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Structure of Lower Carboniferous basins of NW Ireland, and its implications for structural inheritance and Cenozoic faulting

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ABSTRACT

The geometry of Lower Carboniferous basins across the northern part of Ireland is characterised by a gradual change in polarity of structure from a predominantly southward dipping fault system in Northern Ireland through the Lough Allen Basin and into a mainly northward dipping fault system of Connemara in the southwest. This polarity change is reflected in the emergence of northward facing uplifted footwall blocks, such as at Croagh Patrick and the Ox Mountains, in the southwest, with southward facing blocks in the northeast. Despite these structural changes, there is a great degree of along-strike continuity of Lower Carboniferous structure, strain and displacement, with the system forming a link between comparable sized and coeval basins in northern England and Scotland to the east and the Canadian Maritime Provinces to the west. The spatial distribution of Carboniferous normal faults suggests that Caledonian structure, such as the Fair Head-Clew Bay line, plays an important role in the localisation of Post-Caledonian strain, although the reactivation of individual Caledonian structures may be less common. The terrain of the west of Ireland is strongly influenced by major Carboniferous faults offsetting the base Carboniferous unconformity, as opposed to previously suggested Cenozoic normal faulting of a Tertiary peneplain.

1. Introduction

Previous work has established the basic geometry and growth of Lower Carboniferous extensional basins in the British Isles and attributed their existence to an approximately N–S extension during the Lower Carboniferous (e.g. Fraser and Gawthorpe, 1990, 2003; Guion et al., 2000; Figs. 1 and 2). The Lower Carboniferous structure of Britain comprises laterally discontinuous faults, together with related footwall highs and associated basins, a configuration which is particularly well-defined because of the availability of seismic datasets in addition to both outcrop and borehole data (Fig. 1). By contrast, the geometry and growth of Lower Carboniferous basins in Ireland is often difficult to establish, mainly because of the paucity of seismic data and because of the relatively poor outcrop and poorly preserved Carboniferous stratigraphic record (Fig. 3). High quality subsurface fault data associated with Irish Pb–Zn mines represent an important, though often localised, departure from the generally less well-defined regional Carboniferous structure. Despite these difficulties, recent work has managed to provide good definition of the structure of Carboniferous basins in parts of Ireland. This paper presents a detailed consideration of the post-base Carboniferous structure of a well-defined zone, approximately 80 km wide, trending NE–SW from the north of Ireland through to Connemara: post-base Carboniferous structures are those which post-date the local base of the Carboniferous succession which is of variable, though generally Lower Carboniferous, age. This zone includes areas of Ireland where structural definition and timing constraints for post-base Carboniferous faults can be quite poor, such as in the west of Ireland, where associated structures are not well exposed and post-base Carboniferous sequences are poorly preserved. Nevertheless, using constraints from previously published work, basic map data and this study's analysis, it is possible to investigate a number of key issues related to the structure of this zone including: (i) the nature of along-strike structural and strain variations, (ii) the potential impact of later Cenozoic faulting and (iii) the impact of earlier structure on post-base Carboniferous faulting.

The first issue this study will examine is the distribution of structure, strain and displacement along this system, from the Carboniferous basins of the Fintona Block in the north and the Lough Allen Basins in Leitrim, further south into the post-base

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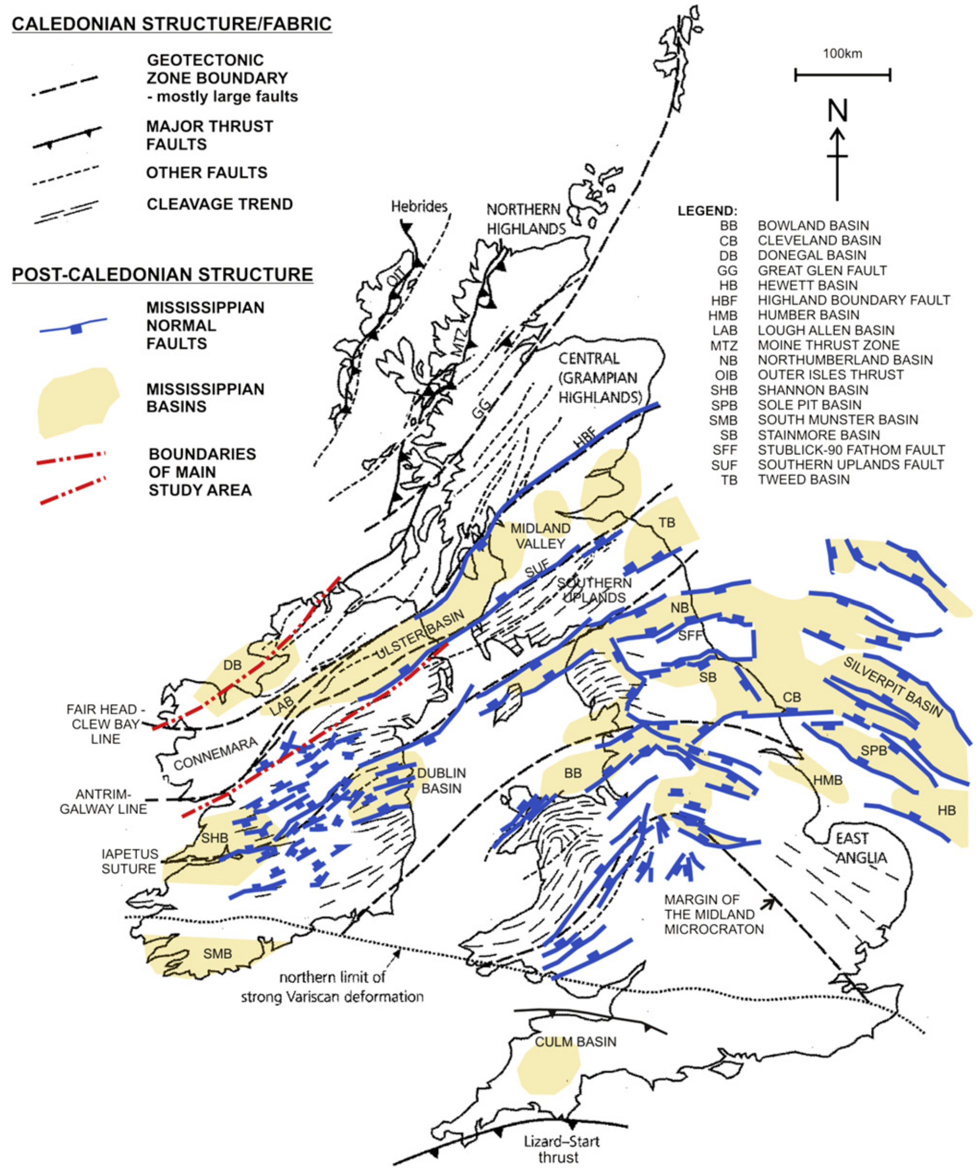

Fig. 1. Map showing the distribution of Lower Carboniferous (i.e. Mississippian age) basins and associated major faults alongside the Caledonian fabric and structures across the UK and Ireland (compiled from the work of Guion et al., 2000; Woodcock and Strachan, 2000; Johnston et al., 1996). The boundary of the study area is highlighted.

Carboniferous faults of the Ox Mountains and into Clew Bay and Connemara (Figs. 1 and 3). We will attempt to define the structure and timing of the fault system within this zone and the extent to which it is similar to those of better constrained study areas in both Britain and Ireland (Guion et al., 2000; Price and Max, 1988; Johnston et al., 1996; Sevastopulo and Wyse Jackson, 2009). Our analysis will investigate the continuity of strain along the system and will consider whether the system is consistent with the lateral continuity of Lower Carboniferous structure from Britain through Ireland and into the Canadian Maritime Provinces (Mitchell, 1992).

The second issue examined relates to previous work suggesting the importance of a phase of Cenozoic normal faulting in the westernmost part of this zone around Clew Bay and Connemara (Dewey and McKerrow, 1963; Dewey, 2000; Badley, 2001). The deeper level of erosion in this area compared to further NE, combined with poor exposure, presents significant difficulties in constraining the timing and growth of large, NE–SW to E–W trending post-base Carboniferous normal faults. These faults are defined in this region where they juxtapose Lower Carboniferous rocks against older Lower Palaeozoic basement and offset the base Carboniferous surface (a regional unconformity) by several hundreds of metres, downthrown to the north (Figs. 3 and 4). Previous work argued for a Cenozoic phase of normal faulting to account for what was considered to be the 'fresh' appearance of the faulted Connemara landscape (Fig. 4c), which was interpreted to represent a faulted Cenozoic peneplain (Dewey and McKerrow, 1963; Dewey, 2000). This study reviews previously cited evidence, investigates Cenozoic faulting on a regional scale (offshore and onshore) and examines differences between syn- and post-Lower Carboniferous fault displacements, in an attempt to define the significance of Cenozoic normal displacements on the west of Ireland landscape.

