Palaeogene Alpine tectonics and Icelandic plume-related magmatism and deformation in Northern Ireland

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The Cenozoic tectonic history of NW Europe is generally attributed to some combination of three principal controlling factors: North Atlantic opening, Alpine collision and formation of the Icelandic mantle plume. Using constraints from the high resolution Tellus aeromagnetic survey of Northern Ireland, we show that Palaeogene tectonics can be attributed to approximately N-S Alpine-related compression, forming NNW-trending dextral and ENE-trending sinistral conjugate faults, with the latter defined by kilometre-scale displacements along reactivated Caledonian/Carboniferous faults. This tectonism was, however, punctuated by pulsed magmatic intrusive and extrusive events, including four distinct dyke swarms which are attributed to NE-SW to E-W directed plume-related extension. Whilst this evidence shows, for the first time, that N-S Alpine compression was periodically overwhelmed by the dynamic stresses and uplift associated with pulsed mantle plume-related deformation, associated strike-slip faulting may have controlled the locus of

volcanic activity and central igneous complexes, and the location of sedimentary depocentres.

During the Late Cretaceous and Palaeogene, the Iceland Plume or 'hot spot' was centred under Greenland and was responsible for magmatism that extended over an area in excess of 2000 km in diameter, within what is referred to as the North Atlantic Igneous Province ((Fig. 1a; White 1989). Crustal doming caused by the rising of this thermal plume is believed to have driven and accommodated the development of intrusive and extrusive complexes between 62 and 55 Ma (Brodie & White 1994; Jones *et al.* 2002; White and McKenzie 1989), and was ultimately followed by opening of the North Atlantic Ocean at about 55 Ma (Ritchie *et al.* 1999). Although rifting between Greenland and Northern Europe was caused by NW-SE extension (Doré *et al.* 1999), earlier basic dykes within the United Kingdom and Ireland are generally WNW to NNW trending, subscribing to an approximately radial pattern relative to the Iceland plume and defining two main swarms of olivine basalt or dolerite dykes which are best exposed in SW Scotland and Northern Ireland (Cooper and Johnston 2004b; Gibson and Lyle 1993; Preston 1967; Preston 2001) (Fig. 1). Dyke intrusion in Northern Ireland took place throughout the Palaeocene, overlapping spatially and temporally with the Antrim Lava Group, a *c.* 1 km thick sequence of flood basalts extruded between 61 and 58 Ma (Cooper 2004 and references therein; Preston 2001), and the younger central igneous complexes of Slieve Gullion and the Mourne Mountains which were formed between 57 and 55 Ma (Gamble *et al.* 1999; Geological Survey of Northern Ireland 1997).

Whilst studies of Palaeocene magmatism in Britain and Ireland highlight the importance of plume-related deformation, the tectonics of the British Isles is generally attributed to N-S Alpine compression, with associated deformation possibly waning during the Palaeocene, either side of major phases of compression in the Late Cretaceous and Neogene (Hillis *et al.* 2008; Nielsen *et al.* 2007). This deformation usually takes the form of inversion along earlier NE- through to SE-trending faults (Hillis *et al.* 2008), particularly in the south of England, and movement along NNW-trending dextral strike-slip faults. The latter includes the Codling Fault, mapped from Irish Sea seismic data (British Geological Survey 2009; Croker 1995; Dunford *et al.* 2001; Izatt *et al.* 2001; Judd *et al.* 2007), and its probable onshore extension in

Northern Ireland, the Newry Fault (Fig. 1b). Recent work has suggested that kilometre-scale displacement along the Newry Fault is transferred via a pull-apart basin located under Lough Neagh, onto the similarly oriented Loughguile Fault located to the north-east (Fig. 1b; Quinn 2006). The associated pull-apart is filled with over 400 m of Oligocene sediments, but thickening of the older Antrim Lava Group sequences close to Lough Neagh also suggests the existence of the pull-apart back into Palaeocene times (Quinn 2006).

Here we present the results of an interpretation of high resolution aeromagnetic imagery from the Tellus survey of Northern Ireland. This dataset distinguishes four distinct dyke swarms, which together with the known extrusive history of the Antrim Lava Group and intrusive history of the central igneous complexes, supports the concept that Palaeocene plume activity was pulsed Differential displacement of the dyke swarms and central igneous complexes by both sinistral and dextral strike-slip faults indicates, for the first time, that N-S Alpine compression, of Palaeocene through to Oligocene age, temporally overlapped with plume-related intrusions.

Tellus dataset

The Tellus regional airborne geophysical survey of Northern Ireland (Fig. 2) was flown during the summers of 2005 and 2006 by the Joint Airborne-geoscience Capability, a partnership of the British Geological Survey and the Geological Survey of Finland. The aircraft, a De Havilland Twin Otter, was equipped with two magnetometer sensors, an electrical conductivity mapping system and a gamma-ray spectrometer. Survey lines, 200m apart, were orientated at 345° or 165°. The terrain clearance was a nominal 56 m in rural areas, rising to 240 m over urban and other build up areas. The magnetometers were sampled at 0.1 s intervals, equivalent to approximately 7 m. Data were gridded onto a 50 x 50 m net and a variety of processing techniques were applied to improve the resolution of linear features.

Dyke and fault mapping

Apart from the prominent anomalies associated with the distribution of Palaeocene basalt lavas and central igneous complexes (Fig. 2), the most striking features highlighted by the Northern Ireland aeromagnetic data are the numerous dykes and associated swarms. The data therefore provide an excellent means of mapping dykes, which from outcrop studies have sub-vertical dips and generally have thicknesses of

1-10 m, although there are mega-dykes, particularly in the western part of Northern Ireland, which can be up to 100 m wide (Cooper and Johnston 2004b; Gibson *et al.* 2009; Gibson and Lyle 1993; Preston 1967). The aeromagnetic data also show that many of the dykes are clearly offset by ENE-trending sinistral strike-slip faults (Fig. 3 & 4), the most significant of which are the Tempo-Sixmilecross Fault and the Omagh Fault (sometimes referred to as the Omagh Thrust, because of evidence for Early and/or Late Palaeozoic reverse displacement; Cooper and Johnston 2004a; Mitchell 2004a). These faults accommodate km-scale lateral displacements and, together with other key geological relationships (described below), provide a basis for defining the relative ages of the dyke swarms on the premise that older dykes will have larger displacements than younger dykes (details of fault kinematics are discussed later). Despite the associated temporal overlap between dyke swarms and faulting there is no aeromagnetic evidence for dyke intrusions along these faults.

