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Geological characterisation and cross-section study of the Fell Sandstone Formation in the Berwick-upon-Tweed area, Northumberland

Groundwater Science / Regional Geology Programme

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BRITISH GEOLOGICAL SURVEY

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Foreword

This report is a published product of a study completed by the British Geological Survey (BGS) on behalf of the Environment Agency (EA). The report describes the main outputs from a geological characterisation and cross-section study of the Carboniferous-age Fell Sandstone Formation in the Berwick-upon-Tweed area, Northumberland. As a principal aquifer, the Fell Sandstone Formation is used for small local, private supplies and for strategic drinking water supplies including the public supply for Berwick-upon-Tweed operated by Northumbrian Water Limited (NWL). The EA believes that the NWL licensed abstractions from the Fell Sandstone Formation may not be sustainable when assessed against Water Framework Directive targets for the water body. The aim of this study is to provide the EA and NWL with an improved geological understanding of the Fell Sandstone Formation for use in their ongoing investigations into the local hydrogeology.

Acknowledgements

This study considers a wide-range of data, maps, reports and drill-core made available by the EA and NWL. The authors would like to thank Melissa Swartz (EA) and Jeremy Dearlove (NWL) for granting access to these resources and for their support and constructive discussions throughout the project.

The authors would like to thank landowners in the study area for granting access to field localities in the study area.

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Executive Summary

The Carboniferous age Fell Sandstone Formation (henceforth referred to as the Fell Sandstone) forms a principal aquifer in Northern England. It comprises interbedded sandstone, siltstone and mudstone layers. Water abstracted from the sandstone layers provides drinking water for Berwick-upon-Tweed and the surrounding area. The Environment Agency (EA) believes that the licensed abstractions from the Fell Sandstone operated by Northumbrian Water Limited (NWL) may not be sustainable. Assessing the sustainability of the groundwater system requires a robust geological understanding.

Existing geological interpretations of the Fell Sandstone show contrasting numbers and geometries of sandstone layers. This study, commissioned by the EA, presents a revised geological interpretation of the Fell Sandstone and the overlying superficial deposits in Berwick-upon-Tweed and the surrounding area. An integrated and iterative approach has been used, combining borehole analysis, remote sensing and targeted geological fieldwork. The results of this study depict the sandstone layers within the Fell Sandstone as a series of schematic cross-sections and a revised 1:50,000-scale bedrock map. A locally-revised superficial map is also provided. These outputs are intended for use by the EA and NWL to support their hydrogeological investigations.

The revised interpretation of the Fell Sandstone shows a 225 to 350 m thick interbedded succession of mudstone-dominated and sandstone-dominated layers. Seven main (locally subdivided), and several lesser sandstone-dominated layers have been recognised in the cross-sections and inferred at the ground surface. Where possible, these layers have been traced across the study area and are depicted on the revised bedrock map. Numerous thin sandstone units occur within the mudstone-dominated layers. Similarly, the sandstone-dominated layers contain thin mudstone and siltstone units. For the purpose of this study, siltstones have generally been included in the mudstone-dominated layers. Overall, the proportion of mudstone- and sandstone-dominated layers is roughly even.

The Fell Sandstone dips towards the southeast across the south and central parts of the study area by about 10 degrees. In the north, the beds undergo a distinct steepening and assume a more easterly dip of about 15 to 25 degrees. The revised interpretation shows 2 *conjectural* geological faults in the south of the study area. It is likely that faulting of the succession is more widespread than the revised interpretation shows. Such faulting may result in the juxtaposition of different sand-dominated layers or introduce breaks in the continuity of the succession that could affect groundwater flow. Further evidence is required to confirm if additional structures are present.

This study presents a revised interpretation that is consistent with, as far as practicable, a range of data including borehole records, digital elevation models and recent & historical geological map data. Modern techniques have been used to interpret and integrate these datasets and ensure consistency between the cross-sections and geological map linework. However, it should be noted that the position of geological boundaries and the correlation between boreholes and across the study area remains uncertain. The Fell Sandstone is complex (in terms of the exact number, thickness, lateral extent and connectivity of sandstone layers, and faulting). The density and distribution of borehole data, and the limited extent of recent field mapping is insufficient to resolve this complexity with a high level of confidence.

To help reduce the uncertainty in the revised geological interpretation a series of recommendations are made: targeted drilling including the acquisition and detailed analysis of drill-core (sandstones and mudstones) to aid correlation and an improved understanding of sandstone connectivity across the study area; targeted geological mapping to validate the revised interpretation and gather additional geomorphological evidence to better-constrain the surface and subsurface expressions

and connections of the sandstones between boreholes; geological mapping in the northern part of the study area to test and improve the existing superficial geological mapping and support a refined understanding of recharge potential in the study area.

1 Introduction

The Carboniferous age Fell Sandstone forms a principal aquifer in Northern England where the formation is represented by a sequence of sandstones, siltstones and mudstones (Jones et al. 2000). Northumbrian Water Limited (NWL) abstract groundwater from various layers of the Fell Sandstone aquifer in order to provide drinking water to Berwick-upon-Tweed and the surrounding area (Dearlove, 2018). The Environment Agency (EA) believes that the NWL-licensed abstractions from the Fell Sandstone may not be sustainable when assessed against Water Framework Directive targets for the Fell Sandstone water body.

This report summarises a commissioned study carried out by the BGS on behalf of the EA to provide the EA and NWL with an improved 3D geological understanding of the Fell Sandstone for use in their ongoing investigations into the local hydrogeology. The principal outputs from the project are: a series of schematic cross-sections showing the distribution of sandstone layers in the Fell Sandstone; revised 1:50,000-scale geological linework for the Fell Sandstone and overlying superficial deposits; and, this brief summary report.

In the Berwick-upon-Tweed area the Fell Sandstone is described by Turner et al. (1993) as comprising 7 named (locally subdivided) and several unnamed sandstone layers. Existing 1:50,000-scale BGS geological maps of the area do not generally depict the individual sandstone layers, although locally up to 3 named sandstone members are shown. Geological interpretations provided by the EA show a complex arrangement of up to 10 sandstone layers. NWL mapping presents local revisions to the EA arrangement. The sub-surface geometry of the sand bodies is illustrated by cross-sections in several EA and NWL reports (e.g. Dearlove, 2018).

Although there is good agreement between these interpretations in some parts of the study area (notably in the central part of the study area where the sand layers are locally exposed), there exist considerable differences between the interpretations across much of the study area in terms of the number, position and geometry of the sand layers.

These differences are due several factors including: the relative timing of the studies (with respect to available data); the scope of the studies (ranging from research paper to strategic mapping); the scale of the studies (the EA interpretation being the most detailed at a scale of approximately 1:10,000-scale); and significantly, the inherent complexity of the sandstone layers coupled with sparse outcrop and extensive glacial deposits and sculpting that obscures much of the bedrock and its associated geomorphology.

This study builds on the existing work in the area. It combines remote sensing, targeted field mapping, and borehole correlation to synthesise these datasets provide a revised interpretation of the Fell Sandstone and overlying superficial deposits. The methods and results of this study are described in the following sections of this report.

2 Physiography

The study covers an area of approximately 40 km^2 that follows the Fell Sandstone outcrop from Berwick-upon-Tweed in the north to Felkington in the south (Figure 1; all figures are compiled at the back of this report). In the largely rural area to the south of Berwick-upon-Tweed, the principal land-cover types are arable and improved grassland. Ground elevations range from 0 mOD at the coast in the north to approximately 110 mOD inland (Figure 2). The landscape is characterised by well-developed west-northwest to east-southeast trending ridges and hollows (associated with glacial erosion, deposition of till, and ‘drumlinisation’), locally pronounced southwest to northeast trending escarpments (associated with sandstone and mudstone layers of contrasting hardness, for example at Murton High Craggs), and dissection of the escarpments by east-west, west-northwest to south-southeast, and southwest-northeast valleys. Notable flat-lying topographic depressions include Thornton Bogs in the centre of the study area. The landscape has been modified by a variety of anthropogenic processes including sandstone quarrying, the creation of embankments and cuttings for road and rail infrastructure, landscaping for building construction and agricultural reshaping of the near-surface (including prominent ‘ridge and furrow’ within parts of the study area).

3 Geological Setting

The Fell Sandstone of the Border Group is found in outcrop from Burnmouth, in Scotland, to the Solway basin in the west (Figure 3). In Northumberland the beds dip to the east and are known to extend offshore beneath the present area of the North Sea (Cameron 1993; Bruce and Stemmerik 2003; Kearsey *et al.* 2018, 2015).

The Carboniferous in the United Kingdom is defined by the opening of east-west seaways which cut east-west across the country (Arsenikos *et al.* 2015; Kearsey *et al.* 2018). The Fell Sandstone, which represents the genesis of a major delta fluvial system that probably originated in contemporary mountains situated to the north, spread coarse-grained sand in stacked, multi-storey sheets southwards (Figure 4). In north Northumberland, the sand sheets form sandstones that probably fill incised channels. As the sand sheets prograde southwestwards into the Northumberland Basin, the corresponding sandstones in the upper part of the formation are intercalated with marine siltstones (Turner *et al.* 1997).

The Fell Sandstone has been the subject of extensive sedimentological studies by Munro (1986), Turner and Monro (1987), Turner *et al.* (1993, 1997) and Martin and Turner (1998). These studies have focused predominantly on the sandstones, but have led to an advanced understanding of the local paleogeography of the Tweed and Northumberland basin. Less is known about the mudstone units, mostly because they seem to be localised to the area around Berwick-upon-Tweed (Turner *et al.* 1993). Near Berwick-upon-Tweed, the Fell Sandstone comprises of up to 50 – 60% mudstone, based on borehole data (Turner *et al.* 1993). Because outcrops are biased towards sandstone, studies based on outcrop alone may under-estimate the amount of mudstone by 20-30% (Turner *et al.* 1993). From Alnwick southwards, the Fell Sandstone becomes dominated by sandstone both at outrcop and at depth within boreholes (Turner *et al*. 1997).

