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Early Tertiary paleo-thermal effects in Northern England: reconciling results from apatite fission track analysis with geological evidence

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Abstract

The Paleozoic Lake District Block in northwest England has traditionally been thought of as tectonically stable since the Late Paleozoic, receiving only small thicknesses of Late Paleozoic to Mesozoic cover (although some workers have put forward different views). Apatite fission track analysis (AFTA) data from outcrop samples across the region reveal Early Tertiary paleotemperatures around 100 °C, requiring kilometre-scale Late Paleozoic and Mesozoic cover, removed during Tertiary uplift and erosion. With no evidence for elevated basal heat flow in NW England during the Early Tertiary, and no a priori justification for invoking it, earlier studies favoured an explanation involving burial by up to 3 km of overburden removed during Tertiary uplift and erosion. This conclusion was met with scepticism by many workers, and provoked a range of comments and criticisms, with a variety of alternative interpretations put forward, although these are also open to criticism. Results from the West Newton-1 hydrocarbon exploration well on the northern flank of the Lake District gave the first indication of a possibly more realistic interpretation, involving a combination of elevated heat flow and more restricted burial, but some aspects of the interpretation of these data were equivocal. More detailed sampling was therefore undertaken, in order to shed more light on the origin of the elevated Early Tertiary paleotemperatures observed across NW England. New AFTA data in outcrop samples from different elevations around Sca Fell (characterised by the highest elevations in the Lake District with the summit of Scafell Pike at 978 m asl) define an Early Tertiary paleogeothermal gradient of 61 °C/km, and require around 700 m of section removed from the summit during Tertiary uplift and erosion. These results, together with those from the West Newton-1 well, provide strong support for an interpretation involving Early Tertiary paleogeothermal gradients between 50% and 100% higher than present-day values, providing clear evidence of elevated basal heat flow during the Early Tertiary, contrary to earlier assumptions. Combined with amounts of section removed during Tertiary exhumation varying between ~0.7 km (from mountain peaks) and ~1.5–2 km (from coastal plains and glacial valleys near sea level) over the region, this interpretation finally provides a geologically plausible mechanism for the origin of the observed Early Tertiary paleo-thermal effects in NW England.

Keywords: Apatite; Fission track analysis; Exhumation; Heat flow; Lake District

1. Introduction

Until relatively recently, the Early Paleozoic Lake District Block in Northwest England has generally been regarded as having been tectonically stable since

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the Late Paleozoic, with very little in the way of post-Early Paleozoic cover having been deposited. Although some notable workers have put forward different views (as reviewed by Holliday, 1993), most paleogeographic reconstructions of the region (e.g., Cope et al., 1992; Ziegler, 1990) have shown NW England as an emergent High throughout most of the Late Paleozoic, Mesozoic and Tertiary.

More recently, results from apatite fission track analysis (reviewed in Section 3) provided strong support for what might be traditionally considered the minority view that the geological evolution of the region during Late Paleozoic and Mesozoic time was more complex than generally accepted, involving deposition of significant thicknesses of post-Paleozoic cover, subsequently removed by Tertiary uplift and erosion. These results and models invoked to explain them were met with a number of comments and criticisms, and a variety of alternative models have been suggested, although these models are also open to criticism. More detailed sampling was therefore undertaken, in order to shed more light on the origin of the observed Early Tertiary paleotemperatures. These latest results, presented here, finally provide a geologically plausible explanation of the Early Tertiary paleothermal effects observed in NW England.

2. Apatite fission track analysis

Apatite fission track analysis (AFTA®) depends on analysis of radiation damage features ('fission tracks') in either accessory apatite crystals separated from igneous rocks or in detrital apatite grains obtained from sandstones and other clastic rock types (Green et al., 1989a). Fission tracks are generated continuously through time by spontaneous fission of uranium impurity atoms, present within the apatite lattice at ppm levels, and can be easily revealed in a polished surface by etching with dilute acid. The areal density of tracks present in a polished surface of an apatite grain depends on the uranium content of the grain, the time over which tracks have accumulated and the length of the tracks. This provides the basis for determination of a fission track age (Fleischer et al., 1975) which, in the absence of other effects, would measure the time over which tracks have accumulated in an apatite crystal. But in practice, while tracks are formed with an initial length within a narrow range, they shorten (by a process known as "annealing") at a rate which depends on the prevailing temperature. Thus, as the temperature of a sample increases, tracks become shorter, and since temperature dominates over time in the kinetics of the shortening process, all tracks are reduced to more or less the same length regardless of when they were formed (Green et al., 1989b). This process is irreversible, and if the temperature subsequently drops, all tracks formed up to that time are effectively "frozen" at the length attained at the maximum temperature. Tracks that form after cooling are longer, due to the lower prevailing temperatures. Thus, the proportion of short to long tracks measured in an apatite at the present-day reflects the time of cooling, while the mean length of the shorter component of tracks reflects the maximum paleotemperature. The fission track age is also reduced as a result of the track length reduction, due to the reduced probability of tracks intersecting a polished surface. Thus, the fission track age becomes a parameter with no fundamental meaning in its own right (in most cases), which must be interpreted together with the track length data to provide thermal history information. At some critical paleotemperature the damage constituting the track is totally repaired, and the length is reduced to zero ('total annealing'). The precise temperature where this occurs depends on the heating rate and the Cl content of the apatite. In samples that reached higher paleotemperatures, tracks are only retained after cooling below this limit. AFTA data from such samples provide only a minimum estimate of the maximum paleotemperature, but typically provide good constraints on the timing of the cooling episode.