The final major issue considered is the extent to which post-base Carboniferous faulting is controlled by earlier structure. Previous work has suggested that basement structure has a major impact on the geometry and localisation of later structures. This relationship has been advocated by previous workers studying Carboniferous basins in the UK (e.g. Bott, 1987; Kimble et al., 1989; Fraser and

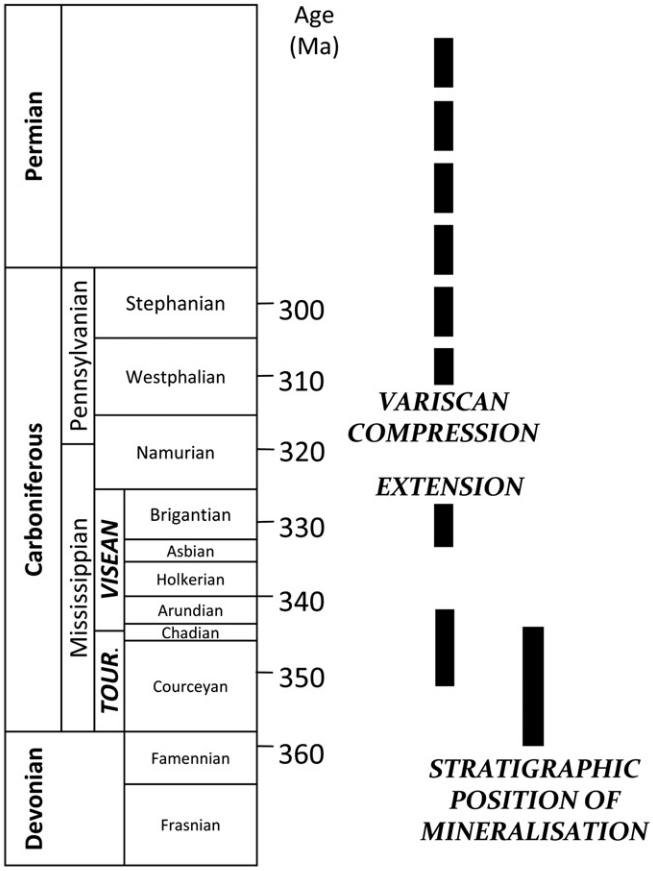

Fig. 2. Tectonic timescale showing the timing of Lower Carboniferous extension and later Variscan compression in Ireland, together with the stratigraphic position of Lower Carboniferous Zn–Pb mineralisation (adapted from Hitzman, 1999): the timing of mineralization is believed to be either synchronous with, or post-date, the early Carboniferous phase of normal faulting. We have retained the common usage of Courceyan, though it has recently been replaced by the Hasterian and the Ivorian (Menning et al., 2006).

Gawthorpe, 1990, 2003; Chadwick and Holliday, 1991; Woodcock and Strachan, 2000; Guion et al., 2000) where basin structure clearly parallels Caledonian fabric (Fig. 1) and the inheritance of structure has also been suggested in Ireland where Carboniferous faults and basins follow the NE–SW trends of Caledonian fabric (e.g. Brown and Williams, 1985; Johnston et al., 1996, Johnson, 1999; O'Reilly et al., 1999). Although earlier studies recognise the comparable structural trends of Caledonian and Carboniferous structures, demonstration of the reactivation of individual structures has never been possible mainly because of the poor definition of underlying basement structure. A useful associated feature of this study area is that it contains a well-established Caledonian structure, the Fair Head-Clew Bay Line (FHCL), which trends NE–SW across Ireland and is believed to be a continuation of the Highland Boundary Fault (HBF) in the UK. This study therefore examines whether earlier structure has a localising effect on later deformation structures and, supplemented by outcrop studies which are described in more detail elsewhere (see Worthington, 2006), considers whether old structures are reactivated or new structures are formed.

2. Geological setting: Lower Carboniferous basin structure and timing

The Lower Carboniferous is marked by a period of regional submergence with a northwards marine transgression over much of Ireland and the British Isles (Guion et al., 2000; Sevastopulo and Wyse Jackson, 2009). This transgression was accompanied by a general N–S to NNW–SSE extension (Gawthorpe et al., 1989; Fraser and Gawthorpe, 1990, 2003; Johnston et al., 1996) that led to the formation of *ca.* 300 km wide array of large-scale Lower Carboniferous basins distributed across the British Isles (Fig. 1). This array consists of laterally discontinuous normal faults, with associated basins and footwall highs (Guion et al., 2000), which extends westwards from the southern North Sea as a NW–SE trending system, before wrapping around the Midland Microcraton and continuing as a generally NE–SW trending system into Ireland (e.g. the Dublin and Ulster basins; Fig. 1). Despite the relatively poor definition of Lower Carboniferous basin structure in parts of Ireland, compared to that of England, there are a number of well-studied Irish Carboniferous basins. Of particular interest in this paper are the basins of Lough Allen and the Fintona Block areas in the north and northwest of Ireland, situated along-strike from the Ulster Basin that trends NE–SW from the Midland Valley Basin in the UK (Figs. 1 and 3). The structural definition and sedimentary evolution of these basins have benefited greatly from the work of Philcox et al. (1992) and Mitchell and Owens (1990), which makes use of outcrop and borehole data, as well as subsurface geophysical data such as gravimetrics and seismic reflection. Further to the south and west the geometry of Lower Carboniferous fault systems are less well-defined, partly because of the paucity of subsurface data. Nevertheless, the Curlew and Clew Bay-Leck Fault are widely recognised as structures with post-base Carboniferous displacements. Normal faults within NW Ireland have strikes which range from ENE–WSW through to E–W, orientations which could therefore be characterised by a subordinate component of oblique-slip displacement, assuming N–S or NNW–SSE regional extension; the presence of any such obliquity has no significant bearing on the conclusions of our study.

The timing of Carboniferous faulting in Ireland is comparable to that observed in the UK with an initial and main phase of rifting occurring during the Courceyan to Arundian (Fig. 2); the Courceyan has recently been subdivided into the Hasterian and the Ivorian (Menning et al., 2006), but we retain its usage for the purposes of this paper. Following a period of relative quiescence and slow subsidence from Arundian to Early Asbian times, there is believed to have been a phase of renewed activity and reactivation into, at least, the beginning of the Namurian (Brandon and Hodson, 1984; Mitchell and Owens, 1990; Philcox et al., 1992; Kelly, 1996; Somerville Cózar et al., 2009). Post-Namurian to Westphalian times represent the onset of thermal sag in the UK basins (Fraser and Gawthorpe, 2003), as well as within comparable and coeval Carboniferous basins in the Canadian Maritime Provinces (Bradley, 1982). Though constraints on this period of thermal subsidence are not so well-defined in Ireland, a similar timing is proposed (Mitchell and Owens, 1990).

Carboniferous basins within Ireland accumulated up to *ca.* 4 km of Mississippian sediments arising from Lower Carboniferous extension (e.g. Mitchell and Owens, 1990), scales which are comparable to the basins in the UK (Fraser and Gawthorpe, 2003). Initial sedimentation typically consists of non-marine siliciclastics (also referred to as 'basal clastics'), including fault scarp facies, which were later replaced by shallow to deep marine sands, limestones and shales. Later Carboniferous sediments of Namurian-Westphalian age, are typically shallow marine to coastal sequences, which sometimes give way to deeper marine sediments within individual basins (Guion et al., 2000; Sevastopulo, 2009).

Lower Carboniferous Irish Pb–Zn type mineralisation, which is always controlled by normal faults, is believed to be either coeval with or post-date faulting (Fig. 2; Hitzman, 1986, 1999). Mineral deposits are hosted by Courceyan to Arundian limestones with

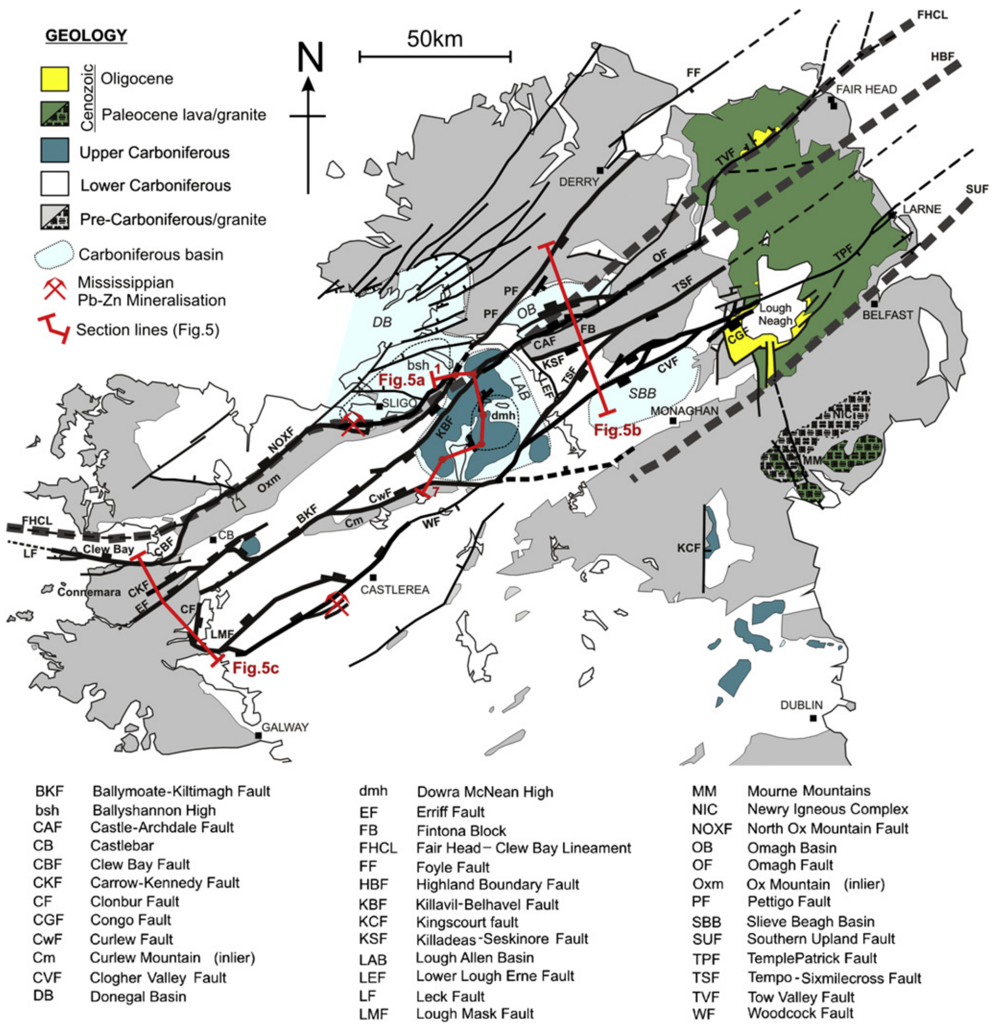

Fig. 3. Simplified geological map and fault map of the study area highlighted in Fig. 1. Faults shown include major post-base Carboniferous normal faults (solid lines with ticks on hanging wall side; short broken lines represent inferred continuations) and major Caledonian basement lineaments (identified as broken lines, only in the eastern and western part of the map). Faults with demonstrable Lower Carboniferous (i.e. Mississipian age) displacements (heavy solid lines) are shown, together with named Carboniferous basins and highs (labelled 'dmh' and 'bsh') referred to in the text. The location of Fig. 5 cross-sections and fence diagram (dots represent borehole sites between 1 and 7 for Fig. 5a) are shown. Fault names and positions are taken from various map and research publications (including, Max and Riddihough, 1975; Mitchell and Owens, 1990; Long et al., 1992; Philcox et al., 1992; Byrne and O'Dwyer, 1994; Long and McConnell, 1995; Harney et al., 1996; Long et al., 1999; McConnell et al., 2002).

