'Block and basin' style rift basins: sedimentological insights from the Mississippian Fell Sandstone Formation

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Abstract

The block and basin tectono-stratigraphic framework for the northern Pennine (rift) Basin, within which buoyant granite intrusions core intra-basin fault-bound blocks, has long held traction. However, many of the elements of this framework are rooted in primitive tectonic models and, perhaps unsurprisingly, corresponding depositional models often reflect this. Using sedimentological and sedimentary provenance approaches, the syn-rift (Mississippian) fluvio-deltaic Fell Sandstone Formation and age-equivalent strata within the northern Pennine Basin are examined. Highlighted divergences from classically depicted models relate to occurrences of pre-Carboniferous basement domes or monoclines, which are unbound by major vertically displacing (>100 m) fault systems. Such structures in the northern Pennine Basin are all granite-cored and their origins are associated with their buoyancy and flexural isostatic processes. One such basement dome, the Cheviot Block, confined and deflected the Fell Sandstone fluvio-deltaic system from the west, causing locally elevated net sand content and variations in dominant palaeodrainage direction. Central parts of the Alston Block, which forms a regional monocline along an E-W axis, were comparatively uplifted because of flexural isostatic responses to granite intrusions. The findings presented are not just at variance with classically depicted depositional models for the region, but also with more general depictions of dominantly normal fault-driven rift basin systems.

Supplementary material: [table of data locations with derivation, trace element data, and major element (oxide) data] is available at https://doi.org/10.6084/m9.figshare.c.5733257

1.0 Introduction

Large granite bodies are known to cause both local basement buoyancy and increase mechanical strength (Bott and Mason-Smith, 1957; Bott *et al*., 1967, 1978; Donato *et al*., 1982, 1983, 1990, 1993, 2020; Kimbell *et al*., 2015). Consequently, continental rift basins that are influenced by granite intrusions are characterised by sporadic and relatively uplifted fault-bound blocks (Leeder, 1982; Chadwick *et al*., 1995; Corfield *et al*., 1996; Howell *et al*., 2019; Phillips *et al*., 2019). Deep basins, bound by vertically displacing fault systems where extensional strain localises (Howell *et al*., 2021), often border these blocks (Chadwick *et al*., 1995). Such systems have, therefore, been loosely defined as 'block and basin' style rift basins (Marr, 1921; Trotter and Hollingworth, 1928; Bott, 1967; Johnson, 1967; Leeder, 1982; Kombrink, 2008; Besly, 2019).

The implications of tectonic 'block and basin' models for the interpretation of a sedimentary rift basin system are numerous (Fig. 1). For example, local drainage systems may be determined by tectonically influenced block and basin topographies (e.g., Gawthorpe and Clemmey, 1985; Leeder and Gawthorpe, 1987), while relatively uplifted granite-cored blocks may comprise localised sediment source areas (e.g., Hallsworth *et al*., 2000; Hallsworth and Chisholm, 2008) or host shallower water successions (e.g., Pickard *et al*., 1994; Southern *et al*., 2010). Borehole penetrations and geological mapping in the Mississippian Pennine Basin of northern England, where this study is focussed and from where theories surrounding 'block and basin' style rifting originate, have long revealed that the sequences in basin areas were far thicker than the typically condensed or absent contemporaneous sequences encountered on blocks (Johnson, 1967) (Fig. 1b). Whereas areas within the basin, such as the Askrigg Block, hosted shallow marine ramp carbonate or platform carbonate facies during Mississippian times (Gawthorpe, 1984), the Bowland Basin and Stainmore Trough hosted predominantly deeper water mudstones and calc-turbidites (Newport *et al*., 2018) (Fig. 1a). Even now, 'block and basin' palaeogeography maps for contemporaneous basins in the central and southern North Sea are frequently re-utilised within the contexts of regional petroleum exploration (e.g., Corfield *et al*., 1996; Glennie, 2005; Booth *et al*., 2020).

As seismic acquisition techniques have improved and better analogues for rift basin systems have emerged, the 'block and basin' rift basin framework has largely become redundant as a tool for hydrocarbon or mineral exploration (e.g., Grayson and Oldham, 1987). The major shortcomings of generic 'block and basin' models relate to their over-simplicity. For example, some of the fault systems that define the major depocentres adjacent to comparatively uplifted 'blocks' consist of several complex splays and overlapping relays rather than a simple and laterally persistent fault plane (Chadwick *et al*., 1995; Manning *et al*., 2007; Besly, 2019). Despite having been depicted as regions of comparative uplift during rifting, occurrences of deeper water facies assemblages are recognised upon several intra-basin blocks (Grayson and Oldham, 1987 and references therein). Many basin-bounding structures have been re-interpreted as tilted fault blocks (Gawthrope, 1984; Fraser and Gawthorpe, 1990). Several deep (>500 m) depocentres can be found situated close to 'blocks' yet unbound by major vertically displacing fault systems. Examples in the Mississippian Pennine Basin include the eastern margin of the Alston Block (Ridd *et al*., 1970), within the Vale of Eden Basin (Chadwick *et al.*, 1995), and to the north of the Cheviot Block in the Tweed Basin (Millward *et al*., 2013) (Fig. 2).

In contrast to traditional 'block and basin' depositional models (e.g., Johnson, 1984), continental rift basins are currently considered largely asymmetrical systems within which sedimentary accommodation are controlled dominantly by normal faulting (Fig. 3) (Leeder and Gawthorpe, 1987; Jackson and White, 1989; Roberts and Jackson, 1991; Sharp *et al*., 2000; Gawthorpe and Leeder, 2000). These relationships are demonstrated by several popular examples of rift basins, such as in the Gulf of Corinth (Moretti *et al*., 2003; Bell *et al*., 2009; Cullen *et al*., 2020), the East African Rift (Ring, 1994; Contreras *et al*., 2000; Morley, 2010), and many additional subsurface examples (Elliott *et al*., 2017; Phillips *et al*., 2019). The evolution of a rift basin system and its influence on drainage (Gawthorpe and Hurst, 1993; Jackson and Leeder, 1994), sediment routing (Schlische, 1991; Whittaker *et al*., 2010; Kirby and Whipple, 2012), and sedimentary accommodation (Faulds and Varga, 1998; Gupta *et al*., 1998; Jackson *et al*., 2005; Duffy *et al*., 2015), may be determined by the varying stages of linkage between adjacent fault systems and the corresponding linkages of adjacent rift basin depocentres (Holz *et al*., 2017). It is perhaps a testament to the relatively little attention the Pennine Basin has received in the past 25 years, that the most popular depositional models for the area remain rooted to the comparatively out-dated 'block and basin' framework and granite intrusions.

In this study, sedimentological characteristics of the Mississippian fluvio-deltaic Fell Sandstone Formation and age-equivalent strata deposited in the northern part of the Pennine Basin are examined, focussing on the interaction of these sediments with the locally underpinning (syn-rift) basin framework. In doing so, insights into how the, until now, poorly defined 'block and basin' style tectonic framework may influence basin dynamics during rifting are gained. Field and borehole-based lithological, petrographical, petrochemical and petrophysical observations and sedimentological and provenance analyses are described. This study is the second of two studies by this authorship that focus on the classically interpreted 'block and basin' style of the Mississippian northern Pennine rift basin (*cf*. Howell *et al*., 2019). Variances between these findings, classic tectono-stratigraphic models for the region, and more popular depictions of rift basin systems are scrutinised. Some key, and otherwise underreported, influences on the evolution of rift basin systems are considered, such as basement density and flexural isostasy.

2.0 Geological setting and stratigraphy

The Mississippian northern Pennine rift basin of northern England is the archetypal example of a 'block and basin' style rift basin. In 1957, Martin Bott first suggested a prominent negative Bouguer gravitational anomaly upon the Alston Block was associated with a concealed granite intrusion (Bott and Mason-Smith, 1957) (Fig. 4). This intrusion, the Weardale Granite, was subsequently proved by the drilling of the Rookhope borehole (Dunham *et al*., 1965), and is believed to be part of a suite of large, predominantly cone-shaped, and buoyant Early Devonian (Emsian) granitic intrusions collectively referred to as the North Pennine Batholith (Fig. 1) (Kimbell *et al*., 2010). The Alston Block is separated from the Northumberland Trough on its northern side by the eastern extent of the Maryport-Stublick-Ninety Fathom fault system, and from the Stainmore Trough on its southern side by the Butterknowle Fault systems (Chadwick *et al*., 1995) (Fig. 2). Directly to the west lies the partially exhumed Lake District Block, which is underlain by the largely Ordovician Lake District Batholith and represented by a further negative Bouguer gravitational anomaly (Fig. 4). To the south-west of the Stainmore Trough, the Wensleydale Granite underpins the Askrigg Block (Fig. 1). The Cheviot Block, which is underpinned by the Cheviot Granite, does not form a traditional faulted high but marks the northern limit of the Northumberland Trough and can be characterised more accurately as a regional (tens of kilometres wide) dome (Fig. 1) (*cf*. Shiells, 1963), which combined with the remainder of the Southern Uplands to form a palaeo-high during Carboniferous times (Howell *et al*., 2021). The northern Pennine Basin formed in response to latest Devonian-Mississippian lithosphere extension (Leeder, 1975). The geometry of these basins was successfully replicated by this authorship, by adopting a 2D lithosphere scale structural and geodynamic numerical modelling methodology and by incorporating subsidence in response to normal faulting and lithospheric extension, and uplift in response to the emplacement of low-density granite intrusions and flexural isostasy (Howell *et al*., 2019).

The Fell Sandstone Formation was deposited in the northern Pennine Basin during the middle of a protracted Mississippian phase of rifting (Fraser and Gawthorpe, 1990). Regionally, mixed fluvial and delta-dominated deposits of the Fell Sandstone Formation represent the western margin of a vast, approximately southward prograding, fluvio-deltaic system that extended as far north as offshore Aberdeen in the northern North Sea and towards the Dutch sector in the southern North Sea (Maynard and Dunay, 1999; Kearsey *et al*., 2019). The onshore Fell Sandstone Formation (Middle Border Group) is typified by sand-rich fluvial deposits that are buried across the northern Pennine Basin and crop out across northern Northumberland (Turner *et al*., 1987). These deposits span the Chadian-Asbian substages (Fig. 5) (Waters *et al*., 2011). The Fell Sandstone Formation pinches out down-system towards the south-west where deposits are mixed clastic-carbonate sediments of deltaic and shallow marine origin (Day, 1970). These mixed, age-equivalent deposits belong partly to the Cambeck Beds of the Lyne Formation, and partly to the Fell Sandstone Formation itself (Armstrong and Purnell, 1987) (Fig. 5). The occurrence of 'seismites' (soft sediment features associated seismic shaking) and the Glencartholm Volcanic Beds (GV; Fig. 5) immediately above the Fell Sandstone Formation in Northumberland is believed to represent one pulse of accelerated basin extension (Leeder, 1975).

In the northern Pennine Basin, successions belonging to the same approximate stratigraphic interval have been informally grouped together as the 'Fell Sandstone succession' (Day, 1970; Turner *et al*., 1993; Dean *et al*., 2011; Bell *et al*., 2017) (Fig. 5). The informal 'Fell Sandstone succession' is adopted here to describe the Fell Sandstone Formation and the age-equivalent Cambeck Beds in the central Northumberland and Solway Basins, and further age-equivalent successions in the broader northern Pennine Basin, deposited by dominantly fluvial or deltaic processes (e.g., Day, 1970) (Fig. 5). As a result, this succession can effectively be constrained within the upper and lower boundaries of the TS miospore zone with the TC and Pu miospore zones, respectively (Fig. 5). Biostratigrapic studies from literature (Day, 1970; Neves *et al*., 1973; Armstrong and Purnell, 1987; Mahdi and Butterworth, 1994; Johnson *et al*., 2011; Waters *et al*., 2011) and borehole reports are summarised in Figure 5. Where biostratigraphic data are absent, such as for the Newcastle Science Central (deep geothermal) borehole (see Fig. 6 for location), the top of the Fell Sandstone succession is taken, as far as this study is concerned, as the top of the lithostratigraphically defined Fell Sandstone Formation, as per the Northumberland Trough (Day, 1970). For the Harton borehole (Fig. 6), the top of the Fell Sandstone succession is taken at the top of the 'unnamed sandstone' unit in the composite log (Ridd *et al*., 1970), based on similarities with the Mississippian succession penetrated more recently in the nearby Newcastle Science Central Geothermal Borehole (Younger *et al*., 2016).

3.0 Data and Methods

This study combines both field and borehole-based sedimentological, petrographical, petrochemical and petrophysical observations and analyses of the Fell Sandstone Formation and stratigraphically equivalent units in the northern Pennine Basin. The localities of borehole and outcrop successions used as part of this study are shown in Figure 6, as well as the types of data analysed or collected at each locality (also refer to Supplementary data table 1). Borehole data were accessed via the British Geological Survey (BGS) core store in Keyworth, online via the BGS onshore Geoindex (bgs.ac.uk/geoindex/) or the UK Onshore Geophysical Library (UKOGL; ukogl.org.uk/), by hard copy through the UK Oil and Gas Authority and via published literature. A more detailed account of borehole data used as part of this study is summarised in Supplementary data table 1. Borehole and outcrop data vary from intact drillcore to drillcore samples, borehole chippings, petrophysical and petrochemical (gamma ray, density, lithology) borehole logs, biostratigraphic data, rock samples for petrographical (thin-section) and petrochemical (handheld XRF) analysis, and outcrop-based sedimentary logs and images.

Lithological and petrochemical facies and facies association schemes are based on conventional sedimentary (grain size, sedimentary structures) and spectral gamma ray logging of the Fell Sandstone succession exposed in the field and borehole successions. Gamma ray responses for the Stonehaugh Borehole succession were collected with the RS 230 Super-Spec BGO spectrometer. Total radioelement abundance was measured for 90 seconds every 50 cm. Net to gross (sand %) map and interpreted facies trends are based on borehole data. Boreholes with over 100 m of penetration through the Fell Sandstone succession are included for the sake of the net to gross map's completeness. Palaeocurrent measurements were taken across 13 field localities to construct a map of regional palaeocurrent.

Sandstones from the Stonehaugh and Harton boreholes and the field were cut as thin sections so that their mineralogical assemblages and textural characteristics could be analysed. Fine to medium-grained sandstones collected from drillcore and from the field were analysed using a Niton XL3t energy dispersive spectrometer at Keele University. The instrument was calibrated using a range of international standard lithological reference materials. Data quality and instrumental drift was evaluated via regular analysis of secondary international reference materials. Precision (2 sigma), which was determined via repeat analysis of standards and samples, was < 6 % for major elements (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, CaO, K_2O) and < 7 % for trace elements (Nb, Zr, Sr, Rb). The mean deviation from the accepted standard values was typically < 5 % for major elements (excluding Al_2O_3 – 8 %) and < 5 % for trace elements. Hand specimen samples were analysed between 3 and 5 times, moving the analysis spot each time, to compensate for sample heterogeneity. The most homogeneously distributed elements within single samples included Sr and Rb; the concentration of these elements varied typically between 10 % and 15 % within single samples. Elements associated more strongly with rarer minerals and were therefore less homogenously distributed included Zr, whose concentration varied around 60 % within single samples. The average of these readings was calculated to ensure representative measurements.

