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Evidence for post-early Eocene tectonic activity in southeastern Ireland

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Abstract – The role played by Cenozoic deformation in denudation and landscape development in Ireland has historically been difficult to assess because of the lack of widespread pre-glacial Cenozoic deposits onshore. Here we combine analysis of apatite fission-track data and geomorphic observations to place constraints on the timing, kinematics and magnitude of onshore deformation in southeastern Ireland. Relationships between apatite fission-track central age and elevation for samples from the Wicklow and Blackstairs Mountains and Tullow Lowland suggest that these rocks record an exhumed apatite partial annealing zone, which after cooling was dismembered by differential vertical displacements of up to several hundred metres. We use inverted models of sample thermal history to show that samples across the region experienced very similar thermal histories up to and including a cooling event in late Paleocene or early Eocene time. This effectively rules out strongly spatially heterogeneous denudation, and implies that differential rock uplift occurred in post-early Eocene time. The central age–elevation relationships define at least three spatial domains with internally consistent apatite fission-track data, separated by known faults or topographic escarpments. Geomorphic analysis of these structures shows that patterns of catchment incision and sinuosity, as well as the presence of antecedent drainage, are best explained by differential vertical displacements at or near the domain boundaries. The kinematics and magnitudes of these displacements are consistent with those implied by the apatite fission-track results, and are compatible with other examples of known Cenozoic deformation from Ireland and the adjacent continental margin.

Keywords: Cenozoic, geomorphology, fission-track, Ireland, denudation.

1. Introduction

Much of the northwestern European continental margin underwent significant tectonic deformation and denudation during Cenozoic time (e.g. Bulat & Stoker, 1987; O'Driscoll *et al*. 1995; Vogt, 1995; Japsen, 1997; Japsen, Boldreel & Chalmers, 1998; Doré *et al*. 1999). Evidence for this includes thermochronological data (Rohrman *et al*. 1995; Rohrman & van der Beek, 1996; Green, Duddy & Bray, 1997; Rowley & White, 1998; Green *et al*. 1999), structural relationships in onshore and offshore basins (e.g. Shannon, 1991; Naylor, 1992; Tate, 1993; Brodie & White, 1995), and coarse clastic sedimentation (Stoker, 1997; Stoker, van Weering & Svaerdborg, 2001). Most of the direct onshore evidence for Cenozoic tectonic deformation in Ireland is based on the displacement of Upper Cretaceous chalk, Paleocene basalt flows and Oligocene sequences in the northeast of the country (Parnell, Shukla & Meighan, 1988; Naylor, 1992; Geoffroy, Bergerat & Angelier, 1996). However, little is known about the Cenozoic tectonic history outside this region due to an absence of stratigraphic resolution (e.g. Naylor, 1992; Allen *et al*. 2002).

The aim of this paper is to elucidate the Cenozoic, denudational and tectonic history of the Wicklow and Blackstairs Mountains and Tullow Lowland of southeastern Ireland. We use a subset of an existing apatite fission-track dataset to define discrete structural domains by comparing apatite fission-track central age with elevation, and we evaluate the spatial and temporal persistence of these domains using a numerical inverse thermal history model coupled to well-established geological constraints. We then examine geomorphic indicators of tectonic activity along structures with inferred or suspected Cenozoic differential displacements. Finally, we relate our findings to observations of known Cenozoic deformation from northeastern Ireland and other parts of the northwestern European continental margin.

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2. Regional setting

The Wicklow and Blackstairs Mountains and Tullow Lowland are largely underlain by the 404 ± 24 Ma Leinster Granite batholith (O'Connor & Brück, 1978), forming the largest contiguous area of high topography on the island (Fig. 1). The Wicklow Mountains form a broad, gently rolling upland, and the Blackstairs Mountains represent the southeastern continuation of this upland, forming a series of elongate, NE-trending ridges, with elevations rising to 800 m above sea level (asl), separated by low-lying passes. To the south and west of the Wicklow Mountains and to the north of the Blackstairs Mountains is the Tullow Lowland, a broad low-relief plain at elevations of 100 to 130 m asl with thin limestone to granite dominated tills (from east to west respectively) interspersed with sporadic granite outcrop (Fig. 1a).

The batholith is bounded to the east and west by Cambrian to Lower Ordovician metasediments, forming the Leinster Massif terrain (Max, Barber & Martinez, 1990), which is in fault contact with Carboniferous limestone of the Dublin Basin to the north (Fig. 1b).

In the southwest, Upper Devonian and Lower Carboniferous rocks rest unconformably on the batholith (Fig. 1b).

2.a. Models of topographic development in southeastern Ireland

The nature and timing of processes that shaped the present-day topography of the Wicklow and Blackstairs Mountains are poorly understood. Granitic clasts derived from the batholith, occur in the Upper Devonian Old Red Sandstone of Counties Kilkenny and Waterford (Jukes, 1862; Capewell, 1956), and feldspars from the batholith occur in Upper Devonian siliciclastics of the eastern Munster basin (Penney, 1980). In County Kilkenny, Upper Devonian Old Red Sandstone onlaps schist to rest on the batholith. Therefore the southern part of the batholith was at least partially unroofed at this time. Similarly, in the Courceyan Dublin Basin to the north, granitic fragments occur in Viséan limestones up to distances of 5 km from the margins of the batholith (Montgomery, 1864–67; Ball, 1888) indicating that the northern part of the Leinster Granite batholith was partially exposed during Carboniferous times.

A number of workers have thus suggested that the Wicklow and Blackstairs Mountains have formed positive topography that underwent continuous denudation from the Middle Palaeozoic onward (Wills, 1951; Freeman, 1960). Others have argued that the Leinster Granite batholith was protected by a younger sedimentary cover, subsequently removed during Cenozoic time to expose granite, schist septa and roof pendants (Jukes, 1862; Cole, 1922; Cole & Hallissy, 1914; Charlesworth, 1963). In support of this theory, these workers noted the discordance of the present-day river systems with respect to structure. The major rivers that drain southeastern Ireland, particularly the rivers Slaney and Barrow (Fig. 1), were inferred to have once flowed to the south or southeast over a low-relief sedimentary cover. As erosion stripped away the cover, the rivers were superimposed on the older underlying structure, and hence inherited a palaeotopography of possible Late Palaeozoic age (Davies, 1960, 1970; Mitchell, 1980). The cover rocks were most likely Upper Cretaceous limestone (Walsh, 1966; Naylor, 1992), deposited during a time of maximum global sea-level rise (Haq, Hardenbol & Vail, 1987). This hypothesis is partly supported by the widespread occurrences of flint in glacial deposits of southeastern Ireland (Davies, 1970).

The northern part of the Blackstairs Mountains extends for 17 km northeast from the River Slaney, at Bunclody (Fig. 1a). This ridge of hills is underlain by schist and sheared, chilled marginal granite (Fig. 1b) and rises to 280 m above the Tullow Lowland, but does not form a watershed boundary. Four rivers cross the axis of the ridge, along with four additional dry valleys. Hence, it has been suggested that the Tullow Lowland must have stood higher than the ridge, assuming that the rivers initially flowed to the southeast across it (Farrington, 1927; Davies, 1960; Davies & Stephens, 1978). Davies (1960, 1970) noted that the granitic summits of the Wicklow Mountains are probably very close to the original roof of the batholith and suggested that the northern part of the Wicklow Mountains had only recently lost its protective schist and younger cover, to expose the granite beneath. Conversely, he argued that the granite in the Tullow Lowland had been exposed for a greater period of time and hence was more deeply eroded.

2.b. Problems

Several geological and geophysical observations cast some doubt on these models of landscape evolution. Granitic rocks of the Leinster Granite batholith are continuous beneath both the Tullow Lowland (Tullow pluton) and adjacent high ground to the north (Lugnaquillia pluton), suggesting that differential resistance to erosion is not responsible for present-day differences in elevation. The survival of roof features of the batholith both on the Tullow Lowland (Brück & O'Connor, 1980) and at higher elevations in the Wicklow Mountains to the north is also incompatible with strongly spatially heterogeneous erosion. Parts of the batholith were exposed in Late Devonian and Early Carboniferous times and so it is unlikely that portions of the batholith roof would have survived to the present day.

