

REPORT

REPORT TITLE:

**Apatite fission track analysis, Shallow Drilling
Barents Sea 1988**

23.1373.00/01/90

REPORT NO.:

AUTHORS:

Geotrack International with preface by IKU



IKU

SINTEF GROUP

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SUMMARY:

Apatite fission track analysis has been performed on IKU Shallow Drilling Barents Sea 1988 core material by Geotrack International. Results and interpretations are presented in the enclosed Geotrack Report no. 193 "Apatite fission track analysis of 16 samples from eight shallow cores from the Barents Sea" supplemented by some introductory comments by IKU.

The samples represent sandstones from Upper Paleozoic and Triassic cores from Finnmark East as well as Triassic and Cretaceous cores farther north. Maximum paleotemperatures have been estimated for 14 of the samples, and the time of onset of cooling is tentatively indicated. The present data combined with earlier data indicate regional trends with respect to maximum paleotemperatures and possibly also provenance.

KEY WORDS: Apatite	Paleotemperatures
Fission track analysis	Finnmark East
Barents Sea	Erosion

APATITE FISSION TRACK ANALYSES, SHALLOW DRILLING BARENTS SEA 1988 BACKGROUND AND COMMENTS

By Mai Britt E. Mørk, IKU

BACKGROUND

Apatite fission track analysis (AFTA) has proven to be a useful tool in modelling of thermal history of sedimentary basins, and has also been performed with success on IKU shallow drilling core material. A disadvantage by using material from the shallow cores is that the depth intervals that can be studied are very limited, thus excluding the possibility to calculate thermal gradients and to reveal detailed erosion histories. On the other hand, by combining fission track data with biostratigraphic datings, the fission track data offer a possibility to interpret maximum burial temperatures. In cases with relatively low diagenetic temperatures, apatite fission track data also have applicability for provenance interpretations.

A database of apatite fission track analyses on IKU shallow core material already exists for Mesozoic sandstones from eight different cores in the Barents Sea (Finnmark East, Nordkapp Basin, Svalis Dome) (Re-edited GEOTRACK reports; Green & Marshallsea 1989 a,b). In the present study, sandstone samples were selected both from the northern area (Bjarmeland Platform: Triassic core 7430/07-U-01 and Cretaceous core 7430/10-U-01) and from several cores near the coast of Norway (Finnmark East: Early Carboniferous cores 7127/10-U-03, -U-02, 7029/03-U-01, Late Carboniferous core 7029/03-U-02, Permian and Early Triassic core 7128/12-U-01 and Triassic core 7128/09-U-01). AFTA results and interpretations are presented in the enclosed GEOTRACK report. The purpose of the present AFT-analysis is:

- 1) To obtain additional data on the maximum burial depths to supplement the studies already given in the IKU drilling report (Bugge et al. 1989).
- 2) To compare AFTA results in different units (with different ages) in the cores in order to look for parameters that can be used to distinguish them (such as points 1 or 4).

- 3) To examine the possibility of regional geographic trends in the maximum burial depths (for rocks of similar age).
- 4) To get information on provenance on a local and regional scale in order to supplement other studies of provenance.

Some comments with reference to points 1-4 above:

1) AFTA data from the Upper Paleozoic cores from Finnmark East from the 1988 drillings generally give maximum burial temperatures of 70 - 80 (90) °C similar to the estimates for the two easternmost cores that were drilled in 1987. One of the cores (7127/10-U-02) gives a somewhat higher maximum paleotemperature (90 - 100 °C) (Fig 1). At similar geothermal gradient conditions the maximum temperature difference of 20 °C may correspond to 0.7 - 0.5 km differences in burial depths (for geothermal gradients of 30-40 °C/km). A previous IKU heat flow measurement offshore to the north of core 7127/10-U-02 indicates a high geothermal gradient (42 - 46 °C/km depending on type of corrections; Sættem 1988). With the high heat flow value the 90 - 100 °C maximum paleotemperatures corresponds to burial depths of more than 2 km, while the more common values between 70 - 80 °C transform to 1.5 - 1.7 km. If the geothermal gradient was more normal, say 30 °C/km, the paleotemperatures would correspond to burial depths of 2.3 - 2.7 km with a maximum burial depth exceeding 3 km for core 7127/10-U-02. If the temperature differences are real, this could either reflect different degrees of burial or local differences in geothermal gradient conditions.

The estimates based on the AFT data indicate deeper burial than concluded in the IKU Shallow Drilling 1988 report where 1 to 1.5 km maximum burial depths are suggested for the Upper Paleozoic cores in the coastal areas. The size of the discrepancy is depending on the geothermal gradients used, but the present AFT data would anyhow indicate deeper maximum burial depths. The largest deviation is for core 7127/10-U-02. In order to solve the problems a more detailed study of the diagenesis based on selected clay mineral fractions would be needed.

The temperatures of the two Triassic cores from Finnmark East (7128/09-U-01) and from the Bjarmeland Platform (7430/07-U-01) are 70 - 80 °C and

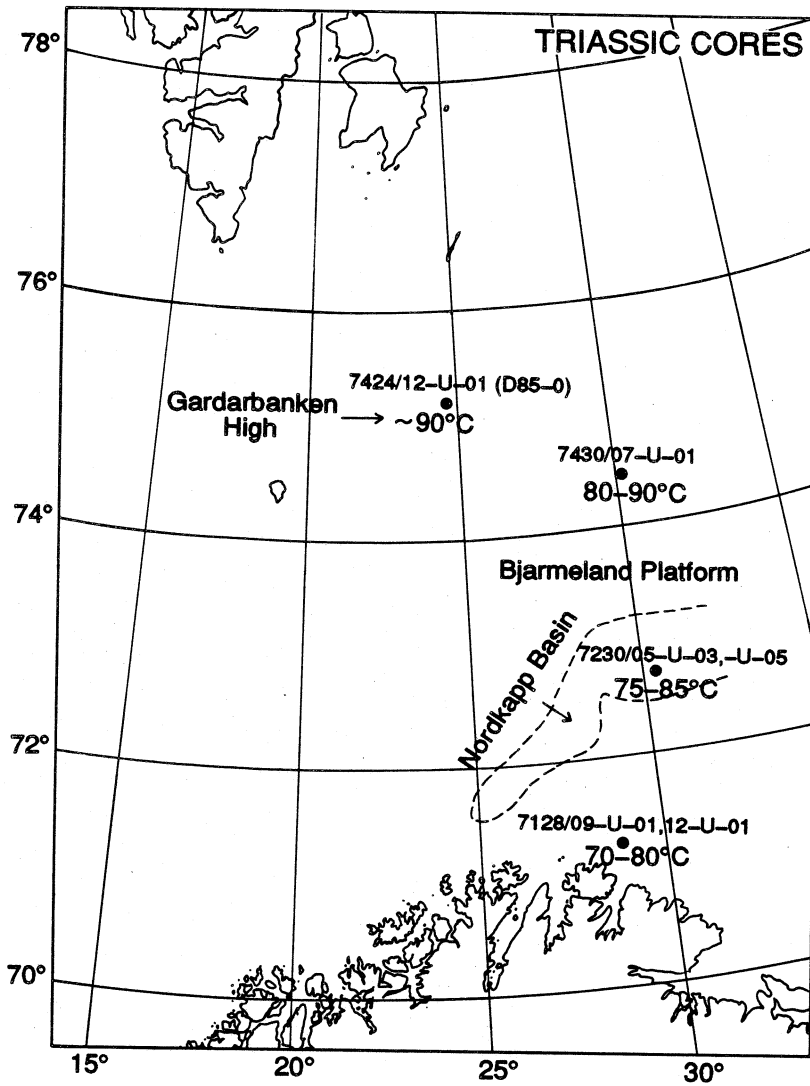


Figure 1a

Maximum paleotemperatures based on apatite fission track analyses for Triassic cores from IKU shallow drilling Barents Sea 1988 (7430/07-U-01, 7128/09-U-01), 1987 (7230/05-U-03, -U-05) and 1985 (7424/12-U-01).

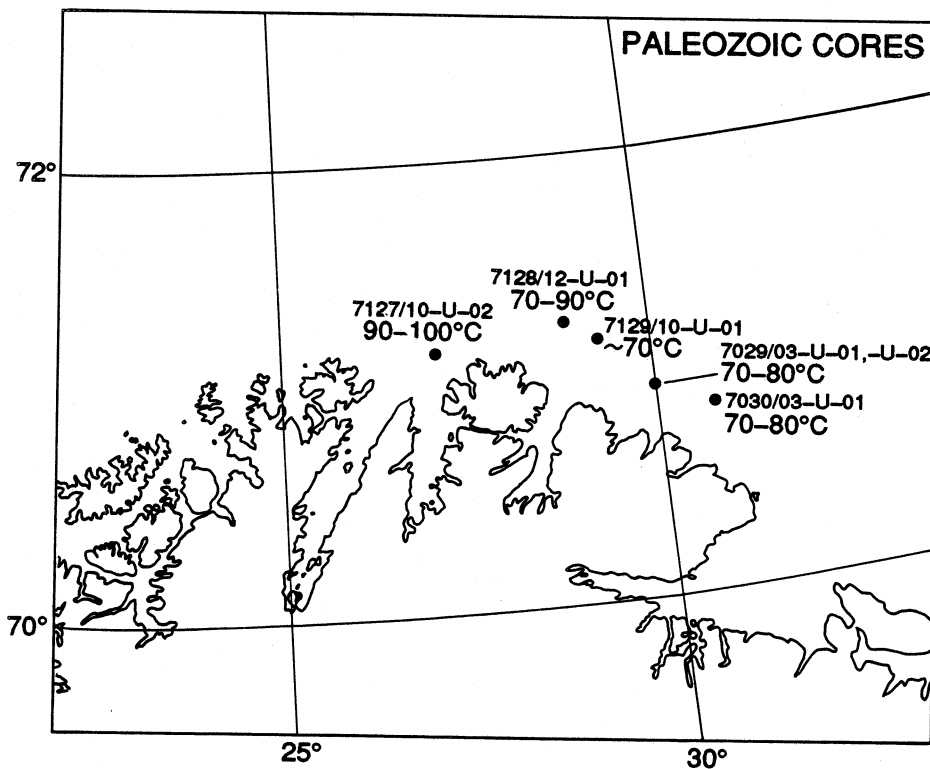


Figure 1b

Maximum paleotemperatures based on apatite fission track analyses for Late Paleozoic cores, Finnmark East, IKU shallow drilling Barents Sea 1988 (7127/10-U-02, 7128/12-U-01, 7029/03-U-01, -U-02) and 1987 (7129/10-U-01, 7030/03-U-01).

80 - 90 °C, respectively, indicating burial depths of 2.3 - 2.7 km and 2.7 - 3.0 km for a geothermal gradient of 30 °C/km (or 1.8 - 2.1 km and 2.1 - 2.4 km using 38 °C/km; cf. heat flow data in northern areas; Sættem 1988). This indicates a deeper burial depth in the northern area than in the coastal area, a trend which has also been reported by the IKU 1988 Shallow Drilling Report, although the maximum burial estimates are somewhat lower in the latter (1.5 - 2 km and 1.0 - 1.5 km for the northern and coastal areas, respectively).

2) The present database does not allow to distinguish between different stratigraphic or seismic units on the basis of the AFT data as exemplified by samples from two different seismic units (Early Carboniferous) in each of the cores 7029/03-U-01, 7029/03-U-02 (Late Carboniferous) and 7128/12-U-01 (Triassic and Permian). The calculated AFT paleotemperatures are either similar or overlapping, and the single-grain age distributions also appear similar for the different units within a core.

3) When the maximum paleotemperatures for the present study and from the previous IKU AFT-Barents Sea studies are considered collectively, a regional trend appears with increasing maximum paleotemperatures towards the north from 70-80 °C in the coastal area (7128/09-U-01) to ca. 90 °C in the Gardarbanken High area (7424/12-U-01). This has been illustrated for the Triassic cores in Fig. 1. This general trend is in harmony with our knowledge from other data that documents increased amounts of erosion towards north in the Barents Sea from the coast of Finnmark.

4) Provenance information may include the shape of the apatite grains and single grain apatite ages at relatively low burial temperatures. The combination of anhedral or subhedral shape of apatite grains and the presence of Early Paleozoic and Precambrian single grain ages in the Carboniferous - Permian cores on Finnmark East clearly reflect derivation from old Baltoscandic basement rocks. By contrast, the oldest single grain apatite ages are absent in the Mesozoic cores (considering the cores with lowest temperatures only), although some Caledonian influence is indicated. When all the present (1988 material) and the earlier IKU Barents Sea AFT data are considered, regional geographic patterns with respect to provenance are tentatively indicated. These include a) the appearance of euhedral (Late Paleozoic or Early Mesozoic) apatites in immature Mesozoic sandstones in the vicinity of the Nordkapp Basin and the Bjarmeland Platform and b) manifestation of the importance of the Baltoscandic (Finnmark) old basement rocks as a sediment source in the coastal Late

Paleozoic rocks. (a) is questioning the possibility of a Late Paleozoic or Early Mesozoic volcanic sediment source.

Follow-up projects:

On the basis of the IKU 1988 drill report and the present apatite fission track data, a follow-up study of the diagenesis on Finnmark East samples from 7127/10-U-02 and -U-03 will be suggested. Such a study will emphasize XRD analysis of concentrated clay mineralogy fractions, but other methods may also be considered.

A follow-up study of provenance has already been suggested under the IKU Arctic Correlation Program. Here, apatite fission track data will be used as a small part together with several other methods (petrography, mineral chemistry, isotopic signatures) to interpret and compare provenance for selected Upper Paleozoic and Mesozoic cores.

