New constraints on the thermal history of North-East Greenland from apatite fission-track analysis

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ABSTRACT

Apatite fission-track analyses from the area north of Jameson Land, East Greenland, indicate that the region has undergone at least three phases of cooling during the Mesozoic and Cenozoic. Two major periods of cooling during the Tertiary have been identified: a middle Tertiary episode, in which cooling began between 40 and 30 Ma, and a late Tertiary episode, in which cooling began between 10 and 5 Ma. The middle Tertiary event is synchronous with emplacement of major intrusive bodies associated with continental rifting and may be due either to uplift and erosion or hydrothermal effects. The late Tertiary event appears to be related to erosion associated with uplift resulting from changes in the North Atlantic spreading direction and associated events. No paleothermal effects have been identified related to the onset of rifting in the early Tertiary. Results from samples farthest from the continental margin reveal an earlier event in which cooling began between 225 and 165 Ma. The origin of this event is not clear, but it may reflect uplift and erosion associated with recognized unconformities within the Jurassic section.

INTRODUCTION

Although the onshore geology of East Greenland has been extensively researched, very little is known about the thermal history of the area. Previous work has concentrated on Jameson Land as a result of petroleum exploration, but the area to the north has received limited attention. Despite field evidence for several post-Paleozoic erosive events in the region, little is known about the magnitude of erosion on these surfaces. Furthermore, the potentially massive thermal perturbations that may have occurred during North Atlantic breakup and associated magmatism have yet to be properly documented. This paper presents new thermal-history data, based on apatite fission-track analysis and vitrinite reflectance, for the area north of Jameson Land. The results document the major post-Paleozoic thermal events that have affected the region. Possible causes of the identified paleothermal events are discussed, related to the major erosive events seen in the field and the wider North Atlantic breakup—and postbreakup—tectonic and thermal events. However, before these new results are presented and their implications discussed, we briefly outline the geologic evolution of East Greenland and the evidence of erosive events.

LATEST PALEOZOIC, MESOZOIC, AND CENOZOIC EVOLUTION OF EAST GREENLAND

A several-kilometer-thick Devonian to Cretaceous sedimentary succession crops out in the outer fjord region of North-East Greenland (Fig. 1). To the west of this, in the inner fjord region, Caledonian and Precambrian basement is exposed. Details of the pre-Permian evolution of the area are discussed in Haller (1971). For a more comprehensive review of the late Paleozoic and Mesozoic tectono-sedimentary history of North-East Greenland, see Surlyk (1990).

Late Carboniferous–Early Permian rifting resulted in pronounced fault-block rotations throughout East Greenland (Haller, 1971; Larsen, 1990; Surlyk et al., 1986). A widespread marine transgression followed regional uplift and peneplanation of the earlier-formed fault blocks; the resulting deposition of the Foldvik Creek Group in the Late Permian marked the onset of thermal subsidence (Surlyk et al., 1986). A fall in sea level toward the end of the Permian caused erosion at the basin margins (e.g., Trümpy, 1969). Early Triassic sedimentation during renewed rifting (ca. 245–240 Ma; Price and Whitham, 1997) deposited the marine Wordie Creek Formation. More steady subsidence occurred from Middle Triassic to Early Jurassic time, and concomitant deposition occurred in a predominantly fluviolacustrine setting. Marine conditions developed in the Jameson Land region in the Pliensbachian (Neill Klinter and Sortehat Formations).

The next significant period of rifting (late Bajocian to end of the Valanginian) can be divided into two discrete events recorded north of Kong Oscar Fjord. The first event (late Bajocian to late Oxfordian) is indicated by the thickening of the shallow-marine, sandstone-dominated Vardekløft and Olympen Formations against faults on Traill Ø and by increased rates of basement subsidence (Price and Whitham, 1997). The second event (middle Volgian to Valanginian) led to rejuvenation of the fault-block topography with submarine fans deposited in half-grabens (Surlyk, 1978). A dramatic reduction in fault spacing also occurred

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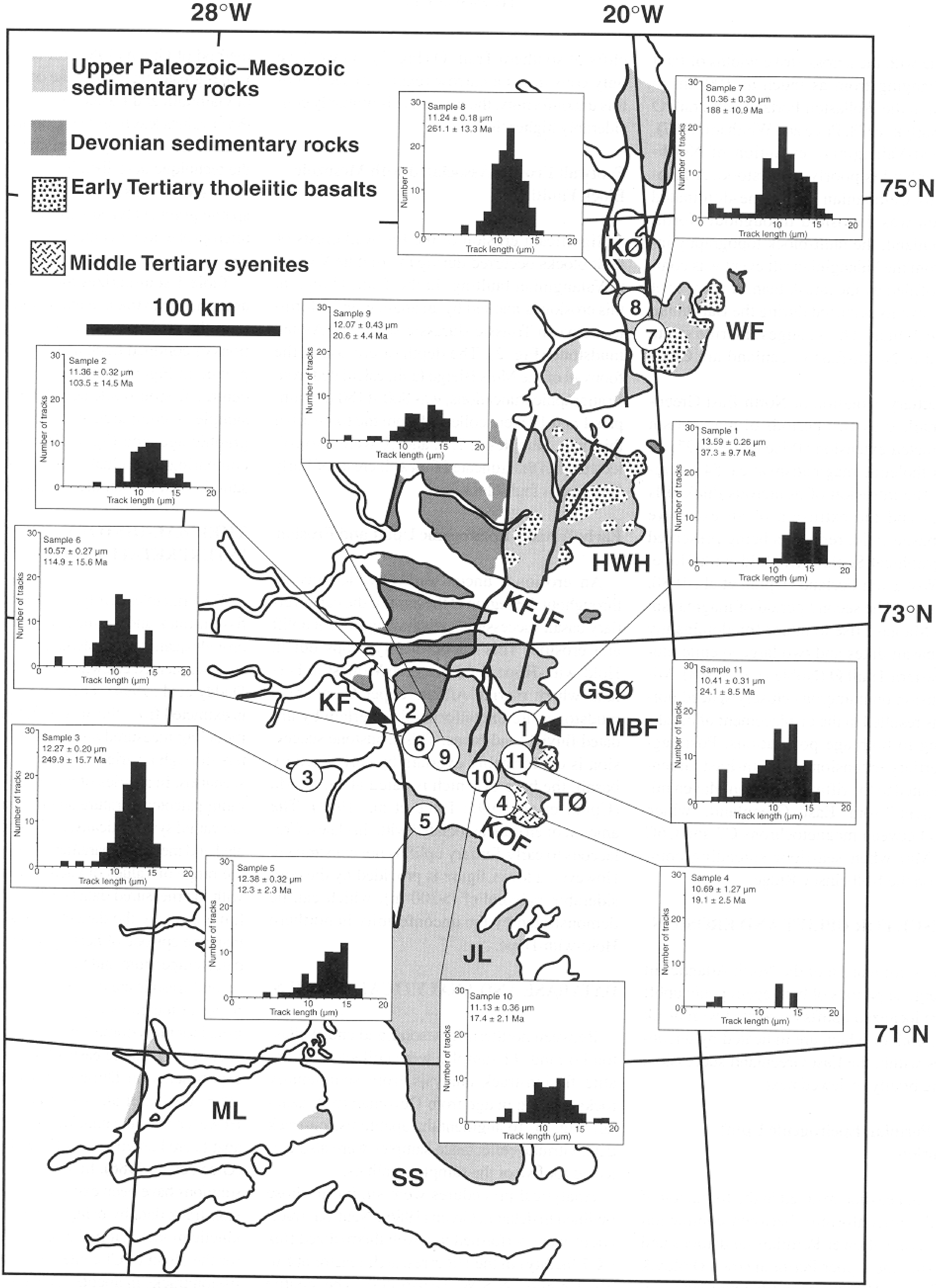

Figure 1. Summary map of North-East Greenland showing the major structural and stratigraphic units and the location of samples collected for apatite fission-track analysis. Histograms illustrating the distribution of confined track lengths, mean track length (μm), and apatite fission-track age (Ma) for each sample. KØ—Kuhn Ø, WF—Wollaston Forland, HWH—Hold-with-Hope, KFJF—Kejser Franz Joseph Fjord, GSØ—Geographical Society Ø, MBF—Mols Bjerge fault, KF—Kuppel fault, TØ—Traill Ø, KOF—Kong Oscar Fjord, JL—Jameson Land, ML—Milne Land, SS—Scoresby Sund.

at this time with the across-strike widths of fault blocks changing from as much as 100 km to ~5–25 km in the Wollaston Forland and Traill Ø regions (Surlyk, 1978; Price and Whitham, 1997).

