quel point les variations dans l'espace et le temps au niveau des vitesses de refroidissement sont imputables aux incidences du tectonisme à l'échelle régionale et aux changements climatiques à long terme.

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Introduction

The cooling rate (temperature vs. time) of rocks during their ascent to the surface is a useful indication of the processes that have controlled regional topography and sediment flux to the nearby ocean. The cooling history can be obtained by using any of more than a dozen thermochronometers, depending on the rock depth (temperature) of interest, duration and rate of the process, and mineralogy available. Using multiple thermochronometers with different closure temperatures (temperatures at which the chronometer begins) in a single rock sample provides a means of establishing the change in the cooling rate with time (cooling history). Furthermore, by collecting multiple samples in space (i.e., bottoms of valleys, tops of mountains, across a fault zone), it is possible to link the cooling history to process and thereby test hypotheses regarding the timing and extent of rock and surface uplift, incision and changes in the onshore sediment flux.

The low-temperature thermochronology samples for this study were collected during the 2012 Hall Peninsula field season (Figure 1). In total, 26 samples were selected for apatite (U-Th)/He (AHe) analysis; additionally, 7 of these samples were also analyzed for zircon (U-Th)/He (ZHe). Sample preparation was completed at the Dalhousie Geochronology Centre and the samples were analyzed at the (U-Th)/He Geo-and-Thermochronometry Lab, University of Texas, Austin (see Creason et al., 2013 for detailed descriptions of the sample lithology, sampling strategy and laboratory procedures for (U-Th)/He thermochronology). The (U-Th)/He thermochronology method is based on the

