Basin analysis using seismic interpretation as tools to examine the extent of a basin ore 'play'

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Abstract

Stratiform and stratabound base metal ores typically form in sedimentary basins during the overall rifting process with mineralising fluids transported along the growing normal faults. Understanding the detailed structural evolution, i.e. the timing, the growth and the extent of the faults, and the distribution and thickness of the syn-faulting sedimentary packages, is critical for focusing exploration efforts. In this paper, we describe how seismic interpretation and basin analysis techniques can help to do this. We assess the potential for Pb-Zn mineralisation within the Northumberland Trough, northern England, in the context of the wider Early Carboniferous basin evolution and the associated base metal ores. Through structural interpretation of seismic reflection data, we consider the detailed evolution of the fault geometries and sedimentation in time and space, to show the extent and distribution of the Early Carboniferous faulting and growth packages at depth in the study area. We conclude that basin evolution and structural framework in northern England is very similar to that associated with the significant Pb-Zn mineralisation in Ireland. We suggest a refined model for

the Carboniferous evolution of this part of the basin. The study demonstrates how the techniques of basin analysis can be a used in ore exploration to establish whether the basic structural and sedimentary framework exists to enable mineralisation. In addition to assessing the general potential of base metal mineralisation, a more precise identification of potentially suitable areas for further investigation can be made. The seismic data and basin analysis approach used in this paper and exemplified through the Northumberland case should be directly applicable to any basin ore 'play' associated with rifting and/or sedimentation. The added, significant advantage of this method is the ability to assess the 3D fault geometries, including fault linkage and growth in space and time, and the associated sedimentation - an unachievable outcome if relying solely on other geophysical and geological data traditionally used in regional ore exploration.

1. Introduction

In hydrocarbons exploration, the concept of a 'play' is routinely used to refer to a group of prospects in a region that are controlled by the same set of geological circumstances. Detailed understanding of these circumstances is key for effective exploration. A number of techniques can be used to analyze plays, but robust understanding of the structural and depositional evolution of the region in time and space always underpins more detailed prospect targeting. For sedimentary basins, seismic reflection data interpretation is the most commonly used tool for to establish the fundamental structural and depositional framework: it is widely used in hydrocarbons exploration (e.g. Jackson and Beales, 1967; Miklereit et al., 1996; Hu et al., 2017); but also, increasingly, in basin ore exploration and research (Gibson et al., 2016; Ashton et al., 2018). Crucially, seismic interpretation and basin analysis allow establish the timing of fault activity and the extent of syn-kinematic (syn-rift) sedimentation by observing and interpreting the thickness increase towards the fault in the sedimentary packages (Fig. 1A-C). In this paper, we demonstrate the usage of the technique of basin analysis through seismic reflection interpretation in the context of basin ores exploration. We establish the timing and structure of a Carboniferous basin in Northern England, showing that the faulting event is of similar nature and timing compared to that associated with the significant base metal mineralisation in Ireland. The method presented here is a powerful tool, especially in the early phases of exploration outwards from a known deposit where it is necessary to investigate the extent of the play: i.e. whether the overall timing and the structure of a basin and the faults and sedimentary packages within it are suitable for mineralisation in the regional context.

The Early Carboniferous lead-zinc play in Ireland is well known with its >25 economic and subeconomic deposits and has been extensively studied (e.g. Max et al., 1983; Taylor, 1984; Hitzman and Large, 1986; Williams et al., 1986; Anderson et al., 1988; Shearley et al., 1992; Hitzman and Beaty, 1996; Everett et al., 1999; Hitzman, 1999; Lewis and Couples, 1999; O'Reilly et al., 1999; Wilkinson, 2010; Ashton et al., 2015; Wilkinson & Hitzman 2015; Torremans et al., 2018; Kyne et al., 2019). Significant mineralisation exists at Tynagh, Silvermines, Lisheen, and at Navan, the latter being a world-class Pb-Zn deposit (Fig. 2). Recently, a 2D seismic survey helped to identify the Tara Deep satellite deposit at Navan which is now under development (Ashton et al., 2018). The mineralisation is normally classified as 'Irish type', which is thought to be a hybrid between Mississippi Valley type (MVT) and SEDEX ores (e.g. Torremans et al., 2018) although some authors consider the Irish type to be a sub-type of the MVT deposits (e.g. Leach et al., 2001). Whatever the detailed classification may be, the key observations for the purposes of this paper are that the Irish mineralisation i) occurs as stratabound replacement ore within the Lower Carboniferous pre- to syn-rift carbonate sequences present across the Irish Midlands basin; and ii) is closely associated with major normal faults which acted as main fluid conduits (e.g. Ashton et al, 2015, 2018; Wilkinson & Hitzman 2015; Torremans et al., 2018; Kyne et al., 2019).

Lateral equivalents of the Lower Carboniferous rocks in Ireland are exposed in northernmost England and southwestern Scotland, particularly in the Northumberland Trough and on the upfaulted Alston Block (Fig. 2). The potential for Carboniferous lead-zinc mineralisation in the Northumberland Trough has not been studied in detail although the possibility has been suggested (e.g. Plant et al., 1988; Jones et al. 1994; Chadwick et al. 1995; Walsh et al. 2018; Baba et al., 2019). Most of the known mineralisation in the area is related to the so-called Northern Pennine Orefield (NPO), with historically mined zinc ores (Figs. 2, 3). The known NPO mineralisation is not of the 'Irish type'; it is around 50 Ma younger (Permian), located structurally higher, and is associated mostly with fractures and fissures within the bedding rather than being a strictly stratabound replacement ore (Fig. 3; e.g. Kimbell et al. 2010). In the absence of sufficient drilling, the most tangible evidence for an 'Irish type' Early Carboniferous mineralising event comes from the British Geological Survey Mineral Reconnaissance Programme: stratabound mineralisation in Lower Carboniferous carbonate rocks has been found at or close to current exposure levels near normal faults around Langholm and Saughtree (Fig. 2), along with some fracture-style mineralisation in the volcanic rocks of the same age and in the Silurian basement (drilling reached depths of ~25 m; Gallagher et al., 1977; Smith et al., 1996). The indications of base metal mineralisation in the

Lower Carboniferous combined with the regional similarities in the Lower Carboniferous geological history between Ireland and northern England raise the possibility that previously unrecognised rifting-related, 'Irish type' Pb-Zn mineralisation could exist at depth in northern England. For this to be the case, the structural setting including the timing of the major faults and the deposition of thick syn-rift sediments of suitable carbonitic composition need to be similar in northern England to those associated with the Irish Pb-Zn deposits. It is very difficult to decipher fault timings, growth and 3D geometries from surface data alone, but basin analysis techniques can greatly illuminate the overall structural setting (Fig. 1). We apply such techniques through interpretation of a grid of 2D seismic lines within the Northumberland Trough, in order to establish the structural setting and evaluate its similarity to the Irish Pb-Zn play. Our analysis incorporates the timing of the major faulting, fault geometries and linkage during growth, and the thickness and distribution of the syn-kinematic sediments in the area - both crucial for the presence of ores similar to the Irish deposits. We discuss the results in the context of Pb-Zn mineralisation in Ireland to propose a refined model for how the main structures within the study area may host mineralisation at depth, therefore potentially extending the lead-zinc play into northern England and southwestern Scotland; the presence of suitable host rock lithologies at depth, however, remains to be tested by drilling. The method used in this paper, exemplified through the Northumberland case, should be directly applicable to any basin-related ore deposit associated with faulting and/or sedimentation.

2. Geological Context

Any basin analysis must be underpinned by robust understanding of the regional geological evolution and local stratigraphy. Therefore, we first summarize the geological history of the British Isles and Ireland during the Carboniferous, focusing on the structural context of the Pb-Zn mineralisation in Ireland and northern England and on the stratigraphy of the study area.

2.1 Geological History

The known Pb-Zn mineralisation in the Irish Midlands and in northern England broadly follows the trend of the Iapetus Suture (Fig. 2; Max et al. 1983; Ashton et al. 2015). The suture is a structurally complex region formed by the closure of the Iapetus Ocean and the subsequent continental collision during the Caledonian Orogeny around 400 Ma (Torsvik et al. 1996; McKerrow et al. 2000; Stone et al. 2010). The dominantly NE-SW Caledonian structural grain controlled the overall trend of the Carboniferous syn-rift faults with which the Irish base metal mineralisation is genetically related (O'Reilly et al. 1999; Ashton et al. 2015; Torremans et al. 2018; Kyne et al., 2019). The Carboniferous rifting was caused by approximately north-south orientated tension, probably due to back-arc extension caused by the northward subduction of the Rheic Ocean beneath the southern margin of the Caledonian basement (Leeder, 1982; Nance et al. 2012). The major basin produced by this north-south divergence extends from both northern England to the Irish Midlands and is characterised by fault-bound blocks separated by deep sub-basins (Leeder 1982; Hitzman 1999). In northern England, faulting localisation was also controlled by granitic Caledonian plutons in the Lake District, the North Pennines and the Cheviots (Fig. 2); these acted as rigid bodies during the extension, forming structural highs or horst blocks (Stone et al., 2010). Subsidence history analysis in northern England shows the initial rapid fault-controlled subsidence (rift phase) during the Tournaisian-Visean was followed by gradually declining regional subsidence (sag phase) from the late-Visean to Westphalian (McKenzie, 1978; Kimbell et al., 1989).

The ENE-WSW trending Northumberland Trough - Solway Basin occupies the generally low-lying land between the Solway Firth and Northumbrian coast (Fig. 2). To the south, the basin margin follows the prominent highs of the Lake District and Alston (North Pennine) Blocks along the Maryport-Stublick-Ninety Fathom fault system. This north-dipping normal fault system was initiated in the Tournaisian and early Visean, resulting in a thick Lower Carboniferous syn-rift sequence accumulating in the Northumberland-Solway Basin and partly outcropping in the northern part of the basin (Chadwick et al., 1995). The northern margin of the Northumberland-Solway Basin is formed by en-échelon, mostly south-dipping faults, antithetic to the Maryport-Stublick-Ninety Fathom faults. The throw on the northern basin-bounding fault system increases westwards, resulting in the Solway Basin having a roughly symmetrical shape in cross section, whilst the Northumberland Trough approximates a half-graben (Chadwick et al. 1995). However, the detailed timings and geometries of individual faults and sedimentary packages remain largely unknown.

Subsidence ceased by the latest Carboniferous and was replaced with the peripheral effects of the Variscan Orogeny around 290 Ma (Matte, 1986; Collier, 1989; Stone et al., 2010). Variscan deformation in northern England is identified by deformation affecting the Westphalian Coal Measures but not the overlying Permian strata. Variscan structures in northern England include gentle folding, minor thrusting/inversion, and removal of up to 2 km of Carboniferous sediment due to uplift and erosion (Chadwick et al., 1995). Some authors suggest that the inversion structures result from transtensional tectonics rather than Variscan compression (De Paola et al., 2005). Intrusion of the Permian Whin Sill complex at 297 Ma and other broadly coeval intrusions (Figs. 3 and 4) post-date the inversion, but pre-date a Permian extensional or transtensional event (Collier, 1989; Dempsey, 2016).

2.2 Stratigraphy of Northumberland

The metamorphosed Lower Paleozoic basement in northern England is unconformably overlain by some Devonian, but mostly Carboniferous rocks (Fig. 4). The late Devonian – early Carboniferous crops out sporadically along the northern margin of the Northumberland Trough; these semi-arid fluvial beds have been described as pre-rift (Leeder, 1973; 1974) or earliest syn-rift (Chadwick and Holliday, 1991). The main rift basin succession is of Carboniferous age, controlled by the evolving normal fault system (Fig. 5; e.g. Dunham, 1990; Chadwick et al., 1995). The syn-rift packages are exposed in the north but buried in the southern part of the basin (Fig. 4). The region is characterised by the general absence of syn-rift sediments from horst tops such as the Alston Block (Fig. 5; Stone et al., 2010). By the end of the Visean, active rifting ceased, allowing Asbian and younger strata to progressively accumulate across the area (Bott et al., 1984; Kimbell et al., 1989).

The syn-rift Courceyan to Chadian age Inverclyde Group rocks are, where observed at outcrop or in boreholes, mainly siliciclastic fluvial to shallow marine sediments, but fine-grained carbonates as nodules and thin beds are also common (Stone et al., 2010). Basaltic lavas are present in this group, at least along the NW margin of the Trough, and are interpreted as marking the onset of rifting (Leeder, 1974). The Border Group forms the main syn-rift basin fill of up to 4 km of fluvial to marine siliciclastic and carbonate rocks (Dunham, 1990). Where exposed (in the north), the dominant rock types especially higher in this group are composed of the fluvial Fell Sandstones, but grade into deltaic then marine conditions towards the south and west (Johnson, 1980). The exposed parts of the Lyne Formation (in NE Northumberland Trough) contain some clastic and nonmarine limestones interpreted as peritidal with increasingly marine limestone layers higher in the succession (Dean et al., 2011). The rock types within the Border Group at depth in the deeper parts of the basin remain unknown as there are few historic drill holes and they mostly reach depths of only a few hundred metres. Evaporite layers present in the Border Group may be important for mineralisation as a potential source of saline fluids (Day, 1970) but also as potential top-seal to control lateral fluid migration (see discussion). Either way, the Inverclyde Group and the Border Group are the approximately time-equivalent sequences in northern England to the sediments hosting the Irish Pb-Zn deposits (Fig. 4).

Late Visean and Namurian rocks of northern England mainly belong to the Yoredale Group. Yoredale facies is characterised by cyclothems of marine limestone overlain by shale, sandstone, and coal (Hudson, 1924; Stone et al., 2010). The early Asbian Tyne Limestone Formation of the Yoredale Group displays greater marine influence than the exposed parts of the underlying Border Group but maintains alternating marine input from the SW and clastic input from the NE (Leeder et al., 1989). Approximately coevally with the Tyne Limestone Formation, a thin (~100 m) sequence of non-Yoredale ramp to shelf carbonates belonging to the Great Scar Limestone Group was deposited on the structurally elevated Alston Block (Stone et al., 2010). By the end of the Asbian, a marine transgression during the regional sag phase covered all of the Alston Block and the Yoredale facies Alston and Stainmore

Formations of the Yoredale Group were deposited across the entire area (Fig. 4; Chadwick et al., 1995). The top of the Alston Formation is marked by the Great Limestone Member, the thickest outcropping limestone in the area at 20 m thickness; this formation hosts a large proportion of the known Permian vein mineralisation (Fig. 3; Dunham, 1990).