A further argument against deep differential erosion of the Leinster Granite in the Tullow Lowland area is the

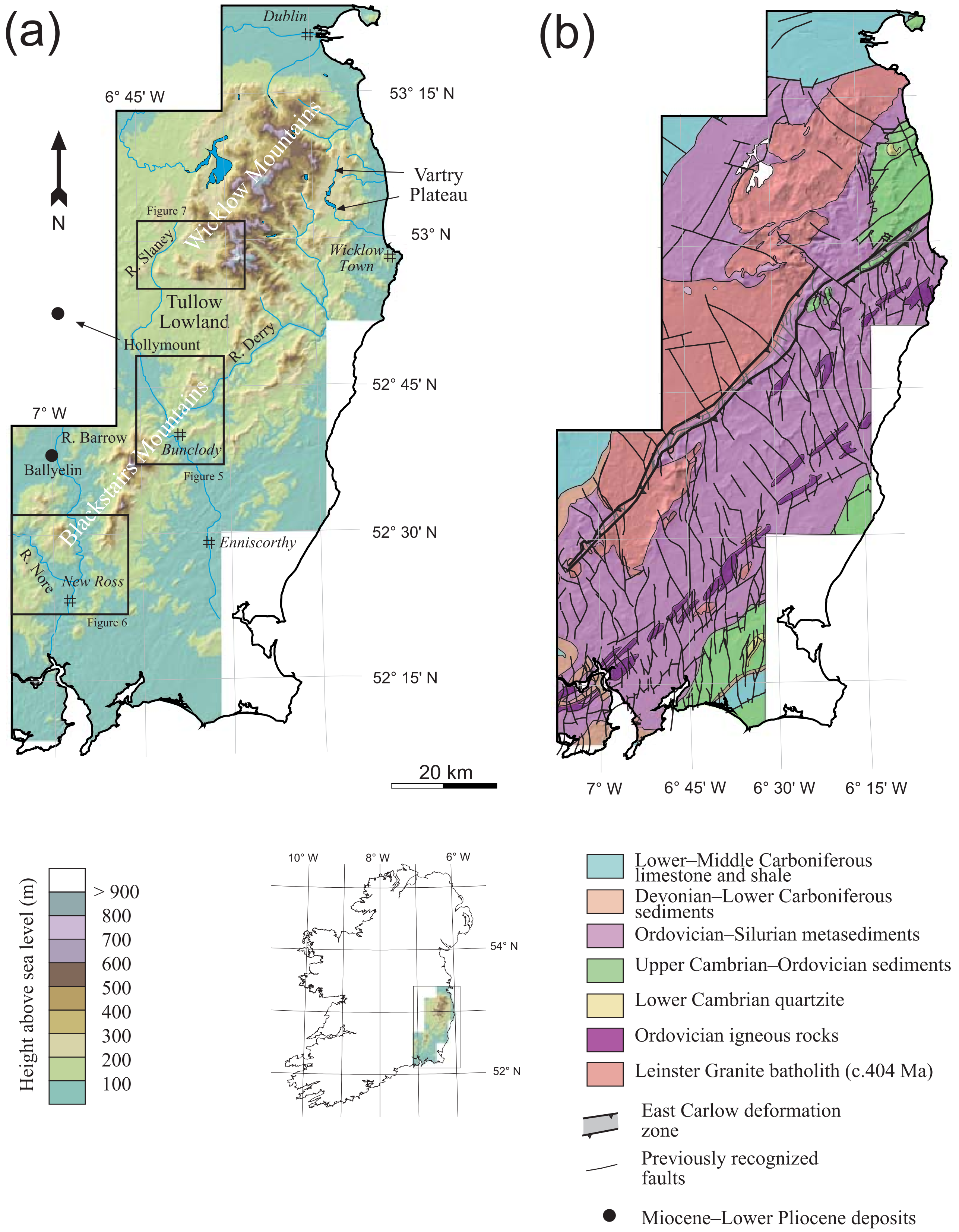

Figure 1. Shaded-relief image of (a) topography and (b) simplified bedrock geology of southeastern Ireland. Topography is derived from Ordnance Survey of Ireland digital contour data, with 50 m cell size. Digital geology provided by courtesy of the Geological Survey of Ireland.

presence of a very low Bouguer gravity anomaly (–30 to –35 mGal) beneath the lowland (Readman, O'Reilly & Murphy, 1997). Negative Bouguer gravity anomalies in Ireland are restricted to regions underlain by significant granitic plutons. In general, the Leinster Granite batholith was asymmetrically emplaced along a NNE–SSW axis (Brindley, 1973) as five dome-like plutons with an en-echelon arrangement. The low Bouguer gravity occurs over much of the Tullow Lowland and therefore is unlikely to reflect the emplacement geometry of the granite body. Unless the Leinster Granite was originally very much thicker beneath the Tullow Lowland, the low Bouguer gravity observations rule out significant localized denudation. The presence of roof features on the northwest margin of the Tullow pluton, however, is inconsistent with a deeply eroded sector of granite here (Fig. 1b).

The Tullow Lowland extends westwards and cuts across Lower Carboniferous limestones which show evidence of prolonged weathering such as hum and doline topography (Mitchell, 1980) and the Miocene–Lower Pliocene sub-aerial deposits at Hollymount and Ballyelin, preserved in conical pipes on the Carboniferous limestone surface (Fig. 1a) (Mitchell, 1980; Naylor, 1992). The lowland also features relict granite hills (tors) and abundant granite core-stones (Farrington, 1934). These features suggest that the Tullow Lowland represents a mature eroded plain of at least post-early Pliocene age.

3. Evidence for differential displacements from apatite fission-track data

If denudation has been strongly spatially or temporally heterogeneous across southeastern Ireland, or if post-Palaeozoic cover rocks have been unevenly deposited and then stripped off, then we may be able to resolve those heterogeneities using apatite fission-track analysis. Fission tracks are linear damage trails in a crystal lattice produced by the spontaneous fission of the isotope ^{238}U. Fission tracks in apatite shorten, or anneal, irreversibly when the host mineral is at elevated temperatures. The rate of annealing increases with increasing temperature and is a function of time, or duration, of exposure to a given temperature. Laslett *et al.* (1987) developed an empirical annealing model, calibrated on laboratory experiments performed on a mono-compositional Durango apatite (Young *et al.* 1969). Extrapolation of this model to geological timescales predicts a partial annealing temperature range from $\sim 60\,^{\circ}$C to $\sim 110\,^{\circ}$C with an uncertainty of about $10\,^{\circ}$C (for timescales of 1–100 Myr). At temperatures above $110 \pm 10\,^{\circ}$C, all tracks are completely annealed over geological timescales, while at temperatures below $60 \pm 10\,^{\circ}$C, partial annealing is negligible. This temperature interval of 60 to $110 \pm 10\,^{\circ}$C is known as the partial annealing zone (Fig. 2) (see Gallagher, Brown & Johnson, 1998, for discussion).

Previous apatite fission-track studies of Ireland, the Irish Sea, and parts of northern and western Britain have consistently shown evidence for two cooling events during Cenozoic time (Green *et al*. 1993, 1999; Allen *et al*. 2002). The first event occurred during the early Palaeogene period and may be attributed to magmatic underplating related to the Iceland hot-spot (e.g. White & Lovell, 1997). The timing and magnitude of the second event is very poorly constrained at present, and while it is generally assigned a post-Middle Miocene age, its existence must be regarded as somewhat speculative (Lewis *et al*. 1992; Cope, 1994, 1998; Green *et al*. 1993, 1999; Allen *et al*. 2002).

Allen *et al.* (2002) quantitatively evaluated the post-Variscan thermal and denudational history of Ireland using an extensive new apatite fission-track dataset derived from surface samples. Stochastic modelling of sample thermal histories (Gallagher, 1995) was used to produce denudation maps for a series of time-slices from Triassic to present using time-dependent palaeogeotherms. The results document moderate rates of denudation around known igneous centres (e.g. the Mourne Mountains of County Down and the Leinster Granite batholith of southeastern Ireland) during Cenozoic time (Table 1). Allen *et al*. (2002) documented broad patterns of Cenozoic cooling and denudation across Ireland, but did not specifically investigate the denudational history of particular regions. In order to address the issues of spatially variable denudation and landscape evolution in southeastern Ireland, we re-analysed a subset of the Allen *et al*. (2002) apatite fission-track database that covers the Wicklow and Blackstairs Mountains and the Tullow Lowland. (For detailed discussion of the samples, data collection and analysis procedures, see Allen *et al.* 2002.) We first compare apatite fission-track central age with elevation for our subset of samples to evaluate the possibility of local perturbations caused, for example, by differential displacements or localized heating events. We then re-model the sample thermal histories with tighter geological constraints to determine the extent and timing of thermal events across the region.

3.a. Elevation–central age relationships

In a vertical profile of apatite fission-track central age versus sample depth, the partial annealing zone is visible as a segment of the profile in which central age is inversely proportional to depth (Fig. 2); above and below the partial annealing zone this correlation is not observed (e.g. Fitzgerald *et al*. 1995). In a landscape that has undergone strong denudation, a 'fossilized' partial annealing zone may thus show up as a monotonic relationship between central age and present-day sample elevation. Deviations from this relationship may result from local effects such as differential rock uplift after cooling, localized heating events that reset some samples, or strongly heterogeneous denudation.