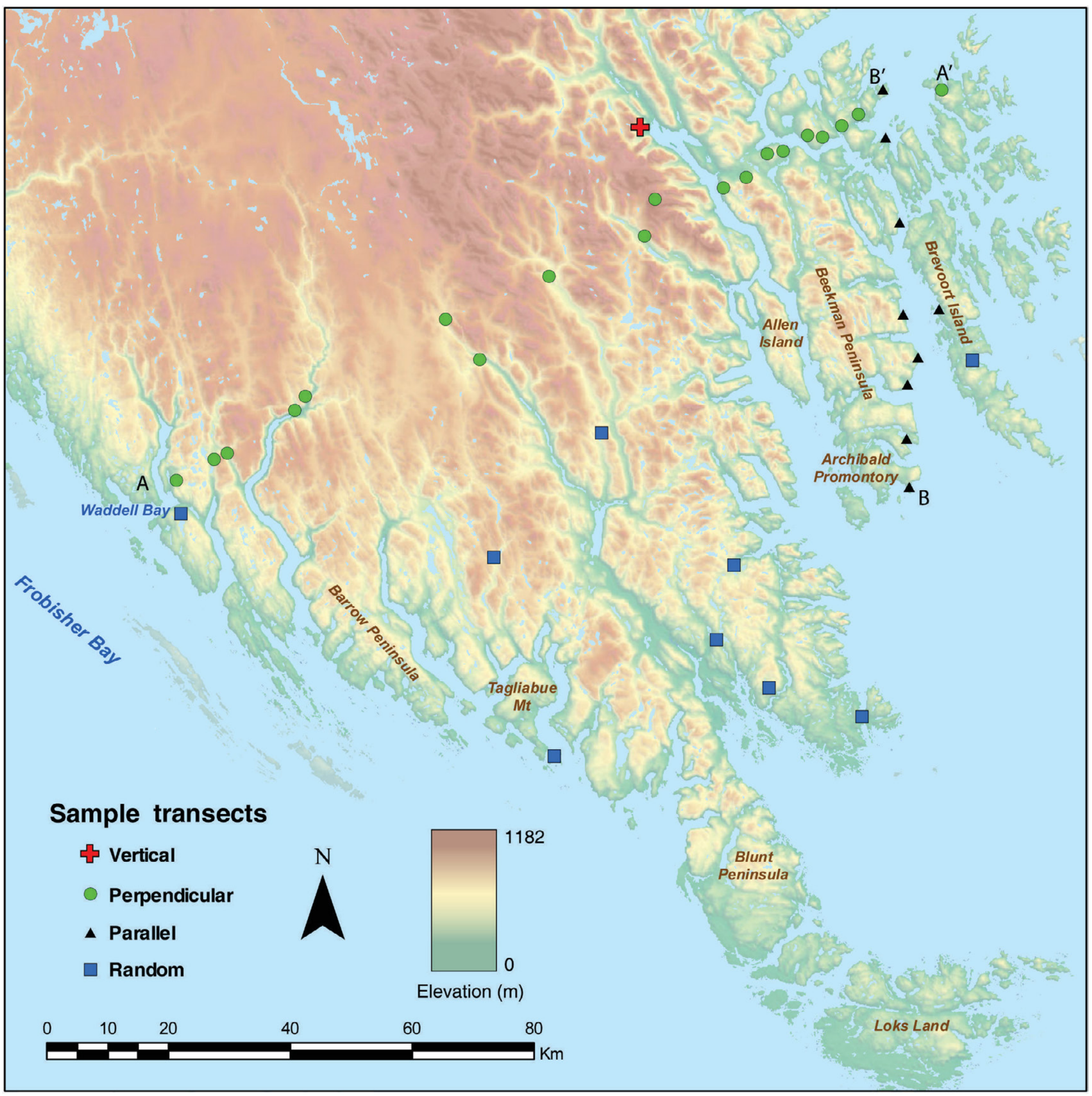

Figure 1: Locations of (U-Th)/He samples collected during the 2012 field season on Hall Peninsula, Baffin Island, Nunavut. Samples were collected from three transects: one vertical transect (capturing the maximum amount of relief) and two constant-elevation transects (one oriented perpendicular to the Cumberland Sound coastline, the other parallel). Additional samples were collected to serve as constraints for Pecube models. Figure from Creason et al. (2013).

diffusion of radiogenic ^{4}He (α-particles) from a grain until its temperature cools to a point at which ^{4}He diffusion is effectively halted (the grain is closed with respect to ^{4}He) and the abundance of ^{4}He within the grain increases proportionally with time since closure.

Preliminary results suggest that the rocks on Hall Peninsula have experienced a history of protracted slow cooling (Figure 2), exposing the samples to a high dose of radiation during their exhumation. Actinide radionuclide decay will cause damage to a crystal lattice. The radiation damage alters the diffusion of ^{4}He, necessitating a correction to the measured He ages, as they no longer conform to the standard He-diffusion kinetics (Shuster et al., 2006; Flowers et al., 2009). This paper focuses on the effect of radiation damage on He diffusion in the AHe thermochronometer and outlines the procedure for interpreting the AHe data. See Goldsmith et al. (2014) for a detailed discussion on the effects of radiation damage in ZHe thermochronometry and the means by which a radiation-damage correction will be applied to the ZHe thermochronology data from Hall Peninsula.

The paper summarizes progress on evaluating the applicability of corrections for existing radiation damage and devising a new correction for grains with high actinide concentrations. It briefly describes two different modelling programs, HeFTy and Pecube, that will be utilized to characterize the subsurface thermal history of Hall Peninsula using the radiation-damaged ^{4}He data. The program HeFTy will be used to develop a time-temperature (t-T) path for each sample. Outputs from the HeFTy models will allow comparison of the corrected results with synthetic data from other low-temperature thermochronometers, such as apatite fission track, and justify the need for further analyses with different thermochronometers to validate the corrected He ages. The program Pecube will be used to derive an exhumation history of Hall Peninsula based on the thermochronometry data and results from HeFTy models, and test a hypothesis that north-south extension preceded the more recent east-west transtensional extension between Baffin and Greenland.

AHe thermochronometry and radiation damage

The (U-Th)/He thermochronology method is based on the thermally controlled retention of radiogenic α-particles (^{4}He) within a mineral (Farley, 2002). This method relies on the understanding that certain minerals only accumulate ^{4}He when they are cooled below a specific temperature, known as their closure temperature (T_c). At temperatures above T_c, secular equilibrium is achieved, whereby the α-particles diffuse through the grain at the same rate they are produced (Farley, 2002). Closure temperature varies with mineral type (e.g., zircon, apatite, magnetite), enabling investigation of many geological processes that affect geothermal fields spanning various depths in the Earth's crust. Selection of an appropriate thermochronometer depends on

