14. Faults, intrusions and flood basalts: the Cenozoic structure of the north of Ireland

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Detailed digital mapping of the Tellus aero-magnetic data set has revealed the extent and timing of igneous activity in the north of Ireland during the Palaeogene period (*c.*66–23 million years). These data have provided a unique opportunity to constrain the geometry, scale and development of similarly aged faults in the region. Recognition and analysis of these structures has broadened the understanding of Cenozoic tectonics of Britain and Ireland, with potential implications for fluid flow in hydrocarbon and groundwater reservoirs.

INTRODUCTION

Extensive evidence of outcrop-scale Cenozoic faulting has been documented across Britain and Ireland. While this work has recognised that regional-scale Cenozoic faults were likely to accommodate kilometre-scale displacements and adhere to broadly north-east to south-west (NE–SW) or NNW–SSE trends, a lack of clear offset markers has prevented accurate constraint on the precise timing and nature of faulting (e.g. Quinn, 2006). This lack of resolution has hindered analysis of the interplay of faulting, attributed to the far-field influence of African–European plate collision, and igneous activity, associated with the development of the Iceland mantle-plume, a topic that is still debated. In this chapter we demonstrate how analysis of the Tellus and Tellus Border aero-magnetic data sets has allowed identification and analysis of regional scale strike-slip faults and their relationship with temporally and spatially overlapping igneous rocks. In an additional project within the Tellus Border programme the implications of this analysis were extended to areas of Ireland adjoining the surveyed zone, as discussed below.

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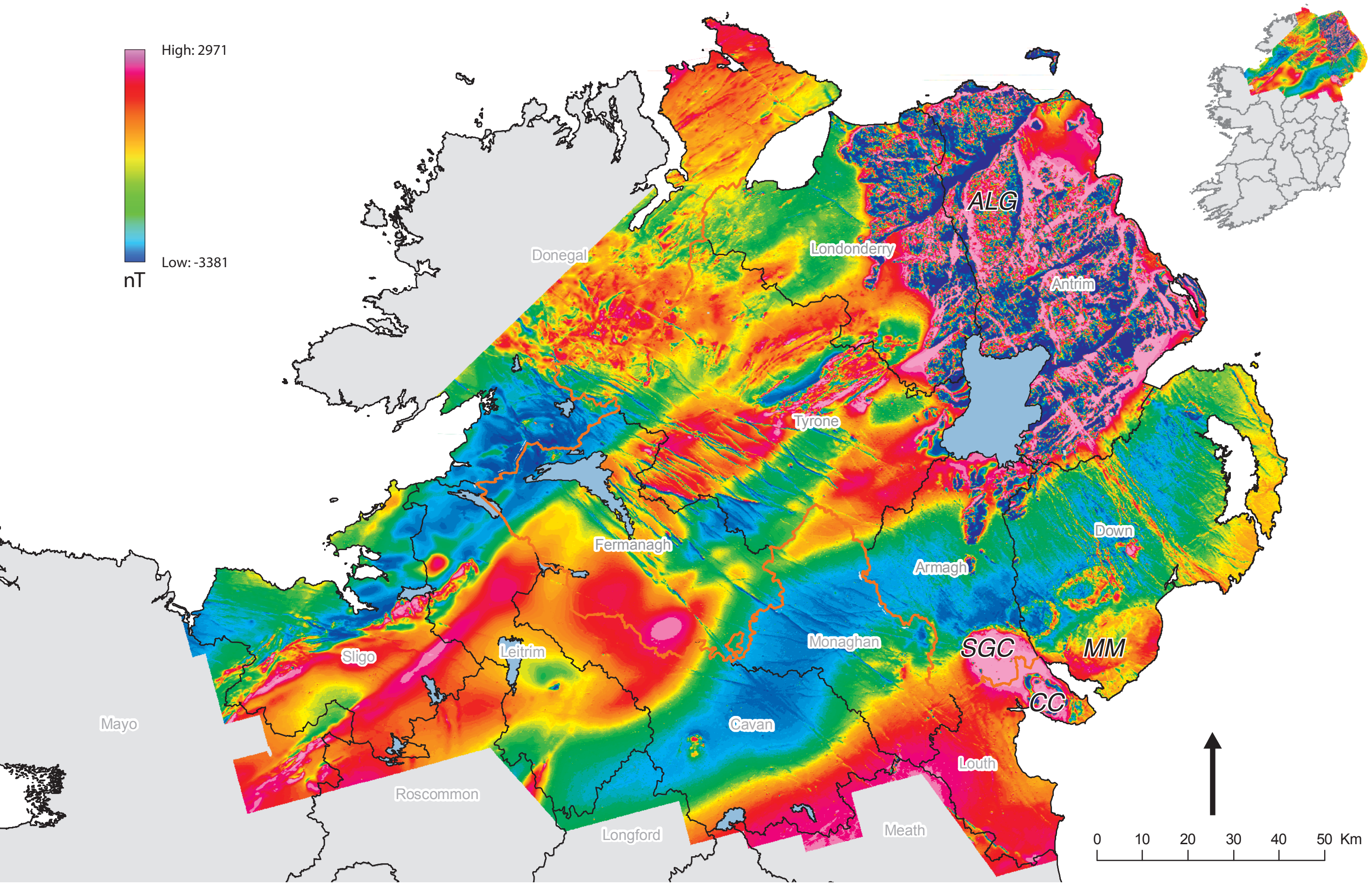

