TIMING OF TERTIARY EPISODES OF COOLING IN RESPONSE TO UPLIFT AND EROSION, NORTHEASTERN BROOKS RANGE, ALASKA

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ABSTRACT

Apatite fission-track (AFT) data from exposed Devonian to Tertiary rocks of the northeastern Brooks Range (NEBR) suggest that four episodes of rapid cooling have occurred during the Tertiary, at ~60±4 Ma, ~43±3 Ma, ~34±3 Ma, and ~25±3 Ma. The first episode, during the Paleocene, affected the southern NEBR near Bathtub Ridge and probably is the eastern continuation of the Paleocene event recorded along the northern foothills of the Brooks Range to the west. The second episode, during the Eocene, affected the Bathtub Ridge area to the south and areas as far north as the Sadlerochit Mountains. During the early Oligocene, the third episode affected the Leffingwell Ridge and Arctic Creek areas. The fourth episode, during the late Oligocene, is recorded directly only in the uplifted units exposed near the Sadlerochit Mountains and in the Sabbath Creek area but is consistently indicated in the AFT parameters at other locations north of Leffingwell Ridge.

The northward younging of fission-track ages within the NEBR is the result of discrete cooling events, interpreted to be due to episodic uplift and erosion. This pattern, in light of the structural geometry of the fold-and-thrust belt, suggests that the cooling events defined by the data constrain the timing of thrusting events in the NEBR. To satisfy the data, each period of uplift and erosion must have occurred over a period not greater than 5 Ma and involved at least 2 km of uplift and subsequent erosion.

INTRODUCTION

This paper reports the interpreted results of a study designed to constrain the Cenozoic thermal and tectonic history of the northeastern Brooks Range (NEBR), using apatite fission-track data from exposed Devonian to Tertiary rocks (Fig.1). The prime purpose of this study was to determine the timing of tectonic events responsible for the development of the NEBR, previously known only in a relative sense because Cretaceous and younger rocks have been eroded throughout most of the NEBR. Detailed interpretations of the results discussed here, as well as a proposed tectonic model that explains the regional results, have already been presented in O'Sullivan (1993) and O'Sullivan et al. (1993) and will not be discussed here. Recent studies have established that fission tracks in apatite grains preserve a record of the thermal history of the host rock below temperatures of ~110°C (e.g., Gleadow et al., 1986; Green et al., 1989). Since other