The following key geological characteristics or relationships have provided a basis for defining the four main dyke swarms and their relative chronology (Fig.5).

(i) Spatial orientation, distribution and character: Each of the dyke swarms has a well defined orientation and occupies a fairly well defined tract with dyke spacing increasing either side of the central swarm. The character of dykes on aeromagnetic data gives some indication of thickness, on the basis of magnetic response and continuity.

(ii) Magnetisation direction: Field occurrences show that many dykes are not single but composite events, i.e. recording multiple injections of magma through time (Cooper and Johnston 2004b). Composite dykes can contain both normal and reverse magnetised rock, but it is the dominant of these which determines the magnetic response seen in the imagery and its interpretation. If the proportion of normal to reverse magnetised rock varies along the length of a dyke its polarity will change from one to the other (as is seen in the Erne dyke swarm (Figs. 2, 3 & 4a)). Local scale observations may reveal magnetic complexity, but at a regional scale of observation the dominant magnetic responses prevail and so the gross differentiation of swarms is considered robust.

(iii) This criterion arises from the premise that dyke swarms offset by different amounts of strike-slip displacement must have different ages, with the oldest swarm, and its associated dykes, having the largest displacement and recording more of the displacement history of a given fault. Whilst the average displacements of dyke swarms across different faults are consistent with no temporal overlap between dyke swarms, there is some variability in the precise displacements of individual dykes within a swarm. This variability is partly attributed to the fact that individual dykes cross-cutting earlier faults may have been characterised by intrusion-related stepping across these structures, and to the possibility that dykes within a given swarm may not have exactly the same age (see below).

(iv) Relationship to other intrusive or extrusive igneous bodies or sequences. Three of the dyke swarms have differing cross-cutting relationships with the Antrim Lava Group, providing a means of defining their relative ages: the remaining dyke swarm does not occur in the vicinity of the Antrim Lava Group.

These criteria have permitted the identification of four dyke swarms, the principal characteristics of which are briefly described. Two distinct swarms occur in the western part of Northern Ireland. The oldest of these, the Erne dyke swarm is concentrated in the west, while the eponymous Donegal-Kingscourt dyke swarm extends for *c.*120km across the study area.

1) The Erne dyke swarm (green and orange on Fig. 3 & 4a), a newly defined swarm, strikes mainly WNW-ESE and, based on field observations and the strength of their magnetic responses, comprises dykes which are generally thicker (up to 100m wide), more widely spaced and fewer in number than the three younger swarms. The dykes are mostly reversely magnetised (green), but in places show normal polarity (orange) along their length (Gibson *et al.* 2009). Dykes of the Erne swarm are sinistrally offset across the Tempo-Sixmilecross Fault by between 1.5 km and 2.3 km (Fig. 3 & 4a), the largest displacement of any dyke swarm across any fault in the study area.

2) The Donegal - Kingscourt dyke swarm (blue on Fig. 3 & 4b) comprises dykes that trend predominantly NW-SE and its existence was previously established from earlier studies (Cooper and Johnston 2004; Gibson and Lyle 1993; Preston 1967). Spacing between dykes increases gradually away from the axis of the swarm, all the dykes are reversely magnetised (Fig.3 & 4b) and are sinistrally offset across the Tempo-Sixmilecross Fault by between 1.0 km and 1.5 km. Whilst this indicates that the Donegal-Kingscourt dykes were intruded after those of the Erne swarm, dykes from both swarms have similar offsets across the Omagh Fault (i.e. 300m to 600m), a

feature which suggests that the fault must post-date the swarms. Aeromagnetic data also indicate that dykes of this swarm are unconformably overlain by basalt lava flows of the Antrim Lava Group along the western edge of their outcrop, a relationship which suggests that they are older than the earliest lava flows of the Lower Basalt Formation (> *c*. 61 Ma); this unconformity is exposed within Carmean Quarry, Moneymore (10km west of Lough Neagh), where it cross-cuts a Donegal-Kingscourt dyke and is overlain by Antrim Lava Group basalts. Examination of the lateral offsets of dykes across different faults suggests that differences in the displacements of dykes may not simply arise from intrusive stepping across faults (point iii above), but could also reflect the presence of multiple pulses within this dyke swarm; this possibility is the subject of ongoing research.

The two younger dyke swarms, mainly occupying the eastern side of Northern Ireland, together used to be referred to as the St. John's Point-Lisburn dyke swarm (Cooper and Johnston 2004). On the basis of stratigraphic constraints and magnetisation, we have now attributed some of the dykes to an older swarm called the Ardglass - Ballycastle dyke swarm.

3) The Ardglass-Ballycastle dyke swarm (purple on Fig. 3), comprises dykes with a trend that varies from NNW to WNW and are thinner than those of the western swarms. The dykes are all reversely magnetised and intrude the Lower Basalt Formation of the Antrim Lava Group but do not appear to cut the Upper Basalt Formation, which constrains their age to between *c*. 60.5 and 59 Ma, a timing which agrees with the geomagnetic polarity timescale of Cande & Kent (1995) (Fig. 5).