The Fell Sandstone is underlain by the Ballagan Formation (previously referred to as 'cementstone') and overlain by the Scremerston Formation (Yoredale Group). The Ballagan Formation is defined as a succession of thin and thick localised sandstones, grey mudstones and siltstones, with nodules and beds of ferroan dolomite (cementstones). The lower boundary of the Fell Sandstone is locally unconformable and diachronous, marked by the incoming of Ballagan Formation cementstones. The upper boundary of the Fell Sandstone is described as an abrupt facies transition from massive sandstones to argillaceous 'coal measures' (BGS Lexicon). Within the study area, a clear distinction between the Fell Sandstone and adjacent units is only possible in isolated areas where detailed borehole descriptions exist.

Carboniferous rocks within this region occupy a broadly northeast-west trending fault-bound graben, bounded on the northern edge by the metamorphic rocks of the Southern Uplands and on the southern side by the volcanic igneous rocks of the Cheviot Hills. The Carboniferous rocks of the Tweed Basin form an open syncline about 20 km in width, the central axis of which dips to the east.

The near-surface unconsolidated cover, or superficial geology on the region is dominated by Devensian-age glaciogenic deposits including till and sand and gravel that are locally associated with an east to east-southeast flowing ice stream (Stone *et al.* 2010). The superficial geology of the study area broadly consists of: glacial till, forming semi-continuous sheets in the low-lying parts of the study area and irregular patches on the eastern side of topographic highs; patches of sand and gravel, closely associated with the till; 'head', or solifluction deposits forming ribbons between till deposits and areas of no superficial cover, especially in the south of the study area; river alluvium and accumulations of peat associated with the modern-day drainage system and topographic depressions, including the Thornton Bog area.

4 Geological Investigation

To investigate the geology of the study area the BGS digital survey workflow has been followed: (1) 3D virtual field reconnaissance and GIS-based remote sensing interpretation; (2) digital data capture of field observations; (3) 3D cross-section construction and GIS-based map compilation (Napier, 2011; Jordan and Napier, 2016; Hughes et. al 2017). This iterative approach has allowed a wide-range of existing subsurface and surface datasets and new observations to be integrated. These datasets and the resulting interpretations, comprising 8 schematic cross-sections (6 main sections pus 2 ancillary sections) and revised 1:50,000-scale geological map data are described below.

4.1 SPATIAL DATA

The principal spatial datasets considered in this study include:

Digital elevation models: NextMap (5 m cell-size) digital surface and digital terrain models; EA IHM 2017 2 m resolution digital terrain model (DTM); BGS Bald-Earth DTM (5 m cell-size);

Topographic data: various scales of modern Ordnance Survey data;

Digital aerial photography: sourced via the Pan Government Agreement;

Existing Geological map data: published BGS 1:50,000-scale digital geological map data;

Historical geological fieldslips: scanned and georectified BGS fieldslips related to the primary geological survey of the district dated 1890 - 1930;

Maps and reports provided by the EA and NWL: various geological map and cross-section interpretations for the Fell Sandstone;

Borehole data: borehole records obtained from the BGS National Geoscience Data centre, plus additional data supplied directly by the EA and NWL (Figure 1);

Recent geological field data: digital geological data acquired as part of this study in the southern part of the study area (indicated on Figure 9).

4.2 SUPERFICIAL DEPOSITS

A comprehensive review and revision of the superficial deposits in the study area is beyond the scope of this project. However, a limited (and largely remote) review of the superficial deposits has been completed as part of the baseline work. The existing BGS 1:50,000-scale superficial deposits map and the revised interpretation are shown in Figure 5 and Figure 6.

Minor revisions have been made to the existing 1:50,000-scale digital superficial deposits in the vicinity of the cross-sections. These revisions include changes to the extent of superficial deposits in areas where there is strong borehole evidence to suggest that either: (1) the extent of superficial deposits is greater than that shown by the existing map (i.e. where selected boreholes record superficial deposits where they are not currently mapped); or (2) the extent of superficial deposits is less than that shown by the existing map (i.e. where selected boreholes record bedrock at surface where superficial deposits are currently shown). In both cases, revisions to the geometry of the existing mapping have been made with reference to historical fieldslips and digital elevation data to ensure consistency with the original field evidence and modern topographic features.

The main changes (indicated on Figure 6) include relatively small modifications to the distribution of till and sand and gravel deposits. These changes ensure consistency in the immediate vicinity of the boreholes considered. However, a conservative approach has been taken when making these revisions and these areas have not been field-checked. A field survey in these areas may show that more widespread changes are possible (see ‘Recommendations’).

Note on the existing BGS 1:50,000-scale superficial deposits map

The revised superficial interpretation shown in Figure 6 is largely derived from GeologyGB50 (formerly DiGMap50), the current version of the dataset that was published in 2017. This version supersedes earlier versions and incorporates localised revisions to the superficial linework in the southern part of the study area (indicated on Figure 5). These revisions are based on BGS mapping undertaken around 2007 and include modifications to the extent and lithostratigraphical classification of superficial deposits. The 2007 mapping typically shows more extensive superficial cover than the previous mapping, including the occurrence of head. Whilst the pre-2007 mapping of superficial deposits in the northern part of the study area is considered to be broadly accurate, further mapping may reveal more extensive and varied superficial deposits than are currently mapped.

It should be noted that the "Fell Sandstone Risk Hydrodomain Map" supplied by the EA to BGS for the purpose of this study appears to predate the current version of DigMap50 (see 'Recommendations').

4.3 BEDROCK AND STRUCTURE

4.3.1 Revised 1:50,000-scale geological linework

The existing BGS 1:50,000-scale bedrock map and structure map and the revised interpretation are shown in Figure 7 and Figure 8. Revisions in the study area are concentrated on the Fell Sandstone. Existing 1:50,000-scale map data for adjacent formations has been merged with the revised interpretation for context. A comparison between the revised interpretation and the existing EA interpretation and subsequent NWL modifications are shown in Figure 10 and Figure 11.

The BGS revised interpretation differentiates the Fell Sandstone on lithological grounds into: sandstone-dominated layers (digitally attributed: "Fell Sandstone Formation – Sandstone, Siltstone and Mudstone") and mudstone-dominated layers ("Fell Sandstone Formation – Mudstone, Siltstone and Sandstone"). The composite lithology attributes reflect the lithological generalisation that has been necessary to accommodate minor variation in the succession that cannot be spatially resolved at 1:50,000-scale.

The sandstone units have been interpreted on the basis of the spatial data described above. In areas of superficial cover, the interpretation is primarily based on the projection of subsurface data. Here, the level of confidence in the interpretation drops rapidly with increasing distance from the boreholes and cross-sections. Where superficial cover is thin or absent, greater use of remote geomorphological analysis has been possible. Where this coincides with recent mapping and borehole data, the relative confidence in the bedrock interpretation is relatively high.

The revised interpretation incudes up to 7 main sandstone layers (plus subdivisions thereof). These layers are not formally designated as lithostratigraphical units. However, for the purposes of this study a tentative relationship with the stratigraphical framework of Turner et al. (1993) has been suggested (Table 1), using the 'Equivalent' suffix to indicate the tentative nature of the correlation.

The main sandstone layers include: laterally persistent units (e.g. the Murton Craggs and part of the Peele Knowe equivalents) and, units that fail within the study area (e.g. the Murton Dean and parts of the Peel Knowe equivalents). Based on borehole evidence, the main sandstones are shown to include mudstone partings (e.g. to the southeast of Murton) and individual sandstone layers are shown to conflate (e.g. around Thornton). As such, the number and thickness of the main sandstone layers varies across the study area.

These factors affect the confidence with which correlation can be made. Further investigation may prove that the lateral extent of the sandstone layers is different from that shown. It is likely that additional evidence will reveal considerably more complexity and less lateral continuity than the revised interpretation shows. Notable areas of high uncertainty in the revised interpretation include (see Figure 9):

1) north of Shoreswood, where borehole evidence indicates that the Murton Craggs Equivalent (that elsewhere maintains a relatively consistent thickness) changes in thickness by about 30 m across the conjectural fault;

2) south of Newburn towards the conjectural fault, where there exists little constraining data;

3) between Allerdean and Thornton Bog where borehole evidence indicates the conflation of the Murton Craggs and South Ord equivalents, termination of the Murton Dean Equivalent and conflation of the Upper and Middle Peal Knowe equivalents;

4) Berwick-upon-Tweed, where the available data suggests considerable local complexity (potentially related to faulting) that has not been possible to resolve on the basis of the available data (see 'Recommendations').

In addition to the main sandstone layers, a number of short, laterally impersistent sandstone layers are shown in the revised 1:50,000-scale bedrock linework. Where sandstone layers are shown to taper to points (e.g. in Berwick-upon-Tweed in the northwest part of cross-section 5), this generally indicates that their lateral continuity is constrained by borehole or geomorphological evidence. Where sandstone layers are laterally-terminated by flat ends (rather than tapering to points; e.g. to the west of Murton Craggy Bog), no evidence exists to suggest their termination and insufficient evidence is available to allow these layers to be traced with sufficient confidence for any greater distance. These layers may terminate locally or may continue beyond their mapped extents, potentially connecting with other sandstone layers. However, it is likely that the laterally-adjacent areas of mudstone include sandstone layers that are not included in the revised interpretation. This is exemplified in Berwick-upon-Tweed area where a high density of detailed borehole data records numerous small sandstone bodies within the lower mudstone-dominated parts of the succession – this may be representative of the succession in other parts of the study area where equivalent data does not exist.