Table 1. Apatite fission-track samples chosen from the TULIP database of Allen *et al.* (2002), showing central age, mean track length, standard deviation, sample elevation, modelled paleotemperatures (5 m.y. increments), cumulative denudation and denudation rates for the Cenozoic (66–10 Ma)

Samples	AFT central age (Ma)	Mean track length (μm)	Standard deviation (μm)	Elevation (m) of samples	[1]Temp. (°C) (65 Ma)	[1]Temp. (°C) (60 Ma)	[1]Temp. (°C) (50 Ma)	[1]Temp. (°C) (40 Ma)	[1]Temp. (°C) (30 Ma)	[1]Temp. (°C) (20 Ma)	[1]Temp. (°C) (10 Ma)	[1]Temp. (°C) (5 Ma)	[2]Total den. (m) 66–10 Ma	[2]Den. rates (m/m.y.)
LG5	142 ± 5	12.85 ± 0.12	1.72	90	**52**	53	54	54	56	55	**53**	33	2555	39
LG7	127 ± 4	12.85 ± 0.15	1.87	150	**50**	50	51	52	57	53	**46**	30	1549	23
LG8	131 ± 4	12.60 ± 0.15	2.14	2	**52**	52	53	54	57	55	**56**	34	2205	33
LG10	151 ± 6	12.53 ± 0.27	2.20	40	**76**	66	53	55	55	53	**37**	27	1418	21
LG11	166 ± 4	12.55 ± 0.12	1.73	240	**54**	54	55	56	56	58	**58**	35	1554	24
LG13	181 ± 5	12.28 ± 0.13	1.85	450	**69**	66	55	56	55	58	**46**	30	1757	27
LG14	177 ± 5	12.78 ± 0.12	1.64	400	**51**	52	53	54	63	56	**58**	35	1826	28
LG15	178 ± 5	12.72 ± 0.12	1.60	470	**54**	55	55	56	56	57	**58**	35	1565	24
LG16	173 ± 4	12.50 ± 0.14	2.02	500	**59**	52	53	54	65	55	**56**	34	1815	28
LG17	170 ± 5	12.22 ± 0.17	1.78	570	**60**	61	61	62	61	65	**63**	37	1749	26
LG18	152 ± 4	12.71 ± 0.11	1.61	520	**54**	53	54	55	61	57	**58**	35	1744	26
LG21	156 ± 5	12.28 ± 0.10	1.47	420	**60**	61	62	63	60	66	**64**	38	1966	30
LG23	169 ± 5	12.38 ± 0.13	1.88	117	**58**	59	60	60	55	62	**60**	36	2091	32
LG26	167 ± 7	12.47 ± 0.15	2.15	260	**58**	59	60	60	62	47	**34**	25	2370	36
LG28	205 ± 6	12.60 ± 0.13	1.83	795	**63**	64	64	64	55	47	**33**	25	1473	22
LG32	136 ± 7	12.74 ± 0.13	1.83	130	**66**	66	67	61	53	49	**41**	29	1354	21
LG36	174 ± 7	12.57 ± 0.12	1.50	740	**72**	72	60	61	55	63	**42**	29	1439	22

Quoted uncertainties for central age and mean and standard deviation of the track length distributions are $\pm 1\sigma$.
Numbers in bold used for calculating (65–10 Ma) denudation.
[1] The precision/resolution of the paleotemperature varies in space and time. We consider a 10 °C uncertainty between 2 points in the thermal history (see Allen *et al.* 2002, for more details).
[2] Palaeogeothermal gradient used for calculating denudation is 22 °C km^{-1}. We estimate a 20 % error on choice of geotherm (see Allen *et al.* 2002, for further details).

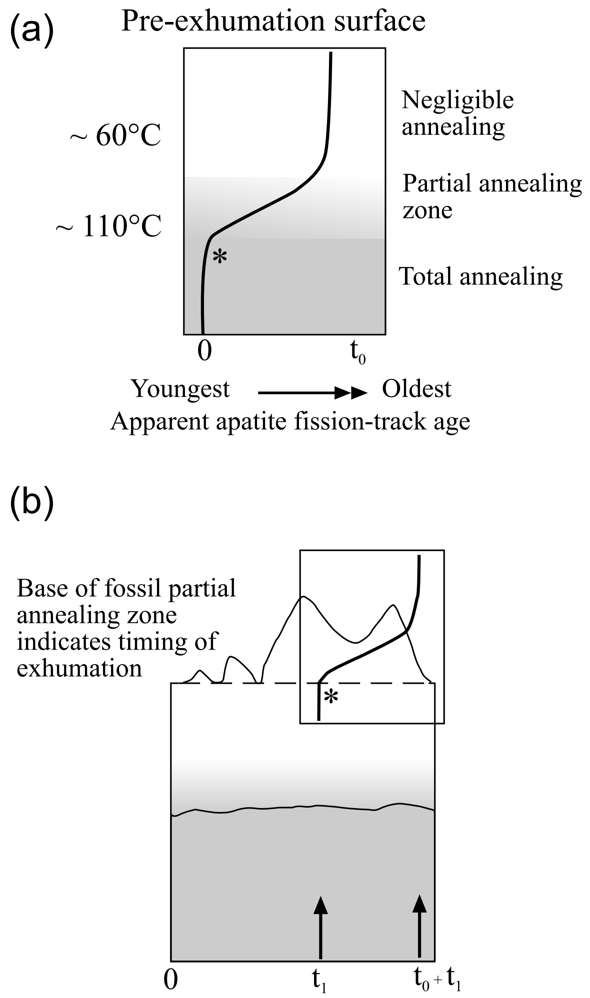

Figure 2. Simple diagram showing the concept of an exhumed partial annealing zone (adapted from Fitzgerald *et al.* 1995). (a) The pre-denudation apatite fission-track age crustal profile, showing the oldest fission-track age, where negligible annealing has taken place below 60 °C. (b) A sudden increase in the rate of denudation at time t_1 after a period of prolonged stability exhumes the existing partial annealing zone (Brown, Summerfield & Gleadow, 1994, Fitzgerald *et al.* 1995). The break in slope in the exhumed profile (marked by the asterisk) shows where the apatite fission-track ages were at zero prior to exhumation. The apatite fission-track age at this point coincides with timing of cooling below 110 ± 10 °C, that is, time t_1, thus yielding the age of increased denudation rates (assuming a rapid rise through the partial annealing zone). The oldest ages in the exhumed profile will therefore be the sum of the pre-exhumation age and the age of onset of increased denudation rate, that is, $t_0 + t_1$.

From the Allen *et al.* (2002) apatite fission-track database, we selected samples that lie along a NNE-trending profile that is roughly coincident with the drainage divide of the Wicklow Mountains (Fig. 3a), continuing south across the Tullow Lowland and over the Blackstairs Mountains. The bedrock geology underlying the profile is dominantly granite, with occasional roof pendants of schist (Fig. 3b). In the northern Wicklow Mountains, sample central age (Allen *et al.* 2002) increases with elevation, with a broadly linear to curvilinear relationship consistent with a fossilized partial annealing zone (Fig. 3c). With few exceptions, samples from north and south of the Lough Dan fault (Fig. 3b) plot along different, sub-parallel profiles, separated by ~ 300 m in elevation or ~ 20 Myr in central age (Fig. 3c). In the southern Wicklow Mountains, sample LG36, near the summit of Lugnaquillia, lies about 480 m above sample LG26, which lies at the northern margin of the Tullow Lowland, and about 620 m above sample LG23, from the Tullow Lowland. All three samples have similar apatite fission-track central ages within 1σ error (Table 1; Figure 3).

These results suggest that the apatite fission-track samples from the Wicklow Mountains may be naturally divided in to two discrete spatial domains, a Northern Domain to the north and a Lugnaquillia Domain to the south, separated by approximately 300 m of elevation. The domain boundary is likely to be the Lough Dan fault. Samples in the Lugnaquillia Domain (LG17, LG18, LG21 and LG36) lie 500 to 600 m higher than the similarly aged sample LG23 in the Tullow Lowland. From this we infer that samples LG23 and LG32 represent a separate, low-elevation domain, termed the Tullow Domain. Sample LG26, which lies at an intermediate elevation between the Lugnaquillia and Tullow domains, is difficult to attribute to either domain. If sample LG26 belongs to the Tullow Domain, then the domain boundary is likely to be the NW-trending Ow River fault (Fig. 3a). If instead it belongs to the Lugnaquillia Domain, then the domain boundary is approximately coincident with a WNW-trending topographic escarpment, here termed the Baltinglass Escarpment, which was interpreted as a Cenozoic fault by Mitchell & Ryan (1997) and which we discuss in Section 4.b. In turn, the Tullow Domain may be distinct from a separate domain in the Blackstairs Mountains defined by sample LG28, but we lack sufficient samples to test this hypothesis. We do note, however, that sample LG28 is separated from the Tullow Domain by a topographic escarpment along the southeastern margin of the Tullow Lowland which is coincident with the East Carlow deformation zone, a multiply reactivated SE-dipping shear zone with evidence of late, brittle dip-slip deformation (McArdle & Kennedy, 1985). The Lough Dan and Ow River faults have previously been identified as Caledonian and acted as major hydrothermal pathways during the Variscan (e.g. Brück & O'Connor, 1980).