Thermal history information is extracted from the AFTA data by modelling measured AFTA parameters (fission track age and track length distributions) through a variety of possible thermal history scenarios, varying the magnitude and timing of the maximum paleotemperature in order to define the range of values of each parameter which give predictions consistent with the measured data within 95% confidence limits. The basics of this modelling procedure are well established for mono-compositional apatites (e.g., Green et al., 1989b). However, the annealing kinetics of fission tracks in apatite are known to be affected by the chlorine content (Green et al., 1986), and in the study described here, thermal history solutions have been extracted from the AFTA data using a "multi-compositional" kinetic model which makes full quantitative allowance for the effect of Cl content on annealing rates of fission tracks in apatite (Green et al., 1996). This model is calibrated using a combination of laboratory and geological data from a variety of sedimentary basins around the world. Paleotemperature estimates from AFTA are quoted as a range (corresponding to $\pm 95\%$ confidence limits) and have an absolute uncertainty of between ± 5 and ± 10 °C. For more details of the interpretive process by which thermal history solutions are extracted from AFTA data, see e.g. Green et al. (1999), Parnell et al. (1999), Thomson et al. (1999a,b).

In regions such as the Lake District where large periods of geological time are not represented in the stratigraphical record, AFTA can be used to study the nature of events during the unrepresented time intervals. In particular, AFTA data from Paleozoic units at outcrop can provide direct evaluation of the timing and nature of paleo-thermal episodes which occurred well after deposition of the youngest units in the preserved rock record. Interpretation of this information in terms of the tectonic processes responsible thus provides unique insight into the post-Paleozoic evolution of the Lake District Block.

3. Early Tertiary paleotemperatures in NW England revealed by AFTA

In an initial study of outcropping Caledonian basement from the Lake District block, Green (1986) reported AFTA data which were interpreted as revealing paleotemperatures between 80 and 110 °C or higher in these rocks prior to cooling which began at around 60 Ma. Insight into the nature of processes responsible for the observed heating and cooling in such situations can be obtained from the manner in which paleotemperatures vary with depth (if sub-surface samples are available), as described for example by Bray et al. (1992), Duddy et al. (1994) and Green et al. (1995a). In particular, such analyses allow estimation of the paleogeothermal gradient, and using this information the observed paleotemperatures can be converted (subject to certain critical assumptions, as outlined in Section 6) to former depths of burial. As will be illustrated in a later section, similar information can also be obtained using surface samples from a range of elevations.

However, the study reported by Green (1986) involved only outcrop samples, and therefore no constraints were possible on paleogeothermal gradients. Green (1986) concluded that although the cause of these late Cretaceous to early Tertiary paleo-thermal effects was not clear, any likely explanation must require kilometre-scale Tertiary uplift and erosion.

Subsequent analysis by Green (1989) of samples from outcrops and exploration wells on the East Midlands Shelf (EMS) and the Pennine High, to the southwest of the Lake District, extended the area showing evidence of Late Cretaceous to Early Tertiary cooling. Green (1989) concluded that on the EMS, paleogeothermal gradients prior to the onset of early Tertiary cooling were close to present values, and that between 1 and 2 km of section had been removed in this region by Tertiary uplift and erosion. This conclusion was subsequently supported by analysis of vitrinite reflectance (VR) data from these EMS wells, and by a more rigorous analysis of the paleotemperature data (Bray et al., 1992).

In an extension of earlier work in northern England, Lewis et al. (1992) found that samples from locations throughout northwest England and the adjacent Irish Sea all showed the effects of elevated paleotemperatures prior to cooling beginning in the interval 65 ± 5 Ma. None of the samples analysed by Lewis et al. (1992) provided any constraints on paleogeothermal gradients, so rigorous estimation of amounts of former burial were not possible. They were therefore forced to seek indirect evidence for the nature of the processes responsible for the observed Early Tertiary paleotemperatures and subsequent cooling. On the basis of:

1: the regional nature of the paleo-thermal effects,
2: Early Tertiary paleogeothermal gradients close to present-day values in EMS wells,
3: a lack of evidence for significantly elevated gradients in northwest England, and
4: published VR data and shale sonic velocity studies from Irish Sea wells.

Lewis et al. (1992) concluded that the most likely explanation of the observed Early Tertiary paleotemperatures was primarily deeper burial, with a paleogeothermal gradient close to present-day values, and that subsequent cooling was due largely to uplift and erosion (exhumation). Lewis et al. (1992) calculated that for an assumed paleogeothermal gradient of 30 °C/km, the observed paleotemperatures required ~ 3 km of section to have been removed over much of the region.

Green (1986) and Lewis et al. (1992) intended their conclusions to be more concerned more with establishing the general scale of eroded cover from northern England (i.e., kilometre-scale), and with establishing the regional nature of Early Tertiary heating (a point emphasised by Green et al., 1993a), rather than with detailed estimation of precise amounts, hence the question mark in the title of Lewis et al. (1992). However, these results were in marked contrast to the prevailing consensus view of very limited post-Paleozoic cover over the Lake District Block, and provoked considerable comment and criticism.

4. Comments, criticisms and other interpretations

Holliday (1993) reviewed the historical debate concerning the extent and thickness of cover removed by Cenozoic erosion across Northern England, opinions varying from several kilometres of former cover to virtually none, with a consensus somewhere near the latter extreme. While accepting that the AFTA studies described above strongly favour the larger option, Holliday (1993) considered 3 km of removed section unacceptably high when compared to the evidence of section preserved in adjacent Mesozoic basins. On this basis Holliday (1993) estimated a probable range of 700–1750 m for the amount of former Mesozoic cover over the Lake District and Pennine blocks. Holliday (1993) also considered that estimates of section removed in wells from the East Midlands Shelf derived from AFTA and VR were too high by ~ 1 km.

