Regional conductivity data used to reassess Lower Palaeozoic structure in the Northern Ireland sector of the Southern Uplands–Down-Longford terrane

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Running header: Lower Palaeozoic structure in Northern Ireland

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Abstract

A high-resolution, airborne conductivity survey has proved spectacularly successful in delineating the zones of carbonaceous mudstone (Moffat Shale Group) that form the structural and stratigraphical base of individual, sandstone-dominated tracts within the Northern Ireland sector of the Southern Uplands–Down-Longford, Ordovician-Silurian accretionary terrane. The anomalies associated with both outcropping and concealed mudstone allow the major, tract boundary faults to be plotted across large areas of poor exposure to reveal a large-scale regional swing in the strike of the major tract boundary faults from their prevalent ENE-WSW trend and into a NE-SW orientation. The fault traces defined by the geophysical anomalies cut across those, deduced by extrapolation into an area of sparse bedrock exposure, which are illustrated on the current geological map. A substantial revision of the regional fault pattern is thus required. In places the major tract boundary faults appear to anastomose into strike-slip duplexes, suggesting transpression in the accretionary regime. However, the wholesale realignment of the strike trend is likely to have had a later, post-accretion origin, perhaps involving a releasing bend on a major, strike-parallel fault that controlled emplacement of the Newry granitoid pluton (425 Ma), and might also be associated with Au mineralization in Armagh and Monaghan.

The paratectonic zone of the British and Irish Caledonides includes the Southern Uplands – Down-Longford (SUDL) Terrane (Fig. 1), an imbricate thrust belt of turbidite-facies strata that developed from the late Ordovician to the mid-Silurian along the Laurentian margin of the Iapetus Ocean. The Southern Upland Fault forms the NW margin of the terrane which, at its southern margin, occupies the hanging wall of the Iapetus Suture (Fig. 1). The SUDL Terrane has outcrop areas of about 10 000 km^2 in southern Scotland and about 6 000 km^2 in Ireland (Fig. 1), where the outcrop extends across much of Counties Down and Armagh in Northern Ireland (c. 3 500 km^2) and thence into the Republic of Ireland, mostly within parts of Counties Louth, Monaghan, Cavan and Longford (c. 2 500 km^2).

Internally, the terrane comprises at least 20 fault-defined tracts elongated NE-SW parallel to strike, in most of which the strata are steeply inclined and become younger towards the NW; in contrast, the minimum ages of individual tracts generally become sequentially younger towards the SE (Floyd 2001 and references therein). Each tract comprises a thick sandstone succession (up to 2 km) typically underlain by a thin mudstone unit (<150 m). Within the Scottish Southern Uplands the minimum age of the component tracts ranges from Caradoc (Late Ordovician) in the NW adjacent to the Southern Upland Fault, to Wenlock (Mid-Silurian) in the SE adjacent to the Iapetus Suture. In Northern Ireland the stratigraphical range at outcrop is more restricted than that seen in Scotland. The north-western terrane boundary, the continuation of the Southern Upland Fault, is overstepped by Carboniferous and younger strata so that the outcrop area of Ordovician tracts is limited and the equivalents to the northernmost tracts of the Southern Uplands, if present, are concealed; rather more Ordovician strata crop out in the Irish Republic. The south-east limit of the terrane lies within the Irish Republic, where Wenlock strata have been reported from County Louth (Vaughan & Johnson 1992); elsewhere the Wenlock and the youngest of the Llandovery tracts are unconformably overlain by Carboniferous strata. Thus the outcrop of the SUDL Terrane in Northern Ireland largely comprises Llandovery tracts of the Gala and Hawick Groups. A more detailed correlation has been established (Barnes *et al.* 1987) for the Gala and Hawick tracts on either side of the North Channel, in the Rhins of Galloway (Scotland) and the Ards

Peninsula (Northern Ireland). From this it is apparent that the Gala Group outcrop has a significantly larger cross-strike width in Northern Ireland (c. 27 km) than in south-west Scotland (c. 16 km) and that it contains more individual tracts.

In south-west Scotland the SUDL terrane is intruded by granitic plutons of Early Devonian age. The Loch Doon pluton was emplaced into the Ordovician sector, the Cairnsmore of Fleet pluton into the Gala Group, and the Criffel pluton into the Hawick Group. In Northern Ireland, the Newry granodiorite pluton, of probable Late Silurian age, straddles the Gala-Hawick group boundary, and at its western end has itself been intruded by the Palaeogene Slieve Gullion central complex. Other largely granitic, Palaeogene intrusions into the Hawick Group, make up the Mourne Mountains central complex.

Despite the geological similarities between the Scottish and Irish sectors of the terrane, there are marked topographical differences strongly influenced by contrasting histories of glaciation. In Scotland, the Southern Uplands region is a range of moorland hills with summit plateaux, rising to well over 300 m OD, mostly either formed in exposed bedrock or in bedrock covered by only a thin veneer of peat and glacial deposits. Fast-flowing streams draining the high ground commonly cut through the flanking glacial deposits to expose bedrock. In contrast, the SUDL terrane in Northern Ireland forms low-lying agricultural land much of which is below 100 m OD. Natural exposure is uncommon and the gently-flowing streams only rarely cut down to bedrock through the thick surface layer of drumlinised till; individual drumlins rise from 5 to 50 m. This inevitably means more uncertainty in geological interpretation for Down-Armagh than for the Scottish Southern Uplands, where the more abundant bedrock exposure provides better control.

This paper is concerned primarily with the Northern Irish part of the terrane (hereafter Down-Armagh), for which new high-resolution geophysical data were acquired in 2005-2006 as part of the Tellus programme of geological exploration, managed by the Geological Survey of Northern Ireland and funded by the Department of Enterprise, Trade and Investment. The particular importance of the geophysical data lies in the insight it brings to bear on a large poorly exposed area, but one in which contrasting lithologies have markedly different physical properties.

Mapping of the electrical conductivity constrasts is provided by the airborne electromagnetic (AEM) component of the geophysical survey data. Conductivity is a fundamental electrical property of rocks. The bulk, or formation, conductivity that is measured by the AEM survey, may be influenced by a number of factors including mineralogy, porosity and fluid content. These associations allow the survey data to be used across a range of geological and structural investigations. The data, of themselves, do not provide discrimination with regard to the prevailing mechanism(s) controlling any observed variation in the property and this becomes a matter of interpretation. The AEM measurement provides a spatial average of bulk conductivity across a significant subsurface volume (Beamish, 2004). Depth discrimination is largely provided by the measurement frequencies employed with depth of penetration increasing with decreasing frequency. The single frequency data set used here is typically most sensitive to variations across a lateral distance of ~180 m and a depth range from ~60 to 100 m.

The AEM data set reveals a marked conductivity contrast between the dominant sandstone lithology and the less abundant, more conductive, carbonaceous mudstone of the Moffat Shale Group that forms the base of the sequence within each structural tract and which has been utilized as a fissile *décollement* horizon during thrust imbrication. We utilize the quasi-linear conductivity anomalies that arise from this contrast to reassess the structural configuration of the SUDL terrane in Down-Longford, and its representation on the current published geological map (Geological Survey of Northern Ireland 1997). A greater complexity of faulting can be demonstrated than has been previously appreciated, whilst there is a major deviation in the regional strike away from the prevalent ENE-WSW trend illustrated on that map.