3.b. Thermal history modelling strategy

While the relationship between apatite fission-track central age and elevation allows us to divide the apatite fission-track samples from the Wicklow and Blackstairs Mountains into discrete domains (Fig. 3), it does not explain the mechanisms by which the domains arose

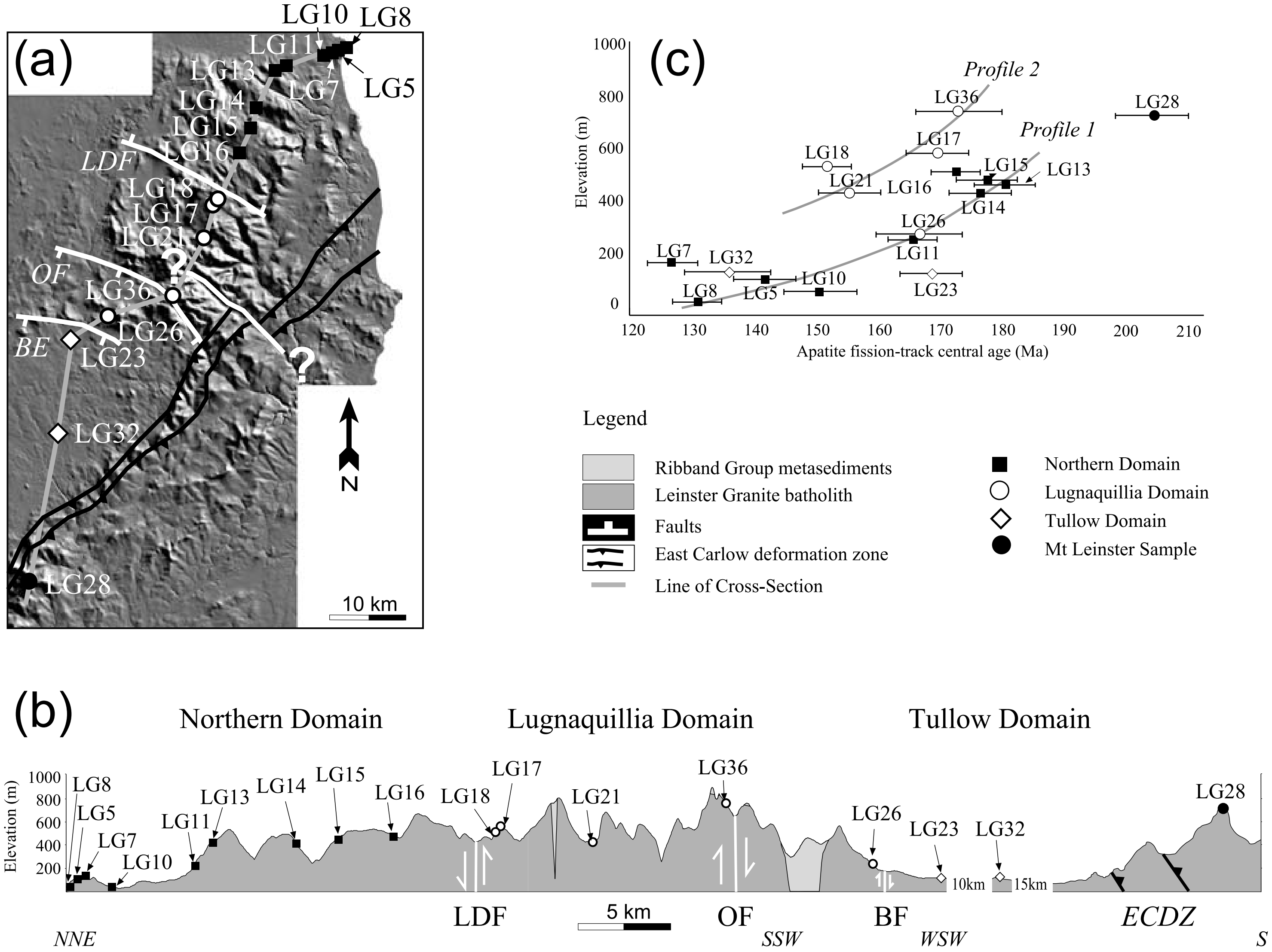

Figure 3. (a) Topography of the Wicklow and Blackstairs Mountains and Tullow Lowland showing location of apatite fission-track profile. BE – Baltinglass fault; LDF – Lough Dan fault; OF – Ow River fault. (b) Topographic line of section along the sample profile showing bedrock geology and sample locations. ECDZ – East Carlow deformation zone. (c) Plot of apatite fission-track central age versus present-day elevation for each sample. See Allen *et al*. (2002) for discussion of samples and analysis. Note that, in general, groups of samples define curvilinear relationships (Profiles 1 and 2). We divide samples into three structural domains: the Northern Domain (north of Lough Dan fault), Lugnaquillia Domain (between Lough Dan fault and Ow River fault or Baltinglass Escarpment), and the Tullow Domain (south of Baltinglass Escarpment). Sample LG28 may define a separate domain in the Blackstairs Mountains (south of the East Carlow deformation zone).

or the timing of their origin. Variations in the age–elevation relationship might be due to (1) differential denudation between two samples, with no movement relative to the geoid (yielding variations in central age); or (2) differential rock uplift between the samples, with no difference in denudation (yielding variations in elevation). To understand better the origins of these domains, and to explore the possibility that they may be due to Cenozoic tectonics, we employ an inverse numerical model to derive thermal histories for samples in each of the three domains.

3.b.1. *Rationale for re-modelling samples*

Thermal history modelling was undertaken using an iterative search procedure based on the maximum likelihood statistic as outlined in Gallagher (1995), combined with the annealing model of Laslett *et al*. (1987). Briefly, this method requires the specification of a series of time–temperature windows (sub-regions in time–temperature space which may or may not overlap), from which points on a possible thermal history are selected. Linear interpolation is used to construct a smooth thermal history function, which is then used to make a prediction of the fission-track parameters (age and length distribution). The strategy adopted uses a genetic algorithm to focus in on the thermal meaning histories that provide better fits to the observed data. The thermal histories are smoothed before predicting the fission-track parameters to avoid overly complex structure in the thermal histories. The inferred thermal histories that best fit each apatite fission-track central age and fission-track length distribution are sensitive to the choice of constraints on the time–temperature path. The procedure requires the input of stratigraphic age and time–temperature windows through which the modelled thermal history passes (Gallagher, 1995). Allen *et al*. (2002) modelled the entire Irish sample set using time–temperature windows with broad bounds in temperature and overlaps in time so as not to restrict the modelling process. They used the same time–temperature windows for all samples across the Irish landmass for consistency.

Here we re-derive thermal histories for the sample profile using a more locally appropriate series of time–temperature windows based on geological observations of the Wicklow and Blackstairs Mountains region and adjacent areas offshore. Whilst doing this, we have kept the time–temperature constraints as loose as possible to allow for a wide range of possible solutions to be considered.

3.b.2. *Geological constraints*

All the apatite fission-track samples analysed in this study are plutonic rocks from the Leinster Granite batholith, which has a crystallization age of 404 ± 24 Ma (O'Connor & Brück, 1978). The first time–temperature window is therefore chosen to constrain the temperature to be in excess of the full annealing (closure) temperature for apatite ($110 \pm 10\,^{\circ}$C) at 404 ± 24 Ma. The second window allows for significant cooling and partial unroofing of the batholith during the Devonian period with temperatures of $70 \pm 50\,^{\circ}$C at 370 ± 20 Ma. Tectonic and thermal events associated with the Variscan orogeny caused widespread deformation in southern Ireland and resulted in high thermal maturity (Clayton *et al*. 1989), assumed to have been imparted in Late Carboniferous time. The third window, with temperatures of $90 \pm 30\,^{\circ}$C at 300 ± 20 Ma (Late Carboniferous to Early Permian), is chosen to represent this Variscan heating.

Lower Jurassic sediments in the Celtic Sea Basins are thought to be derived, in part, from exposed Old Red Sandstone rocks in southwestern Ireland and from the Wicklow Mountains region (Petrie *et al*. 1989). Likewise, the Kish Bank and Cardigan Bay basins accumulated great thicknesses of Lower Jurassic sediments (e.g. Broughan, Naylor & Anstley, 1989). The presence of Middle Jurassic red beds and Upper Jurassic fluviolacustrine deposits along the northern flank of the Celtic Sea Basins, however, suggests that southeastern Ireland was an area of sub-aerial topography and a sediment source throughout much of the Jurassic period. Therefore, the corresponding window is chosen as $70 \pm 50\,^{\circ}$C at 180 ± 30 Ma to allow for the possibility of relatively cool temperatures at shallow burial depths during Jurassic time.

In the southern offshore basins, Lower Cretaceous continental Wealden sedimentary rocks pass up into Lower Cretaceous marine sandstones and shales, overlain unconformably by Upper Cretaceous chalks (Naylor & Shannon, 1982). This suggests that the Irish landmass became progressively flooded during the Cretaceous period. To allow for the possibility of burial and heating of southeastern Ireland under a sedimentary overburden, the corresponding window is chosen as $90 \pm 50\,^{\circ}$C at 110 ± 40 Ma.