The post-Valanginian evolution of North-East Greenland is poorly understood. A Hauterivian to Campanian mudstone-dominated succession was deposited throughout North-East Greenland; the fault-block topography inherited from the Valanginian rift event was completely in-filled by the late Albian. A number of minor rift events occurred during the Barremian to middle Albian. The youngest marine strata preserved in North-East Greenland are Campanian in age.

The Tertiary evolution of North-East Greenland is marked by two periods of magmatism and protracted extension (Price et al., 1997). A period of tholeiitic magmatism at ca. 54 Ma resulted in the intrusion of numerous thick sills and dikes and the extrusion of an extensive plateau-basalt field, remnants being preserved on Geographical Society Ø, Hold-with-Hope, and the Wollaston Forland (Upton et al., 1980, 1995; Fig. 1). The second period of magmatism at ca. 36 Ma gave rise to minor (predominantly alkalic) basalt dikes and two large syenite plutons in eastern Traill Ø (Noble et al., 1988). Minor extension on numerous closely spaced normal faults resulted in the displacement of basalts belonging to both age populations. Postmagmatic Tertiary extension in North-East Greenland is related to the rifting of the Jan Mayen microcontinent from East Greenland, which occurred between magnetochrons C7 and C6C (ca. 25 Ma) when sea-floor spreading commenced on the Kolbeinsey Ridge.

EVIDENCE FOR UPLIFT AND EROSION

The western margin of the North Atlantic rift has undergone periods of both epeirogenic uplift and more localized uplifts associated with block faulting, both of which are indicated by unconformities within the East Greenland succession. These are briefly reviewed next.

Middle Permian Epeirogenic Uplift and Erosion

Uplift and erosion resulted in the formation of an angular unconformity between continental Carboniferous–Lower Permian sandstones and shallow-marine Upper Permian strata (Foldvik Creek Group). The unconformity represents a regional peneplanation event of unknown cause. The thickness of strata removed is difficult to constrain; a minimum of ~950 m is obtained by calculating the vertical section of strata cut out at the middle Permian unconformity exposed in the cliffs of southern Traill Ø (Fig. 2). As we have only considered a narrow (exposed) section of this unconformity, the true value is probably considerably higher than this.

Footwall Erosion Associated with Mesozoic Block Faulting

Significant erosion of the footwall crests of fault blocks occurred during the middle Volgian to Valanginian faulting. In the Traill Ø region, this erosion is marked by an angular unconformity between Triassic–Jurassic strata and Albian mudstone (Fig. 2). The depth of erosion in the footwall of the Mols Bjerge fault, calculated from stratigraphic truncations, was 800–1180 m. Samples 1 and 11 were collected from the footwall of this fault. Samples 4, 7, 8, and 10 were also collected from the truncated footwall crests of Early Cretaceous fault blocks.

Early Tertiary Epeirogenic Uplift and Erosion

An erosional unconformity, which occurs throughout the region at the base of the early Tertiary basalt succession, indicates significant uplift and erosion. This unconformity crops out in Hold-with-Hope and in eastern Wollaston Forland where marine Albian–upper Campanian mudstones are unconformably overlain by undated fluvial sandstones. This sandstone succession is conformably overlain by early Tertiary basalt, the base of which is dated at ca. 55 Ma (Upton et al., 1995; Price et al., 1997). The amount of erosion associated with this latest Cretaceous to early Tertiary uplift is not constrained. However, a lower figure is provided by the considerable paleorelief (>200 m), which can be demonstrated by the unconformity in northern Hold-with-Hope.

DATABASE AND ANALYTICAL DETAILS

Between northern Jameson Land and Wollaston Forland, 11 samples were collected for apatite fission-track analysis from sedimentary rocks ranging in age from Devonian to Ryazanian (Fig. 1). To augment the apatite fission-track data, vitrinite-reflectance samples were also collected for five of the sample localities.

Analytical procedures were similar to those outlined in detail in Green (1986). Neutron irradiations were performed in a well thermalized flux (X-7 facility) in the Hifar research reactor at Lucas Heights, N.S.W. (Australia). The apatite mounts were analyzed by the external detector method, and apatite ages were calculated by using the zeta calibration method described by Hurford and Green (1983) and Green (1985). Age errors were calculated either by using the conventional method of Green (1981) for samples with $P(\chi^2)$ values greater than 5% or the central age approach of Galbraith and Laslett (1993) for samples with $P(\chi^2)$ values less than 5%. Confined track lengths were measured only on prismatic surfaces, and the technique described in Gleadow et al. (1986) was used. In all samples, the Cl content of each apatite grain analyzed was measured by electron microprobe, as Cl content is known to affect annealing kinetics.

Table 1 summarizes the apatite fission-track ages and mean track length in each sample, along with the vitrinite-reflectance results. Distributions of confined track length in each sample are plotted in Figure 1. In Figure 3A, the pooled or central fission-track age determined for each sample is compared with the sample's stratigraphic age, and Figure 3B shows radial plots comparing individual apatite grain ages in each sample with the sample's stratigraphic age.

THERMAL-HISTORY INTERPRETATION METHOD

The principles involved in application of apatite fission-track and vitrinite-reflectance analyses to provide quantitative paleotemperature information are documented elsewhere (e.g., Bray et al., 1992; Duddy et al., 1994). Thermal-history information is extracted from the apatite fission-track data by modeling measured apatite fission-track parameters through a variety of possible thermal-history scenarios. In a series of modeling runs, the maximum paleotemperature and the timing of cooling are varied systematically, and comparison of modeled and measured parameters allows definition of the range of values of each parameter consistent with the measured data (within ±95% confidence limits). Where the data allow resolution of more than one episode of heating and cooling, the peak paleotemperature and the timing of cooling in the second episode are defined in similar fashion. The basics of this modeling procedure are well established for monocompositional apatites (e.g., Green et al., 1989), on the basis of a series of laboratory experiments on Durango apatite (Green et al., 1986; Laslett et al., 1987; Duddy et al., 1988). However, the annealing kinetics of fission tracks in apatite are known to be affected by the Cl content (Green et al., 1986). In this study, thermal-history solutions have been extracted from the apatite fission-track data by using a "multicompositional" kinetic model that makes quantitative allowance for the effect of Cl content on annealing rates of fission tracks in apatite. This model is calibrated by using a combination of laboratory and geologic data from a variety of sedimentary basins around the world.

As apatite fission-track data provide no information on the approach to a thermal maximum,