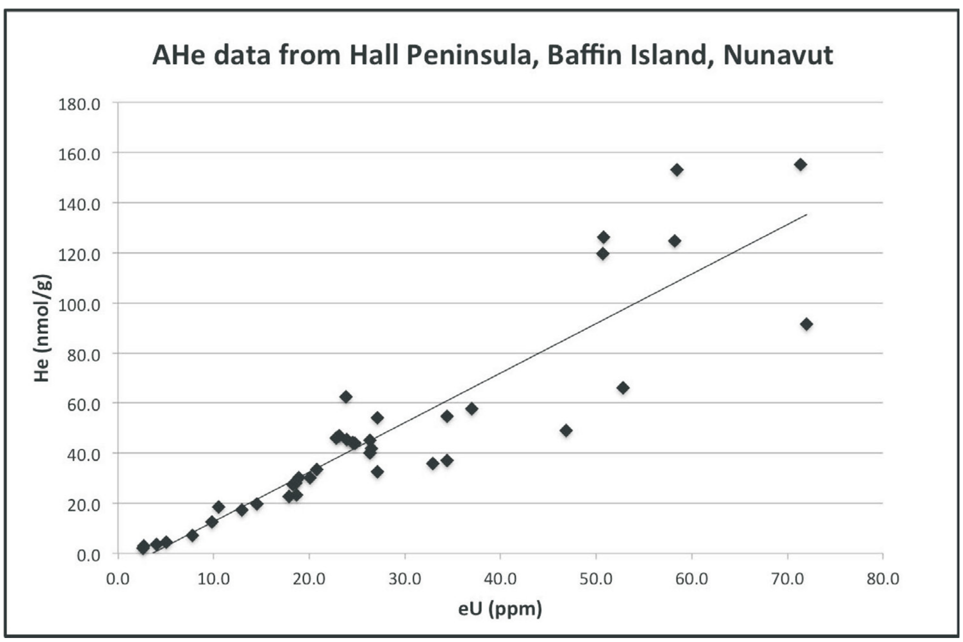

Figure 2: Preliminary AHe data from Hall Peninsula, Baffin Island, Nunavut, illustrating the linear relationship between ^{4}He concentration and the effective concentration of parent radionuclides (eU). This correlation suggests the influence of radiation damage on the diffusion kinetics of ^{4}He within the apatite grains. The plot comprises individual aliquots from several samples collected along a constant-elevation transect spanning southeastern Hall Peninsula and oriented perpendicular to the Cumberland Sound coastline (Creason et al., 2013).

the geological processes of interest to the study, and how those processes affect the subsurface thermal field. Previous studies investigating the landscape evolution of passive margins (e.g., Braun and van der Beek, 2004) demonstrated the appropriateness of apatite and zircon (U-Th)/He thermochronometers for determining the long-term landscape evolution and exhumation history of Hall Peninsula. Apatite-He has a very low T_c (40–75ºC; Ehlers and Farley, 2003), making it sensitive to the tectonism- and climate-induced variations in exhumation of the upper crust of Hall Peninsula. In select samples, ZHe, with higher T_c (~180ºC; Reiners, 2005), was also analyzed to serve as an added constraint in determining the earlier (higher temperature) thermal history with the thermokinematic models.

An underlying premise in (U-Th)/He thermochronometry is that the concentration of radiogenic ^4He in a grain is controlled primarily by the amount of time since it cooled below T_c (Wolf et al., 1996). However, several other factors control ^4He accumulation in a mineral, such as grain size, grain shape, and concentration and distribution of parent radioisotopes in the crystal lattice (Farley, 2002). These factors are considered in each cooling-age calculation. Additionally, the rate of cooling and residence time in the He partial-retention zone (HePRZ) can affect the amount of α-particles retained in the crystal; in cases of protracted slow cooling, these factors can alter the kinetics of ^4He diffusion within the grain (Shuster et al., 2006). Grains exposed to low temperatures for extended periods of time (i.e., tens to hundreds of millions of years) are susceptible to the effects of radiation damage caused by prolonged α-decay, which can alter the He-diffusion kinetics of the mineral (Flowers et al., 2009). The effect of α-induced lattice damage must be considered to account for any changes in ^4He diffusion, and it appears the effect varies with crystal type (apatite, zircon) and actinide concentration.