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**APATITE FISSION TRACK ANALYSIS OF
16 SAMPLES FROM EIGHT SHALLOW CORES
FROM THE BARENTS SEA**

**A report prepared for
IKU, Trondheim, Norway**

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**APATITE FISSION TRACK ANALYSIS OF
SIXTEEN SAMPLES FROM EIGHT SHALLOW CORES
IN THE BARENTS SEA**

CONTENTS

	Page
Executive Summary	i
Paleotemperature Analysis - Table 4	ii
Schematic Thermal History Interpretation - Figure 1	ii
1. Introduction	1
2. Thermal History Interpretation	1
2.1 7430/10-U-01	1
2.2 7430/07-U-01	2
2.3 7128/09-U-01	2
2.4 7128/12-U-01	3
2.5 7127/10-U-03	4
2.6 7127/10-U-02	4
2.7 7029/03-U-02	5
2.8 7029/03-U-01	5
3. Regional Interpretation	6
Appendix A - Sample Details	A1 - A2
Appendix B - Sample Preparation and Experimental Details	B1 - B2
Appendix C - AFTA™ Data Tables and Figures	C1 - C26
Appendix D - Principles of Interpretation of AFTA™ Data	D1 - D6

GEOTRACK™ REPORT #193

**APATITE FISSION TRACK ANALYSIS OF
SIXTEEN SAMPLES FROM EIGHT SHALLOW CORES
IN THE BARENTS SEA**

EXECUTIVE SUMMARY

1. All samples analysed show consistent signs of having been subjected to elevated paleotemperatures at some time in the past. Estimated maximum paleotemperatures fall in the range 70°-100°C.
2. Cooling from maximum paleotemperatures probably began in the late Cretaceous or early Tertiary, in the 50-70 Ma range. No information is available on the style of cooling.
3. The data provide no constraint on the paleogeothermal gradient at the time at which maximum paleotemperatures were attained, and analysis of samples over a wider range of depths (~1 km or more) would be required for this purpose.
4. If the paleogeothermal gradient was ~30°C/km, then the estimates of maximum paleotemperatures in different samples translate to between 2 and 3 km of uplift and erosion since the late Cretaceous or early Tertiary.
5. When the results of this study are considered in the regional context, together with results from a previous report for IKU on similar samples from shallow cores in the Barents Sea (Geotrack Report #147), a consistent pattern emerges, with estimates of maximum paleotemperature showing a general increase to the North, into the Barents Sea from the Norwegian mainland
6. Regional variation of maximum paleotemperatures, over distances of several hundred kilometres, seems most compatible with regional uplift and erosion than from variation in elevated geothermal gradients. Therefore an interpretation of all AFTA data from shallow cores in the Barents Sea in terms of between 2 km (in the south) and 3 km (to the north) of late Cretaceous and early Tertiary uplift and erosion is preferred.

GEOTRACK™ REPORT #193

Table 1: Paleotemperature analysis - Barents Sea shallow cores (Geotrack™ Report #193)

Sample number	Core number	Average depth (m)	Fission track age (Ma)	Corrected age (Ma)	Stratigraphic age (Ma)	Mean track length (μ m)	I_p (μ m)	Present temperature (°C)	Estimated maximum paleotemperature (°C)
GC193-1	7430/10-U-01	44.85	170.5 $\pm$ 41.1	416	138-144	8.94 $\pm$ 1.68	14.5	3	70-90
GC193-2	7430/07-U-01	24.45	213.7 $\pm$ 17.0	281	~225	11.24 $\pm$ 0.24	14.5	2	80-90
GC193-3	7430/07-U-01	70.05	202.3 $\pm$ 32.8	277	~225	10.93 $\pm$ 0.22	14.5	4	80-90
GC193-4	7430/07-U-01	116.15	169.2 $\pm$ 12.4	214	225-231	11.48 $\pm$ 0.29	14.5	5	80-90
GC193-5	7128/09-U-01	85.50	325.7 $\pm$ 15.9	379	243-248	12.36 $\pm$ 0.19	14.5	6	70-80
GC193-6	7128/12-U-01	64.85	322.3 $\pm$ 21.2	370	~248	12.62 $\pm$ 0.29	14.5	5	70-80
GC193-7	7128/12-U-01	113.05	219.7 $\pm$ 36.9	244	248-255	13.05 $\pm$ 0.43	14.5	7	80-90
GC193-8	7128/12-U-01	147.9	262.1 $\pm$ 65.7	-	258-268	-	14.5	8	70-90?
GC193-9	7127/10-U-03	104.7	-	-	333-340	-	14.5	7	?
GC193-10	7127/10-U-02	107.35	-	-	333-340	-	14.5	7	?
GC193-11	7127/10-U-02	183.4	125.0 $\pm$ 35.0	152	333-340	11.82 $\pm$ 1.05	14.5	9	90-100
GC193-12	7029/03-U-02	104.95	301.5 $\pm$ 25.3	343	286-296	12.74 $\pm$ 0.24	14.5	7	70-80
GC193-13	7029/03-U-02	149.60	284.8 $\pm$ 59.1	320	296-320	12.82 $\pm$ 0.57	14.5	8	70-80
GC193-14	7029/03-U-02	194.30	325.0 $\pm$ 45.2	378	286-360	12.52 $\pm$ 0.43	14.5	9	70-80
GC193-15	7029/03-U-01	99.75	300.9 $\pm$ 36.5	359	330-340	12.14 $\pm$ 0.53	14.5	6	70-80
GC193-16	7029/03-U-01	137.10	355.1 $\pm$ 68.5	418	333-352	12.34 $\pm$ 0.37	14.5	8	70-80

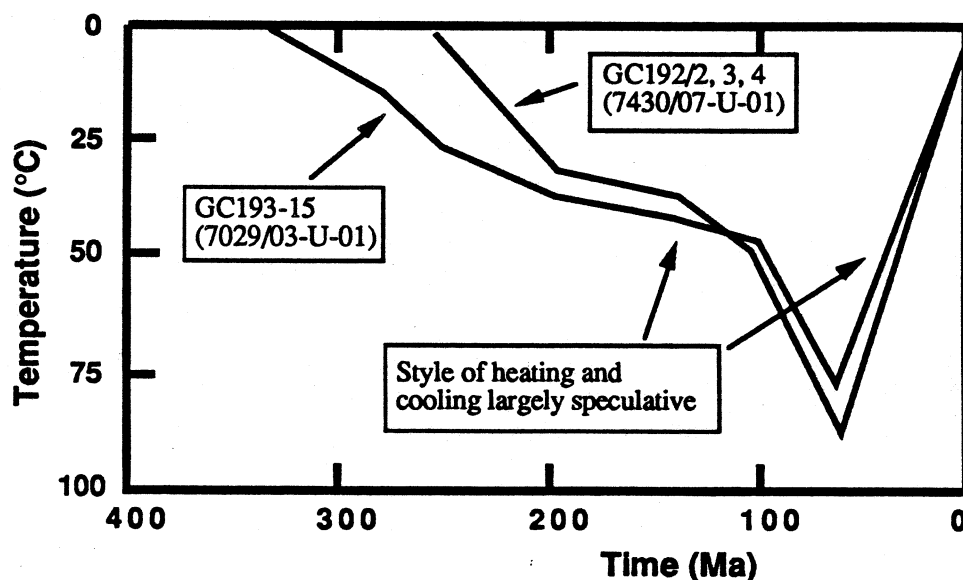


Figure 1: Schematic illustration of preferred thermal history interpretation for AFTA data from Barents Sea shallow cores 7430/07-U-01 and 7029/03-U-01. Data from other cores suggests basically similar interpretations, with the maximum paleotemperature varying slightly between different samples as summarised in Table 1. Note that the approach to maximum paleotemperature and the style of cooling shown in the diagram are largely speculative, as the data allow no real constraint on these aspects of the thermal history. The maximum paleotemperatures are well constrained however, as is the time of the onset of cooling, which appears to have been in the Late Cretaceous or Early Tertiary at ~50-70 Ma.

1. Introduction

This report describes results of an AFTA™ study of sixteen samples from eight shallow cores from the Barents Sea submitted for analysis by the Continental Shelf and Petroleum Technology Research Institute A/S, Trondheim, Norway (IKU). Samples details are summarised in Appendix A, while sample preparation and experimental details etc are described in Appendix B. The AFTA data obtained from the samples are presented in Appendix C, in the form of both Tables and Figures. Details of the data presentation are also discussed in Appendix C, while Appendix D outlines the principles employed in interpreting the AFTA data in terms of thermal histories.

All samples show consistent signs of having been subjected to elevated paleotemperatures at some time in the past, prior to cooling which probably began in the late Cretaceous or early Tertiary, in the 50-70 Ma range. Figure 1 shows a schematic illustration of the main features of the paleotemperature interpretation of the AFTA data in the analysed samples. The estimated maximum paleotemperatures in each sample are summarised in Table 1, together with various AFTA parameters. In the following discussion, the interpretation of AFTA data in samples from each core is briefly discussed, and the final section presents some comments on the regional interpretation of the AFTA data from this study together with results from similar samples from the same area analysed in a previous study for IKU (Geotrack Report #147).

2. Thermal history interpretation

2.1 7430/10-U-01

The single sample analysed from this core shows some evidence of having been subjected to elevated paleotemperatures since deposition. The main lines of evidence are the presence of one grain with a fission track age of 16 ± 12 Ma, which is significantly younger than the stratigraphic age, and the very short mean length of 8.94 ± 1.68 Ma. Although only five track lengths were measured in this sample, all tracks are less than 14 μm , whereas tracks formed since deposition at temperatures less than 50°C would have tracks in the 13-16 μm region. Since the fission track age is only slightly older than the stratigraphic age, the observed degree of length reduction cannot be inherited from source areas, and therefore suggests elevated paleotemperatures.

Because of the scarcity of track lengths in this sample, only a broad estimate of maximum paleotemperature can be obtained for this sample of ~70°-90°C. From this sample alone,

little information is available on the time of cooling, although the single grain with the fission track age of ~16 Ma suggests the possibility of Tertiary cooling.

Since tracks in these samples have clearly undergone some annealing since deposition, it is difficult to extract too much information on the provenance of the analysed apatite grains. With a corrected age of ~418 Ma, and individual grain ages spread from ~16--350 Ma, an original source in Caledonian and/or Hercynian basement is most likely.

2.2 7430/07-U-01

The three Triassic samples analysed from this core (GC193-2, 3 and 4) all show consistent evidence of having been subjected to elevated paleotemperatures at some time since deposition. The mean fission track age of GC193-4 (169.2 ± 12.4 Ma) is significantly less than the stratigraphic age of 225-231 Ma, while in all three samples a number of individual grains give fission track ages which are significantly younger than the stratigraphic age, in the 50-100 Ma range. The track length distributions all show a suggestion of bimodality, with a large proportion of tracks at lengths less than 12 μm . Tracks formed since deposition at temperatures less than 50°C would have lengths in the 13-16 μm region, and since the mean fission track ages of these three samples are less than or indistinguishable from the stratigraphic age, the observed degree of length reduction cannot be inherited from source areas. All these lines of evidence therefore suggest elevated paleotemperatures in the three samples analysed from this core.

A maximum paleotemperature of ~80°-90°C is estimated for these three samples. No firm evidence is available on the timing of cooling, but attempts to reproduce the form of the length distributions, together with the youngest single grain fission track ages, suggest an onset of cooling some time around the end of the Cretaceous or into the early Tertiary, in the 50-70 Ma range.

Since tracks in these samples have clearly undergone appreciable annealing since deposition, it is difficult to extract too much information on the provenance of the analysed apatite grains. Corrected ages of ~280 Ma in GC193-2 and 3 may suggest a source from Hercynian basement, although within the uncertainties associated with the age correction procedure, a contribution from Caledonian terrain cannot be ruled out.

2.3 7128/09-U-01

Fission track age data from the single sample analysed from this core (GC193-5) show no evidence of appreciable annealing since deposition, as the pooled fission track age is greater than the stratigraphic age and none of the single grain ages are significantly less than the stratigraphic age. However, the mean length of only 12.36 ± 0.19 μm is less than the

expected length of tracks which would have formed at the prevailing temperature since deposition, and the lack of a dominant peak in the length distribution at around $\sim 13\text{-}16\text{ }\mu\text{m}$ suggests that a moderate degree of length reduction has occurred since deposition, at elevated paleotemperatures.

A maximum paleotemperature of $\sim 70^{\circ}\text{-}80^{\circ}\text{C}$ would be required to produce the observed degree of length reduction in this sample. No firm evidence is available on the timing of cooling, but attempts to reproduce the form of the length distributions suggest an onset of cooling some time around the end of the Cretaceous or into the early Tertiary, in the 50-70 Ma range, as in GC193-2, 3 and 4, discussed above.

Since tracks in this sample have undergone a rather lower degree of annealing since deposition than the other samples discussed so far, more information can be obtained on the provenance of the analysed apatite grains. With a corrected age of $\sim 379\text{ Ma}$, and individual grain ages mostly above $\sim 250\text{ Ma}$, and bearing in mind the amount of annealing that has occurred, an original source in Caledonian basement is most likely for the apatites analysed in this sample.

2.4 7128/12-U-01

Two of the three samples from this core (GC193-6 and 7) show consistent evidence of exposure to elevated paleotemperatures at some time after deposition. The main evidence in support of this conclusion comes from the track length data in these samples, for the same reasons as in GC193-5. The mean lengths of only $12.62 \pm 0.29\text{ }\mu\text{m}$ and $13.05 \pm 0.43\text{ }\mu\text{m}$ in GC193-6 and 7, respectively, are less than the expected mean length of tracks which would have formed at the prevailing temperature since deposition. The absence of a dominant peak in the length distribution at around $\sim 13\text{-}16\text{ }\mu\text{m}$ suggests that a moderate degree of length reduction has occurred since deposition, at elevated paleotemperatures.

In GC193-6, the fission track age is older than the stratigraphic age and some shortening could, in principle, have been inherited from source regions, although the lack of longer tracks suggests that the dominant reason for the observed shortening is post-depositional annealing. In GC193-7, however, the mean fission track age is close to the stratigraphic age and several grains give fission track ages which are significantly less than the stratigraphic age. In this sample, the observed length reduction cannot have been inherited from source areas, and thus both the age and length data suggest showing that a moderate degree of annealing has occurred after deposition at elevated paleotemperatures. In GC193-8, no confined tracks were measured, and only three grains were found for age determination. The data in this sample show no clear evidence of post-depositional annealing, as all three grains give fission track ages which are compatible with the stratigraphic age. However, it

seems reasonable to extend the conclusion from the two shallower samples to this sample also.

Maximum paleotemperatures of $\sim 70^{\circ}\text{--}80^{\circ}\text{C}$ in GC193-6 and $\sim 80^{\circ}\text{--}90^{\circ}\text{C}$ in GC193-7 are indicated by the observations summarised above, and a value in the broad range $70^{\circ}\text{--}90^{\circ}\text{C}$ is probably applicable to GC193-8. No firm evidence is available on the timing of cooling, although attempts to reproduce the form of the length distributions are consistent with the conclusion from samples discussed above, involving an onset of cooling some time around the end of the Cretaceous or into the early Tertiary, in the 50-70 Ma range. Note that because fewer tracks were measured in GC193-6 and 7 than in GC193-2, 3, 4 and 5, the form of the observed track length distribution is less reliable in independently defining the time of cooling.