McCulloch (1994a,b) raised a number of criticisms regarding the AFTA data from Northern England, including questioning the timing of the main phase of cooling, the mechanisms of heating and cooling, and points of detail regarding data interpretation. All these criticisms were answered by Green et al. (1995b,c).

Subsequent studies by Cope (1994) and Chadwick et al. (1994) suggested a growing acceptance of the general concept of km-scale Tertiary exhumation, even if exact amounts were still uncertain. On the basis of using heat flow modelling to reproduce the Early Tertiary paleotemperatures revealed by AFTA, Chadwick et al. (1994) estimated a minimum of around 1.75 km of removed section from the central region of the Lake District, increasing to values in excess of 3 km in more basinal settings to the North and South. These values from the central Lake District lie at the upper extreme of the range of values considered by Holliday (1993) to be consistent with geological evidence. The erosion map drawn by Cope (1994), mainly on the basis of geological inference, showing a "bullseye" pattern over the Irish Sea was certainly an appealing concept, but the erosion contours show a very poor match to the observed regional variation in Early Tertiary paleotemperatures (Fig. 1; see also Fig. 10 of Green et al., 1997). In detail, Cope (1994) suggests maximum erosion of more than 2 km over Anglesey, equal amounts of erosion in Northern Ireland as in the Lake District (1–2 km), and a zero erosion contour cutting the Cleveland Basin. In contrast, the results in Fig. 1 show highest paleotemperatures focussed in the northern part of the Lake District and the northern coast of the Solway Firth, while Early Tertiary paleotemperatures around Anglesey and Northern Ireland are much lower (see Fig. 10, Green et al., 1997). In addition, results from the Cleveland Basin (reported by Green et al., 1993a) show this area to be another focus of major Early Tertiary paleo-thermal effects, with paleotemperatures around 100 °C or above obtained from outcrop samples along the coast in that region.

Therefore, from the studies reviewed in this section, the origin of the Early Tertiary paleotemperatures revealed by AFTA in Northern England remains enigmatic, with the underlying cause being unclear.

5. First insights into the mechanism of Early Tertiary heating

Subsequent to the studies described so far, an increasing focus on hydrocarbon exploration in the Irish Sea and adjacent regions led to major improvements in definition of thermal history styles across the region. In addition to recognising the occurrence of Mesozoic paleo-thermal episodes (Green et al., 1997), this work resulted in much tighter constraints on the nature of Early Tertiary paleo-thermal effects, the first hints of which were reported by Green et al. (1993b).

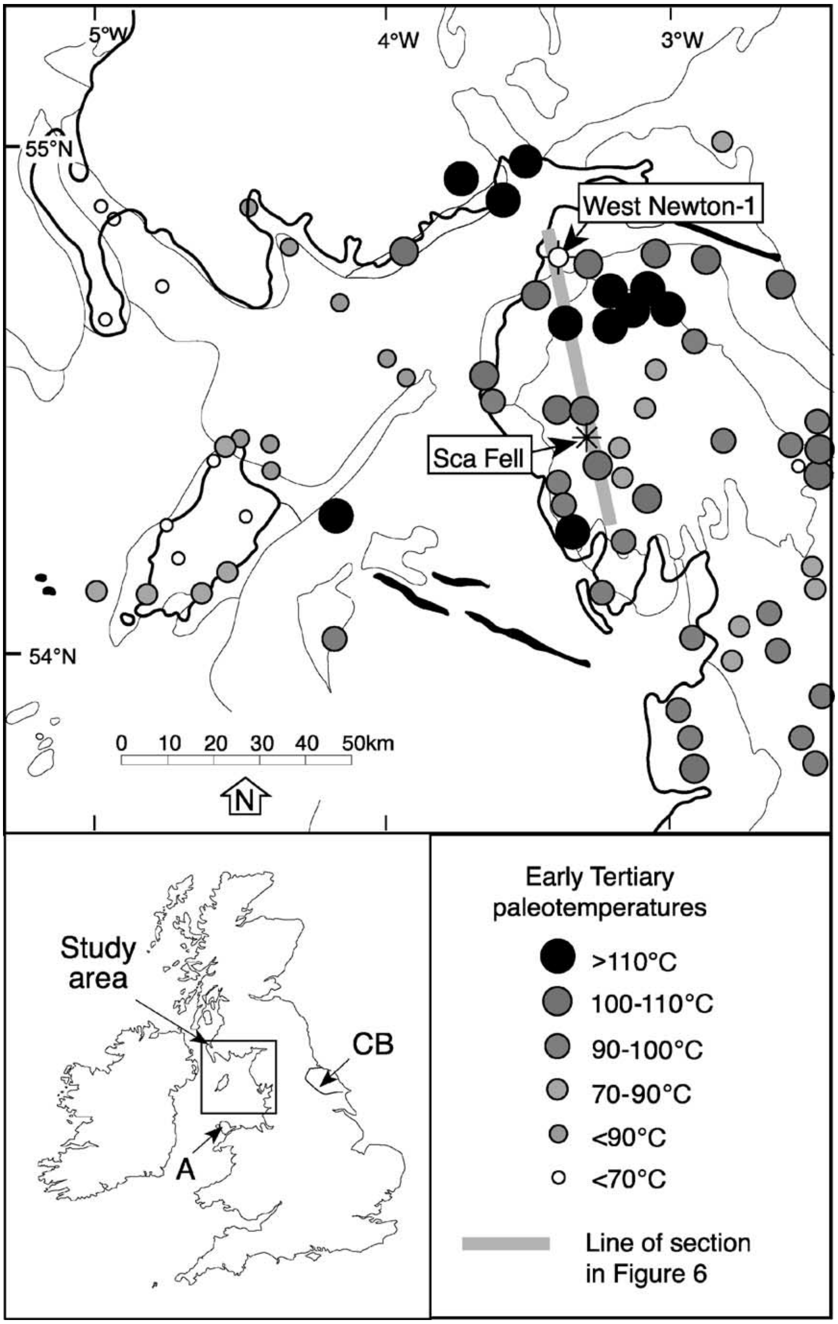

Fig. 1. Early Tertiary paleotemperature map for outcrop samples from NW England and the Irish Sea (based on Fig. 10 of Green et al., 1997). The line of the schematic section reconstructed in Fig. 6 is also shown. Locations referred to in the text are also shown (CB = Cleveland Basin; A = Anglesey). Wasdale Head and Wastwater, also mentioned in the text, are adjacent to the location of Sca Fell.

