Journal of the Geological Society, *London*, Vol. **158**, 2001, pp. 59–73. Printed in Great Britain.

Recognition of tectonic events in undeformed regions: contrasting results from the Midland Platform and East Midlands Shelf, Central England

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Abstract: Apatite fission-track and vitrinite reflectance data from Central England demonstrate how these techniques can reveal otherwise unrecognized tectonic and/or palaeothermal episodes in apparently tectonically stable areas. The results document the transition from an inverted basinal region in the north (East Midlands Shelf), to a tectonically stable platform in the south (Midland Platform). AFTA data from the region reveal two discrete cooling episodes, in the Early and Late Tertiary. Maximum palaeotemperatures from AFTA and VR data in outcrop samples define a consistent increase from $\leq 50°C$ in Lower Cretaceous and Upper Jurassic units in the SE to around 80–90°C in Triassic and older units in the NW. These Early Tertiary palaeotemperatures reflect a combination of deeper burial and elevated basal heat flow. Results from the Rufford-1 well define an Early Tertiary palaeogeothermal gradient of 40.5°C km^{-1} (32–50°C km^{-1} at $\pm 95\%$ confidence limits), corresponding to deeper burial by 1450 m of additional section (1.1–2.2 km at $\pm 95\%$ confidence limits), subsequently removed by Tertiary erosion. In contrast, geological considerations suggest a maximum overburden of 800–900 m above the base of the Lower Jurassic in the vicinity of Rugby where palaeotemperatures at outcrop are similar to those near the Rufford-1 location. The discrepancy between stratigraphic and palaeo-thermal reconstruction of former burial depths, often noted in earlier studies, remains unresolved. The Late Tertiary episode is much less well-constrained, but results from Rufford- 1 may require between 910 and 1650 m of eroded section. Thus much of the total amount of removed overburden may have been removed during the Late Tertiary. Results from the Apley Barn Borehole (Oxfordshire) reveal a Late Tertiary palaeothermal episode characterized by a highly non-linear palaeotemperature profile which probably reflects local heating due to passage of hot fluids. Despite stratigraphic evidence for some Early Tertiary erosion results from this borehole show no evidence of Early Tertiary effects. Major Early and Late Tertiary exhumation was limited to regions underlain by older Palaeozoic basins while regions overlying Palaeozoic basement were more stable, experiencing significantly less exhumation. We suggest this reflects the preferential reactivation of the weaker basinal regions as a result of compressional events at plate margins. Our results emphasize the importance of incorporating results from both 'inverted' and 'non-inverted' areas in understanding the causal mechanisms of uplift and inversion, and highlight the importance of testing apparent stability using palaeo-thermal methods.

Keywords: AFTA, East Midlands, vitrinite reflectance, exhumation, thermal history.

Apatite fission track analysis (AFTA) and vitrinite reflectance (VR) data have been widely used to study the timing and magnitude of erosional episodes in sedimentary basins where inversion is recognized on structural and/or stratigraphic grounds (e.g. Green *et al.* 1995). Such data can provide unique quantitative constraints on models of the processes responsible for basin inversion. However, use of these techniques to reveal erosional episodes in areas which lack structural and/or stratigraphic evidence for inversion and/or uplift, and consequently have been regarded as tectonically stable (e.g. Thomson *et al.* 1999), is perhaps even more important. Recognition that 'tectonically stable' areas often show evidence for significant regional exhumation synchronous with inversion in adjacent basins (Green *et al.* 1995, 1997) emphasizes the importance of incorporating results from both 'inverted' and 'non-inverted' areas in understanding the causal mechanisms of uplift/inversion, and highlights the importance of testing the apparent stability using palaeo-thermal methods. Here, we present contrasting results from the East Midlands Shelf of eastern England and the adjacent Midland Platform of southern and central England, demonstrating how the methodologies involved in combined AFTA and VR studies can either confirm or radically change perceptions of the tectonic development of apparently stable regions. The implications of the results for mechanisms of regional uplift are also discussed.

Mesozoic tectonic units of southern Britain and their stability

Although elements were inherited from earlier structures, the tectonic framework of southern and eastern England was established in post-Variscan times (Strahan 1913; Kent 1949). The London area, southern East Anglia and the south and east Midlands (Fig. 1) are underlain by thin, flat-lying Mesozoic strata resting on shallow Variscan and older basement. In the southeastern part of this area, Cretaceous strata rest on Palaeozoic rocks forming the London–Brabant Massif while the larger area to the north, where Jurassic rocks are present, forms the Midland Platform (Fig. 1). Together they comprise the London Platform in a broad sense. To the NE this merges

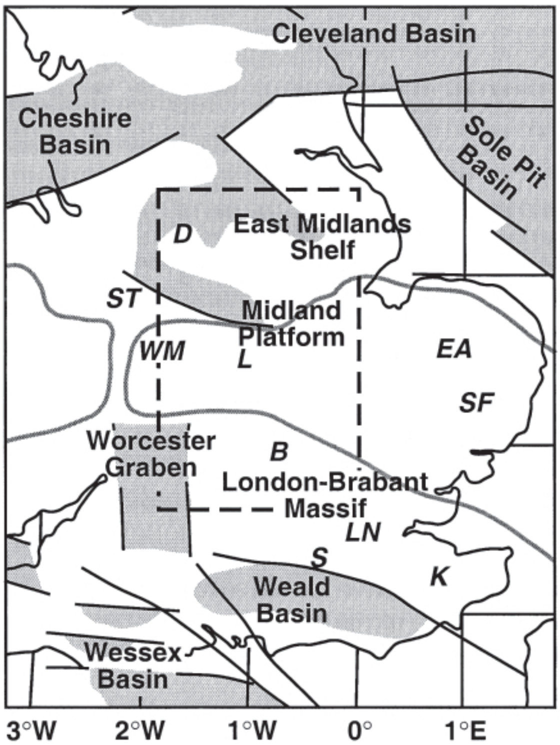

Fig. 1. Location map showing location of the study area (dashed box) in relation to the major tectonic features of the southern Britain. LN, London; S, Surrey; K, Kent; B, Bletchley; WM, West Midlands; L, Leicestershire; D, Derbyshire; EA, East Anglia; SF, Suffolk; ST, Staffordshire.

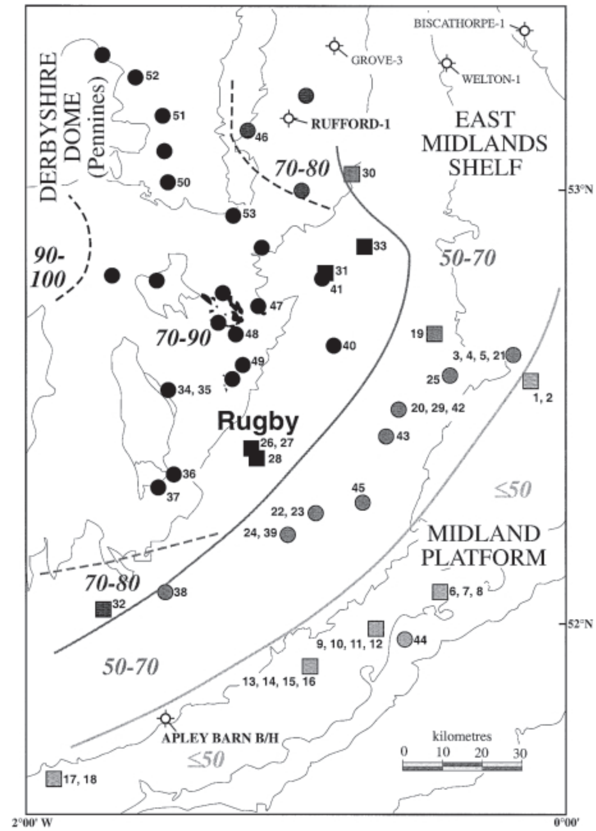

Fig. 2. Location map showing outcrops and wells/boreholes from which samples have been analysed for this study. AFTA locations are shown as circles while VR locations are represented by squares. Outlines of major geological divisions are also shown (not including top-Middle Jurassic), from base Tertiary in the SE to Carboniferous in the NW. Maximum palaeotemperatures derived from AFTA and VR data in samples analysed for this study are superimposed on the map with values summarized in Tables 1 and 2.

gradually into the East Midland Shelf, the shallowly-subsiding western margin of the southern North Sea Basin (Fig. 1), with the East Midland Shelf generally being regarded as the rigid buttress to late Mesozoic/Cenozoic structural inversion in the Cleveland and Sole Pit basins (Hemingway & Riddler 1982; Van Hoorn 1987; Hillis 1995). To the south, the London Platform is separated by an east–west fault zone from the Weald and Wessex basins, which had a Mesozoic history of deeper subsidence and later inversion (Butler & Pullan 1990; Underhill & Paterson 1998; Underhill & Stoneley 1998). The western boundary of the Midland Platform is another fault zone into the Worcester Graben, the most southerly of a series of mainly north-trending horsts and graben extending northwards through the West Midlands into the Midland coalfields, the Derbyshire Dome and the Cheshire Basin (Figs 1 and 2; Whittaker 1985).

The East Midland Shelf has traditionally been regarded as a tectonically stable platform with the lack of structure and the available stratigraphic evidence suggesting a history involving minor burial since Triassic times. When VR data became available from the offshore shelf requiring greater amounts of burial, the impression created by the present-day geology led to the evidence being dismissed (Cope 1986). However, application of AFTA revealed Early Tertiary palaeotemperatures of around 80°C in samples currently at outcrop (Green 1989). Results from a number of hydrocarbon exploration wells showed that heating was due primarily to deeper burial by between 1 and 2.2 km of additional sediments subsequently removed by Tertiary uplift and erosion. Bray *et al.* (1992) integrated AFTA and VR data and broadly confirmed these conclusions with further support being provided by sonic velocity studies (Hillis 1993). Although some aspects of these interpretations have been questioned (e.g. Smith *et al.* 1994; Japsen 1997) it is now established that deeper burial and subsequent uplift and erosion was not restricted to recognized structural inversion axes. The discovery of an erosional remnant of Early Tertiary sediments on the offshore shelf (Stewart & Bailey 1996) provides further evidence of a much more active Tertiary history than previously envisaged.