4) The St. John's Point - Lisburn dyke swarm (red on Fig. 3) comprises mainly NNW-trending dykes that occur in two geographically distinct clusters (labelled a and b on Fig. 3). Dykes of this swarm appear to intrude both the Lower Basalt and Upper Basalt formations of the Antrim Lava Group and are thus younger than *c*. 58 Ma. In the early Palaeogene, two periods of normal magnetisation, one slightly younger than 58 Ma and one close to 56 Ma (Fig.5), are indicated by Cande & Kent (1995), and because dykes of the St. John's Point - Lisburn swarm are mostly truncated by granite intrusions of the Mourne Mountains Complex (~ 56 - 55 Ma), this swarm could have been emplaced at either time. Based on their lower magnetic response, normal magnetisation, narrower dimension and relatively poor continuity, dykes of the Ardglass - Ballycastle and St. Johns Point - Lisburn dyke swarms are easily distinguished from other swarms.

Whilst the spatial distributions, clustering, magnetic polarity and temporal relationships permit the identification of four main dyke swarms from the existing Tellus dataset, we think it is likely that some mappable dykes are, in fact, associated with more subordinate dyke swarms which we cannot yet distinguish, on both spatial and temporal grounds. This problem may be a particular issue in the SE of Northern Ireland, where different dyke swarms have similar orientations. It is likely, for example, that subordinate younger dykes, or swarms, may be coeval with, or post-date, adjacent igneous complexes. The existence of other dykes or swarms does not affect the overall findings of this study.

Multiple dyke swarms - summary

Four main dyke swarms have been defined on the basis of their spatial characteristics, magnetisation direction, fault offsets and relationship to other intrusive/extrusive bodies or sequences (Figs 3 & 5). The newly identified Erne dyke swarm (Fig. 3 & 4a) is the oldest and comprises predominantly WNW-trending dykes which are offset by up to 2.3 km by the Tempo-Sixmilecross Fault. The previously recognised NW-trending Donegal-Kingscourt dyke swarm (Fig. 3 & 4b), which extends across onshore Ireland, is the next youngest, with individual dykes offset sinistrally across the Tempo-Sixmilecross Fault by 1.0-1.5 km. The occurrence of an unconformity visible on Tellus (Figs 2 & 3), and in the field, between dykes of the Donegal Kingscourt swarm and the Antrim Lava Group basalts is strong evidence supporting the relatively older ages of this and the Erne dyke swarms. The newly identified Ardglass-Ballycastle dyke swarm (Fig. 3), comprises generally NNW-trending dykes which appear to intrude the Lower Basalt Formation of the Antrim Lava Group, whilst the previously established St. John's Point-Lisburn dyke swarm (Fig. 3) comprises NNW-trending dykes which intrude both the Lower Basalt and Upper Basalt formations of the Antrim Lava Group. The Erne dyke swarm generally comprises dykes which are thicker (up to 100 m), more widely spaced and fewer in number than those of the three younger dyke swarms, which each show a gradual increase in dyke spacing away from the axis of the swarm. The proposed timing of each of these dyke swarms can be linked to the geomagnetic polarity timescale of Cande & Kent (1995) (Fig. 5), and although there may be some uncertainty in the exact ages of individual intrusive or extrusive bodies or sequences, their relative ages are robust. Whatever the precise timing, the identification of chronologically distinct dyke swarms indicates that magmatism accompanied separate episodes of extension, melt production and intrusion, the implications of which are considered later.

Strike-slip faulting

The lateral offset of vertical Palaeocene dykes provides, for the first time in Ireland, irrefutable evidence of Palaeogene, kilometre-scale sinistral strike-slip displacements on ENE-striking faults, with the Tempo-Sixmilecross and Omagh faults accommodating up to 2.3 km and 0.65 km displacement respectively (Fig. 3 & 4). Both faults are known to have accommodated kilometre-scale normal displacements during Lower Carboniferous rifting (Mitchell and Owens 1990; Worthington and Walsh, in press), while the eastward lateral continuation of the Omagh Fault, the Tow Valley Fault, is interpreted to have been active in the Permo-Triassic through to the Oligocene (Geoffroy *et al.* 1996; Mitchell 2004b; Parnell *et al.* 1989). This study confirms the sense of displacement that was previously suggested from the presence of small Oligocene pull-apart basins associated with two sinistral releasing bends along the Tow Valley Fault (Mitchell 2004b; Parnell *et al.* 1989). The accommodation of such large displacements, so strongly localised onto two faults, is attributed to their reactivated nature. Other pre-Tertiary, mainly Lower Carboniferous, faults exist (Mitchell and Owens 1990; Worthington and Walsh, in press), but their Palaeogene displacements (< 100 m) are much less than the calculated strike-slip displacement on the Tempo-Sixmilecross and Omagh faults. Furthermore, dyke offsets highlight the onset of Palaeocene reactivation of the Tempo-Sixmilecross Fault, with up to 1 km displacement of the Erne dyke swarm accommodated prior to the emplacement of the Donegal-Kingscourt dyke swarm. Offsets of dyke swarms synchronous with the extrusion of the Antrim Lava Group are not clear, however, suggesting that much of the displacement on the Tempo-Sixmilecross Fault may have occurred prior to *c.*61 Ma. In contrast, the Omagh Fault appears to have been reactivated after the intrusion of both the Donegal-Kingscourt and the Erne dyke swarms (i.e. both dyke swarms are offset by the same amount of displacement, up to ca. 0.65km; Fig. 4), with a significant proportion of its displacement (at least 30%) accumulating after the extrusion of basalts of the Antrim Lava Group (Mitchell 2004b). Whilst 100 m scale post-Antrim Lava Group displacements on the Tempo-Sixmilecross Fault cannot be ruled out, it appears that the locus of activity moved northwards from the Tempo-Sixmilecross Fault onto the Omagh-Tow Valley Fault system, with *c.*200 m of post-