Early Chadian Waulsortian reef limestones as the most common host rock. Major Irish Pb–Zn mines are found across Ireland along NE–SW trending Carboniferous fault systems often concentrating close to earlier Caledonian structures such as the Iapetus Suture (e.g. Navan, Co. Meath, Silvermines, Co. Tipperary) and the Fair Head - Clew Bay Lineament (Abbeytown mine, Co. Sligo). Deformation associated with the Variscan orogeny in Ireland followed a phase of post-rifting thermal subsidence during Namurian to Westphalian times. N–S compressional deformation is more extreme in the south with the development of major northerly directed thrusts and associated large-scale, E–W trending folds particularly to the south of the so-called Variscan front (Graham, 2009). Further northwards deformation intensity generally declines and the tighter folds with associated cleavage development in the south is replaced by generally more gentle folding in the NW of Ireland within the study area (Bresser and Walter, 1999). Previous work has shown however that Variscan-related deformation can be accentuated adjacent to pre-existing normal faults, with inversion taking the form of either folding adjacent to, and particularly within the hanging wall of, earlier normal faults (Carboni et al., 2003; Fusciardi et al., 2004), or as reverse faults close to the earlier normal faults (Johnston et al., 1996).

3. Carboniferous normal faulting in Ireland

This study has involved the definition and analysis of post-base Carboniferous faults across the north and northwest of Ireland and Northern Ireland from published work and basic map data, supplemented by additional structural constraints. One of the principal aims was the production of a fault map showing post-base Carboniferous faults, including fault displacement constraints and, where possible, estimates of Carboniferous displacements from sequence growth across-faults. Although the latter may not easily be able to distinguish between Carboniferous syn- and post-rift fault-related thickness changes (i.e. those accompanying fault movement and those arising from post-faulting infill of fault-related bathymetry), this distinction is of secondary importance in this study, which is primarily concerned with defining Carboniferous displacements. The resulting fault map highlights faults with demonstrable syn-Carboniferous displacements and

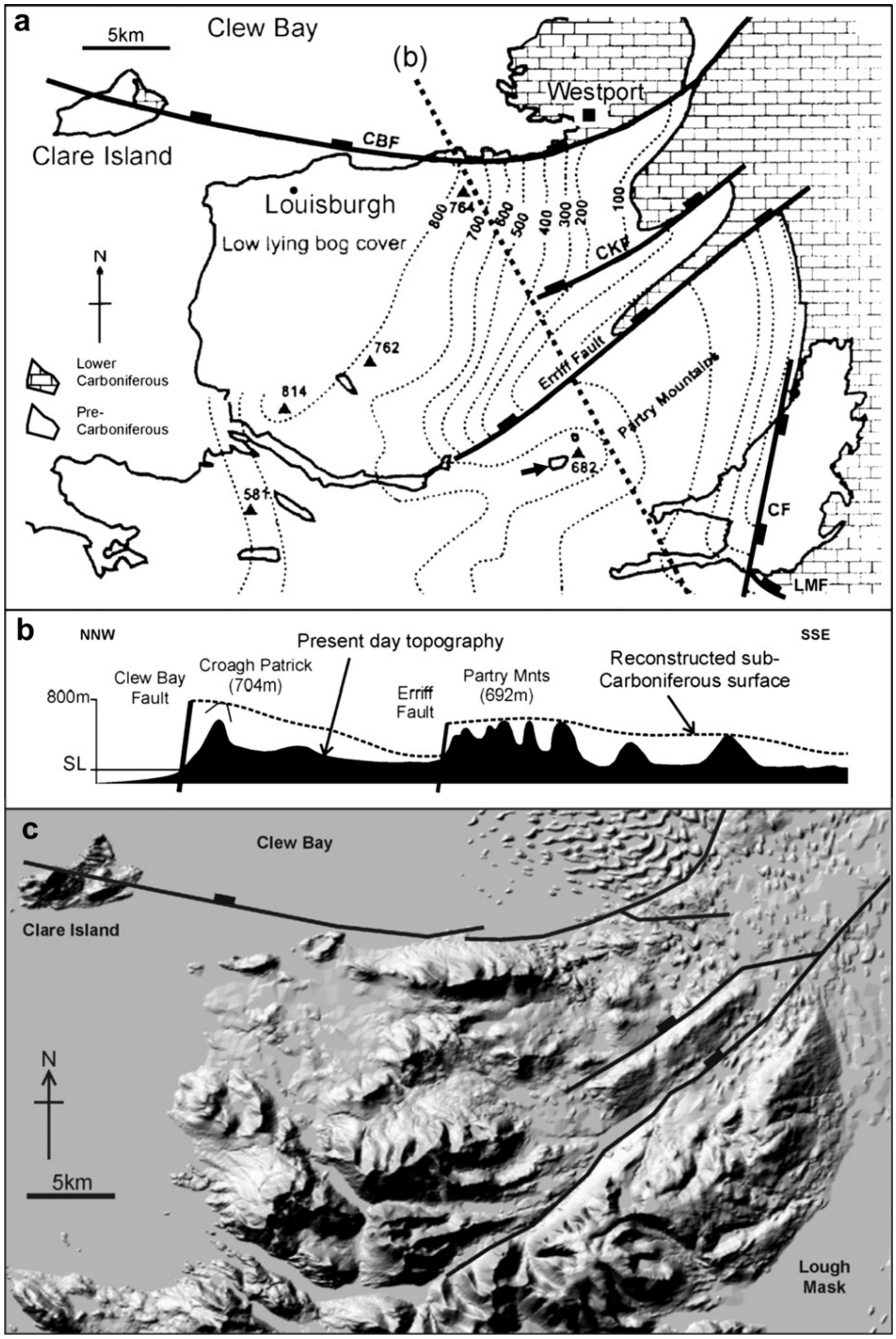

Fig. 4. (a) Map of the area of Clew Bay and Connemara in the west of Ireland, showing the distribution of pre- and post-Carboniferous rocks, large E–W and NE–SW trending post-base Carboniferous faults and structure contours (metres above sea level) of the base Carboniferous surface, derived from Dewey and McKerrow (1963) and Badley (2001). The Carboniferous outlier on the Partry Mountains is identified (arrow). Fault labels are: CBF – Clew Bay Fault, CKF – Carrowkennedy Fault, LMF – Lough Mask Fault, CF – Clonbur Fault. (b) Cross-section showing the terrain, faults and inferred base Carboniferous surface. Location of section shown in (a). (c) A shaded topographic relief map of part of the Clew Bay & Connemara area shown in (a) highlighting the uplifted basement footwall blocks of the Erriff, Carrowkennedy and Clew Bay Faults (data obtained from Ordnance Survey of Ireland, 2004). The numerous small hills in the Clew Bay area are Quaternary drumlins. Light source is from the northwest.

those faults where Carboniferous displacement is suggested (Fig. 3). The map defines an extensive array of NE–SW trending normal faults, extending from Clew Bay and Connemara in the west of Ireland, across the Carboniferous basins of Lough Allen and the Fintona Block in the north and northwest of Ireland. This section provides an account of the structure and timing constraints on faults within the three main areas along the length of the system.

3.1. The Lough Allen Basin

The Lough Allen Basin is a large, NE–SW trending Carboniferous basin, located in the north of Ireland and situated along-strike to the southwest of the Carboniferous basins of the Fintona Block and to the northeast of Clew Bay and Connemara (Fig. 3). The Lough Allen Basin accumulated at least 2.9 km of Lower Carboniferous sediments of Courceyan to Namurian age (Fig. 5a). Previous work by Philcox et al. (1992) using mainly borehole and outcrop data, but also some seismic reflection and gravimetric data, has provided a good understanding of the general structure and depositional history of the basin. Their work recognises key structural highs, fault-controlled sedimentary facies and expanded hanging wall sequences indicative of fault growth. Major basin structures of the Lough Allen Basin include the Ballyshannon High, the Dowra-McNean High and the Curlew Fault (Figs. 3 and 5a).