Radiation damage in the AHe system has been recognized for several decades (e.g., Hurley, 1954). Many studies have speculated on how radiation damage might alter the diffusivity characteristics of apatite (e.g., Wolf et al., 1996; Farley, 2000), but the effect has only recently been quantified (Shuster et al., 2006; Flowers et al., 2007; Flowers, 2009; Flowers et al., 2009; Gautheron et al., 2009). Radiation damage is the result of α-particle recoil damage during α-decay of ^{238}U, ^{235}U, ^{232}Th and ^{147}Sm, as well as the spontaneous fission of ^{238}U (Shuster et al., 2006). Damage begins to accumulate in the apatite crystal structure when the mineral is at or near ~120ºC, the chemistry-sensitive temperature below which the crystal no longer anneals. In apatite, lattice damage acts to decrease the diffusivity of the mineral grains, causing an increased retention of ^4He. Furthermore, grains with a prolonged residence time in the HePRZ are much more sensitive to changes in ^4He diffusivity; in cases of extremely slow cooling (i.e., 1–0.1ºC/m.y.), radiation damage has been suggested as the primary control on ^4He diffusivity (Shuster et al., 2006; Flowers et al., 2009).

Shuster et al. (2006) proposed that radiation damage in apatite leads to the formation of ^4He ‘traps’, which increase the energy required for the ^4He to diffuse through the grain, thus effectively increasing T_c and yielding ‘artificially older’ AHe ages. This understanding led to development of the Helium Trapping Model (HeTM), a correction for radiation damage in apatite that accounts for altered ^4He diffusion (Shuster et al., 2006). The HeTM diffusion model by Shuster et al. (2006) uses ^4He concentration as a proxy for the amount of radiation damage present in the apatite crystal. However, this method is limited because ^4He abundance and damage within the crystal are not accumulated at the same rate. Flowers et al. (2009) built upon HeTM with the radiation-damage accumulation and annealing model (RDAAM). This model uses the effective spontaneous fission-track density (a byproduct of spontaneous ^{238}U fission, calculated in apatite fission-track thermochronology) to quantify the amount of radiation damage present in the apatite grain.

Previous studies on the effects of radiation damage in AHe thermochronometry have provided ways to recognize an altered ^4He diffusion profile (Flowers et al., 2007; Flowers, 2009; Flowers et al., 2009). For example, a key indicator of radiation-damage–induced ^4He diffusion in apatite is a strong positive linear correlation between the effective concentration of all ^4He-parent isotopes (eU) and concentration of ^4He within the grain, resulting in large amounts of scatter in several measured He ages of apatite grains from a single rock sample (Shuster et al., 2006; Flowers et al., 2007). The results from Hall Peninsula reveal a similar ^4He-eU relationship. Owing to very high eU in many of the apatite crystals (>50 ppm), the relationship can be studied over a large eU range. The results indicate that, at eU greater than 20 ppm, the relationship becomes much more scattered (Figure 2). The authors interpret an eU of 20 ppm to be the effective threshold for radiation damage in these apatite grains (i.e., for crystals below T_c for long durations, more radiation damage does not significantly or regularly increase the effect). A similar threshold was observed in the zircon data (Goldsmith et al., 2014). The observed ^4He-eU relationship provides a first-order interpretation of the exhumation and cooling history. The fact that the samples are so extensively altered by radiation damage indicates that the rocks on Hall Peninsula cooled very slowly. This alone provides a beneficial initial constraint for the thermal modelling in both HeFTy and Pecube.

HeFTy Model

The HeFTy modelling program calculates t-T histories for individual thermochronometers in a sample based on mineral type; grain geometry; measured U, Th, Sm and He concentrations; chemical zonation; and ^{4}He diffusion parameters (e.g., Farley (2000) Durango standard diffusion, Shuster et al. (2006) HeTM diffusion and Flowers et al. (2009) RDAAM diffusion). The program is capable of both forward and inverse modelling for many different thermochronometers (e.g., (U-Th)/He, fission track, vitrine reflectance and ^{40}Ar/^{39}Ar). The model computes potential thermal histories that fit the data in accordance with the input parameters and boundary conditions (Ketcham, 2005). The forward model provides an indication of appropriate ^{4}He diffusion profiles based on a prescribed t-T path.