In contrast, stratigraphic evidence suggests that the Jurassic rocks on the Midland Platform have never been buried to more than a few hundred metres, nor been substantially above sea level, since they were deposited (Donovan *et al.* 1979; Cope *et al.* 1980*a*, *b*, 1992; Whittaker 1985; Duff & Smith 1992). Geological evidence suggests that maximum burial was end-Cretaceous, with periods of gentle uplift and erosion in early Cenozoic and in Neogene times (Cope *et al.* 1992; Duff & Smith 1992). Hudson (1978) quotes a maximum burial depth of 545 m, based on the degree of over-compaction in the Lower Oxford Clay. Organic geochemical evidence (Hudson & Martill 1994; Kenig pers. comm.) suggests an upper limit to the maximum post-depositional temperature of around 50°C which, for geothermal gradients of 30–40°C km^{-1}, is consistent with these other estimates. These studies stand in marked contrast to the emerging picture of kilometre-scale cover removed from the East Midland Shelf, just a few tens of

Table 1. *Sample details, data and palaeotemperature analysis summary for outcrop vitrinite samples from the English Midlands*

Sample no.	Source no.	Location*	Map ref.	Stratigraphic age	VR (%)†	*n*‡	Early Tertiary episode Max^m palaeo temperature (°C)§
1	KDT93ST1	Kings Dyke BP	TL248 967	Callovian	0.31	23	≤50
2	KDT9338	Kings Dyke BP	TL248 967	Callovian	0.33	10	50
3	P88-5	Dogsthorpe BP	TF210 020	Callovian	0.35	25	56
4	P88-3	Dogsthorpe BP	TF210 020	Callovian	0.36	25	59
5	P88-1	Dogsthorpe BP	TF210 020	Callovian	0.26	29	≤50
6	S90-10	Quest BP	TL030 430	Callovian	0.32	9	≤50
7	S90-6	Quest BP	TL030 430	Callovian	0.28	26	≤50
8	S90-4	Quest BP	TL030 430	Callovian	0.26	26	≤50
9	B88-9	Bletchley BP	SP862 326	Callovian	0.35	8	56
10	B88-7	Bletchley BP	SP862 326	Callovian	0.24	26	≤50
11	B88-2	Bletchley BP	SP862 326	Callovian	0.24	28	≤50
12	B89-9	Bletchley BP	SP862 326	Callovian	0.24	26	≤50
13	C89-20	Calvert BP	SP702 232	Callovian	0.21	9	≤50
14	C89-12	Calvert BP	SP702 232	Callovian	0.21	26	≤50
15	C89-17	Calvert BP	SP702 232	Callovian	0.22	25	≤50
16	C89-8	Calvert BP	SP702 232	Callovian	0.26	25	≤50
17	CF90-6	Cleveland Fm GP	SP070 943	Callovian	0.32	15	≤50
18	CF90-4	Cleveland Fm GP	SP070 943	Callovian	0.27	11	≤50
19	SWC90-3	Williamson Cliff Pit	TF013 084	Bathonian	0.42	27	70
20	CW91-1	Cowthick Ironstone Pit	SP923 885	Aalenian	0.38	26	63
26	MP262	Borrow Pit, M6	SP557 788	Sinemurian	0.46	12	78
27	MP267	Borrow Pit, M6	SP557 788	Sinemurian	0.51	7	84
28	MP274	M1, Lilbourne	SP567 767	Sin.–Pliensbach.	0.50	15	83
29	MP230	Cowthick Pit	SP926 882	Toarcian	0.44	25	74
30	MP229	Staple Pit	SK805 499	Rhaetian	0.40	7	66
31	MP212	Holwell North Qu.	SK743 239	Toarcian	0.47	11	79
32	MP297	Blockley Station Qu.	SP180 370	L. Pliensbachian	0.45	25	76
33	D.70.Ha.5	Woolsthorpe Qu.	SK842 305	Toarcian	0.50	16	83

*BP, brick pit; GP, gravel pit; Qu., quarry.
†Vitrinite reflectance.
‡Number of grains measured.
§Determined using heating rates of 1°C Ma^{-1} and cooling rates of 10°C Ma^{-1}. These values are assumed arbitrarily, and all palaeotemperature estimates are conditional on this assumed rate. For the kinetics characterizing both AFTA and VR, increasing or decreasing heating rates by an order of magnitude is equivalent to raising or lowering the required maximum palaeotemperature by about 10°C.

kilometres to the north. However, Scotchman (1991, 1994) presented various maturity indices for the Kimmeridge Clay in the Midlands (including vitrinite reflectance values which are higher than reported here for nearby outcrops). His biomarker studies also suggest greater amounts of former burial for the Upper Jurassic, ranging between 1.03 and 1.37 km for the Midland Platform and increasing slightly towards the NE. The study described here was designed to resolve this uncertainty surrounding the tectonic evolution of the Midland Platform, and to investigate possible contrasts with the adjacent East Midlands Shelf.

Database and analytical procedures

Vitrinite Reflectance samples were taken from Upper Triassic, Lower and Middle Jurassic organic-rich mudstones outcrops, the Rufford-1 hydrocarbon exploration well (East Midland Shelf) and the Apley Barn Borehole (Poole 1969). VR values and sample details, are listed in Table 1 for outcrop samples and Table 2 for subsurface samples with sample/borehole locations shown in Fig. 2. All analyses were carried out using standard procedures (Cook 1982) with vitrinite identification being made on textural grounds, allowing an independent assessment to be made of the possible presence of reworked vitrinite populations from petrographic evidence, as well as allowing identification of caved material in sub-surface samples. Alternation between reflectance and fluorescence modes allowed checking for associated fluorescing liptinite, bitumen impregnation, or the presence, intensity, and source of oil-cut which may affect the reading.

AFTA outcrop samples were taken from sandstones of Early Cretaceous, Jurassic, and Triassic age, and from crystalline basement rocks in Leicestershire (Fig. 1). Three samples of Carboniferous (Namurian) age from the Derbyshire Dome (Fig. 2) were also analysed. AFTA data from these three samples, plus the three basement samples and two of the Triassic samples were originally reported by Green (1989). These samples have been reanalysed for this study, with measurement of chlorine contents in all apatite grains analysed, and reinterpretation using an improved kinetic description of fission track annealing (Green *et al.* 1996), as also used for all samples analysed for this study. A full listing of all AFTA data can be obtained from the Society Library or the British Library Document Supply Centre, Boston Spa, Wetherby, West Yorkshire LS23 7BQ, UK as Supplementary Publication No. SUP 18156 (131 pages). Summary fission track data from all outcrop AFTA samples are listed in Table 3 whilst AFTA data from the Rufford-1 hydrocarbon exploration well and the Apley Barn Borehole are summarized in Table 4. Chlorine contents were measured using a semi-automated Jeol JXA-5A electron microprobe equipped with three wavelength dispersive crystal spectrometers, with an accelerating voltage of 15 kV, a beam current of 25 nA and a spot size of 20 μm. All other aspects of analytical procedures and data presentation are as described by Green (1989). In

Table 2. *Sample details, data and palaeotemperature analysis summary for subsurface vitrinite samples from the English Midlands*

Sample no.	Source no.	Depth (m rkb)	Present temperature (°C)	Stratigraphic age	VR (%)*	*n*†	Max palaeotemperature (°C)‡	
Rufford-1							Early Tertiary	
58		450	24	Westphalian	0.59	20	97	
59		500	26	Westphalian	0.59	20	97	
60		600	29	Westphalian	0.65	20	108	
61		675	32	Westphalian	0.61	20	100	
62		750	34	Westphalian	0.71	20	116	
63		825	37	Westphalian	0.66	20	110	
64		875	38	Westph.–Namurian	0.69	20	114	
66		925	40	Westph.–Namurian	0.71	20	116	
67		975	41	Namurian	0.73	20	120	
68		1025	43	Namurian	0.66	20	110	
69		1075	45	Namurian	0.76	20	124	
70		1125	46	Namurian	0.82	20	129	
71		1175	48	Tourn.–Visean	0.85	20	131	
72		1200	49	Tourn.–Visean	0.76	20	124	
73		1210	49	Tourn.–Visean	0.79	3	126	
Apley Barn							Permian	Late Tertiary
74	RD42–1.1	24	11	M. Jurassic	0.31	8		≤50
75	RD42–2.1	25	11	M. Jurassic	0.27	17		≤50
76	RD42–3.1	51	12	L. Jurassic	0.23	25		≤50
82§	RD42–6.1	300	19	Westphalian C/D	0.57, 1.01	6, 26		95, 143
83	RD42–7.1	472	24	Westphalian C/D	0.55	27	91	
84	RD42–8.1	538	26	Westphalian C/D	0.59	25	97	
88	RD42–12.1	805	34	Westphalian C/D	0.66	27	110	
89	RD42–13.1	876	36	Westphalian C/D	0.72	26	118	
90	RD42–14.1	914	37	Westphalian C/D	0.74	13	122	
91	RD42–15.1	1106	43	Westphalian C/D	0.80	28	127	
95	RD42–17.1	1387	52	L. Devonian	1.40	2	168	
96	RD42–18.1	1428	53	L. Devonian	1.37	25	166	

*Vitrinite reflectance.
†Number of grains measured.
‡Determined using heating rates of 1°C Ma^{-1} and cooling rates of 10°C Ma^{-1}. These values are assumed arbitrarily, and all palaeotemperature estimates are conditional on this assumed rate. For the kinetics characterising both AFTA and VR, increasing or decreasing heating rates by an order of magnitude is equivalent to raising or lowering the required maximum palaeotemperature by about 10°C.
§In sample 82, bimodal VR data are thought to represent the Late Tertiary episode but evidence for this is to some extent equivocal.