Tracks in these samples have only undergone a moderate degree of annealing since deposition, and provide some indication of the provenance of the analysed apatite grains. With corrected ages of ~ 370 Ma in GC193-6 and ~ 244 Ma in GC193-7, and individual grain ages extending to ages in excess of 400 Ma, an original source in Caledonian basement is most likely for the apatites analysed in this sample, although some contribution of Hercynian basement is also possible.

2.5 7127/10-U-03

The single sample analysed from this core (GC193-9) provided no apatite, and no conclusions can be reached on the history of this sample.

2.6 7127/10-U-02

One of the samples analysed from this core (GC193-10) provided no apatite, and therefore no conclusions can be reached on the history of this sample. The second sample, GC193-11, shows clear signs of elevated paleotemperatures, since the mean fission track age is significantly less than the stratigraphic age, as are many of the single grain ages. Unfortunately only three track lengths were measured in this sample, and the length data do not allow much constraint on the thermal history. However, from the amount of age reduction that has clearly taken place in this sample, paleotemperatures of $\sim 90^{\circ}\text{--}100^{\circ}\text{C}$ would be required for any reasonable timescale of heating.

The paucity of track lengths in this sample preclude a thorough analysis of the time of cooling. However, inspection of the distribution of single grain ages shows a prominent group of young ages at ~ 50 Ma, and cooling in the early Tertiary would be compatible with the data.

Because of the evident degree of annealing that has occurred in this sample, little information is preserved on the provenance of the analysed apatite grains. However the presence of some grains with ages over 300 Ma suggests a source in Caledonian and/or Hercynian basement is most likely.

2.7 7029/03-U-02

AFTA data from the three samples analysed from this core (GC1993-12, 13 and 14) consistently show signs of elevated paleotemperatures since deposition. The mean fission track ages in all three samples are close to the stratigraphic ages, and in two samples (GC193-12 and 14), single grain ages of between 100 and 150 Ma are significantly less than the stratigraphic age, showing that a moderate degree of annealing has occurred since deposition. In addition, mean track lengths are all ~12.5-12.8 μm , which is less than the value of ~14 μm or more than would be expected for tracks that had been exposed only to temperatures less than ~50°C since deposition. Although only a small number of tracks were measured in two of the samples, none of the distributions shows a dominant contribution of track lengths in the 13-16 μm region. In GC193-12, which provides the most reliable track length data, the distribution shows only a small contribution in this region, suggesting that only a small proportion of the total history has been spent at temperatures below ~50°C.

Maximum paleotemperatures of ~70°-80°C are indicated in the three samples by the observations summarised above. Although the track length data are not as reliable as in some other samples, attempts to model the form of the length distributions are consistent with the conclusion from samples discussed above, involving an onset of cooling some time around the end of the Cretaceous or into the early Tertiary, in the 50-70 Ma range. This is also supported by the younger fission track ages of ~100-150 Ma which provide an upper limit for the onset of cooling.

As tracks in these sample have only undergone a moderate degree of annealing since deposition, they provide some indication of the provenance of the analysed apatite grains. With corrected ages of ~320-380 Ma, and individual grain ages extending to ages in excess of 400 Ma, an original source in Caledonian basement is most likely for the apatites analysed in these samples, although some contribution of Hercynian basement is also possible.

2.8 7029/03-U-01

AFTA parameters in samples from this core are very similar to those in samples GC193-12, 13 and 14 from neighbouring core 7029/03-U-02, discussed above. Therefore similar conclusions may be applied to samples GC193-15 and 16, involving maximum paleotemperatures of ~70°-80°C prior to cooling which began some time around the end of the Cretaceous or into the early Tertiary, in the 50-70 Ma range. A provenance in

Caledonian basement is indicated by the corrected ages of 360-420 Ma, and by single grain ages of up to 600-700 Ma in these samples.

3. Regional interpretation

Since none of the samples analysed for this report have been severely annealed, it is difficult to obtain a direct estimate of the time at which cooling from maximum paleotemperatures began. However, the evidence from the youngest single grain ages in those samples showing the greatest degrees of annealing, together with the form of the track length distributions, particularly those in the three samples from core 7430/07-U-01 (GC193-2, 3 and 4), consistently indicate cooling within the 50-70 Ma range. Data from other samples are broadly consistent with such a timing, and therefore we conclude that cooling took place on a regional scale beginning in the late Cretaceous or early Tertiary, from the maximum paleotemperatures summarised in Table 1. It is not possible to gain much insight into the style of cooling in any of the samples analysed, largely because the great majority of tracks in each sample were formed prior to the attainment of maximum paleotemperatures and these tracks therefore dominate the track length distributions.

Perhaps most importantly, since the analysed samples are taken from only a narrow range of depths, the estimates of maximum paleotemperature in each sample provide no constraint on the paleogeothermal gradient at the time at which maximum paleotemperatures were attained, and analysis of samples over a wider range of depths (~1 km or more) would be required for this purpose. If the paleogeothermal gradient was ~30°C/km, then the estimates of maximum paleotemperatures of between 70° and 100°C, as summarised in Table 1, would translate to between 2 and 3 km of uplift and erosion since the late Cretaceous or early Tertiary.

When the results of this study are considered in the regional context, together with results from a previous report for IKU on similar samples from shallow cores in the Barents Sea (Geotrack Report #147), a consistent pattern emerges. Triassic and older samples from cores in the most southerly regions (7029/03-U-01, 7029/03-U-02, 7127/10-U-02, 7127/10-U-03, 7128/09-U-01, 7128/12-U-01 from this report; 7129/10-U-01 from Geotrack Report #147), generally give estimated maximum paleotemperatures of ~70°-80°C. Triassic samples from cores in the central area 7430/07-U-01 (this report) and 7230/05-U-02, 7230/05-U-03 and 7230/05-U-05 (Geotrack Report #147) give estimated maximum paleotemperatures of ~80°-90°C (75°-85°C in Report #147). The most northerly sample analysed, from core D-85-O (Geotrack Report #147) gave an estimated maximum paleotemperatures of ~90°C (based on the results in this report, this could be revised upwards slightly, to 90°-100°C). Data from Cretaceous and Jurassic samples are more

equivocal, but are in broad agreement with this trend. Thus the estimates of maximum paleotemperature show a general increase to the north, into the Barents Sea from the Norwegian mainland. The only serious exceptions to this trend come from samples GC193-11 and possibly GC193-7 from cores in the southern region, which show evidence of paleotemperatures of 90°C or more. Presumably this is due to local effects superimposed on the general trend.

Whether this regional variation in maximum paleotemperatures prior to cooling in the late Cretaceous or early Tertiary is due to regional variation in paleogeothermal gradients, or is due to variation in the amount of uplift and erosion with geothermal gradients close to present values, cannot be discriminated from available data. As noted above, constraints on the paleogeothermal gradient would be possible if samples were analysed from over a range of depths (of ~1 km or more). In the absence of real constraints, we would suggest that regional variation of maximum paleotemperatures, over distances of several hundred kilometres, seems most compatible with regional uplift and erosion than with variation in elevated geothermal gradients. Therefore an interpretation of all AFTA data from shallow cores in the Barents Sea in terms of between 2 km (in the south) and 3 km (to the north) of uplift and erosion is preferred.

APPENDIX A

Sample Details

Sixteen samples from eight shallow cores from the Barents Sea were submitted by IKU for apatite fission track analysis (AFTA™). Sample details supplied by IKU are summarised in Table 2, together with the yields of detrital apatite obtained after mineral separation. Numerical values for stratigraphic ages have been assigned using the timescale of Harland et al. (1982). Present temperatures are based on an assumed geothermal gradient of 30°C/km and surface temperatures provided by IKU of 1.5°C in GC193-1, 2, 3 and 4; 3.5°C in GC193-5, 6, 7 and 8; 3.7°C in GC123-9, 10 and 11; 3.5°C in GC193-12, 13, 14, 15 and 16.

Fourteen of the sixteen samples provided apatite suitable for analysis, with yields varying from poor to excellent. Most of the apatite grains analysed from each sample were rounded to sub-rounded or anhedral, with only GC193-2 giving dominantly euhedral grains. The quality of the apatites obtained was excellent in all samples, and the overall quality of the data is regarded as excellent, although the small number of apatites obtained from some samples limits the conclusions that can be drawn from the AFTA data.

References

Harland, W.B., Cox, A.V., Llewellyn, P.G., Pickton, C.A.G., Smith, A.G. and Walters, R. 1982, A geologic time scale. Cambridge University Press.

Table 2: Sample details and apatite yields - Barents Sea shallow cores (Geotrack™ Report #193)

Geotrack number	Core number	Depth (m)	Stratigraphic sub-division	Stratigraphic age	Present temperature (Ma)	Raw weight (g)	Washed weight (g)	Apatite yield* ¹ (g)
GC193-1	7430/10-U-01	44.8-44.9	Berriasian	138-144	3	390	160	Poor
GC193-2	7430/07-U-01	24.4-24.5	Late Carnian	~225	2	370	240	Excellent
GC193-3	7430/07-U-01	70.0-70.1	Late Carnian	~225	4	400	220	Good
GC193-4	7430/07-U-01	116.1-116.2	?Early Late Carnian	225-231	5	330	180	Excellent
GC193-5	7128/09-U-01	85.4-85.6	Early Triassic	243-248	6	390	305	Excellent
GC193-6	7128/12-U-01	64.8-64.9	Griesbachian	~248	5	180	65	Excellent
GC193-7	7128/12-U-01	113.0-113.1	Kazanian-Tatarian	248-255	7	320	260	Good
GC193-8	7128/12-U-01	147.7-148.1	Artinskian	258-268	8	265	75	Very Poor
GC193-9	7127/10-U-03	104.6-104.8	Late Visian	333-340	7	320	250	None
GC193-10	7127/10-U-02	107.3-107.4	Late Visian	333-340	7	310	220	None
GC193-11	7127/10-U-02	183.3-183.5	Late Visian	333-340	9	410	270	Poor
GC193-12	7029/03-U-02	104.9-105.0	?Kasimovian/Gzhelian	286-296	7	320	220	Good
GC193-13	7029/03-U-02	149.5-149.7	Bashkirian-Moscovian	296-320	8	330	260	Poor
GC193-14	7029/03-U-02	194.2-194.4	Carboniferous	286-360	9	350	185	Poor
GC193-15	7029/03-U-01	99.7-99.8	Late Visian - ?Early Serpukhovian	330-340	6	240	200	Good
GC193-16	7029/03-U-01	137.0-137.2	Visian	333-352	8	500	325	Fair

*¹ Yield based on quantity of apatite suitable for age determination. Excellent: >20 grains; Very good: ~20 grains; Good: 15-20 grains; Fair: 10-15 grains; Poor: 5-10 grains; Very poor: <5 grains.

APPENDIX B

Sample Preparation and Experimental Details

The core samples were reduced in size in a jaw crusher, and then ground to sand grade in a rotary disc mill. The ground material was then washed to remove dust, dried and processed by conventional heavy liquid and magnetic separation techniques to recover heavy minerals.

Fission track age and length measurements were made using techniques outlined by Green (1986). Apatites were mounted in epoxy resin on glass slides, polished and etched for 20 sec in 5M HNO₃ at 20°C to reveal the fossil fission tracks. Fission track ages were determined by the external detector method or EDM (Gleadow, 1981) using an Autoscan™ microcomputer controlled automatic stage (Smith and Leigh Jones, 1985). The EDM has the advantage of allowing fission track ages to be determined on single grains. Wherever possible, tracks were counted over 20 grains in each mount. In those samples where this number was not present, all available grains were counted, the actual number depending on the availability of suitably etched and oriented apatites. Only grains oriented with surfaces parallel to the crystallographic c-axis were analysed. Such grains can be identified on the basis of the etching characteristics, as well as from morphological evidence in euhedral grains. The grain mount was scanned sequentially, and the first 20 suitably oriented grains identified were analysed. Track counting was carried out using a Zeiss^(R) Axioplan microscope, with an overall linear magnification of 1068 x using dry objectives.

Neutron irradiations were carried out in a well thermalised flux (X-7 facility) in the Australian Atomic Energy Commission's HIFAR research reactor. Total neutron fluence was monitored by counting tracks in mica external detectors attached to two pieces of the NBS standard glass SRM612 included in the irradiation canister at each end of the sample stack. No flux gradient is usually found in the irradiation facility used over the length of the sample package and this was confirmed by the track counts over the two dosimeter glasses. The two values have been pooled to give the single value quoted in Table 3.

For track length studies, the full lengths of 'confined' fission tracks were measured. Confined tracks are those which do not intersect the polished surface but have been etched from other tracks or fractures, so that the whole length of the track is etched. Confined track lengths were measured using a digitising tablet connected to a microcomputer, superimposed on the microscope field of view via a projection tube. With this system, calibrated against a stage graticule ruled in 2 mm divisions, individual tracks can be measured with a precision of ± 0.2

mm divisions. Tracks were measured only in prismatic grains, characterised by sharp polishing scratches with well etched tracks of narrow cone angle in all orientations, because of the anisotropy of annealing of fission tracks in apatite (as discussed by Green et al., 1986). Tracks were also measured following the recommendations of Laslett et al. (1982), the most important of which is that only horizontal tracks should be measured. One hundred tracks were measured whenever possible. In apatite samples with low track density, or in those samples in which only a small number of apatite grains were obtained, fewer confined tracks may be available, and in such cases, the whole mount was scanned to measure as many confined tracks as possible.

References

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APPENDIX C

AFTA™ Data Tables and Figures

Full analytical data for the fission track age determinations are given in Table 3 together with the mean confined track length and the standard deviation of the distribution of confined track lengths in each sample. In Figure 2, the fission track age and mean track length of each sample are plotted in relation to stratigraphic age, (with errors plotted at $\pm 2\sigma$).

Fission track ages were calculated using the standard fission track age equation (Hurford and Green, 1982) and errors are quoted at the level of one standard deviation throughout. All constants used in derivation of the results are shown at the bottom of Table 3 using the nomenclature of Hurford and Green (1982). The Zeta calibration factor has been determined empirically (Green, 1985) by direct comparison with K-Ar ages for a set of carefully chosen age standards, following the methods outlined by Hurford and Green (1983). The pooled or maximum probability age is determined from the ratio of the total spontaneous and induced track counts in all the analysed grains. Errors for the pooled age were calculated using the 'conventional' technique outlined by Green (1981), based on the total number of tracks counted for each track density measurement.