Philcox et al. (1992) describes the basin as a thinning wedge to the southeast, although the general structure displays a more symmetrical, graben-like geometry, as reflected in the basin profile shown in Fig. 5a adapted from their work (this profile is interpreted between local borehole data, not from seismic reflection data). To the northwest the basin is bounded by a northeast trending fault complex which lies along the south-eastern margin of the Ballyshannon High (Fig. 3) and the north-eastern limit of the Ox Mountains. This complex principally comprises what is interpreted to be the lateral extension of the south-dipping Pettigo Fault (Simpson, 1954; Mitchell and Owens, 1990; Long et al., 1999), sometimes accompanied by the northern end of the north-dipping North Ox Mountains Fault (Fig. 3). The southern margin of the basin is bounded by the Curlew Fault, which varies in strike from NE–SW in the west to E–W in the east. The Curlew Mountain Inlier is the footwall block of the Curlew Fault (Fig. 3). Expanded hanging wall sequences across these structures (Fig. 5a) suggest at least 960 m and 1370 m Visean growth for the Pettigo Fault and the Curlew Fault respectively. The central area of the basin is marked by the Dowra-McNean High, which was identified by Philcox et al. (1992)

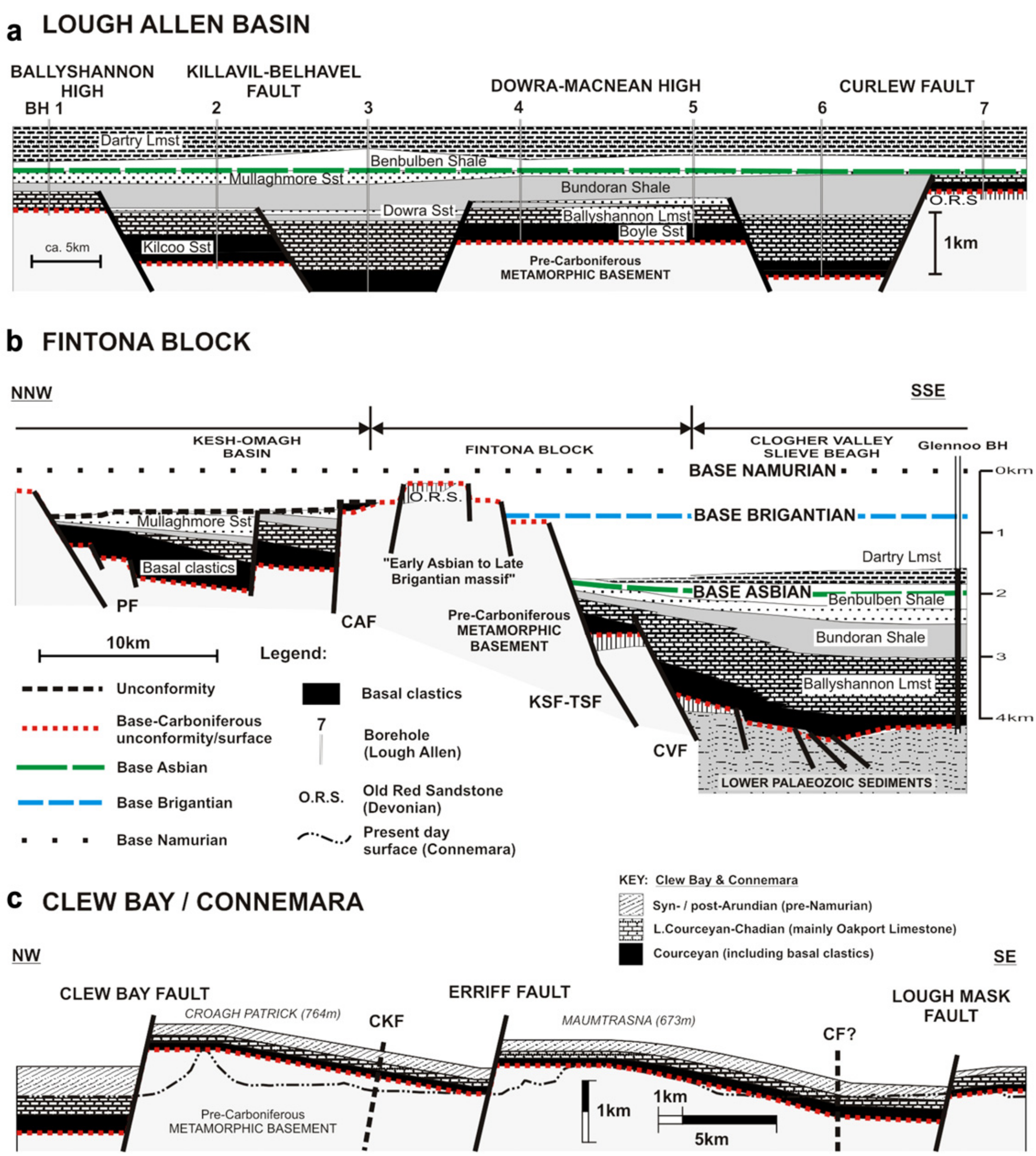

Fig. 5. Cross-sections across the Carboniferous fault system shown in Fig. 3, taken roughly perpendicular to strike. (a) Section of the Lough Allen Basin, modified after the work of Philcox et al. (1992). Section line is constructed from and follows a series of boreholes (1–7, see Fig. 3) and bed geometries are therefore greatly simplified. (b) Section across the Fintona Block derived from Mitchell and Owens (1990). The approximate positions of faults (PF, CAF, KSF, TSF and CVF) from Fig. 3 are shown, as is the approximate position of the Glennoo borehole on the SSE side of the section (Sheridan, 1972). (c) Section across the Clew Bay and Connemara area, interpreted from recent map data (McConnell et al. 2002). The position of the Clonbur Fault (CF) is shown but there are insufficient constraints to define its displacement and geometry. The Carrowkennedy Fault (CKF) is shown with zero displacement because the section crosses the fault at a position close to its tip. The nature of any sequence changes across the Erriff Fault cannot be defined from existing data.

through the use of gravimetric data and also seismic reflection data. Their work suggests that this structure forms a central horst-like structure, with the northern and south-western margins being fault bounded (referred to here as the Dowra-McNean High Faults). Though these faults accommodate up to at least 500 m Lower Carboniferous throw, they are poorly defined, possibly due to the poor quality of available seismic reflection data. The Pettigo Fault, lies along a major Caledonian basement structure, the Fair Head - Clew Bay Lineament (FHCL) that trends NE–SW along the Ox Mountains inlier from Clew Bay in the west to Fair Head in Northern Ireland (Fig. 3). The FHCL is considered to be a continuation of the Highland Boundary Fault in the UK (Fig. 1, Hutton, 1987; Max and Riddihough, 1975).

Lower Carboniferous fault displacement on basinal faults within this area (i.e. the PF, dmh faults, KBF and CF of Fig. 3) is marked by associated sequence thickening, with expanded sequences in the hanging walls of faults, between the Courceyan and the Asbian (Philcox et al., 1992). This time period is slightly longer than the conventional phase of rifting during the Lower Carboniferous in Ireland which is generally believed to have predated the Asbian, possibly not extending much beyond the Arundian (Johnston et al., 1996; Hitzman, 1999). The reason for this discrepancy is that the later sequence expansion may simply reflect the passive infill of post-faulting sea floor bathymetry. Other work suggests that a minor amount of faulting may have continued, possibly as a separate phase, into later Asbian to early Namurian times, and may have involved a component of strike-slip movement (Brandon and Hodson, 1984; Kelly, 1996; Mitchell and Owens, 1990; Somerville et al., 2009). Any measures of fault growth during this later period are, however, poorly constrained, partly because of the relatively poor sequence preservation and the difficulties of distinguishing syn- and post-faulting sequence thickness changes. The 'Carboniferous' displacement measurements established from this study do not include any such later displacements and do not incorporate any displacements which are not reflected in thickness changes. This study's estimates of Lower Carboniferous displacement measurements are therefore considered to be minimum values.

3.2. Carboniferous basins straddling the Fintona Block

A reconstruction of the Carboniferous geology across the Fintona Block in the north of Ireland and Northern Ireland, by Mitchell and Owens (1990) and Mitchell (1992), has provided a good understanding of the evolution of Carboniferous basins contained within this area, including the recognition of major tectonic structures, despite the generally poor-preservation of Carboniferous rocks at outcrop level. Their work was mainly based on outcrop and borehole data, but also included reference to previous work utilising gravimetric data.

The Fintona Block is situated along-strike to the northeast of the Lough Allen Basin (Fig. 3). A number of NE–SW trending Carboniferous basins straddle the Fintona Block, which forms a Devonian high, including the Omagh and Slieve Beagh basins (Fig. 3). These basins are believed to have been connected during the early Mississippian (Mitchell and Owens, 1990), until normal faulting initiated along the Killadeas-Seskinore and Tempo-Sixmilecross Faults, so that the Omagh Basin was separated to the north by the development of a central horst-like structure during the Asbian (Fig. 5b). Mitchell and Owens (1990) suggest that up to 4 km of Mississippian sediments accumulated in the Slieve Beagh Basin (Fig. 5b).

The structure of this area during the Lower Carboniferous consisted of a predominately southward dipping fault system, which resembled a half-graben geometry despite the presence of a central horst-like structure. Major faults include the Pettigo Fault, which bounds the Omagh Basin to the northwest, the Castle-Archdale, Killadeas-Seskinore and Tempo-Sixmilecross Faults, which bound the central early Asbian to late Brigantian massif (i.e. the central horst-like structure) and the Clogher Valley Fault to the southeast (Fig. 3). These faults have interpreted kilometre-scale Carboniferous throws, with the Killadeas-Seskinore and Tempo-Sixmilecross Faults accommodating a combined estimate of between 2.3 and 3.7 km throw during the Lower Carboniferous. The Castle-Archdale Fault lies along the line of the Fair Head - Clew Bay Lineament, on the northern margin of the Fintona Block. To the northeast, the Castle-Archdale Fault continues along the line of this Caledonian structure, as the Omagh Fault (Fig. 3).

3.3. Post-base Carboniferous normal faults from Connemara to the Ox Mountains

Previous work by Dewey and McKerrow (1963) highlighted the existence of large, E–W to NE–SW trending, post-base Carboniferous faults in the Connemara region, which displace the base Carboniferous surface by several hundreds of metres down throw to the north (Fig. 4). Due to the high level of erosion within this region, which is down to Caledonian 'basement' levels on many of these structures (Fig. 3), there are difficulties in constraining the timing of faulting. A Cenozoic age was proposed by Dewey and McKerrow (1963) and Dewey (2000) for the interpreted vertical offset on these structures of what was believed to have been a Cenozoic peneplain. This study suggests, however, that a substantial amount of these displacements are likely to be of Carboniferous age, a view that is supported by an investigation of Cenozoic tectonics across Ireland (offshore and onshore) presented in a later section.

