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Preliminary Apatite Fission Track Thermal History Modelling of the Nares Strait Region of Eastern Ellesmere Island and Northwestern Greenland

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Abstract: Apatite fission track (FT) ages and length characteristics of samples obtained from Cambrian to Paleocene-aged sandstones collected along the margin of Nares Strait in Ellesmere Island in the Canadian Arctic Archipelago are dominated by a thermal history related to Paleogene relative plate movements between Greenland and Ellesmere Island. A preliminary inverse FT thermal model for a Cambrian (Archer Fiord Formation) sandstone in the hanging wall of the Rawlings Bay thrust at Cape Lawrence is consistent with Paleocene exhumational cooling, likely as a result of erosion of the thrust. This suggests that thrusting at Cape Lawrence occurred prior to the onset of Eocene compression, likely due to transpression during earlier strike-slip along the strait. Models for samples from volcaniclastic sandstones of the Late Paleocene Pavy Formation (from Cape Back and near Pavy River), and a sandstone from the Late Paleocene Mount Lawson Formation (at Split Lake, near Makinson Inlet) are also consistent with minor burial heating following known periods of basaltic volcanism in Baffin Bay and Davis Strait (c. 61-59 Ma), or related tholeiitic volcanism and intrusive activity (c. 55-54 Ma). Thermal models for samples from sea level dykes from around Smith Sound suggest a period of Late Cretaceous – Paleocene heating prior to final cooling during Paleocene time.

These model results imply that Paleocene tectonic movements along Nares Strait were significant, and provide limited support for the former existence of the Wegener Fault. Apatite FT data from central Ellesmere Island suggest however, that cooling there occurred during Early Eocene time (c. 50 Ma), which was likely a result of erosion of thrusts during Eurekan compression. This diachronous cooling suggests that Eurekan deformation was partitioned at discrete intervals across Ellesmere Island, and thus it is likely that displacements along the strait were much less than the 150 km that has been previously suggested for the Wegener Fault.

Zusammenfassung: Apatit-Spaltspuren-Alter und Längen-Merkmale von Proben aus kambrischen bis tertiären Sandsteinen der Küste von Ellesmere Island an der Nares-Strait in der kanadischen Arktis dokumentieren überwiegend ein alttertiäres thermisches Ereignis im Zusammenhang mit relativen Plattenbewegungen zwischen Grönland und Ellesmere Island. Ein vorläufiges inverses Spaltspuren-Modell für einen kambrischen (Archer Fjord Formation) Sandstein von Cape Lawrence im Hangenden der Rawlings Bay-Überschiebung dokumentiert Abkühlung durch Exhumierung während des Paläozäns, vermutlich als Resultat der Erosion des Deckenstapels. Dieses Ergebnis weist darauf hin, dass die Überschiebung bei Kap Lawrence vor dem Beginn eozäner Kompression einsetzte, vermutlich im Zusammenhang mit Transpression während einer vorhergehenden Seitenverschiebungstektonik entlang der Nares Strait. Modelle an Proben vulkanoklastischer Sandsteine der spätpaläozänen Pavy Formation (von Cape Back und dem Pavy River) und eines Sandsteins der gleichaltrigen Mount Lawson Formation (vom Split Lake nördlich des Makinson Inlets) dokumentieren schwache Versenkungs-Erwärmung im Anschluss an vulkanische Aktivitäten in Baffin Bay und Davis Strait (61-59 Ma) oder im Zusammenhang mit lokalem tholeiit-basaltischen Vulkanismus und Intrusionen (55-54 Ma). Thermische Modelle an Proben von Gängen auf Meeresspiegel-Niveau aus der Gegend des Smith Sound lassen eine spätkretazisch bis paläozäne Erwärmung vor der endgültigen Abkühlung im Paläozän vermuten.

Die Ergebnisse dieser Modellierungen implizieren bedeutende Bewegungen entlang der Nares Strait im Paläozän und liefern damit zusätzliche, wenn auch in ihrer Aussagekraft beschränkte, Argumente für die Existenz der Wegener Störung zu dieser Zeit. Apatit-Spaltspuren-Alter aus der zentralen Ellesmere Island ergeben dagegen Hinweise für eine dortige Abkühlung im frühen Eozän (ca. 50 Ma), wahrscheinlich im Zusammenhang mit der Erosion der Decken des kompressiven Eureka-Ereignisses. Diese diachrone Abkühlungsgeschichte lässt vermuten, dass die Deformation des Eurekans aufgeteilt in bestimmten Abständen in Ellesmere Island stattfand. Es ist daher wahrscheinlich, dass der Versatz entlang der Nares Strait sehr viel geringer ist als bisher für die Wegener-Störung postuliert.

INTRODUCTION

GRIST & ZENTILLI (2005) presented apatite FT age and TL, and (U-Th-Sm)/He age data for samples from the Nares Strait, Kane Basin and Smith Sound region in Canada and Greenland. Much of that data was interpreted in terms of episodic exhumational cooling of the southwestern sediment source region for the developing Sverdrup Basin in the Canadian Arctic Archipelago during Late Paleozoic and Mesozoic time. However, the apatite FT (U-Th-Sm)/He systems in some samples – in particular, those obtained from coastal exposures in northern Baffin Bay, and from the Nares Strait region in Ellesmere Island – were obviously a result of the thermal effects of Late Cretaceous to Paleocene rifting in Baffin Bay, and related sinistral strike-slip motion of Ellesmere Island with respect to northwestern Greenland. In this paper we present a more detailed interpretation and FT inverse thermal models for some of those samples. We also propose a conceptual model for the Paleogene evolution of Ellesmere Island based on the apatite FT thermochronology and vitrinite reflectance data from the Sverdrup Basin (ARNE et al. 2002) and the apatite FT and (U-Th-Sm)/He thermochronology data for the Nares Strait (GRIST & ZENTILLI 2005) which is consistent with the regional geology of Ellesmere and Axel Heiberg islands and describes their structural evolution during the Eurekan Orogeny from Latest Cretaceous to Eocene time.

Tectonic setting

Nares Strait extends northwards from the failed rifted continental margin that opened the Labrador Sea, Davis Strait, and Baffin Bay during Upper Cretaceous to Paleogene time, and offsets the ridge axis in northern Baffin Bay from the eastern flank of the Lomonosov Ridge in the Arctic Ocean (Fig. 1). Thus, the strait occupies a tectonically similar setting north of Baffin Bay to the Ungava Transform in Davis Strait, which offsets the Labrador Sea and Baffin Bay spreading centres by several hundred kilometres (Fig. 1), and its linear nature suggests that it may also be fault-controlled.

The Nares Strait controversy (e.g., DAWES & KERR 1982a) is an enduring geological debate that revolves around three hypotheses about the nature of a cryptic plate tectonic

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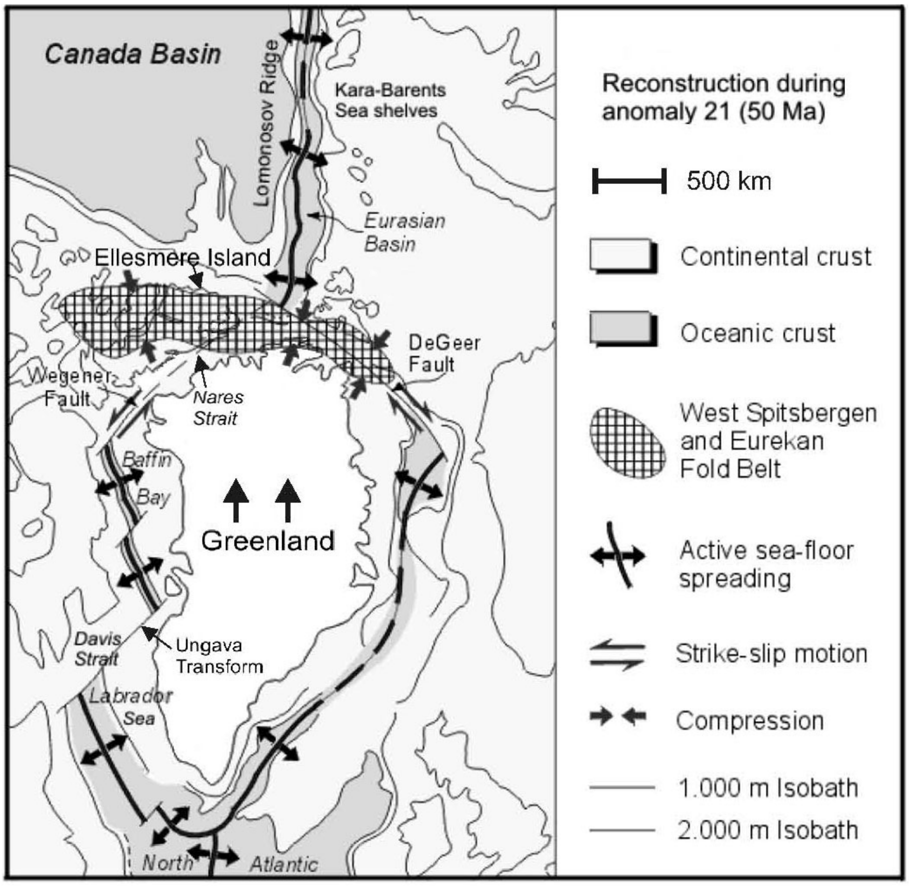


Fig. 1: Diagram of regional plate tectonic setting during the Eurekan Orogeny at magnetic anomaly 21 time (Early Eocene) illustrating how offshore rifting both east and west of Greenland resulted in a northward trajectory of the Greenland Plate, and broad regional compressive deformation in Ellesmere Island (modified from Tessensohn & Piepjohn 2000).

boundary between the North American Plate, and the Greenland microplate in this region. 1) The strait is a major strike-slip fault, (i.e., the Wegener Fault) with c. 150 km of sinistral offset due to Upper Cretaceous to Paleocene-aged rifting that opened Baffin Bay. 2) Plate motion between the North American and Greenland plates has been taken up by a broad band of deformation. 3) Nares Strait is not a major plate tectonic boundary, and the geology can be correlated across it (Dawes & Kerr 1982b).