The variability of fission track ages between individual apatite grains within each sample can be assessed using a chi-squared (χ^2) statistic (Galbraith, 1981), the results of which are summarised for each sample in Table 3. The probability of obtaining the observed χ^2 value, for ν degrees of freedom (where ν = number of crystals - 1), which can be obtained from standard tables, indicates the probability that all the grains counted belong to a single age population. A probability of less than 5% denotes a significant spread of single grain ages, and suggests that real differences exist between the fission track ages of individual apatite grains. A significant spread in grain ages can result either from inheritance of detrital grains from mixed source areas, or from differential annealing in apatite grains of different composition, within a narrow range of temperature (see Appendix D).

Calculation of the pooled age inherently assumes that only a single population of ages is present, and is thus not appropriate to samples containing a significant spread of fission track ages. In such cases the mean of the single grain fission track ages provides a useful measure and this parameter has been used for those samples in which $P(\chi^2) < 5\%$. The error in the mean fission track age is taken as the standard deviation of the single grain ages.

Full details of the fission track age data for individual apatite grains in each sample are given, together with the primary counting results and statistical data, on pages C.13 - C.26. Plots of the single grain age data in each sample are shown in Figure 3. The distributions of single grain ages are shown in histogram form and also as smoothed probability functions. In constructing these functions, each grain is represented by a normal probability curve with mean equal to the single grain age, standard deviation given by the error on the single grain age, and the contributions from all grains analysed in each sample are summed to produce the plotted curve.

Single grain age data are also plotted on radial plot diagrams (Galbraith, 1988) in Figure 3. These plots display the variation of individual grain ages as a plot of $y = (z_i - z) / \sigma_i^2$ against $x = 1/\sigma_i^2$ where z_i is the fission track age of each grain, z is the mean age, and σ_i is the error in each age. In this plot, the slope of a straight line from the origin is equivalent to fission track age, and the value of x is a measure of the precision of each individual grain age. Therefore, precise individual grain ages fall to the right of the plot (high x), enabling precise, young grains to be identified. The age scale is shown radially around the perimeter of the plot (in Ma). If all grains belong to a single age population, all data should scatter between $y = +2$ and $y = -2$, equivalent to scatter within $\pm 2\sigma$. Scatter outside these boundaries shows a significant spread of individual grain ages, as also reflected in the Chi-square statistic in Table 3.

Distributions of confined track lengths in each sample are shown in Figure 4, and have been normalised to 100 tracks for each sample to facilitate comparison. The number of tracks (N) measured for each sample is indicated in Table 3 and full details of the track length distributions are given in Table 4.

Finally, note that throughout this report, the term "fission track age" is understood to denote the parameter calculated from the fission track age equation, using the observed spontaneous and induced track counts (either pooled for all grains or for individual grains). The resulting number (with units of Ma) should not be taken as possessing any significance in terms of events taking place at the time indicated by the measured fission track age, but should rather be regarded as a measure of the integrated thermal history of the sample, and should be interpreted in that light using the principles outlined in Appendix D. Use of the term "apparent age" is not considered to be useful in this regard, as almost every fission track age should be regarded as an apparent age, in the classic sense, and repeated use becomes cumbersome.

References

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Table 3: Apatite fission track analytical results - Barents Sea shallow cores (Geotrack™ Report #193)

Geotrack number	Average depth	Number of grains	Standard track density	Fossil track density	Induced track density	Chi square probability	Fission track age	Uranium	Mean track length	Standard deviation
GC-	(m)		($\times 10^6 \text{ cm}^{-2}$)	($\times 10^6 \text{ cm}^{-2}$)	($\times 10^6 \text{ cm}^{-2}$)	(%)	(Ma)	(ppm)	(μm)	(μm)
193-1	44.85	6	1.353 (2129)	0.922 (87)	1.292 (122)	<1	161.5 $\pm$ 23.2 170.5 $\pm$ 41.1*	12	8.94 $\pm$ 1.68 (5)	3.75
193-2	24.45	19	1.353 (2129)	2.362 (1351)	2.554 (1461)	4	208.6 $\pm$ 10.2 213.7 $\pm$ 17.0*	25	11.24 $\pm$ 0.24 (104)	2.48
193-3	70.05	17	1.353 (2129)	0.799 (812)	0.978 (995)	<1	184.5 $\pm$ 10.5 202.3 $\pm$ 32.8*	10	10.93 $\pm$ 0.22 (101)	2.21
193-4	116.15	20	1.353 (2129)	1.706 (936)	2.238 (1228)	1.3	172.5 $\pm$ 9.2 169.2 $\pm$ 12.4*	22	11.48 $\pm$ 0.29 (102)	2.88
193-5	85.50	20	1.353 (2129)	2.615 (1754)	1.795 (1204)	37	325.7 $\pm$ 15.9	17	12.36 $\pm$ 0.19 (82)	1.72
193-6	64.85	20	1.353 (2129)	2.167 (735)	1.504 (510)	66	322.3 $\pm$ 21.2	15	12.62 $\pm$ 0.29 (40)	1.82
193-7	113.05	16	1.353 (2129)	0.743 (314)	0.757 (320)	1.5	221.2 $\pm$ 18.9 219.7 $\pm$ 36.9*	7	13.05 $\pm$ 0.43 (18)	1.81
193-8	147.75	3	1.353 (2129)	0.316 (35)	0.271 (30)	79	262.1 $\pm$ 65.7	-	-	-
193-9	104.70	0	1.353 (2129)	-	-	-	-	-	-	-
193-10	107.35	0	1.353 (2129)	-	-	-	-	-	-	-
193-11	183.40	9	1.353 (2129)	0.476 (86)	1.489 (269)	<1	72.9 $\pm$ 9.3 125.0 $\pm$ 35.0*	14	11.82 $\pm$ 1.05 (3)	1.82
193-12	104.95	16	1.353 (2129)	2.949 (1392)	2.235 (1055)	<1	295.7 $\pm$ 15.2 301.5 $\pm$ 25.3*	22	12.74 $\pm$ 0.24 (24)	1.32
193-13	149.60	5	1.353 (2129)	1.808 (215)	1.791 (213)	<1	227.4 $\pm$ 23.1 284.8 $\pm$ 59.1*	17	12.82 $\pm$ 0.57 (5)	1.27
193-14	194.30	6	1.353 (2129)	2.636 (418)	1.904 (302)	1	309.8 $\pm$ 25.3 325.0 $\pm$ 45.2*	18	12.52 $\pm$ 0.43 (9)	1.28
193-15	99.75	19	1.353 (2129)	1.803 (724)	1.243 (499)	4	324.4 $\pm$ 21.4 300.9 $\pm$ 36.5*	12	12.14 $\pm$ 0.53 (26)	2.68
193-16	137.10	10	1.353 (2129)	2.547 (436)	2.080 (356)	<1	274.9 $\pm$ 21.4 355.1 $\pm$ 68.5*	20	12.34 $\pm$ 0.37 (13)	1.34

Brackets show number of tracks counted.

Standard and induced track densities measured on mica external detectors ($g=0.5$), and fossil track densities on internal mineral surfaces.

* Mean age, used where pooled data fail χ^2 test at 5%. Errors quoted at $\pm 1\sigma$.

Ages for samples calculated using $\lambda=338.9$ (Analyst: D. Arne) for dosimeter glass SRM612 (Hurford and Green, 1983).

Track length measurements by S.J. Marshall.

Table 4: Length distribution summary data - Barents Sea shallow cores(Geotrack™ Report #193)

Sample number GC-	Core number	Mean track length (μm)	Std dev (μm)	Number of tracks (N)	Number of tracks in length interval (μm)																			
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
193-1	7430/10-U-01	8.94 ± 1.68	3.75	5	-	-	1	-	-	-	-	-	1	-	2	-	1	0	-	-	-	-	-	-
193-2	7430/07-U-01	11.24 ± 0.24	2.48	104	-	-	1	2	-	-	1	6	3	14	17	14	20	17	5	4	-	-	-	-
193-3	7430/07-U-01	10.93 ± 0.22	2.21	101	-	-	-	-	3	-	-	4	6	19	26	14	9	9	9	2	-	-	-	-
193-4	7430/07-U-01	11.48 ± 0.29	2.88	102	-	-	-	2	3	2	2	1	4	11	18	14	7	20	10	6	1	1	-	-
193-5	7128/09-U-01	12.36 ± 0.19	1.72	82	-	-	-	-	2	-	-	-	-	3	7	14	27	22	5	1	1	-	-	-
193-6	7128/12-U-01	12.62 ± 0.29	1.82	40	-	-	-	-	-	-	-	1	1	1	3	5	12	9	6	1	1	-	-	-
193-7	7128/12-U-01	13.05 ± 0.43	1.81	18	-	-	-	-	-	-	-	1	-	-	1	1	3	8	2	1	1	-	-	-
193-8	7128/12-U-01	-	-	No confined tracks																				
193-9	7127/10-U-03	-	-	No confined tracks																				
193-10	7127/10-U-02	-	-	No confined tracks																				
193-11	7127/10-U-02	11.82 ± 1.05	1.82	3	-	-	-	-	-	-	-	-	-	1	-	0	1	1	0	-	-	-	-	-
193-12	7029/03-U-02	12.74 ± 0.24	1.32	24	-	-	-	-	-	-	-	-	-	-	3	5	9	7	3	2	-	-	-	-
193-13	7029/03-U-02	12.82 ± 0.57	1.27	5	-	-	-	-	-	-	-	-	-	-	1	-	1	2	1	-	-	-	-	-
193-14	7029/03-U-02	12.52 ± 0.43	1.28	9	-	-	-	-	-	-	-	-	-	1	-	2	2	4	-	-	-	-	-	-
193-15	7029/03-U-01	12.14 ± 0.53	2.68	26	-	-	-	-	-	1	1	1	-	2	3	1	6	5	2	4	-	-	-	-
193-16	7029/03-U-01	12.34 ± 0.37	1.34	13	-	-	-	-	-	-	-	-	-	-	2	3	5	1	2	-	-	-	-	-

Length measurements by S.J. Marshallsea.

Barents Sea shallow cores

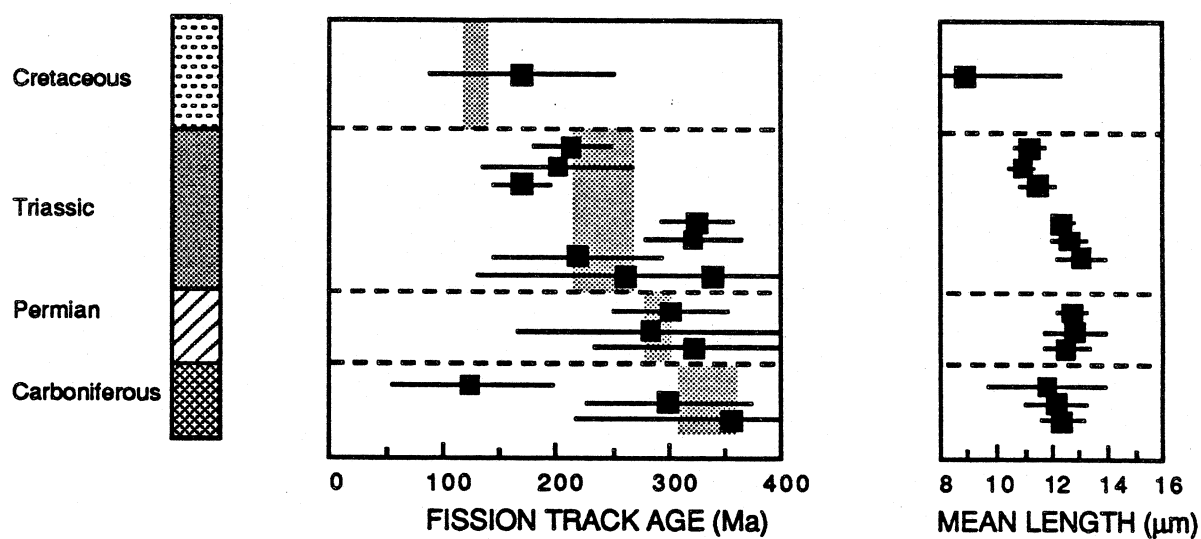
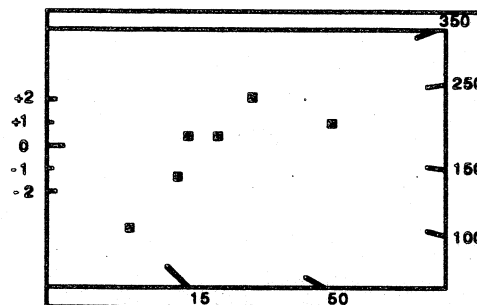
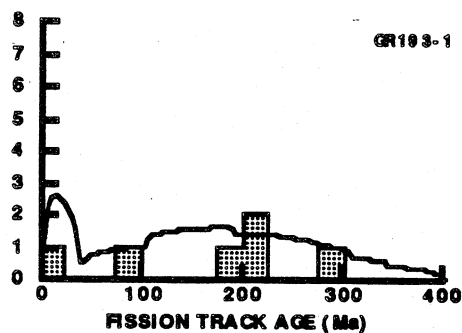
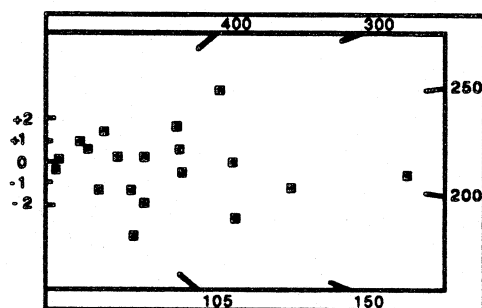
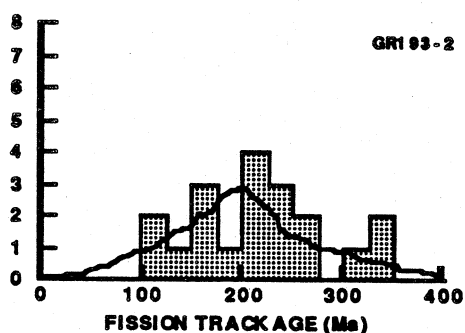


Figure 2: AFTA parameters plotted in relation to stratigraphic age for samples from **Barents Sea shallow cores**. The range of possible stratigraphic age for each sample is shown by the dotted pattern.