As reviewed in detail by Green et al. (1997), AFTA data from exploration wells in the East Irish Sea Basin showed a major difference from south to north. Results across the whole region revealed Early Tertiary paleotemperatures around 100 °C or more at outcrop or seabed, but the depth variation suggested different processes were responsible in different parts of the basin. Wells from the south of the basin define low paleogeothermal gradients suggestive of heating related to hot fluid circulation in the south, whereas the northern parts of the basin were characterised by much higher paleo-gradients, suggesting a major contribution of heating due to elevated basal heat flow.

Evidence from the north of the basin are typified by AFTA and VR data from the onshore West Newton-1 well, reported by Green et al. (1997). Assuming that both AFTA and VR data represent the same paleothermal episode, they define an Early Tertiary paleogeothermal gradient of ~ 50 °C/km, compared with the present-day gradient of ~ 35 °C/km, implying that the Early Tertiary heat flow was up to 50% higher than the present-day value. But as emphasised by Green et al. (1997), some aspects of the results from West Newton-1 remained equivocal. All of the AFTA samples from the Carboniferous section were totally annealed in the Early Tertiary, and the maximum paleotemperatures derived from the VR data (which largely control the paleo-gradient) are all higher than the minimum limits provided by the AFTA data. These data would therefore allow an alternative interpretation whereby the VR data represent an earlier episode (perhaps end-Carboniferous) in which the Carboniferous units reached their maximum post-depositional paleotemperatures, while Early Tertiary paleotemperatures in the Carboniferous section were somewhat lower. In this scenario, the paleotemperature profiles characterising the two episodes would converge at a value around 100 °C in the thin Triassic section near the top of the well, and the Early Tertiary paleogeothermal gradient would have been lower than the value derived from the VR data. Thus, these data are rather equivocal, and doubt still surrounds the origin of the Early Tertiary paleotemperatures revealed by AFTA. (Results discussed in the following section suggest that the AFTA and VR data from the West Newton-1 well do indeed represent the Early Tertiary paleo-thermal episode, and provide strong support for elevated paleogeothermal gradients at that time).

6. Results from an elevation section around Sca Fell

Studies of the variation of fission track parameters in apatite (particularly fission track age) with sample elevation has been a routine aspect of fission track analysis in mountain belts since the earliest development of the technique, as exemplified by the work of Wagner et al. (1977) in the European Alps. This approach has become a sophisticated method for studying relative erosion rates and amounts in mountain belts (e.g., Fitzgerald et al., 1999) but is usually applied to sections spanning elevation ranges of 2 to 3 km or more. In contrast, because of the much more subdued relief in Northern England, this approach has not been considered useful in previous applications of fission track methods to this region (as reviewed above), particularly as most samples have been taken from valleys and lowland regions over a relatively narrow range of elevations.

But if the Early Tertiary paleogeothermal gradient in NW England was around 50 °C/km, as suggested by results from the West Newton-1 well, this would suggest a difference of ~ 50 °C in maximum paleotemperature between sea level and the summit of Sca fell Pike, England's highest mountain with a summit at just under 1000 m elevation, located only ~ 25 km to the south of West Newton-1. Such a difference should be easily resolved using AFTA, provided that most of the section did not exceed ~ 110 °C, which would result in total annealing and hence only minimum estimates of Tertiary paleotemperatures through most of the section. Since the present-day topography in the Lake District is largely a product of Holocene glacial action, data from outcrops at different present-day elevations should constitute a coherent vertical section describing the paleo-thermal structure during the Early Tertiary, and should therefore allow direct assessment of the paleogeothermal gradient at that time.

Therefore, to test the possibility of an elevated Early Tertiary paleogeothermal gradient, a series of outcrop samples were collected for AFTA from various elevations around the Sca Fell region. Sample details are summarised in Table 1, together with the resulting AFTA data. Details of the geology of the Sca Fell region are described e.g. by Branney and Kokelaar (1994). Most samples were taken from the Borrowdale Volcanics of Ordovician (Llandeilo–Caradoc) age,

Table 1
Apatite fission track age and length data in samples from Sca Fell, English Lake District