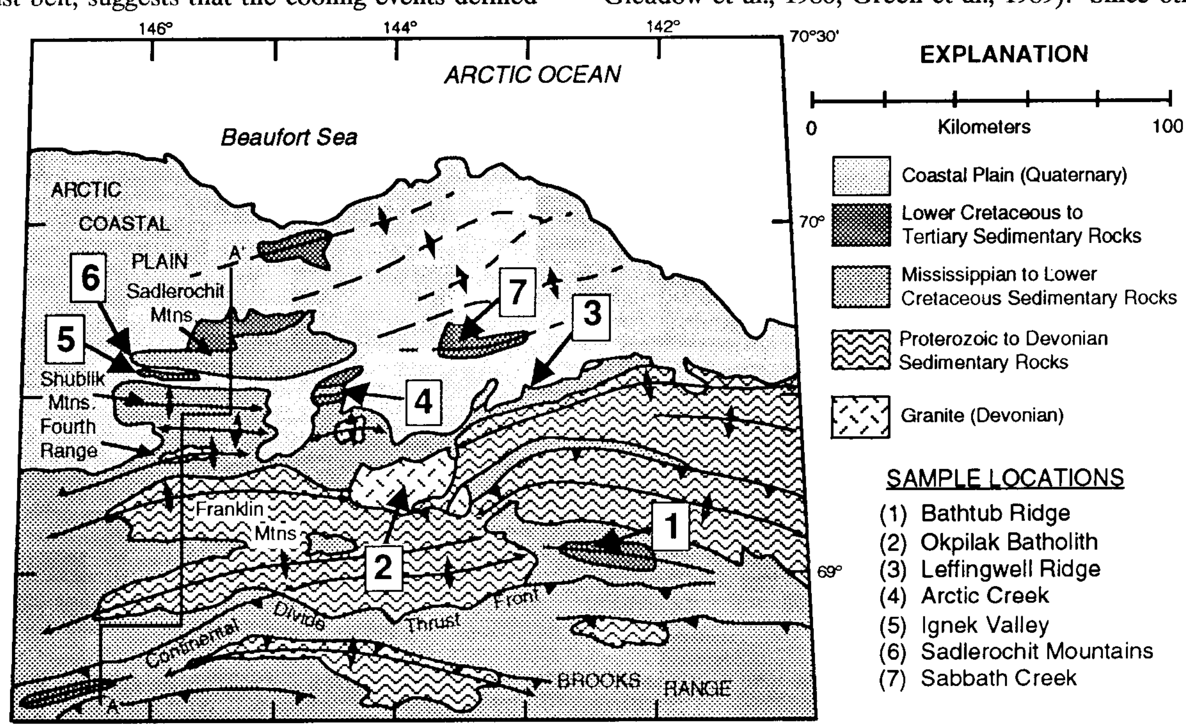

Fig.1. Tectonic map of the northeastern Brooks Range showing the locations of the seven areas sampled for fission-track studies (modified after Wallace and Hanks, 1990).

means of dating rocks exposed in the NEBR provide an incomplete record of the timing of structural events across the region, the AFT data provide a means of deciphering the thermal history of these rocks during Cenozoic orogenic events.

GEOLOGICAL SETTING

Detailed discussions of the regional geology of the northeastern Brooks Range have been presented elsewhere (e.g., Detterman et al., 1975; Mull, 1982; Kelley and Foland, 1987; Hubbard et al., 1987; Wallace and Hanks, 1990), so only a brief summary of the post-Triassic structural setting is given here.

As a result of successful rifting in the Early Cretaceous, the Canada basin was formed to the north of the present-day coastline (Hubbard et al., 1987). Uplift of the rifted margin during the Early Cretaceous resulted in the formation of a regional unconformity; and to the south, continental subduction and mountain building (the Brookian orogeny) during the Late Jurassic to Early Cretaceous created the ancestral Brooks Range (Wallace and Hanks, 1990).

In the eastern North Slope, deformation has continued episodically throughout the Tertiary, resulting in northward migration of the deformation front and consequent uplift and exposure of the NEBR (O'Sullivan et al., 1992, 1993; Wallace and Hanks, 1990). South of the northern range front, K-Ar biotite ages from the Okpilak batholith indicate cooling at ~59 to 61 Ma, following metamorphism related to thrusting (Dillon et al., 1987). Near the range front, Upper Cretaceous and Lower Tertiary rocks have been deformed with older rocks (e.g., Kelley and Foland, 1987), whereas farther north on the coastal plain, Upper Tertiary sedimentary rocks have been folded. Seismic data from the coastal plain have been interpreted to show that Upper Cretaceous and Lower Tertiary rocks are more deformed beneath a prominent Eocene unconformity; but the unconformity also is deformed, indicating that deformation occurred more recently (Bruns et al., 1987; McMillen and O'Sullivan, 1992).

METHODS

Eighty-two samples each of about 2 kg were obtained from granitic and sedimentary rocks throughout the NEBR. Apatite concentrates were separated from the samples using standard magnetic and heavy-liquid techniques. Details of the methodology used to process and analyze fission-track samples are outlined in Naeser (1979).

In this study, AFT data have been interpreted using the AFT system response described by Green et al. (1989) based on an empirical kinetic description of laboratory annealing data in Durango apatite (Laslett et al., 1987). This model gives predictions that are consistent with geological constraints on annealing behavior, as explained by Green et al. (1989). The principles used in this study to interpret apatite fission-track ages and distributions of confined tracks have been explained in detail by Gleadow et al. (1986) and Green et al. (1989).