Figure 14.1. Total magnetic intensity (TMI) anomaly map of the surveyed area showing linear dyke anomalies and other prominent anomalies associated with the Antrim Lava Group (ALG), Carlingford Complex (CC), Slieve Gullion Complex (SGC) and Mourne Mountains Complex (MM).

Detailed mapping of Palaeogene igneous rocks

Many igneous rocks contain a high proportion of magnetic minerals that can record the polarity and magnitude of a regional magnetic field at the time of emplacement. Consequently, igneous intrusions, in contrast to sedimentary rocks, are often represented as normal (+ve) and reverse (–ve) features, or anomalies, on aero-magnetic imagery. Digital analysis of the Tellus and Tellus Border data sets has therefore allowed rocks of the British Palaeogene Igneous Province to be mapped accurately across the north of Ireland. The Antrim Lava Group appears as a large, polarised normal and reverse feature while the Carlingford, Slieve Gullion and Mourne central igneous complexes to the south are predominantly normal (Fig. 14.1). Moreover, the Tellus data have revealed more than 1500 broadly linear anomalies representing a previously unrecognised intensity of dyke emplacement in a series of dyke swarms.

Four criteria were used to categorise each dyke swarm: orientation and distribution; remnant magnetic polarity; differential displacement across regionally significant faults; and stratigraphic relationships with other Palaeogene rocks (Cooper *et al.*, 2012). Five dyke swarms have been defined in this way: (1) the E–W-trending Killala swarm (brown and pale blue, Fig. 14.2) within counties Sligo and Leitrim; (2) the Erne swarm (green and orange, Fig. 14.2) which extends broadly E–W (or WNW-trending) across the border counties; (3) the laterally extensive, NW–SE-trending Donegal–Kingscourt swarm (blue,