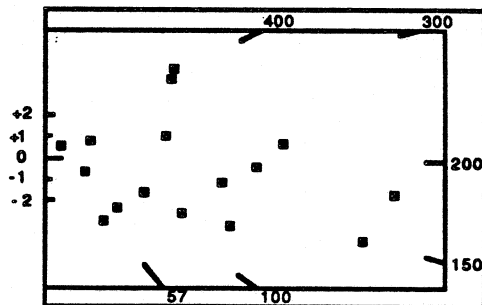
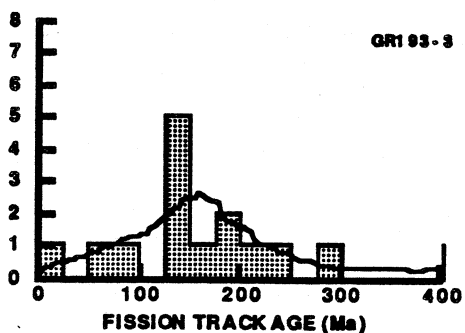
GC193-1



GC193-2



GC193-3



GC193-4

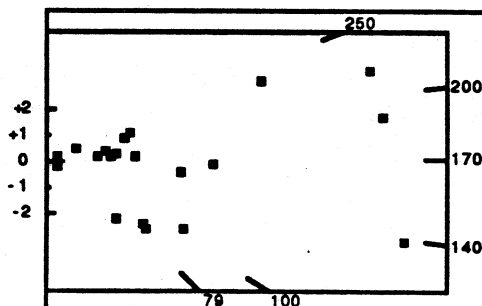
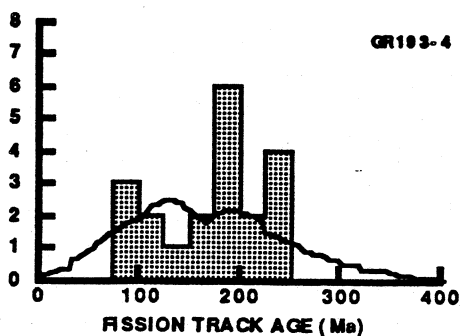
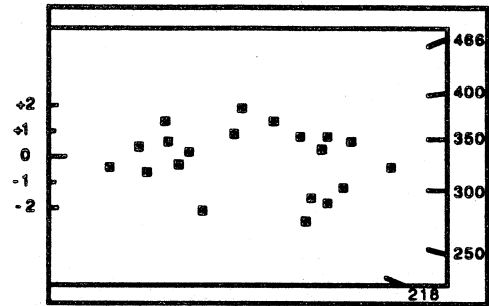
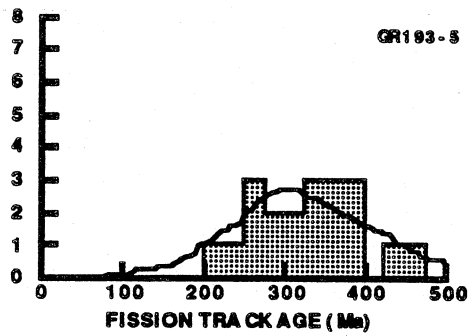


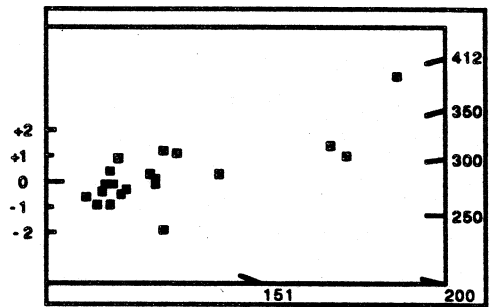
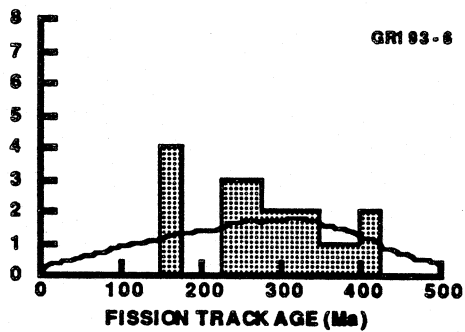
Figure 3: Single grain age distributions with smoothed cumulative age probability distributions (left) and radial plots of single grain age data (right) in apatites from Barents Sea shallow wells. See text for explanation of radial plots.

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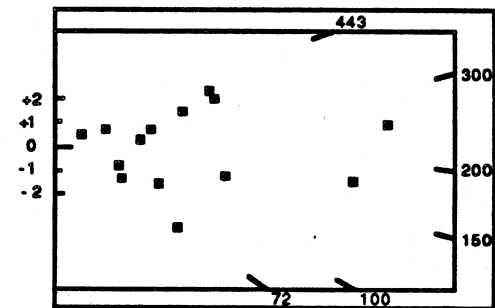
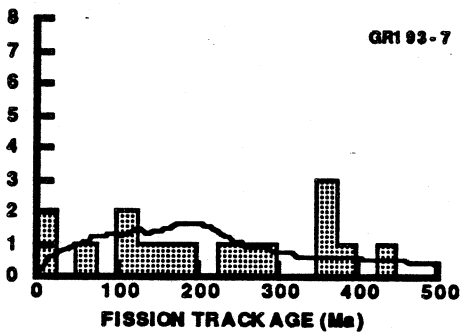
GC193-5



GC193-6



GC193-7



GC193-8

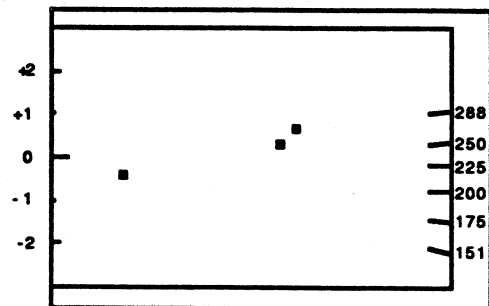
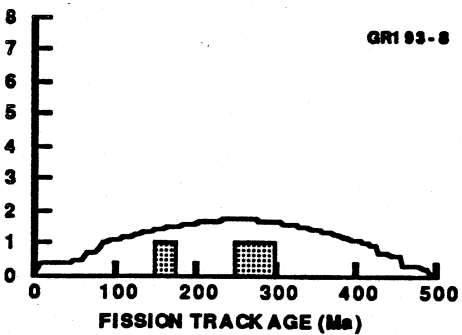


Figure 3: Continued

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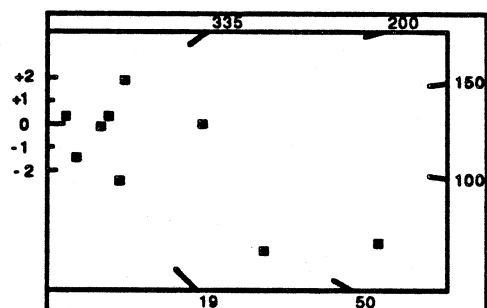
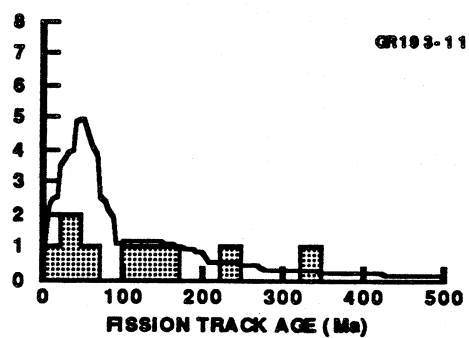
GC193-9

No Apatite

GC193-10

No Apatite

GC193-11



GC193-12

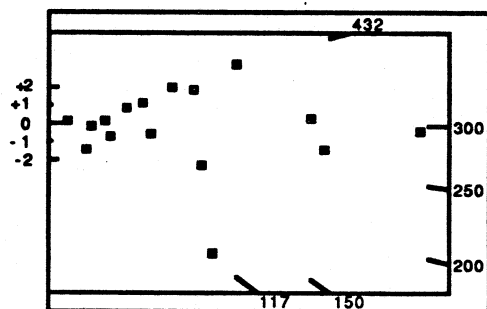
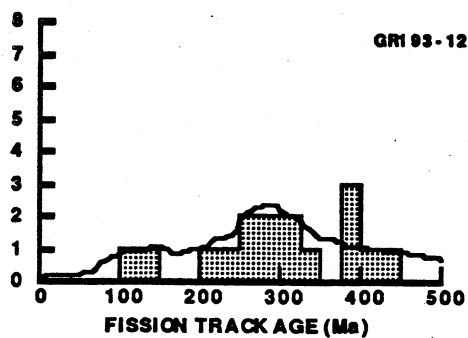
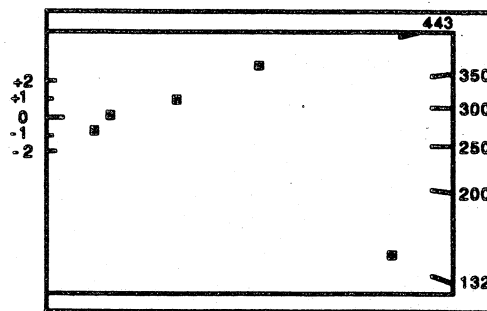
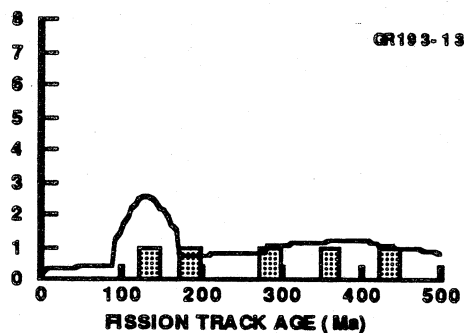


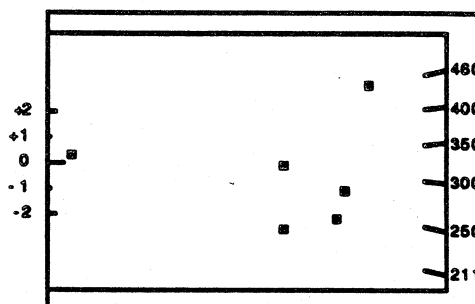
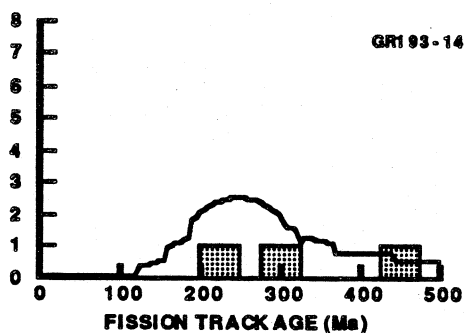
Figure 3: Continued

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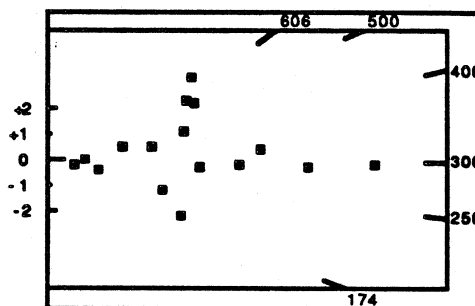
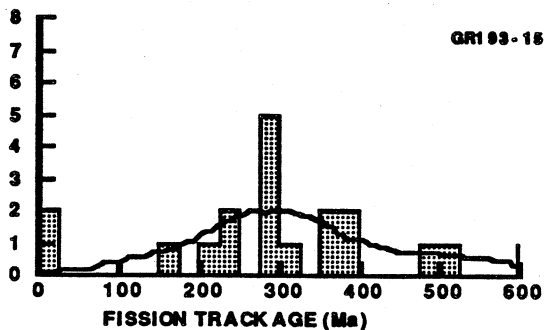
GC193-13



GC193-14



GC193-15



GC193-16

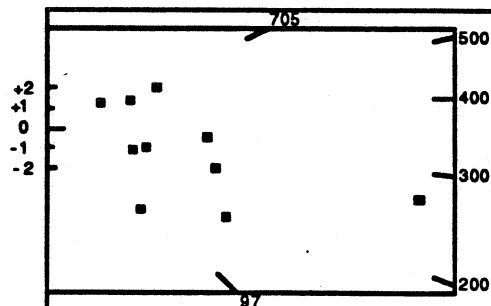
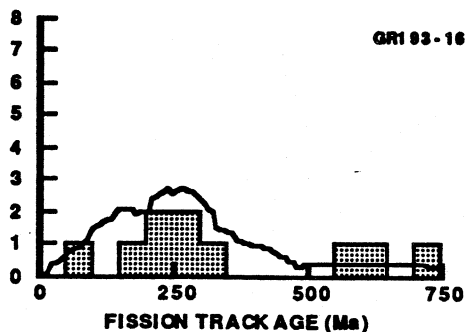
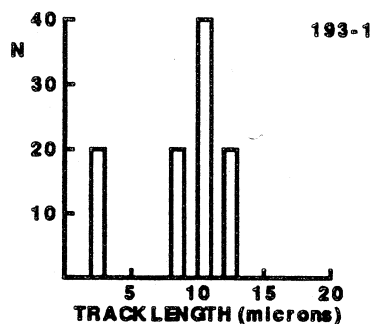
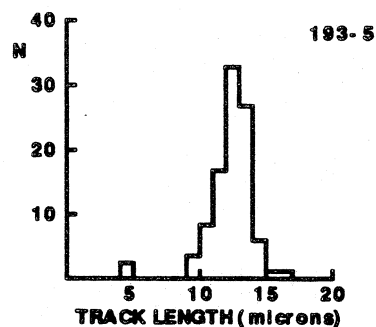


Figure 3: Continued

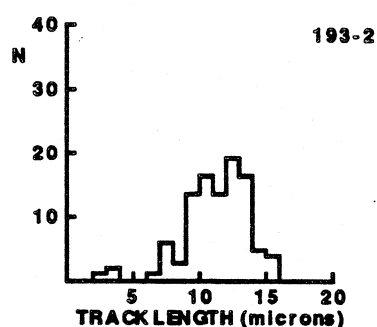
GC193-1



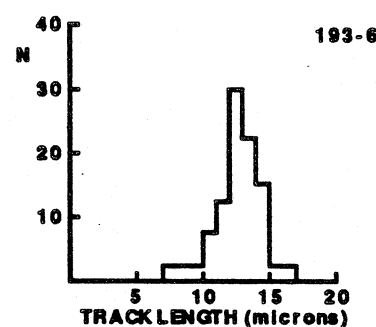
GC193-5



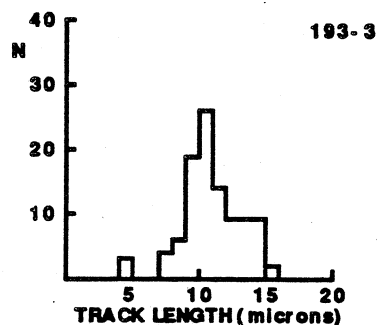
GC193-2



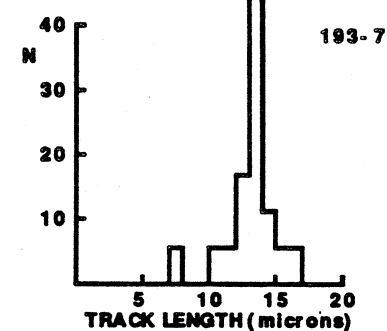
GC193-6



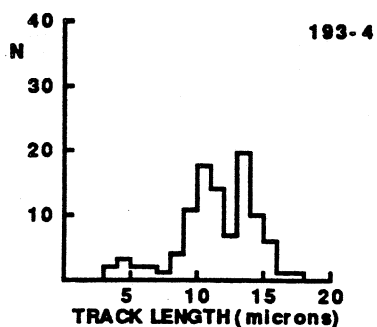
GC193-3



GC193-7



GC193-4



GC193-8

No Confined tracks

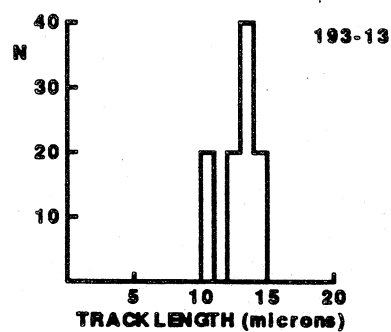
Figure 4: Distributions of confined track lengths in apatites from Barents Sea shallow wells