2.3 Mineralisation: summary of the Irish and NPO lead-zinc ores

We briefly summarize the main characteristics of Irish Pb-Zn mineralisation and the known Pb-Zn mineralisation in the Northern Pennine Orefield (NPO). For a more detailed description of mineralisation and stratigraphy in the NPO, the reader is referred to Dunham (1990), Tucker et al. (2003) and Bott and Smith (2018), and to the BGS Mineral Exploration Programme reports from northern England and southern Scotland (e.g. Smith et al., 1996). For more details on the Irish Carboniferous stratigraphy and Irish base metal mineralisation see e.g. Philcox (1984), Wilkinson and Hitzman (2015), Ashton et al. (2015). Torremans et al. (2018) and Kyne et al. (2019).

'Irish-type' mineralisation is a sedimentary rock-hosted ore deposit type in which large-scale normal faults channel mineralising fluids from depth into the host rocks (typically carbonates; Fig. 6). The mineralisation is predominantly epigenetic with respect to deposition of the host lithologies, but syn-kinematic with respect to the rifting process that created the faults, although fluid flow along faults can continue for a time after active faulting has ceased (e.g. Walsh et al., 2018). Irish-type mineralisation overlaps with both the so-called Mississippi Valley type (MVT) mineralisation which usually forms deeper in a (foreland) basin, and with syn-genetic sedimentary-exhalative (SEDEX) ores deposited directly onto the seafloor. Some authors consider the 'Irish-type' to be a sub-type of the MVT (e.g. Leach et al., 2001). Regardless of the debate on the exact deposit 'type', the key observation for the purposes of this paper is that all of the Irish deposits are a) strongly fault-controlled in terms of the fluid pathways into the system; and b) form stratabound ore lenses close to the faults and within the syn-rift stratigraphy.

In Ireland, the faulting patterns related to ore genesis are complex especially in the world-class Navan deposit and its newly discovered Tara Deep satellite deposit (Ashton et al., 2018). Some crucial commonalities can, however, be observed. The main ore-controlling faults are large normal or slightly normal-oblique faults (>100 m throw, at Navan possibly up to >2km; Table 2). They mostly trend NE-SW although smaller faults within relay ramps between the main faults are probably significant: at e.g. Silvermines and Lisheen E-W to NW-SE striking relay-ramp breaching faults are linked to mineralisation (Torremans et al., 2018). The deposits are stratabound to stratiform lenses which thin away from their feeder faults over several hundred metres (e.g. Lewis and Couples, 1999; Torremans et al., 2018; Kyne et al., 2019). The Lower Carboniferous rocks that host mineralisation in the Irish Midlands are a transgressive carbonate sequence of mostly Courceyan age (Hitzman and Large, 1986). Mineralisation is generally found in non-argillaceous carbonates, oolitic limestones, or clean dolostones, usually in the stratigraphically lowest horizon with any of those lithologies present (e.g. Hitzman and Beaty, 1996). In the northern and central Irish Midlands, this is the Meath Formation (informally known as 'Pale Beds') of the Navan Group, deposited as variable shallow water shelf carbonates. South- and southwest-wards, the Navan Group becomes increasingly shale-rich and passes into the Lower Limestone Shale, representing a deepening of the palaeo-basin (Hitzman and Beaty, 1996). Here, mineralisation is found in the stratigraphically higher late Courceyan-Chadian reef limestones of the Feltrim Formation (the 'Waulsortian Limestone'; Hitzman and Beaty, 1996). The exact timing of mineralisation is debated but probably occurred <5 Ma after the deposition of the host rocks in most areas, constrained by both isotope evidence and erosion-mineralisation relationships; late Chadian or early Arundian age is likely for the majority of the deposits but mineralisation may have started as early as Courceyan in some areas (Anderson et al., 1998; Ashton et al., 2015). Mineralisation is, in summary, controlled primarily by suitable host lithologies and structures, rather than being constrained to a certain stratigraphic horizon.

In the Irish Midlands, deposits occur mostly on the downthrown side of the normal fault segments but footwall ores also exist (Hitzman, 1999; Ashton et al., 2018). Feeder zones to the orebodies are spatially associated with points of maximum throw on the faults or with deformed (breached) relay ramps (Taylor, 1984; Shearley et al., 1992; Hitzman and Beaty, 1996; Torremans et al., 2018; Kyne et al., 2019). At the world-class Navan deposit, most of the mineralisation of the main ore body is concentrated within a highly fractured relay ramp between the two major NW-dipping faults (Ashton et al., 2015, 2018). However, a new satellite deposit, Tara Deep, has been identified deeper in the palaeobasin, SE of a basement horst delimiting the main ore body where it seems to be associated with the footwall of the major basin-bounding Navan Fault with km-scale displacement (Table 2; Ashton et al., 2018).

In detail, the genesis of 'Irish-type' ores remains contentious. Most authors agree that mineralisation occurred during or soon after active faulting and involved mixing of deep ('basinal'), high-temperature, acidic, metal-bearing fluids and shallow, low-temperature, high-sulphur, high-salinity brines derived from seawater/basin sediments (Fig. 6; e.g. Wilkinson, 2010; Wilkinson and Hitzman, 2015). At Navan, the shallow sulphur-rich fluids were produced by bacterial reduction of Lower Carboniferous seawater, likely in deep half-grabens formed during the rifting (Anderson et al., 1998). Mixing of the two fluids was facilitated by the faults which acted as permeable conduits, focusing fluid flow and allowing episodic tapping of the deep metal-rich fluid reservoir during the faulting cycle (Wilkinson and Hitzman, 2015). The last stages of syn-sedimentary faulting at Navan are interpreted to be Chadian-Arundian, suggesting that the mineralisation occurred <5 Ma after deposition of the host rocks (Hitzman and Beaty, 1996). The exact timing and depth of mineralisation may be variable; there is some evidence for syn-genetic exhalation of minerals (SEDEX-type mineralisation) into seawater in the later, topmost parts of the multi-layered deposit (especially within the so-called ‘slide complex’), but most of the ore seems to have formed through deeper epigenetic processes (Ashton et al., 2015; Wilkinson and Hitzman, 2015).

In contrast to Irish Midlands, the known (Pb-)Zn mineralisation in northern England is mainly Permian, although indications of possible Carboniferous mineralisation have also been found. The Permian mineralisation is dated at 294±29 Ma by Os-Os dating (Dempsey 2016) and at 292±20 Ma by U-Pb dating (Dunham, 1990). It occurs mainly within a thin Carboniferous sequence on the Alston Block, deposited in baryte-fluorite veins with some strata-bound, mineralised wall rock replacement (alteration) zones (Fig. 3; Table 1; e.g. Bouch et al., 2006). Significant mineralisation also occurs within the Alston Formation in the southern Northumberland Trough, north of the Stublick Fault (Fig. 3; e.g. Dunham, 1988; Kimbell et al., 2010). In terms of Carboniferous mineralisation, BGS surveys near Langholm and Saughtree (Fig. 2) revealed stratabound sphalerite, occurring as replacement minerals in dolomitic vugs in the exposed Lower Carboniferous carbonate rocks, and also found a number of Zn and Ba anomalies during stream sediment heavy concentrate sampling (Gallagher et al., 1977; Smith et al., 1996). Other, indirect evidence comes from a regional panning programme in the southern and eastern parts of the Northumberland Trough which revealed significant lead, zinc, and copper anomalies in stream sediments where Lower Carboniferous sediments are exposed (Bateson et al., 1983).

Both the Irish Midlands and the NPO are highly prospective areas for Pb-Zn mineralisation. Although Early Carboniferous Irish-type deposits have not been found in Northern England, the possibility is apparent from; i) the existence of the major normal fault systems associated with Carboniferous rifting; ii) the projection of mineral-bounding lineaments in Ireland across the Irish Sea into northern England; iii) the presence of suitable carbonate-bearing host-rocks of similar Lower Carboniferous age in both areas (Jones et al., 1994). The discovered stratabound sulphide mineralisation in Lower Carboniferous rocks in northern England and southwestern Scotland indeed point towards a functioning base metal deposition system during Lower Carboniferous (Gallagher et al., 1977; Smith et al., 1996). In order to establish whether Irish-style ores may have developed in northern England, we need a better understanding of the timing, geometry and extent of Early Carboniferous faulting along with the extent of and thickness variations within the syn-rift sedimentary packages. Basin analysis techniques utilising seismic reflection data interpretation can be used to test whether this Early Carboniferous favourable structural framework exists in northern England (Fig. 1).

3. Data and methods

The principal method was interpretation of seismic reflection data, assisted by borehole data, following the standard approach described in e.g. Gerhardstein and Brown (1984) and in Fig. 1. The seismic reflection lines were provided in standard SEG-Y format by the UK Onshore Geophysical Library (UKOGL; see www.ukogl.org.uk for their interactive seismic line viewer). All seismic lines used are time-migrated 2D land surveys (i.e. the vertical extent is expressed in seconds Two-Way Travel time, TWT, rather than in metres), shot throughout the 1980's using Vibroseis sources. The quality of the dataset is highly variable. Given the range of vintages, processing parameters, and need for static corrections in land surveying, small mis-ties between surveys do occur. Despite the quality variations, several lines provide a good overview of the geometries of the basement and the interpreted basin infill horizons, clearly picking out the main features and giving a reasonable estimate of the sub-surface structure and fault configuration as per the procedure outlined in Fig. 1. The available lines were ranked based on quality, the ranking subsequently informing the geological interpretation in terms of uncertainty assessment; the poorest quality lines were not interpreted.

Basic information of several boreholes, often with both formation tops and time-depth charts, are available at the UKOGL library. Two boreholes, Longhorsley-1 and Stonehaugh, are located within the study area and these were used to assist interpretation of the seismic data (Fig. 4). The Stonehaugh borehole penetrates down to the Fell Sandstone Formation (601 m total length), whilst Longhorsley-1 reaches the upper part of the underlying Lyne Formation at 1829 m in the shallower parts of the basin. This leaves a large thickness (>>1 km) of basin sediment unsampled, especially within the deeper parts of the basin, leaving their character unknown. British Geological Survey 1:50000 scale digital surface geology mapping provided an indication of the outcrop pattern of the main formation boundaries and the locations of the main fault structures. The geological maps give the rock types associated with each formation at outcrop, but their lateral facies changes at depth towards the south and west remain unknown. The top of the Early Carboniferous Fell Sandstone Formation of the Border Group has outcrop control in the far NW of the study area and is the only horizon that can be tied to both boreholes. The Tyne Limestone and Alston formations of the overlying Yoredale

Group are present in the Longhorsley-1 well only, although both have extensive outcrop control to the south and east.

Structural interpretation was performed using IHS Kingdom suite seismic interpretation software. Borehole formation tops and seismic surveys are referenced to mean sea level (MSL) datum; this is given in the processing information for some but not all vintage lines. Of the available UKOGL seismic dataset, only those surveys with sufficient quality to be useful were used in interpretation; their traces are shown in Figure 4. Fixing minor mis-ties between surveys (<0.05 s TWT) was considered impractical for the purposes of this study, considering that the required time shift may vary along each survey due to static corrections in land surveying. Boreholes helped to constrain the main contacts (Top Lower Groups, Top Tyne Limestone Fm., and Top Alston Fm.; Fig. 5). An approximate Top Basement was also interpreted, identified by the deepest recognisable coherent reflectors underlain by featureless seismic signal (Fig. 8). Seismic interpretation was performed using the loop tying method so that any inconsistencies and mis-ties could be identified and corrected (see e.g. Gerhardstein and Brown, 1984 for details). The presence of mis-ties meant that in some lines the estimated depths to the interpreted horizons had to be adjusted manually during loop-tying (exemplified by the offset of the Top Basement in Fig. 8). Faults were identified with reference to the surface geological maps and correlation polygons were used to identify the location of the sedimentary horizons across faults, although the result was not always without a degree of uncertainty. Sedimentary horizons were not extrapolated across the basin-bounding faults (the Stublick Fault and Ninety Fathom Fault) due to difficulty identifying suitable reflectors on their footwall and the knowledge that syn-rift formations are likely to be largely absent beyond the basin (Stone et al., 2010; Fig. 5).

3D (2.5D) interpretations in the form of structure maps with fault polygons were produced for the interpreted horizons (Fig. 9). The maps were produced using the Flex Gridding algorithm in Kingdom Suite and a grid size of 100 m. Isochron maps for the intervals defined by the interpreted horizons were also produced from the horizon grids in order to approximate the TWT thicknesses of the interpreted packages (Fig. 10).

A degree of epistemic uncertainty is inherent in all seismic interpretation. The purpose of this study is to interpret the general features such as the sedimentary package architecture in relation to the main faults. We consider the quality of the used lines to be sufficient as these main structural features are mostly fairly clearly imaged. The greatest cause for uncertainty in the interpretation arose from assessing the magnitude of displacement across faults where there is no nearby well or outcrop control, or where mis-ties between lines occur (e.g. such as in Fig. 8). Using correlation polygons (reflection pattern mis-matches) mitigates the issue somewhat, although variable data quality is an issue especially in the west part of the area. Therefore, misinterpretation of up to ~0.05 s TWT should be considered when analysing the structure maps and the thickness maps (see next section). The surface geology map and the two boreholes greatly help to constrain the locations of the horizons across faults so that the main geometries of the faults and the syn-rift packages, and their relationships, can be interpreted with reasonable certainty.

4. Results

4.1 Seismic reflection interpretation

The representative seismic lines and their interpretations in Figure 8 show the general features of the results. Three main sedimentary packages were interpreted within the study area: the 'Lower Groups' (delimited by Top Basement and Top Fell Sandstone), the Tyne Limestone Formation, and the Alston Formation (Fig. 5).

The Lower Groups package consists of the Border Group and Inverclyde Group with undefined relative thicknesses. These units are grouped together because, due to the lack of well control penetrating the deeper units, the Top Fell Sandstone Formation (top of the Border Group) is the deepest known horizon which can be reliably interpreted in the sub-surface. The total thickness of the Lower Groups approaches 2 s TWT towards the west (Fig. 8B). Depending on the seismic velocity of the rocks (typically 2500-4000 m s^{-1} for sedimentary rocks) this represents at least 2.5 km, but probably well over 3 km, of basin sediment about which very little is known (see Kimbell et al., 1989 who estimate that the velocities may be up to 4500 m s^{-1} within the basin). The dataset allows some interpretation of the internal geometries within the Lower Groups (yellow dashed lines in Fig. 8. There are some distinctly wedge-shaped geometries present especially in the lower parts of this succession; these are especially evident on the strike sections as exemplified in Fig. 8B. Indications of significant acoustic impedance changes that would be expected from a layered sandstone-mudstone-limestone sequence do occur, such as the prominent high amplitude reflectors found at the base of the succession and locally towards the middle (e.g. around 0.8 ms TWT in Fig. 8B). An area of noticeably lower amplitudes with sometimes chaotic reflectors occurs towards the base of the succession (e.g. around c. 1.4-1.5 s TWT in the west part of Fig. 8B); the cause for these is unknown but they could be caused by evaporites known to be present elsewhere within the Inverclyde Group. The transition from coherent reflectors to featureless seismic signal at depth is interpreted to mark the Top Basement composed of the metamorphosed Caledonian rocks.