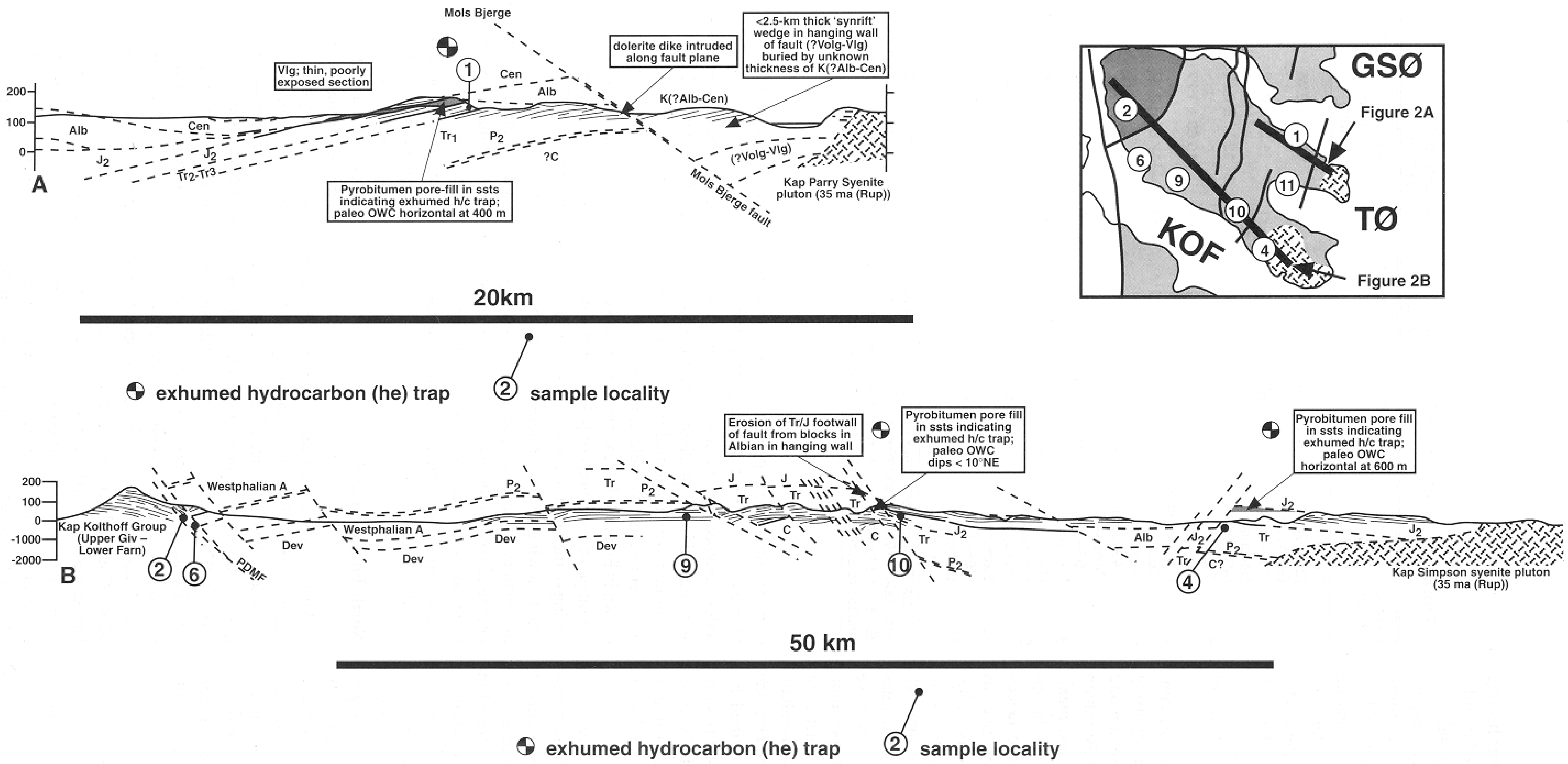

Figure 2. Structural cross sections from the study area illustrating the tilted fault blocks that form the dominant structural feature of the area and the relationship between the sample localities and the fault blocks. GSØ—Geographical Society Ø, TØ—Traill Ø, KOF—Kong Oscar Fjord.

they cannot independently constrain the heating rate; a value must therefore be assumed in order to interpret the data. Arbitrary heating and cooling rates of 1 °C/m.y. and 10 °C/m.y., respectively, have been assumed, and the resulting paleotemperature estimates are conditional on these assumed values. A change in the heating rate of an order of magnitude is equivalent to a difference in the required maximum paleotemperature of ~10 °C. Apatite fission-track paleotemperature estimates are typically quoted as a range, and absolute values have an uncertainty of between 5 and 10 °C.

Observed vitrinite-reflectance values are converted to maximum paleotemperatures by using the kinetic model developed by Burnham and Sweeney (1989) and Sweeney and Burnham (1990). Information on the timing of these maximum paleotemperatures is provided by the apatite fission-track data. The vitrinite-reflectance–derived paleotemperature estimates are given as single values but probably have a precision between 5 and 10 °C. As vitrinite-reflectance data also do not provide information on the approach to a thermal maximum, heating and cooling rates of 1 °C/m.y. and 10 °C/m.y., respectively, have been assumed, consistent with the interpretation of the apatite fission-track data. The kinetics of vitrinite reflectance as described by Burnham and Sweeney (1989) are essentially similar to the fission-track annealing kinetics described by Laslett et al. (1987). In particular, total fission-track annealing in apatites with typical Cl content corresponds to a vitrinite-reflectance value of ~0.7% (Duddy et al., 1991, 1994), regardless of heating rate.

Apatite fission-track data do provide some control on the history after cooling from maximum paleotemperatures, through the lengths of tracks formed during this period. Wherever possible, data from each sample are interpreted in terms of two episodes of heating and cooling through the use of assumed heating and cooling rates during each episode and with the assumption that the maximum paleotemperature was reached during the earlier episode. The timing of the onset of cooling and the peak paleotemperatures during the two episodes are varied systematically; thus by comparing predicted and measured parameters, the range of conditions that are compatible with the data can be defined. One additional episode during the cooling history is normally the limit of resolution from typical apatite fission-track data.

TABLE 1. SUMMARY OF APATITE FISSION-TRACK ANALYSES RESULTS FOR 11 OUTCROP SAMPLES FROM NORTH-EAST GREENLAND

Sample number	Stratigraphic age (Ma)	Apatite fission-track age (Ma)	Number of grains	$P(\chi^2)$	Mean track length (μm)	Number of tracks measured	Vitrinite reflectance (R_o%)
1	Triassic (245–208)	37.3 ± 9.7	20	<1	13.59 ± 0.26	43	1.50
2	Devonian (409–363)	103.5 ± 14.5	20	<1	11.36 ± 0.32	55	
3	Devonian (409–363)	249.9 ± 15.7	20	3	12.27 ± 0.20	105	
4	Triassic (245–208)	19.1 ± 2.5	19	41	10.69 ± 1.27	11	
5	Carboniferous (363–290)	12.3 ± 2.3	20	<1	12.38 ± 0.32	58	1.15
6	Visean (349–333)	114.9 ± 15.6	20	<1	10.57 ± 0.27	78	0.91
7	Callovian (157–146)	118.0 ± 10.9	20	20	10.36 ± 0.30	103	0.54
8	Ryazanian (146–132)	261.1 ± 13.3	20	81	11.24 ± 0.18	105	0.60
9	Westphalian (318–303)	20.6 ± 4.4	20	<1	12.07 ± 0.43	45	
10	Bathonian (166–157)	17.4 ± 2.1	20	10	11.13 ± 0.36	60	
11	Bathonian (166–157)	24.1 ± 8.5	20	<1	10.41 ± 0.31	103	

Notes: Quoted fission-track ages are pooled ages for samples in which $P(\chi^2) > 5\%$, and central ages (Galbraith and Laslett, 1993) for samples with $P(\chi^2) < 5\%$. Ages calculated using a zeta value (Hurford and Green, 1982) of 354.8 ± 6.3 for samples 1 to 4, and 360.3 ± 6.8 for samples 5 to 11. Full details of the apatite fission-track data and results are available from the authors on request.

THERMAL-HISTORY RESULTS

A summary of the thermal-history interpretation of apatite fission-track data from each sample is given in Table 2 (in terms of the magnitude of maximum or peak paleotemperatures and the timing of cooling in individual paleothermal episodes, obtained from the apatite fission-track data as explained in the previous section). Schematic illustrations of the thermal-history interpretation in a representative selection of samples are shown in Figure 4. For each sample, boxes define the range of conditions of paleotemperature and timing of the onset of cooling as listed in Table 2. The following sections briefly describe the thermal history of each sample, grouped on a geographical basis, after which the results are synthesized into an overall thermal-history framework. The implications of the results are then discussed.

North Jameson Land

Apatite fission-track and vitrinite-reflectance data for sample 5, the most southerly location in this study, show evidence of major Tertiary cooling, consistent with previous studies (Hansen, 1988, 1992). Apatite fission-track data suggest two distinct cooling episodes (Table 2)—an earlier episode in which cooling began between 40 and 15 Ma from a maximum paleotemperature of >130 °C and a later cooling event from a paleotemperature of 95–105 °C to surface temperatures within the past 10 m.y. These events are required to explain both the fission-track age of 12.3 ± 2.3 Ma and the short track lengths measured in this sample. The relatively high lower limit to the maximum paleotemperature of 130 °C arises because of the presence of an apatite grain with a high Cl content (1.22 wt%), which was totally annealed (along with all the other grains).

A measured vitrinite-reflectance value of 1.15% at this location (Table 1) suggests a maximum paleotemperature of 150 °C, consistent with the apatite fission-track data. The difference of 20 °C between the minimum paleotemperature limit determined from apatite fission-track analysis and the maximum value derived from vitrinite reflectance would allow the interpretation that this maximum paleotemperature was reached in an earlier episode. However, given the general similarity in the two values, it seems reasonable to suppose that the vitrinite reflectance represents the middle Tertiary event revealed by apatite fission-track analysis.