The regional tectonostratigraphic setting

The structural geometry of the SUDL terrane developed within an accretionary thrust complex at the Laurentian continental margin during northward subduction of the Iapetus Ocean (Leggett *et al*. 1979; Anderson 2001, 2004; Stone & Merriman 2004 and references therein). The sequential incorporation of tectonic tracts into an active thrust system means that the first deformation was diachronous, older in the north than in the south (Barnes *et al*. 1989), and the structural profiles can vary along strike (Rushton *et al*. 1996). Each tract ideally comprises a very thin (generally <150 m) black shale sequence (the Moffat Shale Group) overlain by a very much thicker (up to about 2 000 m) sandstone succession. The Moffat Shale Group (MSG) may span a range of late Ordovician to Silurian graptolite biozones, the upper limit becoming younger southward, but it is rare for the sandstone succession to contain strata spanning more than one biozone (Floyd 2001). Each biozone represents an interval of about 1.5 million years in the late Ordovician, reducing to nearer 0.5 million years by the mid-Silurian (Hughes 1995). The tract relationships are the critical evidence for the imbricate thrust geometry.

Whilst much of the detailed work on the SUDL terrane has been in the Scottish sector, its application to the Northern Ireland sector is well established. In regional terms (Fig. 1), the northern tracts of Caradoc and Ashgill (Upper Ordovician) age comprise the Leadhills Supergroup (Floyd 1996) for which the Orlock Bridge Fault (Anderson & Oliver 1986) forms the southern margin. This zone is also known as the Northern Belt, following Peach & Horne (1899); though originally applied in southern Scotland the term is also in common usage for the Ordovician rocks north of the Orlock Bridge Fault in Ireland. Southwards from the Orlock Bridge Fault in south-west Scotland, and as far as the Balmae Burn Fault, a series of Llandovery (Lower Silurian) tracts forms the Gala and Hawick groups. These two groups are separated from each other by the Laurieston Fault in Scotland (Akhurst *et al*. 2001), the equivalent structure in Northern Ireland being known as the Cloghy Fault (Anderson and Cameron 1979). Following Peach and Horne (1899) the whole Llandovery zone, together with its MSG Ordovician inliers, is also known as the Central Belt throughout the SUDL terrane. South of the Balmae Burn Fault in Scotland, the Riccarton Group comprises Wenlock (Middle Silurian) tracts and is otherwise known as the Southern Belt (Peach & Horne 1899); there is no equivalent at outcrop in Northern Ireland though Wenlock strata occur some 22 km to the south in the Irish Republic (Vaughan & Johnson 1992).

Despite the broad, large-scale continuity of the structural tracts and their boundary faults there is considerable variation in the detail of the thrust architecture along strike. Rushton et al. (1996) have discussed variation within the Southern Uplands sector of the SUDL terrane in terms of a prograding thrust front being locally obstructed with resulting development of back thrusts (creating structural pop-ups) and out-of-sequence thrusts (cf. McCurry & Anderson, 1989). It is also clear that the accretion of the youngest Gala Group (and some subsequent) tracts was effected under the influence of a sinistrally transpressive stress regime. This was a widespread phenomenon during the Silurian closure of the Iapetus Ocean (Anderson 1987, 2001; Soper *et al*. 1992).

The Central Belt represents a far greater proportion of the SUDL terrane in Northern Ireland than it does in south-west Scotland. There would appear to be more similarity with the north-east of the Scottish sector, where the Ordovician tracts are eliminated by a combination of faulting and an unconformable cover of Carboniferous strata. In tandem with this effect, the Scottish Central Belt widens progressively north-eastward through the multiplication of Hawick Group tracts and the introduction of an eastward-broadening structural wedge, bounded by the Moffat Valley and Ettrick Valley faults, in which several tracts have compositional characteristics that are in some ways intermediate between the Gala and Hawick groups. If these are assigned to the Gala Group there is a corresponding increase in the number of younger tracts therein, but the effect on the Group's outcrop width is mitigated by a loss of older Gala Group tracts (Rushton *et al*. 1996). So, for example, in the Rhins of Galloway the Gala Group outcrop has been divided into a series of structural tracts (Stone 1995) numbered in terms of age from 1 (the oldest, most northerly tract) to 8 (the youngest and most southerly tract; tracts 7 and 8 form the southern 25% of the Gala Group's outcrop width. This compares with the situation farther north-east, in the Peebles district, where the repetition of Gala 7 tracts, coupled with the structural elimination of several younger tracts, means that strata of Gala 7 age make up about 75% of the Group's outcrop (Rushton *et al*., 1996). A comparable situation is described from Northern Ireland (Anderson, 2004) where, on the Ards Peninsula, tracts of Gala 7 age (or younger) make up almost 80% of the Gala Group's outcrop width. In this respect an important correlative structure is the major strike fault marking the northern limit of Gala 7 tracts: the Drumbreddan Bay Fault in south-west Scotland, the Southern Coalpit Bay Fault in Northern Ireland.

Independent confirmation of the compositional continuity within individual tracts is provided by regional geochemical data derived from the systematic analysis of stream sediment. Over the Southern Uplands, the pattern of bedrock tracts, extended NE-SW along strike but relatively narrow in the NW-SW cross-strike direction, is mirrored in the striped patterns of element distribution seen in the British Geological Survey's regional geochemical dataset (G-BASE: British Geological Survey 1993). Despite glaciation, the stream sediment geochemical patterns spatially mimic the outcrop of underlying bedrock lithologies so that, over the sandstone-dominated tracts of the Southern Uplands sector of the SUDL terrane, contoured regional geochemical data for many elements produce a marked strike-parallel, NE-SW linearity. Although the steepest concentration gradients commonly coincide with tract-bounding faults, different elements show different distribution patterns, a relationship that has been interpreted as reflecting the compositional contrasts between the sandstones contained within the various tracts (Stone *et al*. 1999, 2004 and references therein). Regional geochemical data collected as part of the Tellus programme show that comparable patterns of element distribution can be established over the Northern Ireland sector of the SUDL terrane.

In Down-Armagh, a pattern of generally linear, fault-defined tracts similar to that seen in the Southern Uplands has been well established in the fairly continuous outcrop on the County Down coast (Anderson and Cameron 1979, Cameron 1981, Craig 1984) and then extrapolated westward, with much less certainty, across inland Down and Armagh using the relatively small number of MSG outcrops and an even smaller number of age determinations based on the contained graptolites. As we demonstrate below, the new conductivity data dictate a significant revision of the current tract maps, particularly in western Armagh, where the Lower Palaeozoic rocks have not been mapped for over a century and are probably less well exposed than in any other part of the SUDL Terrane.

Geophysical methodology

The Tellus airborne geophysical survey collected magnetic, radiometric and electromagnetic (EM) data at 200 m line intervals across Northern Ireland. The nominal flight height was 56 m and survey lines were oriented at 345 degrees, roughly perpendicular to the Down-Armagh tract boundaries. The present study uses the EM data obtained across the SUDL terrane with a sampling interval of ~15 m along the flight direction. The Tellus project acquired two-frequency EM data (3 and 14 kHz) in 2005 across the western area and four-frequency data (0.9, 3, 12 and 25 kHz) across the eastern area in 2006. The lowest, and deepest penetrating, common frequency across the entire SUDL Terrane is provided by the data acquired at 3 kHz.