4.0 Facies and facies tracts

For lithofacies and architectural element descriptions of the Fell Sandstone succession of the northern Pennine Basin, the reader should refer to Tables 1 and 2. In this section, two broad facies tracts are summarised. These are: *fluvial-dominated deposits* and *delta-dominated deposits*.

4.1 Fluvial-dominated deposits

Description

This association comprises five architectural elements: fluvial channels (FC), sheets (S), lateral and downstream accretion (LA and DA) and floodplain (FP) (see Table 1 for architectural element descriptions). Sandy channels (FC) and accretionary elements (LA/DA) dominate the association with minimal floodplain deposits (FP) preserved within outcrop (Fig. 7a). Channels (FC) are typically stacked and amalgamated with minor conglomeratic bases and generally show a progressive fining upwards fill. Most channels are dominated by planar (Spl) or trough cross-bedded sandstones (St), whereas some are structureless or contain heterolithics (Sh) (Figs. 7b-d). Sheet-like elements (S) make up a very small proportion of the association and are dominated by structureless (Sm) to parallel-laminated sandstone (Sla). The lateral accretion elements (LA) have a lensoidal geometry with internal second and third-order bounding surfaces, with the dip of the internal cross-bedding (Sp) approximately parallel to the strike of the higher order bounding surfaces. The downstream accretionary elements (DA) also have a lensoidal geometry and contain internal third-order bounding surfaces, but the internal cross-bedding dips (Sp) approximately perpendicular to the strike of the higher order bounding surfaces. Finer-grained elements are rarely preserved within observed field sections (Fig. 7e). However, from core analysis, locally floodplain elements (FP) may constitute up to 50 % of the succession (Fig. 8). Floodplain elements are dominated by structureless to parallel-laminated siltstone (Fm, Fpl), are often heavily bioturbated (Ffb) and typically contain pedogenic (Pg, Pn) facies and minor coals (C).

Interpretation

This association represents the development and build-up of a fluvial channel belt in a dominantly low sinuosity and bedload dominant fluvial system. The progressively fining upward fill of the channels is interpreted as the gradual abandonment of channels with a steady rate of flow (Bromley, 1991), with the basal conglomeratic units representing channel lag deposits formed from bedload transport within high-energy flows (Bridge 1993; Fielding *et al*., 2018). Structureless channels are interpreted to have been produced from marginal sandbank collapse (Turner *et al*., 1987). The heterolithic channel elements represent channel abandonment (Martin & Turner, 1998).

Lateral accretionary elements are interpreted as bank-attached point bars/macroforms deposited on the inside of the channel bend and indicate a moderate degree of sinuosity (Miall, 1977), whereas downstream accretionary elements are interpreted as the deposits of mid-channel bars within the channel belt representing an intermediate channel sinuosity (Miall, 1985; Ashworth *et al*., 2000). Pedogenesis and coal development within the floodplain element suggests a terrestrial origin of the structureless to parallel-laminated siltstones; forming in a humid to semi-humid environment (Kraus *et al*., 1999; Spears, 2012). Seatearth (gleyed) and coal provide evidence of cohesive, vegetated overbank material with permanently waterlogged soils (Besly and Fielding, 1989).

4.2 Delta-dominated deposits

Description

This association comprises five architectural elements: delta front distributary channels (DC), delta front bars (DB), delta slope (DS), pro-delta (PD) and floodplain (FP). Coarsening upwards successions of pro-delta sediments through to delta front channels dominate this association. The pro-delta (PD) siltstones (e.g., Fb, Fpl) are typically interbedded with sporadic carbonate lenses (Lm, Lc), and with thin sandstone lenses (Sf, Sr) that increase in frequency upwards (Fig. 7f). The siltstones are typically weakly bioturbated (Fb) and contain shell and crinoid fragments as well as marine ostracods (Fig. 7g, h). Delta slope elements (DS) also coarsen upwards and are dominantly composed of parallel-laminated siltstone (Fpl) with minor sandstone lenses (Sl) which increase in abundance upwards through the association. The delta front bars (DB) have lensoidal geometries and are dominantly composed of coarsening upwards successions of planar cross-bedded sandstones with flaser to lenticular sandstones and siltstones (Sf, Sl) which are sporadically bioturbated (Fig. 8). The delta front channels (DC) have an erosional basal bounding surface and progressively fining upwards fills. The channels are dominated by planar (Sp) and trough cross-bedded sandstones (St) with minor gravel lenses and conglomeratic foresets (Sgt). Floodplain elements (FP) are rarely preserved within outcrop, but when preserved, they are dominated by structureless to parallel-laminated siltstone (Fpl, Fm), and are often heavily bioturbated (Ffb, Pg), containing pedogenic facies and minor coal fragments (Fig. 8).

Interpretation

This dominantly coarsening upwards association represents the progradation of deltaic deposits into a marginal marine environment (Mount, 1984; Smith and Holliday, 1991). The presence and types of bioturbation and marine fossiliferous assemblages suggest deposition in shallow marine conditions (Turner *et al.,* 1997). Siltstones are likely to have been deposited through suspension settling away from the sediment source (Stow and Shanmugam, 1980), whilst inter-bedded parallel and ripple-laminated sandstones are likely to have been transported from up-dip deltaic systems (Blair and McPherson, 2008). Minor carbonate lenses within the parallel-laminated siltstones suggest periods of temporarily low clastic supply accommodating the production of carbonate in shallow water (Mount, 1984). Cross-bedded sandstones indicate the deposition of channel fill material, as dune-scale bedform trains fill distributary channels (Bristow *et al*., 1993). Thin floodplain deposits with seatearth suggests prolonged periods of non-deposition and sub-aerial exposure, perhaps due to the up-dip avulsion of alluvial feeder systems (Nemec and Postma, 1993).

5.0 Facies and palaeocurrent trend analysis

5.1 Facies trends

Poor surface bedrock exposure limits the scope of a detailed facies analysis. However, a decrease of craggy hillside features in the landscape from the north-eastern Northumberland Basin south-westwards reflects decreased concentrations of weathering-resistant sandy fluvial channel (FC) and lateral to downstream (LA/DA) accretionary facies within the succession and increasing amounts of fluvial-dominated floodplain (FP) facies. Two logged borehole successions from the north-eastern Northumberland Trough and the central Northumberland-Solway Basin further substantiate these spatial facies trend (Fig. 8). In the north-eastern Northumberland Basin, the Alnwick borehole succession comprises over 100 m of stacked, typically erosive, and fluvial-dominated channel (FC) and accretionary sand (LA/DA) facies with subsidiary inter-bedded silty to very-fine sand floodplain facies (FP). The presence of rooted structures within these finer-grained units indicates their deposition under dominantly terrestrial conditions; although Turner *et al*. (1997) reported a brief, approximately 30 cm thick, ostracod-bearing mudstone interval within this succession at approximately 68 m (MD) that indicates a short-lived marine incursion. Conversely, the Stonehaugh borehole succession in the central Northumberland-Solway Basin, comprises a higher proportion of finer-grained delta-dominated facies inter-bedded with coarser fluvial-dominated facies.

The distribution of gamma ray (GR) facies echoes those trends observed at outcrop and through drillcore. For the most proximal borehole penetration, with respect to palaeodrainage, for which there is a GR log associated, the Longhorsley borehole, GR response is largely subdued (Fig. 9). Based on the facies and facies tracts analysis presented in Section 4 (also see Table 1), the overall blocky response of this GR log indicates the presence of fluvial-dominated deposits. 'Cleaning upwards' gamma ray trends (i.e., where gamma ray response decreases upwards) inter-dispersed within this succession are interpreted as representing inter-bedded delta-dominated deposits. The proportion of these cleaning upwards trends observed within stratigraphically equivalent GR successions increases progressively towards the faulted southerly basin margin of the Northumberland-Solway Basin. In the Westnewton borehole succession, drilled in the western part of the Solway Basin, blocky and more subdued GR responses again comprise a higher proportion of the Fell Sandstone succession. However, much of these facies are comprised predominantly of fossiliferous or crystalline marine limestones (Lm), rather than sandstone-rich fluvial-dominated deposits. Outcropping or drillcore equivalents to these deposits were not encountered in the study area. The uppermost part of the contemporaneous succession penetrated by the Brafferton borehole, in the Stainmore Basin, is comprised almost entirely of these carbonate deposits. Lithological logs for boreholes penetrating the Fell Sandstone Formation along the largely unfaulted eastern margin of the Alston Block indicate a mixed sandstone-siltstone succession here, with few inter-bedded limestones.

5.2 Net to gross (sand %) trends

Although not all boreholes sunk into the Fell Sandstone succession across the study area provide intact drillcore or detailed records of sedimentary facies, an analysis of net to gross (sand %) trends apparent from borehole records with brief lithological descriptions further illustrates regional depositional trends, which are not shown in Figures 8 or 9. Around the Berwick-upon-Tweed area (Fig. 6), a cluster of boreholes drilled predominantly for water resource purposes penetrate the Fell Sandstone succession and reveal variable net sand contents of between 40 % and 80 % (see inset Fig. 10a). These values are consistent with observations made by several previous authors who have reported a more heterolithic Fell Sandstone succession in this area (Hodgson and Gardiner, 1971; Bell, 1978; Turner *et al*., 1993). Many of these boreholes were drilled at ground level into basal Scremerston Formation strata and therefore penetrate the upper 100 m, and more, of the Fell Sandstone succession; the Fell Sandstone Formation is believed to be approximately 330 m thick in the vicinity of Berwick-upon-Tweed (Turner *et al*., 1993). Further to the south, down-system and along the unfaulted eastern margin of the Cheviot Block, documented boreholes penetrations are sparse. In the Rothbury area, the succession in the Alnwick borehole reveals 99 % net sand within a

104 m succession (Fig. 10a) (also see Fig. 8). The Longframlington borehole, which was drilled approximately 7 km south-westwards, reveals a similarly high 95 % net sand content in a 92 m thick succession. Equally, observations of the exposed Fell Sandstone succession here and several tens of kilometres to the north also suggest locally high or entirely sand-bearing compositions (Monro, 1986). Between Berwick-upon-Tweed and Alnwick, the overall net sand content decreases down system, towards the south. A series of sparsely distributed boreholes through the Northumberland-Solway Basin, drilled predominantly during a short-lived period of hydrocarbon exploration in the area (Barrett, 1988), reveal a gradual down-system decrease in preserved net sand content. In the western part of the Solway Basin, the Fell Sandstone succession comprises only 14 % sand. Along the eastern margin of the Alston Block, 46 % and 74 % overall net sand contents are encountered in the Newcastle Science Central and Harton boreholes, respectively. In the Stainmore Trough, immediately to the south, the Seal Sands and Brafferton Fell Sandstone successions comprise only 48 % and 26 % net sand respectively; although in the Brafferton borehole succession, less than 10 % net sand is encountered in the uppermost 400 m of the Fell Sandstone succession.

5.3 Palaeocurrent trends

In basins that have suffered little post-depositional structural modification, palaeocurrent measurements provide direct indications of palaeo-drainage systems. Around the Berwick-upon-Tweed area and in concurrence with previous literary reports (Turner *et al*., 1993), the dominant palaeocurrent direction for the Fell Sandstone succession is to the south-west (Fig. 10b). However, between 10 and 20 km to the south and along the eastern margin of the Cheviot Block, there is a roughly 90 ° anticlockwise rotation in the dominant palaeocurrent direction. The dominant south to south-eastwards palaeocurrent direction here is roughly parallel with the unfaulted eastern margin of the granite-cored Cheviot Block and approximately consistent with the area of increased downstream net sand composition for the Fell Sandstone succession. The dominant SSE palaeocurrent trend continues down-system towards the Rothbury area where, in meeting the north-eastern apex of the onshore Northumberland-Solway Basin, palaeocurrent rotates back, roughly towards the west and south-west so that it is parallel with the dominant local structural trend in that region. In the Northumberland Trough, and in the eastern part of the Solway Basin, the dispersion in palaeocurrent direction is generally greater than along the eastern margin of the Cheviot Block. Here, the dominant palaeocurrent 'doglegs' slightly, varying between subparallel and perpendicular to the dominant trend of normal faults. Progressively towards the south and south-west, and ultimately towards the key basin-bounding faults of the Northumberland-Solway basins, palaeocurrent direction rotates more dominantly towards the south.

6.0 Sedimentary provenance analysis

Localised aberrancies from regional trends often relate to the complex source-to-sink relationships present within some accommodating sedimentary basins, particularly for fluvio-deltaic systems (Mikesell *et al*., 2010). In this next section, elemental and mineralogical composition trends are examined for sandstones belonging to the Fell Sandstone succession across the northern Pennine Basin. Compositional trends are compared progressively downstream between immediately adjacent sub-basins or depocentres. Basement rock compositions are plotted against measured compositions for the Fell Sandstone succession to determine the degree to which potential source lithologies may have provided clastic sediment to the various depocentres that together comprise the study area. For a full list of geochemical data, the reader may refer to Supplementary data tables 2 and 3.

6.1 Tweed Basin

The detrital components of sandstones taken from the Tweed Basin are typically rounded-subrounded. Sandstones encountered here are compositionally orthoquartzitic-subarkosic (Fig. 11). As concentrations of major oxides such as CaO and SiO_2 appear to vary greatly in response to cement and weathering, rather than detrital composition, the concentrations of less soluble oxides and trace elements such as Fe (expressed as Fe_2O_3), K (expressed as K_2O), Ti (expressed as TiO_2), Sr, Rb and Zr are focussed upon here (Fig. 12). Such trace elemental concentrations are generally sparse, particularly in the Tweed Basin, reflecting the comparatively pure compositions of the sandstones. Rb/Sr ratios, a common reference point for the chemical evolution of igneous material (Halliday *et al.*, 1991), are generally between 0.5 and 1.5 around Berwick and reduce downstream. Excluding samples with measurements below the limit of detection, Sr compositions average 10.19 ppm whilst Rb averages 9.87 ppm. Zirconium and TiO_2 concentrations vary between 40 and 240 ppm, and 0.05 and 0.18 % respectively. Iron coated grains appear frequently in the Tweed Basin suite in thin section. However, the detrital components of these sandstones appear lower with respect to Fe_2O_3 compared with the remainder of the samples with average overall concentrations of 0.34 %. K_2O concentrations for the Tweed Basin are also reduced with respect to downstream areas of the northern Pennine Basin.