Sample number[a]	Elevation (m)	Grid reference	ρ_D[b] (10^6 tracks/cm^2)	ρ_s[b] (10^6 tracks/cm^2)	ρ_i[b] (10^6 tracks/cm^2)	Pooled/Central fission track age (Ma)[c]	$P(\chi^2)$ (%) (number of grains)	Mean track length[d] (μm)	Standard deviation (μm)
GC579-13	966	21480715	1.209 (1882)	0.753 (430)	0.513 (293)	333.2 ± 26.6	25 (20)	12.29 ± 0.22 (39)	1.39
GC579-14	808	21350755	1.204 (1882)	1.032 (919)	0.731 (651)	319.5 ± 18.31	83 (24)	12.88 ± 0.14 (100)	1.38
GC579-12	701	20750710		–	–	no apatite	–	–	–
GC579-15	588	21850843	1.199 (1882)	0.680 (532)	0.459 (359)	333.6 ± 24.3	61 (20)	11.78 ± 0.22 (105)	2.23
GC579-16	472	21800945	1.194 (1882)	0.169 (10)	0.304 (18)	126.6 ± 50.0	17 (2)	–	–
GC579-11	244	19250732	1.219 (1882)	0.201 (58)	0.713 (206)	65.8 ± 9.9	82 (8)	10.56 ± 2.25 (5)	5.02
GC579-17	122	18600925	1.189 (1882)	0.371 (249)	1.458 (978)	58.1 ± 4.4	54 (20)	13.16 ± 0.50 (12)	1.72

ρ_s—spontaneous track density; ρ_i, induced track density; ρ_D, dosimeter track density; $P(\chi^2)$, chi-squared probability (Galbraith, 1981).

[a] All samples are from the Borrowdale Volcanics, of Ordovician (Caradoc – Llandeilo) age, with the exception of sample GC579-17, which is from an offshoot of the Eskdale Granite (also of Ordovician age).

[b] Numbers in parentheses show the number of tracks counted.

[c] All ages are "Pooled ages" (Green, 1981) as the data show no significant spread in single grain ages ($P(\chi^2) > 5\%$ in all samples). Ages calculated using a "Zeta" (Hurford and Green, 1983) of 385.5 ± 4.3 for CN5 dosimeter glass. Other details as described by Green (1986), with the exception that the thermal neutron irradiation was characterised by a significant flux gradient, and the appropriate values of ρ_D were determined by linear interpolation through the stack of grain mounts.

[d] Numbers in parentheses show the number of track lengths measured.

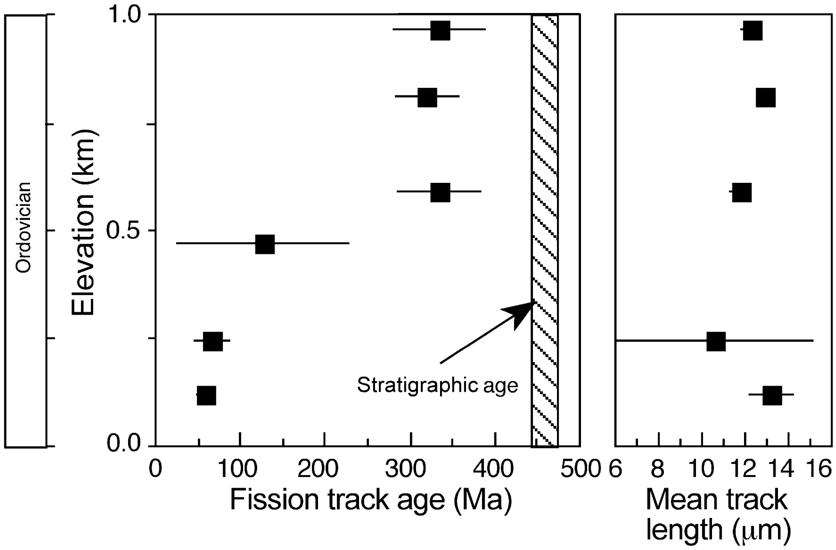

Fig. 2. Fission track age and mean confined track length in samples from Sca Fell, plotted against sample elevation (asl). The ages show a pronounced drop from values around 300 Ma above 500 m to around 60 Ma at the lowest sampled elevations. As discussed in the text, this is controlled partly by thermal history but also in part by variations in apatite chlorine content through the section (see Fig. 3).

while one sample (GC579-17) was taken from an offshoot of the Eskdale Granite intruding the Borrowdale Volcanics near Wasdale Head. Hughes et al. (1996) reported a zircon U–Pb age of 450 ± 3 Ma for the Eskdale Granite, which supports earlier suggestions that the Eskdale granite represents a sub-volcanic intrusion, related to the Borrowdale volcanics.

Fig. 2 shows apatite fission track age and mean confined track length plotted against elevation. The fission track ages show a clear transition from values around 300 Ma or above at elevations greater than ~ 500 m to around 60 Ma at the lowest sampled elevation near the shores of Wastwater. Fig. 3 shows the fission track ages of individual apatite grains in each sample plotted against the chlorine content (in wt.%), together with the distribution of confined track lengths measured in each sample. The plots of single grain ages against wt.% Cl emphasise the variation in chlorine content within these samples, with the majority of grains in Borrowdale Volcanics samples showing containing significant amounts of chlorine, up to 0.8 wt.% in sample GC579-15. In the granite sample, GC579-17, most grains have Cl contents between 0 and 0.1 wt.%, these data being much more typical of granitic apatites.

The evident variation in chlorine content between the samples makes a direct comparison of the pooled fission track age of each sample in Fig. 1 much less meaningful than if all grains had the same Cl content, as variable annealing sensitivities exerts additional influence on the trend of age vs. elevation. Extraction of thermal history solutions using a kinetic description of annealing which includes the influence of chlorine content is therefore required, in order to take full advantage of these data. Thermal history interpretation of these data, using techniques described earlier, gives results as described in Table 2, which focuses on the Early Tertiary signature from these data (in most samples, earlier episodes of cooling are also revealed, but these are not discussed here). As summarised in

Fig. 3. Plots of single grain fission track ages against chlorine content and distributions of confined track lengths, for each sample. Chlorine contents increase from sample-13 to sample-15, which results in the measured fission track age remaining more or less constant (Fig. 2) despite the increasing Early Tertiary paleotemperature through this section (Fig. 4). The granitic sample (GC579-17) at the base of the section has much lower Cl contents, as typically observed in such samples. The distribution of Cl in each sample has been taken into account explicitly in obtaining thermal history information from the AFTA data (Table 2).