Antrim Lava Group strike-slip accompanied by up to 400 m of dip-slip displacement associated with the Oligocene pull-apart basins (Mitchell 2004; Parnell *et al.* 1989). Evidence of Palaeogene sinistral reactivation of pre-existing NE-striking faults has been diagnosed elsewhere in Britain and Ireland (Bevins *et al.* 1996, 1997; Cunningham *et al.* 2003; Maddock *et al.* 2007; Turner 1997; Williams *et al*. 2005), but these indicators are either somewhat controversial or indirect compared to the excellent constraints provided by the Tellus dataset. Our study does, however, provide strong support for a paper suggesting substantial sinistral displacements of Tertiary dykes across the Menai Strait Fault System (and the Berw and Aber Dinlle Faults, in particular; Fig.1b) from much poorer quality magnetic data, an interpretation which was criticized at the time (Bevins *et al.* 1996, 1997; Maddock *et al*. 1997). Evidence for Palaeocene-Oligocene sinistral strike-slip movement along ENE-striking faults is not, however, consistent with a recently advanced model involving a major phase of Eocene-Oligocene normal faulting, with up to 1km scale dip-slip displacements, derived from an analysis of E-W and ENE-striking faults in the west of Ireland (Dewey 2000). Instead, we concur with a recent study suggesting that such large dip-slip displacements are attributable mainly to an earlier phase of Lower Carboniferous faulting (Worthington and Walsh, in press), sometimes compounded by often localised Cenozoic vertical displacements (generally less than ca 100m, apart from within the Lough Neagh Basin and along the Tow Valley Fault; George 1967) associated with predominantly strike-slip fault reactivation in Palaeocene-Oligocene times.

In common with earlier work, the Tellus aeromagnetic data also highlight the presence of kilometre-scale dextral offsets of the Late Palaeozoic Newry Igneous Complex by the Newry Fault, and of the Slieve Gullion Igneous Complex by the Camlough Fault ((Fig. 3; Geological Survey of Northern Ireland 1997), which are together considered to be north-northwesterly extensions of the Codling Fault in the mid-Irish Sea (British Geological Survey 2009), and to be related to the Sticklepath dextral strike-slip fault in SW England (Dunford *et al.* 2001; Ruffell and Carey 2001). Whilst a total offset of 2.4 and 2.0 km of the Newry Igneous Complex and the Slieve Gullion Complex can be measured on the Newry Fault and Camlough Fault respectively, offsets of sometimes sub-parallel dykes along these faults are more difficult to measure and may even be smaller (Fig.3). A protracted Palaeocene-Oligocene history of dextral displacement on the Newry Fault is supported by the greater displacement of the margin of the Newry Igneous Complex compared to those of the younger dyke swarms, though a more precise measure of Tertiary fault growth must await further studies. Since offshore seismic data has failed to highlight any evidence of pre-Tertiary across-fault sequence thickness changes associated with NNW-striking dextral faults, such as the Codling Fault, they may be newly formed, rather than reactivated, structures.

The identification of equivalent strike-slip faults is much more difficult elsewhere in Ireland, where Palaeogene sequences are not exposed and equivalent geophysical data are unavailable. NNW-striking dextral strike-slip faults interpreted to be of Palaeogene age have, however, recently been identified within Zn-Pb mines in Central Ireland (Carboni *et al.* 2003; Fusciardi *et al.* 2004). Whatever the details of fault growth history, it is nevertheless clear that movement occurred on both sinistral and dextral strike-slip faults in Palaeogene times, from the Palaeocene through to the Oligocene. We suggest that together these faults form conjugate sets consistent with N-S Alpine compression, an origin which, given the difficulty of establishing Palaeogene sinistral displacement along pre-existing NE-SW striking faults, was previously principally applied to dextral strike-slip faults, with sinistral faulting being of subordinate nature and bounded by the pre-eminent dextral structures (Cunningham *et al.* 2003, 2004; Williams *et al.* 2005; Quinn 2006). What the Tellus aeromagnetic data demonstrates is that km-scale displacements are characteristic of both sinistral and dextral strike-slip faults, which therefore together constitute a conjugate system arising from the reactivation of older faults, in one case, and possibly from the formation of new faults in the other. The fact that the location of the maximum thickness of basalt lavas of the Palaeocene Antrim Lava Group and of sediments of the Oligocene Lough Neagh Group coincides with the intersection zone of the principal conjugate strike-slip faults, suggests that faulting may have played an important role in the magmatic and sedimentary evolution of the region from Palaeocene through to at least Oligocene times (Quinn 2006). Testing of this hypothesis must await improved definition of the relative timing of fault movements and basin evolution. Existing constraints in Northern Ireland suggest that fault activity and related Alpine compression occurred in the early Palaeocene, between the intrusion of the Erne dyke swarm and the Donegal-Kingscourt dyke swarm, and in the Oligocene. Faulting may have progressed over the intervening period, but it is also possible that there was a temporary cessation of fault activity for much of this period, a suggestion which would be consistent with some plate reconstructions of Alpine convergence (e.g. Rosenbaum *et al.* 2002).

Discussion

High resolution aeromagnetic data from the Tellus project provides excellent definition of four Palaeocene dyke swarms in Northern Ireland. A variety of criteria have been used to identify the extent and internal components of the dyke swarms which are both spatially and temporally distinct. The WNW to NNW trends of individual dyke swarms cannot be reconciled with the slightly later North Atlantic opening and are, instead, attributed to crustal doming and deformation related to the ascent of the Icelandic mantle plume. The principal dyke orientations are most easily attributed to approximately NE-SW stretching arising from plume-related radial dyking complicated by localised variant dyke patterns associated with separate igneous complexes (England 1988). A recent study has suggested, however, that early Palaeocene igneous activity of the North Atlantic Igneous Province could arise from an early phase of North Atlantic breakup arising from weak NE-SW rifting, in which plate break-up was probably enhanced by the Palaeocene phase of Alpine collision (Lundin and Dore 2005). Whilst our study indicates that dyke opening and Alpine deformation may overlap in time, associated stresses are not mutually enhancing and we favour the pre-eminent plume-related models. Nevertheless, the principal conclusions of our study could still be reconciled with a pulsed plate break-up model. The significance of an apparent clockwise rotation of dyke swarms with time is unclear, but may reflect a progressive change in plume- or intrusion-related dynamic stresses, or a systematic change in stress orientations towards the NW-SE rifting of the later phase of North Atlantic breakup described by Lundin and Dore (2005).