Sample 3, the westernmost sample analyzed, gives one of the oldest fission-track ages at 249.9 ± 15.7 Ma. This result is significantly younger than the Devonian age of this sample and therefore reveals significant postdepositional heating. Apatite fission-track data from this sample can be explained by two episodes of heating and cooling (Table 2): an earlier episode of cooling from a paleotemperature of 95–100 °C, which began between 275 and 165 Ma, and a later episode of cooling from 60–75 °C, which began between 65 and 5 Ma. As discussed later, this more recent

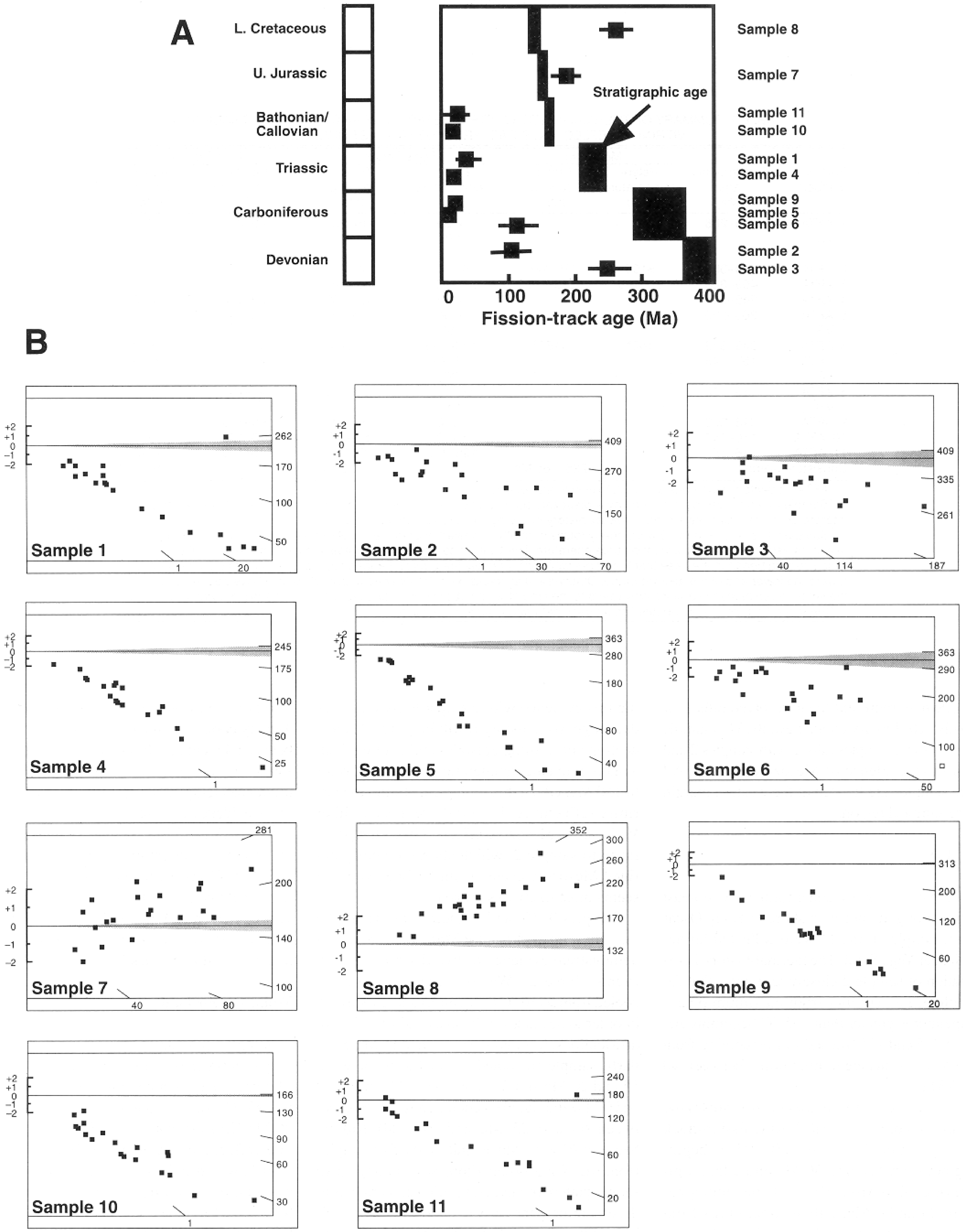

Figure 3. (A) Apatite fission-track and stratigraphic age plotted against stratigraphic section for each sample. (B) Single-grain ages for the samples; the horizontal line or shaded area in the radial plot diagram represents the stratigraphic age of the sample.

TABLE 2. SUMMARY OF THERMAL-HISTORY INTERPRETATION OF APATITE FISSION TRACK AND VITRINITE-REFLECTANCE DATA FROM NORTH-EAST GREENLAND

Sample number*	Stratigraphic age (Ma)	Mesozoic		Middle Tertiary		Late Tertiary	
		Paleo-temperature (°C)	Time of cooling (Ma)	Paleo-temperature (°C)	Time of cooling (Ma)	Paleo-temperature (°C)	Time of cooling (Ma)
1: AFTA	245–208			>125	45–25§	60–85	25–5
VR				170			
2: AFTA	409–363	>105	225–125§	85–95	40–5†		
3: AFTA	409–363	95–100	275–165	60–75	65–5†		
4: AFTA	245–208			>125	60–25§	80–100	20–0
5: AFTA	363–290			>130	40–15§	95–105	10–0
VR				150			
6: AFTA	349–333	140#	>150#	100–105	190–30	80–95	25–0
7: AFTA	157–146			85–95	70–20	20–75	30–0
VR				90			
8: AFTA	146–132			80–105	146–15	45–75	25–0
VR				100			
9: AFTA	318–303			>110	55–20§	90–105	15–0
10: AFTA	166–157			>120	55–20§	90–100	10–0
11: AFTA	166–157			105–135	50–15	95–100	15–0
Consistent overlap:			225–165 Ma		40–30 Ma		10–5 Ma

*AFTA—apatite fission-track analysis; VR—vitrinite reflectance.

†Samples 2 and 3 can be explained by a Mesozoic cooling episode and a single Tertiary cooling event. However, this interpretation may disguise a more complex history involving multiple Tertiary episodes.

§Samples 1, 2, 4, 5, 9, and 10 were nearly totally or totally annealed prior to the onset of cooling and only provide a minimum estimate of the maximum paleotemperature. The time for cooling given in these samples only refers to the time at which cooling began in the case that the tracks were only partially (near totally) annealed, with a maximum paleotemperature toward the lower end of the allowed range. Otherwise, if all tracks were totally annealed, cooling may have begun earlier, and the timing given in these samples only refers to the time at which tracks began to be retained on cooling to lower temperatures.

#Evidence from combined apatite fission track data and vitrinite reflectance.

episode may represent the unresolved effects of two discrete Tertiary cooling events. This sample is one of three samples (along with samples 2 and 6) to show evidence of Mesozoic cooling. All three samples are located at the western margin of the sampled region.

Traill Ø

Samples 2, 6, 9, 10, and 4 form a west-to-east section along the northern shore of Kong Oscar Fjord; samples 1 and 11 were collected farther north near Vega Sund. The thermal-history interpretation of sample 2 closely resembles that for sample 3, i.e., cooling from maximum paleotemperatures greater than 105 °C beginning between 225 and 125 Ma and further cooling from 85–95 °C to surface temperatures between 40 and 5 Ma.

For sample 6, the evidence for Mesozoic cooling is more equivocal. Apatite fission-track data suggest cooling from 100–105 °C beginning between 190 and 30 Ma and a later episode of cooling from 80–95 °C beginning between 25 and 0 Ma. Paleotemperatures from apatite fission-track analysis in the earlier episode correspond to vitrinite-reflectance values between 0.61% and 0.63%, whereas a value of 0.91% was measured at this location. Combining this evidence with the apatite fission-track data suggests a history involving three discrete heating and cooling episodes and cooling from a maximum paleotemperature of ~140 °C prior to 150 Ma. Given this timing constraint, the vitrinite-reflectance data could represent either Variscan or Mesozoic effects. Given the proximity to sample 2, which shows a clearly defined Mesozoic event, a similar interpretation seems most likely in sample 6.

Samples 9, 10, and 4, located farther to the east, show no evidence for Mesozoic cooling but demonstrate evidence of two discrete Tertiary events (Table 2). We conclude that sample 9 cooled from >110 °C between 55 and 20 Ma and, in order to account for the ages and track length distributions, from 90–105 °C since 15 Ma. Similarly, sample 10 cooled from >120 °C between 55 and 20 Ma and from 90–100 °C between 10 and 0 Ma, and sample 4 cooled from >125 °C between 60 and 25 Ma and from 80–100 °C between 20 and 0 Ma. Results in the five samples from the Kong Oscar Fjord section appear to show a pattern of increasing paleotemperatures to the east prior to the early to middle Tertiary cooling event and possibly for the later event as well. The implications of this trend are discussed in a later section.

In the region of Vega Sund, samples 1 and 11 also provide further evidence for two phases of Tertiary cooling. Sample 1 cooled from >125 °C between 45 and 25 Ma, consistent with the measured vitrinite-reflectance value of 1.5% (maximum paleotemperature of 170 °C), and also provides evidence for later cooling from 60–85 °C between 25 and 5 Ma. Sample 11 suggests cooling from a maximum paleotemperature of 105–135 °C starting between 50 and 15 Ma, the upper paleotemperature limit being set by one very Cl-rich grain. Later cooling from 95–100 °C since 15 Ma is also needed to account for both age reduction and short track lengths.