A representative cross-section of the Clew Bay and Connemara area has been derived from recent Geological Survey map data (McConnell et al., 2002, Fig. 5c). In areas where post-base Carboniferous cover sequences have been removed by erosion, Carboniferous across-fault sequence thickness changes were inferred from adjacent and more stratigraphically complete areas within 5 km to the east of the section. The extrapolation of base Carboniferous over Lower Palaeozoic basement is supported by the presence of an outlier of Carboniferous age on the top of Partry Mountains (Ordovician basement) at 682 m (Fig. 4). It is recognised that lateral extrapolations of thickness are subject to error, but they provide a good indication of significant sequence growth. Two important features are apparent from this section: (i) the predominately downthrown to the north offsets of the Carboniferous sequences, with the Clew Bay – Leck Fault being the largest of these structures (with at least *ca.* 750 m throw), and (ii) the existence of expanded Lower Carboniferous sequences within the hanging walls of both the Clew Bay and the Lough Mask Faults.

Expanded sequences in the hanging wall of the Clew Bay Fault (Fig. 5c) are highlighted by comparison of thickness estimates from published geological maps (Long et al., 1992; Long and McConnell, 1995; McConnell et al., 2002) and indicate a phase of Lower Carboniferous growth of between 400 and 660 m which is about 50% of the total throw (and up to *ca.* 75% of the 750 m throw estimated by Dewey and McKerrow, 1963). Due to the incomplete Carboniferous stratigraphic record, this estimate of Lower Carboniferous growth is a minimum. The Clew Bay Fault can be traced as a major post-base Carboniferous fault to the west onto Clare Island, where it continues as the Leck Fault, and to the east along the northern margin of the Ox Mountains Inlier as the North Ox Mountains Fault. Basic map data of the area around the Ox Mountains indicates that there is a significant vertical down throw to the north (Fig. 6) of up to 1.4 km, of the base Carboniferous surface across the North Ox Mountain Fault. Once again, expanded

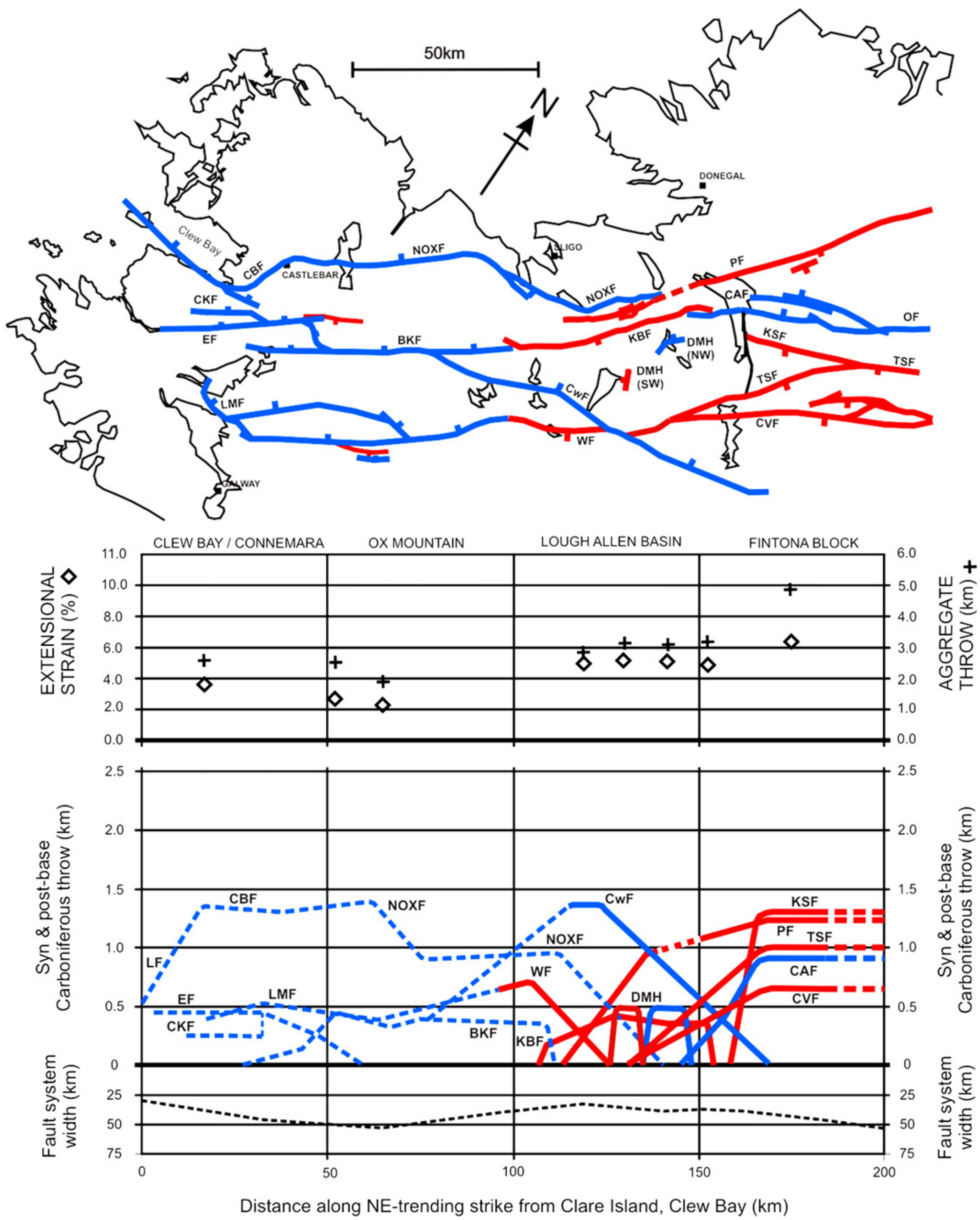

Fig. 6. Along-strike displacement and strain profiles for the main Carboniferous faults of the study area. Post-base Carboniferous throws and syn-Lower Carboniferous throws are discriminated (shown as broken and solid lines, respectively): the latter have been interpreted in the NE of the study area from sequence thickness changes (Mitchell and Owens, 1990; Philcox et al., 1989, 1992), whereas towards the SW only a proportion of the total post-base Carboniferous displacement can sometimes be shown to be of Lower Carboniferous age. Northward and southward dipping faults are discriminated and fault labels are the same as those provided in Fig. 3. Aggregate throw and extensional strain values are taken from sample lines orientated perpendicular to the NE–SW fault trend. Extensional strains are calculated from the estimated aggregate heave across the width of the fault system, which is derived from the aggregate throw assuming a 60° fault dip.

Lower Carboniferous sequences in the hanging wall are demonstrated from map data, suggesting at least 750 m of Lower Carboniferous growth (*ca.* 50% of the total throw). Indications of fault activity during the Lower Carboniferous is supported by evidence of siliciclastic sediments preserved within the hanging wall, which are believed to have been sourced from the Ox Mountain Inlier which must have been exposed, possibly as an emergent, uplifted footwall block at this time (Philcox et al., 1989; Ian Somerville *pers comm.* 2005). Further evidence of activity is marked by the presence of Lower Carboniferous Pb–Zn mineralisation associated with along-strike equivalents of this structure, such as the Abbeytown mine to the northeast (Hitzman, 1999, Fig. 3).

The Lough Mask Fault has a total throw of in excess of 400 m, with at least 100 m being Lower Carboniferous in age (Fig. 5c); as with other areas, the incomplete stratigraphic record means that estimates of Lower Carboniferous displacements are minimum values. The continuation of this structure to the west, within Connemara, is uncertain, though it can be traced towards the northeast to the Woodcock Fault, which flanks the southern side of the Curlew Mountain Inlier. As with the North Ox Mountains Fault, there is evidence of Lower Carboniferous Pb–Zn mineralisation along-strike near Castlerea (Castlerea East: Zn, Pollremon: Fe, and Slieve Dart: Zn–Pb, Fig. 3) indicative of a phase of faulting during the Lower Carboniferous associated with these mineral deposits (Fig. 3).

The Erriff Fault, situated between the Clew Bay and Lough Mask Faults, shows no clear evidence of expanded sequences in either the footwall or the hanging wall, a situation which arises from the paucity of stratigraphic constraints. Along the entire section shown in Fig. 5c, there is a suggestion that the sequence may thin towards the north onto the footwall of the Clew Bay-Leck Fault. Similar thickness variations associated with well-defined examples of Lower Carboniferous faults in England, such as the North Craven fault in northern England, can be seen to be accompanied by complementary facies changes, (Gibson et al., 1989). Future work may help to define facies changes associated with the major faults in this area (e.g. Clew Bay-Leck Fault, North Ox Mountains Fault).

4. Continuity of structure, strain and displacement

The analysis of post-base Carboniferous faulting from a variety of data sources has provided a basis for generating a map of an extensive array of NE–SW trending Carboniferous normal faults, within a zone roughly 80 km wide, extending from Clew Bay and Connemara in the west of Ireland, across Lough Allen and the Fintona Block and into Northern Ireland (Figs. 3 and 6). The broad structure of this array changes from a predominately southeast-dipping system in the northeast, to that of a northwest-dipping system in the southwest, with base Carboniferous displacements ranging from several hundreds of metres through to kilometre-scale. Lower Carboniferous displacements can be demonstrated on most of the faults within this array (Fig. 3 – bold lines highlight faults with demonstrable Lower Carboniferous displacements), although the proportion of displacement of the base Carboniferous which is demonstrably Lower Carboniferous in age, varies from fault to fault and with the quality of supporting data. Whatever the timing of fault displacements, plots showing the along-strike changes in displacement on individual faults, provide a basis for examining lateral changes in both aggregate displacement and strain along the system as a whole.