Story et al. (1998) suggested that tholeiitic volcanism and rifting in northern Baffin Bay was initiated by the development of the Iceland mantle plume at about 62 Ma. The offset of the rift axis from Labrador Sea to Baffin Bay along the Ungava Transform was also accompanied by an episode of substantial basaltic volcanism (the North Atlantic igneous province) on both the Baffin Island and the Greenland continental margins at about 55 Ma (e.g., Riisager et al. 2003, Story et al. 1998). Thus, if Nares Strait was also a continental rift transform active during Paleocene rifting in northern Baffin Bay, the thermal effects of accompanying tholeiitic and/or basaltic volcanism would likely be discernable using low-temperature thermochronometric methods such as apatite FT dating.

Regional geology

The geology of the Canadian Arctic and western Greenland was summarized in Trettin (1991). The oldest rocks comprise Archean to Paleoproterozoic meta-sedimentary rocks, granitic intrusives, dykes and sills and Mid-Proterozoic clastic and carbonate rocks belonging to the Canadian Shield. These rocks outcrop across the southern part of the study area in south-eastern Ellesmere Island (Inglefield Uplift), and Inglefield Land, in western Greenland (Fig. 2). The shield rocks are unconformably overlain to the northwest by Cambrian to Devonian shelf carbonates and clastic rocks of the Arctic Platform, shelf, and deep-water provinces, which comprise part of the Franklinian Mobile Belt. These rocks were all strongly deformed, metamorphosed and intruded during the accretion of the Pearya Terrain to the northwest (Fig. 2), which culminated in the Late Devonian – Early Carboniferous Ellesmerian Orogeny.

By mid-Carboniferous time the Sverdrup Basin, a complex successor basin, formed within the core of the region affected by the former Ellesmerian Orogeny. Thermal subsidence and intermittant sedimentation occurred during Carboniferous and Permian time (e.g., Davies & Nassichuk 1991), followed by more-or-less continuous tectonic subsidence and sedimentation from Triassic to Upper Cretaceous time (e.g., Embry 1991). The influx of sediment into the basin from the south and east likely implies that the Nares Strait and Kane Basin region was undergoing a protracted exhumation during this time.

The Eureka Sound Group (as defined by Troelson 1950) comprises widespread occurrences of sandstone shale and lignites which he believed to postdate the last (Eurekan) orogeny. Miall (1986) suggested these rocks represent the last pulse of clastic sedimentation of the Sverdrup Basin succession, and range in age from Maastrichtian to earliest Oligocene. Subsequent investigations have revealed that formations of the Eureka Sound Group show strong regional variations and reflect a complex paleogeography that was continuously

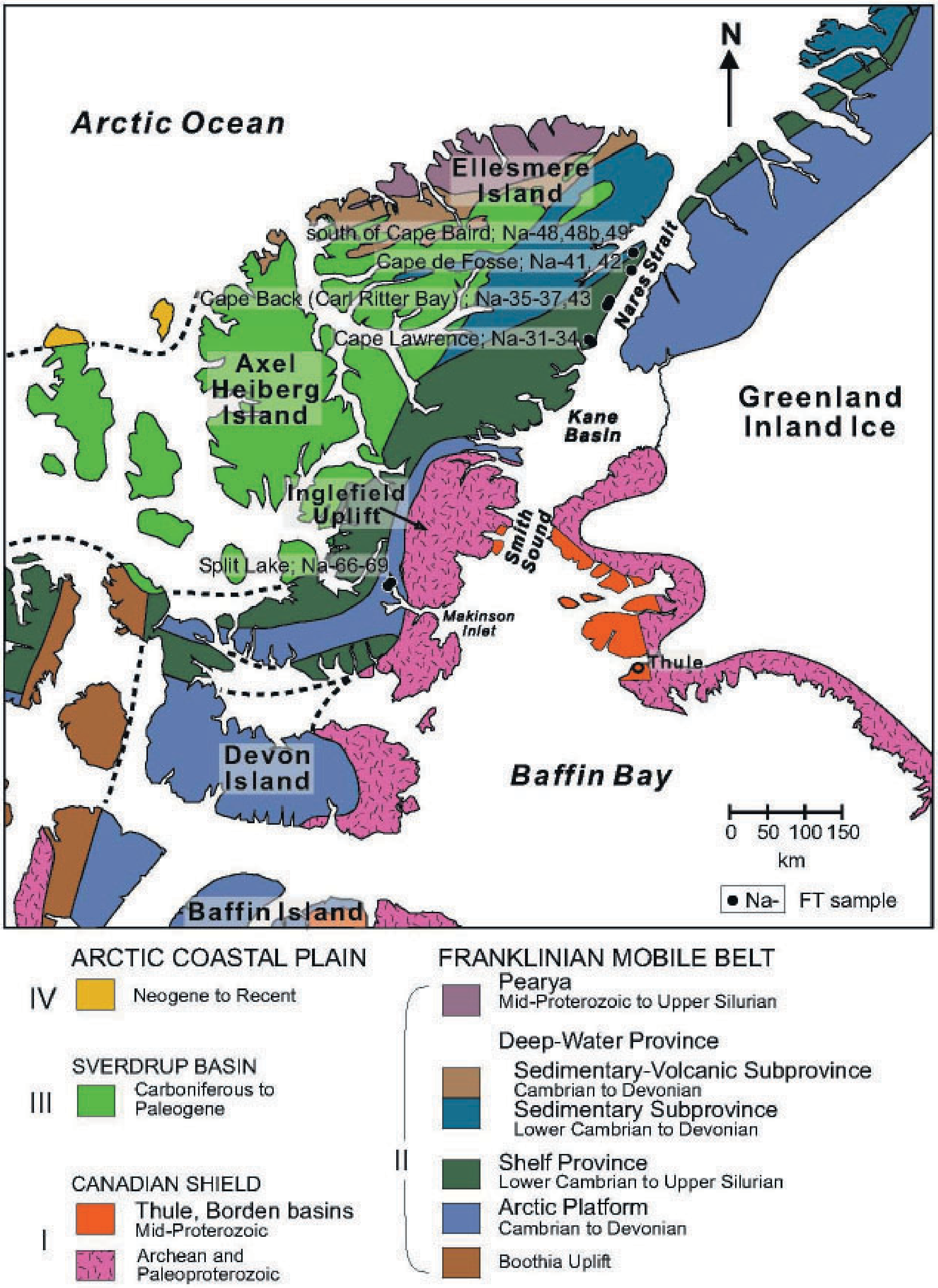


Fig. 2: Simplified geologic map of the Innuitian region (modified from Oakey et al. 2000) showing the locations of FT samples.

evolving in response to contemporaneous movements of the Eurekan Orogeny (e.g., OKULITCH & TRETTIN 1991, MIALL 1991). Recently, HARRISON et al. (1999) reorganized the diverse formations into a number of regionally correlative depositional sequences that range in age from Lower Paleocene to Pleistocene.

The Eurekan Orogeny (THORSTEINSSON & TOZER 1970) originally referred to a phase of compressive deformation that followed deposition of the Eureka Sound Group. However, as discussed above, various authors have suggested that significant deformation occurred during deposition of the Eureka Sound Group. The relative motion between Greenland and Ellesmere Island originally consisted of the counter-clockwise rotation of Greenland as a result of northward propagation of the Labrador Sea-Baffin Bay rift system (KERR 1967). During Early Eocene time the present North Atlantic Ocean began to open east of Greenland with the initiation of rifting activity there and in the Greenland Sea, resulting in the development of a triple junction south of Greenland. Relative motion between Greenland and Ellesmere Island became compressive in Eastern Ellesmere Island (e.g., SRIVASTAVA 1985, TESSENSOHN & PIEPJOHN 2000). Both transpressive and compressive deformation related to the Eurekan Orogeny are now recognized, and the age is broadly considered to range from latest Cretaceous to Early Oligocene (OKULITCH & TRETTIN 1991).

Rifting activity in Baffin Bay ceased in Early Oligocene time and the study area became tectonically inactive. Limited offshore deposition in the region during Oligocene and Neogene time resulted mainly from peneplanation that was strongly influenced by the cooling global climate (e.g., HARRISON et al. 1999). The present-day existence of mountainous terrains around northern Baffin Bay suggests that erosion rates since

Early Oligocene time have been very low.

Apatite FT Analysis

Reviews of the FT method, its application to geological problems, and the development of FT thermal models have been provided by Wagner & van den Haute (1992), Gallagher et al. (1998), Gleadow & Brown (2000), and others. Only a few specifically relevant details are discussed here. The dating aspect of the method is based on the measured density of linear tracks of crystal damage (daughter product) produced by spontaneous fission of trace amounts ^{238}U (parent isotope). In simple, rapidly-cooled systems track densities provide a measure of age with respect to the Dodson (1973) concept of a closure temperature of approximately 100 °C.

Fission tracks in apatite have an initial (un-annealed) length of 16-16.5 μm. Track length (TL) reduction by annealing of fission damage is an incremental and irreversible process that is dominantly thermally activated. Complete annealing occurs at temperatures of c. 100-150 °C (depending on the composition) over geologic time periods (e.g., Wagner & van den Haute 1992), equivalent to a burial depth of 4-5 km (assuming a geothermal gradient of 30 °C km^{-1}). At temperatures of c. 60-120 °C individual tracks are retained, but are shortened in proportion to the highest temperatures they experience. TL distributions are therefore indicative of the integrated thermal history below the closure temperature because tracks are formed continuously through time. However, the probability of a track contributing to the FT age is proportional to its length, and therefore FT ages in systems with complicated thermal histories will likely be apparent ages, which may or may not represent a geologically significant event in time. The range of temperatures over which tracks are shortened but are retained is referred to as the partial annealing zone, or PAZ. In a constant geothermal gradient, FT ages and TL distributions vary predictably with increasing temperature (depth). The PAZ concept is illustrated in Figure 3 (modified after Naeser et al. 1989).