Wollaston Forland

Sample 7 provides clear evidence that two Tertiary events persisted to the far north of the area. Maximum paleotemperatures were between 85 and 95 °C; cooling commenced between 70 and 20 Ma. This estimate is consistent with a vitrinite-reflectance value from this location of 0.54%, which falls within the limits predicted by apatite fission-track analysis (equivalent $R_o\% = 0.51$ to 0.57). The later cooling event is less well defined, but the data do provide evidence for cooling from between 20 and 75 °C since 30 Ma. For sample 8, evidence for the first Tertiary cooling episode is more tentative;

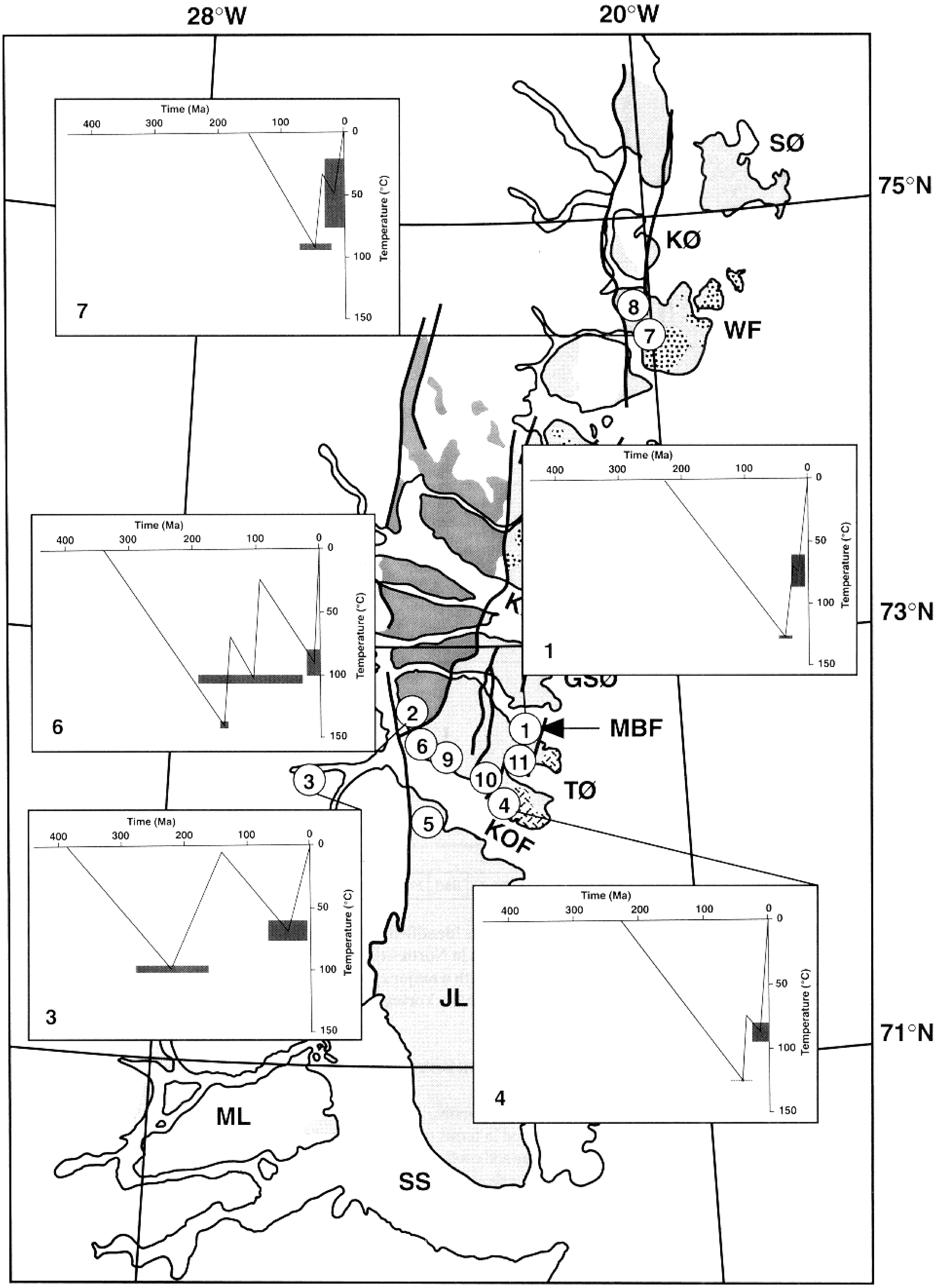

Figure 4. Schematic illustrations of the preferred thermal-history interpretation of apatite fission-track data from selected samples, superimposed on a map of the area (see Fig. 1 for explanation of abbreviations). For each sample illustrated, following the interpretation strategy outlined in the text, shaded boxes denote the range of maximum or peak paleotemperature and timing for the onset of cooling, which are compatible with the data from each sample, as summarized in Table 2.

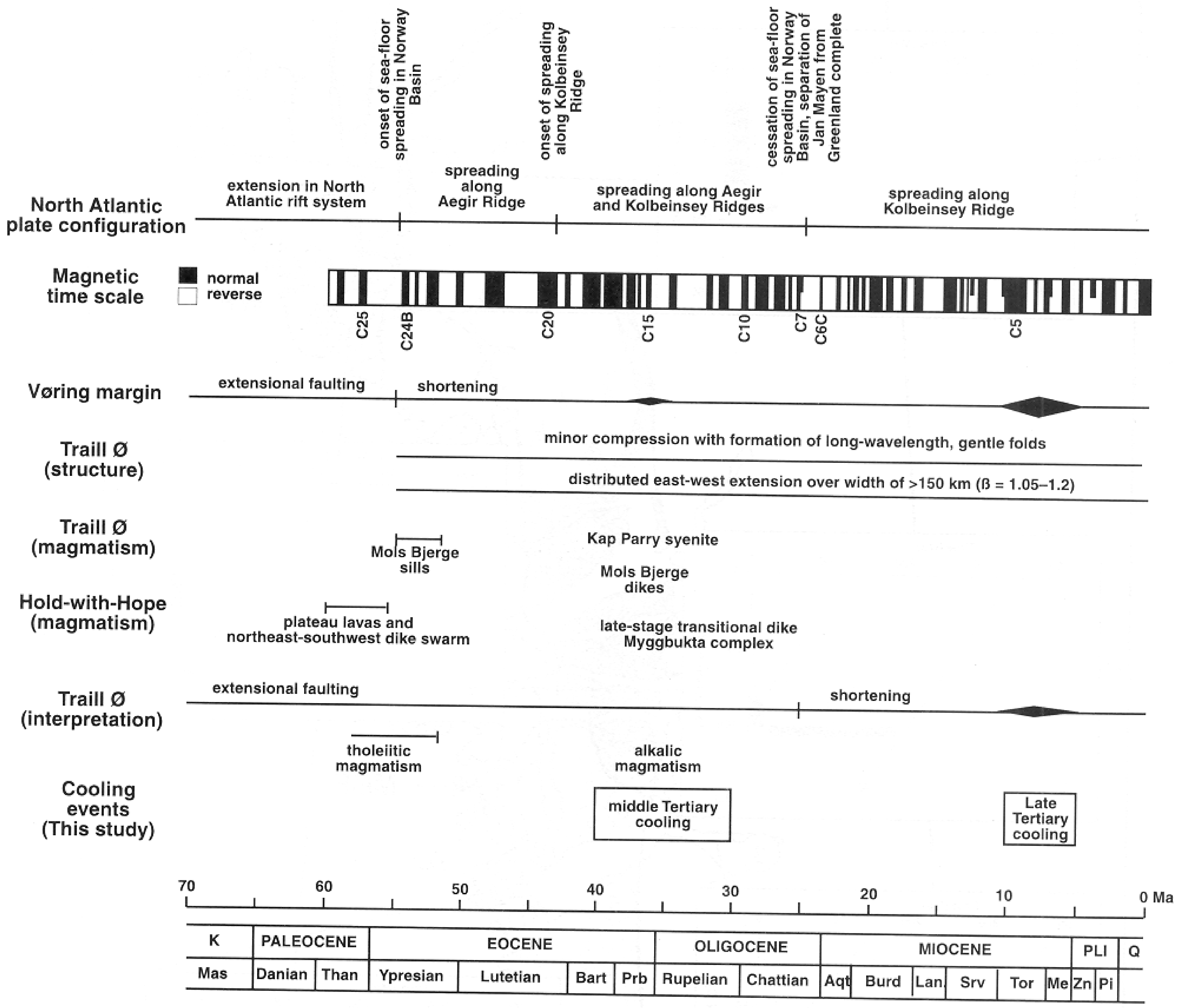

Figure 5. Comparison of the timing of major Tertiary cooling events identified in this study with significant magmatic and tectonic events recognized from geologic evidence in North-East Greenland and changes in North Atlantic plate configuration (based on Fig. 9 of Price et al., 1997). The middle Tertiary paleothermal episode correlates closely in time with a major episode of alkalic magmatism, and the late Tertiary episode correlates with evidence of widespread tectonism from East Greenland to the Voring Margin of Norway.