6.2 Northumberland Trough

Samples taken from the Northumberland Basin show greater proportions of typically andesitic lithic material, as well as quartz pebbles, although they are still orthoquartzitic-subarkosic in composition and comprise mostly subrounded clasts. There is a striking downstream Sr increase for samples taken from the Northumberland Basin, averaging 37.5 ppm overall, compared with samples from the Tweed Basin, and little overlap in this regard (Fig. 12). This relationship is further substantiated when also considering the samples from the comparatively Sr depleted Tweed Basin suite that were below the limit of detection for this this element (also see Supplementary data table 2). Rb/Sr ratios decrease further downstream, with respect to the Tweed Basin suite, to between 0.1 and 0.9. For K_2O, Rb and Zr, there is little downstream variation. For Fe_2O_3, there is an overall downstream increase whilst for TiO_2, there is slight decrease, although given the small magnitude of this depletion, the sampling number is perhaps too small to consider comparative downstream concentrations for this compound in this region of the case study area.

6.3 Alston Block (eastern margin)

Samples taken from remnants of drillcore belonging to the Harton borehole have variable but slightly greater subarkosic compositions with muscovite being prominent and incorporate greater proportions of angular-subangular clasts (Figs. 11a and 11c). Strontium concentrations do not vary significantly between Fell Sandstone samples taken from the Northumberland Basin and from the eastern margin of the Alston Block (Fig. 12b). Likewise, no notable variations in the concentrations of Fe_2O_3, K_2O, Zr or TiO_2 are observed based on the dataset acquired in this region.

Rubidium increases downstream along the eastern margin of the Alston Block with respect to the Northumberland Basin, increasing in concentration from an average of 12.2 ppm, to 16.7 ppm. Between these two depocentres, Rb/Sr ratios increase accordingly, on average, from 0.40 to 0.52. These contrasts are close to the limit of detection. Unlike with comparative Sr increases for the Tweed and Northumberland Basins further upstream. However, there is far more overlap in K_2O and Rb enrichments between the Northumberland Basin and the Alston Block.

7.0 Sedimentary provenance interpretations

Based on textures, and mineralogical and geochemical compositions of sandstones taken from the Tweed Basin (Fig. 11), it is suggested that these sediments were derived from a mature, either reworked or far-travelled, sediment source. Given the dearth of clay material associated with this suite, it is suggested further that the elevated Rb/Sr ratios of these sandstones may be attributed to a more chemically evolved, perhaps granitic, source rock lithology. In the absence of more sophisticated provenance analysis methods, it is postulated that Caledonian granites of northern Scotland, Norway or western Greenland may have constituted potential source rock lithologies, as they are suggested to have done for overlying strata (e.g., Morton *et al.*, 2002).

Although through-going palaeocurrent trends suggest that the Tweed and Northumberland Basins were not entirely separate systems (Fig. 10b), chemical composition variances suggest there was an additional sediment source supplying the Northumberland Basin (Fig. 12). Given the slight downstream enrichment in Fe_2O_3 and the pronounced Sr enrichment for Fell Sandstone samples taken (downstream) in the northern Northumberland Basin (Fig. 12a), it is anticipated that this additional sediment source rock was enriched in these elements. Igneous basement rocks exposed within the Cheviot Block, namely the Cheviot Volcanic Group (Thirwall, 1988) and the Cheviot Granite (Al-Hafdh, 1985), are comparatively enriched in Sr (between 134 and 530 ppm) and Fe_2O_3 (between 1.45 and 7.31 %) compared with sandstones collected from the Tweed Basin. Despite encountering andesite lithic clasts and reports of subordinate granite lithics (Robson, 1977), the comparative TiO_2 enrichments of these basement units (between 0.29 and 1.17 %) casts doubts on their potential as dominant sediment source rocks.

Despite the following units now being largely absent from the Southern Uplands (Browne *et al.*, 2002), eroded stratigraphic equivalents to the unconformable Silurian-Devonian Old Red Sandstone Group may have represented a remobilised Sr and Fe_2O_3 enriched, yet less TiO_2 enriched, potential sediment source lithology (Fig. 12a) (Breward, 2004; Everett *et al.*, 2019). An abundance of incorporated volcaniclastic detritus in these basement units (e.g., McKellar *et al.*, 2020) suggests that similar detritus incorporated within the Fell Sandstone need not have been derived solely from the Cheviot Volcanic Group. Moreover, previous petrological studies on underlying parts of the Carboniferous syn-rift succession of the Northumberland-Solway Basin imply a prolonged history of orthoquartzitic material derived from the Southern Uplands (Nairn, 1958). It is suggested, therefore, that comparative downstream enrichments in Sr and Fe_2O_3 in the Northumberland Trough may have been due to supply from Devonian Old Red Sandstone Group basement rock from the Southern Uplands. The Southern Uplands, which were underpinned by low-density granite intrusions such as the Cheviot Pluton, may have undergone progressive un-roofing during deposition of the Fell Sandstone succession (Fig. 13).

Slight downstream petrographical and geochemical deviations between samples taken from the Northumberland Basin, and the eastern margin of the Alston Block, suggest a continuous palaeo-drainage system in this region of the northern Pennine Basin with mixing from an additional clastic sediment source. Based on downstream geochemical deviations between the Northumberland Basin and Alston Block, an additional sediment source enriched in Rb, and slightly depleted in TiO_2 is anticipated. Given the textural immaturity, and comparative mineralogical immaturity indicated by the transition from sub-arkosic to sub-lithic (Fig. 11a), of sandstones taken along the eastern margin of the Alston Block (Fig. 11c), it is postulated that this additional source lithology was local. Unconformably underlaying younger Carboniferous strata upon the central part Alston Block and sampled only via the Rookhope and Eastgate boreholes, the chemically evolved Weardale Granite, which is connected at depth to the remainder of the North Pennine Batholith, may represent one such Rb enriched and TiO_2 depleted basement source lithology (Fig. 12b) (Dunham *et al*., 1965). Ordovician-Silurian turbiditic metasediments, like those of the Lake District (Stone *et al*., 2010), comprise one further component of basement rock along the western margin Alston Block (Dunham *et al*., 1962). By comparison, the latter is enriched with major oxides such as Fe_2O_3 and TiO_2 with respect to sandstones taken from the Northumberland Basin (British Geological Survey, 1992). Based on the downstream TiO_2 depletion of sandstones between the Northumberland Trough and the Alston Block, and enrichments in Rb, it is suggested that the Weardale Granite was exposed during deposition of the Fell Sandstone succession and comprised one additional sediment source lithology for the eastern margin of the Alston Block (Fig. 13). Based on seismic reflection profiles (Fig. 3), no accommodating fault system is suggested to have separated this comparative high, upon the central part of the Alston Block, from the depocenter along the block's eastern margin.

8.0 Facies and palaeocurrent trend interpretations

Within the Northumberland-Solway Basin, the increased preservation of finer-grained sediments and coal towards the south-west (Fig. 8) suggests progressively less sediment reworking (*cf*. Ghinassi *et al*., 2016), perhaps because of greater rates of accommodation space creation. Greater overall thicknesses in the south and south-west of the Northumberland-Solway Basin for early Carboniferous sediments support this idea (Fig. 9) (Chadwick *et al*., 1995). Such facies trends are consistent with distributive fluvial systems, within which coarse sediment is dispersed radially from an apex (e.g., Weissman *et al*., 2010), or fluvio-deltaic tectono-stratigraphic tilt-block models, within which alluvial fans prograde downslope from an upper hangingwall dipslope towards an axis of maximum subsidence (Gawthorpe and Leeder, 2000). Similarly, palaeocurrent is directed towards the south-west within the Northumberland-Solway Basin. The Northumberland and Solway basins appear to have formed one coherent depocentre during deposition of the Fell Sandstone Formation, given that there is no obvious interruption in regional palaeocurrent trend (Fig. 10b). Within the Northumberland-Solway Basin, any interruptions to this dominant trend are localised and perhaps related to the influences of intra-basin normal faulting (*cf*. Turner *et al*., 1993). The accumulation and preservation of greater amounts of deeper water facies assemblages towards the south may be a response to asymmetric, basin-bounding normal faulting induced subsidence (*cf*. Leeder and

Gawthorpe, 1987). Such systems may react to normal faulting or tilting by preserving sediments indicative of transgression (Barrett *et al.*, 2019).

Within the Tweed Basin and along the eastern margin of the Cheviot Block, which is unbound by major (>100 m) vertically displacing normal faults, palaeocurrent and preserved facies trends suggest a more complicated basin geometry influenced sedimentation (Fig. 13). The overall south-eastwards deflection in palaeocurrent and coarser preserved fluvial-dominated deposits along the eastern margin of the Cheviot Block, suggesting greater reworking, indicate local confinement of palaeodrainage because of this topographic feature. The preservation of greater finer grained sediments up dip, towards the Tweed Basin, may indicate progressively less reworking, perhaps due to the greater rates of accommodation in this part of the broader basin system. Sedimentary provenance analyses, and palaeocurrent and facies trend analyses, suggest that the Cheviot Block had been at least partly exposed during deposition of the Fell Sandstone Formation. In contrast, borehole penetrations reveal that the Tweed Basin had accumulated at least hundreds of metres of older (Ballagan Formation) Carboniferous sediments (Millward *et al.*, 2013). Whilst no 2D seismic reflection profiles have been acquired in this part of the UK, there are few suggestions of major (>100 m) vertically displacing fault systems here to accommodate subsidence along the eastern margin of the Cheviot Block (Fig. 1b) (Shiells, 1963). Based on the presence of a low-density granite intrusion within the core of the Cheviot Block, it is suggested that the Tweed Basin and the Cheviot Block together may have resembled a regional monocline, like the central and eastern parts of the Alston Block (Fig. 2). Facies based comparisons cannot be made between the Tweed Basin and the eastern part of the Alston Block, due to burial of the latter. However, both the central part of the Alston Block and the Cheviot Block are suggested to have been exposed and providing sediment during deposition of the Fell Sandstone Formation.

9.0 Influences of low-density granite intrusions, flexural isostasy and uplift on basin geometry and sedimentation

In an earlier publication, this authorship suggested that the origin of basement monoclines in the northern Pennine Basin can be associated with the buoyant composition of their uplifted limbs, and flexural isostasy (Howell *et al.*, 2019). In the same way that regional basement synclines form as a flexural isostatic response to positive lithospheric loads imposed by the mass of volcanic islands (e.g., Watts, 1978), monoclines can form in response to flexurally compensated negative loads imposed by local basement buoyancy, and perhaps the locally thickened crust (Fig. 14). Two-dimensional lithosphere scale numerical modelling experiments show that such structures may form irrespectively of normal faulting but depend more so on the rigidity or effective elastic thickness (T_e) of the lithosphere (Howell *et al.*, 2019). Lateral subsidence variations may occur in response to differential sediment loading, and perhaps differential compaction of the underlying sedimentary sequence (*cf*. Collier, 1989). The sedimentological and provenance-based studies presented in this study suggest that the uplifted limbs of these monoclines, or basement domes, associated with buoyant granite intrusions can influence sediment preservation, palaeodrainage and local sediment supply (Figs. 10c and 13). The findings thus presented are not just at variance with classically depicted depositional models for the 'block and basin' style northern Pennine rift basin (e.g., Johnson, 1967), within which faulted blocks are bound by major vertically displacing normal faults, but also with more modern depictions of dominantly normal fault driven rift basins (Fig. 3) (e.g., Gawthorpe and Leeder, 2000).

10.0 Conclusions

Based on the results of this study, it is suggested that some aspects of the Mississippian Fell Sandstone Formation, and stratigraphically equivalent deposits in the northern Pennine Basin, match classically depicted models for 'block and basin' style rift basin systems, within which granite-cored basement blocks are bound by major (>100 m) vertically displacing normal faults. These include the overall basinward increase in deeper water and delta-dominant facies in the Northumberland-Solway Basin, the dominant basinward palaeocurrent direction in the Northumberland-Solway Basin, and the derivation of sediment from comparatively uplifted 'blocks'. However, other aspects, such as the up-system decrease in net sand content north-east of the Cheviot Block, the south-eastwards deflection in palaeocurrent in the Tweed Basin, and the contemporaneous uplift and shedding of sediment on central parts of the Alston Block and accumulation of kilometre-thick sediment along the eastern margin of the Alston Block, may not.

Highlighted divergences from pre-existing depositional models for 'block and basin' rift basin systems relate to occurrences of granite-cored and largely unfaulted pre-Carboniferous basement highs and monoclines. In 3D, they form regional domes, on to which the Carboniferous succession onlaps unconformably. All unfaulted basement highs in the northern Pennine Basin coincide with low-density granite intrusions. It is suggested that one such basement high, the Cheviot Block, confined and deflected the Fell Sandstone fluvio-deltaic system from the west, causing localised elevations in net sand content, due to reworking, and variations in palaeocurrent. Central parts of the Alston Block were comparatively uplifted with respect to its eastern margin because of flexural isostatic responses to buoyant basement rock. The findings thus presented are not just at variance with classically depicted depositional models for the 'block and basin' style northern Pennine rift basin, but also with more modern depictions of dominantly normal fault driven rift basins.

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Table captions

Table 1: Facies for the Fell Sandstone Formation and contemporaneous deposits across the northern Pennine Basin. The photographed scale bars are in centimetre increments.

Table 2: Architectural elements for the Fell Sandstone Formation and contemporaneous deposits across the northern Pennine Basin.

Figure captions

Figure 1a: A palaeogeographical and simplified regional structural map for the northern Pennine Basin. Flt. = Fault. For similar examples, see Booth *et al.* (2020), Corfield *et al.* (1996), Glennie (2005). 1b: A regional cross-section through northern England and Scotland (adapted from Stone, 2008). SUFZ = Southern Upland Fault.

Figure 2: Uninterpreted and interpreted seismic sections from the northern Pennine Basin, northern England. Seismic reflection profiles are courtesy of the UK Onshore Geophysical Library (UKOGL). See Figure 6 for locations. Figure 2a shows an E-W transect from the central and granite-cored part of the Alston Block to the Alston Block's eastern margin. Carboniferous sediments are penetrated by deep boreholes and can be seen onlapping against the Alston Block in response to the low-density North Pennine Batholith. Figure 2b shows a N-S transect from the Alston Block to the central part of the Northumberland Trough. The Northumberland Trough forms a tilted half-graben, with Carboniferous sediments thickening to the north.

Figure 3: Schematic tectono-stratigraphic models for (top row) 'block and basin' style rift basins (after Leeder, 1982); (middle row) tilt-blocks or half-grabens (after Leeder and Gawthorpe, 1987) and; (bottom row) active rift basins (after Gawthorpe and Leeder, 2000).