RESULTS

Seven regions within the NEBR were selected for the purpose of studying the timing of cooling events recorded by AFT in the NEBR (Fig.1): (1) Bathtub Ridge, (2) the Okpilak batholith, (3) Leffingwell Ridge, (4) Arctic Creek, (5) Ignek Valley, (6) the Sadlerochit Mountains, and (7) Sabbath Creek. General information, such as the number of samples analyzed, the stratigraphic ages of the samples, and the range in AFT ages, is shown in Table 1. The map locations, stratigraphic details, analytical results, and detailed interpretations for all 82 samples are presented in O'Sullivan (1993) and O'Sullivan et al. (1993). Basic counting data, individual crystal ages, etc., are available in O'Sullivan (1993) or on request from the author. It is important to note that the summaries discussed below are interpretive, and the actual data sets from many of the areas are quite complicated. All errors reported throughout this paper are $\pm 2\sigma$ unless otherwise stated. The proposed cooling histories suggested by the interpreted data are shown in Fig.2.

Table 1. Sample information.

Area	Number of Samples	Stratigraphic Range (Ma)	Range in F.T. Ages (Ma)
Bathtub Ridge	18	~97-290	~49-74
Okpilak (granite)	18	~362-408	~31-42
Okpilak (sed.)	3	~235-362	~24-29
Leffingwell Ridge	13	~208-355	~26-64
Arctic Creek	7	~97-112	~30-40
Ignek Valley	13	~60-245	~31-50
Sadlerochit Mtns.	5	~60-245	~30-47
Sabbath Creek	5	~56-74	~19-25

Bathtub Ridge

Eighteen apatite fission-track ages from this area range between 74±15 and 49±10 Ma, mean track lengths between 15.5±0.4 and 11.0±3.3 μm, and standard deviations between 4.40 and 0.64 μm. The apatite fission-track ages decrease from ~60 Ma (weighted mean age of ~60±4 Ma) at the top of the sampled ~2,600 m section, to ~50 Ma at the base. Track-length distributions from the top of the section are narrow (standard deviations less than ~1.2 μm), whereas those in samples downsection are slightly broader (standard deviations greater than ~1.5 μm) and consist of a small "tail" of tracks ~8 to 12 μm in length and a sharp peak of lengths of ~13 to 14 μm.

Throughout the section, the apatite fission-track ages of samples are younger than their stratigraphic ages. However, the narrow track-length distributions and long mean lengths imply that all confined tracks within the samples at the top of the section were formed at temperatures less than ~60°C. Therefore, apatite ages from these samples must have been totally reset prior to rapid cooling in the Paleocene at ~60±4 Ma. Vitrinite reflectance values of between ~1.7 and 4.0 percent reported by Magoon et al. (1987) suggest that the rocks were exposured to elevated paleotemperatures greater than ~200°C.

Modeling of the AFT data from Bathtub Ridge suggests that following exposure to elevated paleotemperatures, the area experienced at least two episodes of rapid cooling during the Tertiary. The first occurred during the Paleocene at ~60±4 Ma, resulting in the top of the section cooling from elevated paleotemperatures to less than ~60°C. The second episode occurred at some time after ~50 Ma, resulting in ~50°C of cooling within the section. It is possible that the area experienced further cooling during the late Oligocene, as proposed for other areas in the region; however, this cannot be determined using the present data set.

Okpilak Batholith

Twenty-one apatite fission-track ages from this area range between 42±7 and 24±3 Ma, mean track lengths between 14.8±0.2 and 11.1±1.8 μm, and standard deviations between 3.05 and 0.82 μm. At the top of the batholith (elevation = ~2,500 m), the apatite fission-track ages are ~41 Ma (weighted mean = 40±3 Ma), whereas at lower elevations (~800 m) the apatite ages decrease to ~33 Ma. In a structurally lower sequence of sedimentary rocks, the apatite ages decrease further to ~25 Ma (weighted mean = 25.4±1.8 Ma). Track-length distributions are typically narrow with mean track lengths greater than ~14.0 μm and standard deviations of ~1.0 μm for samples from the top of the batholith, broad with mean track lengths less than ~12.5 μm and standard deviations greater than ~2.0 μm at lower elevations, and narrow with mean track lengths greater than ~13.0 μm and standard deviations less than ~1.5 μm for samples from the underlying sedimentary rocks.