Further details on the sedimentology of the sandstones and mudstones and are given in report section 4.3.4.

Localised revisions have been made to the boundaries between the Fell Sandstone and the Scremerston and Ballagan formations. These boundaries are generally derived from the existing 1:50,000 scale map data and corresponding 1:10,560-scale historical fieldslips. Field evidence to support these interpretations is sparse and the boundaries are inferred. Localised revisions have been made to ensure consistency with available borehole data (for example, to accommodate the Scremerston Formation where boreholes record distinctive 'coal measures' lithologies), to maintain lateral continuity of the Fell Sandstone interpretation based on the cross-sections and outcrop data (for example, to accommodate an appropriate thickness of the Scremerston Formation and continuity of sandstone layers within the formation) and, to honour the geomorphological interpretation (to ensure appropriate topographic intersections).

To the west of Berwick-upon-Tweed along cross-section 5 (see below), the revised interpretation includes a localised sub-division of the upper part of the Ballagan Formation into sandstone- and mudstone-dominated layers. This area corresponds with a cluster of boreholes that are interpreted to intersect the Scremerston-Ballagan boundary. The boundary has been placed at the top of a thick sandstone-dominated layer that is assumed to be part of the Ballagan Formation. However, it should be noted that the borehole data in this area does not provide strong evidence (e.g. reference to 'cementstone') to support this interpretation; the sandstone layer may be a basal unit of the Fell Sandstone that has incised the underlying Ballagan Formation.

Faulting is shown in the south of the study area. These structures are *conjectural*, and are described in more detail in the report section 4.3.5.

4.3.2 Schematic Cross-Sections

Using available data eight schematic cross-sections have been created that provide context on the possible geometries of the various sandstone and mudstone units that comprise the Fell Sandstone. Of these cross-sections, six are orientated in a broadly perpendicular to the strike direction (cross-sections 001 – 004 and 005) and two are orientated in a more strike-parallel orientation (cross-sections 004a and L1).

Cross-sections 1 to 5, excluding 001a and 004a are drawn to start within the underlying Ballagan Formation and extend through the complete succession of the Fell Sandstone into the overlying Scremerston Formation. Sections 001a and 004a do not show the complete Fell Sandstone succession and were constructed as ancillary cross-sections to aid in the geological line work correlation exercise.

Section L1 is the longest section, drawn to the south of the Fell Sandstone outcrop in order for it to include the entire succession.

4.3.3 Methodology

The following sub-sections provide an overview of the creation of the cross-section. For ease communication the various stages of the process are outlined below, and a numbering systems shows the individual steps involved.

4.3.3.1 Borehole selection and coding

1. A defined area of interest (AOI) was created in collaboration with the EA
2. BGS-held borehole datasets were integrated and records occurring within the AOI or within 1 km of it were retrieved from the BGS National Geoscience Data Centre collection.
3. Of the 355 boreholes within or adjacent to the AOI, those with drilled lengths less 5 m were excluded (leaving 175).
4. The remaining 175 boreholes were preferentially coded, with deeper boreholes and those in more isolated areas being coded first. Coding of the boreholes recorded as much sedimentological information (grainsize, composition texture, structure etc.) as possible to aid subsequent correlation.
5. A larger number of shallower boreholes (drilled depths 10 – 5 m) in the relatively densely cored region at Berwick-upon-Tweed town were excluded for reasons of expediency.
6. A number of EA and NWL borehole logs sets were ingested, that provided either completely new data points (completely borehole records) or added further useful detail to existing BGS-held records.
7. A phase of dialogue between BGS and the EA ensured that borehole locations and names were consistent, in cases where differences were apparent between EA-provided data and existing BGS records.
8. Of the initial 355 boreholes records, 83 have been used in the construction of the schematic cross-sections and revised 1:50,000-scale geological linework.

4.3.3.2 Schematic Cross-section creation

The schematic cross-sections were created using BGS in-house software 'Groundhog' using a Bald Earth digital elevation model (DEM) as the capping surface. Information of the software's capabilities and function can be found on the BGS website.

(https://www.bgs.ac.uk/research/environmentalModelling/groundhogDesktop.html).

1. The placement of the cross-sections was highly-constrained in the eastern parts of the AOI, with available isolated boreholes providing the individual 'point's upon which the cross-section lines were drawn. In general, cross-sections 001 to 005 were drawn in dip-parallel

(strike perpendicular) orientations. It should be noted that the orientation of the individual segments within each cross-section lead to sudden changes in the apparent dip of the units; this is a function of the two-dimensional representation (cross-section) of three-dimensional objects (the drawn geological units).

2. Where individual cross-sections (001 to 005) did not fully include the full thickness of the Fell Sandstone, they were extended to include the full thickness of the Fell Sandstone, with the exception of section 001, where the AOI boundary starts within the Fell Sandstone.
3. Cross-section L1, situated south of the Fell Sandstone outcrop, was drawn in a strike-parallel orientation incorporating the full thickness of the Fell Sandstone.
4. Two additional ancillary cross-sections (001a and 004a) were created in order to aid in the resolution of geologically-complex parts of the AOI.
5. Using the coded boreholes situated along the individual cross-section, correlations were made between boreholes. The resultant geometries, for individual sandstone and mudstone layers, combined with a regional understanding of the dip of the Fell Sandstone, enabled the projection of these individual sandstone and mudstone units to the ground surface or the base of superficial deposits.
6. These projected surfaces were used to create a derived geological linework along each cross-section. This derived linework was imported into the project geographic information system and tested against other available data sets outlined in section 4.1.
7. This testing highlighted areas of agreement/disagreement with the drawn cross-section geometries of individual sandstone and mudstone units in each cross-section. This was used to amend (where necessary) the surface position of the various units and re-calculate individual geometries for the sandstone and mudstones.
8. Steps six and seven were iterated as the surface linework progressed and the lateral continuity/discontinuity of individual sandstones and mudstones was constrained.

4.3.3.3 Schematic Cross-Section Results & Uncertainty

It should be noted that the architecture and arrangement of the sandstone and mudstone units in the cross-sections is one of multiple possible ‘models’ that could fit the available data. The paucity of data has created significant areas of uncertainty, notably when moving even modest distances away from borehole data or surface linework (mapped geological boundaries). There is uncertainty relating to the lateral continuity of sandstone and mudstone units in sections where they layers are not constrained by borehole data, for example the deeper (older) sandstones and mudstone layers in cross-section 001 are not penetrated by any of the boreholes upon which the section is constructed. In this example, the placement of the units is reliant on the surface linework and expectations of lateral continuity from neighbouring cross-sections where these units are better constrained.

The relative levels of uncertainty in the cross-section interpretations is indicated in Figure 20 to Figure 27.

4.3.3.4 Sandstone Thickness variations

The sandstones drawn within the cross-sections are all shown to have variable thicknesses across the AOI. This is most notable for the relatively thicker sandstone units (Murton Dean and Peel Knowe equivalents). There are a number of potential reasons for the thickness variations observed, these could include:

1. <u>Differences in sandstone thicknesses related to the depositional environment</u>. The sandstones in the Fell Sandstone were deposited in a fluvial to deltaic setting, in broad large erosively-based valleys. The geometry of these sandstones is assumed to conform to

standard rules such that sandstones deposited at the margins of these large valley systems are likely to be thinner than those deposited towards the centre of valley system.

2. Variations in apparent thickness. While regionally the Fell Sandstone possesses a broadly south-easterly dip at 8-12º, folding at Berwick-upon-Tweed town has had the effect of considerably steepening the bedding. Any vertical drilled boreholes intersecting these steeper inclined units would record anomalously thick sandstones and mudstones potentially, miss-construing the drilled [apparent] thickness with the 'true' thickness of the unit.
3. Conflation of sand bodies. The variable thickness of interleaving mudstones separating sandstone units provides supporting evidence for discrete sandstone joining and providing hydro-connectivity. The sandstones units where deposited in a series of incised valley fill successions that responded to variations in sea-level during their deposition. This created sandstone units that are directly overlying erosive surfaces. It is likely that the deposition of subsequent erosively based sandstone units locally removed the interleaving mudstones. The south-easterly parts of cross-section 002 show a very thin interleaving mudstone between the South Ord and Murton Craggs sandstone equivalents. Directly northeast of section 002, geological evidence suggests that the South Ord sandstone equivalent completely removes this mudstone shown in the section and overlies directly the Murton Craggs sandstone equivalent.
4. The sandstones and mudstone layers shown within the cross-sections are considered to be primarily composed of sandstone and mudstone respectively, but borehole data and outcrop studies indicate that they are not entirely composed of homogeneous sandstone or mudstone entirely. It is expected that relatively thin lenses of mudstone or sandstones (<3 m) might occur sporadically within any part of the section. Additionally, borehole records indicate relatively heterogeneous successions of 'muddy sandstone' and 'sandy mudstone'.

4.3.4 Sedimentological Observations

4.3.4.1 Sandstones

Collectively, units within the Fell Sandstone were deposited within a fluvial-deltaic setting, with the sandstone units representing the higher energy deposits (compared to the mudstone) generated within the river channels and on the delta itself. The mudstones within the Fell Sandstone are the product of either floodplain deposition (associated with the channel sandstones) or were laid-down within marine environments. Relatively little work has been conducted to discriminate between these two types of mudstone, though the ability to do so could allow for more accurate sub-dividivision and correlation of the Fell Sandstone.