Previous thermal history investigations

A comprehensive review of existing radiometric age determinations for Cenozoic igneous rocks in the circum-Arctic region was provided by Harrison et al. (1999). Cande & Kent (1995) determined that the onset of volcanism in the West Greenland margin occurred at 60.9 to 61.3 Ma. Story et al. (1998), determined several ^{40}Ar/^{39}Ar age spectra for volcanic glasses from Paleocene flood basalts and plagioclase feldspar from tholeiitic basalts and dykes in the Disko Island-Svartenhuk Halvo area of the West Greenland Tertiary volcanic province. They identified a previously unrecognized episode of Eocene volcanic activity that they attributed to decompression and partial melting of the asthenosphere as a result of motion along the Ungava Transform at ca. 55 Ma.

Arne et al. (1998) used apatite FT thermochronology to study the timing and magnitude of Paleocene displacements across the Vesle Fiord Thrust, within the Sverdrup Basin in central Ellesmere Island. More recent studies have combined apatite FT with vitrinite reflectance (Arne et al. 2002) and with apatite (U-Th-Sm)/He dating (Grist & Zentilli 2005) to investigate the regional inversion and cooling of the Sverdrup Basin on Ellesmere and Axel Heiberg Islands and around Nares Strait – Kane Basin – Smith Sound related to the Eurekan Orogeny.

Arne et al. (2002) found that within the Sverdrup Basin, FT age and TL trends are controlled by the distribution of thrust faults. Maximum exhumational cooling to below the base of the former PAZ occurs in the hanging walls of major thrusts, resulting in the youngest FT ages and longest mean TL in those samples (Fig. 3). These apparent FT ages were interpreted to indicate thrust-related exhumation at that time (Fig. 3). In samples obtained from thrust footwalls, and away from thrusts, FT ages were much older with broader length distributions and shorter mean lengths. These samples experienced less exhumation and prior to cooling were within the former PAZ, suggesting that these apparent FT ages are likely not geologically meaningful (Fig. 3).

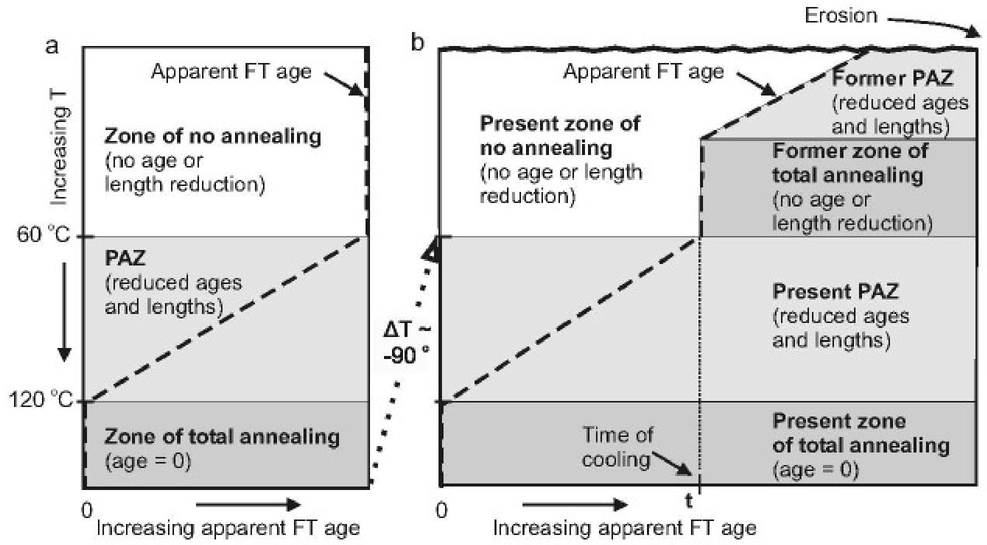


Fig. 3: Schematic representations of the expected distributions of reduced FT ages and lengths with increasing temperature (or depth) for a simple partial annealing zone (PAZ; a) and a rapidly cooled (or exhumed) PAZ (b; modified from Naeser et al. 1989).
(a): No age or length reduction occurs below c. 60 °C. At increasing temperatures, both ages and lengths are reduced systematically to 0, corresponding to a temperature of approximately 120 °C. If the section experiences substantial rapid cooling (c. 60-120 °C) such as might occur by erosion of a thrust sheet, this pattern of reduced ages and lengths can be preserved.
(b): It shows an example with c. 90 C° of cooling. The former PAZ is now above the present PAZ. Reduced apparent FT ages and length distributions are seen at low temperatures, and there is a distinct break in slope indicates the base of the former PAZ (i.e., temperatures >120 °C). The time of cooling (exhumation) is preserved, and is given by the vertical pattern of invariant FT ages and lengths below the base of the former PAZ. A new PAZ is also superimposed on the former PAZ.

Grist & Zentilli (2005) inferred several periods of accelerated cooling and exhumation in the sediment source region for the Sverdrup Basin in eastern Ellesmere Island and northwestern Greenland. In Early Mesozoic time this was likely a result of epeirogenic denudational cooling during periods of high sediment supply to the basin from well developed river systems. In Late Paleozoic time, local exhumational cooling of proximal areas may have resulted from erosion of uplifted rift flanks during periods of widespread deposition of clastic sediments. Grist & Zentilli (2005) also inferred erosional cooling of uplifted rift flanks in response to Late Cretaceous rifting in several samples from around northen Baffin Bay.

SAMPLING STRATEGY

Our overall sampling strategy in the Nares Strait region was intended to investigate the following possible thermal history elements related to Late Cretaceous to Eocene Eurekan tectonics. 1) Cooling of uplifted rift flanks following the Late Cretaceous onset of Baffin Bay rifting at c. 85 Ma; (anomaly 34, Srivastava 1978, Tessensohn & Piepjohn 2000). 2) Cooling and possible exhumation following volcanism from decompression and partial melting of the underlying asthenosphere (e.g., Story et al. 1998) related to the development of a rift transform at the northern end of the Baffin Bay rift (the Wegener Fault) during Paleocene time (anomaly 27-24). 3) Cooling from exhumation of thrust hanging walls related to Eocene (55-35 Ma) Eurekan compression.

The Late Paleocene volcanogenic mafic sandstones of the Pavy Formation, sampled near Cape Baird and at Cape Back on the Judge Daly Promontory (Figs. 4, 5), are well suited to study the post-depositional thermal history of these units. Estrada et al. (in press) determined several ^{40}Ar/^{39}Ar hornblende and K-feldspar age spectra for volcanogenic clasts

Fig. 4: Photo of Cape Back, Ellesmere Island, showing the locations of samples Na-35, Na-36 (Pavy Fm.), Na-37, and Na-43 (Cape Back Fm.).

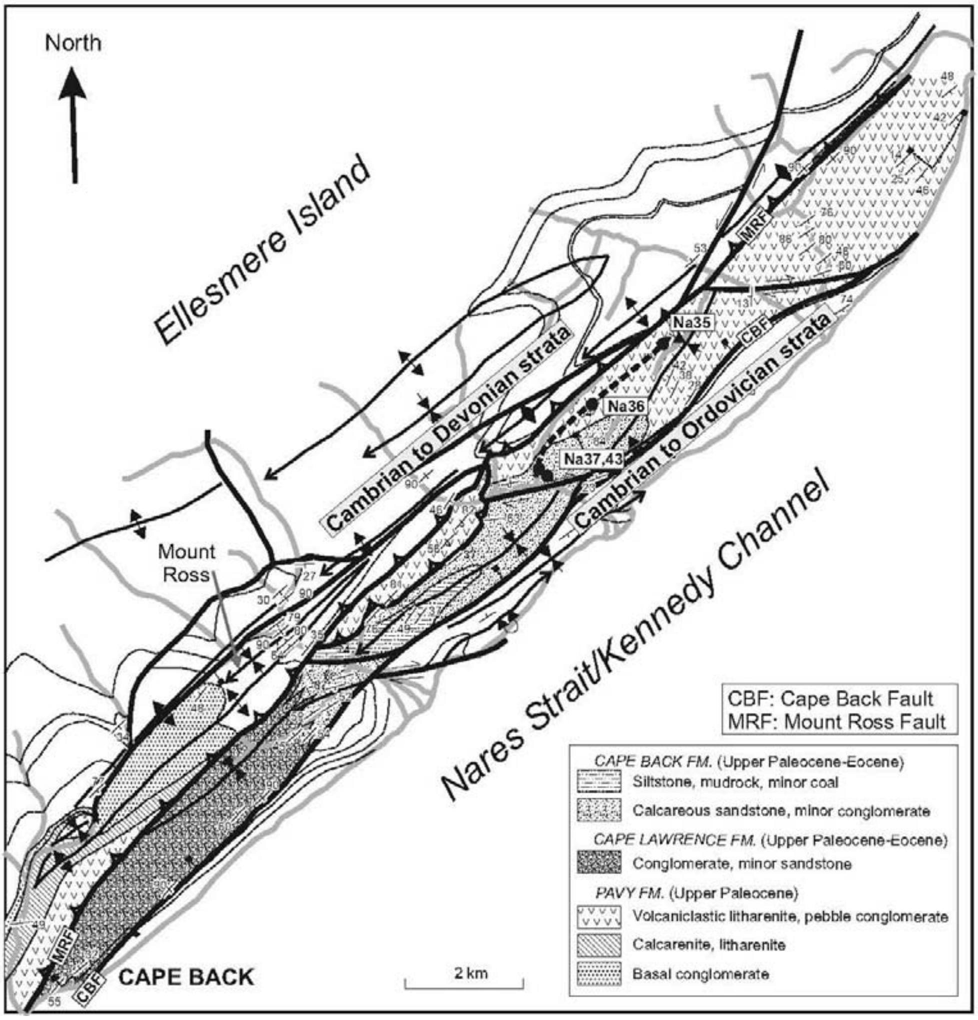


Fig. 5: Simplified geologic map of the Cape Back area (C. Harrison pers. comm. 2003). The map shows approximately the same area as Figure 4, and is similarly oriented. Sample locations are shown with black dots.

obtained from the Pavy Formation at Cape Back. Plateau ages for both mineral phases (corresponding to closure temperatures of c. 500 and 250 °C, respectively) were indistinguishable and ranged from 58.5 to 61.1 Ma. These data were interpreted to indicate that active volcanism was probably contemporaneous with sedimentation at that time. Apatite in these units would therefore have a simple pre-depositional thermal history because of their likely volcanic provenance. During the course of sampling we also discovered that the Pavy Formation sandstones have the highest magnetic susceptibilities of any of the sampled units in the Nares Strait region (Tab. 1) and are the source of a major NNE-SSW trending magnetic anomaly along the Ellesmere Island coast detected during the aeromagnetic survey (DAMASKE & OAKEY (2006).