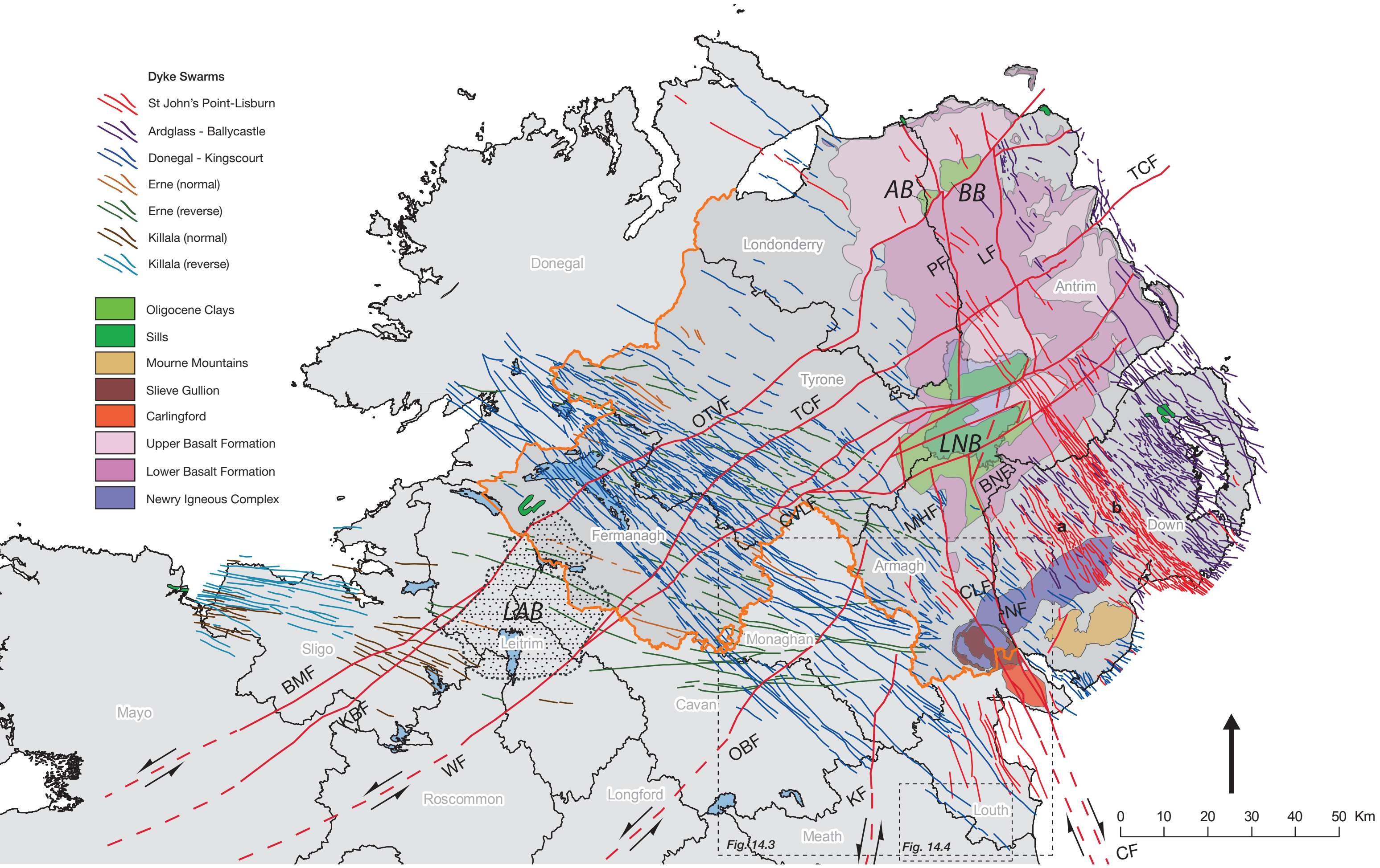

Figure 14.2. Palaeogene dyke swarms, sills and faults are delineated: Ballymote Fault (BMF), Bann Fault (BNF), Camlough Fault (CLF), Clogher Valley–Larne Fault (CVLF), Markethill Fault (MHF), Killavil–Belhavel Fault (KBF), Kingscourt Fault (KF), Loughguile Fault (LF), Newry Fault (NF), Orlock Bridge Fault (OBF), Omagh–Tow Valley Fault (OTVF), Portrush Fault (PF) and Tempo–Carnlough Fault (TCF); other intrusive and extrusive igneous bodies; and basins – Agivey Basin (AG), Ballymoney Basin (BB), Lough Allen Basin (LAB) and Lough Neagh Basin (LNB).

Fig. 14.2), which extends from Donegal through to Armagh and Louth; (4) the Ardglass–Ballycastle swarm (purple, Fig. 14.2), a NNW-trending system restricted towards the east coast of Northern Ireland; and (5) the most northerly-trending St John's Point–Lisburn swarm (red, Fig. 14.2), the centre of which extends through Lough Neagh. Each defined dyke swarm was then correlated with the geomagnetic polarity timescale to constrain its timing of emplacement during the Palaeogene.

Analysis of Cenozoic fault geometry and displacements

Interpretation of the Tellus aero-magnetic data set has indicated that two orientations of conjugate strike-slip faults, left-lateral (sinistral) NE-trending and right-lateral (dextral) NNW-trending structures, accommodated kilometre-scale displacements during the Cenozoic (Cooper *et al.*, 2012). The geometry and nature of each fault is constrained by identifying and measuring displacement of Palaeogene dykes, central igneous complexes and flood basalts.