A regional unconformity exists within all the sedimentary basins off southern Ireland overlying Cenomanian–Maastrichtian chalks (Naylor & Shannon, 1982) with the amplitude of erosion increasing towards the Irish Sea (Blundell, 1979; Rowley & White, 1998). An extensive vitrinite reflectance and apatite fission-track database in the Irish Sea area suggests regional denudation during Palaeogene time. In order to capture a wide range of thermal possibilities during Cenozoic time, we have chosen four highly permissive time–temperature windows at 70 ± 10 Ma, 50 ± 10 Ma, 30 ± 10 Ma, and 10 ± 10 Ma, each with allowable temperatures of $60 \pm 60\,^{\circ}$C. The final constraint is the present day temperature of $10 \pm 10\,^{\circ}$C.

3.c. Modelled thermal histories

Representative best-fit thermal histories, along with the modelled and observed fission-track length

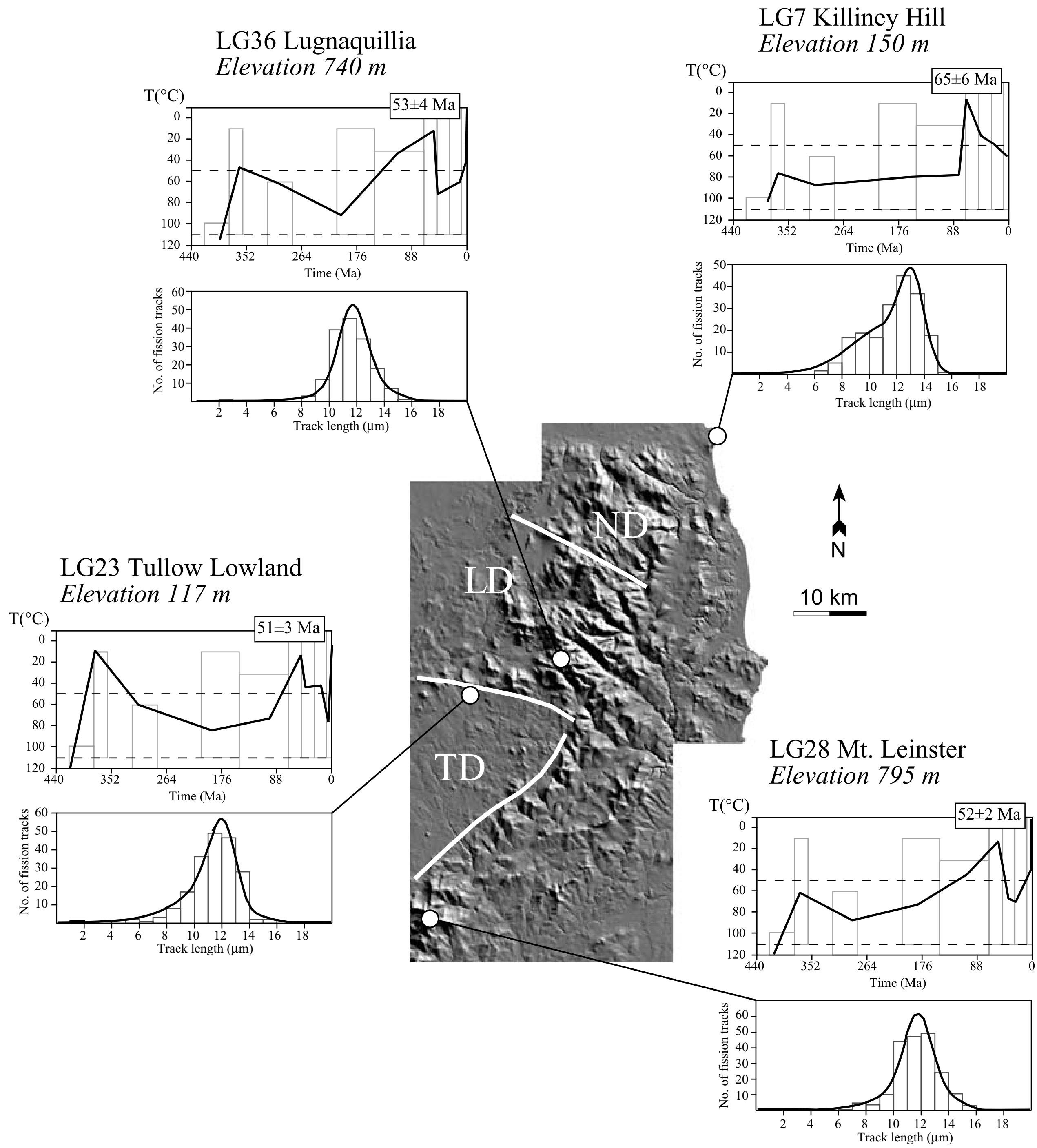

Figure 4. Optimal modelled thermal histories of representative apatite fission-track samples in each of the domains defined in Figure 3c. LD – Lugnaquillia Domain; ND – Northern Domain; TD – Tullow Domain. Numbers in boxes (e.g. 55 ± 4 Ma) denote timing of peak Paleogene cooling event. Note that, in all cases, samples experienced a long period of residence in the partial annealing zone, followed by Paleogene cooling. Post-early Eocene thermal histories differ, but all samples show mid-Cenozoic heating followed by relatively late cooling. Consistent thermal histories across the region suggest that present-day elevations were established late in the thermal history after Paleogene cooling.

distributions, are shown in Figure 4. The most striking result is the strong similarity in the temperature–time history between the samples, regardless of their location or present-day elevation. All of the samples show rapid cooling shortly after crystallization, followed by slow heating and a long period of residence in the partial annealing zone. This phase of partial annealing is followed in all cases by cooling to $<60\,^{\circ}$C during the Paleocene to early Eocene. Details of the later Cenozoic thermal histories differ between samples, but in all cases they show slight heating during late Paleogene or Neogene times to temperatures of $>60\,^{\circ}$C, followed by cooling to the present day. Overall, the thermal histories inferred here are broadly consistent with the findings of other regional apatite fission-track studies (e.g. Keeley *et al*. 1993; Green *et al*. 1999, 2000; Allen *et al*. 2002).

Based on the re-modelling of the apatite fission-track samples, it appears that the Wicklow and Blackstairs Mountains and the Tullow Lowland underwent a consistent thermal history up to, and including, an episode of cooling during the Palaeogene at $\sim 55 \pm 4$ Ma. Importantly, we see no evidence of strong differential denudation between samples in different domains. Thus, for example, sample LG23 from the Tullow Lowland has a similar thermal history to samples from Lugnaquillia (LG36) and Mt Leinster (LG28), despite elevation differences of 620 and 680 m, respectively (Fig. 4). If these elevation differences, and the low relief of the Tullow Lowland, were due to extensive and localized denudation (e.g. Davies, 1970), then we would expect to see cooling specific to the Tullow Lowland. Instead, the consistent thermal histories across the region suggest that both highland and lowland samples experienced the same thermal history at least until late Paleocene or early Eocene time. Thus, the present offsets in elevation–age profiles (e.g. Figure 3c) must be due, not to differential denudation, but to differential rock uplift that post-dates sample residence in the partial annealing zone, and which therefore must be post-early Eocene in age. Subtle heating variations of the apatite fission-track samples in Early Neogene time (Fig. 4, Table 1) may be due to differential localized isostatic effects arising from denudation of fault blocks but this is not resolvable using current apatite fission-track analysis techniques.

3.d. Summary of apatite fission-track results

Apatite fission-track samples from the Wicklow and Blackstairs Mountains and Tullow Lowland appear to record a fossilized partial annealing zone, and group into at least three distinct spatial domains. The broad similarity of modelled thermal histories across the region argues that present-day differences in elevation are due not to differential denudation but to differential rock uplift that occurred in post-early Eocene time, when temperatures cooled below 60 ± 10 °C. This differential movement may have been accommodated on specific faults, including the Lough Dan and Ow River faults, and/or the Baltinglass Escarpment, and the East Carlow deformation zone, which appear to bound blocks with internally consistent elevation–central age relationships. The magnitude of the displacements, as determined by offset of the central age–elevation profiles, ranges from ~ 300 m across the Lough Dan fault to ~ 600–700 m on the Ow River fault or the Baltinglass Escarpment. The consistent timing of Palaeogene cooling suggests that differential displacement must have begun sometime after approximately 50 Ma.

4. Geomorphic indicators of tectonic activity

The topography of a region reflects the time-integrated effects of both tectonic and climatic activity (Summerfield, 1994). If southeastern Ireland has been affected by differential rock uplift of up to several hundred metres in post-early Eocene time, as we suggest from the apatite fission-track analysis, then we expect some evidence of this deformation to be preserved in the landscape. To test for this, we analyse the spatial patterns of the two largest river systems draining the region: the rivers Slaney and Barrow (Fig. 1). Lacking appropriate Cenozoic sediments, we cannot use geomorphic observations to corroborate the timing of deformation in southeastern Ireland. We show, however, that the major rivers are out of equilibrium with the present topography in a manner that is consistent with the locations, magnitudes and kinematics of displacements inferred from the apatite fission-track analysis.