Elsewhere on eastern Ellesmere Island our strategy was to sample the hanging wall and footwall of regional thrust faults, such as the Rawlings Bay Thrust at Cape Lawrence (Fig. 6), and the Mount Ross Fault at Cape Back, (Fig. 5). In many locations Tertiary sediments, interpreted to have been deposited in a foreland basin setting (e.g., Piepjohn et al. 2000), are overridden by Eurekan thrusting and involved in complex deformation; a fact which indicates that active tectonism existed prior to the onset of thrusting.

Sample number, location and rock type	Ø magnetic susceptibili (x 10^{-4} SI)
Na-35 Cape Back, Pavy Formation, sandstone	2.70
Na-36 Cape Back, Pavy Forrmation, sandstone	2.60
Na-37 Cape Back, Cape Back Fm., tan sandstone	0.02
Na-41 Cape de Fosse, flysch sandstone	0.01
Na-42 Cape de Fosse, sandstone	0.01
Na-48 near Cape Baird, footwall Pavy Formation, sandstone	1.70
Na-48b near Cape Baird, footwall Pavy Formation, sandstone	3.70
Na-58 Orne Island, dyke	3.0
Na-66 Split Lake, Mt. Lawson Fm., sandstone	0.46
Na-68 Split Lake, Mt. Lawson Fm., sandstone	0.02
Na-69 Split Lake, Mt. Lawson Fm., sandstone	0.10

Tab. 1: Field measurements of magnetic susceptibility of selected FT samples determined using an EDA K-2 magnetic susceptibility meter.

FISSION TRACK RESULTS

Samples processed for FT analysis are shown in Table 2. The carbonate-rich clastic sandstone/conglomerate of the Cape Lawrence Formation was found to contain no apatite. Analytical procedures used at Dalhousie University to measure FT ages using the external detector method, and confined TL distributions have been described by GRIST & ZENTILLI (2003) and others. FT age and confined TL data for samples collected during the Nares Strait Geocruise were given in GRIST & ZENTILLI (2005). For convenience, data for samples from the Nares Strait region described below are also shown here (Tab. 3). Radial plots (GALBRAITH 1990, GALBRAITH & LASLETT 1993) of the FT age data (left column) and corresponding confined TL histograms (right column) for these samples are shown in Figures 7 through 10.

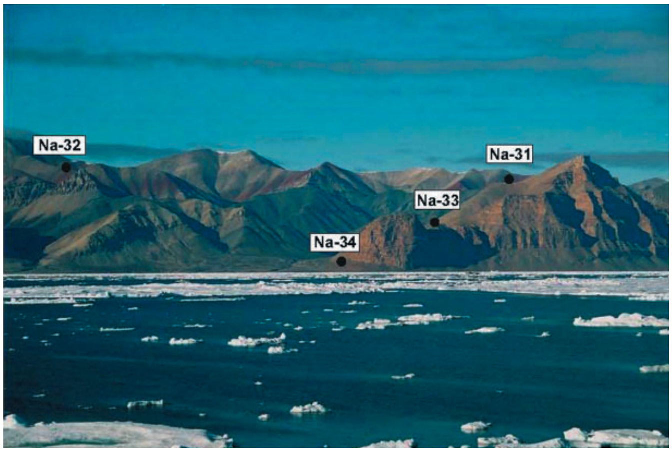


Fig. 6: Photo of Cape Lawrence, Ellesmere Island, showing the locations of samples Na-31 (Cape Lawrence Fm.), Na-32 (Archer Fiord Fm.), Na-33, and Na-34 (Cape Lawrence Formation).

Na-58, a sample obtained from a mafic dyke near sea level on Orne Island in Smith Sound, gave a Late Cretaceous FT age (84 Ma). The track length distribution is peaked and negatively skewed (Fig. 7), with a mean TL of 13.1 μm. Sample Na-57, obtained from a similar-looking mafic dyke on nearby Cape Faraday gave an FT age of 160 Ma. The confined TL for this sample is bimodal, with peaks at 10-11 μm and 13-14 μm. Sample Na-76, obtained from a near sea level mafic dyke on the Carey Øer in northern Baffin Bay, yielded an FT age 253 Ma. This sample has a broad (possibly bimodal) distribution of confined tracks, and a mean TL of 11.3 μm (Fig. 7).

Four samples obtained from volcaniclastic sandstones of the Pavy Formation near Cape Back (Figs. 4, 5, 8), and near Cape Baird (Fig. 9) on the Judge Daly Promontory, gave FT ages of 56.0-62.4 Ma (Tab. 3). The FT ages are statistically indistinguishable from the hornblende and K-feldspar ^{40}Ar/^{39}Ar ages obtained for these units (ESTRADA et al. in press) and match or exceed the depositional age determined from palynomorphs. Track lengths distributions for these samples are narrow and peaked, with mean lengths of 13.9 to 14.3 μm. A single sample obtained at Cape Back from Paleocene-aged sandstone of the Cape Back Formation (Na-37) gave an FT age of 171 Ma (Figs. 4, 5, 8). However, this sample failed the chi-square statistical test and its radial plot appears bimodal (Fig. 8) indicating that it is composed of more than one age population. The sample has a broad, flat length distribution and a mean TL of 11.5 μm.

Na-32, a sample obtained from the (Cambrian) Archer Fiord Formation sandstone at 1015 m elevation in the hanging wall of the Rawlings Bay Thrust at Cape Lawrence (Figs. 2, 6) gave an FT age of 63.4 Ma, It has a narrow, peaked distribution of confined track lengths and a mean TL of 14.1 µm (Fig. 10). The footwall samples at this location (Cape Lawrence Formation; Tab. 2) did not yield any dateable apatite. Several samples were obtained from the Late Paleocene Mount Lawson Formation in highly faulted strata at Split Lake, near Makinson Inlet west of the Inglefield Uplift (Fig. 2). Data for two of these

Sample	Location and lithology	Latitude - Longitude	Elevation	Result
Na-31	Cape Lawrence, Cape Lawrence Formation, limestone	80°24.0'NN 69°28.5'NW	884 m	no ap
Na-32	Cape Lawrence, Archer Fiord Formation, sandstone	80°23.7'NN 69°43.4'NW	1015 m	done
Na-33	Cape Lawrence, Cape Lawrence Formation. sandstone/conglomerate	80°22.6'NN 69°29.9'NW	366 m	no ap
Na-34	Cape Lawrence, Cape Lawrence Formation, conglomerate	80°22.3'NN 69°31.8'NW	125 m	NP
Na-35	Cape Back, Pavy Formation, (volcanogenic) sandstone	80°59.8'NN 66°58.8'NW	411 m	done
Na-36	Cape Back, Pavy Formation, (volcanogenic) sandstone.	80°59.4'NN 67°00.4'NW	279 m	done
Na-37	Cape Back, Cape Back Formation, tan sandstone	80°59.4'NN 67°01.1'NW	173 m	done
Na-41	Cape de Fosse, flysch sandstone	81°14.2'NN 65°42.4'NW	3 m	no ap
Na-42	Cape de Fosse, Eids Formation sandstone	81°14.6'NN 65°37.7'NW	535 m	done
Na-43	Cape Back, Cape Back Formation, tan sandstone	80° 59.4'NN 66°59.8'NW	314 m	inc.
Na-48	near Cape Baird, footwall Pavy Formation sandstone	81°28.3'NN 65°17.4'NW	215 m	done
Na-48b	near Cape Baird. footwall Pavy Formation sandstone	81°28.3'NN 65°17.4'NW	215 m	done
Na-49	Cape de Fosse, hanging wall sandstone	81°30.7'NN 65°07.6'NW	482 m	no ap
Na-57	Cape Faraday, dyke	77°53.9'NN 77°38.8'NW	3 m	done
Na-58	Orne Island, dyke	77°52.9'NN 76°19.1'NW	10 m	done
Na-66	Makinson Inlet/Split Lake, Mount Lawson Formation, sandstone	77°51.3'NN 81°37.0'NW	398 m	done
Na-67	Makinson Inlet/Split Lake. Mount Lawson Formation, sandstone	77°51.3'NN 81°39.8'NW	171 m	no ap
Na-68	Makinson Inlet/Split Lake, Mount Lawson Formation, sandstone	77°51.3'NN 82°27.3'NW	172 m	inc.
Na-69	Makinson Inlet/Split Lake, Mount Lawson Formation, sandstone	77°51.3'NN 81°40.1'NW	143 m	NP
Na-76	Carey Øer, dyke	76°44.3'NN 73°13.5'NW	15 m	done

Tab. 2: Selected samples collected during the Nares Strait Geocruise 2001; done = samples are reported in Tab. 3; NP = have not yet been processed; inc. = have not yet been analyzed.; no ap = have insufficient apatite (or none) to permit analysis.

samples (Na-67, Na-68; Tab. 2) are still pending. Na-66, a sample from a dark-coloured sandstone, gave an FT age of 60.2 Ma. This sample also has a narrow, peaked distribution of confined track lengths and a mean TL of 14.1 μm (Fig. 10).

The sample from the Eids Formation at Cape de Fosse gave an FT age that is significantly older than the mainly Tertiary FT ages for samples from the Nares Strait area, or the sample from near Makinson Inlet (discussed above). This sample also failed the chi-square test because of some scatter in the individual grain ages (Fig. 9), however unlike the Cape Back Formation sample, they do not appear to be bimodal. The distribution of confined track lengths in this sample is less peaked, and its mean TL is c. 1-2 μm shorter, than that of the samples with Paleocene-FT ages.