cooling from maximum paleotemperatures of ~80 to 105 °C began between deposition and 15 Ma. Although in principle this result could be interpreted as the effect of shorter tracks inherited from sediment source areas, a vitrinite-reflectance value of 0.60% from this location (Table 1) corresponds to a maximum paleotemperature of 100 °C, which confirms an earlier episode. Tighter constraints on timing from sample 7 suggest that this maximum paleotemperature in sample 8 represents a distinct middle Tertiary cooling event. In addition, the track-length data in sample 8 clearly require a late Tertiary cooling episode from paleotemperatures of 45 to 75 °C since 25 Ma.

THERMAL-HISTORY SYNTHESIS

Even though each individual sample's results can be explained in terms of two dominant episodes of heating and cooling, combining evidence from all samples shows that at least three episodes are clearly required to explain all the data (Table 2). The consistency of results throughout the region suggests that (1) the events were regionally synchronous and (2) the best estimates of their timing that are consistent with the data from all samples are Mesozoic (225–165 Ma), middle Tertiary (40–30 Ma), and late Tertiary (10–5 Ma).

Since samples were not collected over a range of elevations at any particular location, these data do not place any limits on the paleogeothermal gradients during any of the episodes, and it is not possible to directly estimate amounts of eroded section. However, as summarized in Figure 5, the Tertiary episodes identified in this study correlate closely with a number of regionally significant tectonic events, and therefore in the following sections we use regional geological information to deduce the nature of the three paleothermal episodes.

MESOZOIC COOLING AND EARLIER EPISODES

The three westernmost samples (Fig. 6) show consistent evidence of Mesozoic cooling, which

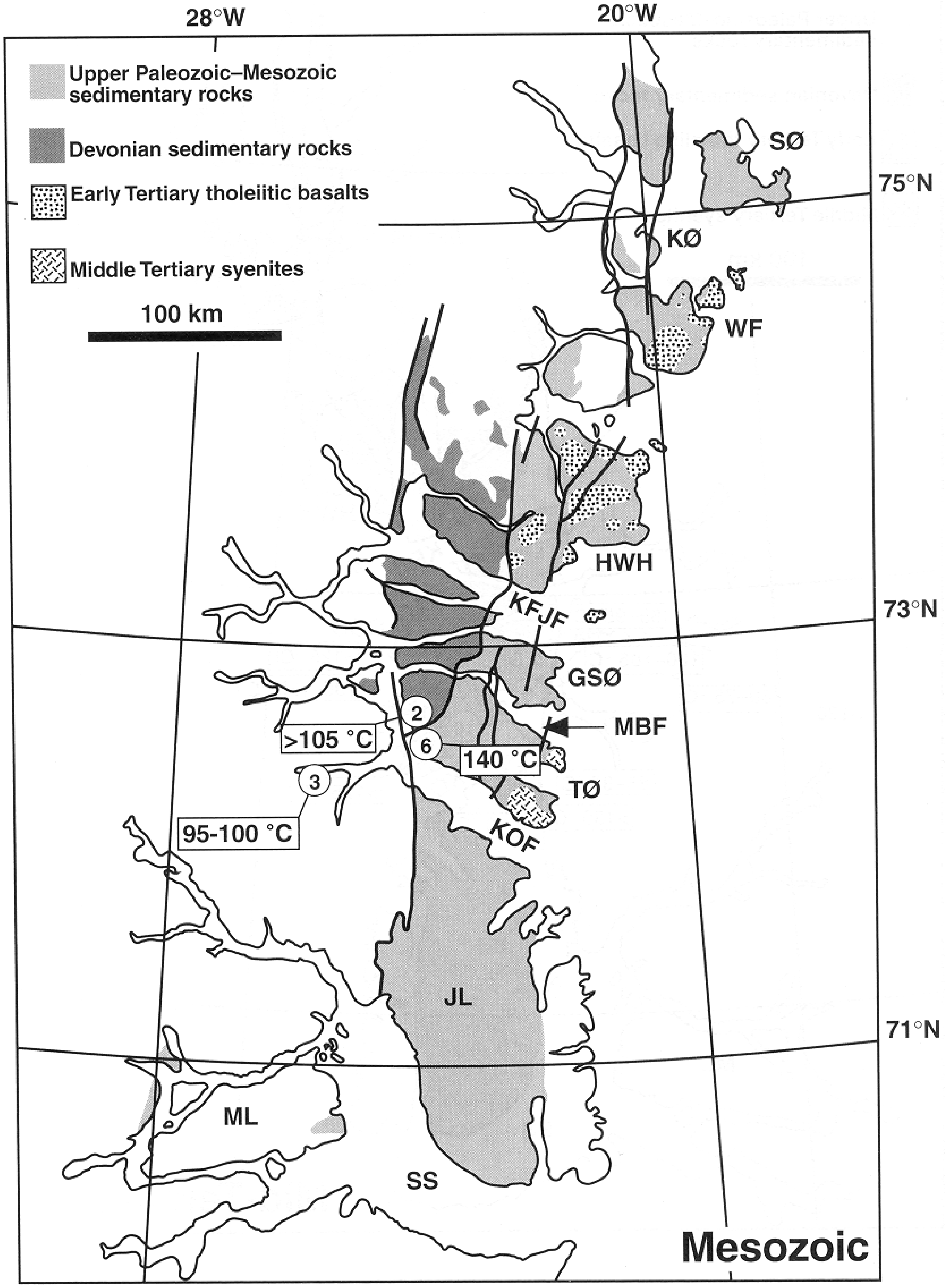

Figure 6. Mesozoic (225–165 Ma) paleotemperature map for East Greenland (see Fig. 1 for explanation of abbreviations).

began between 225 and 165 Ma. Maximum paleotemperatures immediately prior to the onset of cooling were between 95 and 140 °C. The true areal extent of this cooling event is not clear, but it would appear likely that it extended farther to the east but has been subsequently masked by Cenozoic thermal events (Figs. 7 and 8). The timing of this episode defined by apatite fission-track analysis allows several possible interpretations, but cooling related to uplift and erosion associated with an unconformity within the Jurassic sequence appears to be the most likely alternative. More detailed information is required on the regional extent and the pattern of variation in paleotemperatures characterizing this episode before a more definitive interpretation is possible.

The presence of additional unconformities within the Permian and older section suggests