Limited surface outcrop examples in the region show that the sandstones are commonly medium- to coarse-grained, moderately rounded, moderately sorted and ubiquitously cross-bedded. Though crossbedding is very common, the scale and type of crossbedding could potentially be used as a framework for sub-division of the various sandstone units; though this would require a detailed and large data set to establish. Crossbedding in the sandstones was created primarily by the downstream migration of various sized subaqueous sand dunes. Theses sand dunes migrated down river (in the palaeo-drainage direction) and as a result of the rate of sediment supply within the system, were able to be preserved as stacked successions of crossbedded lithofacies. The size of the crossbedding sets is controlled primarily by the maximum depth of water in which the sand dunes were deposited. Though not certain, thicker sandbodies (e.g. Murton Craggs & Pell Knowe equivalents) are more likely to contain well-developed and thicker crossbedded units. Large-scale crossbeds (>2 m thick, for instance) could be used to inform the identification and correlation of thicker sand units, or possibly, to distinguish thinner sand units in which well-developed, and thicker cross-bedding may be less likely (e.g. South Ord, Thornton Park equivalents etc).

At a larger-scale, the separation of the succession into predominately mudstone- and sandstone-dominated layers (e.g. Table 1) is likely driven by cyclical changes in the sea-level during the deposition of the Fell Sandstone (e.g. Turner et al., 1997). The start of the deposition of the sandstones (their base) likely represent periods of relative sea-level low, whereby the rivers of the Fell Sandstone flowed out over the continental shelf for greater distances to reach the ocean into which they drained. The fall in relative sea-level would have also had the effect of causing the fluvial system to incise and erode underlying material. Some of the mudstones (the lateral more persistent interleaving mudstones between the sandstones; Table 1) are likely to be of marine origin and record periods of higher sea-levels, whereby sea water would have inundated or drowned areas previously occupied by the fluvio-deltaic systems. Repetitions and cycles of sea-level rise and fall are ultimately responsible for the gross-scale geometry of the succession. It is important to note as previously stated, that the sandstone units overlie erosion (incision) surfaces, and locally could completely remove the interleaving mudstones to deposit directly onto other sands units; this could have the effect of creating hydro-conductivity between various sandstone layers. Such erosion could feasibly occur between any of the sandstones and might occur as regionally recognised juxtaposition of sandbodies or as minor local-scale connectivity.

A number of field sedimentary logs were taken at the available outcrops in the region (Murton High Craggs and two localities in Shoreswood; Quarry and field cutting). The sedimentary logs are presented in Figure 21. These sedimentary logs were taken to identify the sedimentological architecture of the exposed sandstones. Interestingly, the Murton High Craggs and Shoreswood Quarry sedimentary logs show a remarkably similar succession and lithofacies ordering. The similarities provide a point of evidence to these two outcrops belonging to the same named sandstone equivalent. The thicker succession at Murton high Craggs and the inclusion of small pebbles in the ‘trough crossbedded coset’ lithofacies (c.f. the Shoreswood Quarry log), is interpreted as reflecting more central and marginal channel locations respectively. A central channel location is likely to contain deeper and faster flowing water allowing the lithofacies to be thicker and contain higher energy deposits (e.g. including pebbles). Channel marginal settings are generally in shallower and quieter water, though still subject to the same general conditions to the related central channel position.

The presence of a laterally extensive (>40 m) highly-deformed horizon of crossbedded sandstones at Murton High Craggs (shown on the log as seismite unit, 7.9 – 9.3 m), is interpreted as a ‘seismite’. Seismites are ‘normal’ deposits which have deformed by local- to regional-scale tectonic event(s) that cause ‘slumping’ in the non-lithified (loose sediment) deposits. If these are facies are seismites, the tectonism occurred during the deposition of the Murton Craggs Sandstone and was geologically instantaneous as the underlying and overlying lithofacies are not deformed. A similar smaller-scale deformed unit was recorded at Shoreswood Quarry. This deformed unit, also interpreted as a seismite, occurs at the top of the same lithofacies succession identified at Murton Craggs. Given the identification of the same lithofacies order, it is interpreted that these two units are in fact the same, and are time and lateral equivalents. It is important to note that whilst seismites have potential correlatable utility, that similar seismites may occur elsewhere in the succession. The two locations (Murton High Craggs and Shoreswood) are situated ~4 km apart, suggesting that if they are lateral equivalents, that the tectonism was at least sufficiently vigorous to impact at a minimum on this broad distance.

Table 1 - Generalised succession of the main sandstone layers shown in the study area; thin, laterally impersistent sandstone units not shown

BGS Revised interpretation (Tentative correlation with Turner et al. 1993 where appropriate)			**Comments**
		Scremerston Formation	
Fell Sandstone Formation		Mudstone	Locally absent
		South Ord equivalent	10-15 m thick. Locally absent
		Mudstone (locally absent)	Locally absent. Not present just east of Thornton.
		Murton Craggs equivalent; includes mudstone partings	Relatively thickness variations from 20 – 50 m. NB. Inferred considerable thickness change around Shoreswood is poorly constrained. Directly underlies South Ord equivalent in places.
		Mudstone	Relatively persistent.
		Murton Dean equivalent	5-20 m. Poorly constrained and possibly absent in the south of the study area
		Mudstone	Relatively variable thickness, 5-15 m?
	Peel Knowe equivalent (undivided)	Peel Knowe equivalent upper leaf	10-20 m Present in the central part of the study area.
		Mudstone	Highly variable unit. Appears to form as both interleaving mudstone between upper and middle Peel Knowe leaf equivalents and also as isolated mudstone lenses within the Peel Knowe where the leafs conflate.
		Peel Knowe equivalent middle leaf	Thickness is hard to define (up to 40m?), as it appear to merge with lower Peel Knowe leaf frequently.
		Mudstone	Highly variable unit. Appears to form as both interleaving mudstone between upper and middle Peel Knowe leaf equivalents and also as isolated mudstone lenses within the Peel Knowe where the leafs conflate.
		Peel Knowe equivalent lower leaf; includes mudstone partings	Likely the thinnest of the Peel Knowe leafs; thickness (5-15m? Conflates with lower leaf in the southern part of the study area
		Mudstone	Absent in the southern part of the study area
		Middle Ord equivalent	5-10 m thick. Recognised in the central and northern parts of the study area
		Mudstone	Relatively lateral persistent mudstone unit. Thickness likely >15 m
		Royalty Sandstone equivalent	Recognised in the southern part of the study area Thickness varies up to about 20 m
		Mudstone	Relatively lateral persistent mudstone unit. Thickness about 15 m
		Thornton Park equivalent	Very poorly constrained, with little borehole evidence. Thickness ~10m? Recognised in the central and northern parts of the study area
		Mudstone	Relatively lateral persistent mudstone unit. Thickness likely at least 10 m
		Ballagan Formation	

4.3.4.2 MUDSTONES

The mudstone units have not been observed in outcrop but have been identified in borehole logs and core. We had the opportunity to examine an interval from Murton Craggy Bogs Observation Borehole 1 (Figure 28). This revealed that much of the mudstone represents stacked palaeosols (fossilized Carboniferous soil profiles). These are dark reddish brown mudstones with no evidence of internal lamination and often exhibiting yellow mottles and faint bluish grey streaks (Plate 1). The reddening indicates the palaeosols were not waterlogged when formed. These mudstones were originally deposited as siltstones in fluvial overbank floods (floodplain deposits) on the Carboniferous river flood plain. Subsequent and repeated colonization by plants and the formation of palaeosols altered the silt to mud.

As previously mentioned, some of the mudstone units were formed in a marine environment. The interval between 38 – 44 m in the Murton Craggy Bogs Observation Borehole 1 contains units with climbing or symmetrical ripples and intense bioturbation (trace fossils resulting from the action of plants and animals). In-situ bio-activity in an “optimum” environment for life to survive – deposition below water, in an oxygen-rich water column, likely within the photic zone. Unlike the palaeosols, these units were probably deposited in a large standing body of water, such as a lake or lagoon. The level of bioturbation suggests that this was most likely to have a marine connection. The interbedding and overprinting of the bioturbated intervals and the palaeosol suggests that, in this interval, the rocks were deposited at the very edge of a water body.

Marine influenced sediments are specific horizons that can form during periods of high sea-level where marine water inundates up river systems and creates estuarine sediments further inland. These sediments can contain diagnostic microfossils. The time-gap between marine floods can be sufficiently great that the animals and plants ‘brought in’ by successive floods have evolved and bear recognisable differences to those brought in the previous marine events. As such, the identification of the zonal microfossils within these bands has good correlatable ability and if present in the succession may allow the identification of valuable marker horizons for regional correlation. It is important to note that sandstone layers are often laterally impersistent and can show similar bulk sedimentological characteristics. By contrast, marine flooding sediments (if present in the Fell Sandstone succession) may be laterally more persistent and present diagnostic microfossil content, overcoming some of the challenges of correlation based only on sandstone layers. If marine bands are present then given that the mudstones in the region are not exposed, it is likely that their identification could only occur within cored boreholes.

4.3.5 Structure

At a regional-scale, the study area is located on the northern limb of an easterly-plunging, west-east trending syncline. This regional structure is bounded to the south by the fault-bounded Cheviot Block and to the north by outcrops of Lower Palaeozoic strata. At a local scale, the southeasterly regional dip is affected by smaller-scale folds and inflexions that are generally fault-bounded. In the north of the study area, the area around Berwick-upon-Tweed is affected by a pronounced rotation towards an easterly-dip and steepening of the bedding (responsible for the apparent thinning of the Fell Sandstone at outcrop in the northern part of the study area). The hinge of this asymmetrical fold is oriented approximately northwest-southeast. It is likely that this fold is associated with fracturing and faulting, including structures that are not currently shown on the 1:50,000-scale map and have not been resolvable through this study (see ‘Recommendations’).