Displacement profiles on individual faults have been constructed from available cross-section and map data, by measuring along the length of individual faults either the vertical offsets of horizons or the across-fault sequence thickness changes, and by incorporating the interpreted positions of fault tips (i.e. zero displacement ends of faults) into displacement estimates (Fig. 6). Displacement measurements are always for fault throw, i.e. the vertical component of displacement (which is subject to less error than measurements of fault heave, the horizontal component of displacement), and are generally expected to be minimum values because of incomplete preservation of the stratigraphic sequence. Even though these profiles are derived from the best available constraints, they are subject to significant uncertainties. The latter arise not only from the vagaries of sparse and incomplete geological data, but also from complications arising from possible subsequent Variscan and even Cenozoic deformation. To judge from constraints in the rest of Central and Northern Ireland, the amount of Variscan reverse displacements on individual faults is likely to be subordinate to earlier normal fault displacements, and would not, in any case, be included in any syn-depositional Lower Carboniferous displacement measurements arising from sequence thickness changes. The significance of Cenozoic displacements is considered later. The measured displacement profiles provide a means of calculating aggregate displacement profiles along the length of the array, in which the displacements of all faults intersecting strike perpendicular sample lines are aggregated: the sample lines were chosen to coincide with the higher quality constraints along the system. The lateral changes suggest a gradual decrease in aggregate throw from *ca.* 3 km in the northwest to 2.5 km in the southwest. Higher displacements in the most northeasterly position along the length of the array correspond to those derived from the study of Mitchell and Owens (1990). What distinguishes these estimates from others further along-strike is that they derive from a more complete interpretation of Carboniferous tectonics, up to base Namurian times, than it is possible to generate in other areas. Nevertheless, it is possible that the high displacements reflect a real northeastward increase in displacement. Given the uncertainties in displacement measurements, which could be more than +/−500 m for the aggregate throws, the rapid increase in displacement between Lough Allen and Fintona (i.e. at 150 km distance on Fig. 6) may be more gradual than is suggested by the aggregate throw profile and marked by lateral displacement gradients which, at *ca.* 50 m/km, are well within those of other better constrained fault systems. The basic feature of the aggregate throw profile is that displacements along the length of the system suggest a measure of coherence about the fault system, with the preservation of total aggregate throw accommodated by displacement transfer between different faults within the system. This continuity would suggest that the along-strike accommodation of displacement is broadly contemporaneous. Furthermore, because a substantial amount of the measured displacements can be shown to be of Lower Carboniferous age in areas of good data constraints, such as in the Lough Allen and Fintona areas (Fig. 7), the displacements in areas where the precise timing of much of the post-base Carboniferous displacements is less clear is also likely to be predominantly of Carboniferous in age, rather than later. A similar coherence of fault-related extensional strain would also be expected assuming that fault dips and slip direction are relatively consistent. Taking a representative fault dip of 60° provides estimates of fault heave which would suggest relatively low extensional strains of *ca.* 5%, values that are typical of the well-studied fault systems of the Inner Moray Firth and of the Timor Sea (Meyer et al., 2002; Walsh et al., 2002, 2003; Underhill, 1991). Fault-related strain estimates of between 2 and 10% have been recorded in other Lower Carboniferous basins, such as the along-strike equivalent basins in UK (Fraser and Gawthorpe, 1990, 2003) and the Canadian Maritime Provinces (Bradley, 1982). Work by Mitchell (1992) correlated Carboniferous basins of north-western Ireland (e.g. the Lough Allen Basin and the basins of the Fintona Block) to that of the Canadian Maritime Provinces, demonstrating that structure and sedimentation history are both comparable and coeval. The existence of these basins along-strike and the continuity of Irish Lower Carboniferous structure and strain, supports the view that a continuous rift system extended from the southern North Sea across Ireland and into Canada.

5. A consideration of possible Cenozoic tectonics

The large post-base Carboniferous normal faults in the area of Clew Bay and Connemara, have previously been interpreted by Dewey and McKerrow (1963) and Dewey (2000) as being of Cenozoic age. The structure of the system was defined from offsets of the interpreted base Carboniferous unconformity (Fig. 4), which was believed to have been broadly coincident with a Tertiary peneplain. Various other lines of evidence were presented favouring a Cenozoic age for the faulting, such as normal displacements of igneous intrusions and the 'fresh' juvenile appearance of fault scarps which were interpreted to have offset rivers. Here, we briefly consider some of the available evidence for the timing of fault

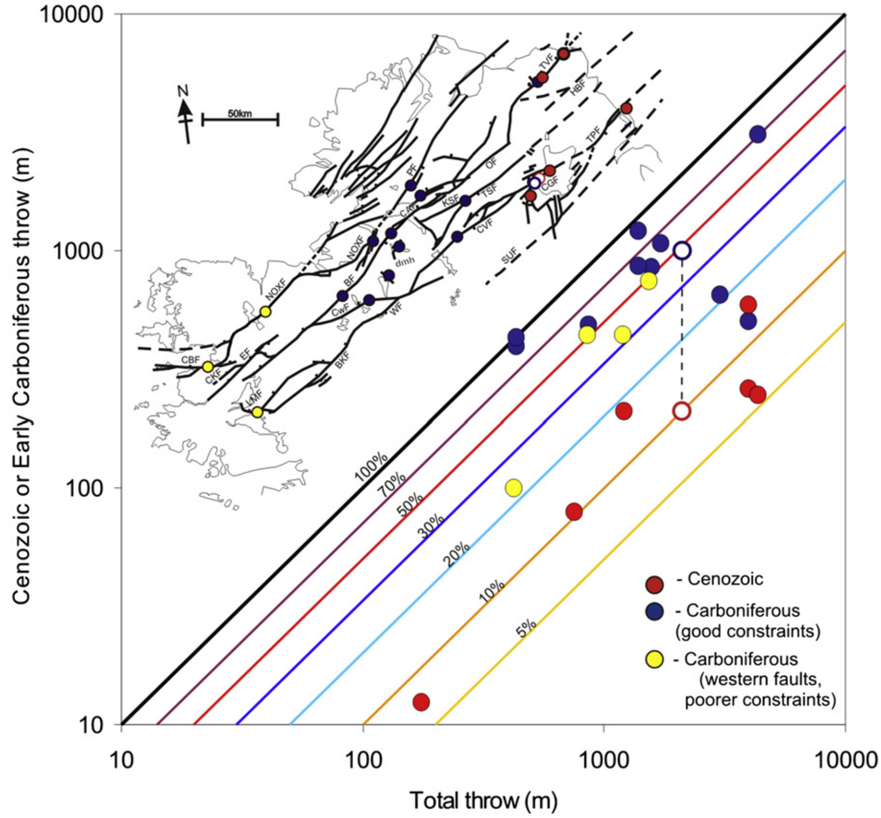

Fig. 7. Displacement data of major NE–SW trending faults. Syn-depositional Lower Carboniferous throw (blue and yellow data points) against total throw of individual faults. Where there are good constraints, up to 100% of the total throw on these faults is demonstrably Lower Carboniferous (blue data points and blue dots on inserted locality map). To the west (yellow data points and dots), where constraints are relatively poor, smaller proportions of the total throw can be demonstrated to be Lower Carboniferous in age. In the east, measurable Cenozoic throws (red data points and red dots) represent roughly 10% of the total throw on faults. The two unfilled dots represent displacement data associated with the Congo Fault, 'CGF', which occurs in the Lough Neagh area to the east of the Clogher Valley Fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

motions, and suggest that the existing evidence strongly favours a predominantly Carboniferous age for the normal fault displacements.

Previously published studies of Cenozoic igneous intrusions in the west and northwest of Ireland provide no direct evidence of fault-related vertical offsets of more than a few metres (Mohr, 1982, 1986; Mohr et al., 1984), a view which is supported by a recent comprehensive study of these intrusions (Bennett, 2006). It has been suggested that river offsets and associated river profiles support the presence of Cenozoic displacements, and yet so-called fault scarps are represented by 'major kinks' with heights of no more than a few 10's of metres. Given the lithological differences across such faults and the scale of their displacements, such fault scarps may simply be an erosional effect, reflecting either no or minimal recent displacements (e.g. the profiles of Dewey (2000) indicate that the Erriff Fault has a displacement: scarp height ratio of in excess of 10). An alternative explanation for the 'youthful' nature of the Connemara terrain is that differential erosion of Carboniferous cover (typically limestone) above the Caledonian basement has preferentially exposed the base Carboniferous unconformity, producing a horizon which is reminiscent of a peneplain, but instead, reflects differential erosion of a faulted stratigraphic sequence. Such erosion across buried, 'dead', faults has led to the formation of resequent fault scarps which are observed in parts of the Western USA (Babenroth and Strahler, 1945); the latter have fault scarp topographic expressions which can be similar to those of currently active Basin and Range normal faults, even though they are pre-Cenozoic structures.

Indirect evidence suggesting that several hundred metre-scale Cenozoic normal fault displacements are unrealistic is provided by constraints derived to the west and further to the east. Given the scale of these faults one would expect some evidence in offshore west of Ireland for the presence of equivalent-sized structures. Nevertheless, no such evidence exists either in the Slyne Trough, immediately to the west, or within the Porcupine Basin further to the southwest (Shannon et al., 1993). Tectonic normal faults within the Slyne Trough which could be Cenozoic in age, are very sparse and in any case have displacements of no greater than *ca.* 100 m and fault strikes which are roughly N–S (Cunningham, 2000), characteristics which are therefore entirely at variance with those of the onshore faults of Connemara. Cenozoic tectonic normal faults within the Porcupine Basin are more abundant, but are still relatively unusual, and have throws of no greater than 200 m and are N–S striking (Shannon et al., 1993; Worthington, 2006). The Porcupine faults reflect a very minor phase of reactivation of earlier Jurassic faults arising from E–W extension during the Late Eocene. The faulting of the Connemara area has, by contrast, been attributed by Dewey (2000) to Cenozoic extensional block faulting probably superimposed upon a rift shoulder related to major offshore extension in the Porcupine, Slyne and Erris troughs. Since there is no compelling evidence for any kinematic association between the minor normal faults in offshore west of Ireland and the much larger and differently oriented normal faults of Connemara, there are therefore no grounds for suggesting that the latter are Cenozoic in age. Although our analysis concurs with a recent study attributing the deformation of the base Carboniferous unconformity to fault-related deformation, including the footwall uplift and hanging wall rollover predicted by flexural isostatic models of faulting (Badley, 2001), we suggest that the deformation is predominantly of Carboniferous, rather than Cenozoic, age, a suggestion that is perfectly reasonable from a modelling perspective (Mike Badley *pers com.,* 2004).