The Top Tyne Limestone Formation and the overlying Top Alston Formation are interpreted above the Lower Groups (Fig. 8). The Tyne Limestone Formation contains some very high amplitude reflectors; again, the cause of these is unclear but they possibly represent contacts of limestone beds developed due to the increasing marine influence on this formation. The Alston Formation is characterised by lower amplitude, higher frequency reflectors than the underlying formations. The rocks above the Alston Formation belong to the Namurian Stainmore Formation, locally overlain by the Westphalian Coal Measures.

From the horizon interpretations, it can be observed that both the Top Basement and the sedimentary succession reflections dip southwards into the Stublick fault hanging-wall (Fig. 8A). Near the Stublick Fault, especially the sedimentary successions above the Lower Groups form a broad syncline, with the reflections shallowing out before dipping slightly northwards in the immediate vicinity of the fault. The Lower Groups thicken significantly southwards towards the Stublick Fault and are therefore broadly interpreted as the syn-rift package. The Tyne Limestone Formation appears to thin slightly towards the Stublick Fault, whereas the Alston Formation maintains approximately constant thickness; these formations can thus be broadly classified as post-rift. The wedge-shaped geometry of the interpreted syn-rift Lower Groups succession is even clearer in the E-W direction (Fig. 8B); a west-dipping Top Basement is overlain by the syn-rift Lower Groups which display an obvious thickening towards the west, roughly parallel to the strike to the Stublick Fault. However, this strike-section shows more clearly that the topmost part of the Lower Groups show approximately even thickness and may thus be post-rift. The Tyne Limestone Formation thickness seems to remain approximately constant in the E-W direction.

All identified faults are normal faults, with approximate throws ranging from the lower limit of vertical seismic resolution (around 20-60 m for these surveys) to possibly up to 2 km. Some faults show weak positive inversion expressed by features such as the anticline between the synthetic-antithetic fault pair in Figure 8A and the hanging-wall anticline in Figure 8B. Both of these anticlines affect the post-rift packages, constraining the maximum age of the folding to Middle Carboniferous. The seismic sections in Figure 8 are vertically exaggerated, which steepens the overall apparent fault dip, although the dip for many large faults appears to shallow out slightly with depth. More faults are identified on north-south sections than east-west sections, due to the dominantly E-W to ENE-WSW strikes of the faults.

The Stublick Fault dips northwards and is the longest fault and the largest in terms of displacement. Horizons generally cannot be followed across to its foot-wall, although the Top Basement is interpreted, with some uncertainty, to be displaced by up to 1 s TWT (2 km using an average velocity of 4000 m s^{-1} for the hanging wall rocks). Interpreted major splays of the Stublick fault are common (Fig. 8A). Overall, the displacement clearly increases towards the west along this major fault zone as indicated by the wedge-shaped growth geometries of the Lower Groups.

The Antonstown Fault and Sweethope Fault are examples of other major (>200 m throw) faults. These are found north of the Stublick Fault and show south- and north-ward dips respectively. Both faults can be interpreted to penetrate down into the basement and they may be linked to form a flower structure across the relay zone between these faults (Fig. 8A).

Further north- and south-dipping faults with throws of around 100 m or less are frequent in the interpretation.

4.2 Structure maps

TWT horizon maps were constructed from the interpreted horizons to illustrate the interpreted 3D structure (Fig. 9).

The basement consists of highly deformed, metamorphosed Caledonian schists and gneisses. The Top Basement geometry, equivalent to the base of the sedimentary basin fill, is dominated by a 10-20 km wide E-W trending asymmetric depression on the downthrown northern side of the Stublick fault: this is the Northumberland Trough (Fig. 9A). The trace of the Stublick Fault is not straight and shows a prominent ‘embayment’ just east of the centre. The TWT to the Top Basement along the fault commonly exceeds 2 s, with major structural lows on both sides of the embayment and another two minor lows interpreted within the embayment itself. We interpret that the Stublick Fault formed through linkage of several smaller faults, probably through relay ramp breaching. At Top Basement level the easternmost part of the Stublick Fault seems to have initiated as a NE-SE striking, basin boundary-parallel fault before linking up with the more E-W striking segments of the Stublick Fault.. The maximum displacements of each of these smaller faults are still recognisable as local TWT lows along the fault strike.

The Ninety-Fathom Fault can only be reliably interpreted using Top Basement. The interpreted segment is of a limited extent but it too shows a non-linear geometry with highly variable strikes. The Top Basement deepens towards the east along this fault, forming a relay ramp between the Stublick fault and the Ninety-Fathom fault. A basement high belonging to the Alston Block is interpreted in the SE of the area, in the foot-wall of the Ninety Fathom Fault.

The Top Basement along the northern margin of the trough is characterised by a southerly dip and the absence of a continuous fault zone. The northern margin is around ~1.5 s TWT to basement, but rapidly increases towards the trough centre before levelling out somewhat. The Antonstown Fault and the Sweethope Fault cut through the Top Basement near the steeper dips, and sub-seismic resolution faults may be present along the zone of steeper dips (with associated relay ramps contributing to the basement topography in this region), but overall the northern margin does not show obvious faulting within the basement at seismic resolution. The maximum throw on both the Antonstown Fault and the Sweethope Fault at basement level is around 0.25 s TWT (~300-500 m). Towards the east, the Top Basement becomes east-dipping.

The Top Fell Sandstone is significantly more faulted than the Top Basement, especially along the northern margin of the basement trough (Fig. 9B). The dominant strike of the faults is E-W to ENE-WSW, although ESE-WNW striking faults also occur in the east. North-dipping faults are more frequent than south-dipping faults. The throw on most faults is too small to have much impact at the scale of the structure map. The most significant faults are the Antonstown Fault and the Sweethope Fault, although the maximum throw at this level is reduced to 0.10 s and 0.20 s TWT respectively. However, the strike lengths of both faults have significantly increased relative to what can be interpreted from the seismic at Top Basement level, especially that of the Sweethope Fault. In addition, the distance between the faults and, consequently, the width of the minor graben between them has also increased. Other significant faults within this zone include the Causey Park Fault, the Hallington Reservoir Fault, and both Stobswood Faults. The maximum throw on these faults does not exceed 0.08 s TWT but they have significant lengths of up to several tens of kilometres. Several relay ramps can be identified between the various faults.

The elongated depression in the Stublick Fault hanging-wall is significantly narrower than the depression defined by the Top Basement. The eastward projection of the Stublick Fault potentially links with the up-dip continuation of the Ninety-Fathom Fault, although this cannot be determined from the available data. Structural lows along the Stublick Fault are confined to the eastern part of the study area, whilst towards the west the lows are situated near smaller (splay?) faults.

The Fell Sandstone Formation reaches outcrop in the western of the area of the interpreted seismic lines. The eastern part of the structure map is again dominated by a shallow eastward dip, reflecting the arcuate outcrop pattern of the Carboniferous sediments as they become east-dipping (Fig. 4).

The Top Tyne Limestone Formation and the Top Alston Formation cover a smaller area in the interpretation as erosion has removed them from the NW (Figs. 9C and 9D). The general structure of both horizons is very similar to the Top Fell Sandstone Formation in terms of dip trends and faulting. The horizons dip generally southwards towards the Stublick Fault, forming small trough structures, with a gentle easterly dip becoming dominant towards the east part of the map. The syncline near the western part of the Stublick Fault is present in the Top Tyne Limestone Formation map but can no longer be identified in the younger Alston Formation. Farther north, the Sweethope Fault, the Causey Park Fault, the Stobswood Fault and the Hallington Reservoir Fault, along with several minor faults, are all interpreted to penetrate up to the Top Alston Formation. Note, however, that the seismic data are not processed above ~0.2 s TWT, and that here the horizons have been interpreted by extrapolation from deeper reflectors, introducing uncertainty into the near-surface fault identification, even compared with outcrop data. Either way, it is clear that the majority of the faults have been active after (and possibly during) the deposition of these Visean packages although the displacements are generally small (~200 m at most).

4.3 Thickness maps

3D maps illustrating thickness variations within each interpreted package (i.e. TWT thickness maps) can be constructed by subtracting the thicknesses of the overlaying packages from the TWT depth to the base of the package in question (Fig. 1D). The TWT thickness maps for the interpreted packages are shown in Fig. 10. Figure 10A illustrates the thickening of the Lower Groups (Top Basement to Top Fell Sandstone) from the minimum value of around 0.63 s TWT in the NE part of the study area, to a maximum of 2.00 s TWT in the W. This represents a 52% deviation from the average thickness (min thickness + max thickness / 2) of 1.32 s TWT for this package. The maximum thickness occurs approximately 5 km north of the Stublick Fault and increases westwards along the Northumberland Trough; this is probably due to the sediment accumulation pattern switching from thickening towards the fault during Courceyan-Chadian active faulting, to thickening *away* from the fault after active rifting waned during the subsequent sag phase. Although the Stublick Fault has the most noticeable effect on the thickness distribution, the Antonstown-Sweethope Fault zone also seem to have a minor control the thickening on the northern margin of the trough, indicating that they may have been active during the earliest Carboniferous.

The Tyne Limestone Formation (Top Fell Sandstone to Top Tyne Limestone) has a minimum thickness of 0.21 s TWT and a maximum thickness of 0.52 s TWT (Fig. 10B). The thickest interval is found in the central part with a 42% change from the average sequence thickness of 0.37 s TWT. The maximum thickness is attained farther east than in the Lower Groups and around 10-12 km to the north of the Stublick Fault, centred between two smaller, unnamed faults between the Stublick Fault and the Sweethope Fault. This thickness change does not seem to be controlled by any earlier (basement) faults. The thickness change is close to the approximate interpretational error margin of ~0.05 s TWT, but another possible explanation is that there was some active normal faulting along the two unnamed faults and/or differential compaction during the sag phase during the Asbian when these sediments were deposited. Another area with larger than average thicknesses is present westwards along the trough, with thicknesses commonly at ~0.5 s TWT, changing rapidly from ~0.3-0.4 s TWT and therefore not within interpretational error margin. Sub-resolution Asbian faulting may control this thickening; alternatively some local accommodation space for the Asbian sediments may have remained from the earlier basin subsidence and differential sediment compaction.

The Alston Formation (Top Tyne Limestone to Top Alston) thickness map is of limited use due to its small extent before this formation reaches outcrop (Fig. 10C). Overall, the Alston Formation thickens slightly southwards towards the Stublick Fault, from around 0.12 s TWT in the north to a maximum of 0.24 s TWT 2-3 km north of the fault. This is a 33% change from a 0.18 s TWT average thickness. However, most of the thickness variation seen in this package is within the interpretational error margin of ~0.05 s TWT. The trend towards greater thicknesses towards the SW of the map is very poorly constrained by the seismic data, and noisy seismic inhibits reliable interpretation of Top Alston Fm. in the SW.

5. Discussion

There is a clear overall reduction in magnitude of thickness variation upwards within the sedimentary succession, reflecting the transition from syn-rift to late- or post-rift packages. The older, deeper packages, especially within the middle and lower Lower Groups, display much greater thickness variations with thickness increases both towards the Stublick Fault and towards the deeper parts of the basin, both in terms of absolute values and relative to the average thickness of each package. The higher Lower Groups and the Tyne Limestone Formation seem to have been affected by the waning fault activity along the original, basin-bounding faults and by the onset of the thermal sag phase with thickening increasingly towards the basin centre; this overall subsidence is reflected in the increasingly marine (limestone) successions of the ~Chadian to Asbian packages. The observations described above, made from the interpreted 3D maps therefore help us to constrain the fault timings, relative fault displacement magnitudes, and the distribution and geometries of the syn-rift packages.

To summarize, the Northumberland Trough is controlled by the large east-west trending, north-dipping Stublick Fault. The kilometre-scale throw affecting the basement is consistent with the Stublick fault being a part of the basin-bounding fault system that comprises the Ninety-Fathom Fault, Stublick Fault and the Maryport Fault systems (Fig. 2 inset). The Stublick Fault system is, except for its south-easternmost part, approximately E-W trending as opposed to the other two which have generally more NE-SW orientations; this may indicate that Stublick Fault formed a large breaching fault system within a relay ramp between the Ninety-Fathom Fault and the Maryport Fault systems. The seismic data does not extend far enough west, however, to draw definite conclusions about this. In more detail, the discrete structural low points seen in Fig. 9 in the hanging-wall of the Stublick fault at Top basement level may represent individual depocentres, hinting at a possible segmentation of the Stublick fault (i.e. lateral fault linkage during fault growth; Cowie et al., 2000). This interpretation is also supported by the non-linear nature of the fault with the strike changes correlating with the structural lows. The Ninety Fathom fault in the far SE of the area runs parallel to the NE segments of the Stublick fault and also displays kilometre-scale throw at the Top Basement level. It is therefore probably the en-echelon, right-stepping, eastwards continuation of the basin-bounding fault system in this area. The Stublick and Ninety Fathom faults are interpreted to be soft-linked at Top Basement level, separated by an east-dipping relay ramp, although this is poorly constrained and the relay ramp between the two faults may be breached (Figure 10A).

Other significant, early rift-related faults are the Sweethope Fault and the Antonstown Fault. Based on the interpreted variability of throw and strike of these (and many other) faults, they too seem to have been highly segmented initially and gained length through relay ramp breakage.

Although we were unable to interpret horizons older than the Top Fell Sandstone Formation, an attempt was made to further constrain the initiation of rifting. The Early Carboniferous, syn-rift Lower Groups thicken into the Stublick Fault hanging-wall (Figs. 8A, 10A). The thickening is especially visible in the middle and lower parts of the Lower Groups, indicating that Stublick Fault was active when this part of the succession was deposited, i.e. during the Early Carboniferous (~Courceyan-Chadian). On dip lines (Fig. 8A) the thickening within the Lower Groups switches approximately in the middle of the succession to thicken *away* from the Stublick Fault, possibly indicating the waning of active faulting in this area and initiation of the thermal subsidence (sag) phase. Both the top and the bottom ~0.3 s of the group maintain an approximately constant thickness. This suggests that a pre-rift package may present above the basement, and a syn-rift succession is correspondingly present towards the top of the package. The reflections just above the basement have previously been interpreted as basaltic lavas associated with the onset of rifting (Leeder, 1974; Fraser and Gawthorpe, 2003). We consider that interpreting this interval as pre-rift sediments rather than basalts is more consistent with the >40km-scale extent, the modest acoustic impedance contrast, and the regular geometry of this package.