Fig. 3, fission-track ages are contrasted with the stratigraphic age range for individual outcrop samples. In Fig. 4, fission track ages and mean track lengths are plotted as a function of depth and present temperature with stratigraphic age through each section also plotted for comparison.

Thermal history information has been extracted from the AFTA data by modelling measured parameters (fission track age and track length distributions and their variation with Cl content) through a variety of possible thermal history scenarios, varying the magnitude and timing of the maximum palaeotemperature 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 procedure are well established for mono-compositional apatites (e.g. Green *et al.* 1989*a*, *b*), based on a series of laboratory experiments on Durango apatite (Green *et al.* 1986; Laslett *et al.* 1987; Duddy *et al.* 1988). However, the annealing kinetics of fission tracks in apatite are known to be affected by chlorine content (Green *et al.* 1986), and in the studies 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 chlorine 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. Palaeotemperature estimates from AFTA are quoted as a range (corresponding to ±95% confidence limits) and have an absolute uncertainty of better than ±10°C.

Values of VR are converted to maximum palaeotemperatures using the kinetic model of Burnham & Sweeney (1989) and Sweeney & Burnham (1990). Information on the timing of these maximum palaeotemperatures is provided by the AFTA data. The VR derived palaeotemperature estimates are shown as single values in Table 1 for the outcrop samples and Table 2 for the subsurface samples and are robust to better than ±10°C. The kinetic response of vitrinite reflectance as described by Burnham & Sweeney (1989) is very similar to the fission track annealing kinetic model developed by Laslett *et al.* (1987) to describe the kinetics of fission track annealing in Durango apatite. Total fission track annealing in apatites with typical chlorine content corresponds to a VR value of *c.* 0.7%, regardless of heating rate (Duddy *et al.* 1991, 1994).

Values of maximum palaeotemperature and the time at which cooling from that palaeotemperature began are quoted for each AFTA sample in Tables 3 and 4 (surface and sub-surface samples respectively). Unlike VR data, AFTA data also provide some control on the history after cooling from maximum palaeotemperatures, through the lengths of tracks formed during this period. Wherever possible, AFTA data from each sample have been interpreted in terms of two episodes of heating and cooling, using assumed heating and cooling rates during each episode, with the maximum palaeotemperature reached during the earlier episode. In practise, resolution of two episodes is only possible when the maximum palaeotemperature in the earlier episode was around 90°C or more. In some cases, while the data from a particular sample may be better explained in terms of two episodes

Table 3. *Sample details, data and palaeotemperature analysis summary for outcrop AFTA samples from the English Midlands*

Sample no.	Source no.	Location[1]	Map ref.	Stratigraphic age	Fission track age (Ma)	$P(\chi^2)$[2] (no. of grains)	Mean length (μm) (no. of measurements)	Max palaeotemperature (°C)[3]	Onset of cooling Ma	Max palaeotemperature (°C)[3]	Onset of cooling Ma
								Early Tertiary		Late Tertiary	
21	LEIUG96715	Dogsthorpe BP	TF210 020	Callovian	644 ± 151	<1 (2)	12.39 ± 0.25 (13)	*≤80 (≤95)*	*80–0 (post-depn)*	*≤80*	*80–0*
22	DUS85-1	New Duston Qu.	SP714 627	Aalenian	294 ± 19	76 (14)	12.86 ± 0.18 (62)	*50–80 (50–95)*	*120–0 (post-depn)*	*≤70*	*90–0*
23	DUS85-1	New Duston Qu.	SP714 627	Aalenian	269 ± 21	<1 (20)	12.95 ± 0.13 (101)	*50–90*	*Post-depn*	≤65	*55–0*
24	S9-6	Stowe-Nine-Churches Qu.	SP6445 750	Aalenian	No apatite	—	—	No apatite			
25	RHQ	Ring Haw Qu.	TL053 975	Bajocian	294 ± 14	5 (20)	12.96 ± 0.10 (111)	*55–80*	*Post-depn*	*≤65*	*45–0*
34	RGC.96.PG.1	Judkins Qu.	SP348 930	Anisian-Ladinian	221 ± 9	31 (20)	12.37 ± 0.13 (155)	80–90	190–55	45–70	35–0
35	RGC.96.PG.2	Judkins Qu.	SP348 930	Anisian-Ladinian	237 ± 13	4 (20)	12.13 ± 0.13 (167)	80–90	140–40	20–75	55–0
36	RGC.96.PG.3&4	Quarryfield House Qu.	SP358 723	Anisian?	235 ± 9	11 (20)	12.68 ± 0.11 (151)	60–80	70–20	*≤80*	*70–0*
37	RGC.96.PG.5	Quarry Bank	SP317 687	Anisian?	240 ± 16	<1 (20)	12.61 ± 0.11 (159)	*65–90 (65–110)*	*200–10 (>200)*	35–70	25–0
38	RGC.96.PG.6	Winderton Rd	SP341 408	Aalenian	199 ± 23	34 (4)	12.67 ± 0.42 (14)	60–80	120–0	*≤80*	*120–0*
39	RGC.96.PG.7	Stowe Nine Churches Qu.	SP644 575	Aalenian	240 ± 19	32 (7)	12.76 ± 0.24 (37)	60–80	130–10	*≤80*	*105–0*
40	RGC.96.PG.8	Tilton Rly Cutting	SK7625 0535	M. Lower Jurassic	211 ± 11	67 (20)	12.75 ± 0.13 (101)	*70–85 (70–100)*	*120–25 (>120)*	20–70	40–0
41	RGC.96.PG.9	Brown's Hill Qu.	SK7420 2340	M. Lower Jurassic	222 ± 18	<1 (20)	12.53 ± 0.14 (107)	*70–90 (70–100)*	*145–20 (>145)*	20–70	40–0
42	W3 (ex D/84/5)	Cowthick Qu.	SP9266 8752	Bajocian	249 ± 13	20 (18)	12.66 ± 0.25 (66)	60–75	95–15	*≤75*	*90–0*
43	DSS/G/96/1	Geddington Grange Qu.	SP888 819	Bathonian	233 ± 13	69 (13)	12.83 ± 0.18 (47)	60–80	90–0	*≤80*	*80–0*
44	CB 4B	Chamberlains Barn Pit	SP930 266	Aptian-Albian	301 ± 27	<1 (20)	13.23 ± 0.12 (148)	45–65	75–0	*≤45*	*75–0*
45	DSS 93/45	Ecton North Lodge	SP825 650	Aalenian	234 ± 21	<1 (20)	12.98 ± 0.13 (116)	55–70	80–10	*≤70*	*80–0*
46	8624–32	Berry Hill Qu.	SK550 597	Early Triassic	258 ± 10	98 (20)	12.68 ± 0.11 (211)	60–80	65–20	*≤80*	*50–0*
47	8624–37	Cocklaw Qu.	SK569 151	Mt Sorrel Granodiorite	390 ± 17	60 (20)	12.82 ± 0.09 (193)	60–80	65–0	*≤80*	*50–0*
48[4]	8624–38	Groby Qu.	SK526 083	Precambrian	290 ± 17	27 (20)	11.99 ± 0.15 (100)	*80–90 (80–110)*	*115–0 (>115)*	*≤85*	*45–0*
49[5]	8624–39	Enderby Qu.	SK540 000	Precambrian	469 ± 36	92 (20)	14.02 ± 0.13 (120)	40–70	300–0	*≤70*	*300–0*
50	8624–43	Milford Qu.	SK352451	Namurian	272 ± 23	<1 (20)	11.94 ± 0.14 (107)	*80–90 (80–100)*	*150–10 (>150)*	*≤90*	*45–0*
51[6]	8624–45	Slack Hill	SK333 629	Namurian	204 ± 12	<1 (20)	12.22 ± 0.21 (75)	65–85	65–5	*≤90*	*45–0*
52	8624–46	Gordon's Edge	SK273 737	Namurian	257 ± 18	<1 (20)	12.39 ± 0.21 (57)	80–90	105–30	*≤80*	*40–0*
53	8724–48	Bramcote, Notts	SK500 384	Early Triassic	284 ± 24	<1 (20)	12.20 ± 0.15 (94)	60–80	80–10	*≤80*	*50–0*
							Combined timing constraints:		**65–55**		**25–0**

[1]BP, brick pit; GP, gravel pit; Qu., quarry.

[2]Quoted fission track ages are pooled ages for samples in which $P(\chi^2)$ >5%, and central ages (Galbraith & Laslett 1993) for samples with $P(\chi^2)$ <5%. Ages calculated using a zeta value (Hurford & Green 1982) of 353.5 ± 3.9 for all samples. Full details of the apatite fission track data and results are available as a Supplementary Publication, see p. 61.

[3]Determined using heating rates of 1°C Ma^{-1} and cooling rates of 10°C Ma^{-1}. These values are assumed arbitrarily, and all palaeotemperature estimates are conditional on this assumed rate. For the kinetics characterising both AFTA and VR, increasing or decreasing heating rates by an order of magnitude is equivalent to raising or lowering the required maximum palaeotemperature by about 10°C. Where thermal history solutions are shown in italics, interpretation is to some degree equivocal, but data show tentative evidence for the conditions listed.