Figure 4: Bouguer gravity anomaly map for northern England and southern Scotland (after Kimbell and Williamson, 2015). Negative gravitational anomalies associated with low-density granite intrusions are annotated. TP = Tweedale Pluton; CH = Cheviot Pluton; CD = Criffel-Dalbeattie Pluton; NPB = North Pennine Batholith; LDB = Lake District Batholith. Co-ordinate system is the British National Grid.

Figure 5: Latest Devonian-Early Carboniferous (Mississippian) stratigraphy of the northern Pennine Basin. The miospore zonation scheme of Waters *et al.* (2011), based on Clayton *et al.* (1977, 1978) and revised later by Clayton *et al.* (1985), and the onshore Carboniferous lithostratigraphic framework of Waters *et al.* (2007) are used. The former Carboniferous stratigraphic subdivisions of NW Europe are adopted, and a comparison is made with current international stratigraphic nomenclature based on Davydov *et al.* (2004). Note that the Tournaissian, Visean and Serpukhovian Stages constitute the Mississippian Series under the current International stratigraphic subdivisions and the Tournaissian, Visean and Namurian Stages constituted the Dinantian Series under the former Carboniferous stratigraphic subdivisions of NW Europe. NPB = North Pennine Batholith; CP = Cheviot Pluton; SL = Sixth Limestone; CB = Clattering Band (Knightsbridge Limestone); LAB = Lower Antiquatonia Beds; K/B = Kelso Lavas and Birrenswark Volcanics; GV = Glencartholm Volcanics.

Figure 6: A map of the northern Pennines indicating borehole and outcrop localities used as part of this study and the data associated with each locality. Refer to Supplementary data table 3 for a further list of borehole data used as part of this study. The locations of seismic lines displayed in Figure 2 are also indicated. Contains BGS DiGmapGB-250 Scale data © UKRI (British Geological Survey, 2008). Co-ordinate system is the British National Grid.

Figure 7: Photoplate showing the facies of the Fell Sandstone Formation and contemporaneous distal sediments from the northern Pennine Basin (see Figure 6 for location of outcrops). 7a: Orthorecitified image of the upper Bowden Doors section showing a high sand content, amalgamated channel sets and stacked crossbed sets. 7b: Thick tabular cross-bedded set overlying a massive structureless concave-up sandstone from Bowden Doors (also see Turner *et al*., 1987). 7c: Trough-cross-bed sets showing some soft sediment deformation and recumbence at Long Crag section, near Rothbury. 7d: Very coarse, poorly sorted sandstone with andesitic and lithic clasts. 7e: Poorly preserved mixed fine sand-silt overbank deposits at Long Crag with coarse-grained trough cross-bedded sandstone sets overlying. 7f: Distal mudstone and siltstone facies from Whiteberry Burn, note bedding is near vertical. 7g: Algal-bound limestone from the Whiteberry Burn section. 7h: Bioturbated shallow marine sandstone bedding plane from Whiteberry Burn.

Figure 8: Sedimentary logs for the Fell Sandstone succession across the northern Pennine Basin. Each log captures the uppermost Fell Sandstone succession and the succession immediately below it. The Stonehaugh borehole succession was logged directly from drillcore at the BGS core store in Keyworth. The Alnwick and New Murton boreholes were drawn up based on field logs and records by B. Turner (scans.bgs.ac.uk/; also see Turner *et al*., 1997) and A. Hodgson (scans.bgs.ac.uk/).

Figure 9: Regional correlation of the Fell Sandstone and contemporaneous deposits across the northern Pennine Basin (Tweed Basin, the eastern margin of the Cheviot Block, Northumberland-Solway Basin, Alston Block and Stainmore Trough). See Figure 6 and Supplementary data table 1 for borehole locations and data derivation. The Berwick outcrop succession is after Turner *et al*. (1993).

Figure 10a: Net to gross (sand %) trends for the Fell Sandstone Formation and contemporaneous deposits across the northern Pennine Basin, based on annotated borehole recordings and cubic interpolation in MATLAB. For more detailed descriptions of borehole locations, the reader may refer to Figure 6 or refer to Supplementary data table 1 for original metadata. Co-ordinate system is the British National Grid. 11b: Palaeocurrent trends for the Fell Sandstone Formation and contemporaneous deposits across the northern Pennine Basin. Outcrop localities, at which palaeocurrent data were taken, are indicated by black dots. Extent of Fell Sandstone Formation and faulting outcrop is also indicated. Contains BGS DiGmapGB-250 Scale data © UKRI (British Geological Survey, 2008). See also palaeocurrent trends for the Fell Sandstone Formation presented by Monro (1986) and Turner *et al*. (1993). Co-ordinate system is the British National Grid. 10c: A summary of key findings based on data presented in this manuscript.

Figure 11a: Ternary diagram of mineral composition for sandstones (arenites) belonging to the Fell Sandstone Formation in the northern Pennine Basin. 11b: Representative cross-polarised (XPL) photomicrographs of mineral assemblage and texture for the Fell Sandstone Formation sandstones in the northern Northumberland Basin. 11c: Representative cross-polarised (XPL) photomicrographs of mineral assemblage and texture for the Fell Sandstone Formation sandstones along the eastern margin of the Alston Block.

Figure 12a: Selected trace and major element oxide compositions for medium-grained and well-sorted sandstones across the Tweed and Northumberland Basins and basement rock compositions for the Cheviot Block. 12b: Selected trace element and major element oxide compositions for medium-grained and well-sorted sandstones across the Northumberland and the Alston Block's eastern margin and basement rock compositions for the Alston Block. Also see Supplementary data tables 2 and 3. Geochemical values for potential source rock lithologies taken from Breward (2004), Everett *et al*. (2019), Thirlwall (1988), Al-Hafdh (1985), Dunham *et al.* (1965), BGS (1992) and Everett *et al*. (2019).

Figure 13: A depositional model for the Fell Sandstone Formation and stratigraphically equivalent deposits in the northern Pennine Basin.

Figure 14: Schematic illustrations of isostatic responses to subsurface low-density (buoyant) granite intrusions (*cf*. Howell *et al*., 2019) and a comparison with the lithosphere's isostatic response to a volcanic island (after Watts, 1978).

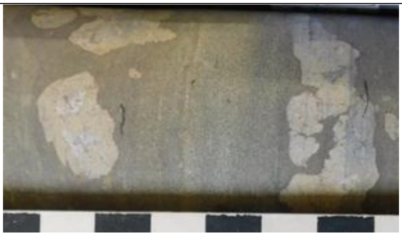
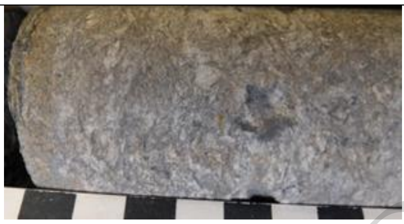
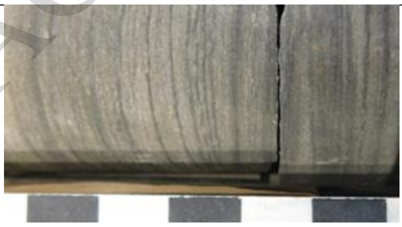
Supplementary data table captions

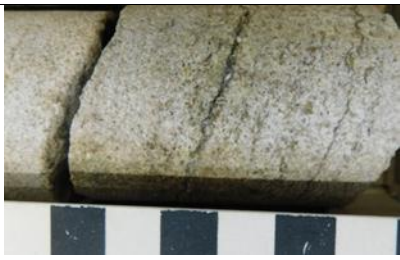
Supplementary data table 1: Borehole data with derivation and web links.

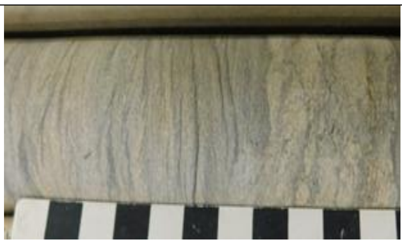
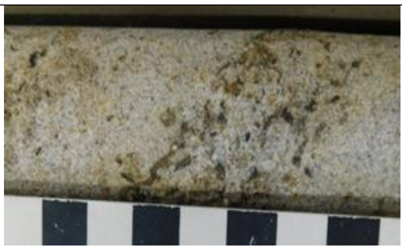
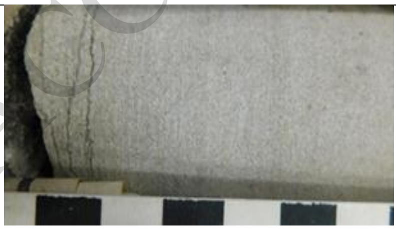
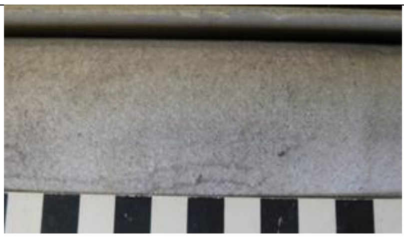
Supplementary data table 2: Concentrations of selected elements in parts per million (ppm) for sandstone samples belonging to the Fell Sandstone Formation across the northern Pennine Basin. Bdl = below limit of detection.

Supplementary data table 3: Concentrations of selected element oxides in weight per cent (wt. %) for sandstone samples belonging to the Fell Sandstone Formation across the northern Pennine Basin. Bdl = below limit of detection.

Table 1

Code	Photo	Lithology & Texture	Structure & Other Features	Interpretation
C		Black, bituminous to anthracitic coal.	Thinly laminated.	Plant and tree growth in swamps or shallow pools.
Fb		Grey to dark grey, carbonaceous siltstone.	Structureless to crudely parallel-laminated frequent bioturbation and sporadic wood/plant fragments/coal.	Suspension fall out from stationary waters. Stabilization for vegetation to develop and pedogenesis removing any of the lamination.
Ffb		Grey to dark grey, carbonaceous siltstone.	Structureless, heavily bioturbated, with sporadic wood/plant fragments.	Suspension fall out from stationary waters. Stabilization for vegetation to develop.
Fm		Dark grey, carbonaceous mudstone to siltstone.	Structureless with frequent plant debris.	Suspension fall out from stationary waters. Stabilization for vegetation to develop and pedogensis removing any of the lamination.
Fpl		Grey to dark grey siltstone.	Parallel-laminated.	Suspension fall out from stationary waters.

Gm		Grey, granule to pebble sized, poorly sorted, sub-rounded to sub-angular, clast supported conglomerate.	Structureless.	Sub-aqueous, high energy Newtonian flow under high sediment load conditions, with suppressed bedform development.
Gt		Grey, granule to pebble sized, poorly sorted, sub-angular to angular, clast supported conglomerate.	Trough cross-bedded.	Sub-aqueous lower flow regime conditions with high sediment load, intermittent development and migration of dune-forms.
Lc		Light grey, sparitic limestone.	Structureless.	Sub-aqueous precipitation and crystallisation of carbonate.
Lm		Grey to dark grey, carbonate mudstone to wackestone.	Fossiliferous laminations with frequent Ostracods, shell and Crinoid fragments.	Sub-aqueous reworking of allochthonous carbonate
Pg		Grey to dark grey siltstone with brown mottling and up to pebble grade angular clasts.	Structureless to crudely laminated with frequent plant debris.	Suspension fall out from stationary waters. Stabilization for vegetation to develop. Alteration and weathering leading to the pedogenesis of siltstone.
Pn		Dark grey siltstone with rusty brown nodules.	Structureless to crudely laminated with occasional siderite nodules,	Suspension fall out from stationary waters. Stabilization for vegetation to develop. Alteration

			plant debris and root traces.	and weathering leading to the pedogenesis of siltstone.
Sf		Grey siltstone to fine-grained, poorly sorted, sub-rounded sandstone.	Flaser laminations with sporadic roots and bioturbation.	Alternation between oscillatory and unidirectional currents with periods of slack water.
Sgt		Grey, medium to coarse-grained, poorly sorted, sub-angular sandstone with gravel grade clasts.	Gravel lined planar cross-bedding.	Sub-aqueous lower flow regime conditions with high sediment load, intermittent development and migration of dune-forms.
Sh		Light grey to dark grey mudstone to fine-grained, sub-rounded sandstone with bimodal sorting.	Heterolithic bedding with occasional soft sediment deformation.	Oscillatory and unidirectional currents with rapidly fluctuating energy conditions.
Sl		Light grey to grey, siltstone to fine-grained, sub-rounded sandstone, with bimodal sorting.	Lenticular lamination.	Alternation between oscillatory and unidirectional currents with periods of slack water.
Sla		Light grey, very fine to fine-grained, moderate to well sorted, sub-rounded sandstone.	Parallel-laminated.	Sub-aqueous aggrading upper flow regime flat beds.
Sm		Light grey to grey, medium to coarse-grained, moderate to well sorted, sub-rounded sandstone.	Structureless.	Rapid deposition in high sediment load suppressing bedform development.

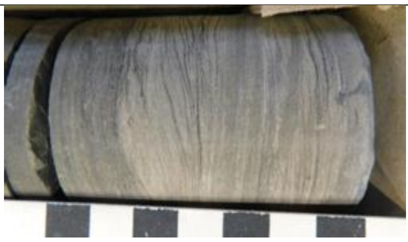
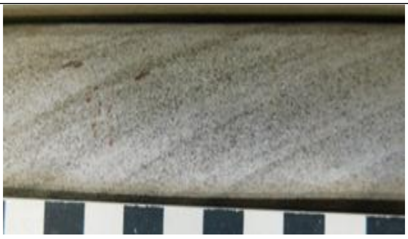
Sp		Light grey to grey, very fine to medium-grained, moderately sorted, sub-rounded sandstone.	Planar cross-bedded.	Migration of straight-crested dune-scale bedforms and dune trains sub-aqueously under lower flow regime conditions.
Sr		Light grey to grey, very fine to fine-grained, moderately sorted, sub-rounded sandstone.	Asymmetrical ripple-laminated.	Migration of ripple-scale bedforms in lower flow regime.
St		Light grey, fine to coarse-grained, moderately sorted, sub-rounded sandstone.	Trough cross-bedded with sporadic slumping.	Migration of sinuous-crested dune-scale bedforms and dune trains sub-aqueously under lower flow regime conditions.

Table 1: Facies for the Fell Sandstone Formation and contemporaneous deposits across the northern Pennine Basin. The photographed scale bars are in centimetre increments.