The identification of four chronologically distinct dyke swarms indicates that magmatism took place as a series of distinct pulses of melt production and intrusion. The timing of these intrusive phases and their punctuated nature is consistent with the pulsed mantle plume activity previously diagnosed from the deposition of offshore submarine fans and tuffs within the UK North Sea (White and Lovell 1997) (Fig. 5). Plume-related periods of uplift and erosion, linked to submarine fan deposition, are supported by direct evidence of pulsed dyke swarms, at least two of which are associated in Northern Ireland with the base, and the boundary between the lower and upper sequences, of the laterally extensive basalt lava flows of the Antrim Lava Group. The activity of contemporaneous conjugate sinistral and dextral strike-slip faults with km-scale displacements arising from approximately N-S Alpine compression may at first appear to conflict with the main orientations of dyke swarms. The pulsed nature of these swarms provides, however, a rationale for their formation in a tectonic regime which was otherwise characterised by Alpine-related deformation at least during the early Palaeocene and the Oligocene, with pulsed plume-related dynamic stresses and related deformation temporarily overwhelming the background far-field tectonic stresses and strain. The operation of both influences nevertheless supports the model that strike-slip faulting could be partly responsible for the localisation of Palaeocene volcanic activity and of Oligocene sedimentary depocentres (Quinn 2006).

Conclusions

Using constraints from the high resolution Tellus aeromagnetic survey of Northern Ireland, we show that Palaeogene tectonics can be attributed to approximately N-S Alpine-related compression, forming NNW-trending dextral and ENE-trending sinistral conjugate faults, with up to kilometre-scale displacements accommodated on either newly formed or reactivated Caledonian/Carboniferous faults, respectively. This tectonism was, however, punctuated by pulsed magmatic intrusive and extrusive events, including four distinct dyke swarms which are attributed to NE-SW to E-W directed plume-related extension. Strike-slip faulting may have controlled the locus of volcanic activity and central igneous complexes, and the location of sedimentary depocentres.

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FIGURE CAPTIONS

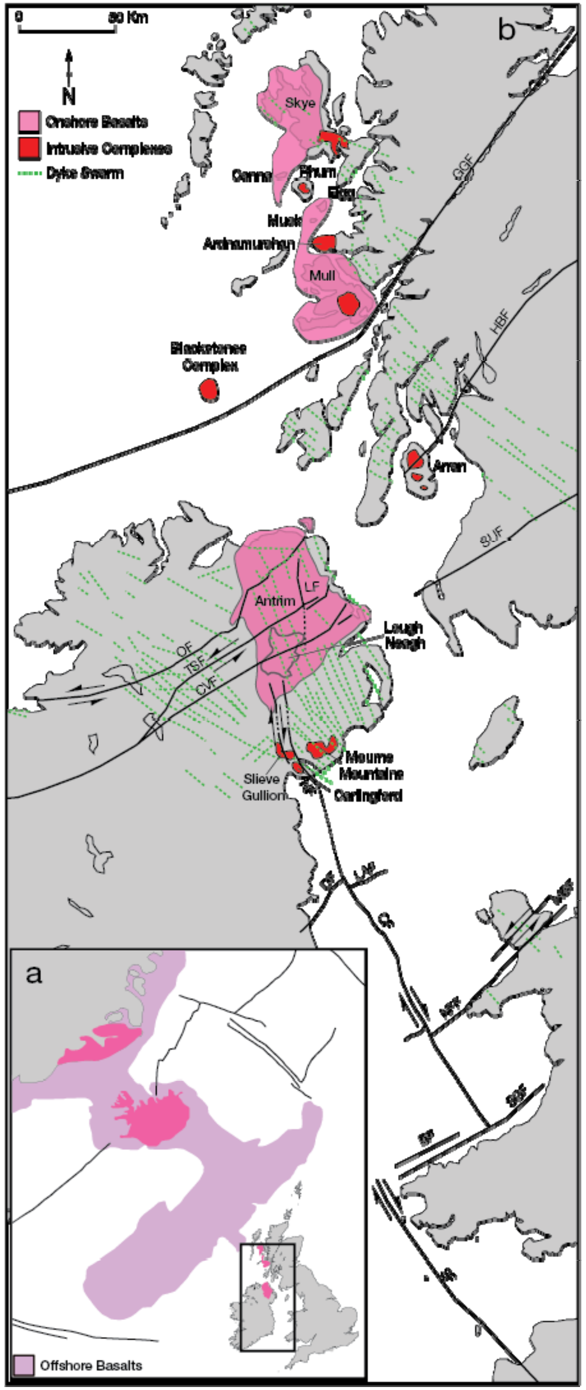
Fig. 1. Location and simplified Palaeogene geology of the North Atlantic Igneous Province in the region surrounding Northern Ireland. The outcrop of basalts of the Antrim Lava Group and of central intrusive complexes and the principal orientation and distribution of related dyke swarms and faults are shown. Inset map shows the onshore and offshore basalts associated with the Icelandic plume. Fault names are as follows: BF – Bala Fault, CF - Codling Fault, CVF - Clogher Valley Fault, DF – Dalkey Fault; GGF - Great Glen Fault, HBF - Highland Boundary Fault, LAF – Lambay Fault, LF – Loughguile Fault, MSF – Menai Strait Fault System, NF - Newry Fault, NFF – Northwest Flank Fault, OF - Omagh Fault, SF - Sticklepath Fault, SGF – St.George's Fault, SUF - Southern Uplands Fault, TSF - Tempo-Sixmilecross Fault. Lough Neagh is labelled LN. Map is compiled from material presented in the following papers: Bevin *et al.* 1996; British Geological Survey 2009; Cooper 2004; Cooper and Johnston 2004b; Cunningham *et al.* 2003; Dunford *et al.* 2001; Ryan *et al.* 1995; Turner 1997; Williams *et al.* 2005. The southern extension of the Loughguile Fault (broken line) towards the north-east corner of Lough Neagh was defined by Quinn (2005) on the basis of gravity data.