[4]Data from sample 48 also suggest heating to >110°C prior to cooling below 110°C between 390 and 275 Ma, in order to explain the fission track age data.

[5]Data from sample 49 provide only quite coarse palaeotemperature constraints, because most apatite grains from this sample have Cl contents >1% Cl, and the degree of track length reduction is very minor.

[6]Data from sample 51 also suggest heating to between 95 and 105°C prior to cooling beginning between 260 and 120 Ma, in order to explain the fission track age data. No other sample shows any definite evidence of this cooling episode, which appears to have been of only local extent.

Table 4. *Sample details, data and palaeotemperature analysis summary for subsurface AFTA samples from the English Midlands*

Sample no.	Source no.	Depth (m rkb)	Present temperature (°C)	Stratigraphic age	Fission track age (Ma)	$P(\chi^2)$* (no. of grains)	Mean length (μm) (no. of measurements)	Max palaeotemperature (°C)†	Onset of cooling (Ma)	Max palaeotemperature (°C)†	Onset of cooling (Ma)
Rufford-1								Early Tertiary		Late Tertiary	
56	8622–96	10–60	11	Triassic	214 ± 28	<1 (14)	12.28 ± 0.17 (78)	70–85	65–10		
57	8622–97	319–325	20	Westphalian	272 ± 14	24 (20)	11.74 ± 0.20 (100)	85–110	>40	50–75	40–0
65	8622–101	913–922	40	Westph.–Namurian	70 ± 5	<1 (20)	12.12 ± 0.12 (102)	>105	85–60	70–85	40–5
							Combined timing constraints:		**65–60**		**40–5**
Apley Barn								Permian		Late Tertiary	
77	RD42–4	182–193	16	Keuper	251 ± 12	69 (20)	13.14 ± 0.11 (105)			55–70	70–0
78	RD42–4.1	183	16	Keuper		—	—	—	—		
79	RD42–19	241	17	Keuper	285 ± 11	7 (20)	12.88 ± 0.07 (164)			60–70	30–0
80	RD42–5	247	17	Keuper	274 ± 16	<1 (20)	12.85 ± 0.07 (209)			60–70	30–0
81	RD42–6	300	19	Westphalian C/D	258 ± 25	84 (8)	11.58 ± 0.44 (15)			70–90	130–0
85	RD42–9	619	29	Westphalian C/D	264 ± 12	26 (15)	11.81 ± 0.14 (106)	*>100*	*>200*	*70–80*	60–0
86	RD42–10.1	669	30	Westphalian C/D							
87	RD42–11.1	750	32	Westphalian C/D							
92	RD42–20	1123	44	Westphalian C/D	258 ± 12	21 (20)	11.70 ± 0.14 (111)	>100	>245	80–90	90–0
93	RD42–16	1298	49	U. Devonian	186 ± 12	13 (20)	11.64 ± 0.22 (75)	>100	270–190	80–90	120–0
94	RD42–17	1387	52	L. Devonian	184 ± 14	28 (11)	11.22 ± 0.24 (17)	>100	300–210	80–90	50–0
							Combined timing constraints:		**270–245**		**30–0**

*Quoted fission track ages are pooled ages for samples in which $P(\chi^2)$ >5%, and central ages (Galbraith & Laslett 1993) for samples with $P(\chi^2)$ <5%. Ages calculated using a zeta value (Hurford & Green 1982) of 353.5 ± 3.9 for all samples. Full details of the apatite fission track data and results are available as a Supplementary Publication, see p. 61.

†Determined using heating rates of 1°C Ma^{-1} and cooling rates of 10°C Ma^{-1}. These values are assumed arbitrarily, and all palaeotemperature estimates are conditional on this assumed rate. For the kinetics characterising both AFTA and VR, increasing or decreasing heating rates by an order of magnitude is equivalent to raising or lowering the required maximum palaeotemperature by about 10°C. Where thermal history solutions are shown in italics, interpretation is to some degree equivocal, but data show tentative evidence for the conditions listed.

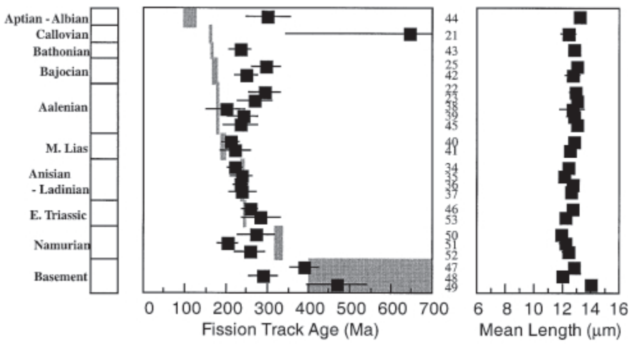

Fig. 3. Summary fission track ages, contrasted with the stratigraphic age, in outcrop samples from the East Midlands Shelf and the Midland Platform (locations shown in Fig. 2).

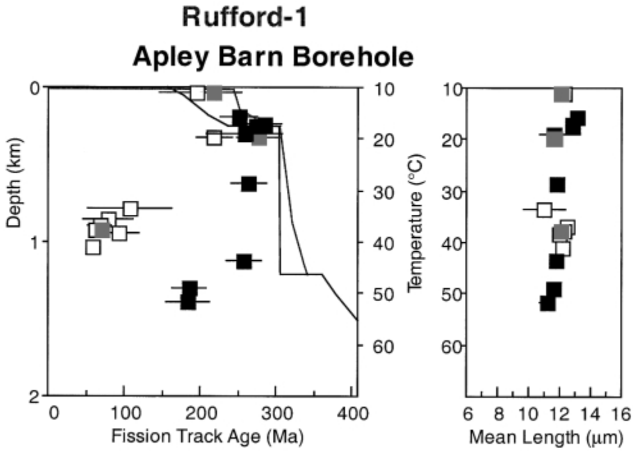

Fig. 4. Fission-track ages and mean track lengths in samples from the Rufford-1 hydrocarbon exploration well and the Apley Barn Borehole, plotted against depth sub-surface and temperature. Results from this study for samples from the Rufford-1 well are shown as grey squares, while data from the same well reported by Green (1989) are shown as white squares with black outlines. Results from the Apley Barn borehole as shown in solid black. Fission track ages from the two downhole sections show significant differences, with profound implications for the thermal history of the respective sections as discussed in the text.

rather than one, the difference may not be statistically significant, but the AFTA data can provide constraints on the allowed range of palaeotemperatures during a possible earlier episode. Such cases, where the earlier episode is allowed but not required by the data, are indicated in Tables 3 and 4.

Thermal history results

AFTA data from outcrop samples all show clear evidence for Cenozoic cooling. Assuming that cooling in these samples represent common events, involving synchronous cooling across the region, we can combine estimates of the timing of cooling in individual samples to obtain the best estimate of the timing of these major cooling episodes. On this basis, comparison of all results in Table 3 suggests an earlier episode involving cooling beginning between 65 and 55 Ma (Early Tertiary), and a later episode in which cooling began between 25 and 0 Ma (Late Tertiary). The quoted ranges refer to the interval during which cooling *began*, and it is not implied either that all cooling in each episode occurred within each interval or that cooling necessarily encompassed the entire interval.

Figure 2 shows the maximum palaeotemperatures from AFTA and VR data in individual samples mapped across the study region. Towards the NW corner, a region characterized by maximum palaeotemperatures of 90–100°C has also been included, on the basis of AFTA data from outcrops in Staffordshire (Fig. 1), originally reported by Green (1989). Results from AFTA and VR are clearly highly consistent. For example, VR values of 0.46–0.51% from the Lower Jurassic around Rugby (Fig. 2; Samples 26, 27 and 28) indicate maximum palaeotemperatures of *c.* 80°C which are very similar to the Early Tertiary palaeotemperatures (generally between 70 and 90°C) indicated by AFTA data from the underlying Triassic section (Samples 34, 35, 36 and 37). Results from nearby Lower Jurassic sandstone (Sample 40) also provide tentative evidence for Early Tertiary palaeotemperatures between 70 and 85°C which is confirmed by these VR data from the Lower Jurassic. Thus it is clear that towards the NW, samples cooled from their maximum post-depositional palaeotemperatures in the Early Tertiary.

At the other extreme in the SE of the study region, VR data from the Oxford Clay around Bletchley (Fig. 1) indicate maximum palaeotemperatures less than 50°C, while AFTA data from the overlying Early Cretaceous section suggest a maximum palaeotemperature between 45 and 65°C. Because of the relatively low maximum palaeotemperature in this sample, it is not possible to resolve two discrete cooling episodes and the timing constraint from AFTA (75–0 Ma) encompasses both the Early and Late Tertiary cooling episodes identified in Table 3. Similar comments apply to AFTA data from most of the Jurassic sandstones.

The maximum palaeotemperatures in Fig. 2 define a very regular progression, from values less than 50°C in the SE, to values of 90–100°C in the NW. This trend coincides closely with the increasing erosional level towards the northwest, suggesting that the Early Tertiary palaeotemperatures in the NW are probably related, at least in part, to greater degrees of former burial. However, it is necessary to use data from the sub-surface to provide tighter constraints on mechanisms of heating and cooling.