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GC193-9

No Apatite

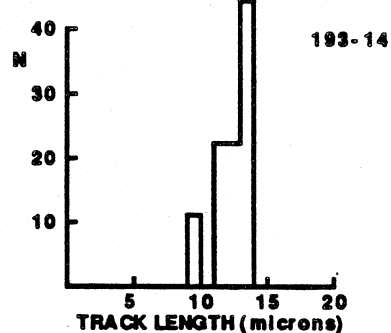
GC193-13



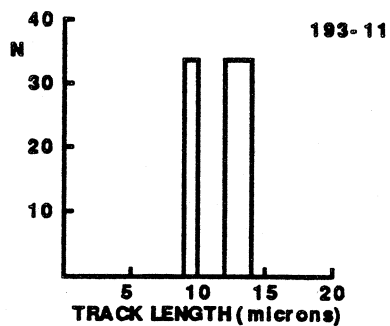
GC193-10

No Apatite

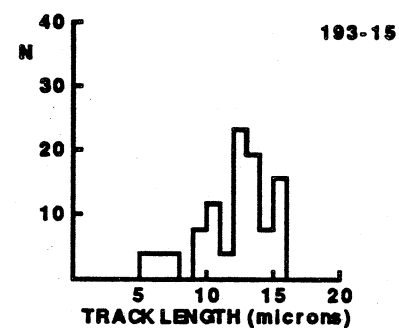
GC193-14



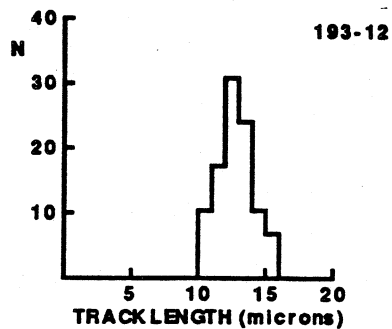
GC193-11



GC193-15



GC193-12



GC193-16

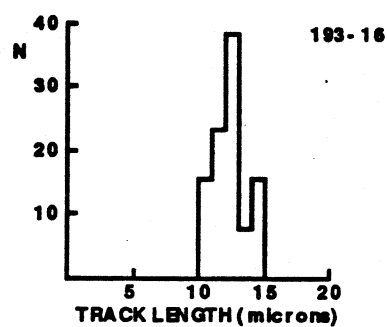


Figure 4: Continued.

GR193-1 APATITE

IRRADIATION G072

SLIDE NUMBER 1

COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	6	14	30	0.429	7.1	3.178E+05	7.416E+05	97.5 ± 47.7
2	10	11	24	0.909	7.0	6.621E+05	7.283E+05	205.2 ± 89.9
3	2	29	25	0.069	18.1	1.271E+05	1.843E+06	15.8 ± 11.6
4	13	15	35	0.867	6.5	5.902E+05	6.810E+05	195.7 ± 74.4
5	24	18	20	1.333	13.9	1.907E+06	1.430E+06	298.7 ± 93.6
6	32	35	16	0.914	33.5	3.178E+06	3.476E+06	206.3 ± 50.9
87		122			12.6	9.217E+05	1.292E+06	

Area of basic unit = 6.293E-07 cm-2

CHI SQUARED = 22.673 WITH 5 DEGREES OF FREEDOM

P(chi squared) = 0.0 %

CORRELATION COEFFICIENT = 0.425

VARIANCE OF SQR(Ns) = 2.44

VARIANCE OF SQR(Ni) = 1.04

Ns/Ni = 0.713 ± 0.100

MEAN RATIO = 0.753 ± 0.180

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm-2; ND = 2129

POOLED AGE = 161.5 ± 23.2 Ma

MEAN AGE = 170.5 ± 41.1 Ma

GR193-2 APATITE

IRRADIATION G072

SLIDE NUMBER 2

COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	24	24	30	1.000	12.3	1.271E+06	1.271E+06	225.3 ± 65.4
2	24	34	50	0.706	10.5	7.628E+05	1.081E+06	159.9 ± 42.9
3	2	2	25	1.000	1.2	1.271E+05	1.271E+05	225.3 ± 225.4
4	183	212	25	0.863	130.4	1.163E+07	1.348E+07	195.0 ± 20.6
5	121	128	25	0.945	78.8	7.691E+06	8.136E+06	213.2 ± 27.8
6	99	135	32	0.733	64.9	4.916E+06	6.704E+06	166.0 ± 22.6
7	20	43	60	0.465	11.0	5.297E+05	1.139E+06	105.8 ± 28.8
8	65	73	25	0.890	44.9	4.132E+06	4.640E+06	201.0 ± 34.9
9	39	40	64	0.975	9.6	9.683E+05	9.932E+05	219.8 ± 49.9
10	1	2	36	0.500	0.9	4.414E+04	8.828E+04	113.6 ± 139.2
11	406	441	49	0.921	138.4	1.317E+07	1.430E+07	207.7 ± 15.7
12	9	6	70	1.500	1.3	2.043E+05	1.362E+05	335.1 ± 176.9
13	140	104	50	1.346	32.0	4.449E+06	3.305E+06	301.5 ± 40.2
14	11	9	49	1.222	2.8	3.567E+05	2.919E+05	274.3 ± 123.6
15	10	17	100	0.588	2.6	1.589E+05	2.701E+05	133.5 ± 53.4
16	76	64	50	1.188	19.7	2.415E+06	2.034E+06	266.7 ± 46.0
17	30	45	60	0.667	11.5	7.945E+05	1.192E+06	151.1 ± 35.9
18	22	15	49	1.467	4.7	7.135E+05	4.864E+05	327.8 ± 110.3
19	69	67	60	1.030	17.2	1.827E+06	1.774E+06	231.9 ± 40.4
1351		1461			24.7	2.362E+06	2.554E+06	

Area of basic unit = 6.293E-07 cm²

CHI SQUARED = 29.292 WITH 18 DEGREES OF FREEDOM

P(chi squared) = 4.5 %

CORRELATION COEFFICIENT = 0.988

VARIANCE OF SQR(Ns) = 22.46

VARIANCE OF SQR(Ni) = 23.84

Ns/Ni = 0.925 ± 0.035

MEAN RATIO = 0.948 ± 0.069

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm⁻²; ND = 2129

POOLED AGE = 208.6 ± 10.2 Ma

MEAN AGE = 213.7 ± 17.0 Ma

GR193-3 APATITE

IRRADIATION G072

SLIDE NUMBER 3

COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	8	6	100	1.333	0.9	1.271E+05	9.534E+04	298.7 ± 161.6
2	4	7	100	0.571	1.1	6.356E+04	1.112E+05	129.7 ± 81.4
3	130	198	100	0.657	30.5	2.066E+06	3.146E+06	148.8 ± 17.4
4	34	31	100	1.097	4.8	5.403E+05	4.926E+05	246.7 ± 61.8
5	2	1	100	2.000	0.2	3.178E+04	1.589E+04	443.0 ± 542.8
6	105	109	36	0.963	46.6	4.635E+06	4.811E+06	217.2 ± 30.5
7	5	20	100	0.250	3.1	7.945E+04	3.178E+05	57.1 ± 28.6
8	181	230	100	0.787	35.4	2.876E+06	3.655E+06	178.0 ± 18.5
9	8	20	100	0.400	3.1	1.271E+05	3.178E+05	91.1 ± 38.2
10	0	1	100	0.000	0.2	0.000E+00	1.589E+04	0.0 ± 0.0
11	45	78	100	0.577	12.0	7.151E+05	1.239E+06	131.0 ± 24.9
12	26	47	100	0.553	7.2	4.132E+05	7.469E+05	125.6 ± 31.0
13	63	32	100	1.969	4.9	1.001E+06	5.085E+05	436.3 ± 95.7
14	56	30	100	1.867	4.6	8.899E+05	4.767E+05	414.4 ± 94.7
15	16	27	100	0.593	4.2	2.542E+05	4.290E+05	134.5 ± 42.6
16	52	68	80	0.765	13.1	1.033E+06	1.351E+06	173.0 ± 32.3
17	77	90	100	0.856	13.8	1.224E+06	1.430E+06	193.3 ± 30.6
812		995			9.5	7.985E+05	9.784E+05	

Area of basic unit = 6.293E-07 cm-2

CHI SQUARED = 57.621 WITH 16 DEGREES OF FREEDOM

P(chi squared) = 0.0 %

CORRELATION COEFFICIENT = 0.951

VARIANCE OF SQR(Ns) = 14.39

VARIANCE OF SQR(Ni) = 16.86

Ns/Ni = 0.816 ± 0.039

MEAN RATIO = 0.896 ± 0.142

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm-2; ND = 2129

POOLED AGE = 184.5 ± 10.5 Ma

MEAN AGE = 202.3 ± 32.8 Ma

GR193-4 APATITE

IRRADIATION G072
SLIDE NUMBER 4
COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	1	1	49	1.000	0.3	3.243E+04	3.243E+04	225.3 ± 318.7
2	105	101	100	1.040	15.5	1.669E+06	1.605E+06	234.1 ± 33.4
3	14	34	25	0.412	20.9	8.899E+05	2.161E+06	93.7 ± 29.9
4	10	12	30	0.833	6.2	5.297E+05	6.356E+05	188.3 ± 80.8
5	19	19	25	1.000	11.7	1.208E+06	1.208E+06	225.3 ± 73.4
6	8	10	20	0.800	7.7	6.356E+05	7.945E+05	180.9 ± 86.0
7	11	14	20	0.786	10.8	8.740E+05	1.112E+06	177.7 ± 71.8
8	8	23	36	0.348	9.8	3.531E+05	1.015E+06	79.3 ± 32.6
9	13	16	60	0.812	4.1	3.443E+05	4.238E+05	183.7 ± 68.8
10	18	23	36	0.783	9.8	7.945E+05	1.015E+06	177.0 ± 56.0
11	33	48	40	0.688	18.5	1.311E+06	1.907E+06	155.8 ± 35.6
12	15	37	60	0.405	9.5	3.973E+05	9.799E+05	92.3 ± 28.4
13	202	241	50	0.838	74.1	6.420E+06	7.659E+06	189.4 ± 19.0
14	50	69	80	0.725	13.3	9.932E+05	1.371E+06	164.1 ± 30.9
15	27	57	25	0.474	35.1	1.716E+06	3.623E+06	107.7 ± 25.4
16	1	2	36	0.500	0.9	4.414E+04	8.828E+04	113.6 ± 139.2
17	209	218	40	0.959	83.8	8.303E+06	8.660E+06	216.2 ± 22.0
18	17	18	30	0.944	9.2	9.005E+05	9.534E+05	213.0 ± 72.3
19	4	4	60	1.000	1.0	1.059E+05	1.059E+05	225.3 ± 159.5
20	171	281	50	0.609	86.5	5.435E+06	8.931E+06	138.1 ± 14.1
936					1228	21.7	1.706E+06	2.238E+06

Area of basic unit = 6.293E-07 cm²

CHI SQUARED = 35.181 WITH 19 DEGREES OF FREEDOM

P(chi squared) = 1.3 %

CORRELATION COEFFICIENT = 0.968

VARIANCE OF SQR(Ns) = 17.37

VARIANCE OF SQR(Ni) = 20.99

Ns/Ni = 0.762 ± 0.033

MEAN RATIO = 0.748 ± 0.050

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm⁻²; ND = 2129

POOLED AGE = 172.5 ± 9.2 Ma

MEAN AGE = 169.2 ± 12.4 Ma

GR193-5 APATITE

**IRRADIATION G072
SLIDE NUMBER 5
COUNTED BY: PFG**

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	199	140	100	1.421	21.5	3.162E+06	2.225E+06	318.0 ± 36.5
2	153	95	100	1.611	14.6	2.431E+06	1.510E+06	359.1 ± 48.2
3	18	15	64	1.200	3.6	4.469E+05	3.724E+05	269.5 ± 94.6
4	75	44	49	1.705	13.8	2.432E+06	1.427E+06	379.5 ± 73.0
5	108	88	36	1.227	37.6	4.767E+06	3.884E+06	275.5 ± 40.5
6	94	86	36	1.093	36.7	4.149E+06	3.796E+06	245.9 ± 37.5
7	126	78	64	1.615	18.7	3.128E+06	1.937E+06	360.2 ± 53.1
8	20	12	42	1.667	4.4	7.567E+05	4.540E+05	371.3 ± 136.1
9	34	35	70	0.971	7.7	7.718E+05	7.945E+05	219.0 ± 53.2
10	8	7	36	1.143	3.0	3.531E+05	3.090E+05	256.9 ± 133.2
11	141	108	50	1.306	33.2	4.481E+06	3.432E+06	292.6 ± 38.5
12	172	110	49	1.564	34.5	5.578E+06	3.567E+06	348.9 ± 44.0
13	93	47	64	1.979	11.3	2.309E+06	1.167E+06	438.5 ± 79.7
14	139	91	36	1.527	38.9	6.136E+06	4.017E+06	341.1 ± 47.2
15	33	24	36	1.375	10.3	1.457E+06	1.059E+06	307.8 ± 83.1
16	117	97	50	1.206	29.8	3.718E+06	3.083E+06	270.8 ± 38.1
17	34	20	40	1.700	7.7	1.351E+06	7.945E+05	378.5 ± 107.3
18	41	27	36	1.519	11.5	1.810E+06	1.192E+06	339.1 ± 84.7
19	38	18	60	2.111	4.6	1.006E+06	4.767E+05	466.8 ± 134.4
20	111	62	48	1.790	19.9	3.675E+06	2.053E+06	398.0 ± 64.3
1754		1204			17.4	2.615E+06	1.795E+06	