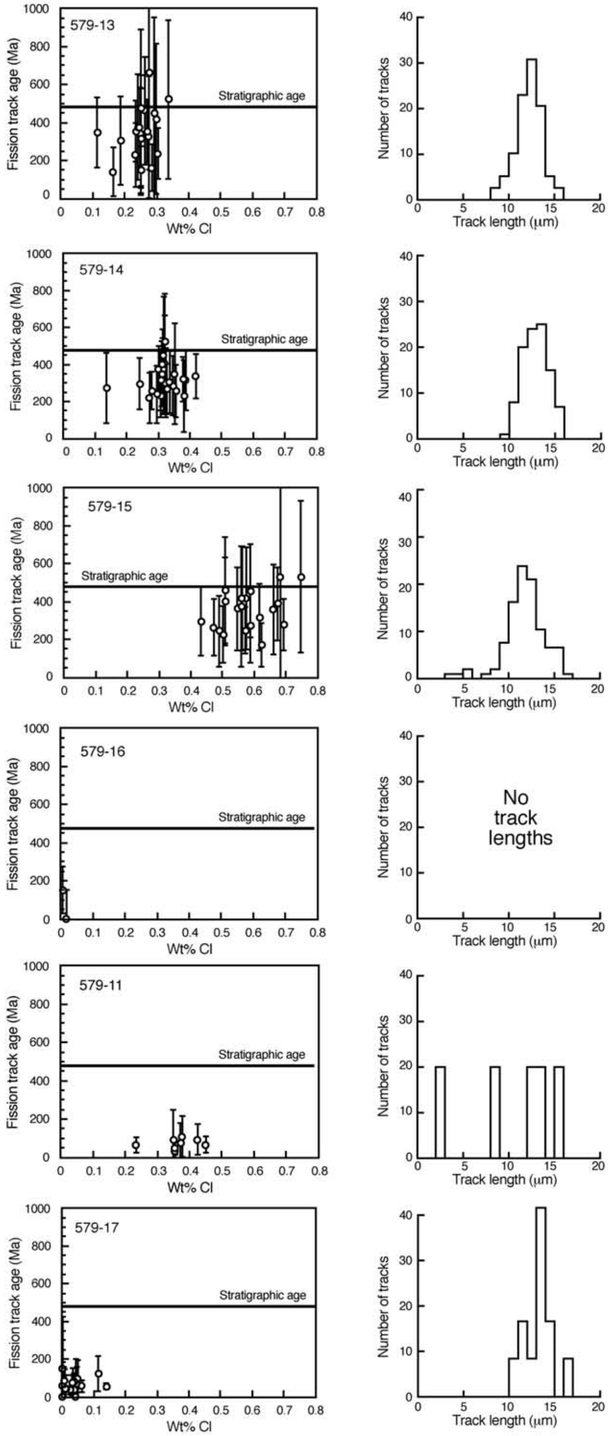
579-13
579-14
579-15
579-16
579-11
579-17
Stratigraphic age
Fission track age (Ma)
Wt% Cl
Number of tracks
Track length (μm)
No
track
lengths

Table 2
Thermal history interpretation of AFTA data in samples from Sca Fell, English Lake District

Sample number	Elevation (m)	Timing of cooling from AFTA (Ma)	Early Tertiary paleotemperature (°C)
GC579-13	966	75–0	55–80
GC579-14	808	100–0	40–75
GC579-12	701	–	–
GC579-15	588	90–25	85–95
GC579-16	472	100–0	< 105
GC579-11	244	65–0	100–110
GC579-17	122	80–50	>105
Common timing:		65–50 Ma	

Table 2, combining timing estimates from all samples suggests that cooling began some time between 65 and 50 Ma (Early Tertiary), consistent with earlier work from the region reviewed in Section 3. Early Tertiary paleotemperatures are plotted against sample elevation (asl) in Fig. 4. In some samples, the range of allowed paleotemperatures is quite large (e.g., 50 to 80 °C in sample 13; 40 to 75 °C in sample GC579-14). This results from the moderate degree of track length reduction in these samples, which allows a wide range of possible interpretations. The lack of data from apatites with between 0.0 and 0.1 wt.% Cl in these samples is an additional contributing factor, since track lengths from such apatites would show larger degrees of shortening than those with higher Cl contents, which would allow tighter control on the magnitude of Tertiary paleotemperatures. As the degree of annealing increases down the section, the allowed range of paleotemperatures is much reduced, although due to the poor quality of the data from sample GC579-16, with only two grains analysed and no track lengths, the data allow only an upper limit to the maximum Early Tertiary paleotemperature. In sample GC579-17, all grains were totally annealed prior to the onset of cooling, and the data provide only a lower limit to the maximum Early Tertiary paleotemperature.

The Early Tertiary paleotemperature constraints from AFTA in these six samples define a generally linear profile with depth in Fig. 4. As described by Bray et al. (1992), the slope of such a profile provides an

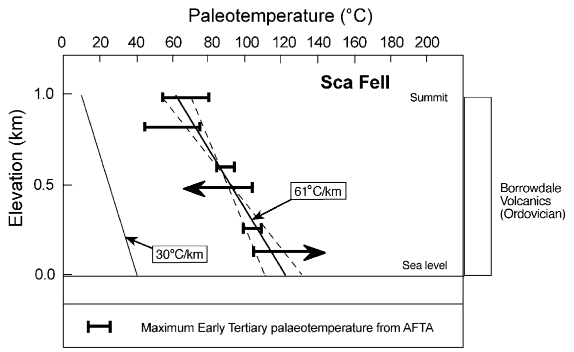

Fig. 4. Estimates of Early Tertiary paleotemperature derived from the AFTA data shown in Fig. 2, plotted against sample elevation (asl). These results show a progressive decrease with increasing elevation, and are in general agreement with a linear profile. As illustrated in Fig. 5, statistical analysis of these paleotemperature constraints defines a maximum likelihood paleogeothermal gradient of 61 °C/km (solid line), with upper and lower 95% limits on the paleogeothermal gradient of 40 and 80 °C/km (dashed lines). The entire range of allowed values is higher than the (assumed) present-day thermal gradient of 30 °C/km, suggesting that Early Tertiary heating was characterised by an elevated basal heat flow.