The Rufford-1 well (Fig. 2) is located in the region where Early and Late Tertiary effects are clearly resolved, with maximum Early Tertiary palaeotemperatures at outcrop around 80°C, while the Apley Barn Borehole (Fig. 2) lies at the lower palaeotemperature extreme, where maximum palaeotemperatures at outcrop are less than 50°C. Fission track ages and mean track lengths in samples from the Rufford-1 well and the Apley Barn Borehole are summarized in Table 4. While results from the post-Carboniferous section in both wells, at depths less than 250 m, are quite similar, there is a clear difference in the two datasets at depths of 1 km or more (Fig. 4). Fission-track ages decrease rapidly with depth in Rufford-1 to values around 100 Ma or less at around 1 km. Values from the Apley Barn borehole decrease much more slowly, and remain close to 200 Ma at 1.4 km depth. These differences reflect a major difference in thermal history, as summarized in Table 4, which lists values of maximum palaeotemperature and time of cooling for two episodes derived from the AFTA data.

Assuming that all results from the Rufford-1 well can be explained in terms of synchronous events, synthesis of data suggests an early cooling episode in which cooling began between 65 and 60 Ma, and a later cooling episode which began between 40 and 5 Ma. These timing constraints correlate closely with those obtained from outcrop samples (65–55 Ma and 25–0 Ma), suggesting that data from the Rufford-1 well and from outcrop represent the same palaeo-thermal episodes. An estimated Early Tertiary palaeotemperature of 70–85°C from AFTA data in a sample of Triassic age at near-surface in the Rufford-l well (note that this palaeotemperature is not high enough to allow resolution of two episodes from the data in this sample) is consistent with the regional pattern derived from the outcrop samples in Fig. 2. AFTA results from the Apley Barn Borehole reveal a significantly different thermal history interpretation as summarized in Table 4. In this case, synthesis of data from all samples suggests an earlier cooling episode which began between 270 and 245 Ma and a later episode that began between 30 and 0 Ma. Thus, while data from the Carboniferous and older section in this borehole show clear evidence of a Permian cooling episode and all samples show evidence of Late Tertiary cooling, none of the data from this well show any evidence of Early Tertiary effects.

Vitrinite reflectance data from the Rufford-1 well and the Apley Barn Borehole are summarized in Table 2, together with estimates of maximum palaeotemperature. VR values from the Carboniferous section in both datasets are remarkably similar, increasing from 0.55 to 0.8% with depth through the section. However, as discussed in more detail in the next section, integration of VR and AFTA data shows that this is coincidental, and the VR data represent the effects of different palaeo-thermal episodes in each case. The following sections also show how the information derived from AFTA and VR data can be used to understand the nature of the various episodes identified from AFTA, leading to an improved understanding of the long-term thermo-tectonic development of the East Midland Shelf and Midland Platform.

Palaeotemperature profiles, palaeogeothermal gradients and mechanisms of heating and cooling

Early Tertiary episode

Palaeotemperature estimates from AFTA and VR in the Rufford-1 well are plotted against depth in Fig. 5. The consistency between the maximum palaeotemperatures derived from VR and the Early Tertiary palaeotemperatures derived from AFTA confirms that both datasets represent the effects of the same palaeo-thermal episode, and that units throughout the well cooled from their maximum palaeotemperatures in the Early Tertiary. The combined Early Tertiary palaeotemperature constraints define a linear profile, with a slope that is higher than that of the present-day temperature profile, suggesting that heating was most likely due to a combination of deeper burial and higher basal heat flow.

Fitting a linear profile to such data using statistical techniques outlined by Bray *et al.* (1992) provides an estimate of the palaeogeothermal gradient, and extrapolating the fitted profile to an assumed palaeo-surface temperature provides an estimate of the amount of section removed by erosion (this analysis depends critically on several assumptions, as discussed by Bray *et al.* 1992). These two parameters are highly correlated, such that higher palaeogeotherrnal gradients require correspondingly lower values of removed section, and vice versa. Statistical techniques allow definition of the range of each parameter allowed by the palaeotemperature constraints within 95% confidence limits.

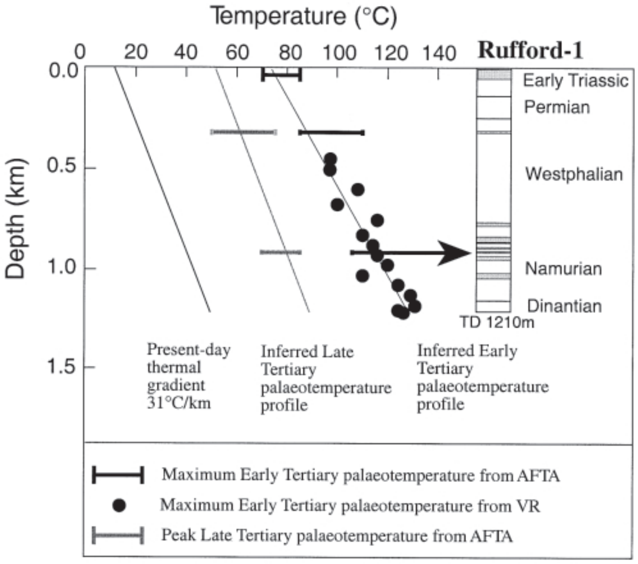

Fig. 5. Early Tertiary and Late Tertiary palaeotemperatures from AFTA and VR in the Rufford-1 well, plotted against depth sub-surface. The Early Tertiary palaeotemperatures define a linear profile, with a higher slope than the present-day temperature profile, suggesting that heating was due to a combination of deeper burial and elevated basal heat flow. The Late Tertiary palaeotemperature profile is much less well-defined, but is consistent with an interpretation in terms of deeper burial.

Results from Rufford-1 define a maximum likelihood estimate of 40.5°C km^{-1} for the Early Tertiary palaeogeothermal gradient, with an allowed range (within 95% confidence limits) of 32–50°C km^{-1}. Palaeoclimate evidence suggests an Early Tertiary surface temperature around 20°C (Duff & Smith 1992), and extrapolation of fitted linear palaeotemperature profiles to this value provides a maximum likelihood estimate of 1450 m of additional section, subsequently removed by Tertiary erosion (with 95% confidence limits of 1.1 and 2.2 km). Figure 6 highlights the correlation between allowed values of palaeogeothermal gradients and removed section, with values of palaeo-gradient towards the higher end of the allowed range requiring correspondingly lower amounts of removed section and vice versa.

Note that if the Early Tertiary palaeo-surface temperature was higher or lower than 20°C, then the quoted values of removed section can be easily converted to apply to other values of palaeo-surface temperature by subtracting or adding the difference in depth equivalent to the difference between this value and the new palaeo-surface temperature, for the appropriate palaeogeothermal gradient. Different heating rates can be allowed for in similar fashion, with an order of magnitude change in heating rate equivalent to a 10°C change in palaeotemperature (palaeotemperatures increase for higher heating rates, and decrease for lower heating rates). For typical values, the assumed heating rate will not affect the shape or slope of the palaeo-temperature profile significantly.

This analysis suggests somewhat lower values than indicated by previous studies based on AFTA and VR data (Bray *et al.* 1992), due largely to the higher palaeo-surface temperature adopted in this discussion (for a value of 10°C, Bray *et al.*'s best estimate of eroded section in the Rufford-1 well was 1.87 km). However, the main point of the analysis is not so much to determine former depths of burial with great precision

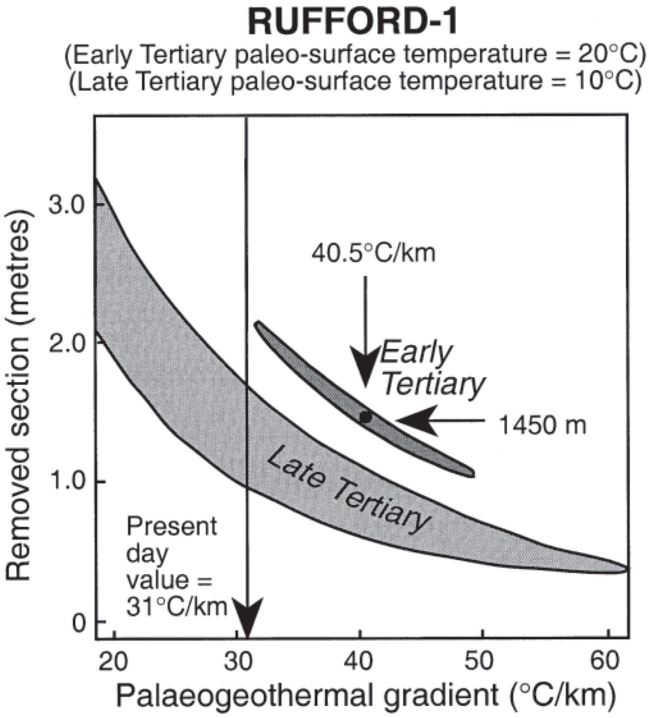

Fig. 6. The shaded regions show the allowed ranges (within 95% confidence limits) of palaeogeothermal gradient and removed section which are consistent with the Early Tertiary and Late Tertiary palaeotemperatures from AFTA and VR in the Rufford-l well. The correlation between the allowed values of the two parameters result because the removed section estimates are obtained by extrapolation of fitted linear palaeotemperature profiles (Bray *et al.* 1992), with higher gradients requiring lower amounts of removed section and vice versa. Maximum likelihood estimates for the Early Tertiary episode are also shown, by the black dot (with values listed). For the Late Tertiary episode, palaeotemperature constraints are available from only two AFTA samples, and therefore the best estimates are not well-defined, while the range of allowed values can still be defined, though the full range of allowed values of each parameters is very broad.

(which is never possible from palaeotemperature data because of the various assumptions required), but more to determine the nature of processes responsible for the observed palaeothermal effects. In addition, it is important to stress that while various aspects of the burial and exhumation history of the sedimentary units preserved in the Rufford-1 well are open to debate, the thermal histories of those units are very well constrained by the AFTA and VR data.