Area of basic unit = 6.293E-07 cm²

CHI SQUARED = 20.352 WITH 19 DEGREES OF FREEDOM

P(chi squared) = 37.4 %

CORRELATION COEFFICIENT = 0.965

VARIANCE OF SQR(Ns) = 11.04

VARIANCE OF SQR(Ni) = 7.73

Ns/Ni = 1.457 ± 0.055

MEAN RATIO = 1.486 ± 0.067

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm⁻²; ND = 2129

POOLED AGE = 325.7 ± 15.9 Ma

MEAN AGE = 332.2 ± 18.2 Ma

GR193-6 APATITE

IRRADIATION G072

SLIDE NUMBER 6

COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	9	9	24	1.000	5.8	5.959E+05	5.959E+05	225.3 ± 106.5
2	6	8	24	0.750	5.1	3.973E+05	5.297E+05	169.7 ± 91.8
3	6	6	21	1.000	4.4	4.540E+05	4.540E+05	225.3 ± 130.3
4	13	7	16	1.857	6.7	1.291E+06	6.952E+05	412.4 ± 193.8
5	19	14	24	1.357	9.0	1.258E+06	9.270E+05	303.9 ± 107.5
6	8	7	24	1.143	4.5	5.297E+05	4.635E+05	256.9 ± 133.2
7	19	16	15	1.188	16.4	2.013E+06	1.695E+06	266.7 ± 90.9
8	15	21	24	0.714	13.5	9.932E+05	1.390E+06	161.7 ± 54.9
9	9	6	16	1.500	5.8	8.938E+05	5.959E+05	335.1 ± 176.9
10	28	16	40	1.750	6.2	1.112E+06	6.356E+05	389.3 ± 122.6
11	46	35	25	1.314	21.5	2.924E+06	2.225E+06	294.5 ± 66.7
12	225	124	36	1.815	53.0	9.932E+06	5.473E+06	403.2 ± 46.8
13	3	4	18	0.750	3.4	2.648E+05	3.531E+05	169.7 ± 129.7
14	33	20	12	1.650	25.6	4.370E+06	2.648E+06	367.7 ± 104.8
15	20	16	40	1.250	6.2	7.945E+05	6.356E+05	280.4 ± 94.5
16	130	94	25	1.383	57.8	8.263E+06	5.975E+06	309.6 ± 43.0
17	124	85	40	1.459	32.7	4.926E+06	3.377E+06	326.1 ± 47.1
18	7	6	50	1.167	1.8	2.225E+05	1.907E+05	262.1 ± 146.1
19	4	6	25	0.667	3.7	2.542E+05	3.814E+05	151.1 ± 97.6
20	11	10	40	1.100	3.8	4.370E+05	3.973E+05	247.4 ± 108.4
735		510			14.6	2.167E+06	1.504E+06	

Area of basic unit = 6.293E-07 cm²

CHI SQUARED = 15.986 WITH 19 DEGREES OF FREEDOM

P(chi squared) = 65.8 %

CORRELATION COEFFICIENT = 0.987

VARIANCE OF SQR(Ns) = 12.66

VARIANCE OF SQR(Ni) = 7.00

Ns/Ni = 1.441 ± 0.083

MEAN RATIO = 1.241 ± 0.082

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm⁻²; ND = 2129

POOLED AGE = 322.3 ± 21.2 Ma

MEAN AGE = 278.4 ± 20.3 Ma

GR193-7 APATITE

IRRADIATION G072

SLIDE NUMBER 7

COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	21	29	50	0.724	8.9	6.674E+05	9.217E+05	163.9 ± 47.3
2	5	3	25	1.667	1.8	3.178E+05	1.907E+05	371.3 ± 271.4
3	92	84	42	1.095	30.8	3.481E+06	3.178E+06	246.4 ± 38.0
4	9	8	50	1.125	2.5	2.860E+05	2.542E+05	252.9 ± 123.2
5	59	74	49	0.797	23.2	1.913E+06	2.400E+06	180.3 ± 32.0
6	34	19	36	1.789	8.1	1.501E+06	8.387E+05	397.8 ± 114.6
7	8	25	49	0.320	7.8	2.594E+05	8.107E+05	73.0 ± 29.7
8	0	1	40	0.000	0.4	0.000E+00	3.973E+04	0.0 ± 0.0
9	8	15	49	0.533	4.7	2.594E+05	4.864E+05	121.2 ± 53.2
10	22	14	32	1.571	6.7	1.092E+06	6.952E+05	350.6 ± 120.4
11	4	7	36	0.571	3.0	1.766E+05	3.090E+05	129.7 ± 81.4
12	12	9	40	1.333	3.5	4.767E+05	3.575E+05	298.7 ± 132.1
13	4	9	36	0.444	3.8	1.766E+05	3.973E+05	101.1 ± 60.8
14	2	1	49	2.000	0.3	6.486E+04	3.243E+04	443.0 ± 542.8
15	0	1	49	0.000	0.3	0.000E+00	3.243E+04	0.0 ± 0.0
16	34	21	40	1.619	8.1	1.351E+06	8.343E+05	361.0 ± 100.8
314		320			7.3	7.425E+05	7.567E+05	

Area of basic unit = 6.293E-07 cm-2

CHI SQUARED = 29.327 WITH 15 DEGREES OF FREEDOM

P(chi squared) = 1.5 %

CORRELATION COEFFICIENT = 0.936

VARIANCE OF SQR(Ns) = 6.93

VARIANCE OF SQR(Ni) = 5.87

Ns/Ni = 0.981 ± 0.078

MEAN RATIO = 0.974 ± 0.161

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm-2; ND = 2129

POOLED AGE = 221.2 ± 18.9 Ma

MEAN AGE = 219.7 ± 36.9 Ma

GR193-8 APATITE

IRRADIATION G072

SLIDE NUMBER 8

COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	18	14	80	1.286	2.7	3.575E+05	2.781E+05	288.3 ± 103.1
2	15	13	36	1.154	5.6	6.621E+05	5.738E+05	259.3 ± 98.6
3	2	3	60	0.667	0.8	5.297E+04	7.945E+04	151.1 ± 138.0
35		30			2.6	3.160E+05	2.709E+05	

Area of basic unit = 6.293E-07 cm²

CHI SQUARED = 0.461 WITH 2 DEGREES OF FREEDOM

P(chi squared) = 79.4 %

CORRELATION COEFFICIENT = 0.995

VARIANCE OF SQR(Ns) = 2.36

VARIANCE OF SQR(Ni) = 1.26

Ns/Ni = 1.167 ± 0.290

MEAN RATIO = 1.035 ± 0.188

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm⁻²; ND = 2129

POOLED AGE = 262.1 ± 65.7 Ma

MEAN AGE = 233.2 ± 43.0 Ma

GR193-11 APATITE

IRRADIATION G072
SLIDE NUMBER 11
COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	15	27	15	0.556	27.7	1.589E+06	2.860E+06	126.2 ± 40.8
2	1	1	18	1.000	0.9	8.828E+04	8.828E+04	225.3 ± 318.7
3	3	21	25	0.143	12.9	1.907E+05	1.335E+06	32.7 ± 20.2
4	15	73	35	0.205	32.1	6.810E+05	3.314E+06	46.9 ± 13.4
5	9	6	30	1.500	3.1	4.767E+05	3.178E+05	335.1 ± 176.9
6	1	12	24	0.083	7.7	6.621E+04	7.945E+05	19.1 ± 19.9
7	3	6	90	0.500	1.0	5.297E+04	1.059E+05	113.6 ± 80.4
8	35	117	25	0.299	72.0	2.225E+06	7.437E+06	68.2 ± 13.3
9	4	6	25	0.667	3.7	2.542E+05	3.814E+05	151.1 ± 97.6
86		269			14.4	4.762E+05	1.489E+06	

Area of basic unit = 6.293E-07 cm-2

CHI SQUARED = 22.288 WITH 8 DEGREES OF FREEDOM

P(chi squared) = 0.4 %

CORRELATION COEFFICIENT = 0.922

VARIANCE OF SQR(Ns) = 2.67

VARIANCE OF SQR(Ni) = 10.33

Ns/Ni = 0.320 ± 0.040

MEAN RATIO = 0.550 ± 0.153

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm-2; ND = 2129

POOLED AGE = 72.9 ± 9.3 Ma

MEAN AGE = 125.0 ± 35.0 Ma

GR193-12 APATITE

IRRADIATION G072
SLIDE NUMBER 12
COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	14	10	50	1.400	3.1	4.449E+05	3.178E+05	313.3 ± 130.1
2	89	50	24	1.780	32.0	5.893E+06	3.311E+06	395.8 ± 71.0
3	400	305	64	1.311	73.3	9.932E+06	7.573E+06	293.9 ± 24.2
4	14	13	35	1.077	5.7	6.356E+05	5.902E+05	242.3 ± 93.6
5	40	23	50	1.739	7.1	1.271E+06	7.310E+05	386.9 ± 102.0
6	215	156	50	1.378	48.0	6.833E+06	4.958E+06	308.5 ± 33.9
7	158	81	42	1.951	29.7	5.978E+06	3.065E+06	432.5 ± 60.6
8	209	174	36	1.201	74.4	9.225E+06	7.680E+06	269.7 ± 28.9
9	42	81	100	0.519	12.5	6.674E+05	1.287E+06	117.8 ± 22.7
10	29	17	37	1.706	7.1	1.245E+06	7.301E+05	379.8 ± 116.6
11	60	62	64	0.968	14.9	1.490E+06	1.539E+06	218.2 ± 40.1
12	9	7	36	1.286	3.0	3.973E+05	3.090E+05	288.3 ± 145.6
13	35	29	90	1.207	5.0	6.180E+05	5.120E+05	271.0 ± 68.6
14	70	37	28	1.892	20.3	3.973E+06	2.100E+06	419.9 ± 86.3
15	3	2	20	1.500	1.5	2.384E+05	1.589E+05	335.1 ± 306.1
16	5	8	24	0.625	5.1	3.311E+05	5.297E+05	141.7 ± 80.9
1392		1055			21.6	2.949E+06	2.235E+06	

Area of basic unit = 6.293E-07 cm²

CHI SQUARED = 48.340 WITH 15 DEGREES OF FREEDOM

P(chi squared) = 0.0 %

CORRELATION COEFFICIENT = 0.974

VARIANCE OF SQR(Ns) = 26.87

VARIANCE OF SQR(Ni) = 19.79

Ns/Ni = 1.319 ± 0.054

MEAN RATIO = 1.346 ± 0.105

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm⁻²; ND = 2129

POOLED AGE = 295.7 ± 15.2 Ma

MEAN AGE = 301.5 ± 25.3 Ma

GR193-13 APATITE

IRRADIATION G072
SLIDE NUMBER 13
COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	92	46	45	2.000	15.7	3.249E+06	1.624E+06	443.0 ± 81.2
2	8	6	24	1.333	3.8	5.297E+05	3.973E+05	298.7 ± 161.6
3	80	137	49	0.584	43.0	2.594E+06	4.443E+06	132.5 ± 19.1
4	4	5	35	0.800	2.2	1.816E+05	2.270E+05	180.9 ± 121.5
5	31	19	36	1.632	8.1	1.368E+06	8.387E+05	363.7 ± 106.6
215		213			17.3	1.808E+06	1.791E+06	

Area of basic unit = 6.293E-07 cm-2

CHI SQUARED = 33.574 WITH 4 DEGREES OF FREEDOM

P(chi squared) = 0.0 %

CORRELATION COEFFICIENT = 0.741

VARIANCE OF SQR(Ns) = 11.90

VARIANCE OF SQR(Ni) = 15.35

Ns/Ni = 1.009 ± 0.098

MEAN RATIO = 1.270 ± 0.261

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm-2; ND = 2129

POOLED AGE = 227.4 ± 23.1 Ma

MEAN AGE = 284.8 ± 59.1 Ma

GR193-14 APATITE

IRRADIATION G072
SLIDE NUMBER 14
COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	154	74	36	2.081	31.6	6.798E+06	3.266E+06	460.4 ± 66.7
2	2	1	45	2.000	0.3	7.063E+04	3.531E+04	443.0 ± 542.8
3	71	67	16	1.060	64.4	7.051E+06	6.654E+06	238.5 ± 41.3
4	62	44	64	1.409	10.6	1.539E+06	1.092E+06	315.3 ± 62.9
5	45	48	49	0.938	15.1	1.459E+06	1.557E+06	211.5 ± 44.4
6	84	68	42	1.235	24.9	3.178E+06	2.573E+06	277.2 ± 46.1
418		302			18.4	2.636E+06	1.904E+06	

Area of basic unit = 6.293E-07 cm-2

CHI SQUARED = 15.059 WITH 5 DEGREES OF FREEDOM

P(chi squared) = 1.0 %

CORRELATION COEFFICIENT = 0.846

VARIANCE OF SQR(Ns) = 13.07

VARIANCE OF SQR(Ni) = 8.14

Ns/Ni = 1.384 ± 0.105

MEAN RATIO = 1.454 ± 0.197

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm-2; ND = 2129

POOLED AGE = 309.8 ± 25.3 Ma

MEAN AGE = 325.0 ± 45.2 Ma

GR193-15 APATITE

IRRADIATION G072
SLIDE NUMBER 15
COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	71	50	15	1.420	51.3	7.522E+06	5.297E+06	317.7 ± 59.5
2	49	21	25	2.333	12.9	3.115E+06	1.335E+06	514.0 ± 135.0
3	13	8	30	1.625	4.1	6.886E+05	4.238E+05	362.3 ± 163.2
4	38	22	15	1.727	22.6	4.026E+06	2.331E+06	384.4 ± 103.7
5	20	26	36	0.769	11.1	8.828E+05	1.148E+06	174.0 ± 52.0
6	18	19	25	0.947	11.7	1.144E+06	1.208E+06	213.7 ± 70.6
7	54	42	16	1.286	40.4	5.363E+06	4.171E+06	288.3 ± 60.0
8	61	22	24	2.773	14.1	4.039E+06	1.457E+06	606.4 ± 152.0
9	52	24	16	2.167	23.1	5.164E+06	2.384E+06	478.6 ± 119.1
10	0	2	40	0.000	0.8	0.000E+00	7.945E+04	0.0 ± 0.0
11	35	28	36	1.250	12.0	1.545E+06	1.236E+06	280.4 ± 71.6
12	147	112	30	1.312	57.4	7.786E+06	5.933E+06	294.2 ± 38.0
13	0	3	60	0.000	0.8	0.000E+00	7.945E+04	0.0 ± 0.0
14	95	74	49	1.284	23.2	3.081E+06	2.400E+06	287.9 ± 45.5
15	38	22	50	1.727	6.8	1.208E+06	6.992E+05	384.4 ± 103.7
16	22	14	50	1.571	4.3	6.992E+05	4.449E+05	350.6 ± 120.4
17	4	3	25	1.333	1.8	2.542E+05	1.907E+05	298.7 ± 228.3
18	5	5	36	1.000	2.1	2.207E+05	2.207E+05	225.3 ± 142.7
19	2	2	60	1.000	0.5	5.297E+04	5.297E+04	225.3 ± 225.4
724		499			12.0	1.803E+06	1.243E+06	