GEOLOGICAL SIGNIFICANCE OF FT RESULTS

Although they pass the chi-square test, the FT characteristics data of at least two of the near sea level dyke samples from Smith Sound and northern Baffin Bay (Na-57, 76) are interpreted to be partly thermally overprinted because the TL distributions are significantly reduced and appear bimodal. Based on this interpretation, the Cape Faraday sample (Na-57) has likely experienced higher temperatures associated with the thermal overprinting because it has a larger proportion of long tracks and a younger FT age than does the Carey Island sample (Na-76). There is some suggestion of a ca. 100 Ma age component in the radial plot for this sample (Fig. 7), which suggests that the thermal overprint likely occurred during Late Cretaceous time. GRIST & ZENTILLI (2005) interpreted these data as likely a result of erosional cooling of uplifted rift flanks associated with the Labrador Sea – Baffin Bay rift. It is not possible to discern based solely on the FT data whether the dyke sample from nearby Orne Island (Na-58) was completely thermally overprinted during Late Cretaceous time, or if it has a Late Cretaceous emplacement age.

TL data of the Pavy Formation samples from Cape Back and

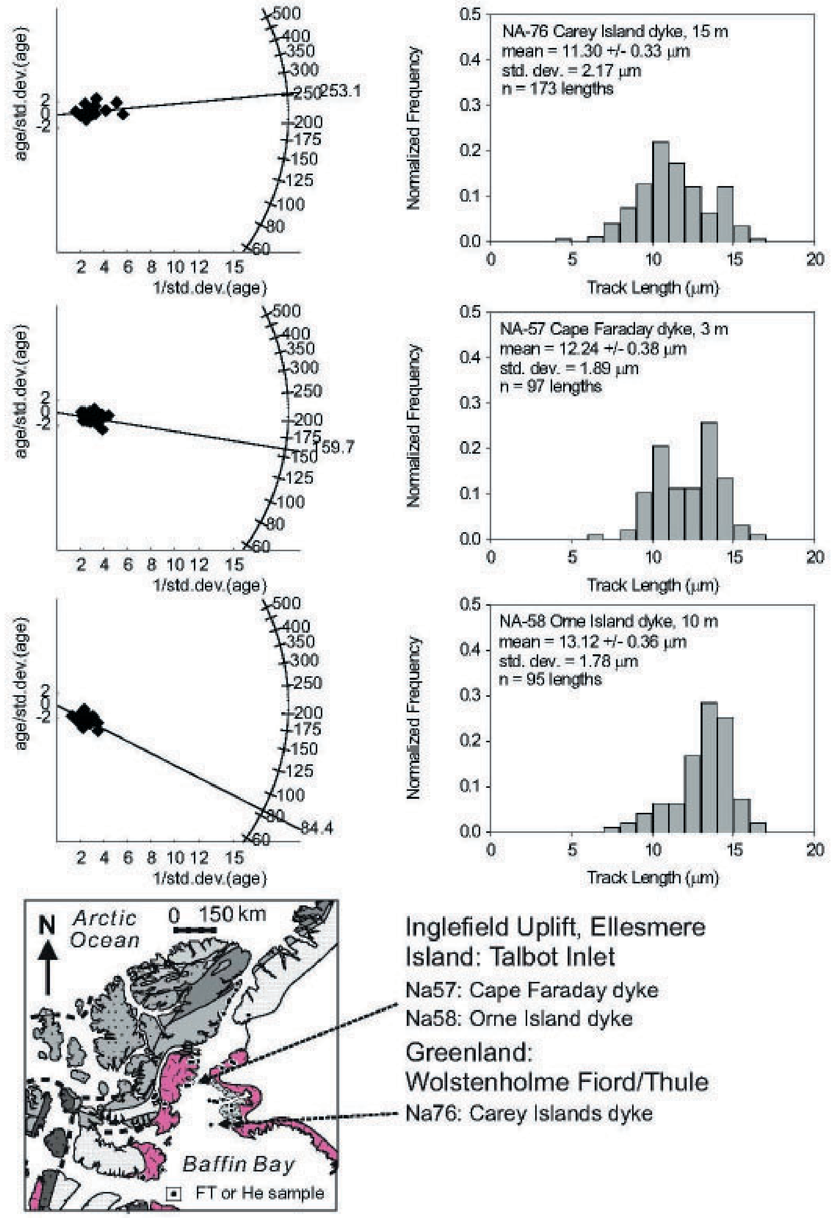


Fig. 7: Radial plots (Galbraith 1990; Galbraith & Laslett 1993) of the fission track age data (left column) and corresponding track length histograms (right column) of samples Na-76 (Carey Øer) Na-57 (Cape Faraday), and Na-58 (Orne Island), obtained from near sea level dykes around Smith Sound (modified from Grist & Zentilli in press).

near Cape Baird are typical of volcanic distributions. FT ages of these samples are indistinguishable from volcanic provenance ages. The samples appear to have experienced little thermal length shortening or age reduction following deposition. Similarly, the sample from the Cape Back Formation at Cape Back has likely experienced little post-depositional burial heating. The data likely reflect the mixing of two detrital populations with quite different thermal histories. Visually, the apatite also appears to consist of two populations. One is dominantly subhedral, and the appearance and individual ages of the grains (c. 60 Ma) are similar to the apatite of the underlying Pavy Formation, suggesting a similar provenance. The grains of the other population are euhedral, with well-developed terminations. Many show distinctive uranium zonation that is similar to that seen in the apatite of the Archer Fiord Formation at Cape Lawrence. The individual grain ages of this population range from c. 200-400 Ma, and most likely also represent the exhumation/cooling age of a much older source lithology. Both populations appear to have retained their detrital age character, and have likely not experienced significant annealing following deposition of the Cape Back Formation.

The relatively long mean TL and narrow, peaked length distribution of the Cambrian Archer Fiord Formation sandstone at Cape Lawrence imply that these rocks cooled rapidly from temperatures that exceeded 120 °C during Early Paleocene time. Although the sample was obtained less than 500 m from the plane of Upper Rawlings Bay Thrust, the FT age significantly predates the onset of Eocene compression. The FT age and TL parameters appear to have been relatively unaffected by the subsequent Eocene thrusting, an interpretation which implies that only relatively minor Eocene thrust uplift (<c. 2 km) occurred in the hanging wall of the Rawlings Bay Thrust at this location.

The FT age and length data for the Mount Lawson Formation sample from Split Lake are similar to that of the volcanogenic Pavy Formation, and are similarly interpreted as reflecting a volcanic provenance of the apatite grains. The apatite has a

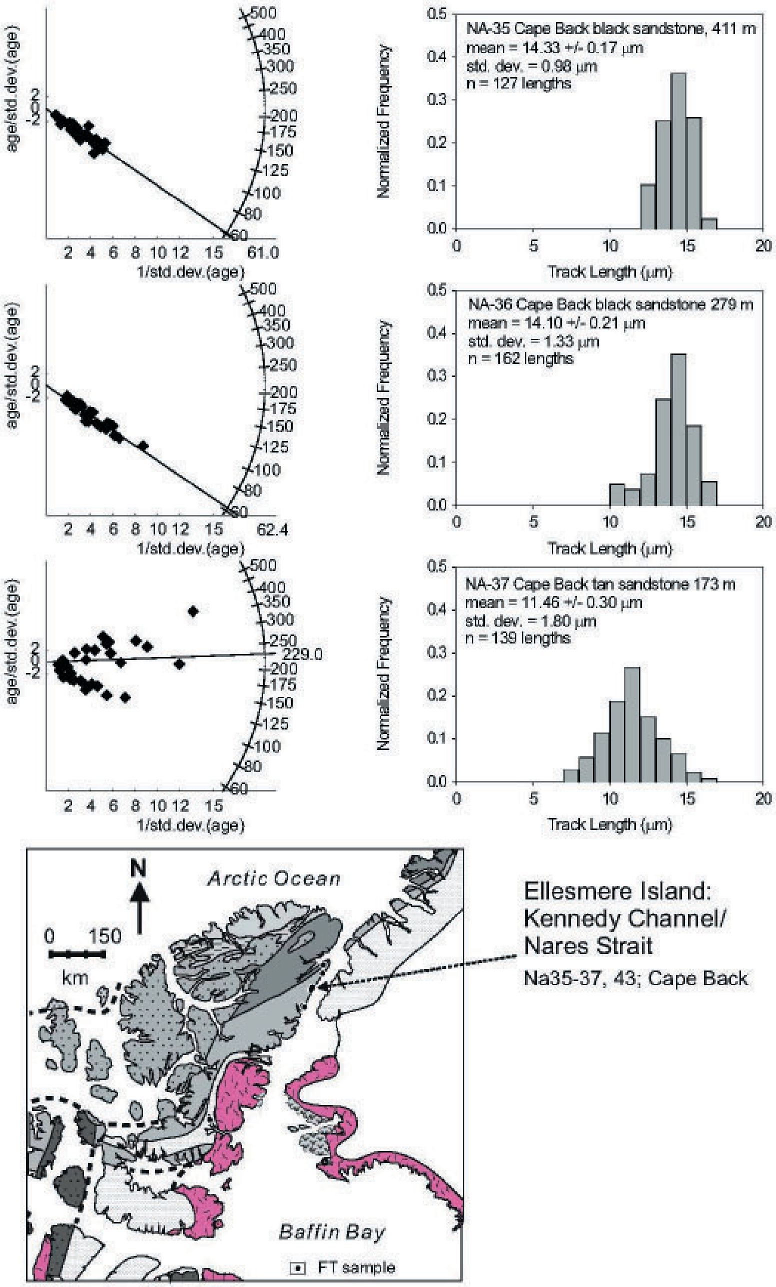


Fig. 8: Radial plots of the fission track age data (left col-umn) and corresponding track length histograms (right column) of the samples from Cape Back (modified from GRIST & ZENTILLI 2005).