Late Tertiary episode

Since only two of the AFTA samples from Rufford-1 provide any constraint on Late Tertiary palaeotemperatures, the form of the palaeotemperature profile characterizing this episode in this well is not well defined and the cause of these palaeotemperatures is more uncertain. For similar reasons, the ranges of palaeogeothermal gradients and removed section allowed by these data, also highlighted in Fig. 6, are much broader and maximum likelihood values are not defined with any certainty. However, if we assume that the Late Tertiary palaeotemperatures are due, at least in part, to burial then the defined range of allowed values defined in Fig. 6 can provide limits for the amount of removed section corresponding to a given value of palaeogeothermal gradient. For example, a Late Tertiary palaeogeothermal gradient equal to the present-day value of 31°C km^{-1} corresponds to between 910 and 1650 m of removed section (for a palaeo-surface temperature of 10°C), while a value of 40°C km^{-1} requires between 600 and 1000 m.

Figure 7 shows palaeotemperature constraints derived from AFTA and VR data in samples from the Apley Barn Borehole plotted against depth. VR data from depths greater than 400 m are consistent with Permian palaeotemperatures defined by AFTA, and clearly represent the effects of pre-Tertiary episodes. These effects are beyond the scope of present discussion and are not discussed further. Tertiary effects in Fig. 7 show a major difference to those from the Rufford-1 well shown in Fig. 5, with a complete absence of detectable Early Tertiary effects and Late Tertiary palaeotemperatures showing a much more complex pattern of variation with depth, leading to a more equivocal interpretation in this case.

VR data from Middle and Lower Jurassic units at shallow depths (<0.32%) show that the maximum post-depositional palaeotemperature must have been less than 50°C. Since this borehole is located close to the inferred 50°C contour (Fig. 2) it is likely that a value close to 50°C would be appropriate for this shallow section. Extremely high quality AFTA data in three samples from the underlying Triassic sandstones, based on up to 200 length measurements, provide very good definition of Late Tertiary palaeotemperatures between 60 and 70°C (Table 4). This represents a very rapid increase of around 10–20°C or more from the Jurassic units over a depth interval of only 220 m, suggesting a local palaeogeothermal gradient of between 45 and 90°C km^{-1}. Passing across the basal-Triassic unconformity, the Late Tertiary palaeotemperature from AFTA near the top of the Carboniferous section (Sample 81) increases further to between 70 and 90°C. VR data from the same depth interval are noteable in showing two distinct populations of reflectance values, with means of 0.57 and 1.01%, corresponding to maximum palaeotemperatures of 95 and 143°C, respectively. The lower of these two values is slightly higher than the range of Late Tertiary palaeotemperatures indicated by the AFTA data, and it is not immediately clear how the AFTA and VR data from this depth interval relate to each other. The AFTA data show no definite evidence of an earlier episode which might explain the VR data, although within resolution they would probably allow a hotter event earlier in the post-depositional history.

The three deepest AFTA samples (92, 93, 94), from the deeper part of the Westphalian section and the Devonian section, clearly reveal two episodes of heating and cooling, while in the shallower Sample 85 the data would allow an earlier episode but does not definitely require it. Significantly, the Late Tertiary palaeotemperatures through the deeper part of the section show little or no increase with depth, remaining at between 70 and 90°C over a depth range of over 1 km, giving a maximum palaeogeothermal gradient through this interval of 20°C km^{-1}. This contrasts strongly with the extremely high values (45–90°C km^{-1}) seen in the shallower section. Thus, Late Tertiary palaeotemperatures derived from AFTA and VR data in the Apley Barn Borehole define a highly non-linear profile (Fig. 7), with a pronounced local anomaly around the top of the Carboniferous section. It is possible that the bimodal VR data from the shallowest Carboniferous sample may also represent the effects of this local anomaly.

One possible explanation for non-linear palaeotemperature profiles might be the presence of local homogeneities in the

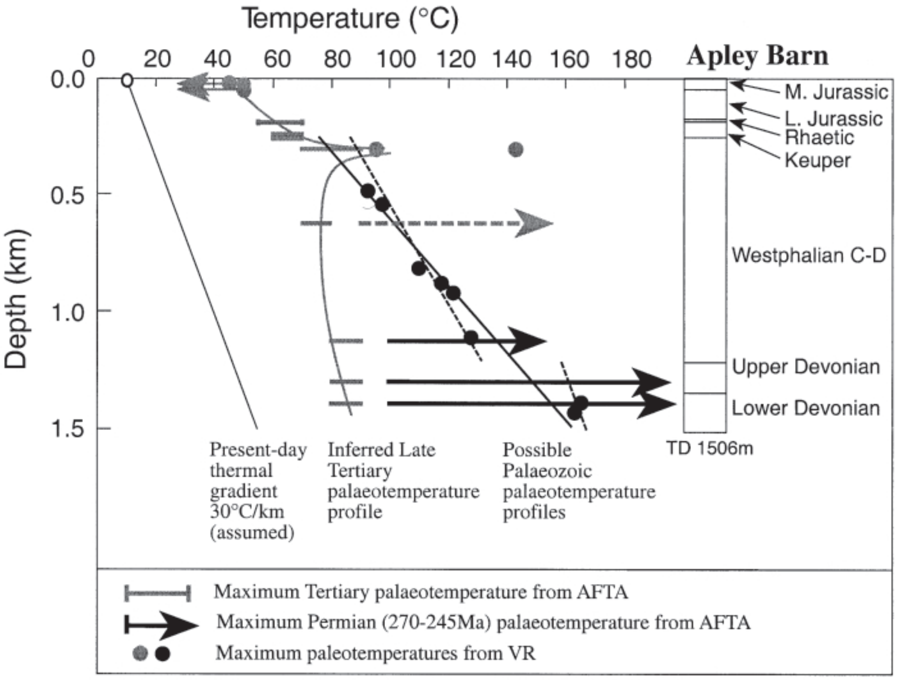

Fig. 7. Palaeotemperature constraints from AFTA and VR in the Apley Barn borehole, plotted against depth sub-surface. Two (possibly three) palaeo-thermal episodes are revealed by the data from this well. Vitrinite reflectance data from the Carboniferous section, combined with AFTA data, reveal a Permian cooling episode. Definition of the palaeotemperature profile characterizing this episode is complicated by uncertainty about the deeper VR data, due to the presence of an unconformity between Devonian and Westphalian units. Thus these VR data from the Devonian may either represent the Permian episode expressed by the VR data from the Westphalian section, or a discrete earlier (Late Devonian–pre-Westphalian) episode. Late Tertiary palaeotemperatures define a highly non-linear profile, suggestive of heating due to lateral introduction of heat at a shallow level (around the top-Carboniferous unconformity), presumably due to hot fluid movement. Thus the Apley Barn borehole data define a very different palaeo-thermal regime as compared to the Rufford-1 well.

thermal conductivity, such as might be caused for instance by a thick sequence of a uniform lithology. Based on the lithologies intersected in the Apley Barn Borehole (Poole 1969), this can be eliminated as the section shows considerable variability in lithologies through the borehole. The most likely explanation therefore appears to be local heating at a relatively shallow level within the section, at a horizon close to the local anomaly defined by AFTA data from Westphalian Sample 81 at a depth of 300 m. The form of the Late Tertiary palaeotemperature profile shown in Fig. 7 is reminiscent of the profiles calculated by Ziagos & Blackwell (1986) to describe the effects of heating due to the passage of hot fluids through a thin aquifer. This process can produce a variety of non-linear palaeotemperature profiles, with different forms depending on the timescale of heating. For very short timescales, the profile takes the form of a very pronounced local anomaly, and as the timescale of heating increases this anomaly becomes progressively diminished as the profile transforms to a dog-leg form, with a higher gradient above the aquifer and a 'normal' gradient below.

The Late Tertiary profile in the Apley Barn Borehole resembles an intermediate form between these end-members, suggesting a relatively short timescale of heating. If this is the case, then the palaeotemperatures reported here, which are based on an assumed heating rate of 1°C Ma^{-1}, may be considerably lower than true values (although this will not affect conclusions based on the shape of the palaeotemperature profile as all values will be affected to a similar extent). As discussed by Duddy *et al.* (1994, 1998), similar effects have been identified from AFTA and VR data in a variety of geological settings. The important point regarding these profiles is that heating due to fluid movement can clearly produce pervasive heating. Heating effects due to minor igneous intrusions will produce purely local anomalies, although they may lead to more widespread effects if they cause circulation of heated fluids on a regional scale (e.g. Summer & Verosub 1989). Regarding a possible source for hot fluids which could have produced the observed effects, one possible origin could be the Weald and Wessex basins to the south, inverted during Late Tertiary time. This is purely speculation at present, and confirmation of this would require more detailed study of sub-surface samples from locations between the Midland Platform and the Wessex Basin.

Finally, while the observed Late Tertiary palaeotemperatures in the Apley Barn borehole cannot be explained by deeper burial, they can be used to set an upper limit to the possible amount of section removed by Late Tertiary uplift and erosion by taking the shallowest and deepest constraints as defining the maximum allowed contribution of heating due to deeper burial. On this basis, a maximum of 40°C of cooling could have occurred during Late Tertiary uplift and erosion which, for a palaeogeothermal gradient similar to the present-day value of 30°C km^{-1}, allows up to 1.3 km of removed section, although the true amount was probably much less.

Amounts of section removed by Tertiary erosion

The results from sub-surface samples provide a framework within which the results from outcrop samples shown in Fig. 2

can be understood. To the northwest of the region, maximum palaeotemperatures around 80–90°C in outcrop samples of Lower Jurassic age and older represent a combination of deeper burial and elevated basal heat flow during the Early Tertiary. In this region, the amount of former cover removed by erosion during the Tertiary was at least 1.5 km (assuming a Early Tertiary palaeogeothermal gradient of 40°C km^{-1}). Late Tertiary palaeotemperatures in outcrop samples from this region may have been as high as 70°C (Table 3). Based on results from the Rufford-1 well (Fig. 6), a major proportion of the former cover may have been removed since the Late Tertiary.