Modeling of the data from the top of the batholith suggests that the samples experienced rapid cooling from elevated paleotemperatures at ~41±3 Ma and have subsequently remained at temperatures less than ~50°C. Exposure to high paleotemperatures is supported by the K-Ar biotite ages mentioned earlier, and zircon fission-track (ZFT) ages of ~45±3 Ma (weighted mean = 45±3 Ma; P. Green, unpublished results), which indicate that the rocks cooled below ~240°C in the Eocene. The fact that the zircon and apatite ages overlap within error, and that the apatite data indicate rapid cooling to temperatures less than ~50°C, suggests that the batholith cooled very rapidly from paleotemperatures above ~240°C to less than ~50°C in the Eocene. Considering that the batholith is only ~35 km northwest of Bathtub Ridge, it is proposed that the second episode of rapid cooling recorded in the data from Bathtub Ridge may have occurred in the Eocene at ~41±3 Ma.

The AFT data from the underlying sedimentary rocks indicate that the Okpilak batholith area subsequently experienced a second episode of rapid cooling from elevated paleotemperatures during the late Oligocene at ~25±2 Ma. Post-depositional exposure to elevated paleotemperatures greater than ~200°C is supported by R_o values of ~2.2 percent reported by Magoon et al. (1987).

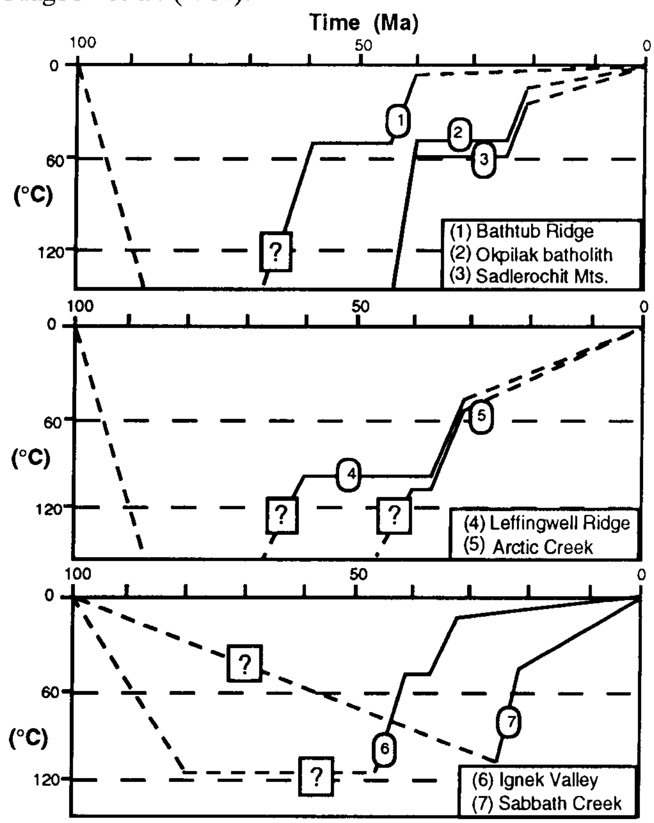

Fig.2. Schematic illustrations of thermal history interpretations for the regions discussed in this study. Dashed lines represent times without good time/temperature control by apatite and zircon fission-track results. Dark shading represents the extent of the errors associated with the ages of individual events.

Leffingwell Ridge

Thirteen apatite fission-track ages from this area range between 64±10 and 26±10 Ma, mean track lengths between 14.5±0.4 and 12.0±0.8 μm, and standard deviations between 2.26 and 0.75 μm. Throughout the sampled sequence, the AFT ages of samples are younger than their stratigraphic ages with AFT ages decreasing from ~65 Ma at the top, to ~33 Ma (weighted mean = 33±4 Ma) at the base. Samples with the youngest apatite ages (~33 Ma) tend to have the longest mean track lengths (greater than ~13.5 μm) and the narrowest length distributions (standard deviations less than ~1.5 μm), whereas the oldest apatite ages (~65 Ma) tend to have shorter mean track lengths (less than ~13.5 μm) and broader length distributions (standard deviations greater than ~1.5 μm).