The HeFTy program is not capable of determining the exact t-T path of a sample; it provides acceptable t-T histories based on the goodness-of-fit value calculated for the He-diffusion profile from all the aliquots in the sample (Ketcham, 2005). For the purposes of the Hall Peninsula thermochronology study, the t-T paths derived from HeFTy will serve two purposes: 1) testing the sensitivity of the RDAAM correction to the AHe data; and 2) establishing preliminary constraints for the three-dimensional (3-D) thermokinematic modelling by establishing the boundary thermal conditions and ^{4}He-diffusion characteristics necessary to yield corrected, geologically meaningful AHe ages. In many instances, inclusion of higher T_c thermochronometers can help constrain the early thermal history of the grain and improve the fit of the modelled histories. Using synthetic-apatite fission-track data, the authors observed that the HeFTy cooling histories in some samples were very sensitive to the early history. Therefore, apatite grains have been strategically selected for fission-track analysis to help constrain the HeFTy models. The HeFTy output will not only provide guidance regarding the timing and therefore potential cause of changes in cooling (exhumation) rates, but it will help constrain the Pecube modelling of the 3-D diffusion throughout the region.

Pecube Model

A 3-D thermokinematic model (Pecube) will be used to predict the spatial distributions of thermochronological ages on Hall Peninsula, in order to test hypotheses regarding the possible rift-related controls on exhumation. Pecube is a finite-element code used to solve the heat-transport equation. It calculates the effect of time-varying finite-amplitude topography on the subsurface thermal field and links changes to the surface topography with the subsurface thermal history (Braun, 2003). After solving the heat-transport equation, Pecube interpolates the calculated 3-D subsurface temperature field onto particles as they travel to the sampled points at the surface, resulting in a time-temperature history controlled by the surface processes that altered the subsurface thermal field during exhumation (Braun, 2003; Braun et al., 2012). The end result is a time-temperature path for the rocks now at the surface, which yields a spatial distribution of He ages (Figure 3) and exhumation rates. Specific patterns in the distribution of He ages can be indicative of various exhumation styles typical of rifted continental margins (i.e., escarpment retreat versus pinned-divide exhumation; e.g., Gallagher and Brown, 1999; Braun and van der Beek, 2004) and if tilting of Hall Peninsula and