Element	Code	Facies	Description	Gamma Ray Response	Association
Fluvial Channel	FC	Gm, Gt, Sgt, St, Sp, Sm, Sh, Sr	'U' shaped, fining upwards association with an erosional basal bounding surface. The association is dominated by planar (Sp) and trough (St) cross-bedded, well-sorted sandstones with minor basal conglomerates.	Low response overall, increasing upwards, suggestive of a fining upwards trend.	Fluvial-dominated
Sheet	S	Sm, Sla	Tabular, sheet-like, fining upwards association with an erosional basal bounding surface. The association in dominated by structureless (Sm) to parallel-laminated (Sla) sandstones.	Very low response overall, showing no disernable variation.	Fluvial-dominated
Lateral Accretion	LA	St, Sp, Sr	Lensoidal, fining upwards association dominantly composed of cross-bedded sandstone (St & Sp) with palaeocurrents of accretionary surfaces between 60° to 120° different to the local palaeoflow.	Low overall, shallow bell-shaped curve, slight increase in gamma response upwards.	Fluvial-dominated
Downstream Accretion	DA	Gt, Gm, Sgt, St, Sp, Sr	Lensoidal, fining upwards association dominantly composed of cross-bedded sandstone (St & Sp) with palaeocurrents of accretionary surfaces less than 60° different to the local palaeoflow.	Low overall, shallow bell-shaped curve, slight increase in gamma response upwards.	Fluvial-dominated
Floodplain	FP	Fpl, C, Fb, Ffb, Fm, Pg, Pn	Tabular association of structureless (Fm) to parallel-laminated (Fpl) siltstone with minor coal (C) and pedogenic facies (Pg & Pn).	High overall, shallow peaks corresponding to coal beds.	Both
Delta Top Distributary Channel	DC	Sgt, Sh, St, Sp, Sr	'U' shaped, fining upwards association with an erosional basal bounding surface. The association is dominated by planar (Sp) and trough (St) cross-bedded sandstones.	Typically higher response than fluvial channel, steep bell-shaped curve. A distinct low value at the base due to rapid change in grainsize.	Delta-dominated
Delta Front	DB	Sp, Sr,	Lensoidal, coarsening upwards	Moderate response	Delta-

Bar		Sl, Sf	association dominantly composed of planar cross-bedded sandstones (Sp) with flaser (Sf) to lenticular (Sl) sandstones and siltstones.	overall, cylindrical to funnel shaped curve, some evidence of coarsening upwards, not always present.	dominated
Delta Slope	DS	Fpl, Fm, Fb	Lensoidal, coarsening upwards association dominantly composed of parallel-laminated siltstone (Fpl) with minor sandstone lenses.	Moderate-high response overall. Funnel-shaped curve, suggestive of a coarsening upwards succession.	Delta-dominated
Pro-delta	PD	Fpl, Lc, Lm	Tabular, coarsening upwards association dominantly composed of parallel-laminated siltstone (Fpl) with minor carbonate lenses.	High response overall. Cylindrical curve with high peaks corresponding to more organic-rich horizons.	Delta-dominated

Table 2: Architectural elements for the Fell Sandstone Formation and contemporaneous deposits across the northern Pennine Basin.

Figure 1

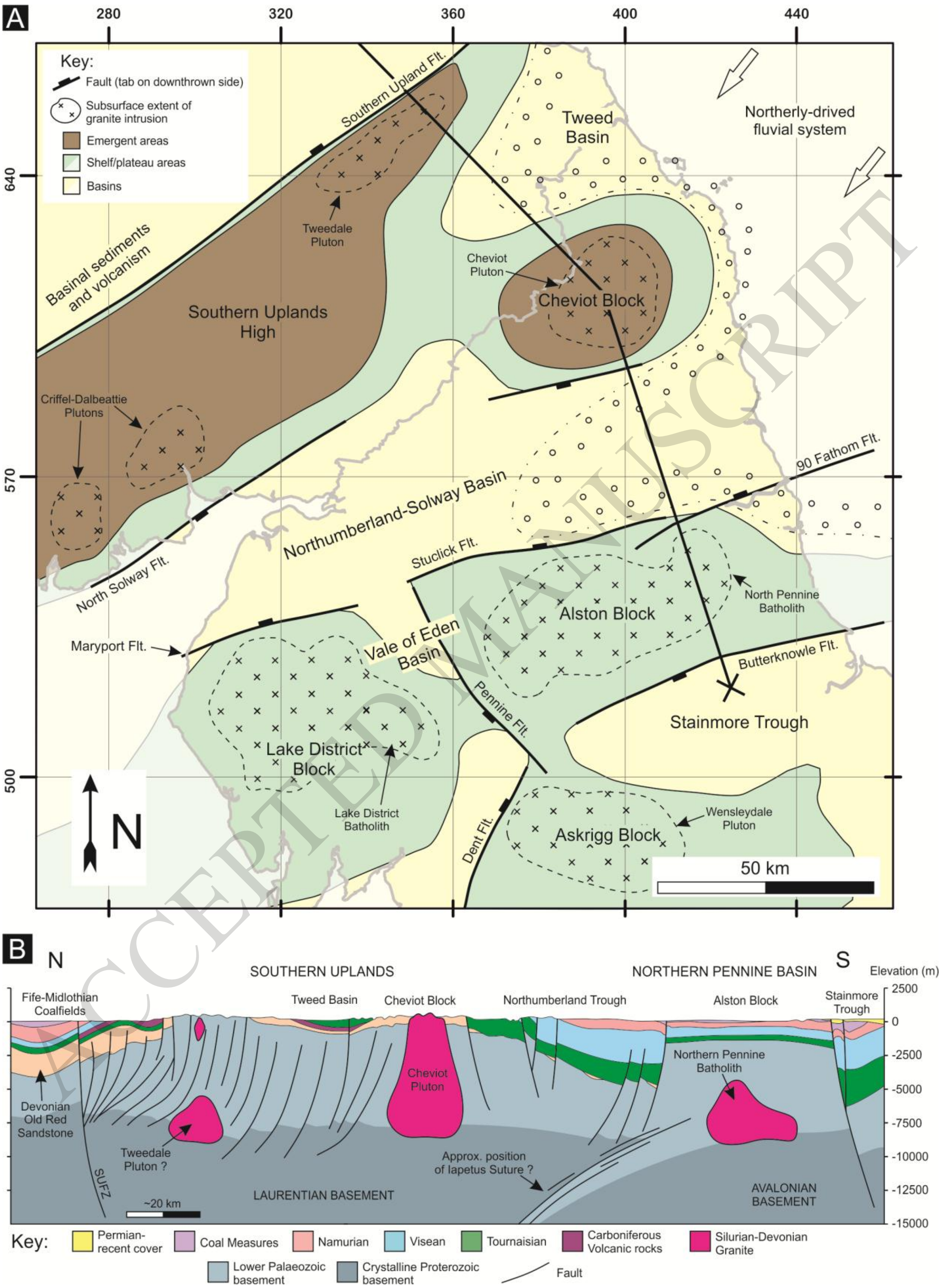

A
Key:
Fault (tab on downthrown side)
Subsurface extent of granite intrusion
Emergent areas
Shelf/plateau areas
Basins
Southern Upland Flt.
Basinal sediments and volcanism
Tweedale Pluton
Southern Uplands High
Tweed Basin
Northerly-drived fluvial system
Cheviot Pluton
Cheviot Block
Criffel-Dalbeattie Plutons
Northumberland-Solway Basin
90 Fathom Flt.
Stublick Flt.
North Solway Flt.
North Pennine Batholith
Alston Block
Maryport Flt.
Vale of Eden Basin
Butterknowle Flt.
Pennine Flt.
Stainmore Trough
Lake District Block
Lake District Batholith
Dent Flt.
Askrigg Block
Wensleydale Pluton
50 km
N
280
320
360
400
440
640
570
500
B
N
S
SOUTHERN UPLANDS
NORTHERN PENNINE BASIN
Elevation (m)
Fife-Midlothian Coalfields
Tweed Basin
Cheviot Block
Northumberland Trough
Alston Block
Stainmore Trough
Devonian Old Red Sandstone
Cheviot Pluton
Northern Pennine Batholith
Tweedale Pluton ?
SUFZ
Approx. position of Iapetus Suture ?
LAURENTIAN BASEMENT
AVALONIAN BASEMENT
~20 km
2500
0
-2500
-5000
-7500
-10000
-12500
-15000
Key:
Permian-recent cover
Coal Measures
Namurian
Visean
Tournaisian
Carboniferous Volcanic rocks
Silurian-Devonian Granite
Lower Palaeozoic basement
Crystalline Proterozoic basement
Fault

Figure 2

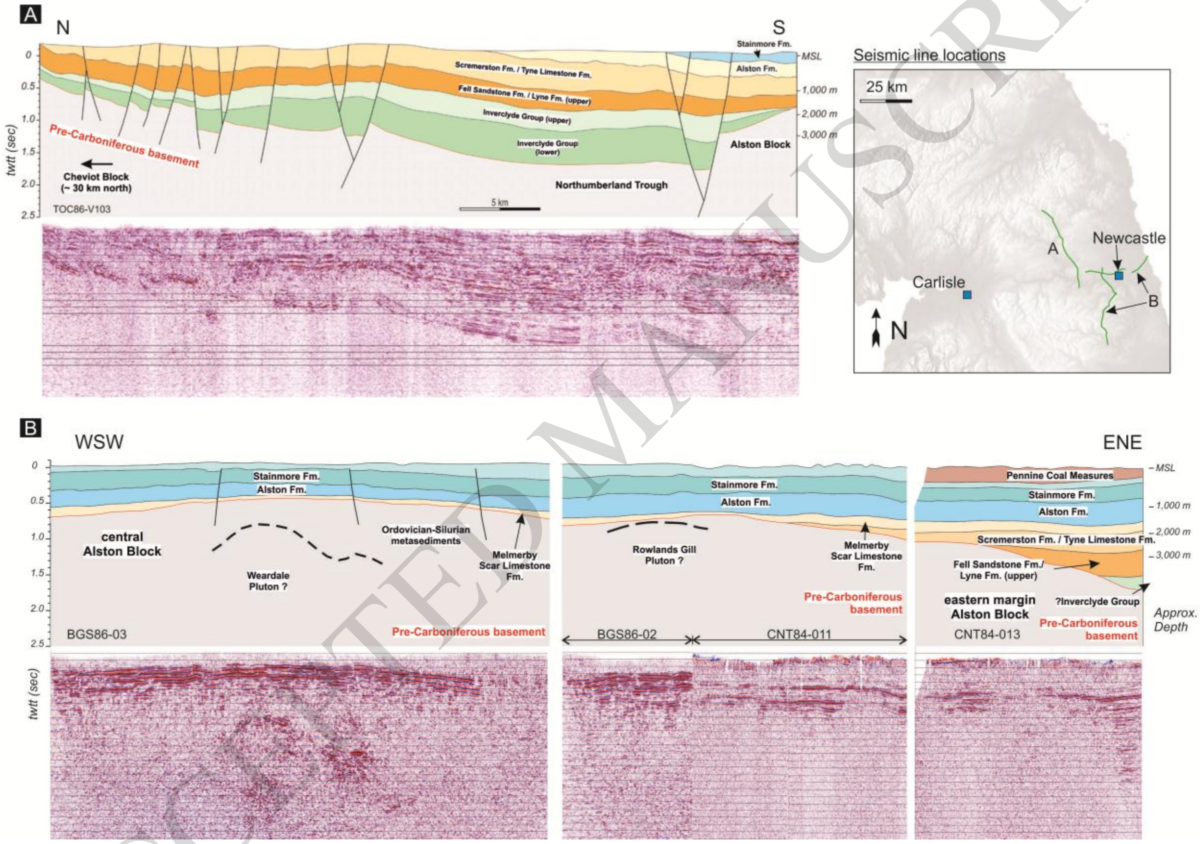

A
N
S
Stainmore Fm.
Alston Fm.
Scremerston Fm. / Tyne Limestone Fm.
Fell Sandstone Fm. / Lyne Fm. (upper)
Inverclyde Group (upper)
Inverclyde Group (lower)
Pre-Carboniferous basement
Cheviot Block
(~ 30 km north)
Alston Block
Northumberland Trough
TOC86-V103
5 km
MSL
1,000 m
2,000 m
3,000 m
twtt (sec)
Seismic line locations
25 km
Newcastle
Carlisle
A
B
N
B
WSW
ENE
Stainmore Fm.
Alston Fm.
central
Alston Block
Ordovician-Silurian
metasediments
Weardale
Pluton ?
Melmerby
Scar Limestone
Fm.
Pre-Carboniferous basement
BGS86-03
Rowlands Gill
Pluton ?
Pre-Carboniferous
basement
BGS86-02
CNT84-011
Pennine Coal Measures
Scremerston Fm. / Tyne Limestone Fm.
Fell Sandstone Fm./
Lyne Fm. (upper)
eastern margin
Alston Block
?Inverclyde Group
CNT84-013
Approx.
Depth

Figure 3

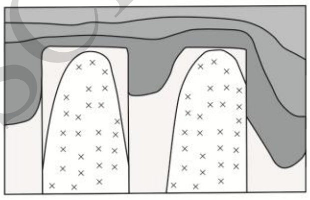
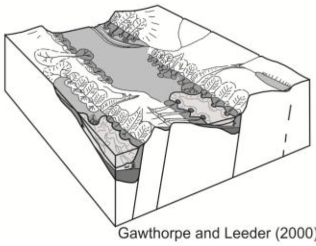
Rift basin models	Key features	Implications for depositional systems	Examples	Schematic illustration
Block and basin model	• Basin-bounding faults form around peripheral margins of comparatively uplifted granite-cored blocks.	• Thick syn-rift successions characterised by deeper water lithofacies accumulate in basins.	Pennine Basin, UK	 Leeder (1982)
Tilt-block or half-graben models	• Tilt-block systems are influenced by tectonically induced slopes resulting from HW down-tilting and FW uplift.	• Prompts axial drainage. • Sediment sourced from FW and HW dipslope. • Transgression caused by fault movement and tilting.	Northumberland Trough, UK Rio Grande Rift, Colorado, USA Lower Rhine graben, western Germany	 Leeder and Gawthorpe (1987)
Models for active extension	• Evolution of rift basins divided into four parts: *initiation*; *fault interaction and linkage*; *through-going fault stage* and; *fault death*.	• Basin linkage and through fault propagation determine drainage and catchment. • Hydrologically closed rifts evolve into open rifts.	Corinth Rift, central Greece Main Ethiopian Rift Suez Rift, Egypt	 Gawthorpe and Leeder (2000)