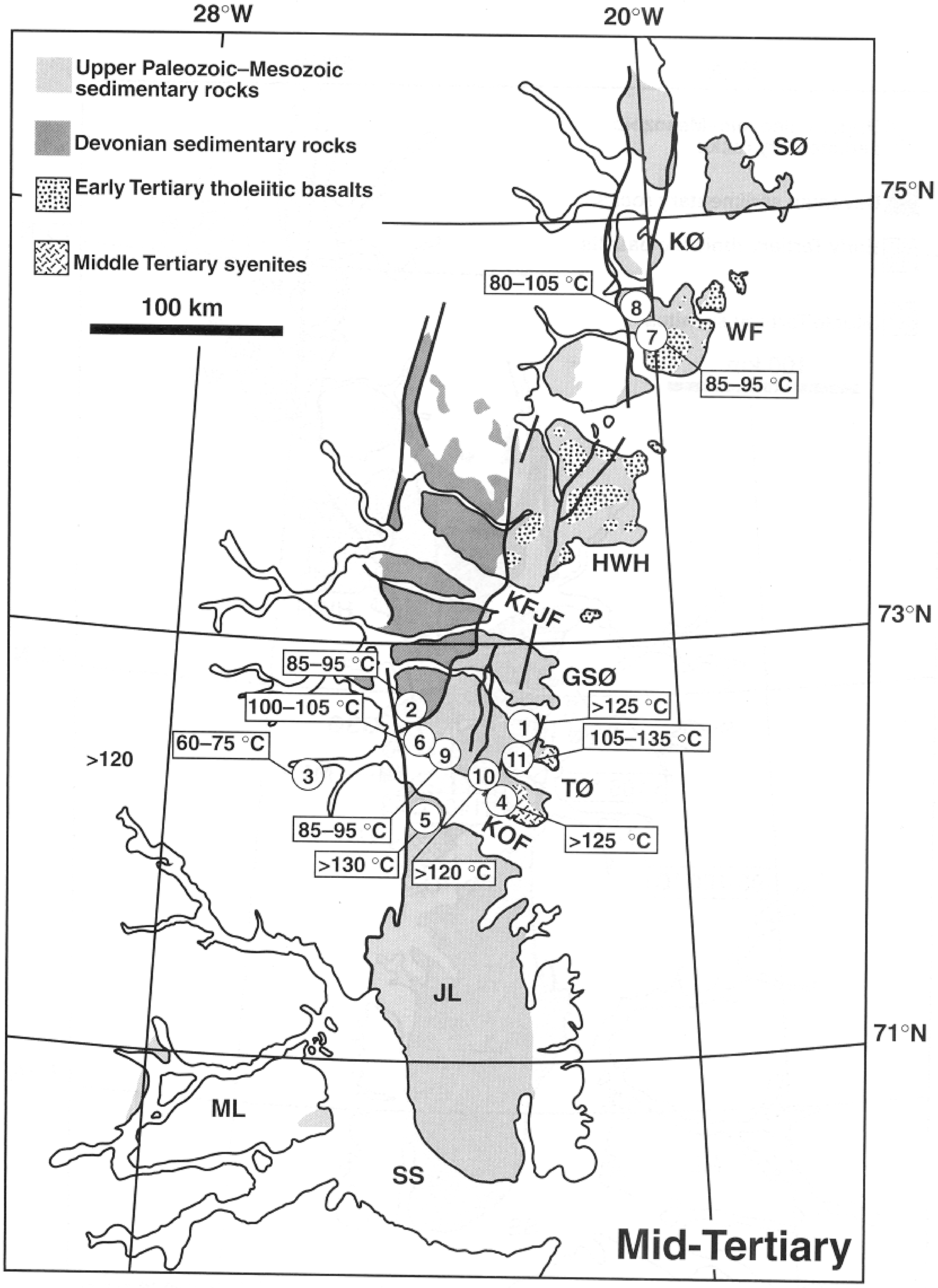

Figure 7. Middle Tertiary (40–30 Ma) paleotemperature map for East Greenland (see Fig. 1 for explanation of abbreviations).

that Carboniferous and older units might have reached higher temperatures during earlier episodes, possibly related to Caledonian or Variscan tectonism. The results of this study clearly show that more recent events dominate the thermal history of Devonian to Cretaceous units within the sampled region, and no evidence is preserved of any earlier events.

MIDDLE TERTIARY MAGMATISM, RIFTING, AND UPLIFT

Apatite fission-track data reveal a middle Tertiary cooling episode, beginning between 40 and 30 Ma, the magnitude of which increases to the east (Table 2 and Fig. 7). This was contemporaneous with alkalic magmatic activity at ca. 36 Ma (Gleadow and Brooks, 1979; Price et al., 1997), represented by the Kap Simpson and Kap Parry intrusions (Fig. 1). Sample 4, contained within the thermal aureole of the Kap Simpson syenite, was totally reset at this time, along with samples 5, 9, and 10 that are located nearby. The consistency between the timing of this regional paleothermal episode derived from

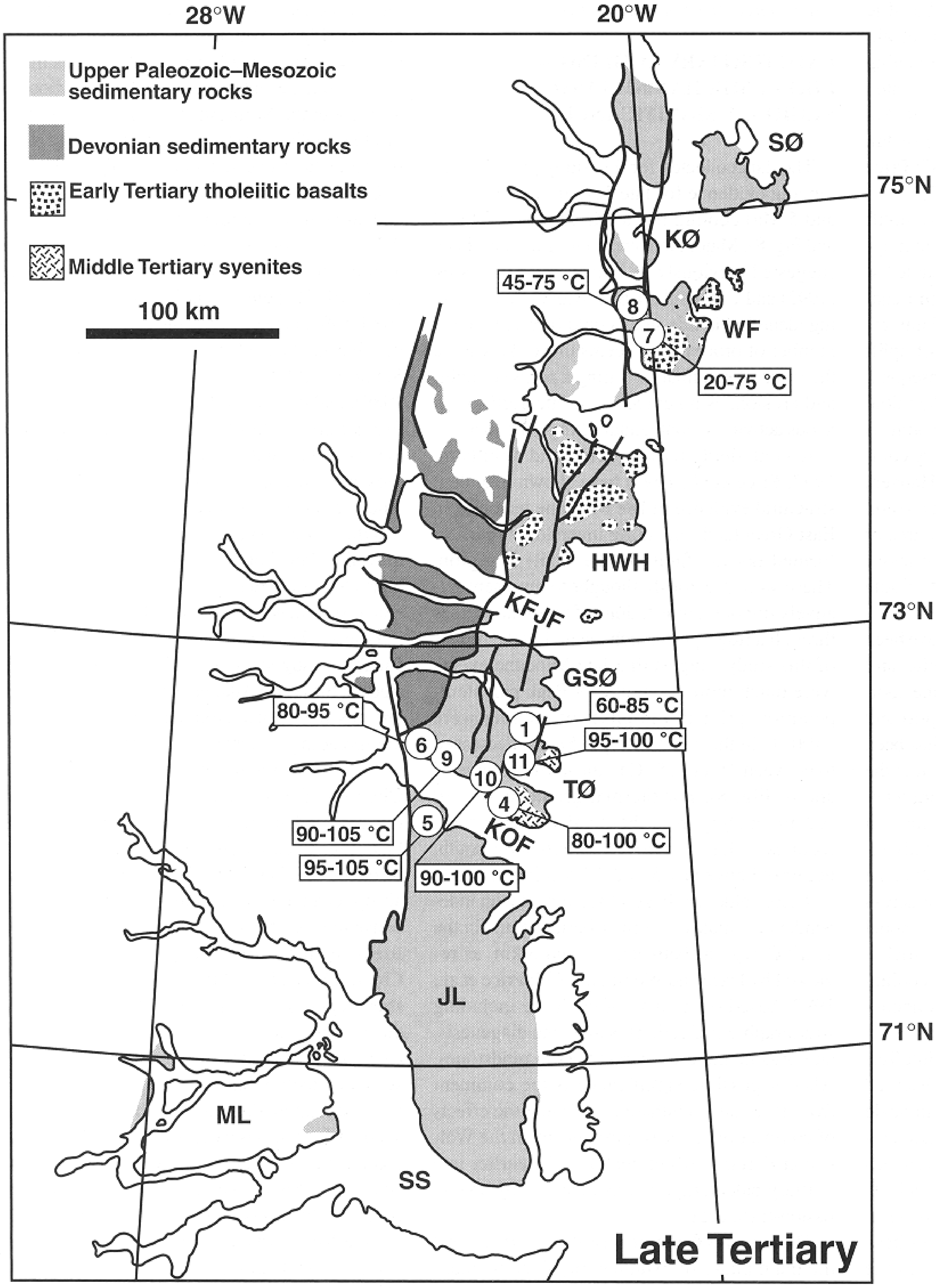

Figure 8. Late Tertiary (10–5 Ma) paleotemperature map for East Greenland (see Fig. 1 for explanation of abbreviations).

apatite fission-track analysis and the age of intrusive activity suggests a close relationship between the two. Since sample 4 lies within the thermal aureole of the Kap Simpson intrusion, the effects in this sample can be explained by contact heating associated with the intrusion. However, results from other samples distant from the intrusion (e.g., sample 2, located at a distance of almost 100 km from the intrusion) show consistent timing, and regional cooling at the same time as intrusion is required to explain the data.

Possible explanations for the regional cooling identified include uplift and erosion due to either crustal thickening associated with igneous activity or flexural uplift of the margins during continental separation, resulting in eastward-increasing uplift and erosion. Following this sort of explanation, we might expect two discrete phases of early to middle Tertiary cooling, the first associated with the tholeiitic basaltic event between 60 and 54 Ma (Upton et al., 1995; Price et al., 1997) related to the opening of the Norway Basin and the second associated with an alkalic magmatic event at ca. 36 Ma (Price et al., 1997) related to the rifting of Jan Mayen from East Greenland (Bott, 1987; Price et al., 1997; Talwani and Eldholm, 1977).