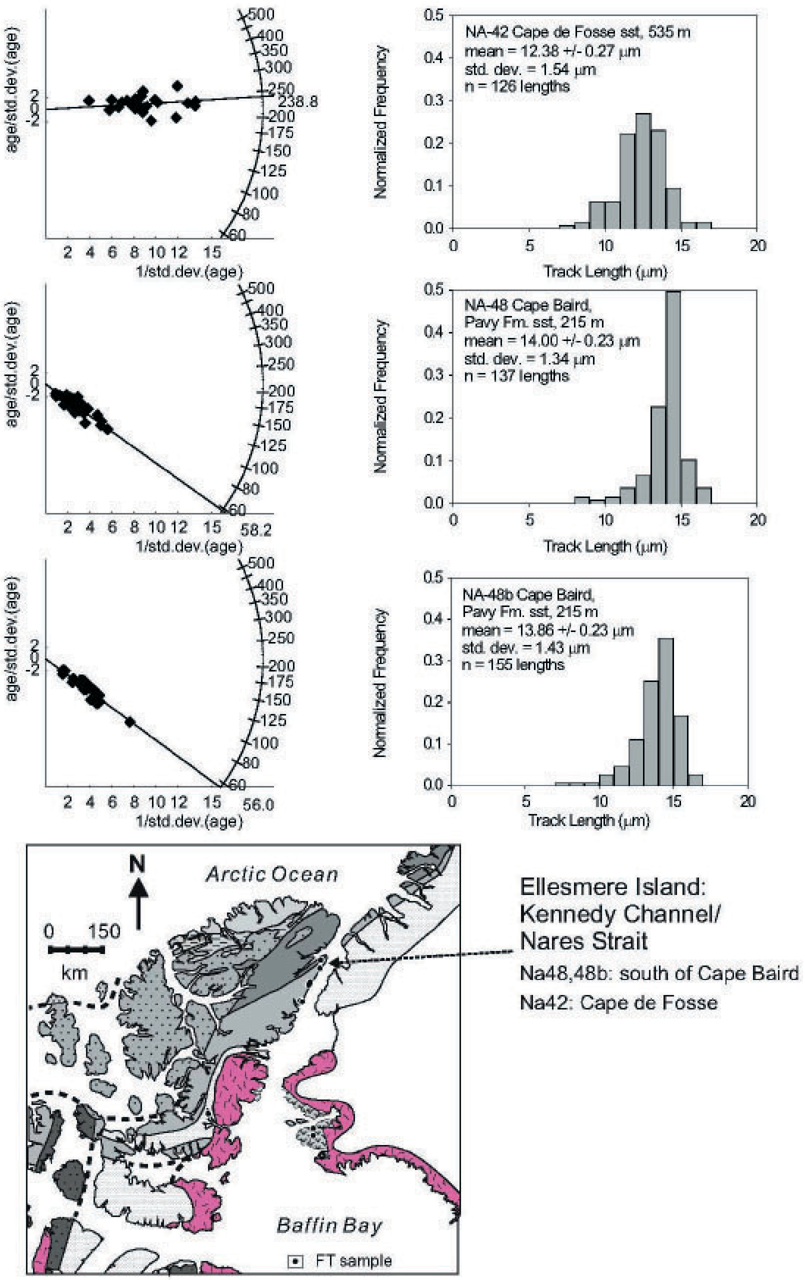


Fig. 9: Radial plots of the fission track age data (left col-umn) and corresponding track length histograms (right column) of the samples from Cape de Fosse and south of Cape Baird (modified from GRIST & ZENTILLI 2005).

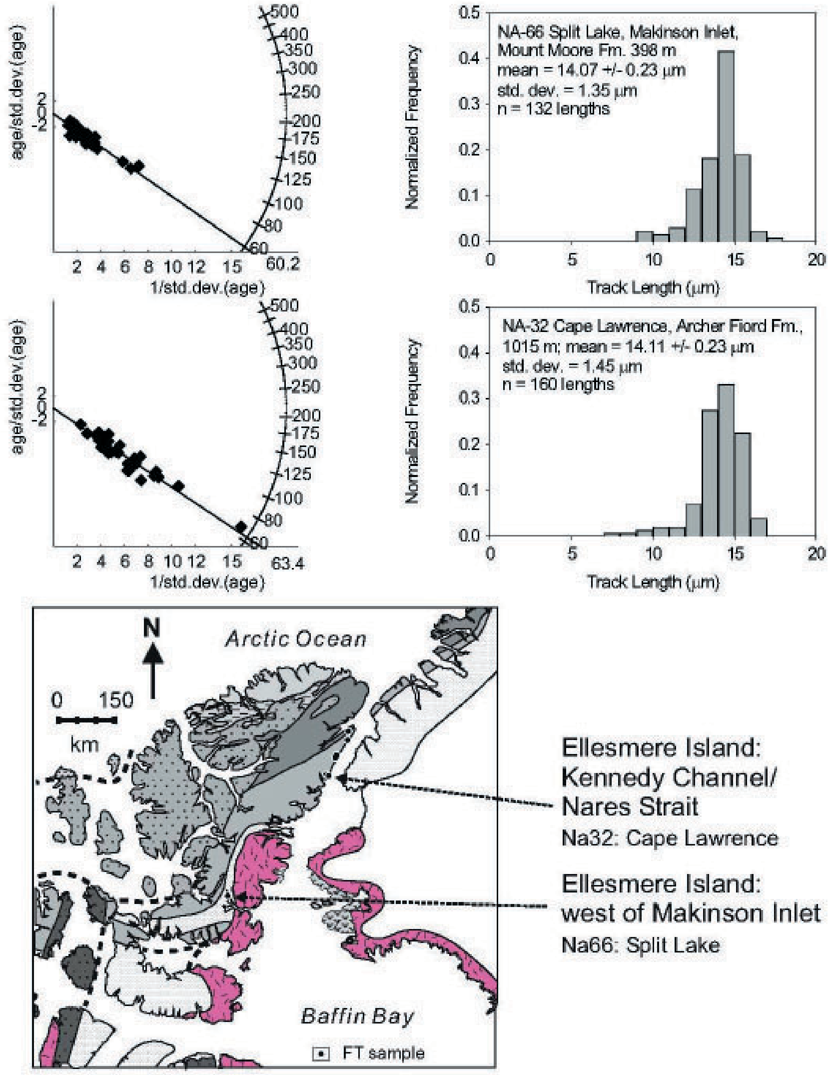


Fig. 10: Radial plots of the fission track age data (left column) and corresponding track length histograms (right column) of the samples from Cape Lawrence and Split Lake, west of Makinson Inlet (modified from Grist & Zentilli 2005).

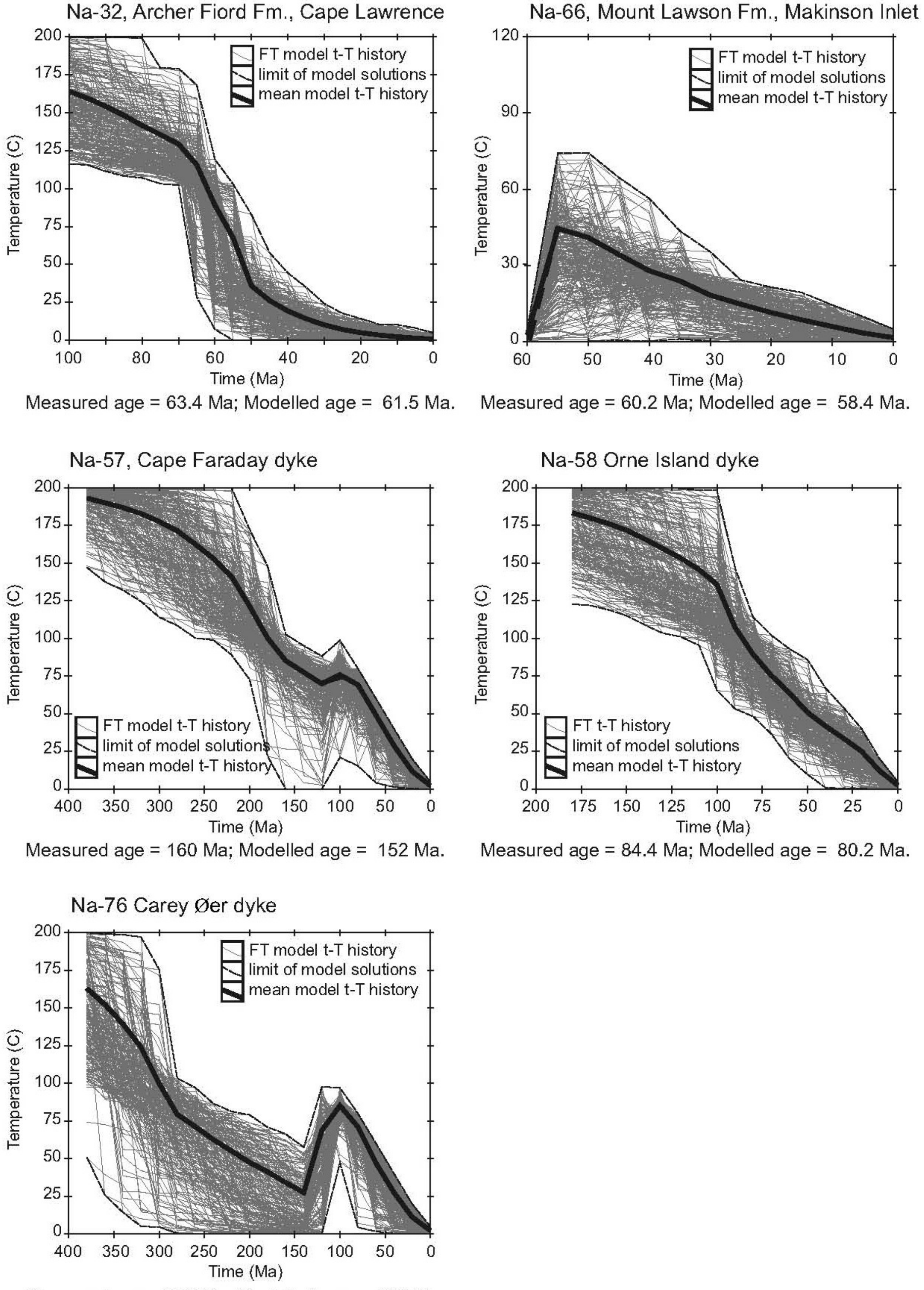
similar appearance to the Pavy Formation samples, and this particular unit also had high magnetic susceptibility (Tab. 1), likely indicating that the Mount Lawson Formation may be partly volcaniclastic. The FT data indicate rapid Paleocene cooling of the source lithology of the Mount Lawson Formation, and only minor post-depositional burial heating and exhumation during Eocene compression.