4.3.6 Bedding Orientation

The paucity of outcrop in the study area means that dip measurements are sparse, often clustered and preferentially reported for the sandstone layers. However, outcrop patterns, recent field measurements and historical field data show that the Fell Sandstone generally dips towards the southeast, turning east around Berwick-upon-Tweed across a distinctly asymmetrical southeast-plunging anticline.

Due to the well-developed cross-bedding in the sandstone layers, reliable dip measurements of the sandstone layers are difficult to acquire. The wide-range of values that are reported on historical fieldslips may reflect 'apparent dips' of inclined bedforms (especially in the southern and central areas where dip measurements range from 5 degrees to 25 degrees are reported). Notwithstanding this, local variation in bedding orientation may be due to the steepening of beds adjacent to faults, although this relationship has not been directly observed in the study area.

For the purpose of this study, including construction of the revised geological linework and schematic cross-sections, a tectonic dip in the order of 8 to 12 degrees has been used to the south of Berwick-upon-Tweed. In association with the fold in the Berwick-upon-Tweed area, tectonic dips in the range of 15 to 25 degrees have been used. These values are based on a combination of evidence, including: selected dip values shown on historical maps, field measurements acquired as part of this study and geometries resulting from the correlation of distinctive horizons between boreholes.

4.3.7 Faulting

Existing 1:50,000-scale geological maps show considerable faulting to the east of the study area within the Scremerston Formation and succeeding parts of the Yoredale Group. Mapped faults are generally oriented west-east to northwest-southeast and exhibit throws of several tens of metres. Only 2 faults are shown to affect the Fell Sandstone or the Ballagan Formation within the study area (Figure 7). This apparent difference in fault-density may be due to the relative lack of observable evidence to support faulting in the Fell Sandstone and Ballagan Formation when compared to the overlying succession including the coal-bearing Scremerston Formation. It is assumed that mine-plan data and more detailed mapping has resulted in a greater number of faults being recognised.

The revised interpretation shows 2 faults in the south of the study area (Figure 8). They have been inferred from recent geological mapping, the geometric reconstruction of the succession based on borehole data and topographic evidence. In both cases, the faults has been informed by existing geological interpretations and extended to join previously mapped structures in the Scremerston Formation.

The west-east trending Shoreswood Fault is inferred to have a downthrow to the north of approximately 40 m. In the revised interpretation this fault is shown to cross the entire Fell Sandstone outcrop. The constraining evidence for this fault is limited. This structure has been included to accommodate local changes in the elevation of the Fell-Scremerston boundary as interpreted from outcrop and borehole data and outcrop.

The west-northwest to east-southeast tending Bleak Ridge Fault is inferred to have a downthrow to the north of up to approximately 20 m on the eastern side of the Fell Sandstone outcrop. Recent geomorphological mapping suggests that this fault fails within the Fell Sandstone succession to the west.

It should be noted that whilst this fault interpretation reflects the available evidence, alternative interpretations are possible including solutions that reposition or remove these faults. Consequently, a low level of confidence should be placed on these *conjectural* faults until further evidence arises to confirm their presence and position.

No faults have been interpreted in the central and northern parts of the study area. Here, although borehole data is generally more abundant and the bedrock geomorphology locally well-developed, insufficient evidence is available to confidently infer or rule-out further faulting. There remains a significant possibility that the succession in this area is affected by (currently unmapped) faulting. Faulting with throws of several metres to several tens of metres could be accommodated in alternative interpretations. Indeed, faulting may explain some of the contrasting geological information that is recorded in closely-spaced boreholes, for example in Berwick-upon-Tweed. Although no faults are shown in this area, numerous small-scale structures are visible in aerial photography to the north along the coast. It should be expected that similar structures may affect the Fell Sandstone within the study area. Faulting may explain some of the apparent truncation of sandstone layers along strike (e.g. in the centre of the study area between Thornton Bog and Allerdean). If present, these faults may juxtapose sandstone-layers and mudstone-layers or juxtapose stratigraphically different sandstone layers.

5 Assumptions and Limitations

In common with geological maps and models in general, the principal outputs from this study are interpretative. Whilst best practice has been followed and a wide-range of new and existing data has been considered, it has been necessary to make certain assumptions in the construction of the revised geological linework and cross-sections. The main assumptions and corresponding limitations (where appropriate) are summarised below:

- **Field mapping:** the fieldwork undertaken as part of this study was limited to: mapping in the southern part of the study area around Grievestead and Shoresdean and, section logging at key localities in the central part of the study area. Field data in these areas has been used to inform the current study and contribute to a more confident interpretation. Elsewhere in the study area, the revised interpretation is based solely on a desk study and carries a lower confidence.
- **Revised superficial interpretation:** the revised superficial deposits map is largely based on existing 1:50,000-scale map data. Localised revisions have been made in proximity to the cross-sections where there are disagreements between borehole data the existing interpretation (assumed to pre-date the boreholes). These disagreements (and a comparison between historical BGS mapping and revisions from 2007 in the south of the study area) indicate the potential for further changes to the interpretation in northern parts of the study area. These potential changes may affect the present understanding of the recharge potential of the Fell Sandstone.
- **Tectonic dips:** a wide range of tectonic dips are reported on historical maps for the study area. Generalised dips have been used for the purpose of this study. This may result in the underrepresentation of localised structural disturbance including potential folding and faulting. The use of alternative dips would support different correlation between boreholes, different thickness determinations and result in different outcrop patterns from those presented in the revised interpretation.
- **Fault interpretation:** due to the general paucity of constraining data, a confident interpretation of faults has not been possible. The 2 faults that have been interpreted within the study area should be considered as *conjectural* features. It is highly likely that the revised interpretation underrepresents faulting in the Fell Sandstone. Additional faults, if present, may offset sandstone and mudstone layers and affect the lateral hydraulic continuity and connectivity of the succession.
- **Correlation:** a 'geological-best-fit' approach has been used to construct the cross-sections and revised geological map. Factors such as sedimentological controls on the likely thickness and lateral continuity of the succession, local and regional structural styles, 3D relationships between adjacent data, cross-sections and the landscape have been used to inform the interpretation. However, it should be noted that alternative interpretations are possible where the available evidence still does not support the confident correlation between adjacent boreholes. In general, the lateral continuity of sandstone layers in the cross-sections and the map data is uncertain.
- **Formation boundaries:** where possible, the position of the upper or lower boundary of the Fell sandstone has been taken on the basis of lithological changes in boreholes, field data or topographic changes. However, in large parts of the study area the evidence, including borehole data, is insufficient to confidently distinguish between the Fell Sandstone and adjacent formations. Consequently, and in order to achieve general agreement with surrounding data, it has been necessary at a local level to place formation boundaries between essentially similar lithologies as presented in borehole logs. The Fell Sandstone (aquifer) may be more-or less extensive than shown in the revised interpretation.

- **Borehole selection:** where closely-spaced borehole records have different depths (and similar geological descriptions), deeper records have been preferentially included in the interpretation.
- **Conflicting data:** where closely-spaced borehole records present contrasting geological descriptions, it has been necessary to preferentially select one record for the interpretation and exclude others. Selection criteria include prioritising: modern records that include more detailed observations; and, selecting records that show similar geological successions to adjacent data. Consequently, some borehole records that may indicate potentially significant geological complexity (sedimentological or structural), are not honoured in the interpretation. Therefore, the resulting interpretation may underestimate the local geological complexity (notably in the Berwick-upon-Tweed area).

6 Recommendations

Although this study has considered a large body of data and research for the Fell Sandstone and associated geology, a number of uncertainties remain. These may be significant in terms of the conceptual understanding of the Fell Sandstone groundwater system. The following recommendations are designed to reduce the outstanding geological uncertainty, address some of the limitations described above, and enable an improved hydrogeological understanding:

- **Targeted drilling including the acquisition and detailed analysis of drill-core.** Acquisition of additional cored boreholes in some key areas of uncertainty (southern and central parts of the AOI) will help test the revised interpretation and supplement the local/regional geological and hydrogeological understanding. The sandstone layers as the water-bearing units, have been the obvious focus for studies in the area, however it is likely that useful information can be gained from the mudstone present in the succession.
  It is recommended new cored drilling be conducted in the areas of uncertainty, and in addition to hydrogeological property measurement this should be accompanied by detailed sedimentological logging and facies analysis (including trace fossils) on both the sandstone and mudstones of the Fell succession. Ideally, cored material should be held in appropriate core facilitates or as a minimum should be high-resolution photographed prior to disposal or degradation.
- **Targeted geological mapping (bedrock emphasis).** Rapid initial field-mapping was essential in providing the evidence for the re-drawing of bedrock linework. Further such targeted and in areas of uncertainty will likely provide greater confidence and more precise surface and subsurface interpretation.
- **Resolve bedrock complexity in the Berwick-upon-Tweed.** Borehole data in Berwick-upon-Tweed indicates a high level of sedimentological/stratigraphical and structural complexity, possibly due in part to proximity to local folding. This assumption is supported by the level of structural complexity that is locally exposed on the nearby coast. A confident interpretation of the bedrock in this area has not been possible with the available data. A more confident interpretation may be achieved through a combination of targeted drilling and mapping, detailed logging and re-interpretation of in the context of existing data. An alternative/complementary approach to aid conceptualisation and numerical groundwater modelling may be to develop a *representative understanding* of local structure and sedimentology by undertaking a detailed study of an equivalent geological 'domain' at the coast and transposing model into the Berwick-upon-Tweed area. The latter approach would not resolve the local complexity *per se*, but would provide a more confident understanding of the likely style and frequency of structures in the area and the potential for fracture-related pathways and breaks in the succession.
- **Targeted geological mapping (superficial emphasis).** Borehole coding as part of this project has indicated that in the southern part of the study area suggests superficial deposits are more extensive and varied than earlier mapping indicates. The current superficial linework in the northern part of the study area is based on earlier mapping. Modern mapping and integrated 3D geological modelling (combining high-resolution DEM data, borehole records and targeted field mapping) could result in an improved spatial understanding of the superficial geology across the study area. An assessment of the significance of superficial deposits and potential benefits of improving their mapping is recommended.
- **Update Fell Sandstone Risk Hydrodomain Map based on latest superficial geological linework**. The EA's current Fell Sandstone Risk Hydrodomain Map is based on a set of geological linework that has since been updated in the southern part of the study. An assessment of the significance of these changes and the benefit of updating the Risk Hydrodomain Map is recommended.