The 3 kHz EM data have been converted to a half-space (i.e. a model that is vertically uniform) estimate of apparent conductivity. The inversion method is described by Beamish (2002). The 3 kHz model estimates, when gridded, form a map of the conductivity distribution that is most influenced by conductivity variations in the upper 60 to 100 m. In order to extract more precise depth information, multi-frequency inversion is used to provide multi-layer models. There are two main interpretation issues that arise when AEM data survey data are obtained across populated areas. The first is that air-space regulations require a high-fly condition above built structures and this results in reduction/loss of signal-to-noise. The second issue arises from a variety of noise sources such as power lines. These perturbations to the conductivity results are invariably high-wavenumber and produce quasi-linear anomalies.

The SUDL Terrane is pervasively resistive and structural influences on conductivity variations arise as largely weak, laterally compact, conductive features. At- and near-surface variations provide the strongest anomalies (Fig. 2); it is apparent however (from modeling studies) that many of the conductive features exist at depths in excess of 60 m. This makes assessments of spatial continuity difficult. For this particular problem we have used a transform that has only been previously applied to magnetic field data. The transform used is the Tilt Angle or Tilt Derivative (TDR) as defined by Millar & Singh (1994) and discussed by Verduzco *et al*. (2004). The TDR transform, as applied to EM data, amplifies and normalizes all the lateral gradients in the conductivity distribution and provides a map outlining all the conductive features. The TDR transform is formed by taking the arctangent of the ratio of the vertical to total horizontal field derivatives. The arctangent function restricts the transform to a range from -90 degrees to 90 degrees. When applied to conductivity data, the mapping of the TDR transform across the interval from 0 degrees to 90 degrees allows the centre and width of conductive zones to be identified (Beamish, 2009). Geological features and cultural noise may be equally amplified. Deeper geological features tend to be associated with signals of longer spatial wavelength so that some filtering of the high-wavenumber, highly localized features may be undertaken to assist with tracing the weaker conductive features in the data. When referring to anomalies we refer to the conductive features (here largely interpreted as the MSG) that are distinct , by virtue of being laterally compact and more conductive, than the dominant sandstone lithologies. Features thought to be due to power-lines and roads have been identified to allow a more robust geological interpretation.

Correlation of geological and geophysical features

A conductivity contrast would be expected between the dominant sandstone lithology and the less abundant mudstone, in particular, the carbonaceous MSG strata that form the *décollement* horizon at the stratigraphical base of many of the structural tracts. Such a lithological contrast would seem to be the likely cause of the linear, though somewhat sinuous, NNE-SSW anomaly pattern (Figure 2), but the association can be most convincingly demonstrated in the geological situation with least lithological contrast. This is found in the south-east of County Down where much of the outcrop consists of Hawick Group strata contained within several structural tracts (Figure 3). In general, the Hawick Group tracts do not feature a basal sequence of black shale, and so would not be expected to have any associated conductivity anomaly. A rare exception to this generality is seen extending south-westwards from the southern end of the Ards Peninsula where a Hawick Group tract has, at its stratigraphical base, the Tieveshilly Shales and Mudstones, a component unit of the Moffat Shale Group and about 80 m thick (Anderson & Rickards 2000). In the outcrop on the Ards Peninsula the Tieveshilly strata lie in the core of a hanging-wall anticline developed immediately north of the major Tieveshilly Fault and separated from that fault by the overlying Gala Group Tara Sandstone Formation (Anderson 2004, figures 4.3 and 4.5). The outcrop of Tieveshilly Shales and Mudstones in the core of the anticline coincides with a linear conductivity anomaly (A on Figure 3) which, when traced to the south-west (B on Figure 3), shows that the southern limb of the anticline is progressively cut out so that the Tieveshilly strata are brought into proximity with the fault. This is a neat demonstration of the association of the conductivity anomaly with the MSG lithology rather than with some specifically fault-related feature. The outcrops of MSG black mudstone extending south-west from Tieveshilly are mapped on the Northern Ireland, 1: 250 000 sheet (Geological Survey of Northern Ireland 1997) as lenticular bodies arranged in a linear zone defining a major tract boundary. Closely coincident with that zone is a linear conductivity anomaly that strongly suggests unexposed continuity between the MSG inliers. A linear west-southwestward extension of a conductivity anomaly for some distance beyond the most southwesterly of the exposed MSG inliers (C on Figure 3) is best explained by the unexposed continuity of the mudstone lithology, albeit the along-strike-correlation is complicated by approximately north-south cross-faults.

The coincidence of the linear Moffat Shale zone with a conductivity anomaly, in an area which is otherwise devoid of carbonaceous mudstone and relatively bland in conductivity terms, is strongly supportive of a more general association between the MSG lithology and zones of increased conductivity. Carrying this association northwards in Figure 3, to the vicinity of Downpatrick, there is another linear conductivity anomaly, parallel to the Tieveshilly zone and in part coincident with the tract boundary separating the Gala and Hawick groups, the Cloghy Fault (Anderson & Cameron 1979). The conductivity anomaly suggests the presence of unexposed MSG mudstone at the base of the southernmost Gala Group tract, and that the boundary between the Gala and Hawick groups, as it runs NE from Downpatrick, is less affected by faulting than has been supposed. However, at this point a note of caution is justified, as follows.

Moffat Shale Group strata have not been recorded along the Cloghy Fault. Further, the Gala Group tract to the north (the Portavogie tract of Anderson & Cameron 1979) is structurally anomalous in that the majority of its beds young towards the south, within the northern limb of a large (and relatively simple) syncline. The hinge zone of the syncline lies close to the Cloghy Fault and there is insufficient room for a symmetrically large and equivalent southern limb between the hinge zone and the fault (for a full structural illustration see Anderson & Cameron’s figure 2). From these observations it is difficult to see how MSG strata could be introduced into the Cloghy

Fault zone, and it is possible that the conductivity anomaly here has a different origin, perhaps associated with mineralization (e.g. due to contact metamorphism associated with possible lamprophyres along the fault) . However, note that in this case the conductivity anomaly still identifies the major tract boundary fault even if the MSG is absent. An illustration of the converse effect – the absence of an anomaly where there is no MSG present – is provided by the Orlock Bridge Fault in the north of County Down. There, the MSG carbonaceous mudstone does not crop out along the well exposed trace of the fault, which is nonetheless marked by intense sinistral shear and separates two distinct structural tracts, Ordovician to the north and Silurian to the south.

Despite the qualifications outlined above, we are satisfied that there is a consistent correlation between the linear conductivity anomalies and the surface traces of the major, tract-boundary faults some of which are defined by the lenticular zones of MSG mudstone. Applying that association regionally, a wealth of structural imbrication is revealed (Fig. 2). Moreover, much of the imbrication thus revealed does not coincide with the interpretations derived from the very limited MSG outcrop. Two areas are illustrative of the complexity. In the Banbridge area sinuous linkages between the main tract boundaries appear to define a sinistral strike-slip duplex structure, whilst further SW, between Keady and Newry, the trend defined by the conductivity lineaments is more NNE-SSW and appears to cut obliquely across the tract boundaries as currently depicted on the 1: 250 000 map of the solid geology of Northern Ireland (1997). Either there is considerable linkage between the major strike-slip faults with MSG strata present on the linking faults but largely absent on the roof and floor structures or, and we think this the more likely, there is a regional swing in strike that is not recognized in current interpretations. It is worth noting that current interpretations of the area most affected by the apparent swing in regional strike are still largely based on mapping by the Geological Survey of Ireland in about 1870.

Banbridge: a strike-slip duplex?