The FT age and TL characteristics of the Eids Formation sample from Cape de Fosse apparently reflects regional exhumation of a sediment source area associated with development of the Sverdrup Basin to the west, (e.g., Grist & Zentilli 2005) and possibly only very limited thermal effects from Paleocene tectonics.

Figure 11a-e shows preliminary FT inverse time-temperature (t-T) models for a) sample Na-32 (Cambrian Archer Fiord Formation, Cape Lawrence); b) Na-66 (Paleocene Mount Lawson Formation, Makinson Inlet); c) Na-57 (Cape Faraday dyke); d); Na-76 (Carey Øer dyke); and e) Na-58 (Orne Island dyke). These t-T models were obtained using AFTINV (Issler 1996, Willett 1997) based on the Laslett et al. (1987) fanning Arrhenius fit of apatite annealing data of Green et al. (1986) for Durango apatite.

Na-32 (Fig. 11a) was modelled using a cooling-only constraint, and suggests that most of the cooling of this sample occurred during Paleocene time, between 65 and 55 Ma. This was prior to the onset of Eocene compression, and likely suggests cooling was a result of exhumation during transpression. The Na-66 model (Fig.11b) assumed a 60 Ma-aged volcanic protolith, and allowed for limited burial heating until 50 Ma. This model indicates only limited post-depositional heating, which likely occurred during Late Paleocene to Early Eocene time, at approximately 55 Ma. Inverse models for the Paleocene Pavy Formation samples are similar to the model for Na-66 (Fig. 11b).

Heating was allowed between 120 and 40 Ma for the Cape Faraday (Fig. 11c) and Carey Øer (Fig. 11d) models (for the reasons described above). Both of these models suggest Late Cretaceous heating to temperatures of about 70-80 °C. The higher proportion of short tracks observed in the Carey Øer sample is expressed in the t-T model for that sample by a protracted cooling history within the PAZ prior to the Late Cretaceous heating. The t-T model for the Orne Island sample (Fig. 11e) was required to find cooling-only solutions, and shows rapid Late Cretaceous cooling from temperatures >120 °C.



Measured age = 63.4 Ma; Modelled age = 61.5 Ma.

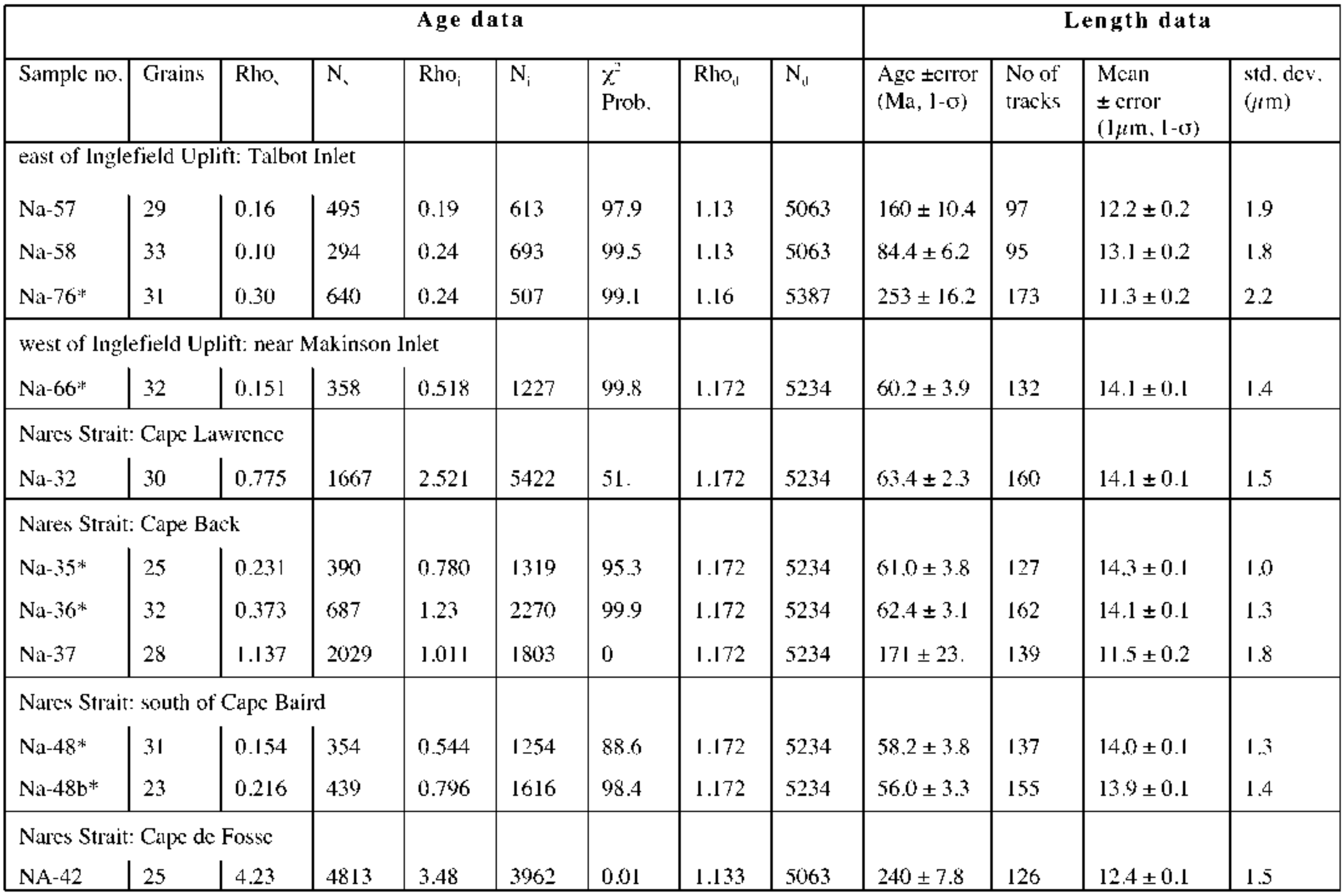
Measured age = 60.2 Ma; Modelled age = 58.4 Ma.

Measured age = 160 Ma; Modelled age = 152 Ma.

Measured age = 84.4 Ma; Modelled age = 80.2 Ma.

Measured age = 253 Ma; Modelled age = 237 Ma.

Fig. 11: Preliminary inverse thermal t-T models for selected samples. Each model shows the 250 t-T histories that pass the foodnes-of-fit test (thin grey lines), the exponential mean of the 250 solutions (thick line) and the upper and lower solution bounding envelopes (dashed lines). The Archer Fiord Formation and Orne Island dyke samples were modelled using a "cooling-only" constraint. The Mount Lawson Formation sample was given a depositional age of 60 Ma, and allowed heating from 60-35 Ma. The Cape Faraday dyke sample was allowed heating from 120-40 Ma. The Carey Øer dyke sample was allowed heating from 140-40 Ma.



Age data									Length data			
Sample no.	Grains	Rho_s	N_s	Rho_i	N_i	χ^2 Prob.	Rho_d	N_d	Age ±error (Ma, 1-σ)	No of tracks	Mean ± error (1μm, 1-σ)	std. dev. (μm)
east of Inglefield Uplift: Talbot Inlet												
Na-57	29	0.16	495	0.19	613	97.9	1.13	5063	160 ± 10.4	97	12.2 ± 0.2	1.9
Na-58	33	0.10	294	0.24	693	99.5	1.13	5063	84.4 ± 6.2	95	13.1 ± 0.2	1.8
Na-76*	31	0.30	640	0.24	507	99.1	1.16	5387	253 ± 16.2	173	11.3 ± 0.2	2.2
west of Inglefield Uplift: near Makinson Inlet												
Na-66*	32	0.151	358	0.518	1227	99.8	1.172	5234	60.2 ± 3.9	132	14.1 ± 0.1	1.4
Nares Strait: Cape Lawrence												
Na-32	30	0.775	1667	2.521	5422	51.	1.172	5234	63.4 ± 2.3	160	14.1 ± 0.1	1.5
Nares Strait: Cape Back												
Na-35*	25	0.231	390	0.780	1319	95.3	1.172	5234	61.0 ± 3.8	127	14.3 ± 0.1	1.0
Na-36*	32	0.373	687	1.23	2270	99.9	1.172	5234	62.4 ± 3.1	162	14.1 ± 0.1	1.3
Na-37	28	1.137	2029	1.011	1803	0	1.172	5234	171 ± 23.	139	11.5 ± 0.2	1.8
Nares Strait: south of Cape Baird												
Na-48*	31	0.154	354	0.544	1254	88.6	1.172	5234	58.2 ± 3.8	137	14.0 ± 0.1	1.3
Na-48b*	23	0.216	439	0.796	1616	98.4	1.172	5234	56.0 ± 3.3	155	13.9 ± 0.1	1.4
Nares Strait: Cape de Fosse												
NA-42	25	4.23	4813	3.48	3962	0.01	1.133	5063	240 ± 7.8	126	12.4 ± 0.1	1.5

Tab. 3: FT age and TL data. Samples with a χ^2 value >5 pass the χ^2 test at the 95 % confidence level. Central ages (± 1-σ error estimates) are reported (Galbraith & Laslett 1993), which are the same as the pooled ages shown on the radial plots for samples which pass the χ^2 test, but provide a better age estimate for samples which fail the χ^2test. N_s, N_i, and N_d are the number of spontaneous, induced, and flux dosimeter (CN-5) tracks, respectively. Rho_s, Rho_i, and Rho_d are the density of spontaneous, induced, and dosimeter tracks (x 10^6 cm^{-2}). A value of 353.5 ±7.1 (CN-5) was used for the zeta factor. For samples marked with an asterisk (*) a ^{252}Cf-irradiated grainmount was used to increase the number of measurable track lengths (analyses by A.M.G.).