- **BGS Borehole and EA records.** Efforts should be made to ensure that borehole naming is consistent between the BGS and EA. This project has highlighted naming differences between records held separately by BGS and the EA. Further work in the area should aim to resolve this issue, likely via the EA confirming preferences for naming of the boreholes with the amendments updated in BGS corporate data sets.

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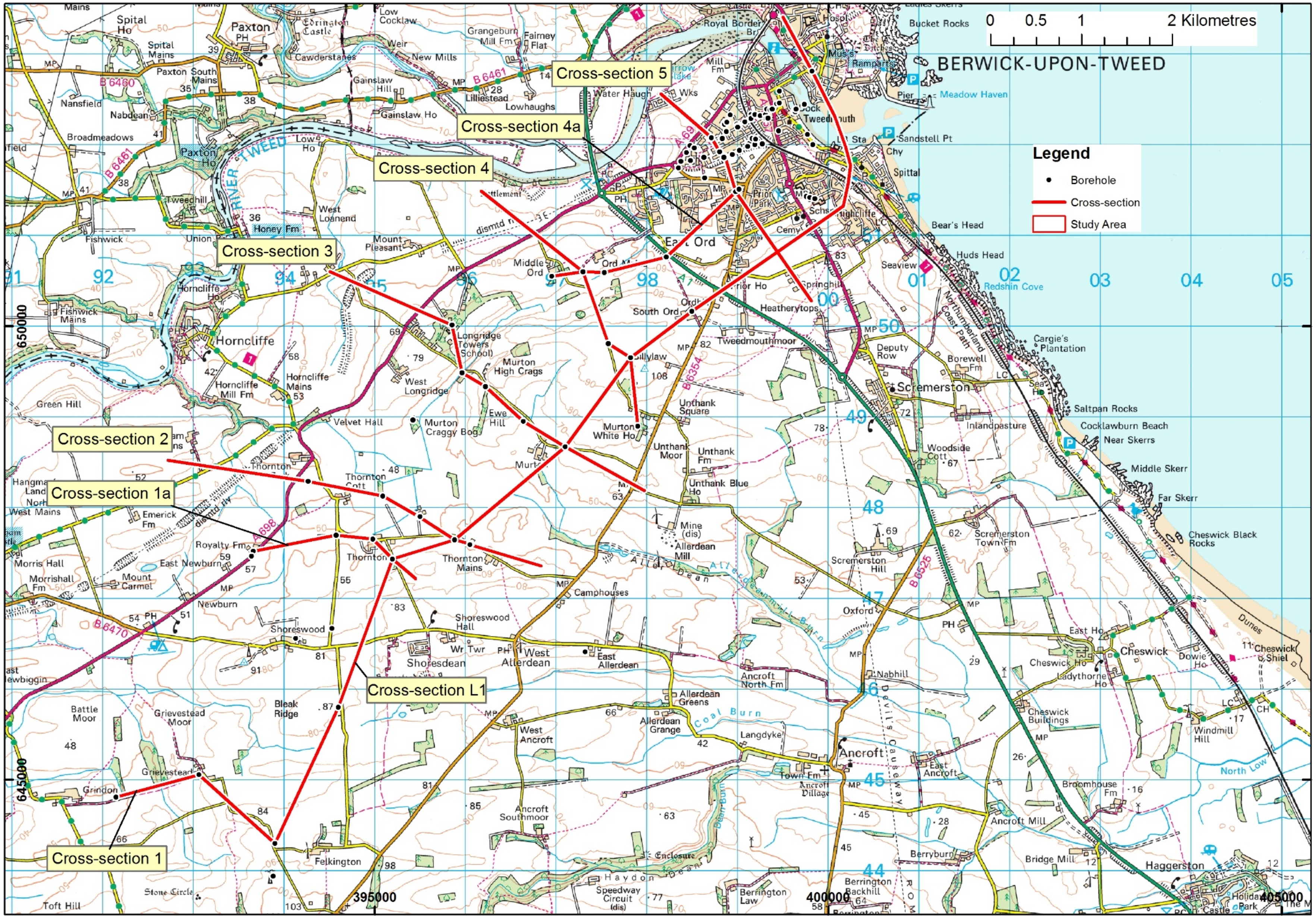

Figure 1 - 1:50,000-scale topographic map showing the study area, cross-section alignment and selected borehole locations. Contains Ordnance Data © Crown Copyright and database rights 2019. Ordnance Survey Licence no. 100021290.

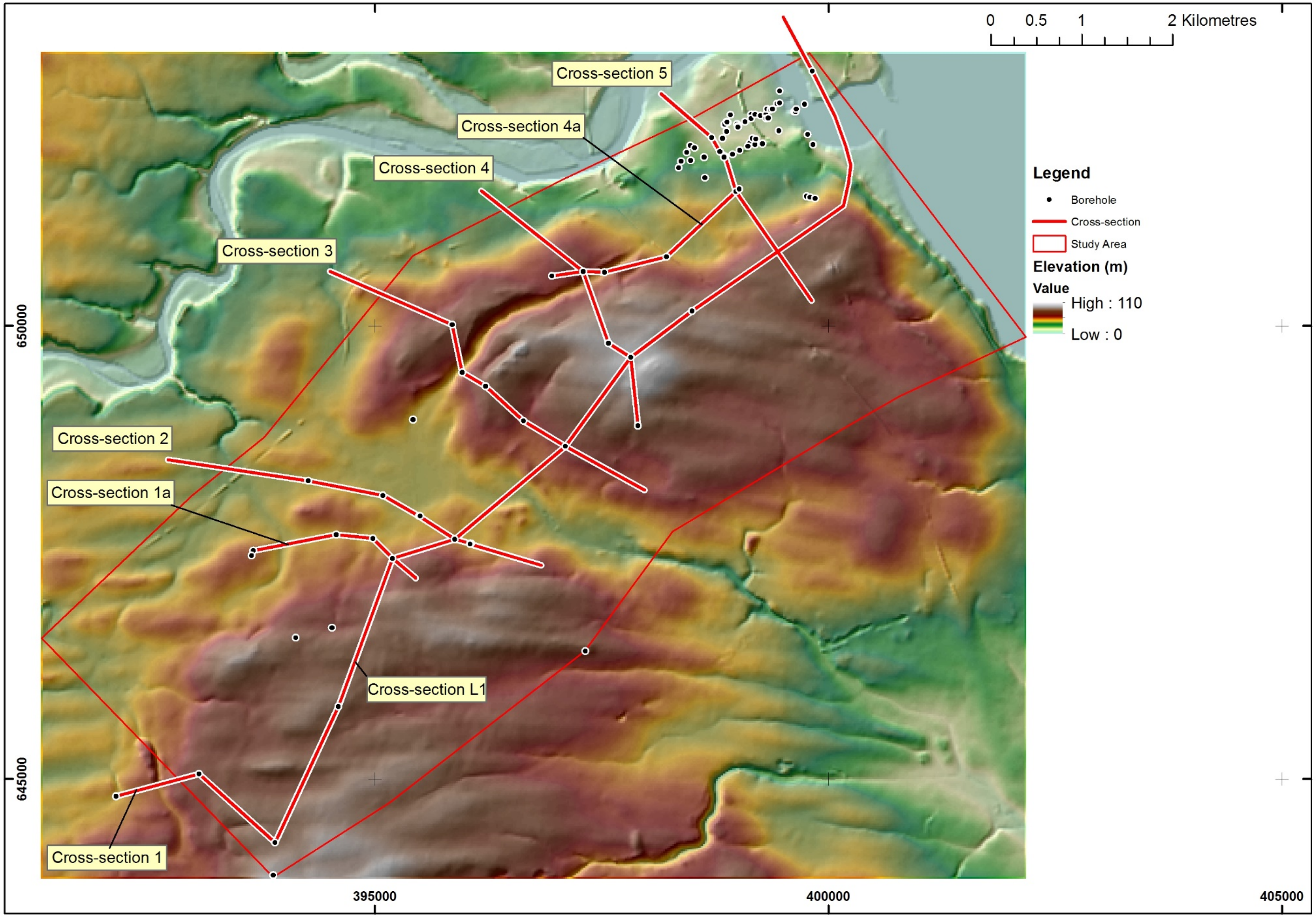

Figure 2 - DTM for the study area based on 5 m resolution NextMap data subsampled to 20 m courtesy of Intermap Technologies. Colour-ramp elevation (metres) and hillshade applied to accentuate principal landforms, including superficial and bedrock features. Cross-sections and selected boreholes shown for reference.