The growth strata thickening is more obvious on strike lines (Fig. 8B) than on dip lines. Westwards thickening of the Lower Groups parallel to the Stublick fault is interpreted to be caused by the general deepening of the basin towards the west in addition to the faulting and sag phases, controlled in this area mainly by the Stublick Fault system but also the Antonstown-Sweethope fault system.

Both the Tyne Limestone Formation and the Alston Formation are extensively faulted, with especially the Tyne Formation showing some possible thickness variation related to the two unnamed faults in the centre of the thickness map (Fig. 10B). Whilst it is possible that minor faulting continued into (or initiated during) the Asbian-Brigantian, some of the thickness variation may be explained by differential compaction during the sag phase. The data does not allow determining with certainty whether these minor faults nucleated on or reactivated existing Lower Carboniferous rift-related faults within the Lower Groups, but this seems unlikely given that the faults do not seem to affect the basement. This makes them unlikely to be important for any possible Irish-style mineralisation in this area as the Irish-style mineralisation is linked with major faults penetrating the basement.

The interpretation of the study area is predominantly consistent with the accepted geological history and existing interpretations of Northumberland Trough (e.g. Collier, 1989; Chadwick et al., 1995; Stone et al., 2010). Rifting occurred under approximately north-south orientated extension during the Lower Carboniferous, with the majority of deformation localising into ~NE-SW trending controlled the older Caledonian basement fabrics; the slightly oblique ~E-W normal fault systems such as the Stublick Fault possibly formed as relay-ramp breaching structures between the NE-SW right-stepping faults. The prediction arising from this is that if the overall extension was NE-SW orientated, the E-W trending faults are probably dextral-normal faults, whilst the NE-SW trending faults are dominantly dip-slip faults. If this is the case, the transtensional nature of the E-W faults could be expected to enhance fluid flow into these fault zones. Either way, the basin analysis approach illustrated here provides closer insights into the timing and the internal geometries of the faults, the fault linkage histories, and the geometries of the coeval depositional packages, understanding of which is key for exploration of basin ores.

5.1. Comparison with Ireland and assessment of mineralisation potential

From the observations made in the previous sections, and with the corresponding timings and geometries in the Pb-Zn play of Ireland well known, we can now perform a more robust comparison between Ireland and Northumberland. The scale and the timing of the Early Carboniferous faulting corresponds exactly to the scale and activity of the major fault systems controlling the Irish Pb-Zn mineralisation (e.g. Ashton et al., 2015, 2018). In Ireland, the main faults that control the formation and location of Pb-Zn deposits are of Courceyan-Arundian age, although another possible regional rifting event is identified during Asbian-Brigantian (e.g. Fraser and Gawthorpe, 1990). E-W or ENE-WSW trending syn-sedimentary normal faults with displacements of hundreds of metres and possibly up to 1.5-2 km within the basement (Table 2; e.g. Hitzman and Beaty, 1996; Ashton et al., 2018). Deposits are normally associated with fault arrays rather than isolated faults, with fluid feeder points typically occurring at areas of maximum fault throw and in broken relay ramps (Hitzman, 1999; Torremans et al., 2018). The crucial role of breached/highly fractured relay ramps at various scales as fluid flow focal points has been suggested at least at Silvermines and Lisheen (Torremans et al., 2018; Kyne et al., 2019) but the Navan deposit and its satellite Tara Deep also show complex fault-ore-breached relay ramp relationships at various scales (see e.g. Fig. 10 in Ashton et al., 2018).

The first-order requirement for faulting extending to the basement, probably Courceyan-Arundian in age, and with throw of at least ~200 m (Table 2) is satisfied by many major faults in Northumberland, but excludes most of the other, isolated faults identified within the study area as they do not affect the basement and have small throws. The major Stublick-Ninety Fathom fault system, along with the Antonstown- Sweethope Fault zone have a suitable Courceyan-Arundian age; possibly also the Stobswood Fault, Causey Park Fault and Hallington Reservoir Fault (Table 2). Significant throws and relay ramp breakage, similar to the Irish faults, is evident along the Stublick Fault (Fig. 9A). The Stublick Fault zone itself may in its eastern parts be a regional-scale relay ramp-breaching fault linking the more NE-SW trending Maryport Fault and Ninety-Fathom Fault systems (Fig. 2, inset), although the seismic data coverage is insufficient to determine this with any certainty. If Irish-type mineralisation exists in the Northumberland Trough, its fluid feeder channels are similarly to Ireland most likely related to the points of maximum throw or, more likely, to the (breached) relay ramps identified in along the central and western parts of the Stublick Fault in FIg. 9A. The larger relay ramp between the Stublick Fault and the Ninety-Fathom Fault (Fig. 9A) is less likely to control mineralisation because i) the basin shallows significantly to the east and, crucially, the relay ramp formed within a structural high with non-deposition of Early Carboniferous carbonates; and ii) it does not seem to be breached at basement level, although the data quality in the area of this relay ramp may prevent detection of any breaching faults.

The potential for the faults within the Northumberland Trough to act as mineralising fluid conduits is shown by baryte and lead mineralisation on the Stublick Fault itself (Dunham, 1990). The Lower Carboniferous sequences are not exposed in this area, but exposures are found 10-20 km north and northwest with some stratabound base metal mineralisation in the proximity of other, southeast-dipping normal faults (near Langholm and Saughtree; Fig. 2; Gallagher et al., 1977; Smith et al., 1996). The timing and downward extents of the faults near Langholm and Saughtree remains unresolved as the seismic data do not extend this far north.

Based on the interpreted structural evolution and the tectonic history of the area, we propose a refined structural model for the Carboniferous evolution of the Northumberland Trough and how it may be linked to Irish-style mineralisation at depth (Fig. 11A-C).

Another key requirement for Irish-style mineralization is the presence of carbonate packages into which the mineralizing fluids can penetrate. The characteristics of the thick syn-rift Lower Groups within the sub-surface Northumberland Trough remain mostly unknown, although the outcropping part of this sequence in the eastern part of the study area shows contrasting fluvial input from the NE and marine input from the SW (Johnson 1980; Leeder et al. 1989). Later Carboniferous (Asbian to Pendeleian) clastic-carbonate cycles of up to 50 m thickness, with the marine limestone component within each cycle of up to 30 m thickness, have been logged in the broader area of NE England (Gallagher et al., 1977; Smith et al., 1996; Tucker et al. 2003; Dean et al. 2011). As such, whilst this paper has highlighted the potential from the structural geology viewpoint for Early Carboniferous mineralisation within the Northumberland Trough, the presence of suitable host lithologies at depth remains to be tested through drilling. The presence of outcropping thin marine limestones, the thicknesses of which seem to increase towards the west and include Lower Carboniferous sulphide-mineralized horizons (Gallagher et al., 1977; Smith et al., 1996) is however an encouraging starting point.

The depth to the target horizon for any potential Irish-type mineralisation within the Northumberland Trough will probably be defined by the lowest carbonate sequences within the syn-rift Lower Groups, adjacent to suitable feeder faults, although in Ireland the ore is not always in the lowermost carbonate sequence (e.g. Torremans et al., 2018). Such a horizon could lie anywhere between the Top Basement and the Top Fell Sandstone reflectors. However, we consider that it is most likely to be present within the middle or towards the top of the Lower Groups once the basin had subsided enough to be influenced by significant marine input: the most prominently wedge-shaped packages with thickening towards the main faults, marking the most active rifting period, are seen in the lower and middle parts of the Lower Groups package (Fig. 8). As identified in this study, the most prospective feeder faults within Northumberland are the Sweethope and Stublick faults. Around the intrabasinal Sweethope fault, the Top Fell Sandstone is typically located at 0.2-0.6 s TWT (~400-1200 m with 4000 m s^{-1}), whereas adjacent to the Stublick fault the top Fell Sandstone usually exceeds 0.6 s TWT (>1200 m).

5.2. Possible link to the Permian mineralisation of the North Pennine Orefield

The cause of the Permian mineralising event is debated as, despite some evidence of regional extension, subsidence and high heat flow at the time, there was no major foreland basin/rifting which would be typical for most MVT ores (e.g. Collier, 1989). The Weardale Granite, a concealed Devonian age batholith (Dunham et al., 1961), probably controlled much of the mineralizing fluid flow in the Alston Block on account of higher fracture density and connectivity (Bott & Mason-Smith 1957; Kimbell et al. 2010), but the fluid and metal sources remain enigmatic. The NPO mineralisation has been suggested to represent a fluoritic sub-type MVT ore, the fluid sources being mixed but probably mostly originating from the adjacent basins (e.g. Crowley et al. 1997; Cann and Banks, 2001; Baba et al., 2019; Kraemer et al. 2019). The MVT model for the NPO envisages dewatering of basin facies sediments (those in the Northumberland and Stainmore Troughs) to generate carrier fluids. Most of the 'MVT-style' models agree that the basinal fluids migrate laterally into the Weardale granite ‘plumbing system’, before mixing with other fluids and travelling upwards along fractures in the granite into the Upper Carboniferous rocks on the Alston Block, where they cool and deposit minerals (Fig. 7; Jackson and Beales, 1967; Dunham, 1983; Brown et al., 1987; Bott and Smith, 2018).

The metal sources for the known Permian mineralisation of the NPO are unknown and various sources from underplated mafic magmas to leaching of the Weardale granite have been suggested. Cann and Banks (2001) use sulphur isotopes to infer the lead probably originated from basement, but the evidence is inconclusive especially as the sulphates may be associated with the surface brines (Bouch et al., 2006). Dempsey (2016), on the other hand, found that at least some of the osmium in NPO pyrites originated from the mantle (i.e. underplated mafic magma potentially underlying the Alston Block), although there was also a significant sample group of higher osmium isotope ratios indicating other, unknown source(s). Kraemer et al. (2019) argue against mafic rocks as a source of fluids and metals, inferring that the REY patterns within the veins correspond better to leaching of metals from basinal shales or the Weardale granite.

Based on the published literature, an intrabasinal metal source from an Early Carboniferous lead-zinc base metal deposit cannot, therefore, be ruled out. There is a significant body of evidence that most of the fluid originated from the basins adjacent to the Alston Block, although mixing with both surface and magmatic fluids is possible (e.g. Jackson and Beales, 1967; Dunham, 1983; Cann and Banks, 2001; Bott and Smith, 2018). Whilst the fluids and the metals do not need to originate from the same source, we hypothesise that the easiest explanation for the presence of the Permian mineralization is the remobilisation of older mineralisation at depth within the basins adjacent to the NPO structural highs (Fig. 11D). Hydrothermal fluid-assisted remobilisation of lead and zinc from galena and sphalerite is a globally known phenomenon and has been reported from e.g. the Ramsbeck Pb-Zn deposit in Germany (Wagner and Boyce, 2001). The basement signature of Cann and Banks (2001) is not inconsistent with a remobilisation hypothesis as any Irish-type ores at depth are likely to carry a basement isotope signature which can be inherited in subsequent remobilisation. The low concentrations of lead (galena) in the sphalerite-dominated Permian NPO deposits are consistent with the remobilisation hypothesis: e.g. Barrett and Anderson (1988) show that ZnS is more soluble than PbS by a factor of up to 100 in NaCl brines of up to 300°C.

Our remobilisation hypothesis is also consistent with the 'circulation cell' model proposed by e.g. Bott & Smith (2018) but refines it by suggesting that not only fluids but also most if not all of the metals originated from remobilized ores within the Northumberland Trough and/or other basins adjacent to the NPO. The presence of at least one Carboniferous sealing horizon such as shale or evaporite within the Northumberland Trough would help to constrain fluid flow. Evidence for the presence of such horizons is given by e.g. Day (1970) and Johnson (1980) who report marine shales and evaporite layers within the Border Group in the northwestern part of the Northumberland Trough.

6. Conclusions

We have used basin analysis through structural interpretation of seismic reflection data to investigate the potential for syn-rift base metal deposition in the Northumberland Trough. Syn-sedimentary faulting in the Northumberland Trough associated with active rifting occurred from the earliest Carboniferous through to at least the late Visean, subsequently giving way to regional subsidence and, during the Permian, to renewed faulting. ENE trending arrays of basin-bounding and intrabasinal normal faults are studied in detail in this paper, in terms of their geometries and timings and their associated sedimentary growth packages. The interpreted scales and the Early Carboniferous timing of the faulting and the sedimentation in the study area is comparable with the fault and sedimentation system that controls lead-zinc mineralisation in the Irish Midlands: this opens up the possibility that the Irish Pb-Zn play extends into northern England. We suggest a refined model for the evolution of the Northumberland Trough, similar to the Irish stratabound Pb-Zn deposits. We suggest that the faults grew through hard linkage by breaching of relay ramps, possibly associated with flow of mineralising fluids from the basement, and identify potential locations for such mineralisation. The presence of suitable host Early Carboniferous host lithologies and stratabound base metal mineralisation at depth remains to be tested by drilling. If present, it could offer the simplest explanation for the presence of the known Permian mineralised veins in the North Pennines Orefield (NPO): through (partial) remobilisation of Early Carboniferous base metal ores within the adjacent basin(s).

Our study demonstrates that basin analysis using seismic reflection interpretation is a powerful tool in basin ore exploration. It allows a much more detailed insight into the timing, geometry and extent of faulting along with the extent of and thickness variations within the syn-rift sedimentary packages than is possible through surface observations and sampling alone. Crucially, it also allows identification of zones of structural complexity such as (breached) relay ramps which commonly function as channels for mineralising basement fluids. Establishing the relationships of these fundamental mineralisation-controlling features is a crucial step in a basin ore play analysis. As shown in this paper, a detailed consideration of the timing, geometry and linkage of the faulting with respect to the sedimentation allows both assessing the general potential of base metal mineralisation and a more precise identification of potentially suitable areas for further investigation.