Further to the northeast of Ireland, there is, however, evidence of significant Cenozoic faulting. In Northern Ireland there is a more extensive Mesozoic to Cenozoic record, which includes Palaeocene basalts (Antrim Plateau Basalts) and Oligocene sediments (Fig. 3). A number of previous workers (Fowler and Robbie, 1961; George, 1967; Kerr, 1989; Legg, 1992) have, using outcrop, borehole and geophysical data (gravimetric, magnetic and some seismic reflection), identified numerous Cenozoic faults within this region. A map of Cenozoic faults, i.e. post-Palaeocene basalts and post-Oligocene sediments, highlights the presence of two fault trends, the first striking NNW–SSE and the second striking NE–SW (Fig. 8). The latter lie along the established Carboniferous and earlier major faults, such as the Tow Valley Fault (TVF) and the Temple-Patrick Fault (TPF), which are believed to have been reactivated (Kerr, 1989). Measurements of Cenozoic throws from published work (Fowler and Robbie, 1961; George, 1967; Kerr, 1989; Legg, 1992) and from map data indicate that, in these circumstances, the Cenozoic normal (i.e. vertical) displacements, which are up to 300 m, represent no more than *ca.* 10% of the total throw on these NE–SW trending faults (Fig. 7). The largest concentration of demonstrable Cenozoic normal faults is associated with the Lough Neagh Basin (Fowler and Robbie, 1961; Charlesworth, 1963; George, 1967; Kerr, 1989). Here, faults typically with NE–SW or N–S strikes, bound the margins of the basin and have displacements of up to *ca.* 250 m: the NE margin is not as clearly faulted as the other margins. Beyond the basin, the larger faults appear to be locally reactivated Palaeozoic/Carboniferous structures, such as the Clogher Valley Fault on the north-western side, although associated normal fault displacements may not be greater than *ca.* 100 m. The localised orthogonal fault pattern, the down-warped nature of this Oligocene basin, in which *ca.* 500 m of Oligocene sediments have accumulated (Fowler and Robbie, 1961; Charlesworth, 1963; George, 1967; Kerr, 1987), and its spatial association with the thickest part of the pre-existing basalts has led to suggestions that its origin may be related to collapse of the basalt pile (Paul Lyle *pers comm*., 2005). Another possibility arises from the spatial association between the basin and an array of N- to NNW-striking dextral strike-slip faults (Quinn, 2006; Cooper et al., 2010). These faults bound the western margin of the basin and extend southwards where they offset the Mourne Tertiary igneous intrusions. Some of these faults are the onshore equivalent of structures like the Codling Fault, a dextral strike-slip fault which extends towards the SSE within the Irish Sea and has km-scale displacements which have been interpreted as being of Cenozoic age (Croker, 1995; Cooper et al., 2010). Another well known dextral strike-slip fault occurring further to the south, the Sticklepath Fault of SW England, is also believed to be of Cenozoic age (Turner, 1997; Anderton, 2000). Whilst it is possible that the Kingscourt Fault (Fig. 8), an east-dipping normal fault which is known to have been active in the Lower Carboniferous (Strogen et al., 1995), may be the southern correlative of some of the N–S striking faults on the western margin of Lough Allen, we think this is unlikely principally because existing maps suggest that it may become an NE-striking structure immediately to the north and south of its central N–S striking segment. Although the eastern margin of the Lough Neagh Basin is not cross-cut by faults with larger, and mappable, normal displacements, it is possible that a dextral fault system could occupy this margin and that the Lough Neagh Basin could have formed, at least partly, as a pull-apart associated with right stepping dextral strike-slip faults (Quinn, 2006; Cooper et al., 2010). All of these strike-slip faults are most easily reconciled with approximately N–S (or NNE–SSW) directed Alpine-related compression (Turner, 1997; Williams et al., 2005).

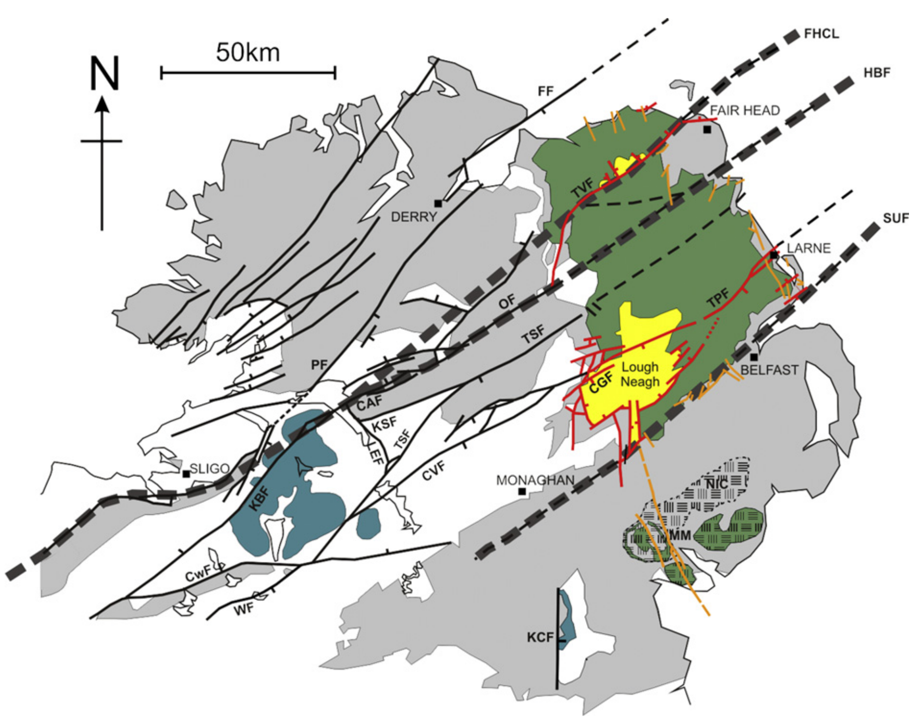

Fig. 8. Simplified geological map and post-base Carboniferous fault map showing post-base Carboniferous normal faults (black), those with measurable Cenozoic throws (red) and small-scale Cenozoic faults of strike-slip or dip-slip origin (orange): the latter include the NNW oriented strike-slip faults transecting the Mourne Mountains granite (MM). Fault labels and key as in Fig. 3. Dashed black lines are likely lateral continuations of post-base Carboniferous faults (short broken line) and the eastern extension of major Caledonian lineaments (long broken lines) are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Why only a single (i.e. dextral) array of strike-slip faults is developed is at first puzzling. However, associated conjugate sinistral strike-slip faults would be expected to be approximately ENE-oriented and, therefore, approximately collinear with pre-existing Caledonian and Carboniferous structures. The Tow Valley Fault is an excellent example of a structure which is believed to have had an earlier history but has, in Cenozoic times, been reactivated as a sinistral strike-slip fault, with the formation of localised pull-apart basins in its hanging wall (Parnell et al., 1989; Mitchell, 2004; Cooper et al., 2010). Support for the operation of sinistral strike-slip displacements along other ENE faults is also provided by recent magnetic data acquired by the Geological Survey of Northern Ireland (Cooper et al., 2010), which demonstrates the existence of up to 2 km-scale sinistral displacements along earlier Caledonian/Carboniferous ENE-oriented faults, such as the Tempo-Six Mile Cross Fault and the Castle-Archdale Fault. The available evidence therefore suggests that conjugate pairs of strike-slip faults arise from Alpine compression, with one fault set which is predominantly newly formed and another set which mainly comprises reactivated structures.

This study sees no evidence, onshore or offshore, for any significant Cenozoic normal faulting across the post-base Carboniferous faults of Clew Bay and Connemara as previously suggested by Dewey and McKerrow (1963) and Dewey (2000). This view is supported by the scale and paucity of Cenozoic normal faults in offshore west of Ireland and by the subordinate nature of possible Cenozoic normal displacements along earlier structures further to the northeast. Instead, the geometries of these normal faults are consistent with Lower Carboniferous faulting, a conclusion which is explored further in a later section.

6. The role of earlier structure

The Carboniferous fault system described in this study runs parallel to recognised Caledonian basement lineaments, such as the Fair Head - Clew Bay Lineament (FHCL), the Southern Uplands Fault (SUF) and the Highland Boundary Fault (HBF; Fig. 3). The most influential of these basement structures in the development of the Carboniferous faults described in this work, is the FHCL, which is believed to be a continuation of the HBF defined in the UK. Not only do these basins parallel and lie proximal to this basement structure, but also the largest displacement faults within these basins, i.e. the CBF, NOXF, BSHF and the CAF, are all located directly along this structure. The importance of this basement structure has previously been suggested by McCaffrey (1997) who showed that it was characterised by large-scale sinistral strike-slip faulting during the Acadian and by the subsequent formation of small strike-slip Old Red Sandstone basins. These observations suggest that existing basement structure is important in localising the structure and strain of later deformations. The present study complements previous work which has referred to the similarity in structural trends between Carboniferous faults and basement structure in the UK (Bott, 1987; Gawthorpe et al., 1989; Kimble et al., 1989; Chadwick and Holliday, 1991; Woodcock and Strachan, 2000; Guion et al., 2000) and also in Ireland (Brown and Williams, 1985; Johnston et al., 1996, Johnson, 1999; O'Reilly et al., 1999). This feature is highlighted by the map of Fig. 1 which shows that Lower Carboniferous basins clearly follow earlier Caledonian structures/trends across both Britain and Ireland. Though it is clear that Carboniferous faults are strongly controlled by existing structure in terms of both their distribution and trend, for a variety of reasons it is thought unlikely that individual Caledonian structures are reactivated. Firstly, there are no grounds for suggesting that pre-existing Caledonian structures, such as the FHCL or the Iapetus Suture which are spatially associated with later Carboniferous faults with km-scale displacements (i.e. the Clew Bay-Leck Fault, and the Navan Fault system), have geometries which are typical of normal faults. Secondly, available constraints for Carboniferous normal faults indicates that they have conventional normal fault geometries, with fault dips of between *ca.* 50°–75°, within Lower Carboniferous rocks (Johnston et al., 1996; Fusciardi et al., 2004; Worthington, 2006). Thirdly, whilst the locus of strain within the normal fault systems broadly reflects the presence of pre-existing structures, the system comprises arrays of faults which are both hard-linked and soft-linked, often displaying along-strike polarity changes, features which are not characteristic of the laterally extensive Caledonian structures. We suggest therefore that although the available evidence does not support the reactivation of individual pre-existing structures as normal faults, major Caledonian lineaments were the locus of higher strain during subsequent Carboniferous rifting and must therefore have represented major crustal heterogeneities in the localisation of later faults. The importance of the inheritance of structure, and trends, is reinforced by the fact that the later Carboniferous normal faults are subsequently reactivated as sinistral strike-slip faults in Cenozoic times (Cooper et al., 2010).