To the east of Banbridge there is a strong conductivity anomaly associated with the westward extension of the Southern Coalpit Bay Fault, which marks the northern limit of Gala 7 tracts. From the Ards Peninsula this combined lineament has followed the regional, WSW trend, but south of Banbridge the conductivity anomaly takes a marked anticlockwise swing towards the SW (Figure 4), deviating from the WSW trace assigned to the Southern Coalpit Bay Fault on the Northern Ireland 1:250 000 geological map. The well-defined conductivity lineament may mark the northern boundary of a strike-slip duplex – either extensional/sinistral or contractional/dextral – but the potential southern boundary fault, though implied by the conductivity data, is not so clearly defined. From the outline fault pattern alone it is not possible to distinguish definitively between sinistral and dextral duplexes (Woodcock & Fischer 1986, see especially their fig. 1). Sinistral transpression has certainly occurred within the SUDL terrane (for evidence and review see Anderson 1987, 2001, 2004 and Phillips *et al*. 1995) and there is no regional evidence for any significant dextral movement. Indeed, where small-scale strike-slip duplex features have been noted in association with the major faults, as for example at Coalpit Bay (TBA, unpublished mapping) adjacent to the Southern Coalpit Bay Fault (Fig. 1), they are exclusively sinistral. Hence an interpretation of the large-scale, Banbridge duplex as an extensional/sinistral structure is favoured here. A few other such tentative features can be identified in the conductivity data for the central part of the Down-Armagh belt, and their occurrence may partly explain the apparent strike swing in that region.

Extrapolating from the duplex model, one interpretation of the regional structure as derived from the conductivity data might be to view the apparently intersecting structural trends as being created by a network of sinistral, extensional strike-slip duplexes. Alternatively, the conductivity contrasts might be assigned to sandstone-mudstone variations within the tract sequences, in which case an overall structural "grain" will be identified rather than the repetition of a particular basal horizon. If, as we believe, the conductivity anomalies are produced by linear outcrops of Moffat Shale, it is most likely that they represent structural planes developed during the initial imbrication of the sequence, probably as part of an underthrusting process active during development of the SUDL terrane as an accretionary complex. In terms of an orthodox thrust model, the NNE-SSW features could then have formed as imbricate splays linking the original floor and roof thrusts (the major NE-SW strike faults) in a structural duplex. However, the broadening of the Central Belt, and the commensurate structural repetition of tracts within that broadened zone, rather suggests a more complex arrangement of asymmetrical and overlapping ramp anticlines. These could be envisaged as growing south-westwards from a single basal thrust, to maintain the dominant sense of younging seen in the exposed accretionary complex but they must have remained a hinterland-dipping sequence. Alternatively, a further activity such as out-of-sequence breaching thrusts could be invoked. Where fully developed such structures would be expected to displace the original roof thrust but, in the circumstances of the SUDL complex, might have merged with it towards the north-east, whilst developing independently as tract boundaries towards the south-west.

The preceding paragraph is largely speculative. The SUDL accretionary complex, though developed within a convergent tectonic regime, does not appear as a typical thrust stack and the problems of its structural interpretation, beyond the scope of this paper, have been examined by Anderson (2001). One fundamental problem has always been the reliable extrapolation and correlation of the major tract-boundary faults. Current interpretations lean heavily on the identification of Moffat Shale Group inliers, and the biostratigraphy of their contained graptolite faunas, in particular the recognition of the youngest biozone. Inevitably, there is a degree of uncertainty in these interpretations, much of which should be removed by the integration of the conductivity anomalies into a regional structural assessment. For the first time, correlation of Moffat Shale inliers along the major faults can be confirmed independently and unequivocally.

Keady – Newry – Crossmaglen: a regional re-orientation of tract boundaries

The trend of the conductivity lineaments becomes more markedly divergent from the prevalent, putative ENE-WSW strike in the western part of the Down-Armagh belt (Fig. 5). Further, in this area of SW Armagh, there is little indication that the conductivity lineaments are linked by possible strike-slip duplexes as described above from Banbridge. Instead, the lineaments, as identifiers of narrow, Moffat Shale zones, define a series of sub-parallel faults. These have a separation similar to the widths of the individual accretionary tracts throughout the SUDL Terrane. They simply swing into more NE-SW trends than have previously been accorded to the Down-Armagh tract boundary faults.

The current 1: 250 000 map interpretation of the Keady area of west Armagh has used the black shale outcrops (MSG) mapped on Sheet 59 of the Geological Survey of Ireland (1875) to help extrapolate the tract boundaries which trend about 060° across County Down westward into and across Armagh. Some necessarily sinistral (southerly) offset of the tract boundary faults as they are followed westward is accommodated by sinistral, cross-strike wrench faulting. However the essentially rectilinear extrapolation postulated appears to overlook the local evidence for strike variation, recorded as dip arrows on the 19th century "one-inch" sheets. For example, south of Newtonhamilton (see Fig. 5) the mean strike recorded in a 30 km^2 area of GSI Sheet 59 is 037°, exactly parallel to the trend of the linear conductivity anomalies across that same area. Our interpretation of the conductivity anomalies eliminates the need for most of the cross-strike wrench faults and diminishes the importance of the remainder.

As described previously, graptolite biostratigraphy provides some control on tract allocation, with the youngest fauna at any one location the crucial feature. The more NE-SW trend for the tract boundaries determined from the conductivity lineaments brings the older, northern tracts farther south without recourse to cross-cutting strike-slips; one possible arrangement is illustrated in Figure 6. Whereas biostratigraphic control in the eastern part of the Down-Armagh belt is good, reliable data become increasingly sparse westward so that the currently available information seems permissive of the interpretation based on the conductivity lineaments. Future fossil discoveries, and reassessment of existing faunas, will test its applicability, though it is unlikely that resolution will be achieved without additional stratigraphical studies in Northern Ireland focused on the western part of the SUDL Terrane.

The strike-swing interpretation reduces the role of cross-strike faulting but does not of itself necessarily account for the westward broadening of the Gala Group's outcrop in Down-Armagh, unless the northward dip of the boundary faults decreases. This does not seem to be a systematic effect. Instead, at least one additional tract can be deduced (Gala 4-south), broadening westward from a position to the north of Banbridge (Figure 6), whilst the possibility of transpressive strike-slip duplex arrays in the western part of the terrane will also effectively broaden the outcrop of each individual tract. The introduction in Down-Armagh of an additional tract (or tracts) broadening westwards is a mirror-image of the situation seen in the Southern Uplands where, to the east of Moffat, additional tracts expand eastwards to broaden the outcrop of the Llandovery Central Belt.

A further, major feature which might be linked with the deviation in regional strike is emplacement of the Newry granodioritic pluton. It is tempting to see that emplacement as occurring, in a transtensional regime, at a releasing bend on a major, strike-parallel fault of sinistral sense. The Cloghy Fault seems an obvious candidate. The c. 425 Ma age of the Newry pluton (Meighan *et al*. 2003) would then date the strike reorganization. If the 425 Ma date is accepted, it requires structural accretion and strike rotation to have occurred within a few million years of sedimentation of the Upper Llandovery, Gala Group strata. Mineralisation is another feature within the zone of regional strike deviation that might have been influenced by formation of a releasing bend. For example, the belt of gold mineralization in south Armagh and neighbouring County Monaghan could have resulted from the releasing bend allowing access to mineralizing fluids.