Figure 4

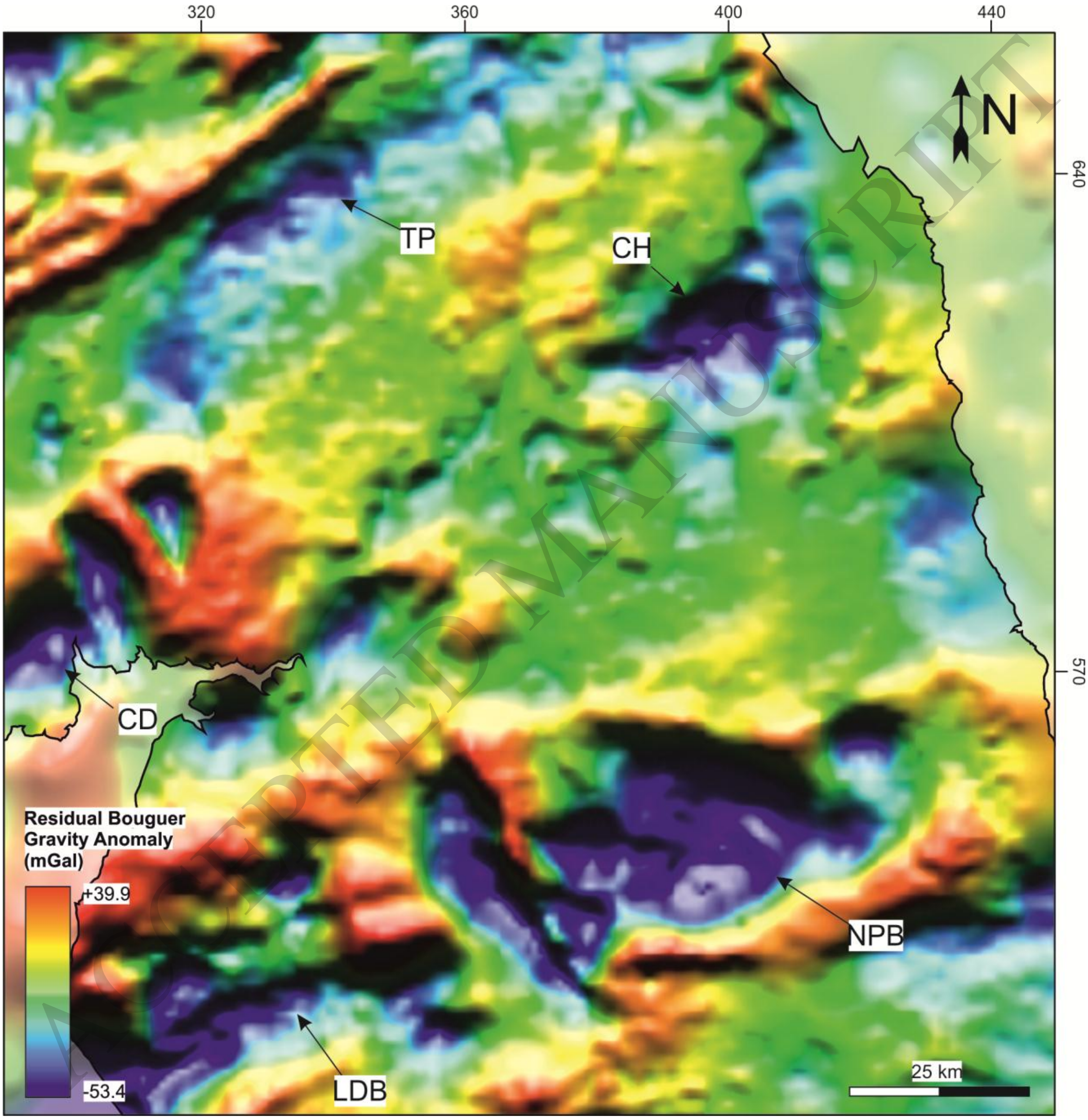

320
360
400
440
640
570
N
TP
CH
CD
NPB
LDB
Residual Bouguer Gravity Anomaly (mGal)
+39.9
-53.4
25 km
ACCEPTED MANUSCRIPT

Figure 5

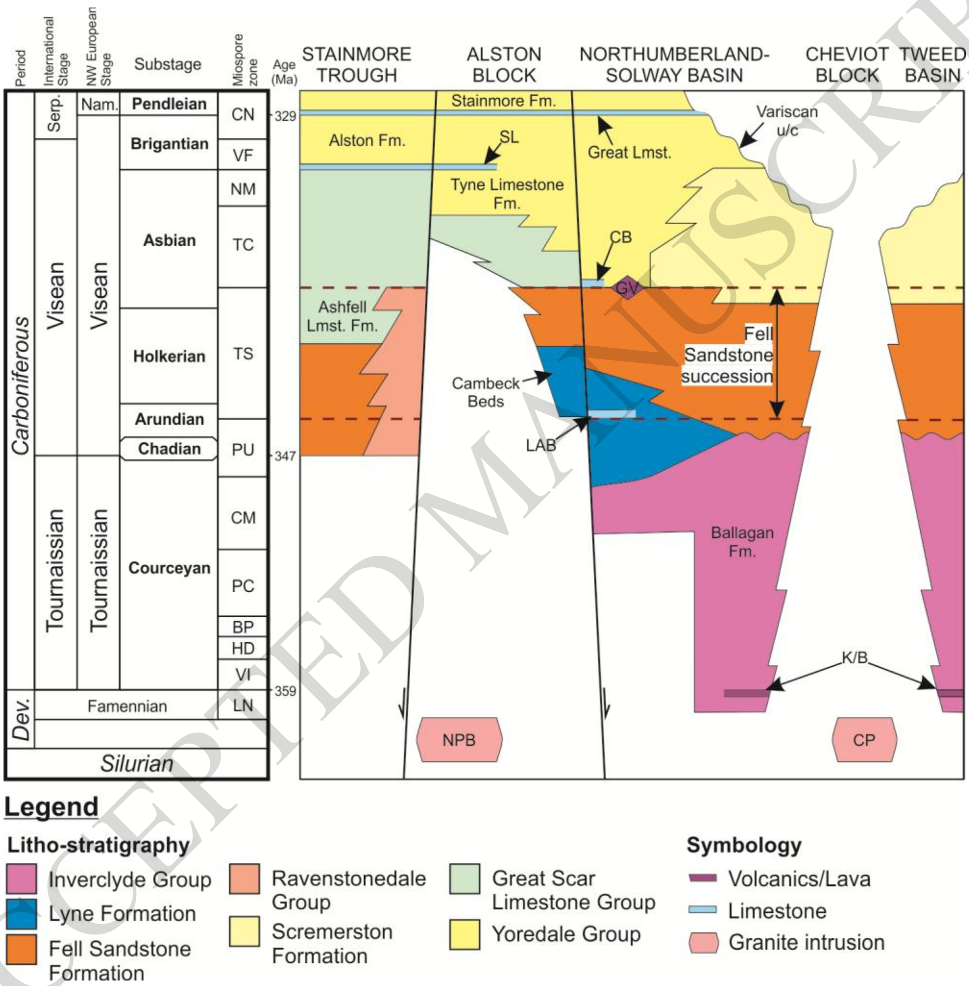

Period
International Stage
NW European Stage
Substage
Miospore zone
Age (Ma)
STAINMORE TROUGH
ALSTON BLOCK
NORTHUMBERLAND-SOLWAY BASIN
CHEVIOT BLOCK
TWEED BASIN
Carboniferous
Serp.
Visean
Tournaissian
Nam.
Pendleian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan
Dev.
Famennian
Silurian
CN
VF
NM
TC
TS
PU
CM
PC
BP
HD
VI
LN
329
347
359
Stainmore Fm.
Alston Fm.
SL
Tyne Limestone Fm.
Great Lmst.
Variscan u/c
CB
GV
Ashfell Lmst. Fm.
Fell Sandstone succession
Cambeck Beds
LAB
Ballagan Fm.
K/B
NPB
CP
Legend
Litho-stratigraphy
Inverclyde Group
Lyne Formation
Fell Sandstone Formation
Ravenstonedale Group
Scremerston Formation
Great Scar Limestone Group
Yoredale Group
Symbology
Volcanics/Lava
Limestone
Granite intrusion

Figure 6

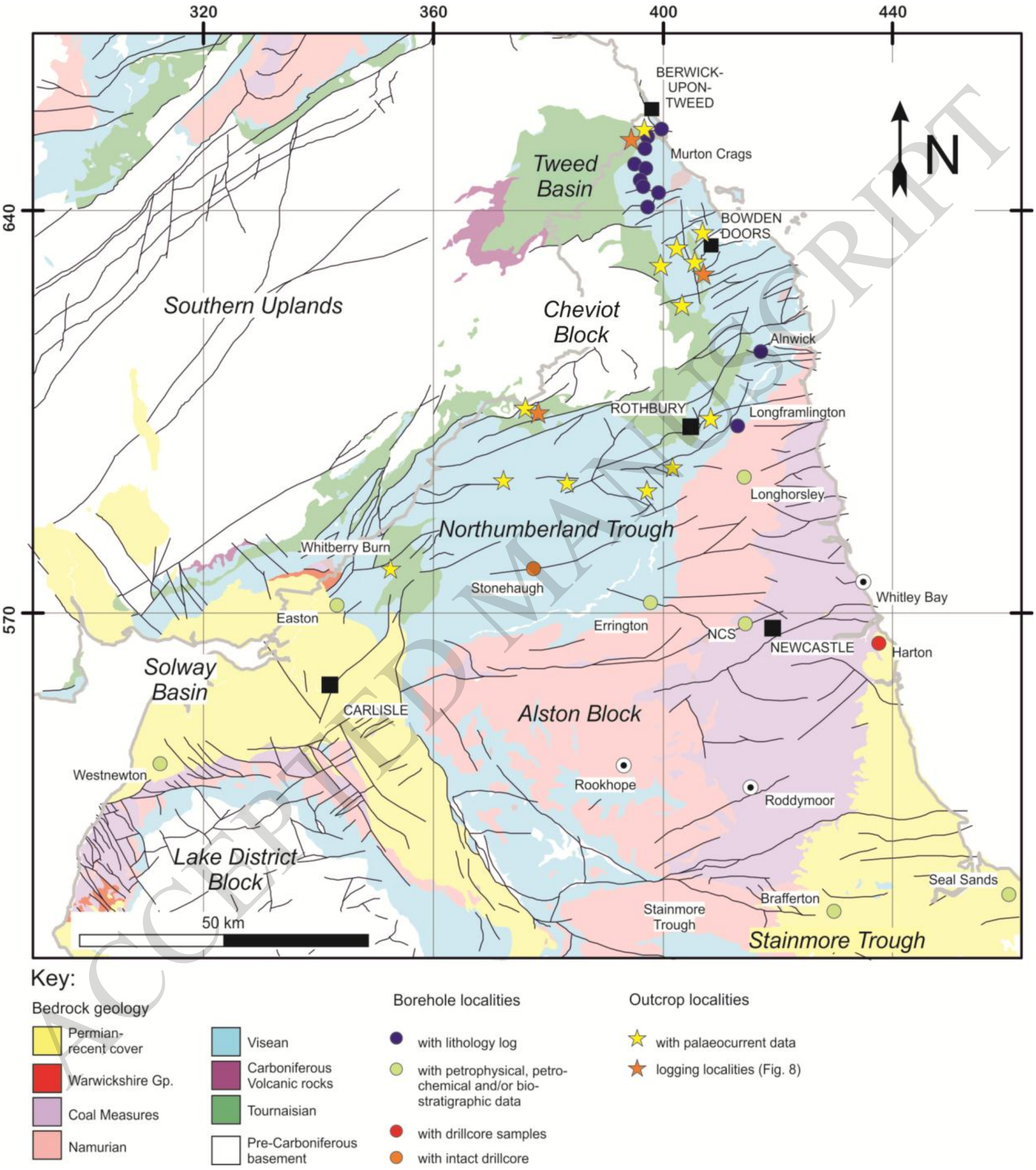

320
360
400
440
640
570
BERWICK-UPON-TWEED
Murton Crags
Tweed Basin
BOWDEN DOORS
Southern Uplands
Cheviot Block
Alnwick
ROTHBURY
Longframlington
Longhorsley
Northumberland Trough
Whitberry Burn
Stonehaugh
Whitley Bay
Easton
Errington
NCS
NEWCASTLE
Harton
Solway Basin
CARLISLE
Alston Block
Westnewton
Rookhope
Roddymoor
Lake District Block
Seal Sands
Brafferton
Stainmore Trough
50 km
Stainmore Trough
N
Key:
Bedrock geology
Permian-recent cover
Warwickshire Gp.
Coal Measures
Namurian
Visean
Carboniferous Volcanic rocks
Tournaisian
Pre-Carboniferous basement
Borehole localities
with lithology log
with petrophysical, petro-chemical and/or bio-stratigraphic data
with drillcore samples
with intact drillcore
Outcrop localities
with palaeocurrent data
logging localities (Fig. 8)

Figure 7

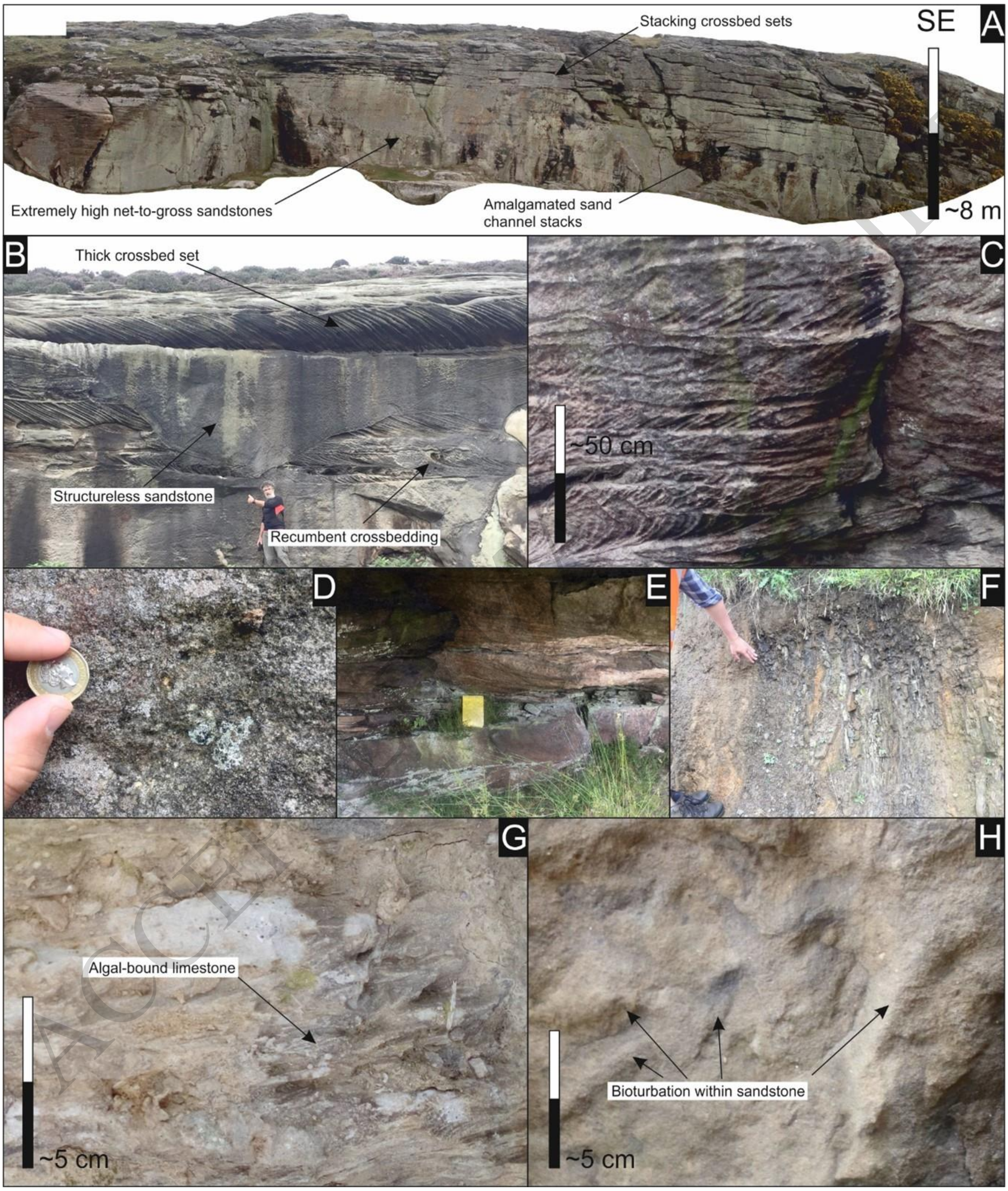

Stacking crossbed sets
SE
A
Extremely high net-to-gross sandstones
Amalgamated sand
channel stacks
~8 m
B
Thick crossbed set
Structureless sandstone
Recumbent crossbedding
C
~50 cm
D
E
F
G
Algal-bound limestone
~5 cm
H
Bioturbation within sandstone
~5 cm