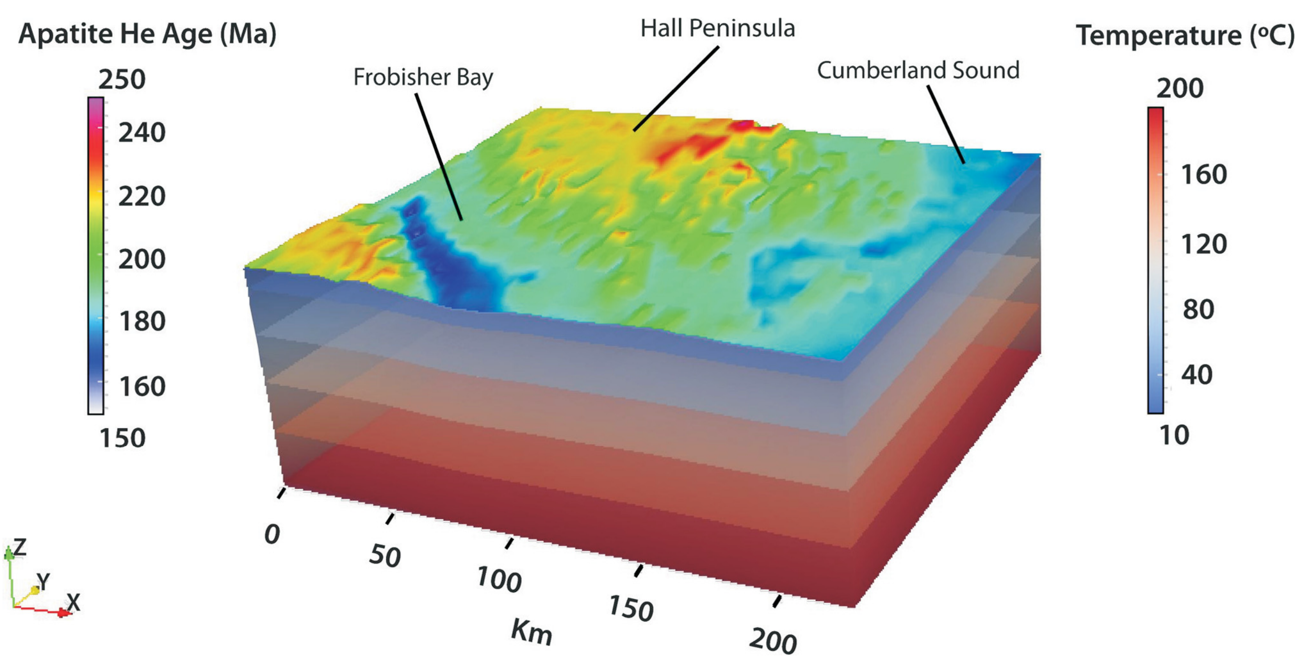

Figure 3: Semischematic Pecube model of Hall Peninsula, as viewed in the 3-D visualization program ParaView (Henderson, 2007). Colours at the surface reflect hypothetical AHe ages, as calculated by a simplified model with uniform uplift and steady-state topography. Subsurface layers represent planes of equal temperature. Vertical exaggeration (i.e., z-axis) is 5 times, to visibly enhance topography.

neighbouring peninsulas occurred during the initial rifting along reactivated Precambrian structures (sutures, faults).

The input requirements for Pecube are a digital-elevation model; spatial co-ordinates and measured cooling ages (He ages) of samples collected in strategically oriented transects; spatial co-ordinates and kinematics of any faults; and various geophysical parameters (e.g., uplift rate, crustal thickness, rock density, effective elastic thickness, thermal conductivity, basal crustal temperature and crustal heat production).

The Pecube program is capable of processing both forward and inverse t-T histories (Braun, 2003). In a forward model, the user defines the initial parameters and runs the scenario for a set time; the model is started at t = 0, simulating an evolution based on the initial model boundaries. Pecube first calculates a velocity field for all particles, then calculates the temperature field at specific user-defined time steps, providing a time window at each time step (Braun et al., 2012). The end result is a prediction of what the modern distribution of He ages at the surface should be, given the prescribed set of model parameters. A Pecube model provides a comparison of the simulated He ages to the measured data by calculating a misfit value for the difference, allowing the user to test various starting conditions and model parameters, and determine the ensuing distribution of surface He ages. The processing time for forward modelling is relatively short, allowing the user to test many different scenarios in a little as a few hours. Results from forward models are often used as boundary constraints for subsequent inverse models.

Inverse models in Pecube are implemented using the Neighbour Algorithm (NA) to create a best-fit scenario for the t-T history. In these models, the user defines a variable range for select parameters. The model is run multiple times (10 000+), modifying the variables within the predefined parameter space. After each model run, the NA analyzes the misfit values for these parameters and selects the next parameter set based on the minimized misfit values (Braun et al., 2012). For more details on the theory of the NA and its application in geophysical modelling, the reader is referred to Sambridge (1999a, b).

Inverse modelling is typically much more computationally intensive than forward modelling; depending on model size and resolution, processing times can range from days to weeks. The current expectation is that the forward models constructed in Pecube will be sufficient for characterizing the exhumation history and resultant long-term landscape evolution of Hall Peninsula.

Initial Pecube experiments involve a simple featureless crust (i.e., no topographic relief) to determine if there is a general spatial relationship between He ages and the location of large-scale structures and coastlines. Subsequent experiments will solve more complex scenarios, and may be scaled up to include data from other parts of Baffin Island.

Economic significance for Nunavut

Developing a quantitative model of the exhumation history of Hall Peninsula will give a detailed history of the Cenozoic sediment flux to Cumberland Sound and Frobisher Bay. However, because Hall Peninsula may be representative of eastern Baffin Island, the results of this study will provide the first land-based history of regional variations in sediment flux to Baffin Bay and Davis Strait, where stratigraphic characterization is of significance to the development of basin-sedimentation models for the petroleum industry. Although the sediment within Baffin Bay and Davis Strait may be, to some extent, far travelled, a detailed exhumation-history and landscape-evolution model of Hall Peninsula, derived from coupling of low-T thermochronology and 3-D thermokinematic modelling (Pecube), will help establish the portion of sediment flux that was derived from Hall Peninsula and, by proxy, eastern Baffin Island.

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