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Figure captions

Fig. 1. Schematic illustrations of the relationships between sediment deposition and faulting, and of the seismic interpretation method and main outputs. Critically, if the age of the syn-rift sediments is known, the timing of the faulting can be established. A) Configuration of the basement and overlying sediments before faulting; B) During active faulting, the sediments will be preferentially deposit into the wedge-shaped accommodation space in the hanging-wall created by the faulting. This wedge geometry with thickening of the sedimentary package towards the active fault is very typical and diagnostic of syn-rift sediments; C) After the fault activity ceases, post-fault sediment deposition will blanket the area with relatively little thickness variation, although some thickening can occur in areas where the basin was not completely filled during active faulting; D) Typical 2D seismic interpretation approach to basin analysis. A grid of seismic reflection profiles is interpreted for structures (e.g. faults) and depths of formation boundaries. Any borehole (well) data or exposure at outcrop will greatly help in constraining the boundaries at depth. The interpretations in the 2D grid are then interpolated to '3D' (2.5D) interpretations, i.e. structural (depth/isochron) and thickness maps which can be used for further interpretation of the basin evolution. A thickness map for an interval of interest is constructed by subtracting the thicknesses of the overlying packages (X) from the thickness of the entire succession (X+Y) along the entire length of the interpreted lines; e.g. (X+Y)-X in the location shown along Line 1 in this figure.

Fig. 2. Generalized regional map showing the main Caledonian to Carboniferous tectonic elements of Ireland and Northern England-Southern Scotland, along with three mined Irish-type deposits in Ireland. Carboniferous normal faults: SF, Stublick fault; NFF, Ninety-Fathom Fault; SCF, South Craven Fault; MCF, Mid-Craven Fault; PF, Pendle Fault; NF, Navan Fault; SMF, Silvermines Fault. Irish-type Pb-Zn deposits: N, Navan deposit; T, Tynagh deposit; S, Silvermines and Lisheen deposits. Modified from Jones et al. (1994) and Treagus (1992). Inset: Map of the main sub-surface Carboniferous tectonic elements in the Northern Pennines Orefield and Solway-Northumberland Basin areas as interpreted by Chadwick et al. (1995). The area of our study shown in Fig. 3. is indicated with a rectangle.

Fig. 3. Generalized map of the surface geology of the Alston block and southern Northumberland Trough, including known occurrences of Permian vein-style Pb-Zn mineralisation. Modified from Stone et al. (2010) and Kimbell et al. (2010).

Fig. 4. Generalized geological map of the study area with the seismic reflection profiles. The type sections in Figures 7A and 7B are indicated with the stippled red lines.

Fig. 5. Generalized stratigraphic column for the Northumberland Trough and Alston Block.

Fig 6. Schematic illustration for the formation of Irish-type Pb-Zn deposits. They form in shallow marine carbonate shelves by stratabound replacement into calcareous host rocks. Mixing of sulphur-rich seawater/brines and metal-bearing hot basement fluids is typically postulated (e.g. Ashton et al. 2015).

Fig 7. Schematic model for the fluid system within the NPO (modified from Bott and Smith, 2018). According to the model, the highly fractured and permeable Weardale granite hosted a convection cell which drew in saline fluids from adjacent deep Carboniferous troughs. The model postulates that the heat to drive the convection cells may have originated from underplated magmas, although others have suggested that the high heat flow and fractured nature of the granite will be enough to drive the cell (e.g. Brown et al., 1987). The pictured Bott and Smith (2018) model suggests that the metals were derived from the mafic magmas; other models for metal source suggest leaching from basin sediments and/or the Weardale granite itself (e.g. Crowley et al. 1997). See section 5.2 for full discussion.

Fig 8. Interpreted seismic type sections, showing the general sequence architecture and main faults using higher quality lines. The line locations are highlighted in Fig. 4. Formation boundaries are shown by coloured solid lines; dashed red lines within the Lower Groups are delineating possible pre- and post-rift packages; also additional, arbitrary horizons are shown to demonstrate the within-sequence wedge geometry of this package, typical for syn-faulting growth packages (i.e. thinning towards the north and the east, especially in the middle and lower parts of the Lower Groups). (**a**) Seismic line TOC86-V102 which runs approximately north-south. (**b**) Seismic line TOC87-V112 which runs roughly west-east. This figure also shows an example of how mis-ties were mitigated: the basement in (a) appears higher than in (b) so that the horizons in (a) had to be manually adjusted downwards; note that manually lowering the horizon in (a) matched the outcropping formation boundaries.

Fig 9. 3D isochron maps of the interpreted formation boundaries (i.e. seismic surface structure maps), interpolated from the 2D seismic line interpretations (in TWT: 1 s equals approximately 1.5-2 km depending on the lithology). Major normal faults (tick-marks on hanging-wall) are numbered with corresponding names at the base of the figures. Grey lines show locations of the interpreted seismic profiles with the type sections in Fig. 8 highlighted in red. (**a**) Top Basement; note especially the areas of maximum TWT depth along the Stublick Fault (dark blue) indicating the areas of maximum throw of each original fault segment, now linked by breached relay ramps (red circles); (**b**) Top Fell Sandstone Formation (i.e. Top Lower Groups); (**c**) Top Tyne Limestone Formation; (**d**) Top Alston Formation. Some areas have not been included in the maps because of the poor quality of the seismic, especially in the western part of the study area.

Fig 10. Thickness maps of the interpreted formation intervals, interpolated from the 2D seismic line interpretations (in TWT: 1 s equals approximately 1.5-2 km depending on the lithology). Fault polygons show the fault loss areas for each package. (**a**) Lower Groups; (**b**) Tyne Limestone Formation; (**c**) Alston Formation. Note especially the thickening of the Lower Groups in (a) towards the west and south.

Fig 11. Schematic evolution model of the Northumberland Trough, including the timing and the most likely location of the possible Early Carboniferous fault-related mineralisation at depth; also shown is the suggestion of how the Permian vein-style mineralisation in the area may be explained by (partial) remobilisation of this earlier mineralisation phase. The majority of the interpreted faults are omitted for clarity. SF, Stublick Fault; NFF, Ninety-Fathom Fault; ShF, Sweethope Fault; AF, Antonstown Fault. (**a**) Rifting initiates during the Courceyan, with the structural high of the Alston Block forming in the south. (**b**) The main rifting continues into the Chadian, with the syn-rift deposition of up to ≈2 km thick package of carbonate and siliciclastic sediments. Stratabound base metal mineralisation within calcareous horizons may form during this stage, similar to Irish Midlands, once sufficient strata have been deposited (note that the possible mineralisation is not presented to real scale for illustration purposes). Any Irish-type Pb-Zn mineralisation is likely to be confined to the vicinity of the Stublick Fault in the southwestern part of the trough which represents deeper parts of the basin and may contain more (shallow) marine sediments as most sub-aerial, siliciclastic material was sourced from the north and the east. (**c**) Fault activity wanes from mid-Visean onwards (thermal subsidence), with the deposition of post-rift sediments of the Yordale Group and younger. (**d**) During the Permian, renewed minor extensional/transtensional faulting and increased heat flow trigger circulation of high-salinity, hot hydrothermal fluids within the trough. These may partially leach and re-mobilize the Carboniferous Pb-Zn mineralisation at depth. A Carboniferous seal (e.g. shale, evaporites) directs the bulk of the fluids towards and into the Stublick Fault and the highly fractured Weardale Granite. Upwards percolation of these fluids leads to near-surface deposition of veins within the Alston Block and southern Northumberland Trough.

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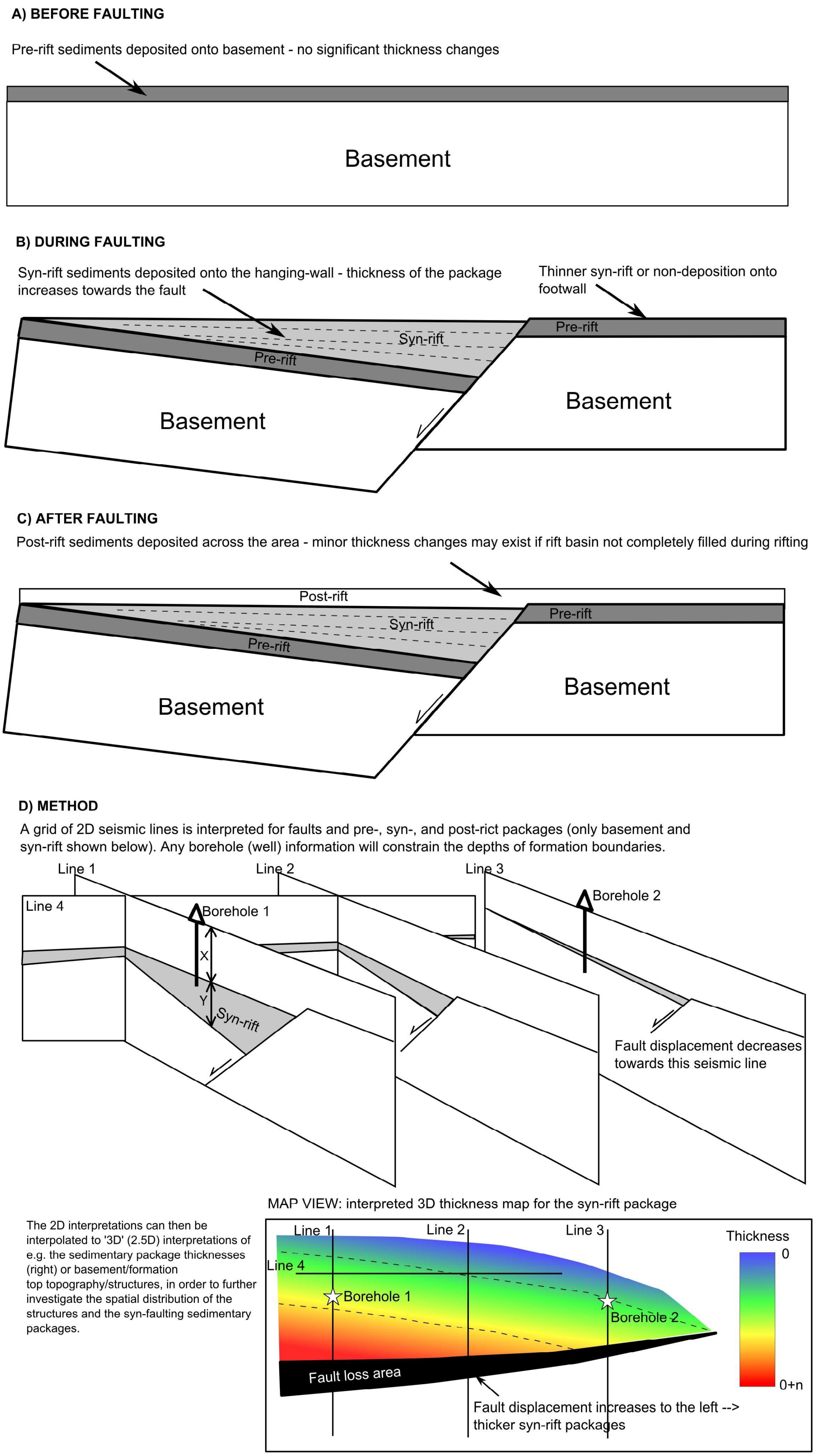

A) BEFORE FAULTING
Pre-rift sediments deposited onto basement - no significant thickness changes
Basement
B) DURING FAULTING
Syn-rift sediments deposited onto the hanging-wall - thickness of the package increases towards the fault
Thinner syn-rift or non-deposition onto footwall
Pre-rift
Syn-rift
Pre-rift
Basement
Basement
C) AFTER FAULTING
Post-rift sediments deposited across the area - minor thickness changes may exist if rift basin not completely filled during rifting
Post-rift
Pre-rift
Syn-rift
Pre-rift
Basement
Basement
D) METHOD
A grid of 2D seismic lines is interpreted for faults and pre-, syn-, and post-rict packages (only basement and syn-rift shown below). Any borehole (well) information will constrain the depths of formation boundaries.
Line 1
Line 2
Line 3
Line 4
Borehole 1
Borehole 2
X
Y
Syn-rift
Fault displacement decreases towards this seismic line
MAP VIEW: interpreted 3D thickness map for the syn-rift package
The 2D interpretations can then be interpolated to '3D' (2.5D) interpretations of e.g. the sedimentary package thicknesses (right) or basement/formation top topography/structures, in order to further investigate the spatial distribution of the structures and the syn-faulting sedimentary packages.
Line 1
Line 2
Line 3
Line 4
Thickness
0
0+n
Borehole 1
Borehole 2
Fault loss area
Fault displacement increases to the left --> thicker syn-rift packages