7. Discussion

Quantitative analysis of structural and stratigraphic data from NW Ireland suggests that Lower Carboniferous deformation is continuous across Ireland, displaying changes in symmetry of normal fault arrays but with kinematically coherent fault displacement patterns and continuity of fault-related strain (Walsh and Watterson, 1991). Along-strike coherence of displacement and strain and associated kinematic constraints together support the notion that deformation is predominantly Carboniferous in age. Associated strains accommodated by normal faulting are, at *ca.* 5%, relatively low but are, nevertheless consistent with other parts of the Carboniferous rift system in both Britain and the Canadian Maritime Provinces. The subordinate nature of Cenozoic normal fault displacements, which represent no more than *ca.* 10% of the vertical displacements on earlier Carboniferous structures, contrasts with the likelihood of significant, km-scale, lateral displacements on newly developed N- and NNW-striking dextral strike-slip faults, with complementary sinistral motion on pre-existing ENE-striking Carboniferous faults (Parnell et al., 1989; Cooper et al., 2010). These conjugate faults, which are interpreted to arise from approximately N–S to NNE–SSW oriented Alpine compression, are apparently best developed in the eastern part of Ireland, with no evidence of km-scale Cenozoic lateral displacements along faults within the western part of Ireland; the presence of Cenozoic lateral displacements is, however, possible and we encourage future studies to investigate their likely significance. Although, Cenozoic fault-related vertical displacements are believed to be of subordinate significance particularly towards the west of Ireland, Carboniferous faulting has indirectly had a profound effect on the Cenozoic, to recent, landscape of Ireland.

In the west of Ireland the base Carboniferous unconformity emerges westwards so that eventually, if exposed at all, it occupies the tops of occasional mountains. This emergence means that the landscape partly reflects the geometry of the faulted base Carboniferous surface, because of the differential erosion of overlying Carboniferous clastic and limestone sequences, on the one hand, and Caledonian 'basement' on the other. As a consequence, initially buried structure now forms emergent and locally very prominent landmarks, such as the scarps associated with the Erriff Faults and the mountains, including the 750 m high Croagh Patrick, on the southern shores of Clew Bay which represent the footwall to the Clew Bay-Leck Fault which downthrows to the north. These features are interpreted to result from differential erosion of Caledonian basement and Carboniferous cover across 'dead' faults, to form resequent fault scarps (Babenroth and Strahler, 1945). Basement rocks commonly form topographic highs across Ireland and the UK, with Carboniferous cover sequences that are dominated by limestones, forming the flat-lying lowlands, particularly noticeable in the Irish Midlands. This relationship is primarily due to the preferential dissolution and erosion of Carboniferous limestone (Simms, 2004), the effect of which is to generate a landscape which to some extent mimics that of the base Carboniferous structure. For example, a major feature of the Carboniferous fault system described in this paper, is the change in polarity from a predominantly southward dipping fault system in the northeast, to a northward dipping fault system in the west of Ireland. This change in polarity is reflected in the landscape, with the presence of either southward or northward facing uplifted footwall blocks, respectively. This is particularly noticeable in the west of Ireland in the area of Clew Bay and Connemara (Fig. 4c) where the uplifted footwall blocks can be clearly defined, such as along the Erriff, Carrowkennedy and Clew Bay Faults. Further to the east the landscape of the Ox Mountains, which is bordered by the major northward downthrowing North Ox Mountains Fault, is reminiscent of an emergent footwall block which defines a dip-slope towards the south. By contrast, the Lough Allen Basin is uniquely situated between two areas of strongly polarised fault systems and due to this symmetrical structure, emergent basement blocks are less prominent and the area is relatively low lying (Fig. 3). The recognition of the existence of Carboniferous faults in the west of Ireland suggests that although the terrain is not that of a faulted Cenozoic peneplain, it does expose the deeper parts of Carboniferous fault systems, a conclusion which may have significance for future studies of the faulting and related fluid flow and Zn–Pb mineralisation of Irish mineral deposits.

Using structural geological constraints, this study suggests that the vertical displacements on Cenozoic faults are subordinate compared to those of Lower Carboniferous structures. A variety of other methods or constraints could, in principle, be used to substantiate, or even contest, these conclusions. Thermal History Construction methods, particularly apatite fission track techniques (Gleadow et al., 1986; Laslett et al., 1987), could lead to an improved understanding of the scale and timing of faulting in Ireland. Apatite fission track analysis provides quantitative constraints on the timing of cooling episodes and the temperature of samples at the onset of those episodes. It can therefore yield useful information on normal faulting leading to footwall uplift, erosion, denudation and as a consequence cooling. Recent studies by Allen et al. (2002) and Cunningham et al. (2003) have examined the uplift/subsidence history of Ireland since post-Variscan times and in particular during the Cenozoic. The findings of Allen et al. (2002) indicated that Ireland was uplifted and emergent during the Cenozoic, remaining relatively stable, though on a smaller temporal and spatial scales there is some evidence that vertical motions occurred on *ca.* 10 km-scale 'patches'. The origin of such small-scale motions is as yet unclear, and it is possible that they are artefacts arising from, for example, sampling effects, complexities in thermal history or inadequacies in the method. Cunningham et al. (2003) tried to explain some apparent small-scale variations in cooling histories (as shown by Allen et al., 2002) transecting the Leinster granite in SE Ireland, by interpreting the presence of WNW striking Cenozoic normal faults, with displacements of up to several hundred metres. However, these interpreted faults do not offset the base Carboniferous unconformity on the western side of the Leinster Granite, even though an apparent offset of several kms would be expected. Although it remains to be seen what significance can be attached to interpreted small-scale spatial variations in vertical motions, the conclusion that Ireland remained relatively stable throughout the Cenozoic (Allen et al., 2002; Green et al., 1993, 1999) is more robust and may provide a rationale for the paucity of Cenozoic faulting across onshore Ireland, a feature which contrasts with the more faulted nature of less stable offshore basins off the west of Ireland (Figs. 3 and 4) and in the Irish sea (e.g. Turner, 1997).

8. Conclusions

1. Lower Carboniferous basin structure, strain, and displacement define a coherent and continuous fault system across the northern parts of Ireland. This system forms a link between comparable sized and coeval basins in Northern England and Scotland to the east and in the Canadian Maritime Provinces to the west.
2. The Lower Carboniferous fault system comprises discontinuous faults which together preserve fault displacements across a system which changes polarity from a predominantly southward dipping system in the Fintona area through to a northward dipping system in the west of Ireland, with the intervening Lough Allen Basin area showing a more symmetrical basin geometry.
3. In Clew Bay and Connemara in the west of Ireland, post-base Carboniferous normal faults provide clear evidence of Lower Carboniferous fault-related sequence thickness changes and by analogy with better defined structures along-strike to the northeast, are interpreted to be predominately Carboniferous structures. There is no direct outcrop evidence for Cenozoic normal faulting in the west of Ireland, and constraints from offshore Ireland and from onshore further to the NE support this view. Cenozoic faulting is dominated by strike-slip displacements on dextral N- and NNE- oriented faults and possibly also by sinistral strike-slip reactivation of ENE Carboniferous and/or Caledonian faults.
4. Pre-existing Caledonian basement structures/fabrics have had a strong influence on the distribution and structure of Carboniferous basins in the northwest of Ireland. Major Carboniferous faults are localised along a major basement structure, the Fair Head-Clew Bay Lineament, which trends NE–SW across Ireland. Pre-existing Caledonian, or earlier, structures or structural heterogeneities are not likely to have been individually reactivated but are responsible for the preferred localisation of later structures.
5. The landscape of Western Ireland, where both Caledonian and Carboniferous rocks are exposed, is to some significant extent controlled by Carboniferous faulting of the base Carboniferous unconformity. Fault system geometry is reflected in the topography by features such as the uplifted emergent basement footwall blocks of the Croagh Patrick and Ox Mountains. The preservation of emergent Caledonian footwall blocks and associated topographically lower, and Carboniferous filled, hanging walls is attributed to differential erosion of Carboniferous limestones and underlying Caledonian basement. Differential erosion exposes 'dead' faults as resequent fault scarps, which are not to be confused with fault scarps arising from more recent Cenozoic faulting.
6. The exposure of deeper levels of Carboniferous faults within the Caledonides of Western Ireland, due to uplift and erosion, provides structural definition which has eluded previous studies in the poorly exposed Carboniferous successions of the Central Plains of Ireland. Analysis of these faults may provide useful constraints on the fluid flow systems underlying and sourcing fault-controlled Carboniferous Zn–Pb mineral deposits.

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