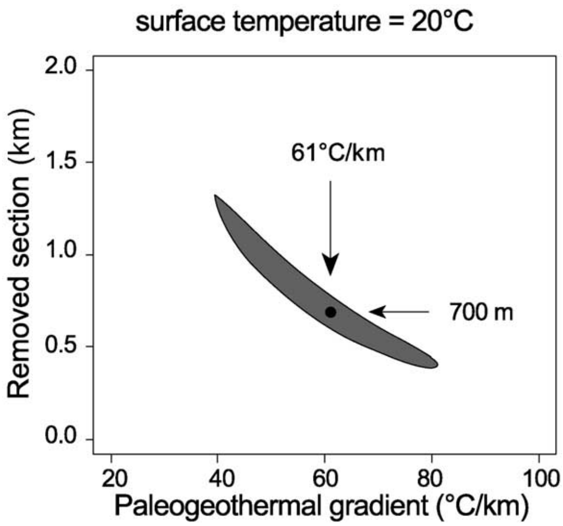

Fig. 5. Fitting linear profiles to the paleotemperature constraints at different elevations in Fig. 4 using likelihood theory, and extrapolating these profiles to an assumed paleo-surface temperature, as described by Bray et al. (1992), allows definition of the range of values of paleogeothermal gradient and removed section that are consistent with the data within 95% confidence limits, as shown by the contoured region in this figure. The two parameters are highly correlated, such that higher paleogeothermal gradients within the range of allowed values require lower values of removed section, while lower gradients require correspondingly higher values of section removed. The data from Sca Fell define a maximum likelihood paleogeothermal gradient of 61 °C/km which, for a paleo-surface temperature of 20 °C, corresponds to 700 m of section removed by Tertiary uplift and erosion.

estimate of the paleogeothermal gradient, while extrapolation of the fitted linear profile to an assumed paleo-surface temperature allows estimation of the amount of section removed by uplift and erosion. Applying the statistical procedures also described by Bray et al. (1992) to these data provides results illustrated in Fig. 5, which shows the range of values of paleogeothermal gradient and removed section allowed by the paleo-temperature constraints, within 95% confidence limits. The zone of allowed values illustrates the correlated nature of these two parameters, with higher paleo-gradients within the allowed range corresponding to lower amounts of removed section, and vice versa.

Fig. 5 also highlights the best-fit ('maximum likelihood') values of ~ 61 °C for the paleogeothermal gradient and 700 m for the removed section. Estimation of removed section was carried out assuming a paleo-surface temperature of 20 °C, based on paleo-climate evidence reviewed by Curry (in Duff and Smith, 1992, p. 407).

It is important to recognise that this analysis depends critically on the assumption that the paleotemperature–depth profile is linear through the preserved section, and can be linearly extrapolated through the removed section to the assumed paleo-surface temperature. Explicit estimation of removed section from paleo-thermal methods is only possible by means of assumptions such as these, which are required in order that the problem can be reduced to a level where formal estimation of paleogeothermal gradients and amounts of exhumation/removed section is possible. More importantly, perhaps, these assumptions also allow determination of the associated uncertainties (± 95% confidence limits), thereby allowing rigorous and objective assessment of the range of scenarios which are consistent with the data.