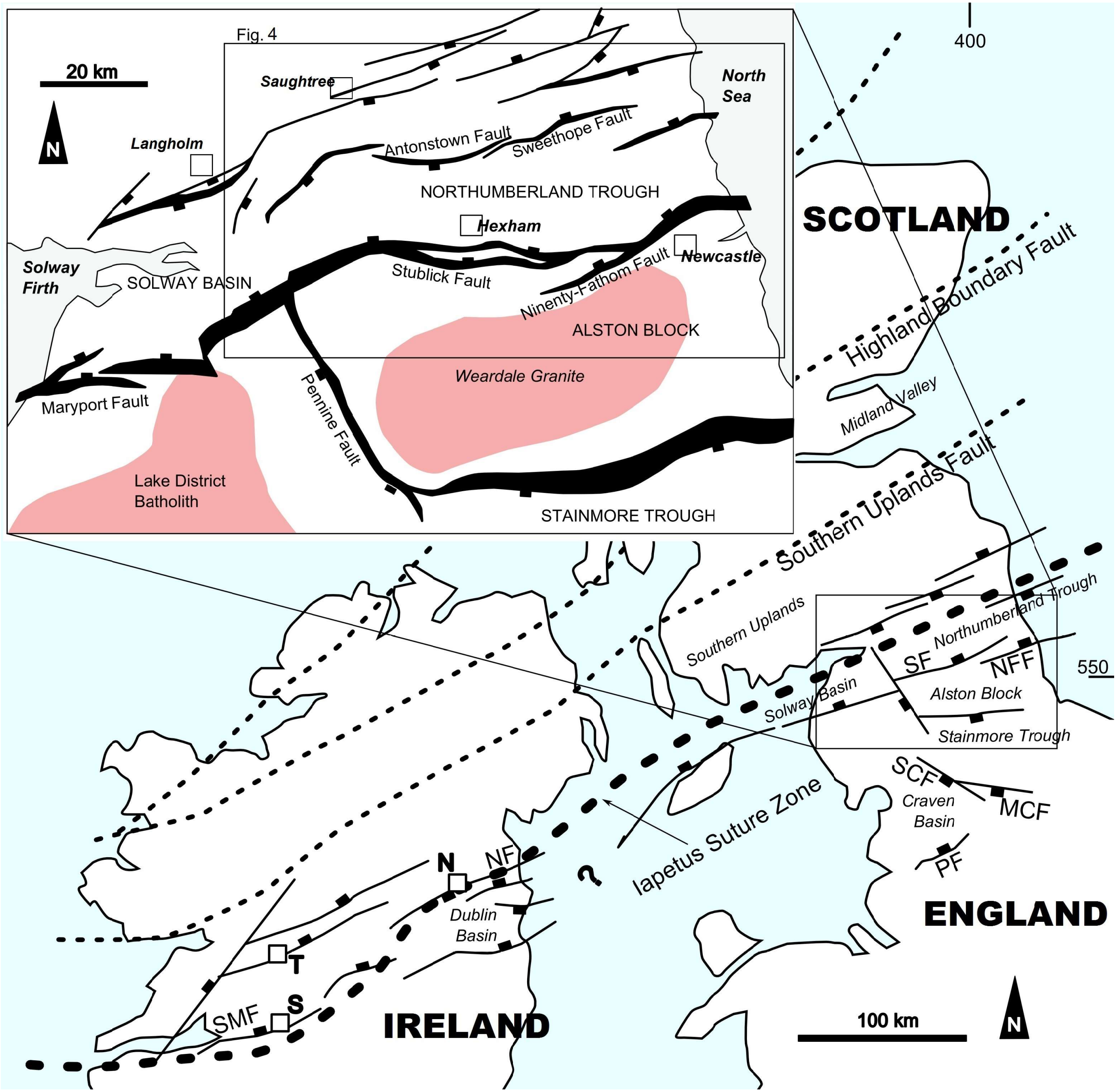
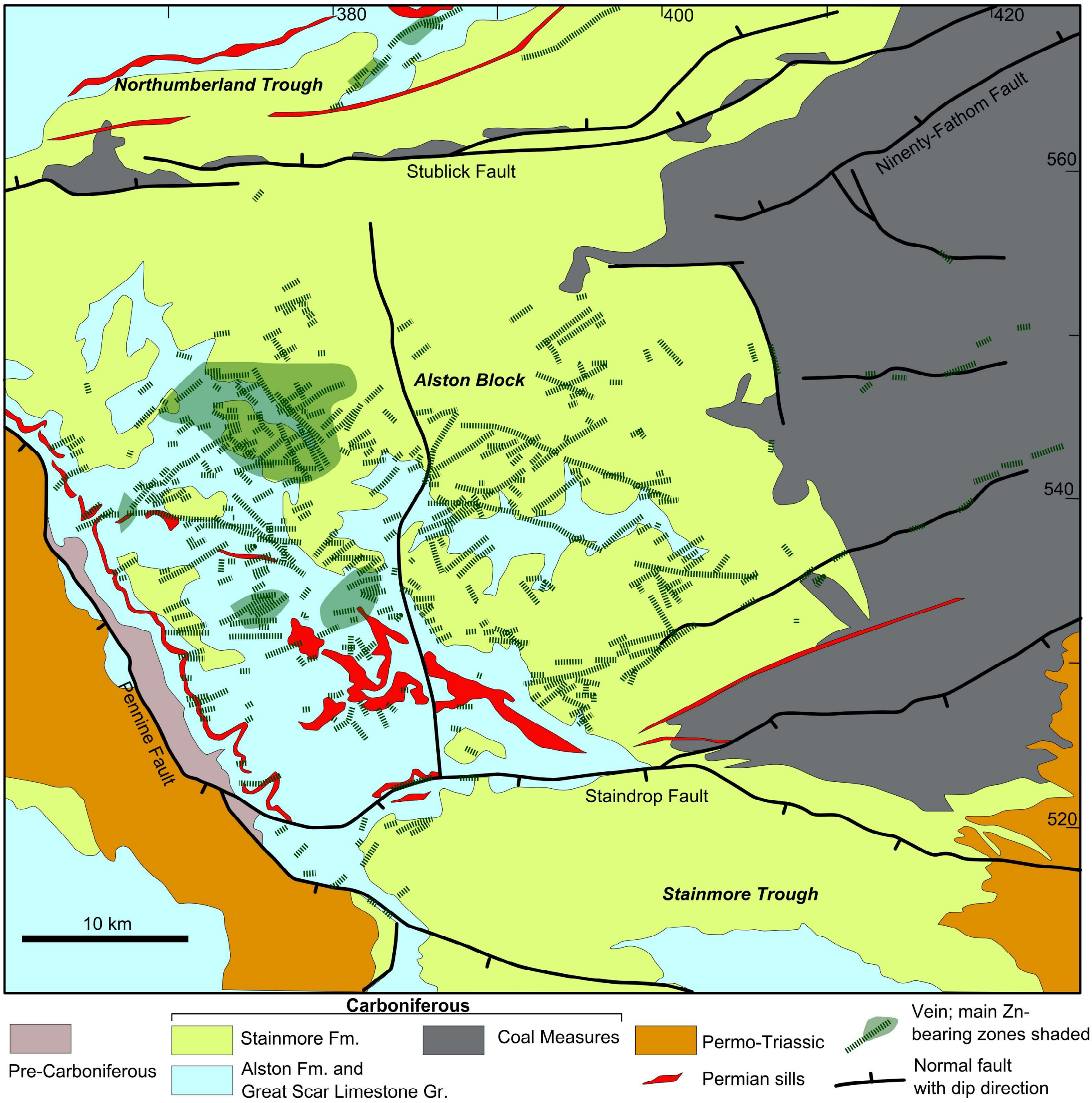
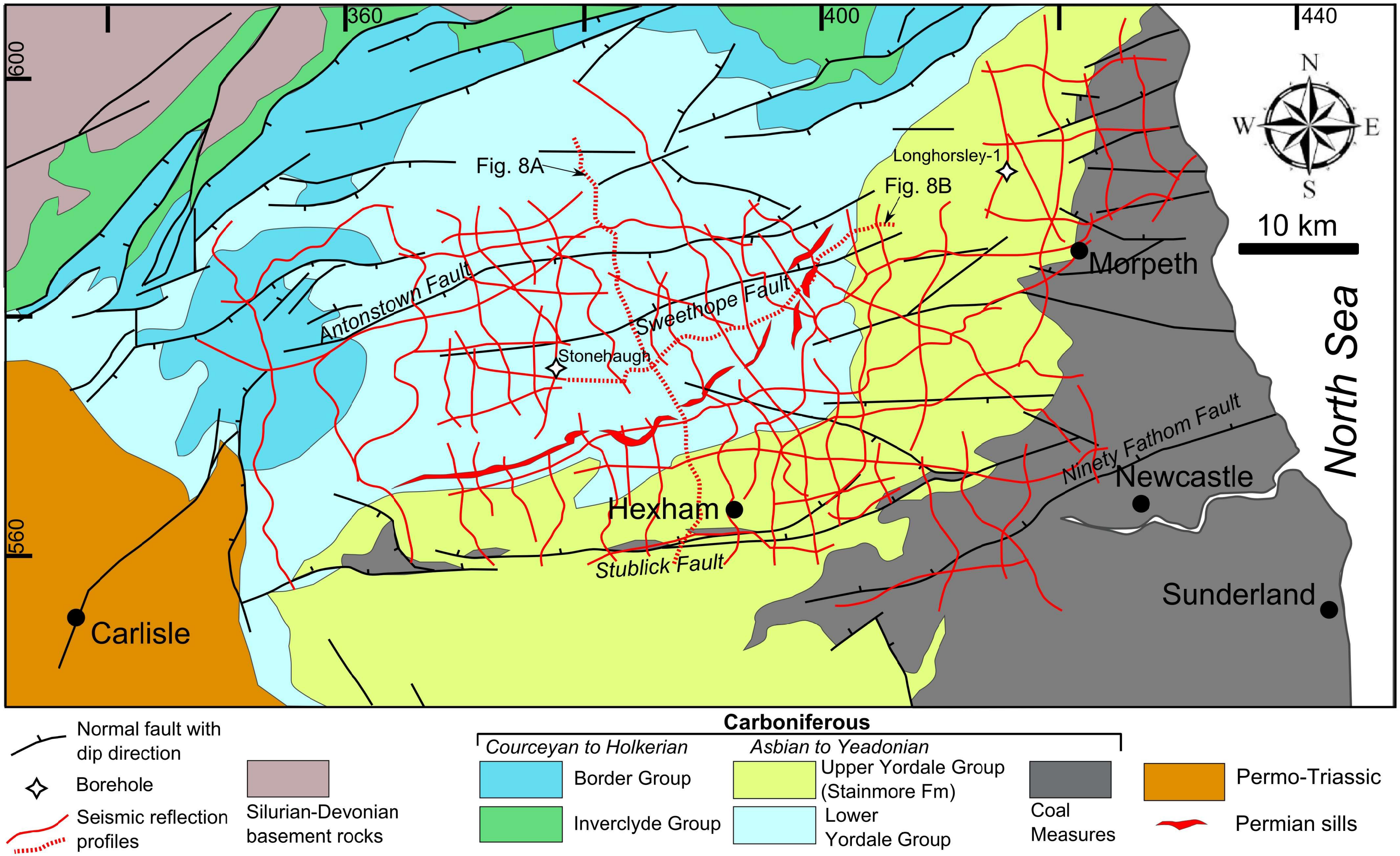


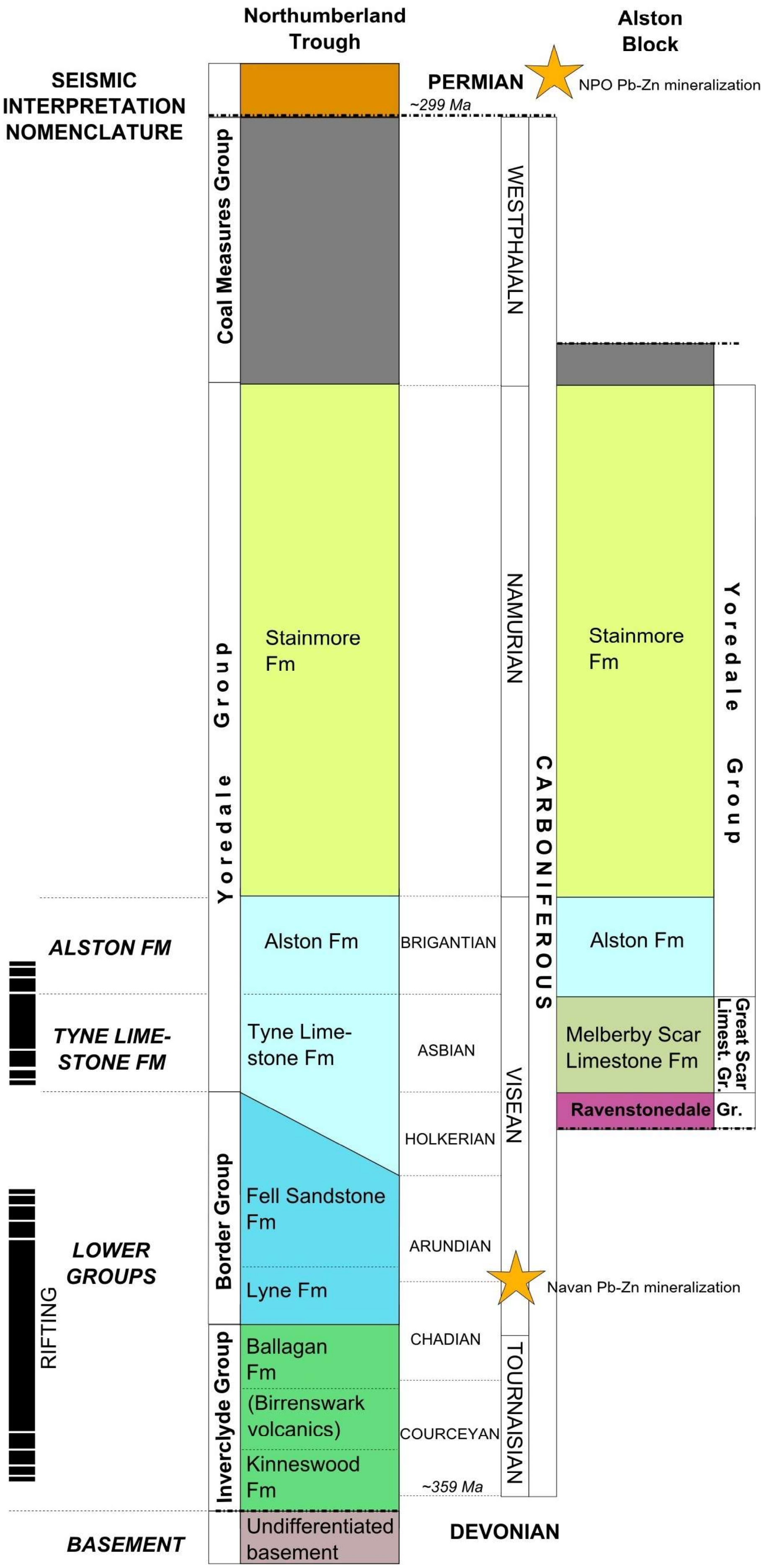
Fig. 4
20 km
N
Saughtree
North Sea
Langholm
Antonstown Fault
Sweethope Fault
NORTHUMBERLAND TROUGH
Hexham
Newcastle
Solway Firth
SOLWAY BASIN
Stublick Fault
Ninenty-Fathom Fault
ALSTON BLOCK
Weardale Granite
Maryport Fault
Pennine Fault
Lake District Batholith
STAINMORE TROUGH
400
SCOTLAND
Highland Boundary Fault
Midland Valley
Southern Uplands Fault
Southern Uplands
Northumberland Trough
SF
NFF
550
Solway Basin
Alston Block
Stainmore Trough
SCF
Craven Basin
MCF
PF
Iapetus Suture Zone
N
NF
Dublin Basin
T
S
SMF
IRELAND
ENGLAND
100 km
N