4.a. Rivers Slaney and Barrow

The River Slaney rises in the southwestern Wicklow Mountains and flows southeastwards across the Tullow Lowland and the Blackstairs Mountains (Fig. 1). The southeastern margin of the Tullow Lowland is bounded by a NE-trending escarpment with peak elevations of up to 400 m asl. The escarpment is divided into discrete hills by a number of SE-trending valleys (Farrington, 1927). However, only four of these valleys contain transverse rivers that flow southeastwards across the ridge: from northwest to southeast, they are the rivers Slaney, Barrow, Nore and Derry (Fig. 1). These four catchments cut directly across the topography and the underlying NE-striking Caledonian structural grain (Fig. 5). The remaining valleys are presently dry and form wind gaps (Fig. 5).

Across the Tullow Lowland, the River Slaney has incised less than 10 m into the landscape and has a moderate sinuosity, expressed as the ratio of thalweg to straight-line distance, of 1.36 (Fig. 5). About 7 km upstream of the escarpment, the course of the Slaney abruptly straightens, with a sinuosity of 1.02 over the next 8 km. Along this reach, incision increases to 50 m as the river crosses the escarpment. Downstream of the escarpment, sinuosity abruptly increases again to 1.37 over the next 10.5 km reach. On the southeastern side of the Blackstairs Mountains, sinuosity decreases to 1.17.

The River Barrow shows a similar increase in incision from 5 to 60 m as it flows south toward the Blackstairs Mountains, and has an equally abrupt increase in sinuosity as it flows across the axis of the Blackstairs Mountains (Fig. 6).

Davies (1970) suggested that the Slaney and Barrow might have originally flowed southeastwards across a widespread, low-relief surface, perhaps composed of

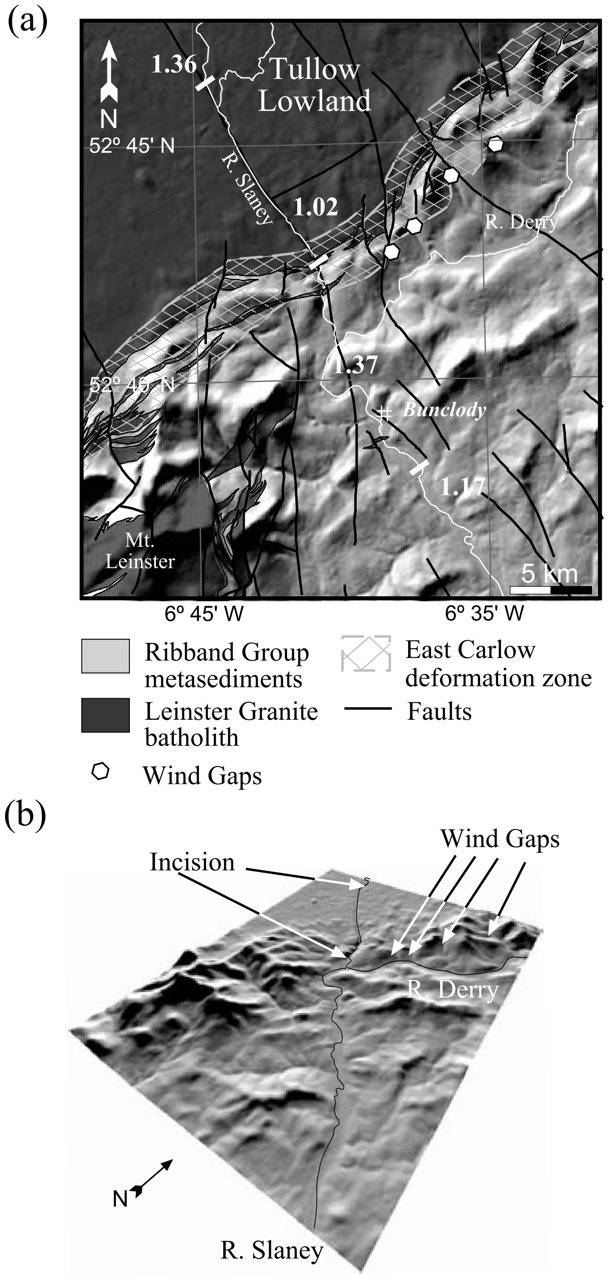

Figure 5. (a) Bedrock geology map of the Bunclody area (after Tietzsch-Tyler & Sleeman, 1994), overlain on shaded-relief image of topography; see Figure 1 for location. The hatched pattern shows extent of the East Carlow deformation zone as mapped by McArdle & Kennedy (1985). The River Slaney flows from northwest to southeast across the East Carlow deformation zone. Sinuosity of the River Slaney is shown for reaches upstream, within, and downstream of the Blackstairs Mountains; white bars show boundaries between reaches. White hexagons show the locations of dry valleys. (b) Perspective view of the same area, looking to the northwest. The River Slaney incises along the straight reach shown by the arrows.

Cretaceous chalk, and would have gradually incised into pre-Cretaceous basement rocks. This model, however, is contradicted by the continuity of the Leinster Granite batholith across the escarpment. Because the Leinster Granite batholith underlies both the Tullow Lowland and the highest peaks of the Blackstairs Mountains, it is difficult to call on erodibility as the source of the present topography. Davies' (1970) model also fails to account for abrupt changes in sinuosity along the rivers Slaney and Barrow and fails to explain why incision along both rivers begins several kilometres upstream of the escarpment in an area of low relief.

A more plausible explanation for the present topography and river pattern, one which accounts for the sinuosity and incision observations, is vertical displacement (southeast side up) along the southeastern margin of the Tullow Lowland, perhaps along the SE-dipping East Carlow deformation zone. We infer that displacement along the East Carlow deformation zone has beheaded smaller catchments, whose stream power was insufficient to keep pace with rock uplift through either incision or aggradation (cf. Burbank, Meigs & Brozovic, 1996; Humphrey & Konrad, 2000). Only the four largest catchments (the rivers Slaney, Barrow, Nore and Derry) possessed sufficient power to maintain their existing courses across the growing escarpment.

The changes in sinuosity and depth of incision along the Slaney are consistent with the response of an alluvial river to rock uplift. Energy slope is held approximately constant, and so river slope is increased upstream of the uplift axis through incision and a decrease in sinuosity. Conversely, river slope decreases, and sinuosity increases, downstream of the uplift axis (Ouchi, 1985; Schumm, 1986). The transition from straight to meandering behaviour along the Slaney, which should correspond to the rock uplift axis, occurs within the East Carlow deformation zone as mapped by McArdle & Kennedy (1985); however, the Slaney has incised along a ∼15 km reach upstream and downstream of this point (Fig. 5), suggesting that the river is responding to base-level change over a relatively broad region. Eustatic changes are incapable of producing this incision, as they cannot produce the wind-gaps observed throughout the Blackstairs Mountains along the trace of the East Carlow deformation zone. A eustatic mechanism also fails to explain why localized incision along the Slaney begins ∼7 km upstream of the Blackstairs Mountains, in the low-relief Tullow Lowland.

4.b. Southern Wicklow Mountains and the Baltinglass Escarpment

A steep, linear, WNW-trending escarpment, termed the Baltinglass Escarpment, separates bedrock of the southwestern Wicklow Mountains from that of the Tullow Lowland (Fig. 7). The escarpment forms a linear range of hills, and so its height is variable along strike, ranging from 150 to 250 m asl, but nowhere is the relief less than ∼50 m. At its westernmost end, the escarpment is roughly coincident with a complex contact between the Leinster Granite batholith to the

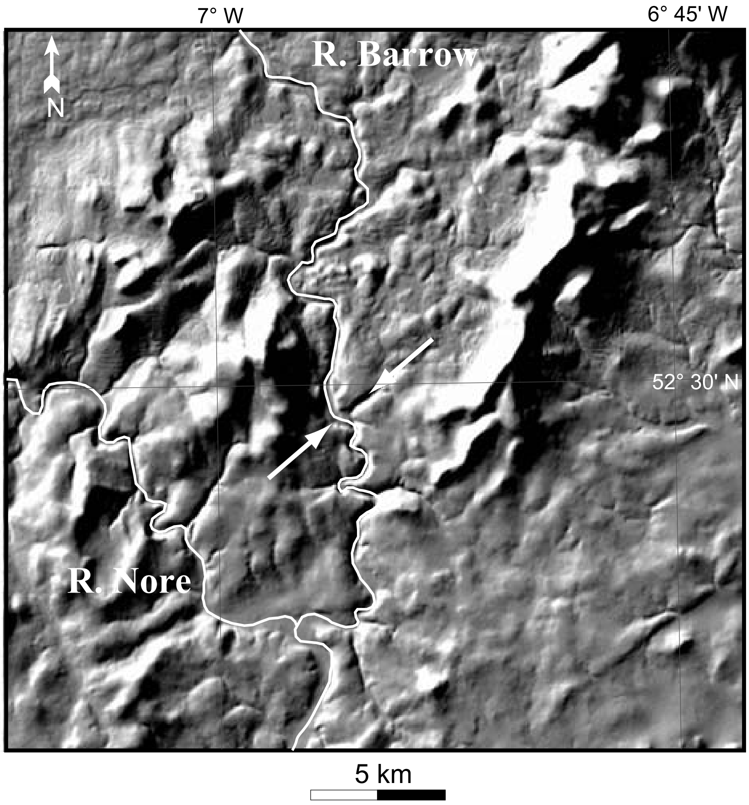

Figure 6. Shaded-relief image of topography in the southern Blackstairs Mountains. The rivers Nore and Barrow flow from north to south and cut directly across the axis of the Blackstairs Mountains. Paired white arrows mark the transition between straight and incised meandering reaches on the River Barrow.