Figure 8

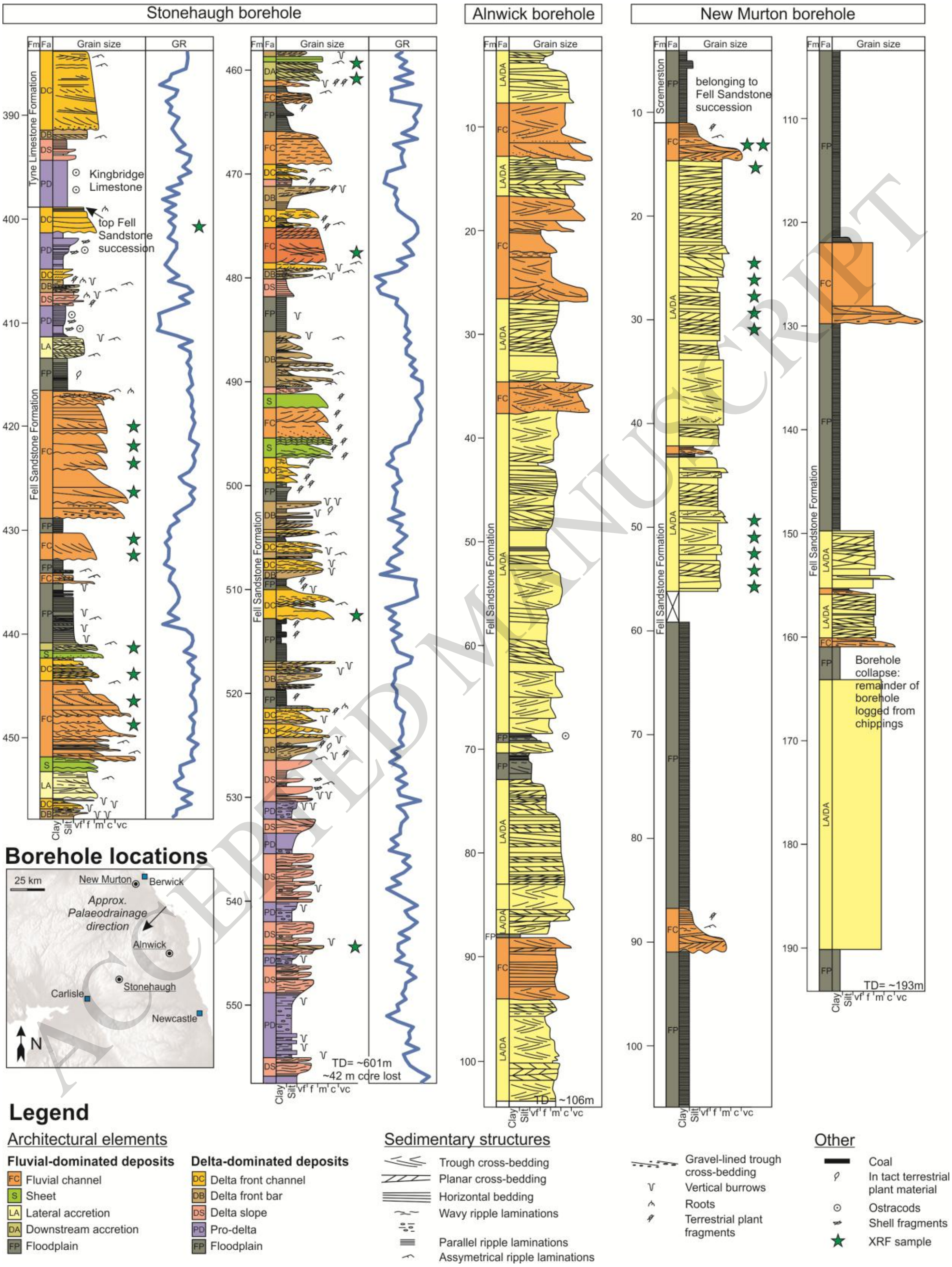

Stonehaugh borehole
Alnwick borehole
New Murton borehole
Tyne Limestone Formation
Fell Sandstone Formation
Kingbridge Limestone
top Fell Sandstone succession
Scremerston
belonging to Fell Sandstone succession
TD= ~601m
~42 m core lost
TD= ~106m
TD= ~193m
Borehole collapse: remainder of borehole logged from chippings
Borehole locations
25 km
New Murton
Berwick
Approx. Palaeodrainage direction
Alnwick
Stonehaugh
Carlisle
Newcastle
N
Legend
Architectural elements
Fluvial-dominated deposits
FC Fluvial channel
S Sheet
LA Lateral accretion
DA Downstream accretion
FP Floodplain
Delta-dominated deposits
DC Delta front channel
DB Delta front bar
DS Delta slope
PD Pro-delta
FP Floodplain
Sedimentary structures
Trough cross-bedding
Planar cross-bedding
Horizontal bedding
Wavy ripple laminations
Parallel ripple laminations
Assymetrical ripple laminations
Gravel-lined trough cross-bedding
Vertical burrows
Roots
Terrestrial plant fragments
Other
Coal
In tact terrestrial plant material
Ostracods
Shell fragments
XRF sample

Figure 9

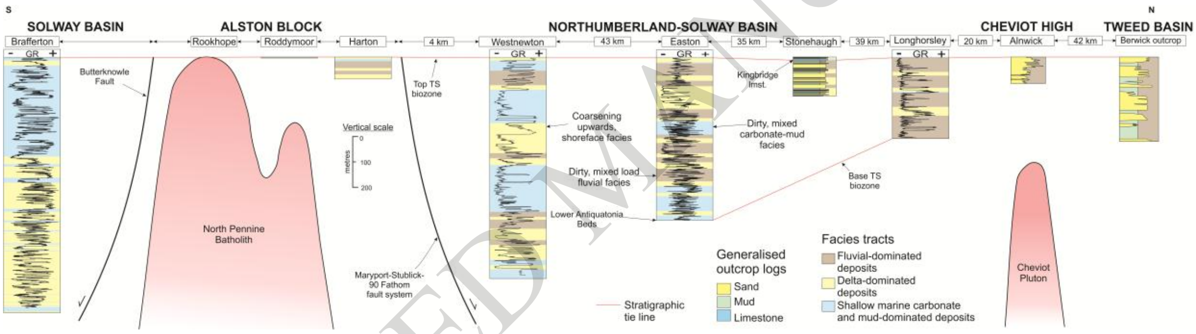

S
N
SOLWAY BASIN
ALSTON BLOCK
NORTHUMBERLAND-SOLWAY BASIN
CHEVIOT HIGH
TWEED BASIN
Brafferton
Rookhope
Roddymoor
Harton
4 km
Westnewton
43 km
Easton
35 km
Stonehaugh
39 km
Longhorsley
20 km
Alnwick
42 km
Berwick outcrop
- GR +
Butterknowle Fault
North Pennine Batholith
Top TS biozone
Vertical scale
metres
0
100
200
Maryport-Stublick-90 Fathom fault system
Coarsening upwards, shoreface facies
Dirty, mixed load fluvial facies
Lower Antiquatonia Beds
Kingbridge lmst.
Dirty, mixed carbonate-mud facies
Base TS biozone
Cheviot Pluton
Stratigraphic tie line
Generalised outcrop logs
Sand
Mud
Limestone
Facies tracts
Fluvial-dominated deposits
Delta-dominated deposits
Shallow marine carbonate and mud-dominated deposits

Figure 10

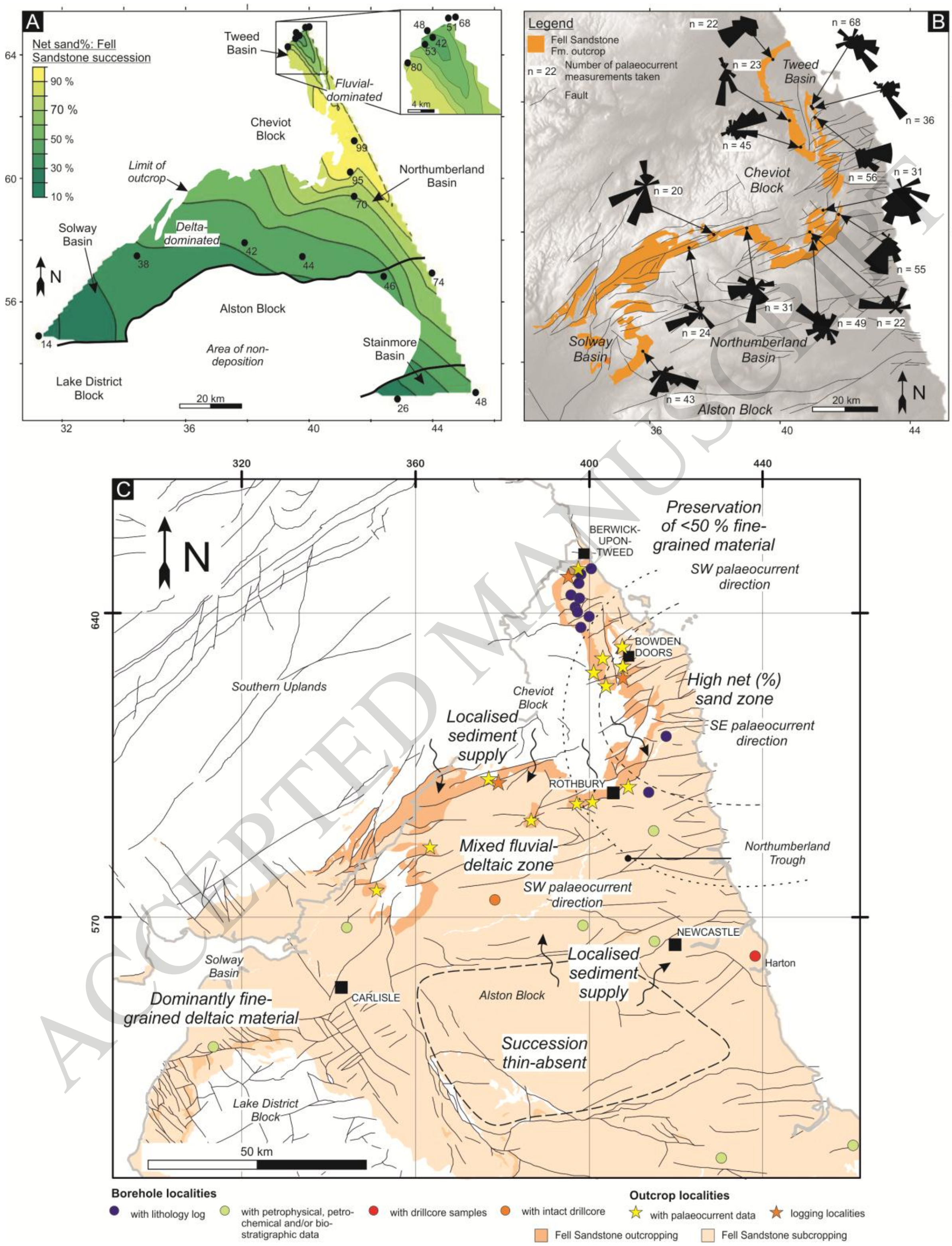

A
Net sand%: Fell Sandstone succession
90 %
70 %
50 %
30 %
10 %
Tweed Basin
Fluvial-dominated
Cheviot Block
Northumberland Basin
Limit of outcrop
Solway Basin
Delta-dominated
Alston Block
Area of non-deposition
Stainmore Basin
Lake District Block
20 km
4 km
N
B
Legend
Fell Sandstone Fm. outcrop
Number of palaeocurrent measurements taken
Fault
Tweed Basin
Cheviot Block
Solway Basin
Northumberland Basin
Alston Block
20 km
C
Preservation of <50 % fine-grained material
SW palaeocurrent direction
BERWICK-UPON-TWEED
BOWDEN DOORS
High net (%) sand zone
SE palaeocurrent direction
Southern Uplands
Cheviot Block
Localised sediment supply
ROTHBURY
Mixed fluvial-deltaic zone
SW palaeocurrent direction
Northumberland Trough
NEWCASTLE
Harton
Solway Basin
CARLISLE
Dominantly fine-grained deltaic material
Alston Block
Localised sediment supply
Succession thin-absent
Lake District Block
50 km
Borehole localities
with lithology log
with petrophysical, petro-chemical and/or bio-stratigraphic data
with drillcore samples
with intact drillcore
Outcrop localities
with palaeocurrent data
logging localities
Fell Sandstone outcropping
Fell Sandstone subcropping