Modeling of the AFT data suggests that after deposition the apatite ages must have been totally reset as a result of exposure to elevated paleotemperatures. Vitrinite reflectance values from the area of greater than ~1.8 percent reported by Magoon et al. (1987) suggest that the rocks were exposed to paleotemperatures greater than ~180°C. Subsequently, between ~70 to 60 Ma, the top of the section cooled to temperatures in the range of ~90 to 100°C, whereas samples at the base of the section remained at paleotemperatures greater than ~110°C. This was followed by a second phase of rapid cooling during the early Oligocene at ~33±4 Ma.

Arctic Creek

Seven apatite fission-track ages from the area range between 30±7 and 40±15 Ma, mean track lengths between 14.0±0.4 and 14.5±0.3 μm, and standard deviations between 2.10 and 1.29 μm. Since the apatite fission-track ages of the Arctic Creek rocks (weighted mean age of 35.1±4.0 Ma) are much younger than their stratigraphic ages and the track-length distributions suggest that most tracks have been formed at temperatures less than ~60°C, this indicates that the apatites from these samples have been totally annealed following deposition and prior to cooling. Magoon et al. (1987) report R_o values from the area of ~1.8 to 2.0 percent, which suggests that the rocks were exposed to paleotemperatures greater than ~180°C. Modeling of the AFT data suggests that the region experienced rapid cooling at ~35±4 Ma.

Ignek Valley

Apatite fission-track ages from the area range between 50±9 and 31±6 Ma, mean track lengths between 14.0±0.4 and 13.0±0.4 μm, and standard deviations between 1.58 and 0.89 μm. The apatite fission-track ages decrease from ~45 Ma (weighted mean age of ~45±5 Ma) at the top of the sampled section to ~34 Ma (weighted mean age of ~34±3 Ma) at the base. Track-length distributions from the top of the sequence are narrow (standard deviations less than ~1.2 μm), whereas those in samples downsection are slightly broader (standard deviations greater than ~1.3 μm) and consist of a small "tail" of tracks ~8 to 12 μm in length.

Throughout the section, the apatite fission-track ages of samples are younger than their stratigraphic ages. However, narrow track-length distributions and long mean lengths imply that all confined tracks within the samples at the top of the section were formed at low temperatures. Therefore, AFT ages from these samples must have been totally reset prior to rapid cooling at ~45±5 Ma.

Detailed modeling of the AFT data from the area suggests that at least two episodes of rapid cooling occurred during the Tertiary. The first episode occurred at ~45±5 Ma and resulted in the top of the section cooling to temperatures less than ~70°C, while the samples at the base of the section remained at paleotemperatures greater than ~110°C. The second episode of rapid cooling occurred in the early Oligocene between ~35 and 30 Ma and resulted in the entire section cooling a minimum of ~50°C.

Sadlerochit Mountains

Five apatite fission-track ages from this area range between 47±13 and 30±8 Ma, mean track lengths between 14.2±0.6 and 12.3±0.5 μm, and standard deviations between 1.81 and 0.72 μm. The apatite fission-track ages decrease from ~45 Ma (weighted mean age of ~45±6 Ma) at the top of the sampled stratigraphic sequence to ~30 Ma at the base of the section. Track-length distributions from the top of the section are narrow (standard deviations less than ~1.3 μm), whereas those in samples downsection are slightly broader (standard deviations greater than ~1.5 μm). Throughout the section, the apatite fission-track ages of samples are younger than their stratigraphic ages. Narrow track-length distributions and long mean lengths imply that all confined tracks within the samples at the top of the section were formed at low temperatures.

Modeling of the AFT data from the area suggests that the apatite ages must have been totally reset as a result of the elevated paleotemperatures followed by at least two episodes of rapid cooling during the Tertiary. The first episode occurred at ~45±6 Ma and resulted in the top of the section cooling to less than ~60°C. The second episode of rapid cooling occurred at some time after ~30 Ma and resulted in the entire section cooling a minimum of ~50°C. New results from along the north flank of the Sadlerochit Mountains (O'Sullivan and Murphy, unpublished results) suggest that the second episode occurred at ~28±3 Ma.