Fig. 2. Total magnetic intensity (TMI) anomaly map (sun shaded 35/075) of Northern Ireland showing dyke swarms and prominent magnetic anomalies associated with the Antrim Plateau (AP), Slieve Gullion (SG) and the Mourne Mountains (MM). Inset map shows the offsets of dykes across the Tempo-Sixmilecross Fault and the Omagh-Tow Valley faults. Colour scale bar is in nanotesla (nT).

Fig. 3. Greyscale shaded relief TMI/DTM image with delineated Palaeogene dyke swarms, sills and faults, together with the Antrim Lava Group and the Slieve Gullion and Mourne Mountain igneous complexes. Legends are provided for each of the dyke swarms, the main igneous bodies and principal faults. (a and b refer to the two separate bundles of dykes that constitute the Ardglass-Ballycastle dyke swarm).

Fig. 4. Greyscale shaded relief TMI/DTM image with mapped Palaeogene dyke swarms and faults. (a) Erne dyke swarm showing positive and negative etc. (b) Donegal-Kingscourt swarm. Fault names are as follows: CVF – Clogher Valley Fault, OF – Omagh Fault, TSF - Tempo-Sixmilecross Fault.

Fig. 5. Early Palaeogene stratigraphic chart showing the main periods of intrusive magmatism, volcanic ash beds and fan deposition for the North Sea (White and Lovell 1997), together with the main phases of igneous activity and dyke intrusion for Northern Ireland. The timescale, including periods of normal and reverse magnetisation (black and white respectively), is from White and Lovell (1997). The ages of dyke swarms derive from this study, whilst those for the igneous bodies of Northern Ireland are from previous studies (Cooper and Johnston 2004b; Cooper 2004): CC - Carlingford Complex, ALG - Antrim Lava Group, SGC - Slieve Gullion Complex, MM - Mourne Mountains Complex. Two potential ages are provided for the Erne and St. John’s Point-Lisburn swarms as their ages cannot be associated with a single magnetic reversal event.



0
50 Km
N
b
Onshore Basalts
Intrusive Complexes
Dyke Swarm
Skye
Canna
Rhum
Eigg
Muck
Ardnamurchan
Mull
Blackstones
Complex
Arran
GGF
HBF
SUF
Antrim
LF
Lough
Neagh
OF
TSF
CVF
Mourne
Mountains
Slieve
Gullion
Carlingford
a
Offshore Basalts