Area of basic unit = 6.293E-07 cm²

CHI SQUARED = 30.184 WITH 18 DEGREES OF FREEDOM

P(chi squared) = 3.6 %

CORRELATION COEFFICIENT = 0.957

VARIANCE OF SQR(Ns) = 10.65

VARIANCE OF SQR(Ni) = 6.03

Ns/Ni = 1.451 ± 0.084

MEAN RATIO = 1.343 ± 0.157

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm⁻²; ND = 2129

POOLED AGE = 324.4 ± 21.4 Ma

MEAN AGE = 300.9 ± 36.5 Ma

GR193-16 APATITE

IRRADIATION G072
SLIDE NUMBER 16
COUNTED BY: PFG

No.	Ns	Ni	Na	RATIO	U (ppm)	RHOs	RHOi (Ma)	F.T. AGE
1	9	21	25	0.429	12.9	5.721E+05	1.335E+06	97.5 ± 39.0
2	42	38	24	1.105	24.4	2.781E+06	2.516E+06	248.6 ± 56.2
3	48	33	16	1.455	31.7	4.767E+06	3.277E+06	325.2 ± 74.2
4	18	15	25	1.200	9.2	1.144E+06	9.534E+05	269.5 ± 94.6
5	35	47	25	0.745	28.9	2.225E+06	2.987E+06	168.5 ± 38.0
6	192	162	30	1.185	83.1	1.017E+07	8.581E+06	266.2 ± 29.6
7	13	4	30	3.250	2.1	6.886E+05	2.119E+05	705.2 ± 403.8
8	42	15	36	2.800	6.4	1.854E+06	6.621E+05	612.1 ± 185.1
9	24	9	36	2.667	3.8	1.059E+06	3.973E+05	584.2 ± 229.1
10	13	12	25	1.083	7.4	8.263E+05	7.628E+05	243.8 ± 97.9
436		356			20.1	2.547E+06	2.080E+06	

Area of basic unit = 6.293E-07 cm-2

CHI SQUARED = 28.976 WITH 9 DEGREES OF FREEDOM

P(chi squared) = 0.1 %

CORRELATION COEFFICIENT = 0.971

VARIANCE OF SQR(Ns) = 9.75

VARIANCE OF SQR(Ni) = 9.18

Ns/Ni = 1.225 ± 0.087

MEAN RATIO = 1.592 ± 0.303

Ages calculated using a zeta of 338.9 ± 7.7 for SRM612 glass

RHO D = 1.353E+06cm-2; ND = 2129

POOLED AGE = 274.9 ± 21.4 Ma

MEAN AGE = 355.1 ± 68.5 Ma

APPENDIX D

Principles of Interpretation of AFTA™ Data in Sedimentary Basins

Detrital apatite grains are incorporated into sedimentary rocks from three dominant sources - crystalline basement rocks, older sediments and from contemporaneous volcanism. Apatites derived from the first two sources will, in general, contain fission tracks when they are deposited, with AFTA parameters characteristic of the source regions. However apatites derived from contemporaneous volcanism, or from rapidly uplifted basement, will contain no tracks when they are deposited. For now, we will restrict discussion to this situation, and generalise at a later point to cover the case of apatites which contain tracks that have been inherited from source regions.

Fission tracks are trails of radiation damage, which are produced within apatite grains at a more or less constant rate through geological time, as a result of the spontaneous fission of ^{238}U impurity atoms. Therefore the number of fission events which occur within an apatite grain during a fixed time interval depends on the magnitude of the time interval and the uranium content of the grain. Each fission event leads to the formation of a single fission track and the proportion of tracks which can intersect a polished surface of an apatite grain depends on the length of the tracks. Therefore, the number of tracks that are etched in unit area of the surface of an apatite grain (the "spontaneous track density") depends on three factors - (i) the time over which tracks have been accumulating, (ii) the uranium content of the apatite grain, and (iii) the distribution of track lengths in the grain. In sedimentary rocks which have not been subjected to temperatures greater than $\sim 50^\circ\text{C}$ since deposition, spontaneous fission tracks have a characteristic distribution of confined track lengths, with a mean length in the range $14\text{--}15\ \mu\text{m}$, and a standard deviation of $\sim 1\ \mu\text{m}$. In such samples, by measuring the spontaneous track density and the uranium content of a collection of apatite grains, a "fission track age" can be calculated which will be equal to the time over which tracks have been accumulating. The technique is calibrated against other isotopic systems using age standards which also have this type of length distribution (see Appendices B and C).

In samples which have been subject to temperatures greater than $\sim 50^\circ\text{C}$ after deposition, fission tracks are shortened because of the gradual repair of the radiation damage which constitutes the unetched tracks. In effect, the tracks shrink from each end, in a process which is known as fission track "annealing". The final length of each individual track is essentially determined by the maximum temperature that track has experienced. Time differences of orders of magnitude

produce changes in fission track parameters that are equivalent to temperature changes of only $\sim 10^{\circ}\text{C}$, so temperature is by far the dominant factor in determining the final fission track parameters. As temperature increases, all existing tracks rapidly shorten to a length determined by the prevailing temperature, regardless of when they were formed. After the temperature has subsequently cooled, all tracks formed prior to the thermal maximum are "frozen" at the degree of length reduction they attained at that time. Thus, the length of each track can be thought of as a maximum-reading thermometer, recording the maximum temperature to which it has been subjected.

In samples for which the present temperature is maximum, all tracks therefore have much the same length resulting in a narrow, symmetric distribution. The degree of shortening will depend on the temperature, with the mean track length falling progressively from $\sim 14\text{ }\mu\text{m}$ at 50°C , to zero at around $110^{\circ}\text{--}120^{\circ}\text{C}$, the actual value depending on the timescale of heating and the composition of the apatites present in the sample (see below). Values quoted here relate to times of the order of $10^7\text{--}10^8$ years, and average apatite composition. If the effective timescale of heating is shorter than $10^7\text{--}10^8$ years, then the temperature responsible for a given degree of track shortening will be higher, depending in detail on the kinetics of the annealing process (Green et al., 1986; Laslett et al., 1987; Duddy et al., 1988; Green et al., 1989b). Shortening of tracks produces an accompanying reduction in the fission track age, because of the reduced proportion of tracks which can intersect the polished surface. Therefore, the fission track age is also highly temperature dependent, falling to zero at around 120°C , due to total erasure of all tracks.

Complex thermal histories produce correspondingly complex length distributions and ages. Samples which have cooled from a thermal maximum (with peak temperature between $\sim 50^{\circ}$ and 120°C) at some time in the past will contain two populations of tracks. Those formed prior to the thermal maximum will all be shortened to more or less the same degree (the precise value depending on the peak temperature) while those formed during and after cooling will be longer due to the lower prevailing temperatures. The length distribution in such samples will be broader than in the simple case, and the fission track age will be a reflection of the amount of length reduction which has occurred. In some cases this kind of history produces a characteristic bimodal distribution of confined track lengths. If cooling is sufficiently rapid, and the final temperature is low enough ($< \sim 50^{\circ}\text{C}$), tracks formed subsequently will have lengths of $14\text{--}15\text{ }\mu\text{m}$, and will contribute a fission track age component corresponding to the age of the cooling "event". If maximum temperatures exceed $\sim 120^{\circ}\text{C}$, all pre-existing tracks will be erased, and all tracks now present will have formed during and subsequent to cooling. The fission track age in such samples therefore relates directly to the time of cooling.

Because temperature dominates the thermal response of tracks in apatite, no information is preserved on the approach to maximum temperature, and the only information available is the magnitude of the maximum temperature, the timing of cooling from that maximum, and some indication of the thermal history since cooling. Note that if temperature increases again, subsequent to the initial cooling, those tracks formed during this second heating phase will undergo greater shortening. If the temperature in the second heating phase reaches similar values to that reached in the original heating, the two generations of tracks will be identical and all information on the original heating phase will be lost. If the temperature during the second heating phase increases beyond that reached in the original heating phase, all tracks are shortened further.

Our understanding of the behaviour of the AFTA system during geological thermal histories is based on study of the response of fission tracks to elevated temperatures in the laboratory (Green et al., 1986; Laslett et al., 1987; Duddy et al., 1988; Green et al., 1989b) and in geological situations (Green et al., 1989a), observations of the lengths of spontaneous tracks in apatites from a wide variety of geological environments (Gleadow et al., 1986), and the relationship between track length reduction and reduction in fission track age observed in controlled laboratory experiments (Green, 1988).

Final interpretation is based on computer modelling of track shortening through likely thermal histories for an apatite of average composition (Green et al., 1989b). As explained by Green et al. (1989b), the uncertainty in estimates of maximum paleotemperature derived using this approach is thought to be $\sim 10^{\circ}\text{C}$. Predictions from these modelling procedures agree well with observed AFTA parameters in apatites of the appropriate composition in samples from the Otway Basin reference wells (Gleadow and Duddy, 1981; Gleadow et al., 1983; Green et al., 1989a), providing support for the validity of extrapolation from laboratory to geological timescales.

The ratio of chlorine to fluorine in the apatite lattice exerts a compositional control on the degree of annealing, with apatites richer in fluorine being more easily annealed than those richer in chlorine. Our understanding of the kinetics of fission track annealing relates to apatite with $\text{Cl}/(\text{Cl}+\text{F})$ of ~ 0.1 (Durango apatite) on which most of our original experimental studies were carried out. Unpublished laboratory annealing studies on a range of different apatites, together with observations of annealing in apatites from the Otway Basin reference wells, which show a wide spread of compositions, afford a means of extending the model predictions to apatites of other compositions. Since the apatite grains analysed in this study are likely to have been originally derived predominantly from basement rocks, a restricted compositional range would be expected in all samples, with $\text{Cl}/(\text{Cl}+\text{F})$ varying from zero (pure fluorapatite) to around 0.1,

the value in Durango apatite. Therefore, in the following discussion, paleotemperature estimates are based on this assumption. Experience with sedimentary rocks derived from a variety of different source terrains suggests that this assumption should be valid.

The basic principle involved in the interpretation of AFTA data in sedimentary basins is to ask whether the degree of annealing shown by tracks in apatite from a particular sample could have been produced by the thermal history suggested by the preserved sedimentary section and the prevailing geothermal gradient.

The degree of annealing is assessed in two ways - from fission track age and track length data. The stratigraphic age provides a basic reference point for the interpretation of fission track age, because reduction of the fission track age below the stratigraphic age unequivocally reveals that appreciable annealing has taken place after deposition of the host sediment. Large degrees of fission track age reduction, with the mean or pooled fission track age very much less than the stratigraphic age, indicate severe annealing, which requires paleotemperatures of at least $\sim 100^{\circ}\text{C}$ for any reasonable geological timescale of heating ($> \sim 10$ Ma). Note that this applies even when apatites contain tracks inherited from source areas. More moderate degrees of annealing can be detected by inspection of the single grain age data, as the most sensitive (fluorine-rich) grains will begin to give fission track ages significantly less than the stratigraphic age before the mean or pooled age has been reduced sufficiently to give a noticeable signal. Note that this aspect of the single grain age data can also be used for apatites which have tracks inherited from source areas. If signs of moderate annealing (from single grain age reduction) or severe annealing (from the mean or pooled age) are seen in samples which are from present temperatures at which the observed degree of annealing would not be expected, then this suggests that the sample has been subjected to elevated paleotemperatures at some time in the past.

Similarly, the present temperature from which a sample is taken, and the way this has been approached (as inferred from the preserved sedimentary section), forms a basic point of reference for track length data (as well as fission track age data). If observed track shortening cannot have been produced from the apparent burial to the present temperature, then this suggests higher paleotemperatures at some time in the past. Using the kinetic description of fission track annealing described in an earlier section, we can predict a value of mean length, l_p , that would be expected in each sample from the thermal history suggested by the burial history derived from the preserved stratigraphic section, and using the present thermal gradient, ie assuming there has been no uplift and erosion, and no changes in thermal gradient through time. These values of l_p are then compared with measured mean track lengths in assessing past variations in paleotemperature. Values of l_p for all samples analysed are shown in Table 1.

The influence of track lengths inherited from source areas can readily be allowed for, by comparison of the fission track age with the stratigraphic age and inspection of the length distribution. If I_p is less than the stratigraphic age then either the sample has been subjected to elevated paleotemperatures, sufficient to produce the observed degree of length reduction, or else the sample contains a large proportion of tracks inherited from source areas. However in such a case, the sample should give a mean or pooled fission track age correspondingly older than the stratigraphic age, and the length distribution should contain a component of longer track lengths corresponding to the value of I_p . It is important in this regard that the length of a track depends primarily on the maximum temperature to which it has been subjected, whether in the source regions or after deposition in the sedimentary basin. Thus any lengths retaining a provenance signature will be towards the shorter end of the length distribution where track lengths will not have "equilibrated" with the prevailing temperature within the basin.

Timing of cooling from maximum paleotemperatures can be estimated from a number of lines of evidence. The most direct of these is "correction" of measured fission track ages for the observed degree of length reduction, which provides an estimate of the time over which tracks have been retained. Corrected ages, shown for each sample in Table 1 are calculated using the relationship between length reduction and the reduction in fission track age during annealing reported by Green (1988). In samples which have been totally annealed prior to cooling, and have undergone a relatively simple history since cooling, the corrected age should directly indicate the time of cooling. Note that any complexity in the thermal history leads to these "corrected ages" underestimating this parameter, but this procedure can often yield useful results. However, corrected ages can be very misleading, particularly in samples which have only been partially annealed.

Inspection of the distribution of single grain ages in partially annealed samples can also often yield useful information on the time of cooling, as the most easily annealed grains (those richest in fluorine) may have been totally annealed prior to cooling. The form of the track length distribution can also provide information, from the relative proportions of tracks with different lengths. Normally, all of these aspects of the data are employed in reaching a consistent thermal history interpretation.

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