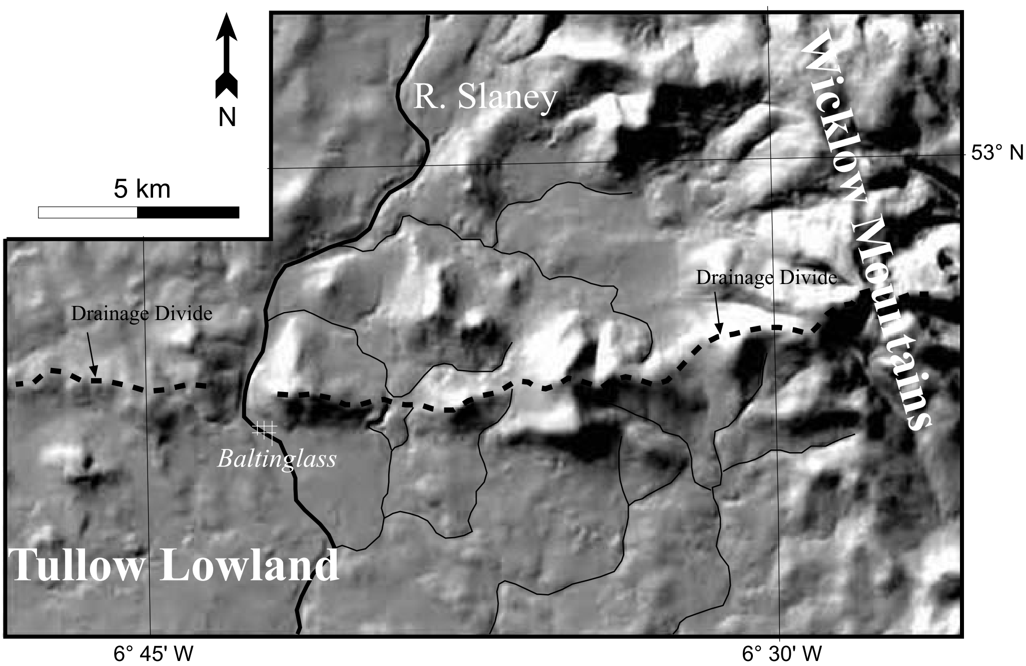

Figure 7. Shaded-relief image of topography in the southern Wicklow Mountains near Baltinglass. Heavy solid line shows the main stem of the River Slaney; flow is from north to south. Light solid lines show tributaries and minor streams. Dashed line is the drainage divide between north-flowing and south-flowing streams. Note that dip-slip motion has caused northward tilting of the region north of the escarpment, creating and maintaining a drainage divide very close to the fault. Short, southward draining streams have incised into the up-thrown block.

south, and Ordovician slate, schist and tuff to the north (Fig. 1b). The eastern 10 km of the escarpment lies entirely within the Leinster Granite batholith. North of the escarpment, relief between valley bottoms and adjacent ridge crests is commonly in excess of 300 m, whereas the greatest valley-to-ridge relief in the Tullow Lowland is less than 50 m.

Despite this strong contrast in elevation and relief, only one large river (the Slaney) flows from north to south across the escarpment (Fig. 7). East of the Slaney, a number of small, south-flowing catchments drain a narrow area immediately north of the escarpment. These catchments are typically incised 10 to 20 m into bedrock as they cross the escarpment; these deeply incised valleys are set into much larger valleys or gaps between hills. The drainage divide between north- and south-flowing catchments lies ~ 1 km north of the topographic escarpment.

The escarpment is only partly coincident with mapped lithological boundaries, and the main contrast in erodibility, between granitic rocks and Ordovician schist (Farrington, 1927), lies to the north of the escarpment. Thus a lithological origin of the escarpment seems unlikely.

Another possibility is that the escarpment is a palaeoseacliff. The base of the escarpment lies at an elevation of ~ 130 m asl along most of its length. However, coastal erosion processes are unlikely to give rise to a drainage divide in such close proximity to the escarpment and the Tullow Lowland displays landforms consistent with prolonged sub-aerial exposure and denudation (Boulter, 1980; Mitchell, 1980; Naylor, 1992).

Mitchell & Ryan (1997) suggested that the escarpment might be tectonic in origin based on its linearity, with a postulated vertical displacement of ~ 800 m. The geomorphic evidence outlined above supports this suggestion, and we thus interpret the escarpment as the surface expression of a previously unmapped fault (Fig. 7). The linear nature of the escarpment is also consistent with the typical morphology of range fronts defined by dip-slip faults. Dip-slip motion has caused northward tilting of the region north of the escarpment (e.g. Stein, King & Rundle, 1988), creating and maintaining a drainage divide very close to the fault. Short, southward-draining streams have incised into the upthrown Wicklow Mountains block, consistent with base-level fall along the escarpment. This suggests that the differential movement between the Lugnaquillia and Tullow domains implied by our apatite fission-track data may have mostly occurred on the Baltinglass Escarpment, rather than the Ow River fault, to account for the differences in elevation between apatite fission-track samples LG36, LG26 and LG23.

5. Discussion

We suggest, on the basis of apatite fission-track elevation–age relationships and thermal history modelling, that the Wicklow and Blackstairs Mountains region in southeastern Ireland can be divided into at least three spatial domains. Post-early Eocene differential vertical displacements of up to several hundred metres occurred between these domains. The boundaries between the domains correspond to recognizable topographic and geological structures, and geomorphic observations support both the inferred kinematics and magnitudes of the displacements on these structures. The lack of widespread Cenozoic sediments or depositional landforms, however, prevents us from refining the timing of deformation beyond post-late Paleocene time. Because of the age and inherited nature of some of the structures (e.g. the East Carlow deformation zone), along with the general difficulty of inverting strain for stress, any attempt to reconcile the inferred displacements with an overall state of stress would be highly speculative in isolation. The orientations and kinematics of post-early Eocene structures in southeastern Ireland, however, are consistent with known Cenozoic deformation observed

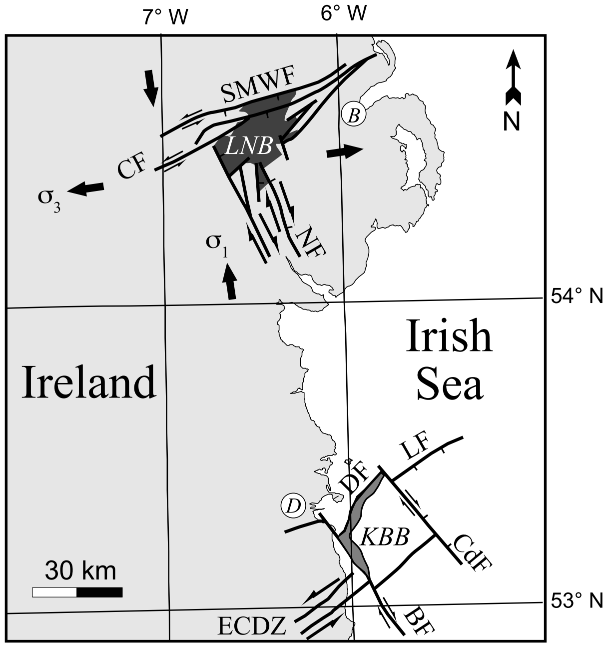

Figure 8. Summary map of tectonic model for eastern Ireland and the western Irish Sea, emphasizing structural correlations between the Kish Bank and Lough Neagh basins. Oligocene and post-Oligocene fill in the Lough Neagh Basin (LNB) is shown by dark grey shading. Liassic fill in Kish Bank Basin (KBB) is shown by medium grey shading. Note the similar orientation and kinematics of the Newry (NF) and Codling (CdF) faults. Also note that kinematics of faults in the Kish Bank region are compatible with the post-Oligocene fault displacements (black arrows) determined for the Lough Neagh region by I. Kerr (unpub. Ph.D. thesis, Queens Univ. Belfast, 1987) and Parnell, Shukla & Meighan (1988). Paired arrows show relative strike-slip displacement across faults; ticks on down-thrown blocks. B – Belfast City; BF – Bray fault; CF – Congo fault; D – Dublin City; DF – Dalkey fault; ECDZ – East Carlow deformation zone; LF – Lambay fault; SMWF – Six Mile Water fault.