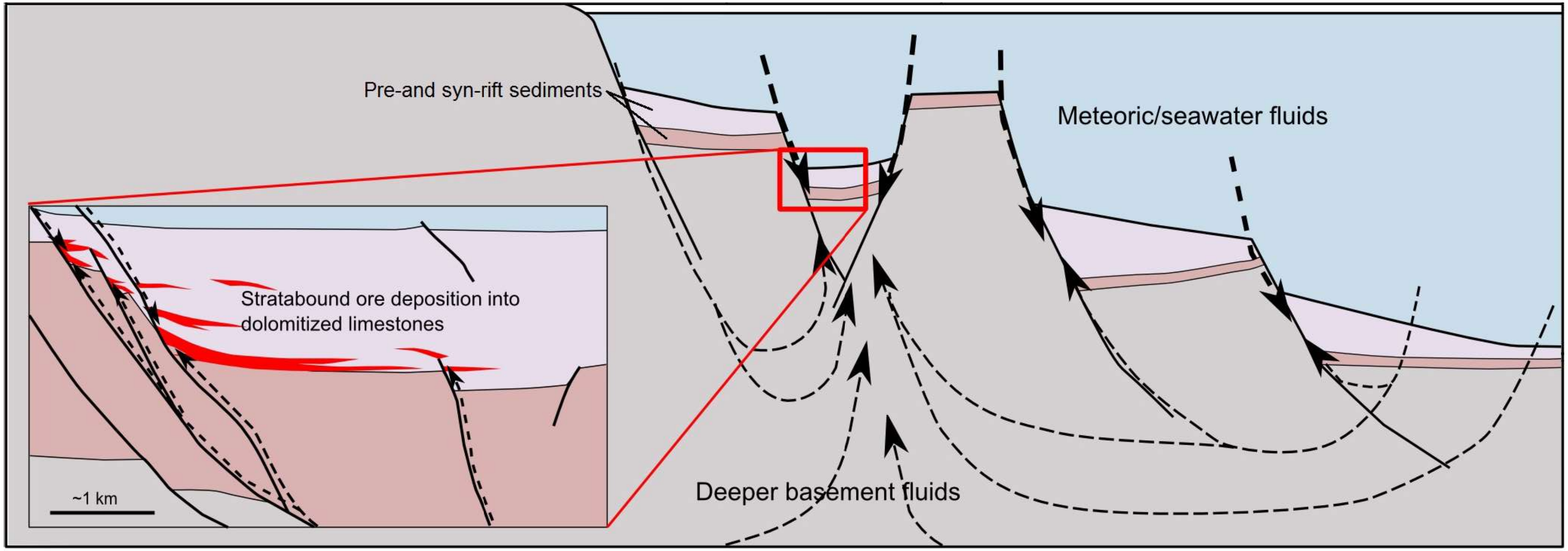


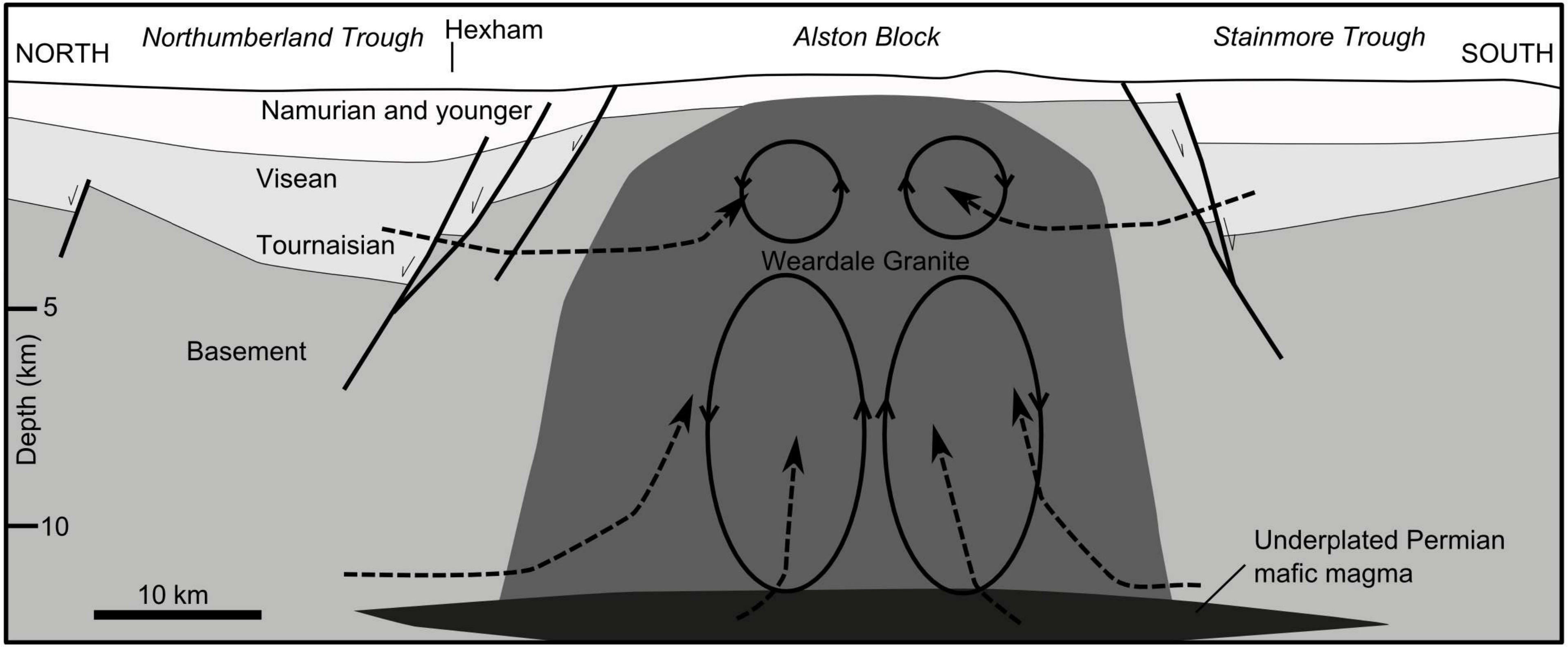
380
400
420
Northumberland Trough
Stublick Fault
Ninenty-Fathom Fault
560
Alston Block
540
Pennine Fault
Staindrop Fault
520
Stainmore Trough
10 km
Carboniferous
Pre-Carboniferous
Stainmore Fm.
Alston Fm. and
Great Scar Limestone Gr.
Coal Measures
Permo-Triassic
Permian sills
Vein; main Zn-
bearing zones shaded
Normal fault
with dip direction

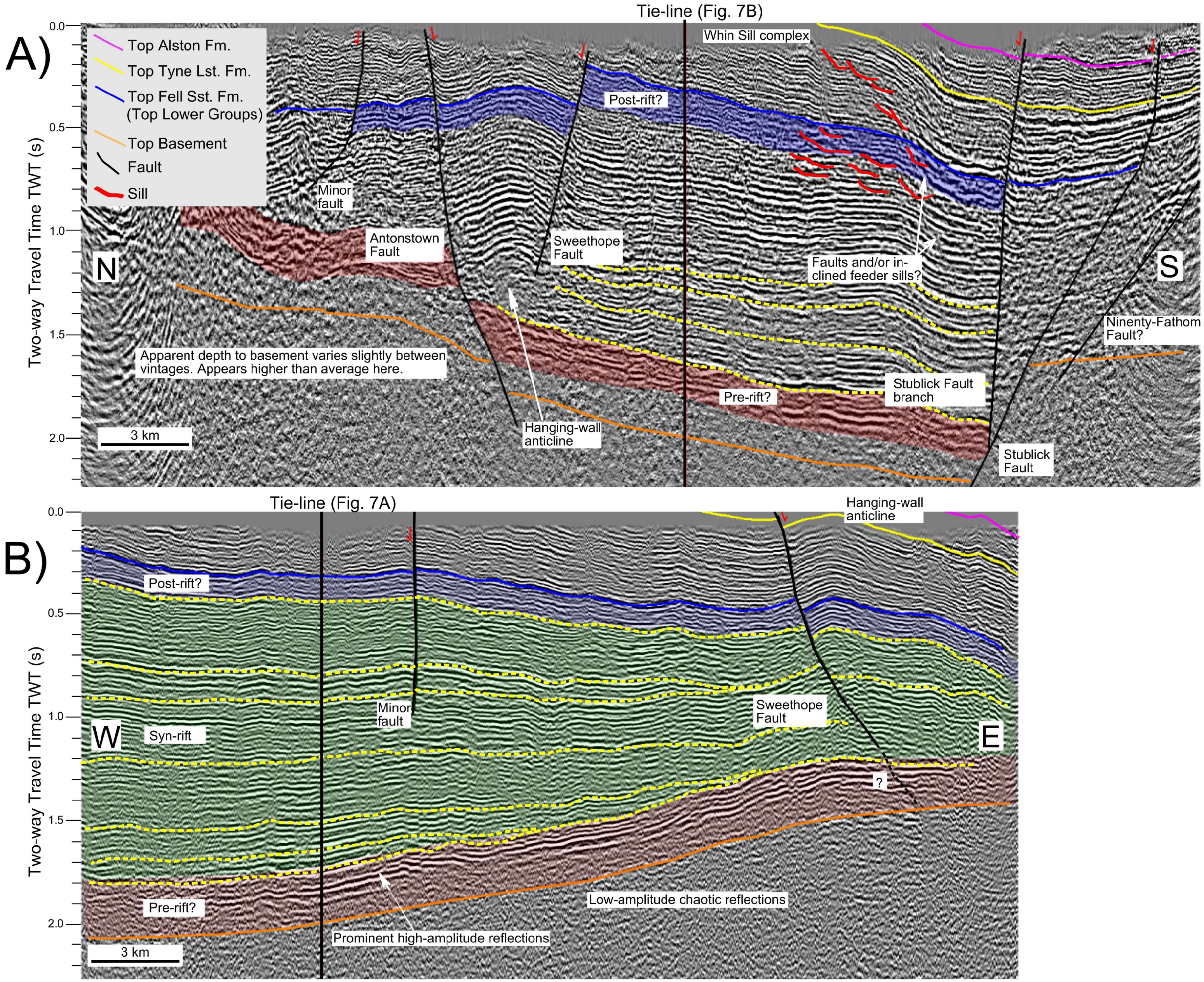


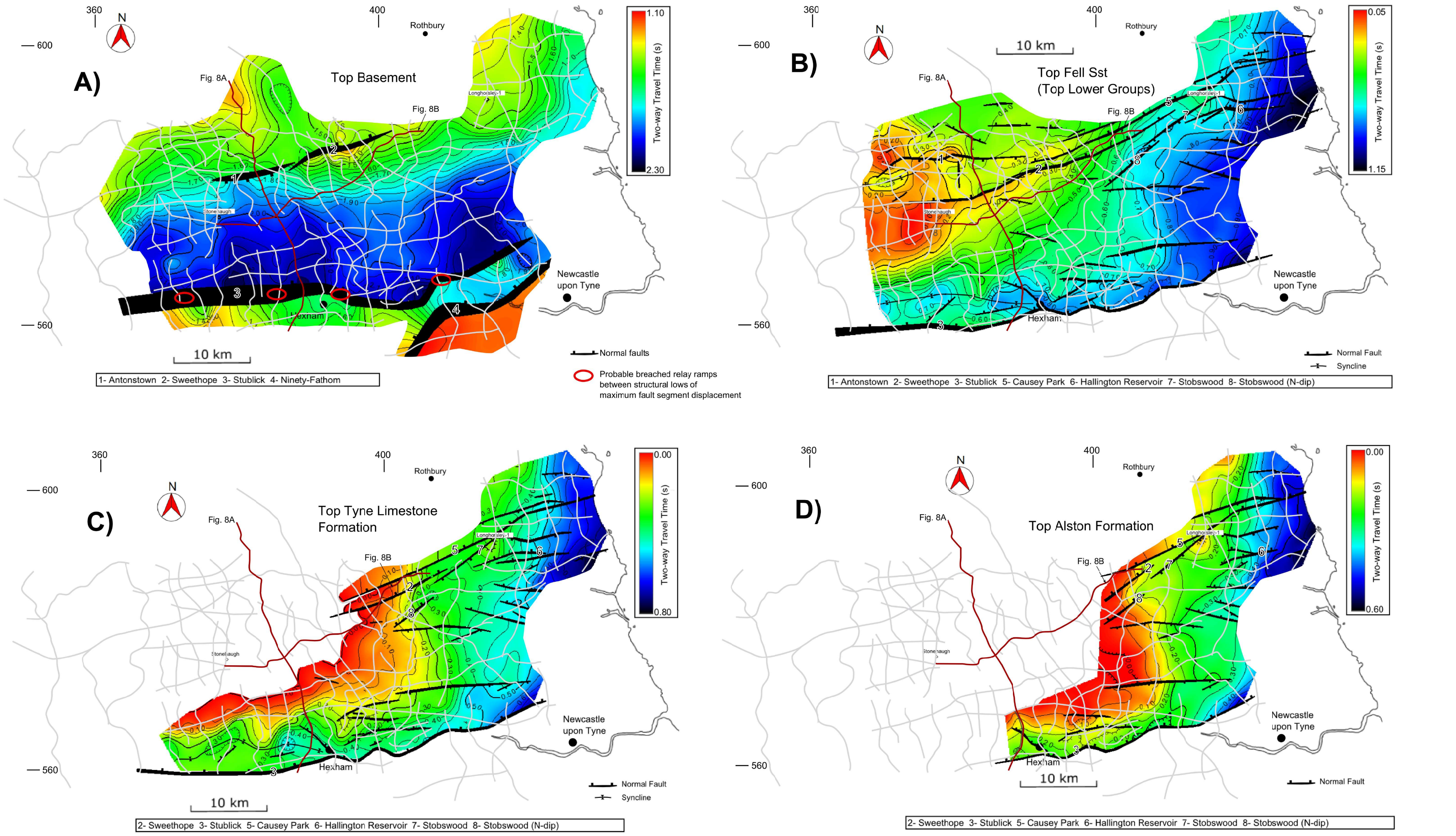
360
400
440
600
560
N
S
W
E
10 km
Fig. 8A
Fig. 8B
Longhorsley-1
Stonehaugh
Antonstown Fault
Sweethope Fault
Ninety Fathom Fault
Stublick Fault
Morpeth
Newcastle
Sunderland
Hexham
Carlisle
North Sea
Normal fault with dip direction
Borehole
Seismic reflection profiles
Silurian-Devonian basement rocks
Carboniferous
Courceyan to Holkerian
Asbian to Yeadonian
Border Group
Inverclyde Group
Upper Yordale Group (Stainmore Fm)
Lower Yordale Group
Coal Measures
Permo-Triassic
Permian sills