NE–SW trending sinistral faults

Three major NE–SW trending structures, the Omagh–Tow Valley, Tempo–Carnlough and Clogher Valley–Larne faults, and their lateral extensions to the south-west can be mapped by the sinistral displacement of dykes and lava flows. Since all of these structures

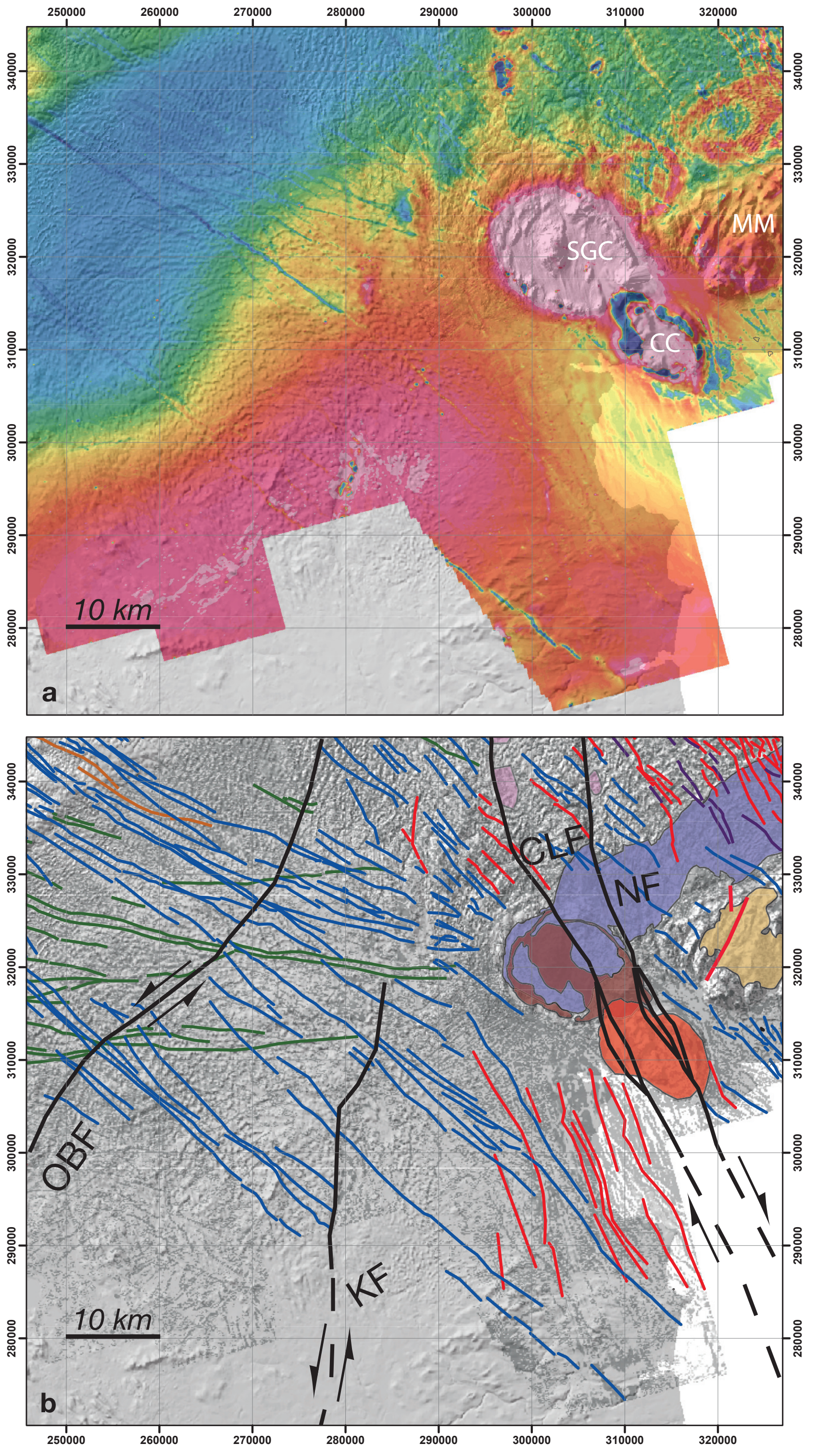

Figure 14.3. (a) TMI of the south-eastern part of the surveyed area, draped over a greyscale digital terrain model, showing magnetic anomalies associated with the dyke swarms and the magnetic highs associated with the central complexes. (b) First vertical derivative/digital terrain model image of the same area with delineated Palaeogene dyke swarms, sills and faults. See Fig. 14.2 for location and key. CC, Carlingford Complex; SGC, Slieve Gullion Complex; MM, Mourne Mountains Complex.

were Carboniferous normal faults (Worthington and Walsh, 2011), their Cenozoic displacements are a result of later reactivation. Furthermore, the timing of strike-slip movement and dyke intrusion suggests a complex interplay between broadly north–south Alpine compression and Iceland plume-related magmatism (Cooper *et al.*, 2012).