Sabbath Creek

Apatite fission-track ages from this area range between 25±6 and 19±10 Ma, mean track lengths between 14.9±0.8 and 14.0±1.4 μm, and standard deviations between 1.22 and 0.09 μm. Since the apatite fission-track ages of the Sabbath Creek rocks (weighted mean age ~23±3 Ma) are much younger than the stratigraphic ages for the same samples (~56-74 Ma), and the track-length distributions show that all tracks were formed at low temperatures, the apatites from these samples have been totally annealed due to exposure to elevated paleotemperatures greater than ~110°C. Modeling of the AFT data suggests that the region experienced rapid cooling at the time indicated by the weighted mean apatite fission-track age of ~23±3 Ma.

THERMAL HISTORY SYNTHESIS

Rates of Cooling

Since the fission-track results constrain the thermal histories experienced by the areas studied from the NEBR, it is proposed that the thermal histories would be approximated by the schematic histories shown in Fig.2. The fission-track parameters of individual samples from throughout the NEBR, characterized by long mean lengths (greater than ~14 μm) and small standard deviations (less than ~1-2 μm), require that the samples experienced rapid cooling from elevated temperatures greater than ~110°C to less than ~60°C over ~3 to 5 Ma. This corresponds to a minimum rate of cooling between ~17°C/Ma (3 Ma) and ~10°C/Ma (5 Ma). For the Okpilak batholith, where ZFT data are available, a more comprehensive rate of cooling can be determined. The zircon data and apatite data indicate that samples cooled below ~240°C at ~45±3 Ma and below ~110°C at ~41±3 Ma. These values suggest that during the Eocene, the Okpilak batholith cooled very rapidly at a rate of ~32°C/Ma.

Vitrinite reflectance values, mentioned previously, show that most areas discussed here have experienced temperatures much greater than ~110°C. However, vitrinite reflectance does not directly constrain the time at which cooling from these maximum paleotemperatures began. Therefore, since fission-track data from the Okpilak batholith suggest that rapid cooling occurred at a rate of ~32°C/Ma during the Eocene, it is possible that other regions in the NEBR experienced cooling at much faster rates than the minimum rates mentioned above.

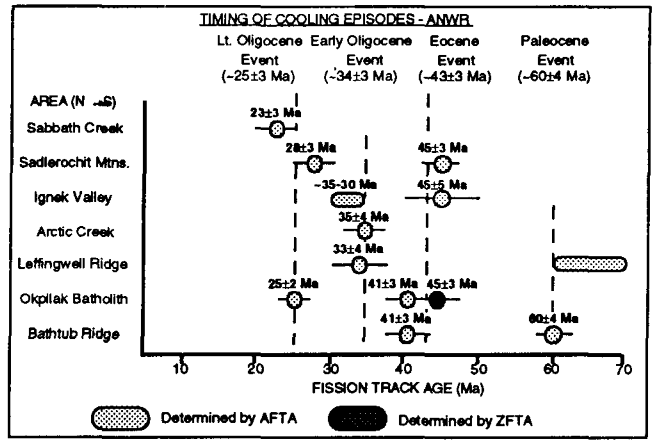

Fig.3. *Plot showing the timing of rapid cooling events for the areas studied (from north to south). Error bars are ±2σ. Resulting trends are discussed in the text.*