Figure 11

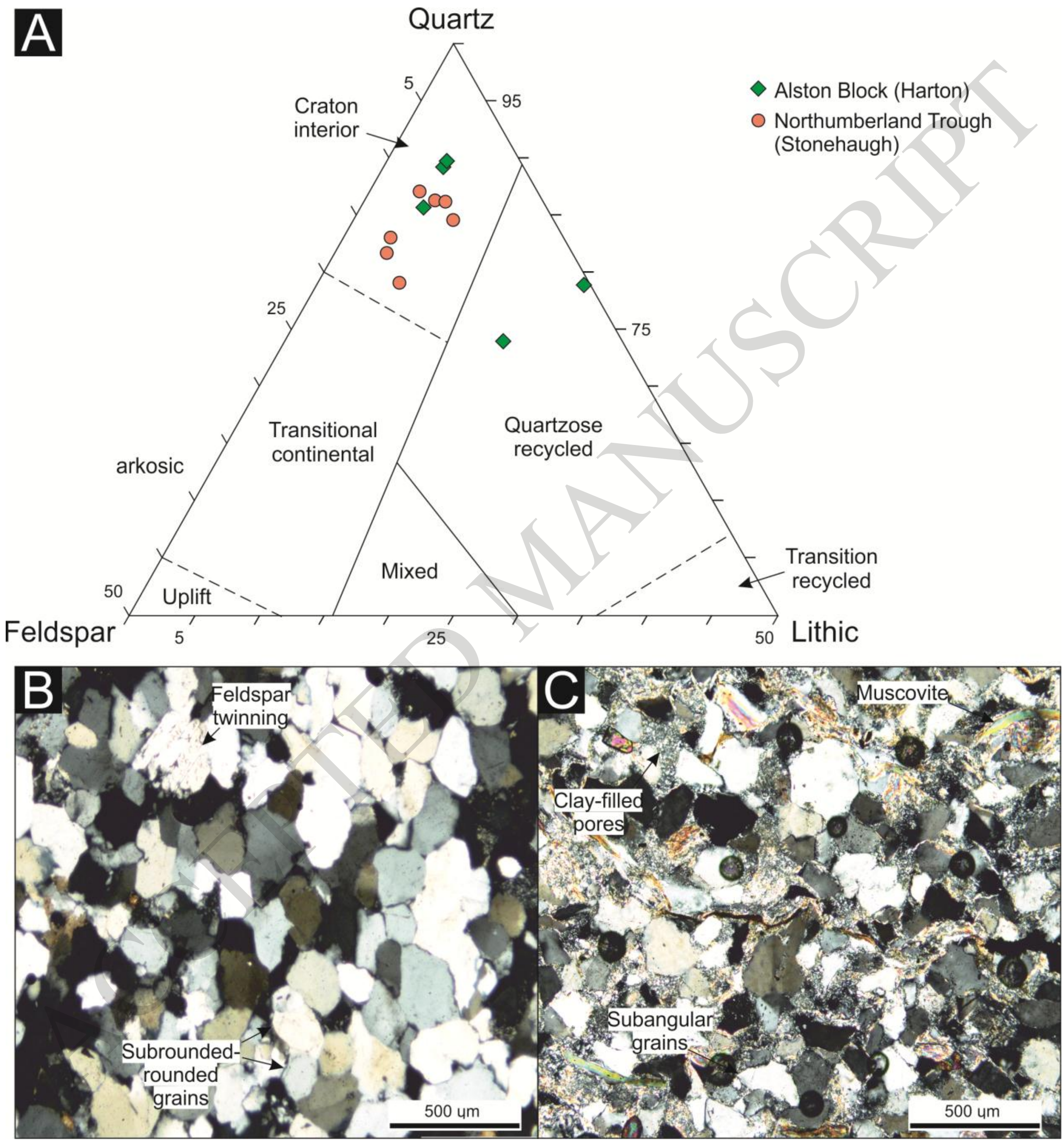

A
Quartz
Feldspar
Lithic
5
95
25
75
50
5
25
50
Craton interior
Transitional continental
Quartzose recycled
arkosic
Mixed
Uplift
Transition recycled
Alston Block (Harton)
Northumberland Trough (Stonehaugh)
B
Feldspar twinning
Subrounded-rounded grains
500 μm
C
Muscovite
Clay-filled pores
Subangular grains
500 μm

Figure 12

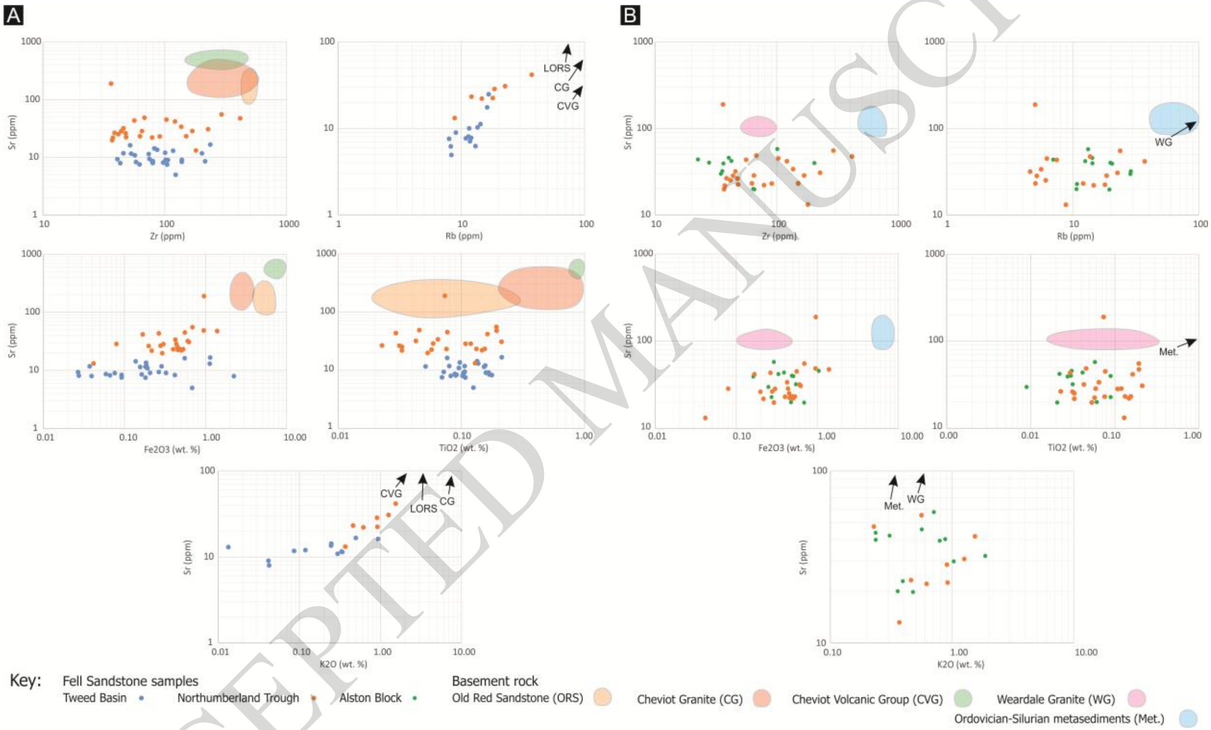
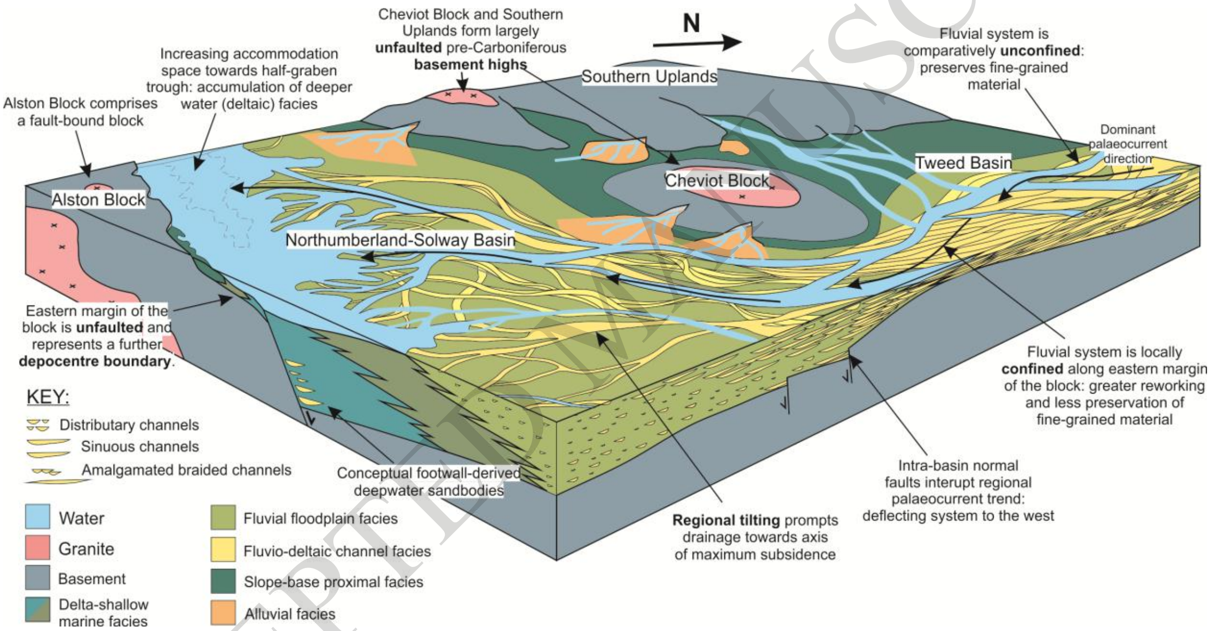
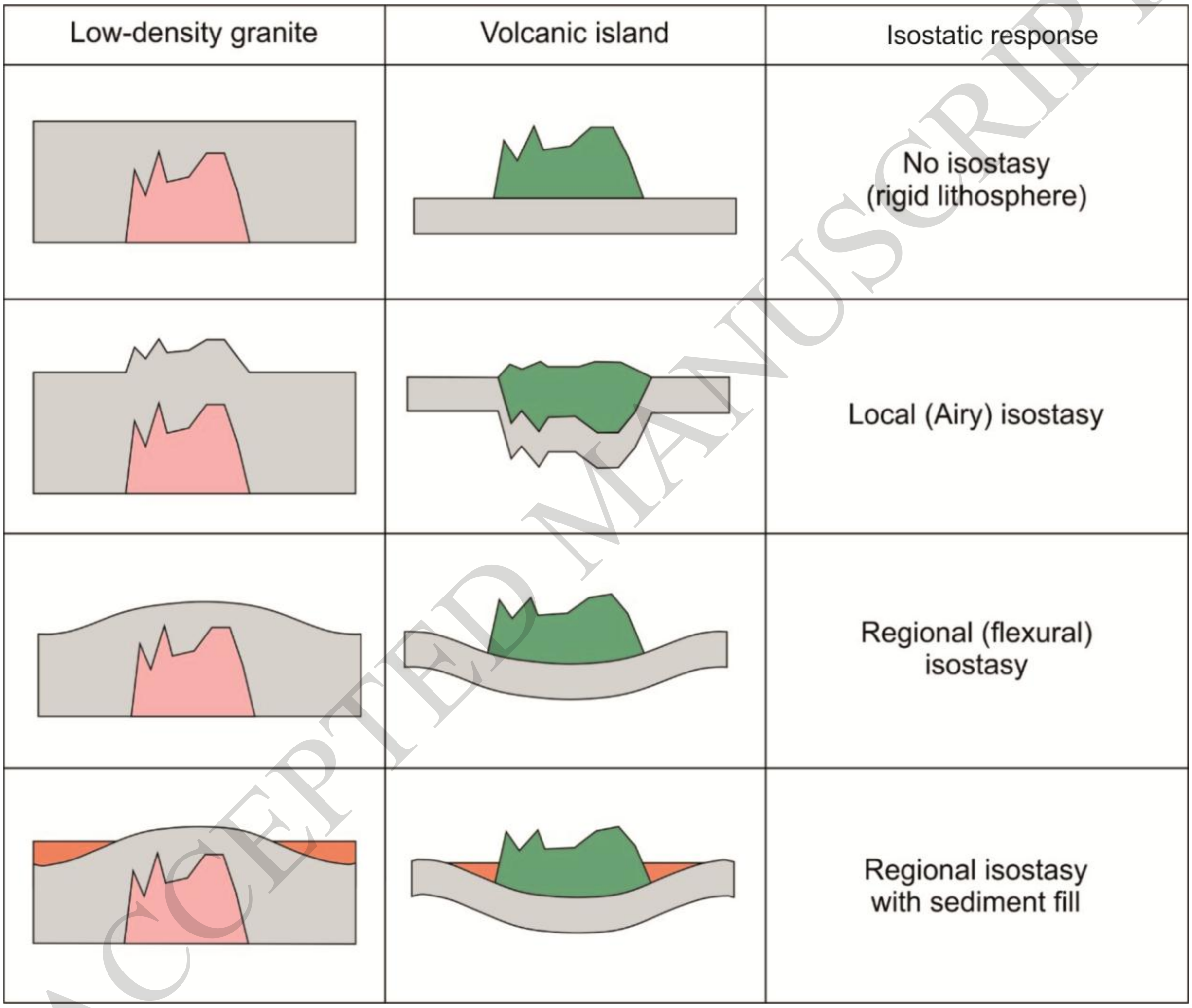

A
B
LORS
CG
CVG
WG
Met.
Sr (ppm)
Zr (ppm)
Rb (ppm)
Fe2O3 (wt. %)
TiO2 (wt. %)
K2O (wt. %)
Key:
Fell Sandstone samples
Tweed Basin
Northumberland Trough
Alston Block
Basement rock
Old Red Sandstone (ORS)
Cheviot Granite (CG)
Cheviot Volcanic Group (CVG)
Weardale Granite (WG)
Ordovician-Silurian metasediments (Met.)

Figure 13



Cheviot Block and Southern Uplands form largely **unfaulted** pre-Carboniferous **basement highs**
N
Fluvial system is comparatively **unconfined**: preserves fine-grained material
Increasing accommodation space towards half-graben trough: accumulation of deeper water (deltaic) facies
Alston Block comprises a fault-bound block
Southern Uplands
Dominant palaeocurrent direction
Tweed Basin
Cheviot Block
Alston Block
Northumberland-Solway Basin
Eastern margin of the block is **unfaulted** and represents a further **depocentre boundary**.
Fluvial system is locally **confined** along eastern margin of the block: greater reworking and less preservation of fine-grained material
KEY:
Distributary channels
Sinuous channels
Amalgamated braided channels
Conceptual footwall-derived deepwater sandbodies
Intra-basin normal faults interupt regional palaeocurrent trend: deflecting system to the west
Regional tilting prompts drainage towards axis of maximum subsidence
Water
Granite
Basement
Delta-shallow marine facies
Fluvial floodplain facies
Fluvio-deltaic channel facies
Slope-base proximal facies
Alluvial facies

Figure 14


Low-density granite
Volcanic island
Isostatic response
No isostasy
(rigid lithosphere)
Local (Airy) isostasy
Regional (flexural)
isostasy
Regional isostasy
with sediment fill