The Omagh–Tow Valley Fault (OTVF, Fig. 14.2) is mapped confidently for approximately 150 km from Ballycastle on the northern coast to Fermanagh. Although the fault is considered here as a single Cenozoic structure, it was previously recognised and mapped as two individual faults, the Omagh and Tow Valley faults, by previous work on older rocks. The structure displaces the Erne and Donegal–Kingscourt swarms by an average of 420 m. To the north-west, two Oligocene (*c.*34–23 Ma) basins are observed overlying the Antrim Lava Group at the location of left-stepping bends on the Tow Valley Fault. The geometry of the basins and the strike-slip nature of movement suggest that associated sinistral displacement has led to the development of pull-apart basins, where the transfer of displacement across bending or stepping faults is accommodated by localised subsidence and the development of rhombic basins. To the south-west the most likely lateral extension of the Omagh–Tow Valley is the newly mapped Ballymote Fault, which exhibits approximately 250 m of sinistral displacement of four Killala swarm dykes (Fig. 14.2).

The Tempo–Carnlough Fault (TCF, Fig. 14.2) can be mapped from the North Channel in the north-east to Fermanagh in the south-west. The fault is composed of two previously recognised structures: the Tempo–Sixmilecross Fault, located to the south-west of the Antrim Lava Group, and the Carnlough Fault, within the basalts. Palaeogene movement on the Tempo–Carnlough Fault is recorded by a maximum sinistral displacement of 2.3 km.

The Clogher Valley–Larne Fault, unlike the faults described above, locally splays along its strike into several strands, each displaying sinistral motion. The splayed faults coincide with a number of mapped structures, the most significant of which is the Larne Fault to the north-east (which is also known as the Sixmilewater Fault but renamed here for clarity). The Clogher Valley–Larne Fault displaces both the Erne and Donegal–Kingscourt swarms by an average of 490 m. The Tellus data set, supported by traditional mapping, indicates that the Tempo–Carnlough and Clogher Valley–Larne Faults converge at the western margin of the aero-magnetic data set to form the Woodcock Fault (Fig. 14.2).

The availability of the Tellus Border data has revealed that a series of structures in the east of Ireland also accommodated 100 m scale Cenozoic displacements. The NE–SW trending Orlock Bridge Fault, one of the major terrane bounding structures of Ireland which formed during the Caledonian Orogeny, sinistrally displaces Erne and Donegal–Kingscourt swarm dykes by up to 1 km (Fig. 14.3), though it cannot be traced with confidence into the eastern part of the Clogher Valley–Larne Fault system (Fig. 14.1). Further east the NNE-trending Kingscourt Fault displaces sinistrally four Donegal–Kingscourt swarm dykes by up to approximately 700 m before apparently dying out to the north-northeast (Fig. 14.3); while the quality of displacement measurements on this fault may be less reliable, the fault is characterised by 100 m scale sinistral displacements. Finally, a prominent NNW-trending Donegal–Kingscourt dyke is displaced by a series of NNE- to ENE-trending faults which transect County Louth (Figs 14.3a and 14.4). Four sinistral faults offset the dyke by a range of displacements from approximately 350 m to approximately 1.3 km, while one dextral fault displaces the intrusion by approximately 350 m. While the lateral extensions of these structures fall outside the surveyed area, traditional mapping suggests that two of the faults intersect or bound the Navan Orebody, the implications of which are discussed below.

NNW-trending dextral faults

The Camlough Fault and its lateral extensions, the Markethill and Portrush Faults, extend from the Irish Sea in the south to the north coast of Northern Ireland. The Camlough Fault dextrally displaces the Slieve Gullion Complex ring dyke by 2.0 km (Fig. 14.3). The fault can be traced to the north-northwest, where it links with the Markethill Fault before losing definition beneath Oligocene Lough Neagh Group sediments. Mapping of both aero-magnetic and gravity data suggests that the fault steps by approximately 10 km to the east to form the newly defined Portrush Fault (Fig. 14.2). To the south-east the Camlough Fault intersects the Carlingford Complex, where structures are accurately defined by the aero-magnetic data.