Conclusions

The high resolution conductivity data acquired during the Tellus survey proved spectacularly successful in delineating the zones of black, carbonaceous mudstone (Moffat Shale Group) that form the structural and stratigraphical base of individual tracts within the Southern Uplands – Down-Longford accretionary terrane. The quasi-linear anomalies associated with the mudstone allow the major, tract boundary faults to be plotted across large areas of poor exposure in Down-Armagh and reveal hitherto unrecognised structural complication. Two features are most apparent:

1. In the western part of Down-Armagh, there is a large-scale regional swing in the strike of the major tract boundary faults away from their generally prevalent ENE-WSW trend into a NE-SW orientation. As a result, they cut across the traces deduced for the faults from sparse bedrock exposure and illustrated on the current geological map. We suggest that a substantial geological re-assessment is appropriate, with an improved knowledge of the

biostratigraphy of the Moffat Shale Group likely to provide the best means of testing the interpretation derived from the conductivity survey.

2. In places the major tract boundary faults appear to anastomose into sinistral strike-slip duplexes, with the effect most marked from the Gala 6 tracts southwards. This would not be an unexpected development if an element of lateral movement was involved in the accretionary regime. Sinistral transpression during accretion is well-established from the late Llandovery, during incorporation of Gala 7 tracts in the Southern Uplands, so may have commenced a little earlier than previously thought.

Though the development of an anastomosing strike-slip duplex array would have been a primary effect during accretion, the wholesale deviation of the Caledonian strike trend may well have a later origin. Post-accretion, Late Silurian transtension across the Iapetus suture zone (Soper and Woodcock 2003) would seem a likely mechanism with, perhaps, the strike-swing in western Down-Armagh indicative of a releasing bend on a major-strike-parallel fault that controlled emplacement of the Newry pluton.

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Figures

1. Outline geology of the Southern Uplands – Down-Longford Terrane.
2. Outline geology and high-resolution conductivity data for the Down-Armagh region, showing location of figures 3, 4 & 5. The 3kHz apparent conductivity data in units of mS/m are shown with shaded relief illuminated from the NW.
3. Tieveshilly – a comparison of the geology and conductivity, the latter shown in shaded relief format (illuminated from the NW), illustrating the coincidence of linear anomalies with the outcrop of Moffat Shale Group strata. Letters are locations referred to in the text. Sections of roads having a clear conductivity response are shown in green. For location of the area shown see Fig. 2.
4. Banbridge – a comparison of the geology and conductivity, the latter shown as the tilt derivative (TDR), illustrating a likely strike-slip duplex structure. The TDR response is shown in blue (0° to 45°) and red (45°to 90°). Sections of roads having a clear conductivity response are shown in green. Power line routes with a clear conductivity response are shown in yellow.
   For location and geological legend see Fig. 2.
5. The western part of the SUDL Terrane in Down-Armagh – a comparison of the geology and conductivity, the latter shown as the tilt derivative (TDR), illustrating the regional deviation of strike from the prevalent ENE-WSW trend. The TDR response is shown in blue (0° to 45°) and red (45°to 90°). Sections of roads having a clear conductivity response are shown in green. Power line routes with a clear conductivity response are shown in yellow. For location and geological legend see Fig. 2.

6. A sketch map of the fault traces in the western part of the SUDL Terrane in Down-Armagh, and their deviation from the prevalent ENE-WSW trend into the NE-SW orientation suggested by the conductivity data. When referring to the reference map of Figure 2a, the sketch map of this western area is restricted to the range of eastings from 275000 (m) to 34000 (m). The trends suggested by the new conductivity data have been formed using the results presented in Figures 2, 4 and 5.

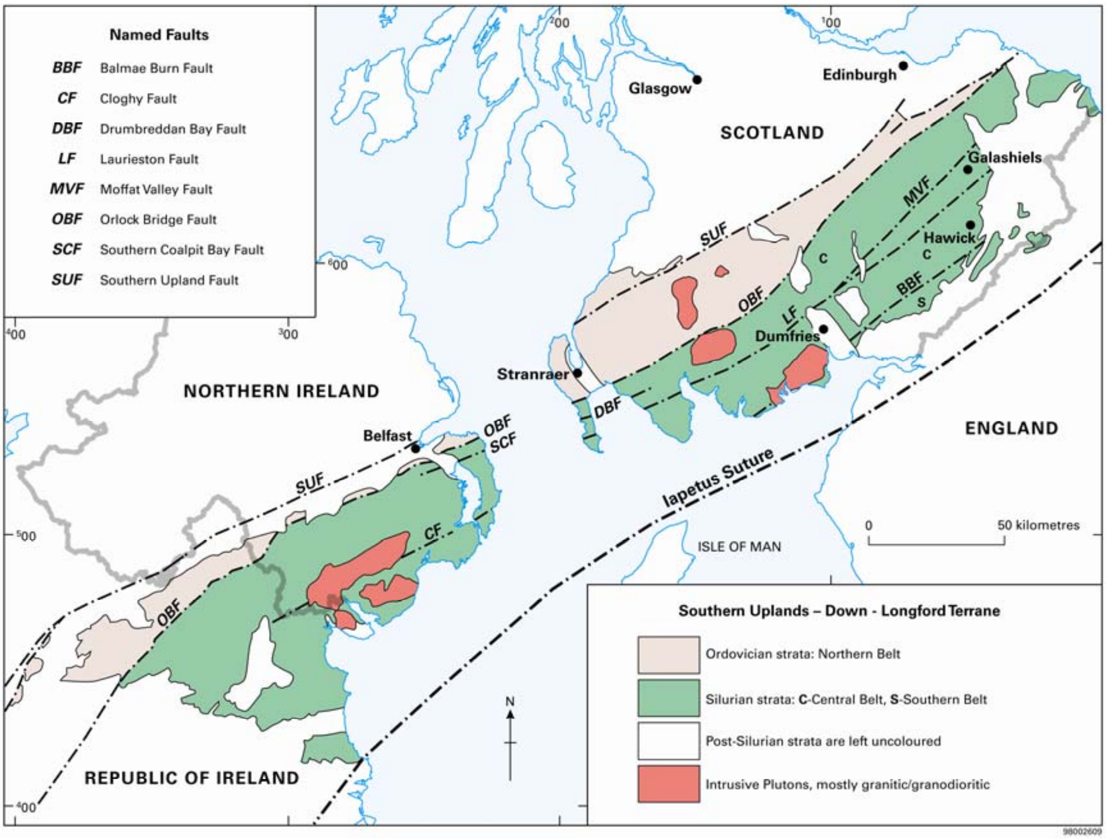
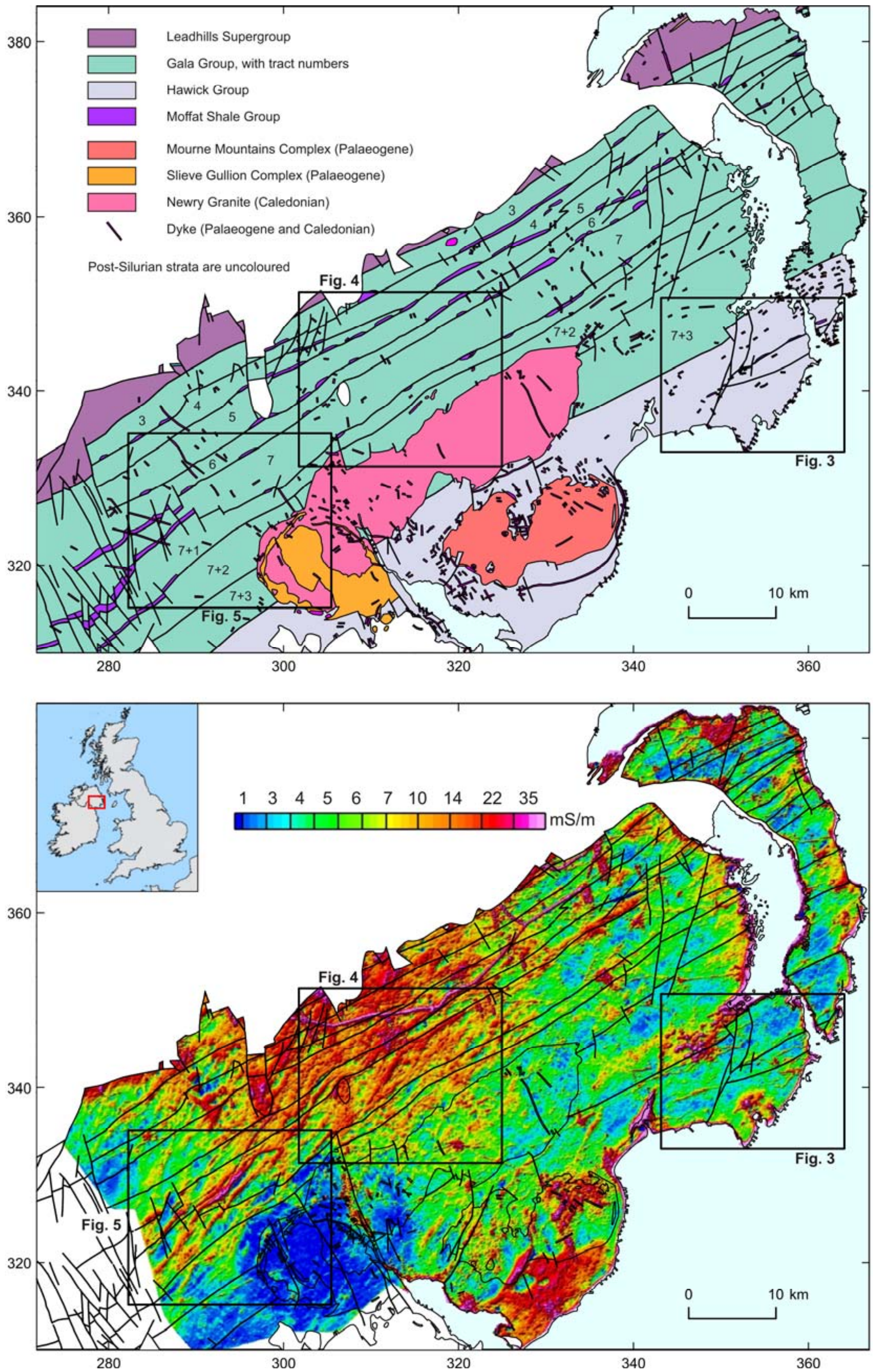