LATE CRETACEOUS – PALEOGENE STRUCTURAL EVOLUTION OF ELLESMERE ISLAND

Estrada et al. (in press) propose the existence of a distinct alkali volcanic province that was active in Nares Strait from 61-58 Ma. Periods of basaltic volcanism at c. 61-59 Ma and related intrusive activity at c. 55-54 Ma have also been determined in the Baffin Bay and Davis Strait regions (e.g., Williamson 2003, Story et al. 1998). The FT data and thermal model for samples from Cape Back and Pavy River are also consistent with active volcanism at this time, which could be related to rift transform volcanism and minor thrusting. The fault-bounded Pavy Formation may therefore represent the present-day expression of the now thrust-overridden Wegener Fault. Thus, the FT data for the Nares Strait are compatible with plate tectonic reconstructions based on magnetic anomalies, and do not refute conclusions based on the reconstructions that require extensive strike slip motion during the Late Paleocene. However, the lack of a ubiquitous Eurekan overprint in the Grist & Zentilli (2005) FT data may suggest that only limited strike-slip has occurred along the proposed Wegener Fault in the Nares Strait region.

Based on the data of Arne et al. (1998, 2002) and the apatite FT data from the present study it is possible to speculate on whether Ellesmere Island acted as a rigid plate, and c.150 km of sinistral offset strike slip deformation occurred only in the strait region, or whether deformation was partitioned across the island, and occurred at discrete intervals. As discussed above, Arne et al. (1998, 2002) found that the geographic distribution of (Late Paleozoic to Early Mesozoic) rocks – in which detrital apatite was inferred to have been completely reset – was restricted to linear belts within the hanging walls of major thrusts, where Late Paleocene to Eocene FT ages were obtained. Hanging wall strata of the Lake Hazen fault zone at Hare Fiord, and from the Vesle Fiord Thrust in central Ellesmere Island had apatite FT ages of 39 Ma - 56 Ma.

Figure 12 shows predicted profile of apatite fission track ages and length distributions for samples in a vertical borehole that has experienced a period of rapid exhumational cooling (from Gleadow & Brown 2000). This figure is similar to Figure 3b in that the break in slope marks the former position of the base of the partial annealing zone (c. 120 °C isotherm). Below the break in slope tracks were totally annealed prior to cooling, resulting in 0 ages. If cooling is rapid enough, samples immediately below the break in slope have long mean track lengths (c. 14 μm) and ages that correspond to the time of onset of cooling (t). A part of this age-length profile can be seen in Arne et al. (2002) data for samples from the Fosheim N-27 well, Ellesmere Island (Fig. 12b). Vitrinite reflectance values of 1 % R_0 indicate that temperatures were formerly high enough (i.e., >120 °C) that fission tracks in the samples were totally annealed (e.g., Arne & Zentilli 1994). Long mean

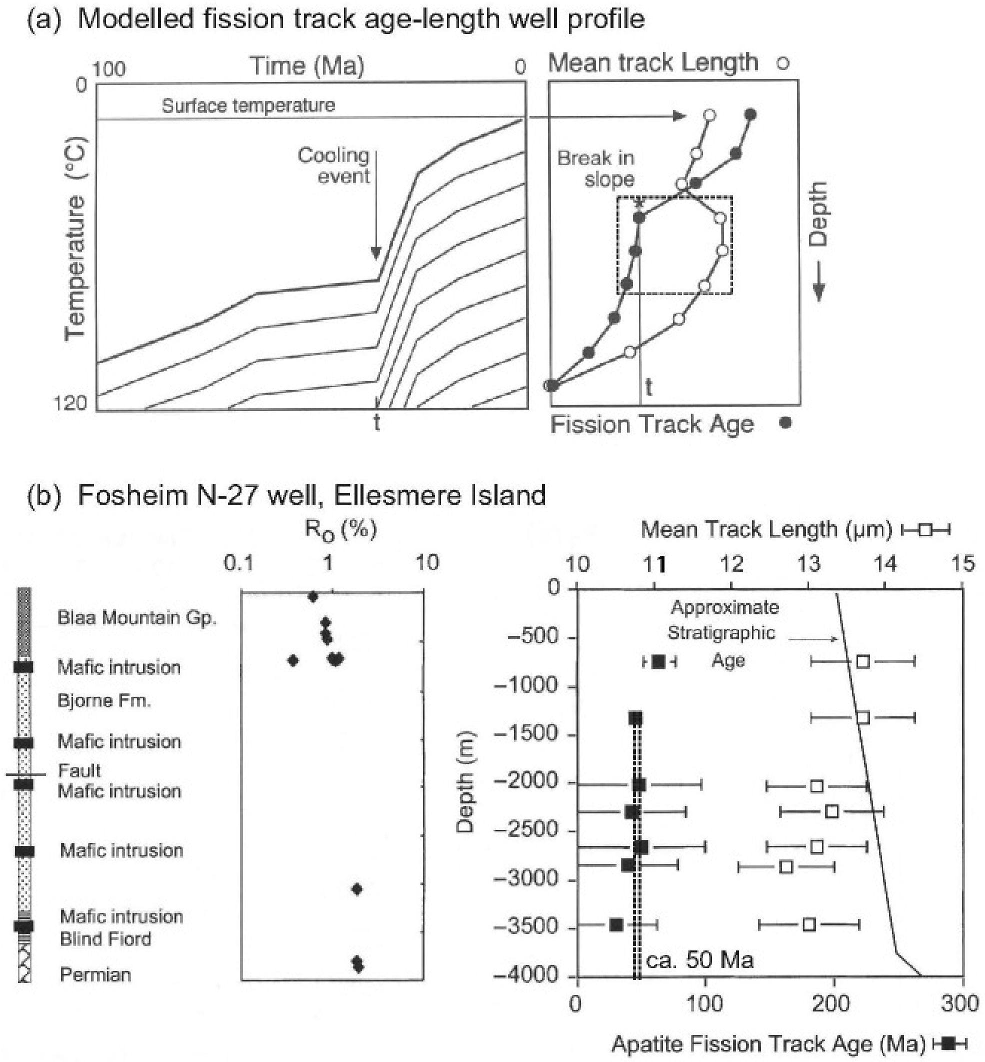


Fig. 12: (a) Predicted profile of apatite fission track ages and length distributions for samples in a vertical borehole that has experienced a period of rapid exhumational cooling (from Gleadow & Brown 2000). This figure is comparable to Figure 3b. A trend of decreasing ages and track lengths with increased temperature is predicted, however there is also an obvious break in slope, which marks the former position of the base of the partial annealing zone (c. 120 °C isotherm). Within the former partial annealing zone (above the break in slope) short tracks are preserved, resulting in finite ages and reduced mean track lengths. Below the break in slope, however, tracks were formerly totally annealed, resulting in 0 ages. If exhumational cooling is rapid, samples immediately below the break in slope have long mean track lengths (c. 14 μm) and ages that correspond to the onset of cooling (t). A part of this age-length profile can be seen Arne et al. (2002) data for samples from the Fosheim N-27 well, Ellesmere Island (b). Vitrinite reflectance values of approximately 1 % R_0 indicate that temperatures were formerly high enough (i.e., >120 °C) that fission tracks in the samples were totally annealed (e.g., Arne & Zentilli (1994). Long mean track lengths for the samples above 2000 m and nearly invariant 50 Ma fission track ages above 3000 m suggest rapid cooling that was initiated during Early Eocene time. The part of the age-length profile in (a) represented by the Fosheim N-27 well data is outlined using a dashed box.

track lengths for the samples above 2000 m and nearly invariant 50 Ma fission track ages above 3000 m suggest rapid cooling that was initiated in Early Eocene time, likely as a result of hanging wall erosion during Eurekan thrusting.

At these locations (west of the present study area) exhumation was apparently more recent than it was along Nares Strait. The FT data for this region also suggest only limited cooling and exhumation from Early Eocene compression, which suggests that much of the Eocene compression was taken up elsewhere, and that Ellesmere Island may not have acted as a rigid plate; that deformation initially focused along the strait region and progressed farther inland during Eocene time.

The southern limit of the proposed Wegener Fault is presently unknown. Additional unpublished FT data suggest that Paleozoic thermal histories are preserved in samples in the Inglefield Uplift region in southeast Ellesmere Island and in similar rocks in the Inglefield Brednig region of Greenland. The Split Lake sample was the only one from this region whose FT age and TL characteristics appear to be a result of Paleogene tectonism. Recent aeromagnetic data by Oakey & Damaske (2006), show linear features interpreted as dykes that apparently cross Smith Sound. A possible explanation for this may be that the Inglefield Uplift region of southeast Ellesmere Island as far north as Bach Peninsula may have been a part of the Greenland plate, and moved in a northeastern direction relative to Ellesmere Island during Paleogene time. This implies a significant contribution of transpressive deformation during the Eurekan Orogeny, and is consistent with the structural grain of the Paleozoic platform and shelf sequence which appears to be deformed by the Archean immediately north and west of the Inglefield Uplift. Ongoing FT and (U-Th)/He studies include a north-south transect of Bach Peninsula designed to investigate this hypothesis.

CONCLUSIONS

The FT data and inverse thermal models for most samples from the Nares Strait region are consistent with Paleogene rift transform volcanism, strike slip exhumation and minor thrust exhumation that was contemporaneous with the Eurekan Orogeny. The data are compatible with plate tectonic reconstructions that require extensive strike slip motion in Nares Strait during the Late Paleocene, however the observation that exhumation was apparently more recent in central Ellesmere Island may indicate that deformation was partitioned at discrete intervals across the island. Data from the Pavy Formation at near Cape Back, and South of Cape Baird, suggest that the fault-bounded Pavy Formation may represent the present-day expression of the former Wegener Fault.

The samples from the Eids Formation at Cape de Fosse and the older grain population of grain ages from the Cape Back Formation at Cape Back have Paleozoic to Triassic apatite FT ages and broad track length distributions, apparently reflecting regional exhumation of basin sediment source areas associated with development of the Sverdrup Basin to the west in central Ellesmere and Axel Heiberg Islands during Paleozoic and Mesozoic time, and possibly only limited thermal effects from Paleogene tectonics.

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