The Newry Fault is located approximately 5 km to the east of the Camlough Fault (Fig. 14.3). It dextrally displaces the Caledonian Newry Igneous Complex by 2.5 km (Cooper and Johnston, 2004). Given the similarities in geometry, location and kinematics, it is assumed that the Newry Fault is broadly contemporaneous with the parallel Camlough Fault, a scenario which is supported by the fact that these faults become the same structure, the Codling Fault, further to the south within the Irish Sea. The fault is extended to the north-west where it is mapped as the Bann Fault, which, like the Markethill Fault to the west, subdivides the Antrim Lava Group into older, Lower, and younger, Upper formations (Fig. 14.2).

Implications for regional tectonics

From the data presented in this and previous studies (Cooper *et al.*, 2012), it is clear that the integrated Tellus data sets have provided unparalleled constraints on the extent of Palaeogene igneous and tectonic activity in the north of Ireland. This has allowed refinement of geological maps of the region and, more significantly, revealed previously unrecognised Cenozoic faulting, along pre-existing NE–SW trending Carboniferous faults and along newly formed NNW–SSE trending faults. The quality of the data set permits detailed regional fault displacement analysis which would otherwise be restricted to high-resolution offshore 3D seismic data sets or small-scale structures in areas of extensive onshore exposure. Early analysis of Tellus data indicated that displacement on NE–SW trending sinistral and NNW–SSE trending dextral faults overlapped temporally with five generations of WNW to NNW oriented Palaeogene dyke swarm (Cooper *et al.*, 2012). To reconcile the apparently conflicting stress regimes, a model has been proposed in which broadly north–south Alpine compression was periodically overwhelmed by approximately NE–SW Icelandic mantle plume-related extension. This model suggests that the far-field effects of plate boundary collision were transmitted further into the European plate than previously thought. Furthermore, analysis of the integrated Tellus data sets indicates that the locus of Palaeocene (66–55 Ma) displacement was focused on reactivated NE-trending sinistral faults, while Oligocene (34–23 Ma) displacements primarily occurred on newly formed NNW-trending dextral structures, a scenario that would be consistent with a progressive anticlockwise rotation in the regional stress field during the Cenozoic (Anderson, 2013). While these conclusions have profound implications for the understanding of the geological history of Northern Ireland, structural analysis of the Tellus data sets has also provided insights that could have potentially significant economic implications.

Economic implications

Analysis of the Tellus data set has revealed clear evidence of Cenozoic faulting that could, in principle, have implications for many geological questions of economic importance in the north of Ireland. Here we restrict our discussion to arguably the four most economically important issues linked to Cenozoic deformation: (1) Lough Allen shale gas basin; (2) zinc–lead mineralization; (3) the lignite deposits of Lough Neagh; and (4) hydrocarbon leakage in the Irish Sea. The backdrop to our considerations is that Cenozoic strike-slip faults have previously been shown to be responsible for localising both groundwater and hydrocarbon flow. Moore and Walsh (2013), for example, suggested that what are interpreted to be Cenozoic dextral strike-slip faults are among the most transmissive structures in the south of Ireland, being responsible for localising groundwater flow in both quarries and mines there. Croker (1995) has also shown that the same aged structures have localised hydrocarbon fluid flow within the Irish Sea (see below). What these studies therefore demonstrate is that Cenozoic faulting is capable of generating conductive fault systems, a finding that has a variety of economic implications.

The Tellus Border aero-magnetic data set reveals that Cenozoic sinistral displacements on reactivated NE-trending Carboniferous faults can be mapped within the Lough Allen Basin, which has been subject to oil and gas exploration since the 1960s. While our analysis indicates that displacement on the Ballymote and Woodcock Faults, which spatially bound Lough Allen, diminishes along strike to the south-east, the faults are likely to accommodate 100 m scale offsets within the basin (Fig. 14.2). The prevalence of related intra-basinal strike-slip faulting may also be accentuated by the fact that both the Woodcock and Ballymote Faults exhibit left-stepping geometries within the Lough Allen Basin (Fig. 14.2), a scenario that, when combined with sinistral displacements, will lead to associated trans-tension and subsidence. In that sense, it is possible that, in combination with quite significant changes in the geometry of the Carboniferous normal fault system