Named Faults
BBF Balmae Burn Fault
CF Cloghy Fault
DBF Drumbreddan Bay Fault
LF Laurieston Fault
MVF Moffat Valley Fault
OBF Orlock Bridge Fault
SCF Southern Coalpit Bay Fault
SUF Southern Upland Fault
Glasgow
Edinburgh
SCOTLAND
Galashiels
Hawick
Dumfries
Stranraer
NORTHERN IRELAND
Belfast
ENGLAND
Iapetus Suture
ISLE OF MAN
REPUBLIC OF IRELAND
0
50 kilometres
N
Southern Uplands – Down - Longford Terrane
Ordovician strata: Northern Belt
Silurian strata: C-Central Belt, S-Southern Belt
Post-Silurian strata are left uncoloured
Intrusive Plutons, mostly granitic/granodioritic

Figure 1



Leadhills Supergroup
Gala Group, with tract numbers
Hawick Group
Moffat Shale Group
Mourne Mountains Complex (Palaeogene)
Slieve Gullion Complex (Palaeogene)
Newry Granite (Caledonian)
Dyke (Palaeogene and Caledonian)
Post-Silurian strata are uncoloured
Fig. 4
Fig. 3
Fig. 5
0 10 km
1 3 4 5 6 7 10 14 22 35 mS/m
380
360
340
320
280
300
320
340
360

Figure 2

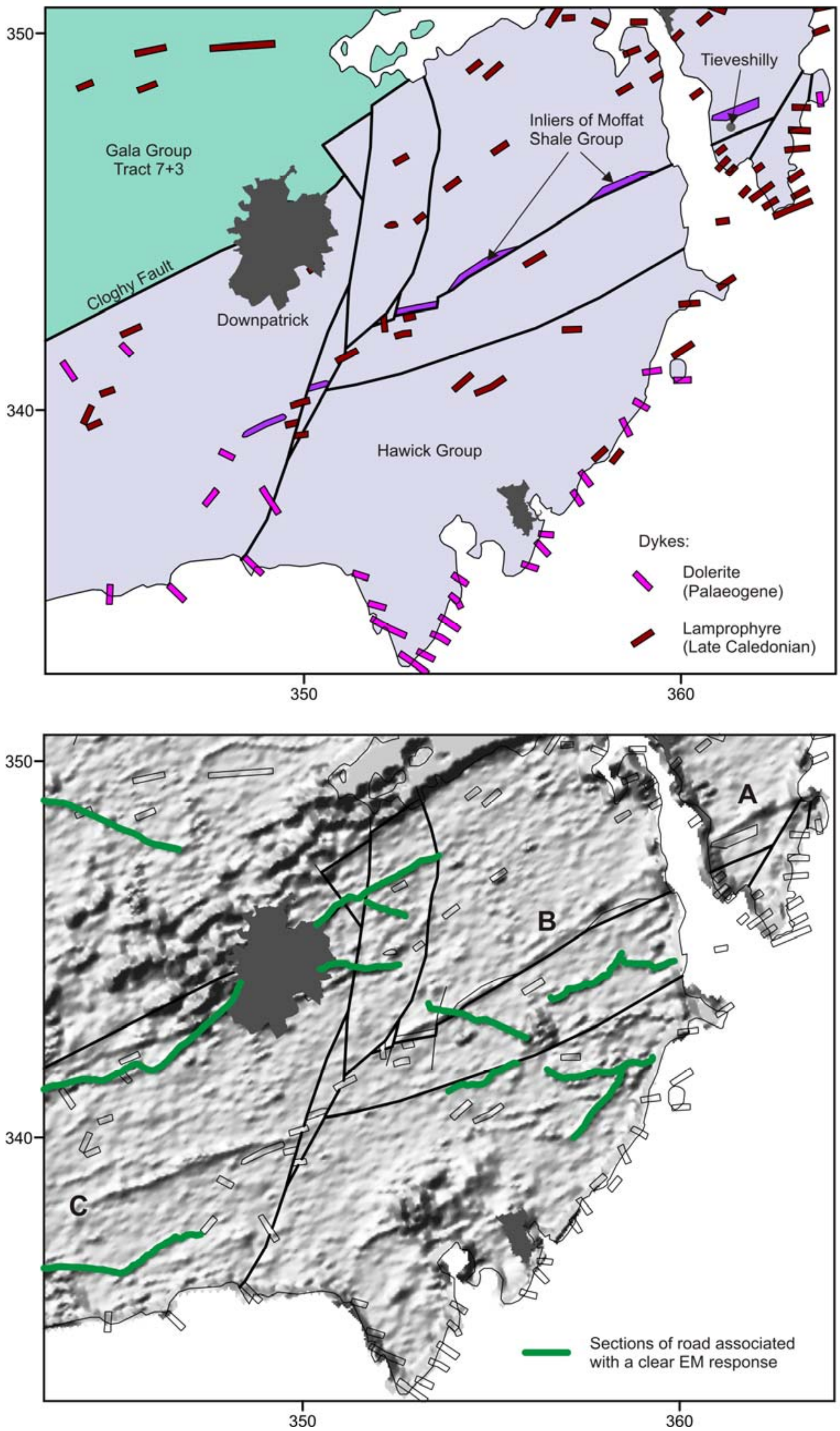

350
340
350
360
Gala Group
Tract 7+3
Cloghy Fault
Downpatrick
Inliers of Moffat
Shale Group
Tieveshilly
Hawick Group
Dykes:
Dolerite
(Palaeogene)
Lamprophyre
(Late Caledonian)
350
340
A
B
C
Sections of road associated
with a clear EM response
350
360