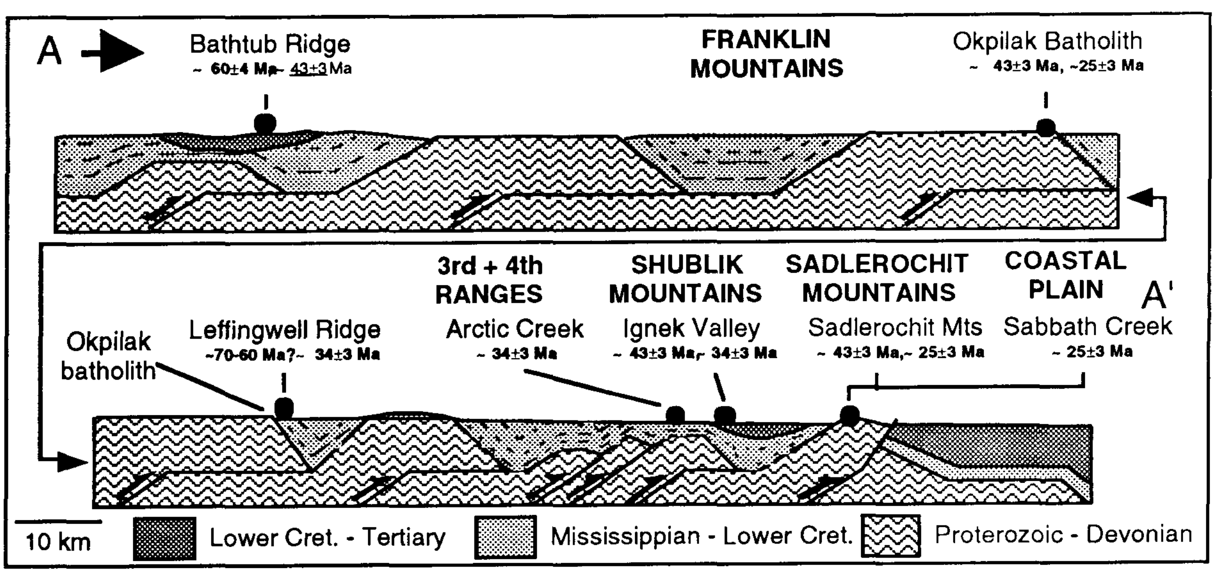

Fig.4. Apatite fission-track data projected along structural strike into equivalent structural position in the northeastern Brooks Range (cross-section modified after Wallace, 1992). Ages in bold type were measured directly, while those underlined are proposed. Cross-section follows line shown in Fig.1.

Timing of Cooling Episodes in Response to Uplift and Erosion

When AFT results from the different areas within the NEBR are plotted together, distinct trends are seen which suggest the occurrence of four discrete cooling episodes at ~60±4 Ma, ~43±3 Ma, ~34±3 Ma, and ~25±3 Ma (Fig.3). Detailed investigation into the cause of these episodes at ~60±4 Ma, ~43±3 Ma, ~34±3 Ma, and ~25±3 Ma trends is beyond the scope of this paper. However, in previous discussions (e.g., O'Sullivan, 1993; O'Sullivan et al., 1992, 1993), it has been shown that the variation in apatite fission-track cooling ages across the NEBR is best explained by progressive uplift and erosion due to thrusting as the deformation front advanced. This being the case, fission-track results from throughout the NEBR have been projected along structural strike into a regional cross-section to show the present-day lateral variation in timing of cooling episodes, in response to uplift and erosion (Fig.4).

During the Paleocene, the first recorded episode of uplift and erosion occurred at ~60±4 Ma in both the Bathtub Ridge and Leffingwell Ridge areas. Subsequently, the Bathtub Ridge area underwent a second episode at some time after ~50 Ma, which--based on AFT and ZFT results from the Okpilak batholith ~35 km to the northwest--probably occurred during the Eocene at ~43±3 Ma. This interpretation is supported by data from the Porcupine Lake area, located ~160 km to the west along the same structural trend as Bathtub Ridge, which was rapidly cooled during the Eocene between ~50 and 45 Ma (O'Sullivan et al., 1992).

During the Eocene, the NEBR, from south of the Okpilak batholith in the Franklin Mountains to north of Ignek Valley and the Sadlerochit Mountains, underwent a major episode of uplift and erosion at ~43±3 Ma. Then during the early Oligocene, the NEBR from around Leffingwell Ridge north to Ignek Valley underwent another episode of uplift and erosion at ~34±3 Ma. This event is recorded by the AFT results at Leffingwell Ridge, Arctic Creek, and Ignek Valley. Finally, in the late Oligocene at ~25±3 Ma, another episode of uplift and erosion occurred in the Okpilak batholith, Sadlerochit Mountains, and Sabbath Creek areas.

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