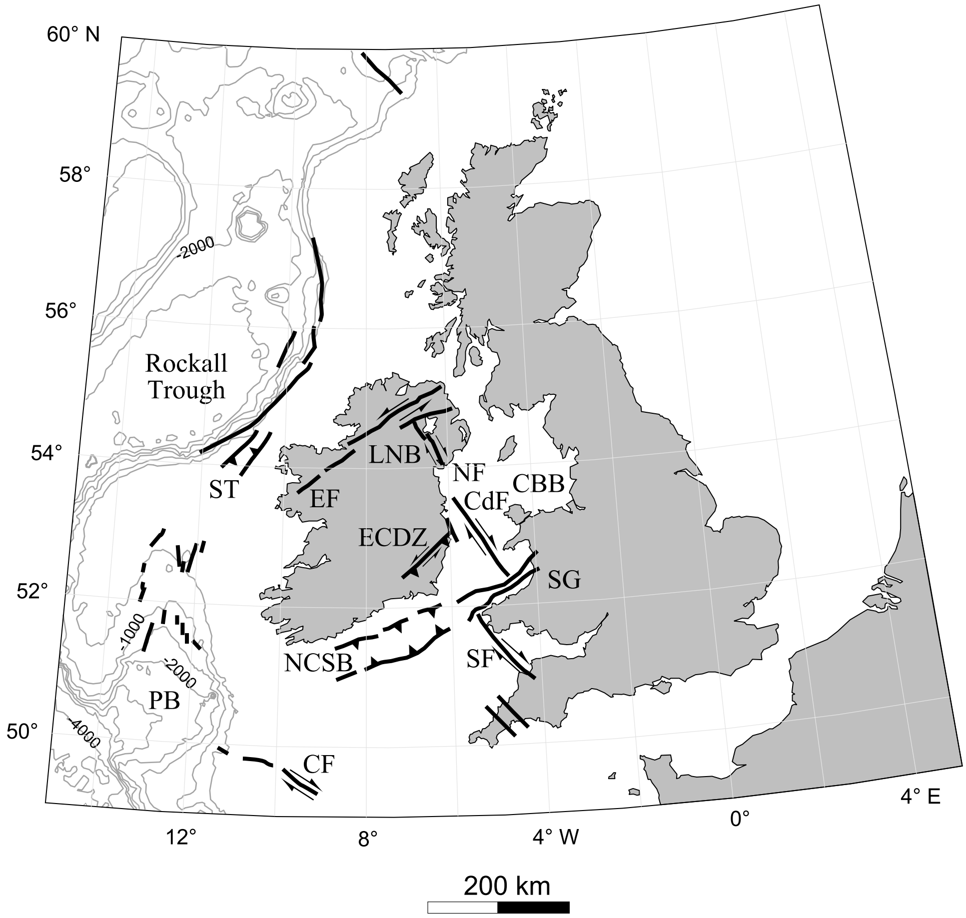

Figure 9. Regional structures active in post-early Eocene time. Solid black lines are structures with known Cenozoic displacements (see text for discussion and references). CBB – Cardigan Bay Basin; CF – Cockburn fault; CdF – Codling fault; ECDZ – East Carlow deformation zone; EF – Erriff fault; LNB – Lough Neagh Basin; NCSB – North Celtic Sea Basin; NF – Newry fault; PB – Porcupine Basin; SF – Sticklepath fault; SG – St George's fault; ST – Slyne Trough.

in northeastern Ireland and along the northwestern European continental margin. This is not surprising, given the small spatial scale of the Irish landmass and its proximity to a number of well-studied offshore basins.

In northeastern Ireland, early Cenozoic sinistral transtensional movement on the NE-trending Toe Valley, Six Mile and Congo faults, and dextral transtension on the NNW-trending Newry fault, resulted in the formation of pull-apart basins, including the Lough Neagh Basin (Fig. 8). These basins were filled with a thick sequence of Oligocene clays and lignites (George, 1967; Fletcher, 1977; Parnell, Shukla & Meighan, 1988; Naylor, 1992), and fault activity on the Newry fault is inferred to have continued into post-Oligocene time (Jenner, 1981; Parnell, Shukla & Meighan, 1988; Geoffroy, Bergerat & Angelier, 1996; Readman, O'Reilly & Murphy, 1997). The Newry fault has been extended south to join the Codling fault, which lies $\sim$30 km offshore to the east of the Dublin Basin and the Wicklow Mountains (Fig. 9). The Codling fault in turn has dextrally offset the Lambay and Dalkey faults by about 4 km during post-Liassic time (Jenner, 1981; Broughan, Naylor & Anstley, 1989; Naylor *et al.* 1993), and appears to have been active into the Late Cenozoic (Corcoran & Clayton, 1999; Dunford, Dancer & Long, 2001). The correlation between the Newry and Codling faults is consistent with models of Cenozoic dextral shear on NW-trending faults in southwestern England and Cardigan Bay (Turner, 1997), including the Neogene dextral-reverse Sticklepath fault (Fig. 9; Bristow & Hughes, 1971).

Our inferred displacements are also consistent with Cenozoic deformation observed in a number of offshore basins. These include (1) post-Oligocene inversion of the North Celtic Sea Basin (Murdoch, Musgrove & Perry, 1995) and the Slyne Trough (Scotchman & Thomas, 1995); (2) post-mid-Miocene deformation in the Porcupine Basin (Tate, 1993; McCann, Shannon & Moore, 1995); (3) late Eocene to mid-Oligocene folding and sinistral deformation at the eastern margin of the Rockall Trough (C. Solla-Hach, unpub. Ph.D. thesis, Univ. Dublin, 2002); and (6) Late Palaeogene and Early Neogene inversion of the Cockburn Basin (Smith, 1995).

In addition, a number of workers have documented significant Neogene sedimentation and tectonic activity (e.g. Stoker, 1997; Japsen, Boldreel & Chalmers, 1998) along portions of the northwestern European continental margin, much of was summarized by Japsen (1997) and Doré *et al.* (1999). Previous regional apatite fission-track studies have consistently shown evidence for a mid-Cenozoic cooling event, beginning ~ 30 Ma and involving > 1 km of inferred denudation (Lewis *et al.* 1992; Green *et al.* 1993, 1999; Rohrman *et al.* 1995). Compaction studies and burial estimates give rise to similar magnitudes of Cenozoic denudation (e.g. Bulat & Stoker, 1987; Murdoch, Musgrove & Perry, 1995; Japsen, 1997).

The mechanisms driving this late activity are enigmatic. Vågnes & Amundsen (1993) called on secondary mantle convection and underplating. Rohrman & van der Beek (1996) invoked asthenospheric diapirism resulting from a Rayleigh-Taylor instability, arguing that the initiation of Neogene tectonic and magmatic activity coincided with the imposition of hot Iceland plume asthenosphere beneath the margin of the European continental lithosphere at ~ 30 Ma. Rohrman & van der Beek (1996) indicated that the northern UK and Ireland should be underlain by an asthenospheric diapir, potentially causing both transient and permanent tectonic rock uplift. Dewey (2000) concluded that northwestern Europe was caught in the jaws of a compressional vice, from 22 to 9 Ma, created by strong convergence between Africa and Europe and North Atlantic ridge push forces.

This diapirism, combined with ridge-derived and African compressional intra-plate stresses, may well provide the impetus for the displacements we observe. Given typical rates of denudational processes (e.g. Summerfield, 1994) and the likely adjustment timescales of Irish rivers, this tectonic and erosional activity should be reflected in the modern Irish landscape. This implies widespread denudation and possible rock uplift within the region during post-Paleocene time, consistent with our inference of tectonic activity in and around Ireland during this period.

6. Conclusions

(1) Relationships between apatite fission-track central age and elevation for Leinster Granite samples in the Wicklow and Blackstairs Mountains and Tullow Lowland, southeastern Ireland, lead us to suggest that these areas can be divided into at least three discrete structural domains. Each domain shows evidence for an exhumed apatite partial annealing zone.

(2) The domains preserve evidence for an exhumed partial annealing zone that is vertically offset across domain boundaries by up to several hundred metres, and these boundaries appear to be coincident with known crustal-scale faults or topographic escarpments.

(3) Thermal modelling of samples along a transect across southeastern Ireland shows that all samples experienced remarkably similar thermal histories up to and including a cooling event in late Paleocene or early Eocene time. Thus, the differential rock uplift that led to dismemberment of the partial annealing zone must post-date this cooling event.

(4) Geomorphic analysis of the East Carlow deformation zone and the Baltinglass Escarpment, both of which bound the Tullow Domain, shows that spatial patterns of catchment incision and sinuosity, as well as the presence of antecedent drainage, are best explained by differential vertical displacements at or near the domain boundaries. The kinematics and magnitudes of these displacements are consistent with those implied by the apatite fission-track results.

(5) The kinematics and magnitudes of displacement on the East Carlow deformation zone and the Baltinglass Escarpment are compatible with observed deformation on known Cenozoic structures in northeastern Ireland, the adjacent offshore basins, and other parts of the northwestern European continental margin.

(6) The geodynamics driving displacements during the Neogene may be attributed to plume diapirism, ridge-derived intra-plate stresses and convergence between Africa and Europe from ~ 30 Ma.

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