Figure 3

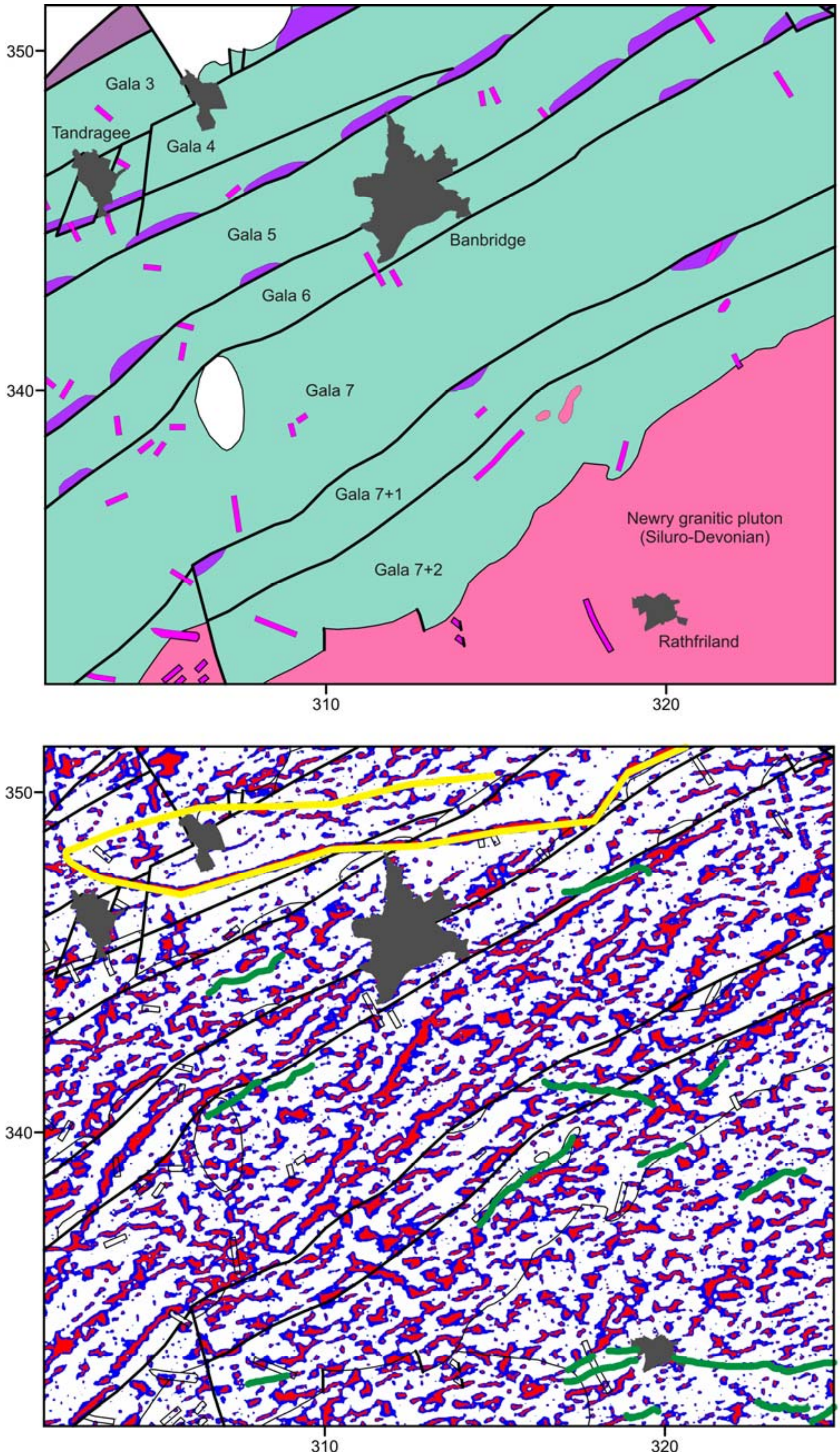
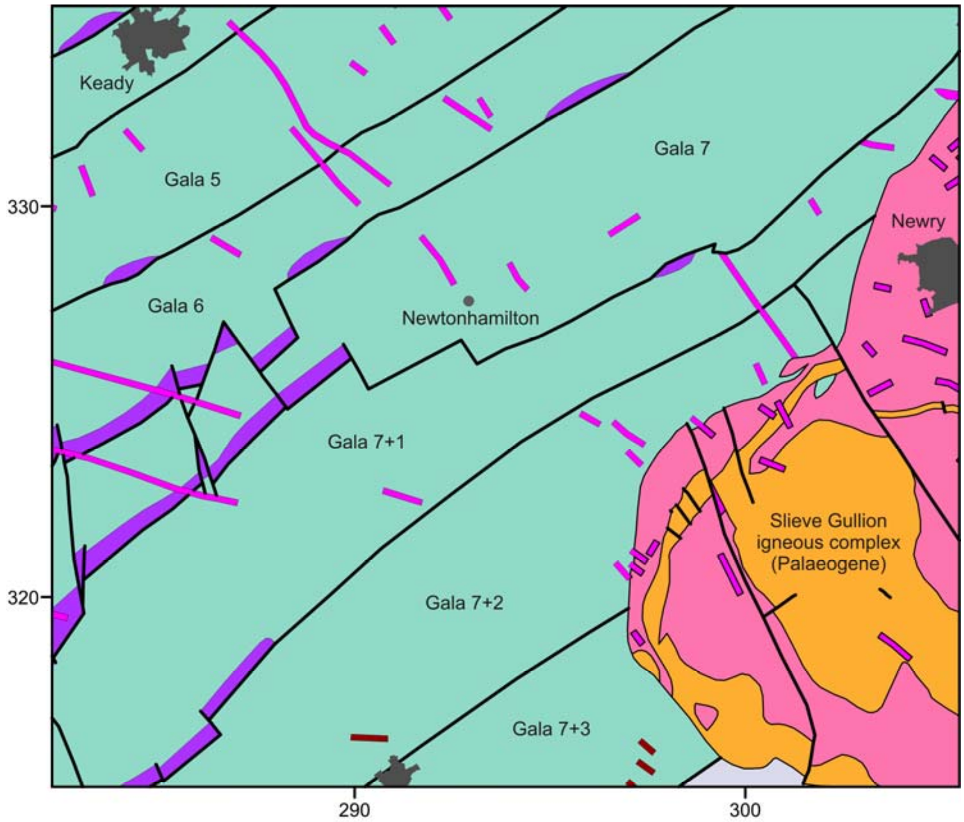