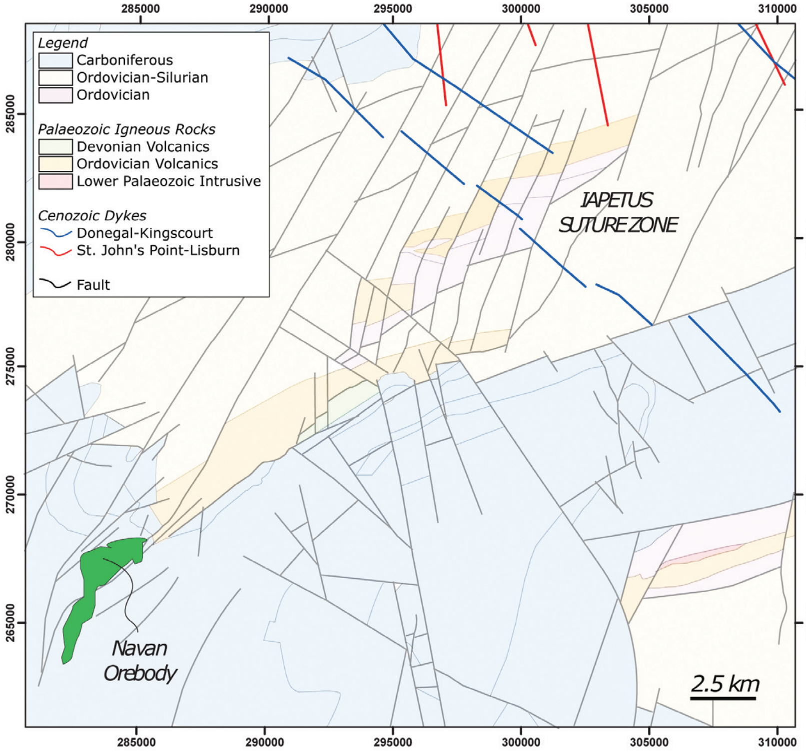

Figure 14.4. Donegal–Kingscourt dykes interpreted from the Tellus data sets overlying a detailed geological map of the region surrounding the Navan zinc–lead mine (Geological Survey of Ireland). Displacement of one of the north-west to south-east dykes highlights north-east to south-west striking strike-slip faults. See Fig. 14.2 for location.

within the basin from predominantly south-east-downthrowing faults in the east through to NW-downthrowing faults in the west (Worthington and Walsh, 2011), fault controlled Cenozoic subsidence may have helped preserve the sequences within the Lough Allen basin. Such large, previously unknown, Cenozoic displacements could have an economic impact in two ways: (1) faulting and associated sub-resolution deformation could complicate the structure of the basin; (2) strike-slip faulting on a range of scales could potentially provide effective barriers or, perhaps more likely, conduits for subsurface fluid flow, and could therefore affect flow both within and between potential subsurface shale gas reservoirs and the groundwater flow system at shallower depths. Future work should therefore investigate the geometry and flow effects of faulting within the basin, in advance of any potential shale gas production.

The importance of faulting in controlling fluid flow systems is well established. Fault zones often act as conduits for accentuated flow, a condition which can have a profound impact on issues such as groundwater flow. Studies in zinc–lead mines in Central Ireland indicate that major influxes of water are associated principally with dextral strike-slip faults, which have been interpreted as Cenozoic in age (Carboni *et al.*, 2003; Fusciardi *et al.*, 2004; Moore and Walsh, 2013). The analysis of the Tellus Border aero-magnetic data has revealed a set of dykes displaying up to kilometre-scale sinistral displacements on a series of NNE–ENE trending faults which have been mapped 15–20 km to the