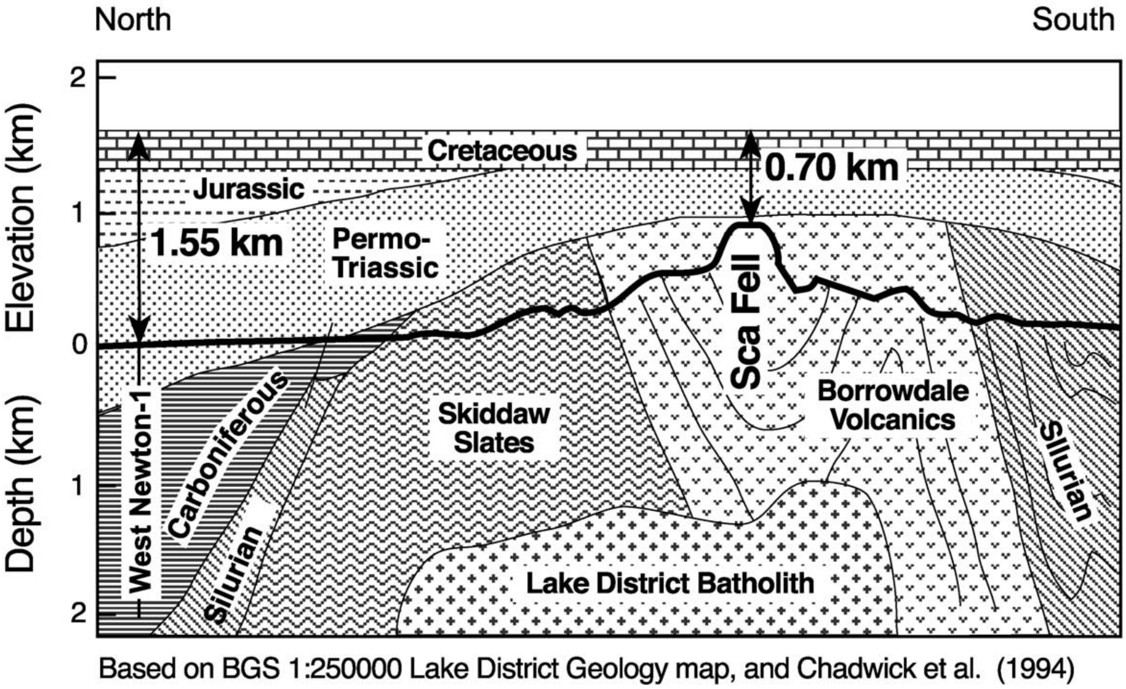

Fig. 6. The difference in the best estimates of Cenozoic exhumation between the location of the West Newton-1 well (1.55 km) and the summit of Sca Fell (0.70 km) is very close to the difference in present-day elevations of the two sites (~ 950 m). This allows a tentative and highly schematic but geologically reasonable reconstruction of the geology of the Lake District and adjacent basins in the Early Tertiary as shown here, involving a post-Paleozoic cover of Triassic, Jurassic and Cretaceous units. (Based in part on the work of Chadwick et al., 1994 and the BGS 1:250,000 Lake District Sheet. Note that the Eskdale Granite, represented by sample GC579-17, is thought to be a sub-volcanic intrusion related to the Borrowdale Volcanics.) The required thicknesses of these post-Paleozoic units removed during Cenozoic uplift and erosion are well within the range of values considered geologically reasonable by Holliday (1993).

As a result of differences in thermal conductivity between the basement rocks of the Lake District and likely sedimentary cover (see Fig. 6), it is possible that paleogeothermal gradients were higher in the sediments than in the basement rocks, in which case estimates of removed section based on the assumption of linear gradients may be too high. Thus, the estimates of removed section quoted here are perhaps best regarded as maximum limits. However, practical experience suggests that in most situations, a linear approximation is reasonable, and results from this approach in well controlled situations are generally highly consistent with estimates of removed section from other sources (see e.g. discussion of the Fresne-1 well in the Taranaki Basin of New Zealand by Green et al., 1995a).

7. A geologically plausible explanation for Early Tertiary paleo-thermal effects in NW England

These observations indicate the occurrence of an episode of elevated heat flow (as revealed by higher paleogeothermal gradients) in the Early Tertiary in the Lake District region, and earlier results can now be readily understood in this context. As reported by Green et al. (1997), extrapolation of the West Newton-1 paleotemperature profile to a paleo-surface temperature of 10 °C suggests that around 1.75 km of post-Early Triassic section has been removed by Tertiary exhumation at that location, while a higher paleo-surface temperature of 20 °C would reduce this to ~ 1.55 km (subtracting a difference of 200 m in section corresponding to a temperature difference of 10 °C for a paleogeothermal gradient of 50 °C/km). The difference of 850 m in removed section between the location of the West Newton-1 well (1.55 km) and Sca Fell (700 m) is very similar in magnitude to the ~ 950 m difference in elevation between the (near-coastal) location of the West Newton-1 well and the summit of Sca Fell, particularly bearing in mind the wider range of allowed values (within 95% confidence limits) at each location (as illustrated for Sca Fell in Fig. 5 and for the West Newton-1 well in Fig. 9 of Green et al., 1997).

These observations allow a tentative but geologically plausible reconstruction of the Early Tertiary geology of the Lake District as shown in Fig. 6. This highly schematic section is based in part on the ideas of Chadwick et al. (1994), involving marginal Carboniferous units (removed from the central region during Variscan erosion) unconformably overlain by Permian and Triassic section, followed by Jurassic units, truncated by erosion on a mid-Cimmerian unconformity, and a thin and relatively uniform Cretaceous (mainly Chalk) cover over the whole region.

Existing AFTA data from the Lake District block can be interpreted within a similar framework, with the amount of section removed during Tertiary exhumation generally varying between ~ 0.7 km (from mountain peaks) and ~ 1.5 to 2 km (from coastal plains and glacial valleys near sea level) over the region. These amounts of removed section required to explain these results are entirely consistent with the conclusions of Holliday (1993) based on regional geological trends. The overall consistency of results from Sca Fell and the West Newton-1 well with this reconstruction provides further support for the general validity, at least in broad terms, of the estimation of removed section at each location presented in earlier discussion.

Thus, detailed sampling combined with improved interpretation methods have resulted in a geologically plausible mechanism for the origin of the observed Early Tertiary paleo-thermal effects in NW England, and should help to reach a consensus on the post-Paleozoic evolution of the Lake District block, ending years of geological debate and uncertainty on this topic.

8. Concluding remarks

While the results discussed above finally provide a geologically plausible explanation for the Early Tertiary paleotemperatures identified from AFTA in Northern England, the observation of elevated heat flow in this region and the significant amounts of Tertiary exhumation required to explain the observed cooling, raise a number of questions regarding the mechanisms involved in producing these effects. As reviewed elsewhere (Green et al., 1999), applications of similar techniques to areas closer to the UK Atlantic margin suggests that in this region Early Tertiary heat flows were close to present-day values, despite copious igneous activity and continental rifting leading to separation of Greenland from Europe at that time. This contrast between apparently "normal" heat flows adjacent to the developing oceanic margin and throughout the UK Tertiary igneous province, and heat flows up to twice present-day values 100s of kilometres inboard from the margin must be highly significant in terms of the nature of processes involved. These aspects of the results will be pursued elsewhere.

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