There is abundant outcrop evidence for uplift and erosion associated with the tholeiitic magmatic event (Price et al., 1997), but the apatite fission-track data show no evidence of significant cooling associated with this event, and any effects of deeper burial prior to this phase of uplift and erosion have been overprinted by subsequent events. It is possible that the effects of the initial rifting event are more pronounced to the south, as witnessed by evidence of an early Tertiary cooling event in southern Jameson Land (Hansen, 1988, 1992), but this phase of uplift and erosion either did not extend to the current study area or associated paleothermal effects were of lesser magnitude than those of the subsequent middle Tertiary episode.

As continental breakup is thought to have been associated with a mantle plume (White and McKenzie, 1989), it is conceivable that the cooling may have been related to thermal uplift and erosion driven by the plume. Indeed, it has been suggested by Lawver and Müller (1994) that the Iceland plume crossed the Greenland margin between 40 and 35 Ma, which may have resulted in thermal uplift and hence erosion in the study region. However, until more data are available, the expected pattern due to plume movement across Greenland cannot be constrained, and this model cannot be proved as yet. Furthermore, such a model cannot explain the early Tertiary cooling seen in Jameson Land or the base Tertiary unconformity in the current study area.

An alternative interpretation of the middle Tertiary paleothermal episode is that the observed paleotemperatures may be due to basin-scale heating as a result of hydrothermal circulation associated with the intrusion of sizable igneous bodies into the sedimentary sequence. Such effects have been identified in a number of sedimentary basins into which igneous bodies have been emplaced, including regions such as the Irish Sea (Green et al., 1995) and the Hebridean basins (unpublished work). Indeed, it might be surprising if emplacement of these intrusive bodies into relatively shallowly buried sediments (1 to 3 km, Price et al., 1997) did not cause extensive hydrothermal effects. As discussed earlier, the consistency of timing between the onset of cooling and the ages of these intrusive bodies strongly suggests a link between the two, and hydrothermal effects provide a mechanism by which the heat of the intrusions could be communicated to the basin sediments.

LATE TERTIARY COOLING—LIKELY MECHANISMS AND REGIONAL SIGNIFICANCE

The data collected for this study provide convincing evidence for late Tertiary (between 10 and 5 Ma) cooling in East Greenland (Table 2 and Fig. 8). Major Neogene cooling has also been suggested previously by Larsen and Marcussen (1992) and Clift et al. (1996). Although the cooling identified in this study could be ascribed to a number of processes, it seems most likely to be the result of exhumation during a period of uplift and erosion, as no evidence of late Tertiary igneous activity or continental rifting is known.

Recent field studies (Price and Whitham, 1997; Price et al., 1997) have shown abundant structural evidence of late Miocene tectonics in East Greenland, including inversion of earlier-formed normal faults in the Traill Ø region. These were previously thought to represent relatively minor manifestations of regional stresses through a ridge-push mechanism, but the results of this study suggest that late Miocene events were much more pronounced. Peak paleotemperatures prior to the onset of cooling were ~100 °C in the south (sample 5), but decreased to between 45 and 75 °C to the north (samples 7 and 8; Fig. 8). For thermal gradients of ~30 °C/km, cooling from these paleotemperatures requires ~3 km of removed section in the south, but only between 1.5 and 2.5 km in the north.

These values are in good agreement with independent estimates of former burial depths in the Traill Ø region (between 1.5 and 3 km, as reviewed by Price and Whitham, 1997; Price et al., 1997) based on a range of evidence including stratigraphic truncations, sandstone diagenesis, and organic maturity parameters in mudstones. Also of possible significance is the comment from Price and Whitham (1997) that the effects of compaction are least pronounced in the Wollaston Forland, which matches the earlier late Tertiary paleotemperatures recorded by apatite fission-track data.

These results therefore raise the possibility that the main phase of exhumation of sedimentary rocks now cropping out along the East Greenland coast may have taken place during the late Miocene (10 to 5 Ma). Such an explanation suggests, in turn, that any earlier episodes of erosion were relatively minor, which would favor an explanation of the middle Tertiary paleotemperatures in terms of hydrothermal circulation.

Although the late Tertiary events along the East Greenland coast could be viewed as purely local phenomena, Price and Whitham (1997) and Price et al. (1997) also highlighted the synchronous nature of tectonic events on the Vøring Margin of Norway (Fig. 5), which is the conjugate margin on the eastern side of the North Atlantic Ocean. In addition, similar events occurred in the late Miocene throughout the North Atlantic region, suggesting that this cooling event is a manifestation of a more fundamental process, acting on a regional scale.

Evidence for Neogene kilometer-scale uplift and erosion can be found throughout the North Atlantic region in Spitsbergen (Manum and Throndsen, 1977), the Barents Sea (Faleide et al., 1993), Fennoscandia (Eidviin and Riis, 1989, 1991; Ghazi, 1992), the marginal basins of the North Sea (Japsen, 1993; Jensen and Schmidt, 1992; van Wihje, 1987; Zagwijn, 1989), and the British Isles (Green et al., 1993). Furthermore, it has been demonstrated that the Faroe-Rockall and Solan Basins underwent compression during the Neogene (Boldreel and Andersen, 1993; Booth et al., 1993), suggesting that the Tertiary folds noted by Price et al. (1997) may also date from this time while the Central North Sea rift underwent a major phase of accelerated subsidence (Nielsen et al., 1986).

Bearing these facts in mind, it would seem reasonable to suggest that all these events on both sides of the North Atlantic have a common cause, one possible explanation being the dynamics of the spreading centers involved. With the extinction of the Labrador Sea spreading axis in the Oligocene, the direction of North Atlantic spreading changed from northwest-southeast in the Paleocene to east-west in the late Oligocene and Neogene (Becker, 1993; Ziegler, 1989). Such an abrupt change in spreading could have serious consequences for the adjacent margins as the stress regime altered. As previously noted by Cloetingh et al. (1990), small changes to the stress regimes of otherwise stable plates can produce significant vertical movements and localized compression or extension. Consequently, it seems plausible that the changes in North Atlantic spreading directions in the Neogene may account for the observed effects by placing the continental plates under a low level of compressive stress. Such a stress regime may then account for the inversion seen in the basins bounding the North Atlantic. Furthermore, intraplate compressional stresses have been shown to amplify existing lithospheric deflections (Cloetingh et al., 1990), accounting for the uplift of onshore East Greenland (the flank to the Tertiary rift), Britain, and Fenno-Scandia (flanks of the North Sea) and the accelerated subsidence observed in the central North Sea. Such an hypothesis would imply that in areas of the North Atlantic margins yet to be examined in detail, similar events can be expected.

CONCLUSIONS

Apatite fission-track data from East Greenland clearly show three episodes of cooling. The earliest episode occurred between 225 and 165 Ma and is only recorded in the western part of the region, although it has probably been masked by later events in the east. The exact timing and cause of this Mesozoic cooling episode is difficult to establish owing to the limited data available, but may reflect uplift and erosion associated with recognized unconformities within the Jurassic section.

A period of middle Tertiary cooling, which began between 40 and 30 Ma, contemporaneous with alkalic magmatic activity, is found throughout the area. One sample locality is contained within the thermal aureole of the Kap Simpson Syenite, and effects in this sample can be ascribed to contact metamorphism, but evidence of regional heating and cooling through the remainder of the area requires another mechanism. Regional middle Tertiary cooling could be due to uplift and erosion as the result of crustal thickening, but the data only show evidence for the cooling associated with the 36 Ma magmatic event; there is no evidence for cooling contemporaneous with an earlier tholeiitic event. Alternatively the cooling event could be due to plate or microplate separation with flexural uplift of the Greenland margin as it separated from the Jan Mayen microplate.

Furthermore, if continental breakup was associated with a mantle plume, it is conceivable that the cooling may be related to transient thermal uplift and erosion, driven by the Iceland plume that crossed the Greenland margin between 40 and 35 Ma. An alternative explanation is that the middle Tertiary paleothermal episode may result from basin-scale hydrothermal circulation, as large amounts of magmatic material were intruded into the crust.

The data also provide convincing evidence for a late Tertiary cooling episode (beginning between 10 and 5 Ma) in East Greenland. Although the cooling could be ascribed to various processes, it seems most likely to be the result of exhumation during a period of uplift and erosion. Independent estimates of former depths of burial suggest that this late Tertiary cooling episode represents the major episode of Tertiary exhumation. This interpretation favors an explanation of middle Tertiary effects in terms of hydrothermal circulation associated with intrusive activity.

The late Tertiary episode is also synchronous with periods of accelerated uplift, subsidence, and inversion throughout the North Atlantic region, suggesting a common underlying cause. The extinction of the Labrador Sea spreading axis in the Oligocene resulted in changes in North Atlantic spreading direction and, hence, changes in plate stress regimes and lithospheric deflection. It is therefore possible that such events may have resulted in uplift, erosion, and, hence, the cooling observed in East Greenland.

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