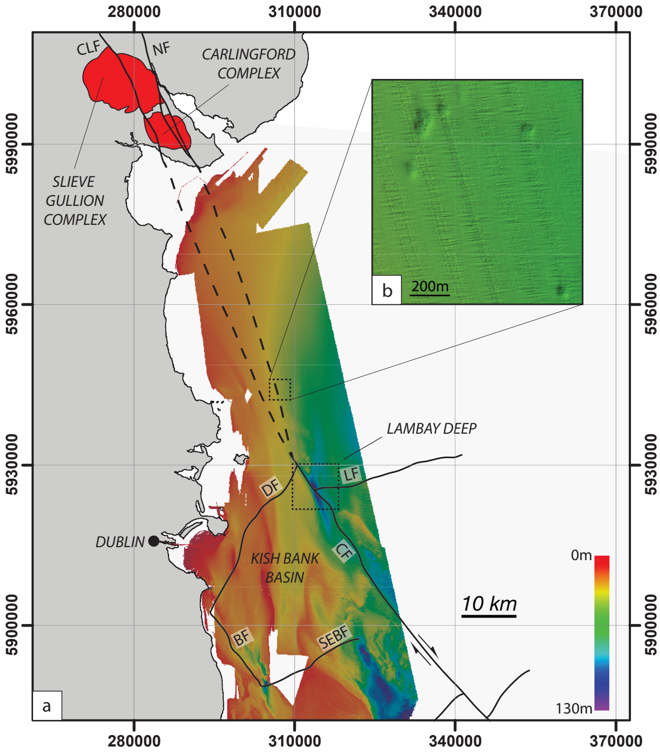

Figure 14.5. (a) Shaded seabed bathymetry of the western Irish Sea (illuminated from the north-east) with subsurface fault map overlain, showing where the Codling and Lambay faults intersect at the Lambay Deep. (b) Pockmarks on the seabed to the north-west of the Kish Bank Basin, interpreted as gas escape structures and correlated with the NW extension of the Codling Fault. Faults: Bray Fault (BF); Codling Fault (CF); Camlough Fault (CLF); Dalkey Fault (DF); Lambay Fault (LF); Newry Fault (NF); South Eastern Boundary Fault (SEBF).

south-west as far as the Navan zinc–lead orebody (Figs 14.3 and 14.4). Similar strike-slip faults have previously been mapped along the north-west and south-east margins of the main orebody, with the Randalstown fault accommodating km-scale displacements. Recent unpublished work in Navan Mines (John Paul Moore, pers. comm.) confirms that equivalent but smaller displacement strike-slip faults are the most conductive structures in the mine and attests to their importance in localising fluid flow. These studies therefore show that as well as having a potentially important impact on groundwater flow, these faults are sometimes large enough to affect the geometry of the Carboniferous orebody itself, a feature that could have important implications for the internal structure of the mine and for future zinc–lead exploration studies.

As proposed by previous research, this study supports the theory that the Oligocene Lough Neagh basin (LNB, Fig. 14.2) and its associated lignite deposits developed primarily as a consequence of displacement transfer on NNW–SSE trending dextral faults, opening a pull-apart basin (Quinn 2006; Cooper *et al.*, 2012). Interpretation of the available geophysical data indicates that the Camlough and Newry Faults step to the east onto the Loughguile Fault and newly defined Portrush Fault, creating two overlapping pull-apart basins. Palaeocene movement on the Clogher Valley–Larne Fault may account for the thickest accumulation of Antrim Lava Group basalt being found at Lough Neagh, though a smaller amount of broadly contemporaneous Palaeocene movement on intersecting

NNW-striking dextral faults could also have contributed. North of Lough Neagh, the Agivey and Ballymoney Oligocene deposits are located on left-stepping bends, where local extension and subsidence is likely to occur on the sinistral Tow Valley Fault.

Offshore, to the south-east of the surveyed area, the Camlough and Newry Faults converge to form the laterally extensive Codling Fault (Fig. 14.5). The association between strike-slip movement on the Codling Fault and fluid flow is supported by pockmarks and surface gas-escape craters, along the southward continuation of the fault towards the Permo-Triassic Kish Bank Basin. Previous work has used geochemical sniffer data to show that hydrocarbon leakage is occurring along the same part of the Codling Fault (Croker, 1995; Dunford *et al.*, 2001; Anderson, 2013). The link between hydrocarbon leakage and Cenozoic NNW-trending strike-slip faults therefore suggests that faults of this nature within the Irish sector of the Irish Sea in particular may have contributed to the relative paucity of hydrocarbon reservoirs compared to the existing important petroleum province within the East Irish Basin.

Conclusions

The Tellus data set has allowed detailed structural mapping and analysis to be performed on a regional scale across the north of Ireland. Analysis of the aero-magnetic data has defined five generations of Palaeocene dyke swarms, which, with central igneous complexes and flood basalts, have been used to constrain kilometre-scale displacements on NE-trending sinistral and NNW-trending dextral structures, usually accommodated along pre-existing Carboniferous normal faults and newly formed faults respectively. The results of this analysis suggest a tectonic setting during the Cenozoic in which pulsed Iceland plume-related extension periodically overwhelmed broadly north–south Alpine-attributed compression. These Cenozoic faults sometimes form conductive pathways for subsurface flow, both onshore and offshore of Ireland, with potential implications for hydrocarbon and groundwater exploration and resource management.

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