A continuing problem in this region, typified by the Rugby area (Fig. 2), is to identify the age and nature of the missing strata. Geological considerations suggest a maximum overburden of 800–900 m above the base of the Lower Jurassic in late Cretaceous–earliest Cenozoic time (cf. Cope 1994; Thomson 1995), whereas Early Tertiary palaeotemperatures around 80°C from VR data (supported by AFTA data from other localities) require around 1500 m of former cover. The discrepancy cannot be solved entirely by postulating thicker Jurassic deposition in grabens, because some of our samples come from horst areas and from the Midland Platform, and the results suggest broad regionally uniform effects across the entire region (Fig. 2). Further discussion of the discrepancy between these two approaches is beyond the scope of the present paper, and remains a major area of uncertainty requiring further investigation. Previous studies involving palaeothermal indicators have been criticized for lack of direct constraints on palaeogeothermal gradients and use of inappropriate palaeo-surface temperatures. While these issues have been addressed here, the discrepancy between stratigraphic and palaeo-thermal reconstruction of former burial depths remains unresolved.

In contrast to results from the north indicating major Tertiary exhumation, maximum postdepositional palaeotemperatures in outcrop samples of Late Jurassic and Early Cretaceous age from the south and SE of the study region were less than 50°C. Results show no evidence of Early Tertiary palaeo-thermal effects in this region, and Late Tertiary effects appear to be dominated by the effects of heating due to fluid movement. Thus the value of 45–65°C for the maximum palaeotemperature in Sample 44 from the Early Cretaceous is best interpreted as also representing this process. Results from this region would allow deeper burial by up to 1.3 km of former cover, removed during Late Tertiary uplift and erosion, although as noted earlier, true amounts were probably much less.

Thus the apparently regular progression of maximum palaeotemperatures shown in Fig. 2 can be understood as representing a transition from a regime dominated by Early Tertiary burial and heat flow in the northwest to a different regime in the south where those effects are not recognized and Late Tertiary heating due to fluid circulation appears to have been the dominant palaeo-thermal process. We presume that Early Tertiary heating also dominates the intermediate zone within the 50–70°C contour in Fig. 2 since the effects of fluid circulation would be expected to diminish to the northwest. For this region, a maximum palaeotemperature of 60°C corresponds to around 1 km of former cover removed as a result of Tertiary uplift and erosion.

While results from the Rufford-1 well are insufficient to provide tight constraints on the amount of section removed during the Late Tertiary, and therefore to apportion the total exhumation between Early and Late Tertiary episodes, it remains clear that a significant proportion of the total exhumation in that region may have occurred during the Late Tertiary. This is of particular interest given the comments of Japsen (1997) highlighting the contrast between results from the onshore East Midland Shelf and the offshore Southern North Sea, where geological evidence suggests that Late Tertiary exhumation may be the dominant event. Thus, rather than a transition from a major but fairly localized Early Tertiary exhumation event in the onshore region to regional Late Tertiary exhumation in the North Sea, it is possible that the major exhumation episode was everywhere Late Tertiary in age, with Early Tertiary cooling due almost solely to a decline in basal heat flow (accompanied by minor exhumation at that time, possibly localized within more basinal settings). This possibility will be tested in future studies.

Regional thermal history and tectonic synthesis

Figure 8 summarises the regional variation in thermal history based on the results of this study. Histories are shown for the Rufford-1 well and Apley Barn Borehole, plus selected outcrop samples. The figure illustrates the ability of combined AFTA and VR studies to establish new and more complex tectonic histories for regions generally regarded as stable due to the lack of structural or stratigraphic evidence to the contrary. The data clearly shows significant exhumation of the East Midland Shelf during both the Early and Late Tertiary. However, the Midland Platform appears to have behaved differently. Results from the Apley Barn Borehole show that units now at or near outcrop level reached palaeotemperatures around 50°C in the Late Tertiary, as did the Lower Cretaceous sands in the SE. As these temperatures did not occur at the surface the data implies that the Midland Platform experienced some degree of exhumation during the Late Tertiary. Consequently, a picture emerges of regional Late Tertiary exhumation across southern Britain with significant exhumation on the East Midland Shelf and to a lesser degree the Midland Platform. Support for such an interpretation can be found in the Miocene/Pliocene sediments of southern Britain. Sands of late Miocene to Pliocene age, forming the Brassington outlier in south Derbyshire (Fig. 1), were deposited near sea level and subsequently uplifted to *c.* 450 m, before subsiding to their present altitude of *c.* 300 m by karstic collapse (Walsh *et al.* 1972). Namurian strata were present on this part of the Derbyshire Dome (Fig. 2) when the sands were deposited, but were removed by post-Pliocene erosion except where they collapsed into cave systems. The marine Lenham Beds of Kent (Fig. 1), of similar age, are at a present height of 180 m resting on Cretaceous Chalk, and the Netley Heath Beds of Surrey (Fig. 1) at 150 m, while the Coralline Crag of slightly younger age in Suffolk (Fig. 1) is near sea level (Duff & Smith 1992). This suggest differential uplift with an amplitude of a few hundred metres between the Pennines and southern England, accompanied by much deeper erosion in the former area.

Geological evidence from the Midland Platform suggests Early Tertiary erosion also affected this region, although to a lesser degree than that revealed in the EMS by AFTA. After the cessation of Chalk deposition erosion removed the upper part of the Chalk, Maastrichtian Chalk being only known on the Norfolk coast. Deepest erosion, judging from the biostratigraphy of surviving Chalk and not taking account of possible variations in thickness originally deposited, was in the

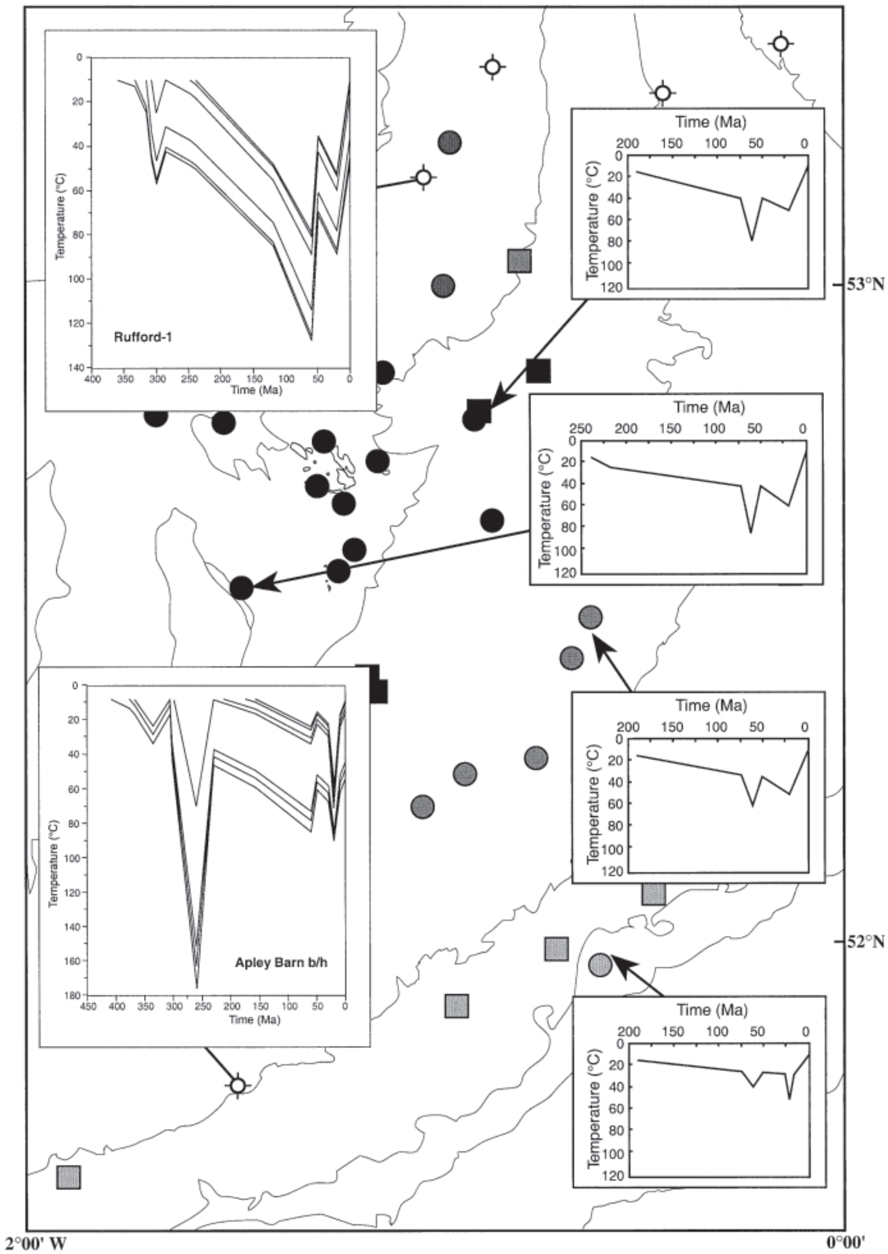

Fig. 8. Summary illustration of the variation in thermal history styles across the region. In the south, Late Tertiary fluid flow dominates the post-Carboniferous history, and masks any effects of Early Tertiary heating, which become dominant towards the north. The history shown for the Apley Barn Borehole corresponds to a 'single Palaeozoic episode' scenario , in which all VR from Carboniferous units are interpreted to represent a single Permian episode (Fig. 7) characterized by an elevated palaeogeothermal gradient.

west of the Midland Platform where Palaeogene rests on Coniacian; there is a broad arch with Palaeogene resting on Santonian running from the Midland Platform southeast through London and into France (Cope *et al.* 1992; Duff & Smith 1992). Consequently, this study highlights the transition from histories dominated by significant Early and Late Tertiary exhumation in the NW (East Midland Shelf) to minor Early and Late Tertiary exhumation in the southeast (Midland Platform). The differing tectonic histories of these regions needs to be placed in a wider context and the validity of currently available models to account for such findings needs to be examined.