350
340
310
320
Gala 3
Tandragee
Gala 4
Gala 5
Banbridge
Gala 6
Gala 7
Gala 7+1
Gala 7+2
Newry granitic pluton
(Siluro-Devonian)
Rathfriland
350
340
310
320

Figure 4


Keady
Gala 5
Gala 7
Newry
330
Gala 6
Newtonhamilton
Gala 7+1
Slieve Gullion
igneous complex
(Palaeogene)
320
Gala 7+2
Gala 7+3
290
300

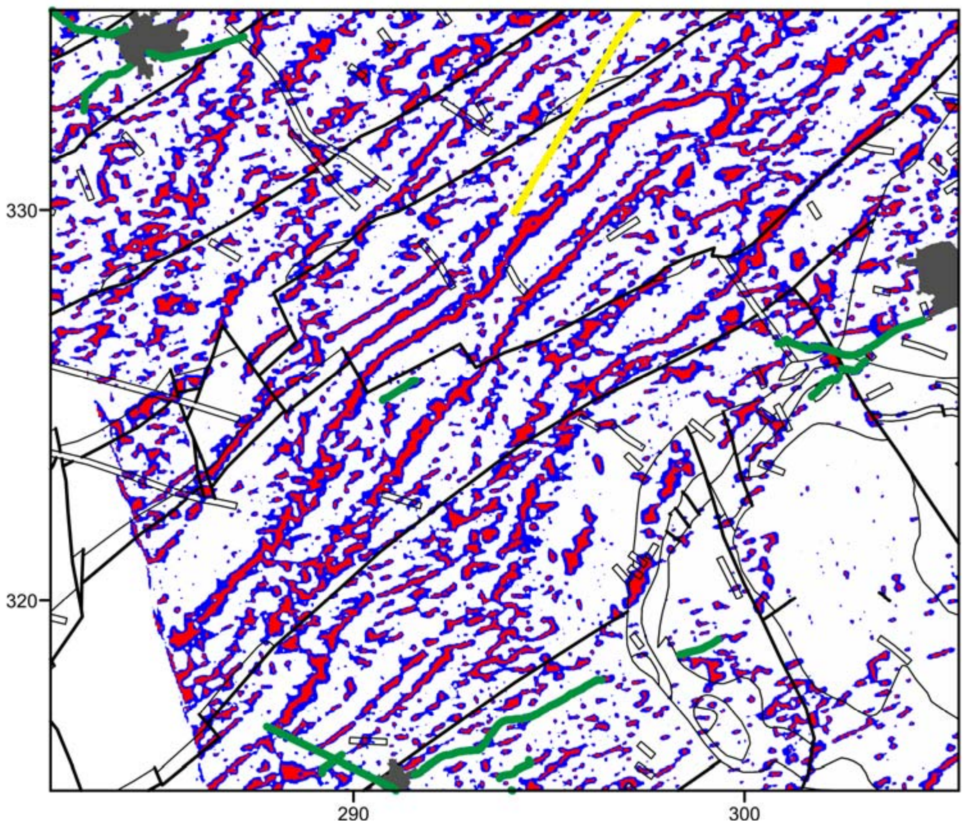

330
320
290
300

Figure 5

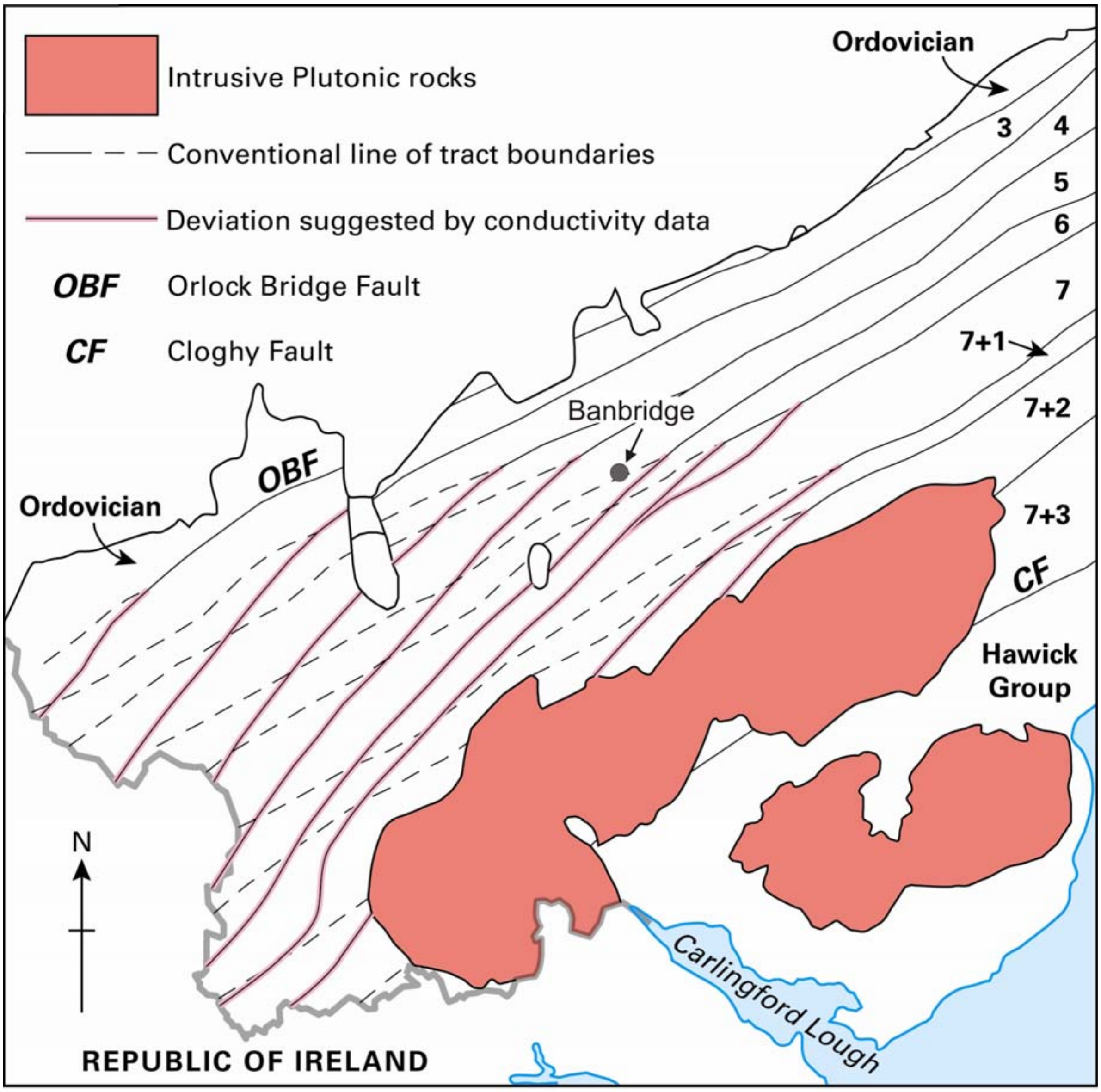

Intrusive Plutonic rocks
Conventional line of tract boundaries
Deviation suggested by conductivity data
OBF Orlock Bridge Fault
CF Cloghy Fault
Ordovician
3
4
5
6
7
7+1
7+2
7+3
Banbridge
OBF
Ordovician
CF
Hawick Group
N
Carlingford Lough
REPUBLIC OF IRELAND

Figure 6