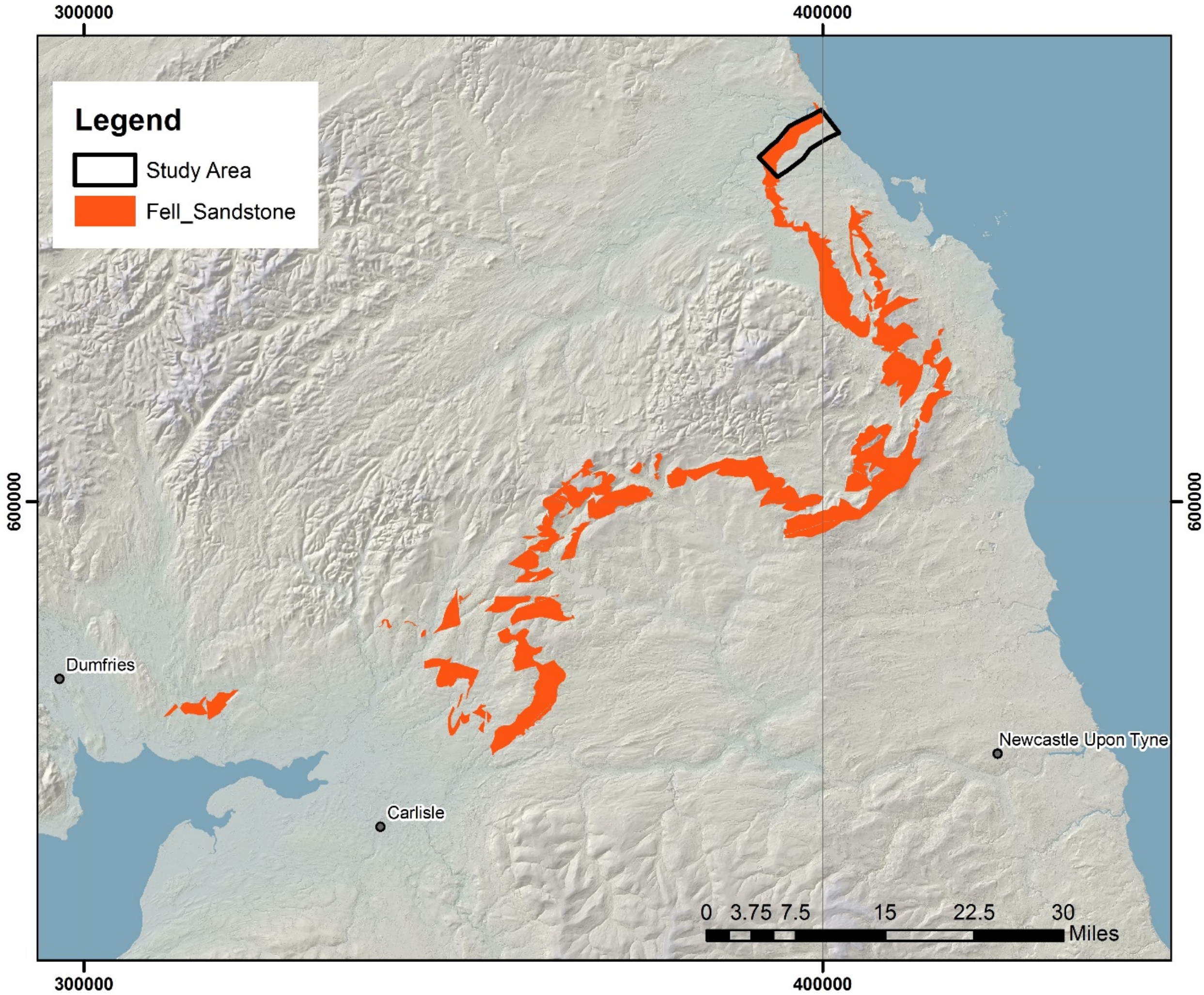

Figure 3 - Map showing the areas where the Fell Sandstone is found at surface. In Northumberland the beds dip generally to the East and are known to continue out under the North Sea. Hillshaded DTM courtesy of Intermap Technologies. Geological data British Geological Survey © UKRI 2019.

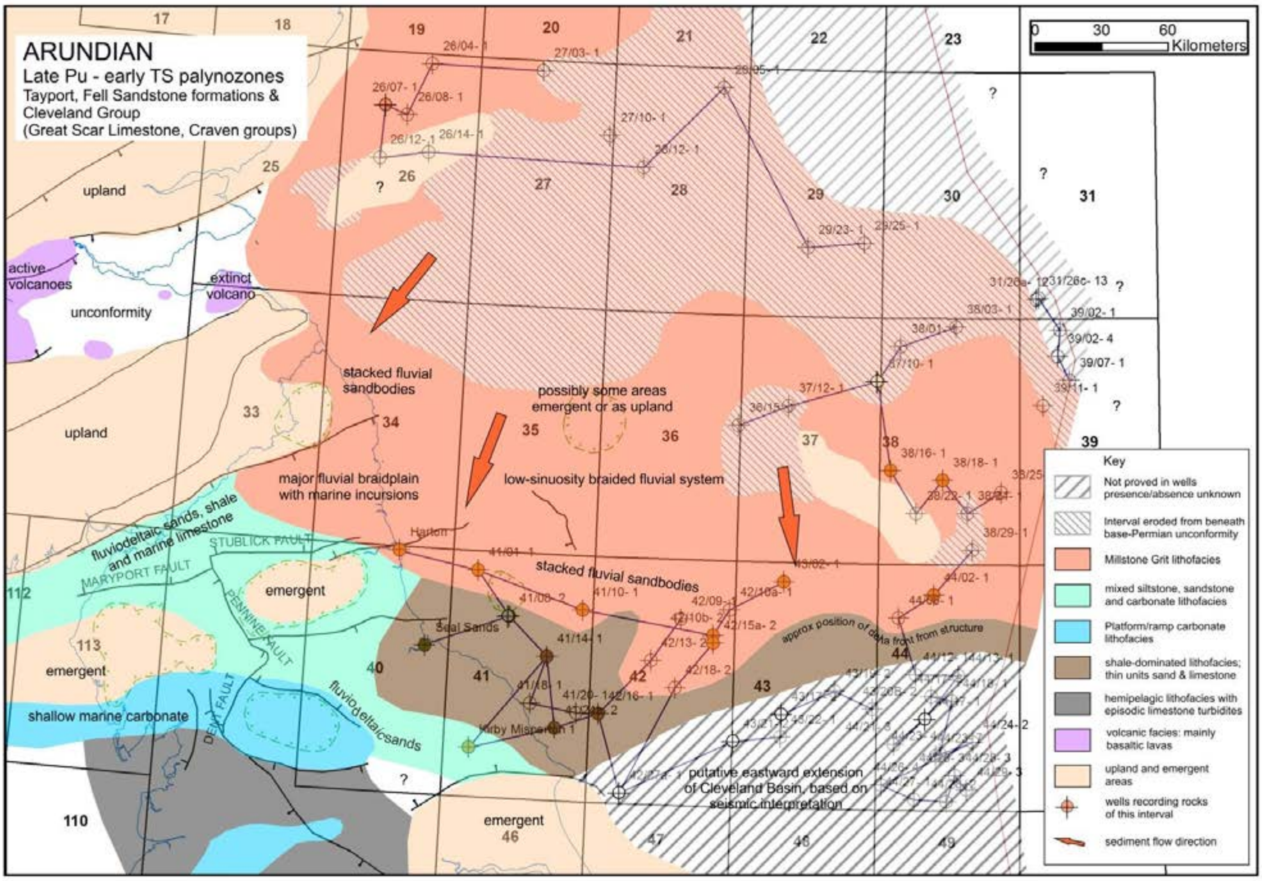

Figure 4 - The palaeography of the UK and central North Sea at the time when the Fell Sandstone was deposited. The Fell Sandstone around Berwick-Upon-Tweed was the edge of a vast delta system which covered much of the area now represented by the North Sea, from Kearsey *et al.* 2015.