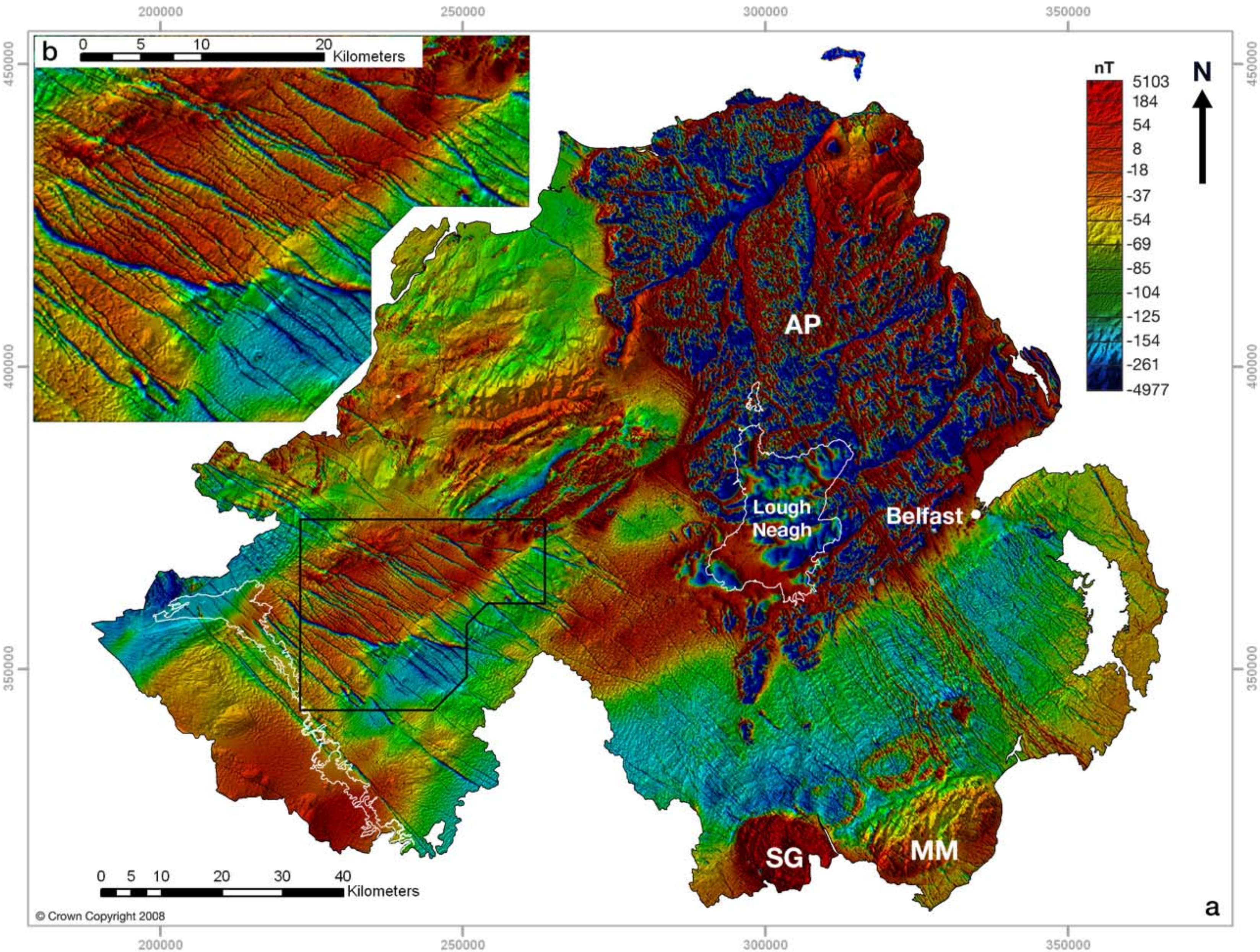
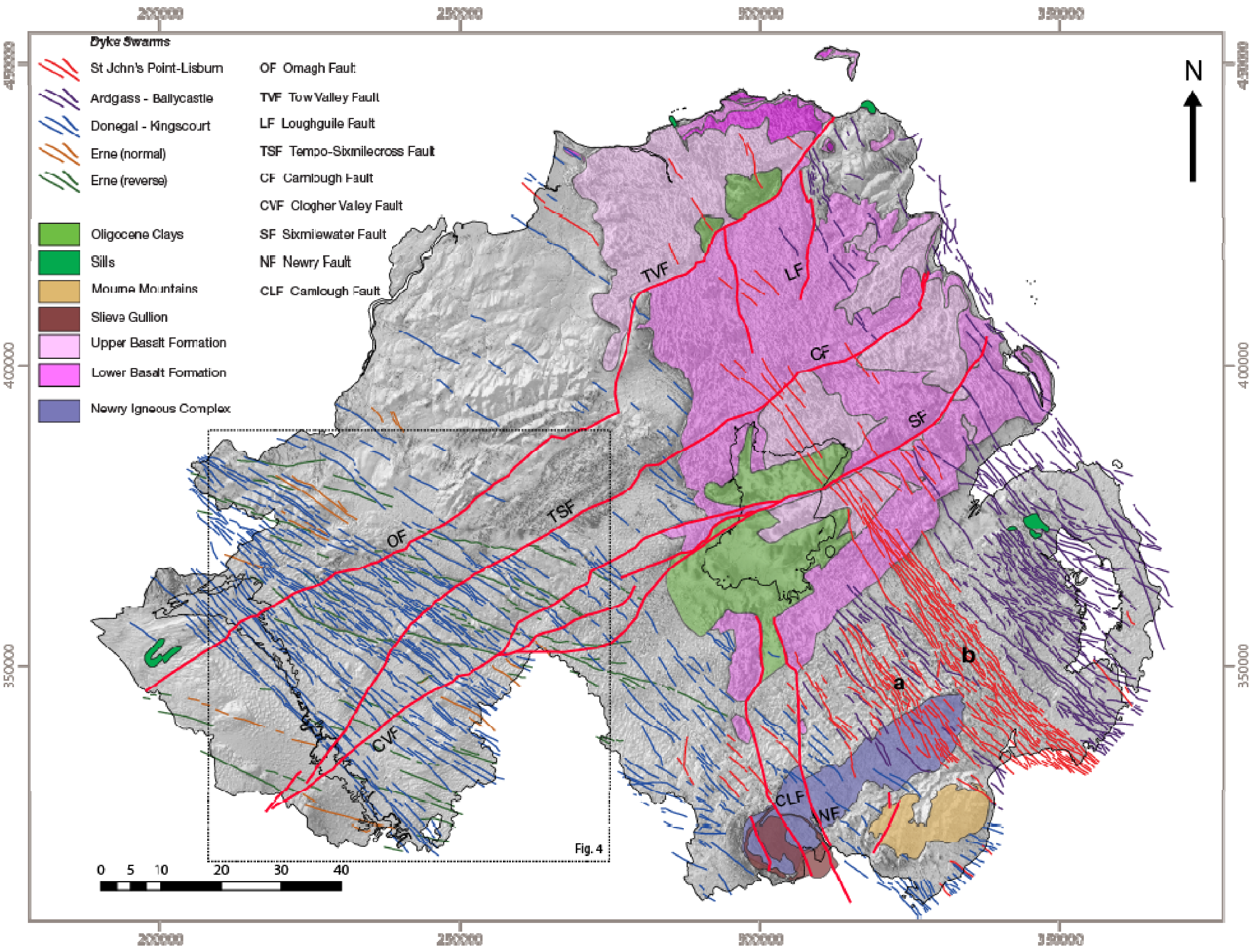
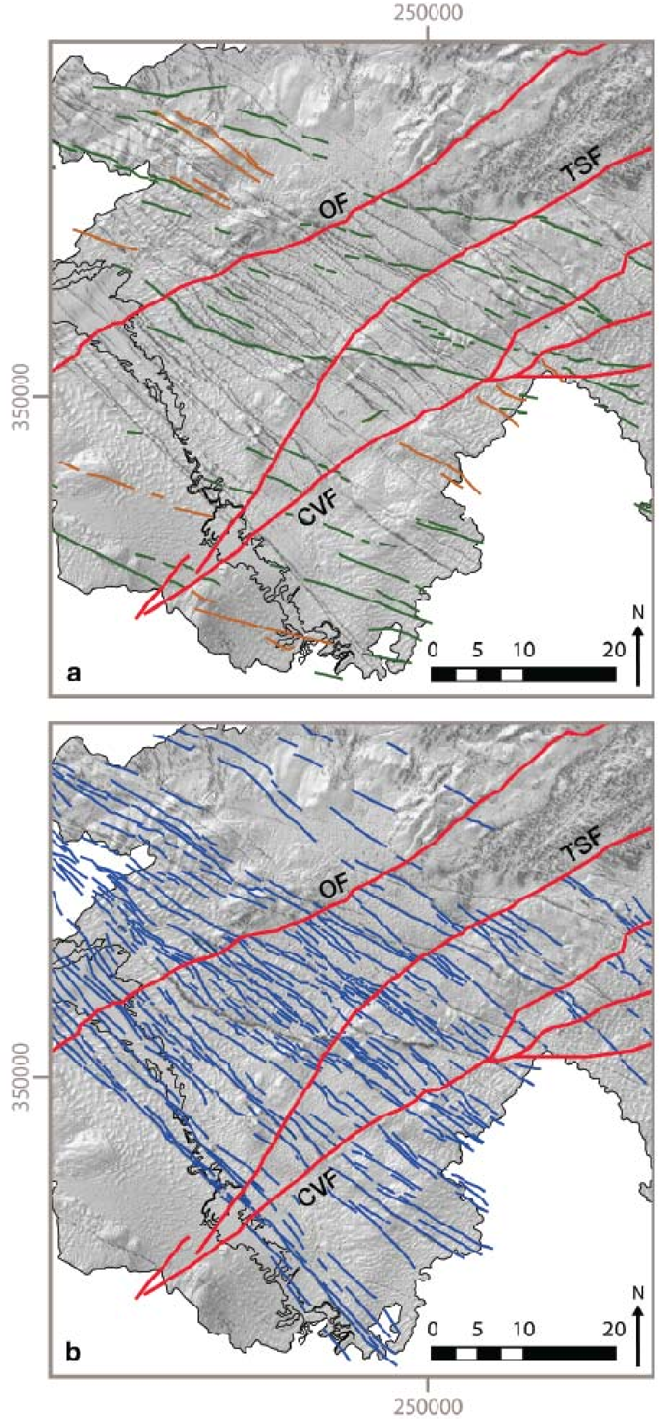