Northumberland Trough
Alston Block
SEISMIC INTERPRETATION NOMENCLATURE
PERMIAN
NPO Pb-Zn mineralization
~299 Ma
Coal Measures Group
WESTPHAIALN
NAMURIAN
CARBONIFEROUS
Yoredale Group
Stainmore Fm
Stainmore Fm
Yoredale Group
ALSTON FM
Alston Fm
BRIGANTIAN
Alston Fm
TYNE LIME-STONE FM
Tyne Lime-stone Fm
ASBIAN
Melberby Scar Limestone Fm
Great Scar Limest. Gr.
Ravenstonedale Gr.
VISEAN
HOLKERIAN
Border Group
Fell Sandstone Fm
ARUNDIAN
LOWER GROUPS
RIFTING
Lyne Fm
Navan Pb-Zn mineralization
Inverclyde Group
Ballagan Fm
CHADIAN
(Birrenswark volcanics)
COURCEYAN
TOURNAISIAN
Kinneswood Fm
~359 Ma
BASEMENT
Undifferentiated basement
DEVONIAN

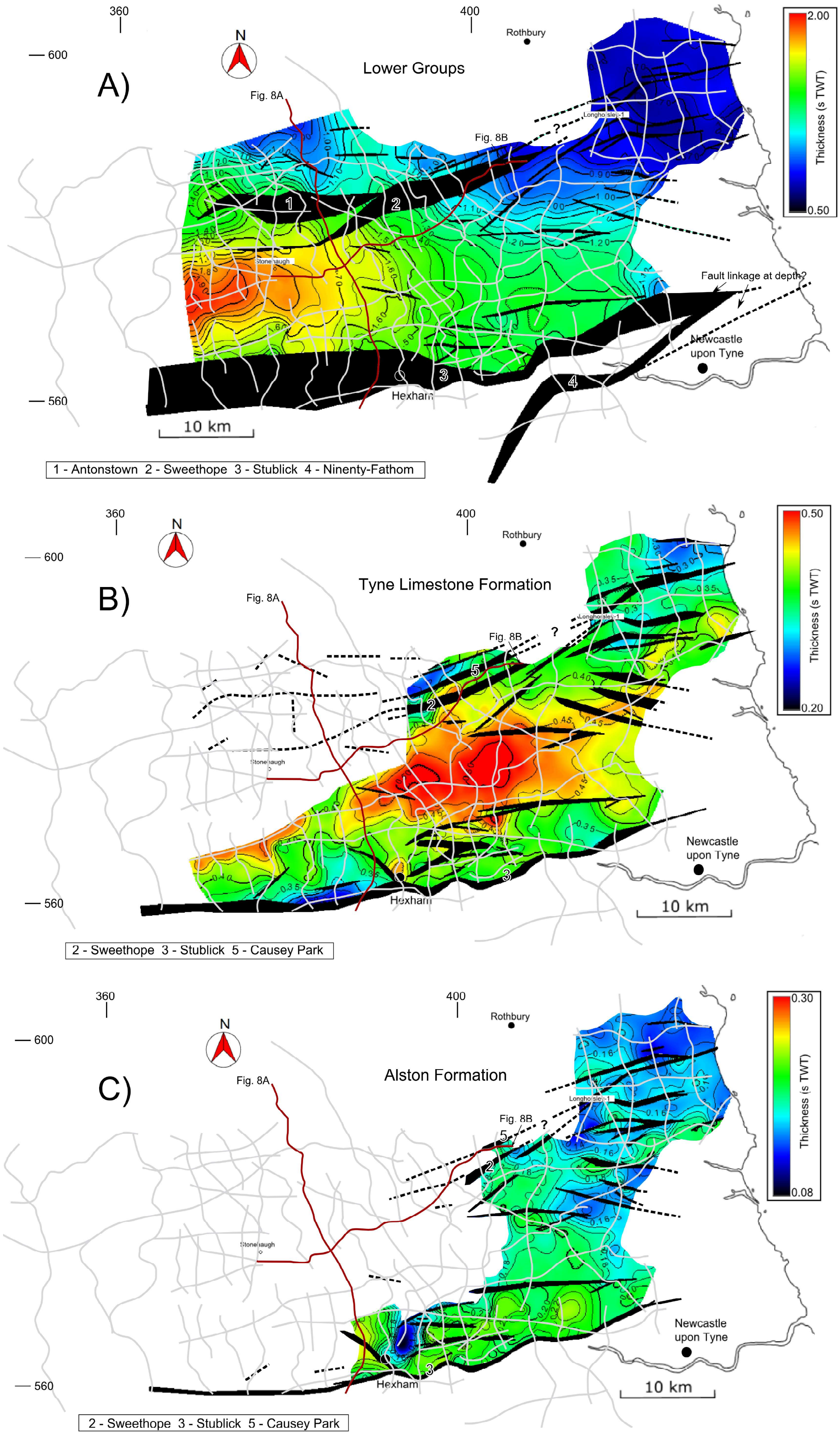

Pre-and syn-rift sediments
Meteoric/seawater fluids
Stratabound ore deposition into
dolomitized limestones
~1 km
Deeper basement fluids


NORTH
Northumberland Trough
Hexham
Alston Block
Stainmore Trough
SOUTH
Namurian and younger
Visean
Tournaisian
Basement
Weardale Granite
5
10
Depth (km)
10 km
Underplated Permian mafic magma


A)
Tie-line (Fig. 7B)
Top Alston Fm.
Top Tyne Lst. Fm.
Top Fell Sst. Fm. (Top Lower Groups)
Top Basement
Fault
Sill
Whin Sill complex
Post-rift?
Minor fault
Antonstown Fault
Sweethope Fault
Faults and/or in-clined feeder sills?
N
S
Ninenty-Fathom Fault?
Apparent depth to basement varies slightly between vintages. Appears higher than average here.
Stublick Fault branch
Pre-rift?
Hanging-wall anticline
Stublick Fault
3 km
Two-way Travel Time TWT (s)
0.0
0.5
1.0
1.5
2.0
B)
Tie-line (Fig. 7A)
Hanging-wall anticline
Post-rift?
Minor fault
Sweethope Fault
W
E
Syn-rift
?
Pre-rift?
Low-amplitude chaotic reflections
Prominent high-amplitude reflections
3 km
Two-way Travel Time TWT (s)
0.0
0.5
1.0
1.5
2.0



A)
Top Basement
Fig. 8A
Fig. 8B
Rothbury
Longhorsley-1
Stonehaugh
Hexham
Newcastle upon Tyne
10 km
Two-way Travel Time (s)
1.10
2.30
Normal faults
Probable breached relay ramps between structural lows of maximum fault segment displacement
1- Antonstown 2- Sweethope 3- Stublick 4- Ninety-Fathom
B)
Top Fell Sst (Top Lower Groups)
0.05
1.15
Normal Fault
Syncline
1- Antonstown 2- Sweethope 3- Stublick 5- Causey Park 6- Hallington Reservoir 7- Stobswood 8- Stobswood (N-dip)
C)
Top Tyne Limestone Formation
0.00
0.80
2- Sweethope 3- Stublick 5- Causey Park 6- Hallington Reservoir 7- Stobswood 8- Stobswood (N-dip)
D)
Top Alston Formation
0.00
0.60
2- Sweethope 3- Stublick 5- Causey Park 6- Hallington Reservoir 7- Stobswood 8- Stobswood (N-dip)



A)
Lower Groups
360
400
600
560
N
Rothbury
Fig. 8A
Fig. 8B
Longhoslee-1
Stonehaugh
Fault linkage at depth?
Newcastle upon Tyne
Hexham
10 km
Thickness (s TWT)
2.00
0.50
1 - Antonstown 2 - Sweethope 3 - Stublick 4 - Ninenty-Fathom
B)
Tyne Limestone Formation
360
400
600
560
N
Rothbury
Fig. 8A
Fig. 8B
Stonehaugh
Newcastle upon Tyne
Hexham
10 km
Thickness (s TWT)
0.50
0.20
2 - Sweethope 3 - Stublick 5 - Causey Park
C)
Alston Formation
360
400
600
560
N
Rothbury
Fig. 8A
Fig. 8B
Stonehaugh
Newcastle upon Tyne
Hexham
10 km
Thickness (s TWT)
0.30
0.08
2 - Sweethope 3 - Stublick 5 - Causey Park

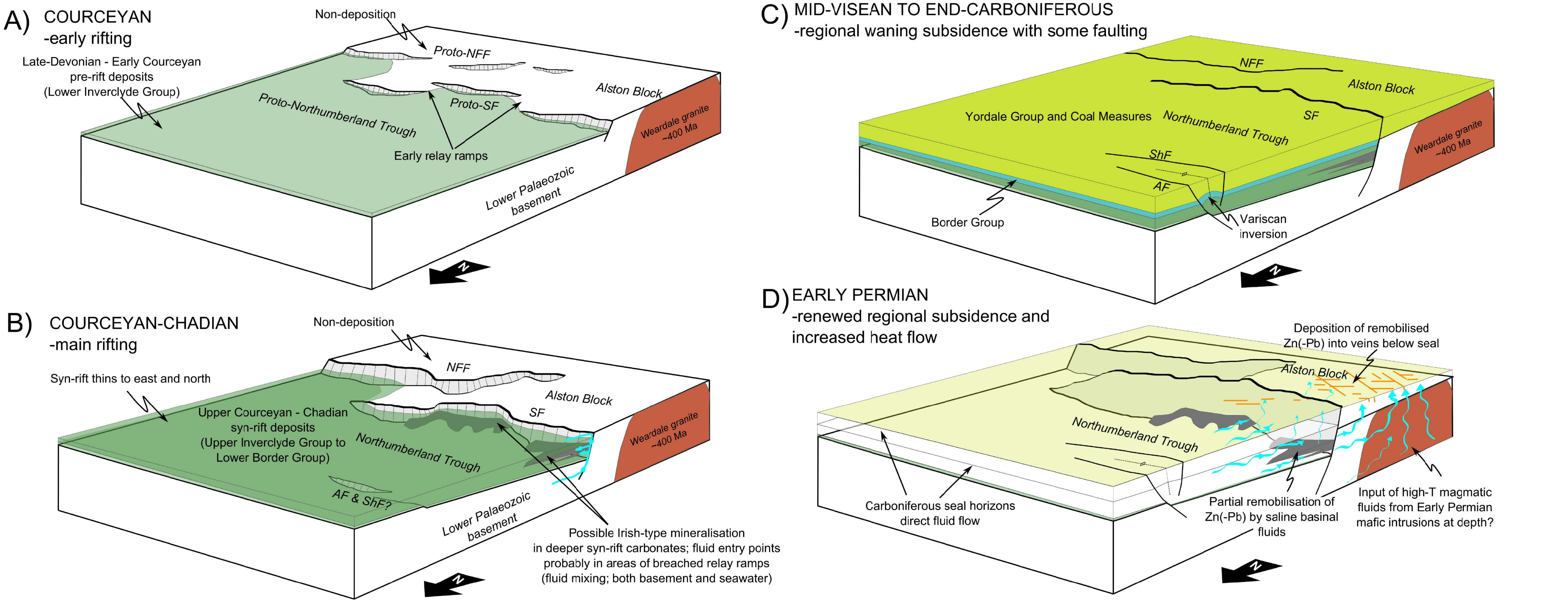

A) COURCEYAN
-early rifting
Non-deposition
Proto-NFF
Late-Devonian - Early Courceyan
pre-rift deposits
(Lower Inverclyde Group)
Alston Block
Proto-Northumberland Trough
Proto-SF
Weardale granite
~400 Ma
Early relay ramps
Lower Palaeozoic
basement
N
B) COURCEYAN-CHADIAN
-main rifting
Non-deposition
NFF
Syn-rift thins to east and north
Alston Block
Upper Courceyan - Chadian
syn-rift deposits
(Upper Inverclyde Group to
Lower Border Group)
SF
Northumberland Trough
Weardale granite
~400 Ma
AF & ShF?
Lower Palaeozoic
basement
Possible Irish-type mineralisation
in deeper syn-rift carbonates; fluid entry points
probably in areas of breached relay ramps
(fluid mixing; both basement and seawater)
N
C) MID-VISEAN TO END-CARBONIFEROUS
-regional waning subsidence with some faulting
NFF
Alston Block
Yordale Group and Coal Measures
Northumberland Trough
SF
Weardale granite
~400 Ma
ShF
AF
Border Group
Variscan
inversion
N
D) EARLY PERMIAN
-renewed regional subsidence and
increased heat flow
Deposition of remobilised
Zn(-Pb) into veins below seal
Alston Block
Northumberland Trough
Carboniferous seal horizons
direct fluid flow
Partial remobilisation of
Zn(-Pb) by saline basinal
fluids
Input of high-T magmatic
fluids from Early Permian
mafic intrusions at depth?
N

Table 1. *Comparison of the known Pb-Zn mineralization in the Irish Midlands and the NPO*

	Irish Midlands	**NPO**
Host lithologies	Shallow water limestones and reef formations	Limestone, sandstone, dolerite (Whin Sill)
Host rock age	Mainly Courceyan	Dinantian and Namurian
Mineralisation style	Sphalerite and galena; replacement of carbonate host rocks at or near palaeo-seafloor (?)	Sphalerite and galena; veining in fractured host rocks, localised replacement of carbonates adjacent to veins
Mineralisation age	Courceyan–Arundian	Early Permian (?)
Tectonic setting	Within or on margins of basin, along major syndepositional faults	Along fractures with small displacement on structurally elevated block
Geodynamic setting	Early stages of basin formation	Associated with Variscan tectonics (?)

Table 2. *Comparison of mineralising feeder faults in Ireland and potential feeder faults in Northumberland*

Northumberland Faults	**Strike**	**Max throw at Top Fell Sst (TWT)***	**Age**
Stublick†	E-W	0.8 s (1800 m)	Lower Carboniferous
Sweethope	ENE-WSW	0.2 s (450 m)	Lower Carboniferous
Causey Park	ENE-WSW	0.05 s (112.5 m)	Unclear
Hallington Reservoir	E-W	0.06 s (135 m)	Unclear
Stobswood (N-dip)	NE-SW	0.05 s (112.5 m)	Unclear
Irish Deposits ‡	**Strike**	**Max throw on feeder faults**	**Age**
Navan	ENE within regional NE-SW trend	500+ m**	Chadian - Arundian
Lisheen	E – ENE within NE-SW regional trend	200 m	Late Courceyan – early Chadian
Silvermines	E-W within NE-SW regional trend	335 m	Late Courceyan
Tynagh	E within NE-SW regional trend	600 m	Late Courceyan – early Chadian

*Converted to meters using Vp = 4500 m s^{-1} from Kimbell et al. (1989)

**Navan Fault with the newly discovered Tara Deep satellite deposit in its footwall up to 1 s TWT throw, i.e. >1.5-2km (Ashton et al., 2018)

†Max throw given at the Top Basement reflector; throw at the Top Fell Sandstone reflector is likely significantly lower

‡ Data compiled from Taylor (1984), Shearley et al. (1995), Hitzman (1999), Ashton et al. (2015)