Traditionally, Cenozoic uplift of NW Europe has been attributed to the effects associated with North Atlantic break-up with Brodie & White (1994) suggesting that inversion and uplift in the region can be adequately explained with reference to igneous underplating. However, as the underplating occurred during the Early Tertiary, and thus the isostatic uplift response was also an Early Tertiary event, it seems difficult to reconcile this process with evidence for Early and Late Tertiary uplift and exhumation in the East Midland Shelf and to a much lesser extent the Midland Platform. This argument can be taken further as Japsen (1997) has also suggested that uplift in the Southern North Sea was also a Late Tertiary event while there is also evidence for Neogene uplift and inversion along the Atlantic margin (e.g. Boldreel & Anderson 1993). Consequently, it seems that igneous underplating alone cannot adequately explain the picture that can emerge once traditionally 'tectonically stable' regions are examined. Other potential models to explain Cenozoic uplift and erosion such as decoupled, two-layer lithospheric compression (Hillis 1992) may adequately explain inversion and uplift in individual tectonic units (e.g. the Western Approaches Basin) but they can not explain why the timing and magnitude of uplift and inversion can vary over the relatively short distances that separate the East Midland Shelf, Southern North Sea and Midland Platform. Consequently, the fundamental question of why the timing and magnitude of uplift and inversion varies needs to be examined before any causal mechanism can be validated.

For such a difference in behaviour to occur, structures are required to accommodate significant Tertiary uplift of the East Midland Shelf whilst the Midland Platform remained relatively stable. As there is no obvious structure cutting through the Mesozoic cover this may seem a problem. However, Fraser & Gawthorpe (1990) note that the Carboniferous basins to the north of the London–Brabant Massif (Fig. 1) were not only inverted during the Variscan but also in the Early Tertiary and Oligo-Miocene. As the north and west of the area studied contains substantial Carboniferous basins with known Tertiary inversion it seems highly likely that these structures may have accommodated the Tertiary uplift events seen in the NW. Furthermore, the west of the study area contains north–south-trending Carboniferous faults as well as the Permo-Triassic Worcester Graben (Fig. 1). Again it seems likely that these structures also contributed to accommodating the Early Tertiary uplift in the west. Conversely there is a lack of such basins in the SE (London–Brabant Massif) and hence significantly less Tertiary exhumation. The apparent role of underlying basement structure in determining the timing and magntude of uplift in the East Midland Shelf and Midland Platform can be further extended into the Southern North Sea which is known to be underlain by Carboniferous basins (Besly 1998) with the Sole Pit Basin inverting during the Santonian/Campanian and the Late Tertiary (Ziegler 1987). Consequently, there appears to be a link between the significant uplift and inversion and the presence of older Palaeozoic basins with regions underlain by stable Palaeozoic basement remaining relatively stable and experiencing minor uplift and exhumation.

Similar findings have been documented for the late Mesozoic and Cenozoic tectonic evolution of western and central Europe, with periods of broadly synchronous deformation involving basin inversion (Ziegler 1987; Cooper & Williams 1989; Buchanan & Buchanan 1995), uplift of basins, platforms and massifs (Green *et al.* 1993; Hillis *et al.* 1994; Thomson *et al.* 1999), accelerations in basin subsidence rates (Cloetingh *et al.* 1990) and extensional, compressional and strike-slip reactivation of pre-existing structures such as the Great Glen Fault (Thomson & Underhill 1993). From the Alpine front to the Atlantic margin the pattern of deformation is complex, as individual phases of deformation did not affect the entire region but were restricted to specific areas, with the intervening areas remaining dormant (Ziegler 1987; Ziegler *et al.* 1998). Some areas were deformed during more than one phase of deformation whilst others were affected once or not at all and the combination of areas affected during each phase of deformation varied in a non-systematic pattern (Ziegler 1987). As the events coincide with the major phases of Alpine orogenic activity and North Atlantic break-up, these major plate tectonic events have been thought the most likely cause, although the mechanism remains a matter for discussion (e.g. Hall & White 1994). However, as the intensity of deformation increases towards the Alpine orogenic front, Ziegler (1987) suggested that the events observed in the European plate are related to intraplate compression due to Alpine collision with a minor role for ridge push or transform related compression on the Atlantic margin.

Although a variety of processes can contribute to intraplate horizontal compressional stresses, Ziegler *et al.* (1998) suggests that collisional coupling of plates exerts a dominant influence on their development. Palaeo-stress regimes fluctuate and the inhomogeneity of the lithosphere means that its weaker areas will be prone to failure whilst other areas will remain unaffected. The spatial and temporal development of compressional intraplate deformations is believed to be controlled by the interaction of fluctuating intraplate stresses and the spatial and temporal changes of the lithosphere strength (Ziegler *et al.* 1998). The strength configuration of the lithosphere primarily depends on its thermo-mechanical structure and can change due to deformation of the lithosphere and its thermal equilibration. Given a relatively constant stress field, spatial variations in the onset of compressional intraplate deformation are controlled by the spatial strength distribution within the lithosphere. However, as the strength of the lithosphere increases during basin inversion, locking of earlier inverted basins can control the progressive propagation of far-field compressional deformations into the interior of continental cratons (Ziegler 1987; Ziegler *et al.* 1998). Such a mechanism seems capable of explaining the differing uplift histories of the East Midlands Shelf, Midland Platform and Sole Pit Basin. The London–Brabant Massif has been undeformed effectively since the Caledonian and hence contains relatively few faults and is rheologically stronger than the surrounding regions containing Carboniferous and younger basins. Consequently, during the early stages of Alpine compression it is most likely that deformation will focus on weak areas first and as the strain accumulates in these regions, and they become stronger, deformation will migrate to other areas. As Alpine stresses built up in the foreland the weak Sole Pit Basin inverted first during the Santonian/Campanian and once sufficiently strained became ‘locked’. As the stresses continued to be present after Sole Pit Basin inversion (although the orientation may have altered), significant deformation switched to the East Midlands Platform with inversion and uplift being accommodated on existing Carboniferous structures whilst the Midland Platform was also affected to a minor degree. Finally, during the Late Tertiary it became possible to mechanically couple the Midlands Platform, East Midland Shelf and Sole Pit Basin to produce a regional Late Tertiary event with the rheologically weaker Sole Pit Basin and East Midland Shelf experiencing significantly more exhumation than the Midland Platform.

Conclusions

Combined AFTA and VR studies have the capability to resolve inversion and uplift events in regions traditionally regarded as tectonically stable due to the lack of structural and or stratigraphic evidence. The technique allows the definition of thermal events, their causes, timings and magnitudes and consequently can contribute to a fuller understanding of regional tectonics. An appreciation of the tectonic activity of areas normally regarded as stable during major regional inversion and uplift events has profound implications for our understanding of the potential mechanisms used to explain such processes.

Combined AFTA and VR data from the East Midlands Shelf and Midland Platform reveal a complex pattern of Cenozoic heating and cooling, with the East Midlands Shelf showing evidence for two uplift and erosion events during the Early and Late Tertiary. The Midland Platform data demonstrates that this area was affected by local Late Tertiary heating due to the passage of hot fluids. Modest cooling of the Midland Platform due to uplift and erosion occurred during the Late Tertiary and probably the Early Tertiary but to a lesser degree than the East Midland Shelf. As the data demonstrates a complex pattern of cooling due to uplift and erosion the general perception that both regions have been tectonically stable since Variscan times can no longer be maintained. The commonly held view that North Atlantic related igneous underplating was the driving mechanism for Cenozoic uplift is difficult to reconcile with the pattern of Cenozoic uplift and inversion as a number of discrete events affected both the East Midland Shelf, Midland Platform and Southern North Sea at varying times, with much of the exhumation occurring much later than the main phase of plume activity. Furthermore, although other models may adequately explain uplift and inversion in individual basins they cannot explain the temporal and spatial pattern observed.

The variation in the magnitude of uplift and inversion between the East Midland Shelf, Midland Platform and Southern North Sea can be correlated with the distribution of Palaeozoic basins. Areas underlain by Palaeozoic basins (East Midland Shelf and Southern North Sea) were exhumed to a greater degree whilst the Midland Platform, resting on Caledonian basement, was affected to a lesser extent. The temporal variation may be related to contrasting rheological strengths between the areas. This pattern suggests that underlying basement structure may have a significant role in determining the local timing of uplift and inversion during regional events. We suggest this reflects the preferential reactivation of the weaker basinal regions as a result of compressional events at plate margins.

We thank R. G. Clements and D. S. Sutherland of Leicester University for their assistance in providing samples from outcrop and in collecting new samples. Samples from the Apley Barn borehole were supplied by University Museum, Oxford, with thanks due to Phillip Powell for his assistance. AFTA samples and VR data from Rufford-1 were provided by BP Petroleum Development. AFTA® is the registered trademark of Geotrack International. Iain Scotchman and John Underhill are thanked for their constructive reviews of the paper.

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Received 2 December 1999; revised typescript accepted 2 August 2000.
Scientific editing by John McArthur.