Fig 2. © Cooper. Anderson, Walsh et al. 2010



Dyke Swarms
St John's Point-Lisburn
Ardgass - Ballycastle
Donegal - Kingscourt
Erne (normal)
Erne (reverse)
Oligocene Clays
Sills
Mourne Mountains
Slieve Gullion
Upper Basalt Formation
Lower Basalt Formation
Newry Igneous Complex
OF Omagh Fault
TVF Tow Valley Fault
LF Loughguile Fault
TSF Tempo-Sixmilecross Fault
CF Camlough Fault
CVF Clogher Valley Fault
SF Sixmilewater Fault
NF Newry Fault
CLF Camlough Fault
N
TVF
LF
CF
SF
OF
TSF
CVF
CLF
NF
a
b
Fig. 4
0 5 10 20 30 40
200000
250000
300000
350000
400000
450000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b
250000

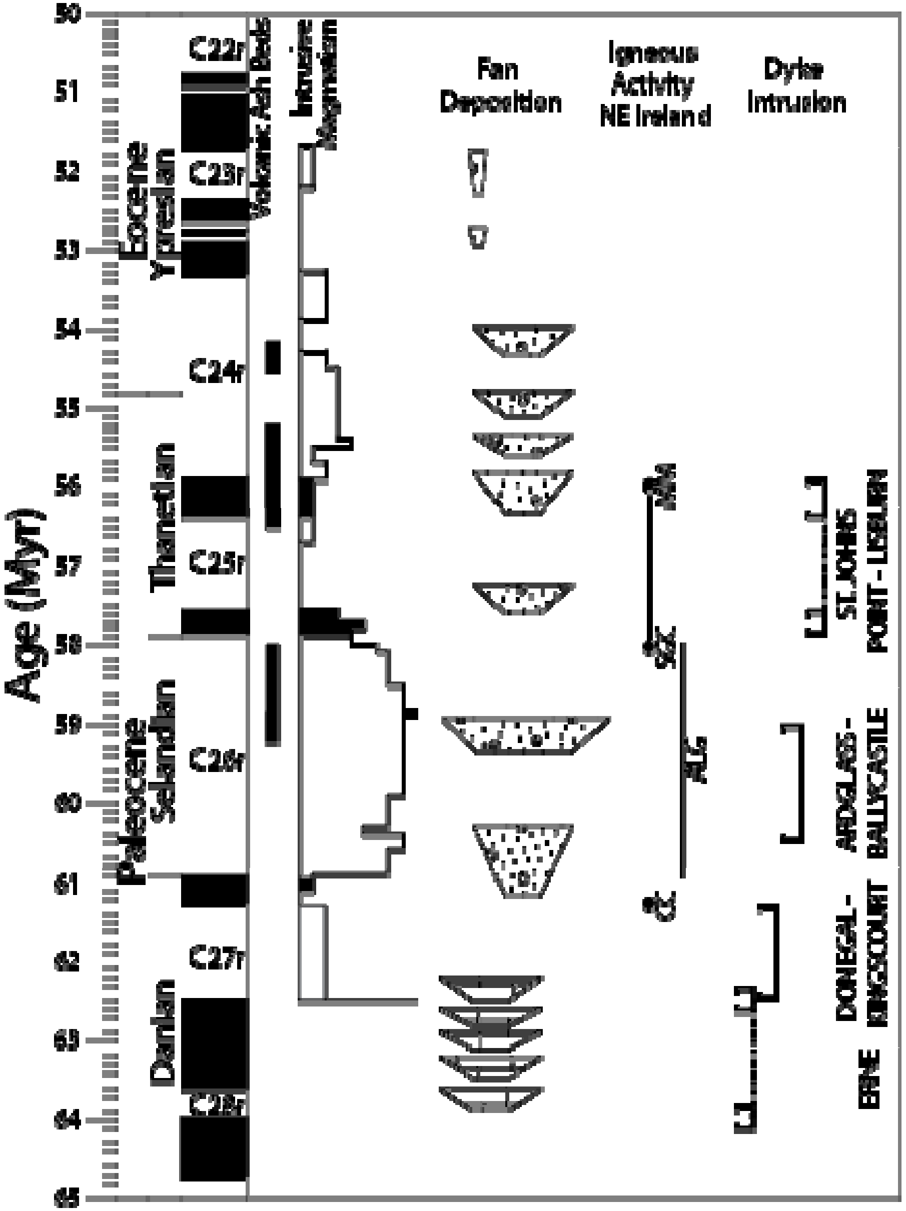
Age (Myr)
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
Eocene
Ypresian
Thanetian
Paleocene
Selandian
Danian
C22r
C23r
C24r
C25r
C26r
C27r
C28r
Volcanic Ash Beds
Intrusive Magmatism
Fan Deposition
Igneous Activity NE Ireland
Dyke Intrusion
ST. JOHNS POINT - LISBURN
ARDGLASS - BALLYCASTLE
DONEGAL - KINGSCOURT
ERNE

Fig. 4.