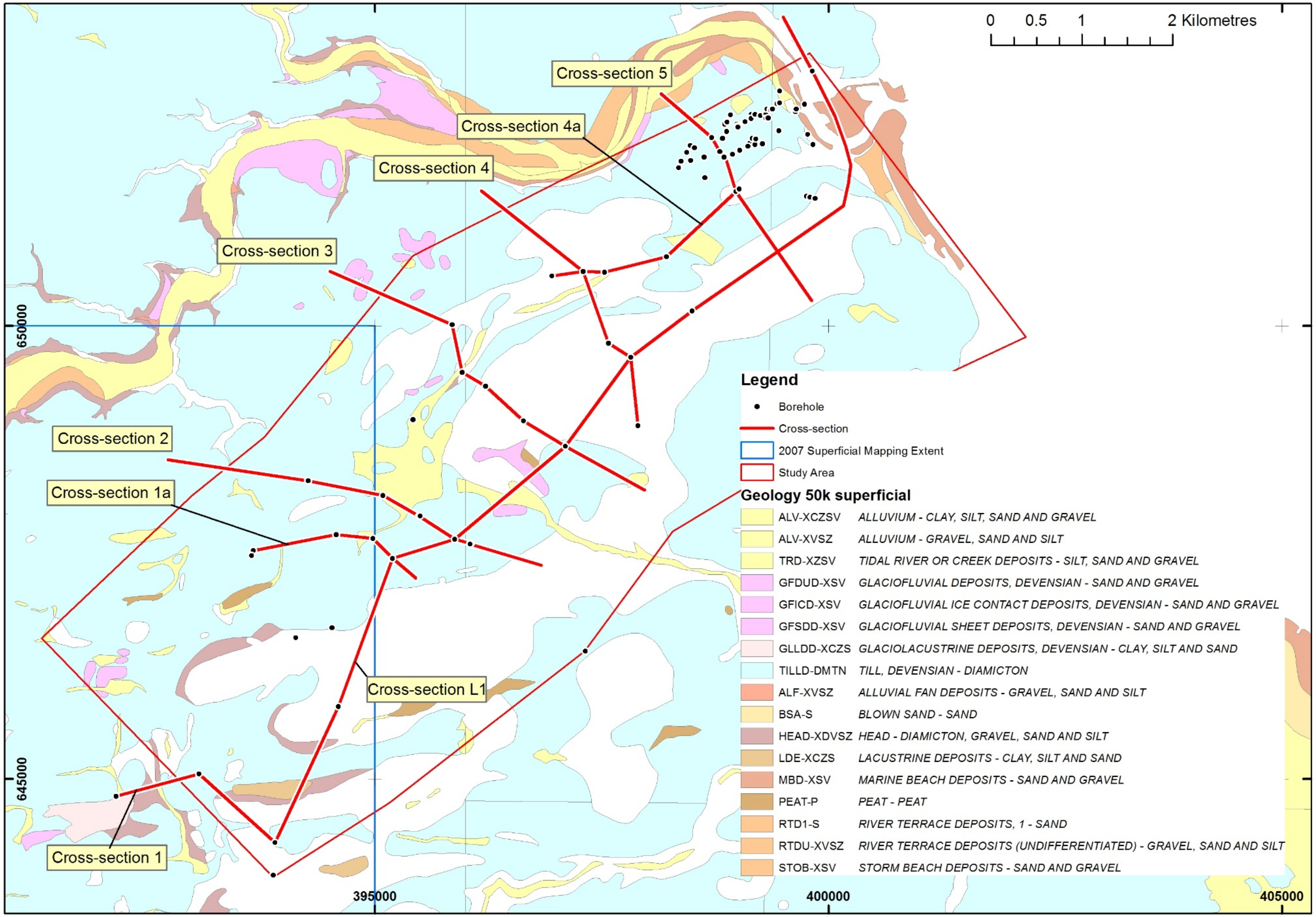

Figure 5 – Existing 'BGS Geology 50k' superficial deposits map data. See the digital data for differentiation of similarly-coloured deposits. "2007 Superficial Mapping Extent" refers to the area to the southwest of the blue outline. Geological data British Geological Survey © UKRI 2019.

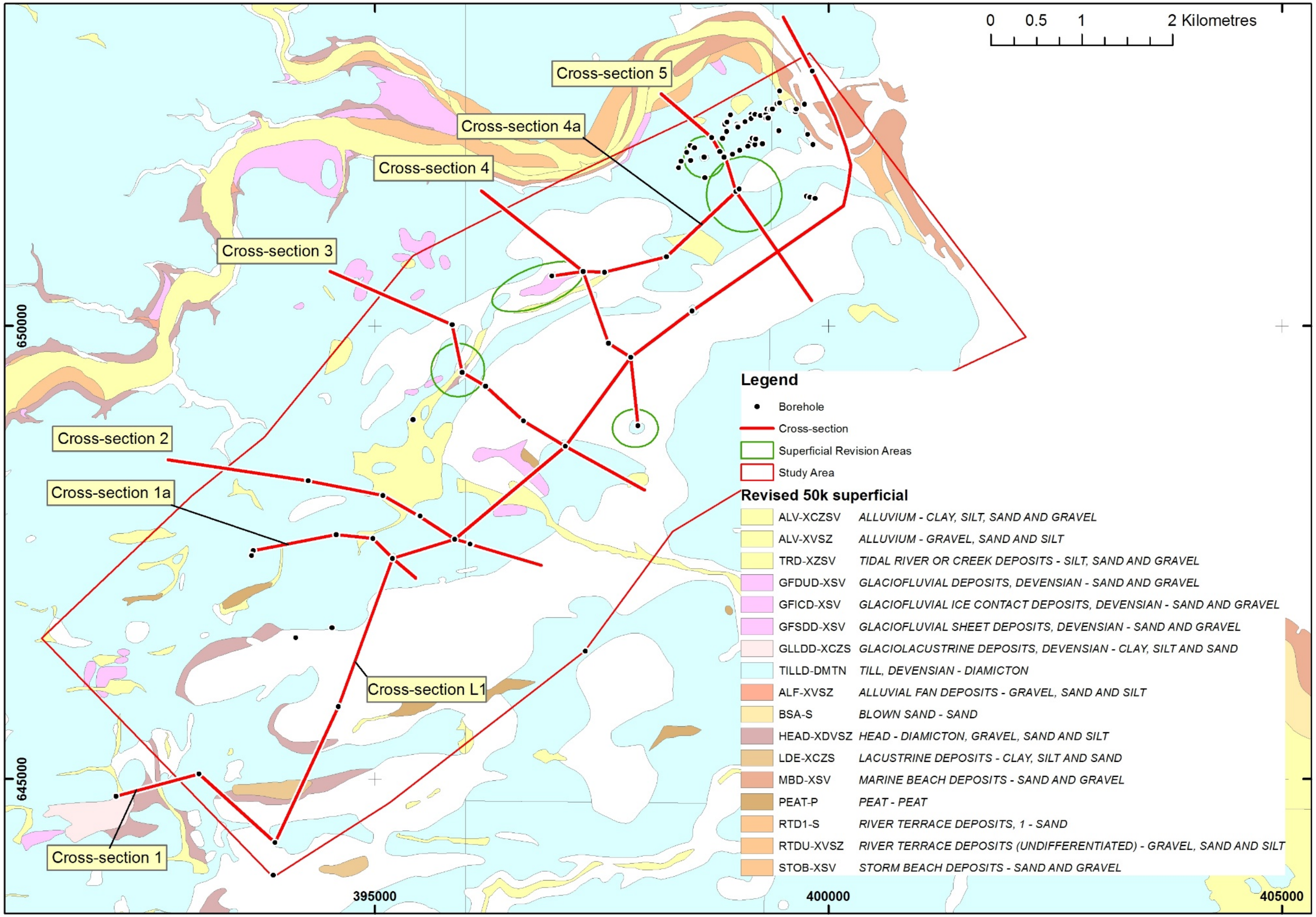

Figure 6 – Revised 1:50,000-scale superficial deposits map data. See the digital data for differentiation of similarly-coloured deposits. Geological data British Geological Survey © UKRI 2019.

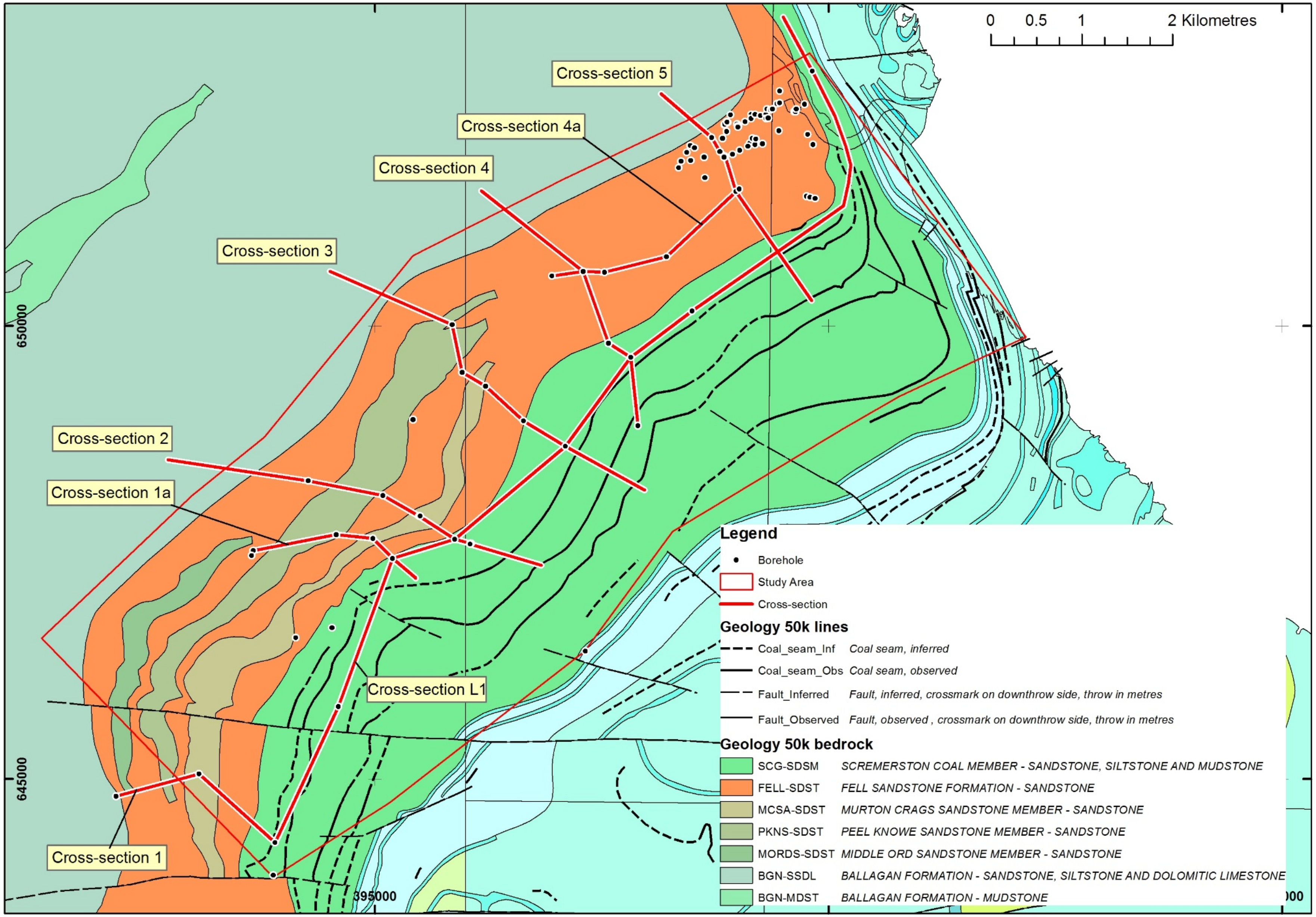

Figure 7 – Existing BGS digital 1:50,000-scale bedrock geology map of the Fell Sandstone and adjacent strata. See the digital data for attribution of the units not represeented in the legend. Geological data British Geological Survey © UKRI 2019.

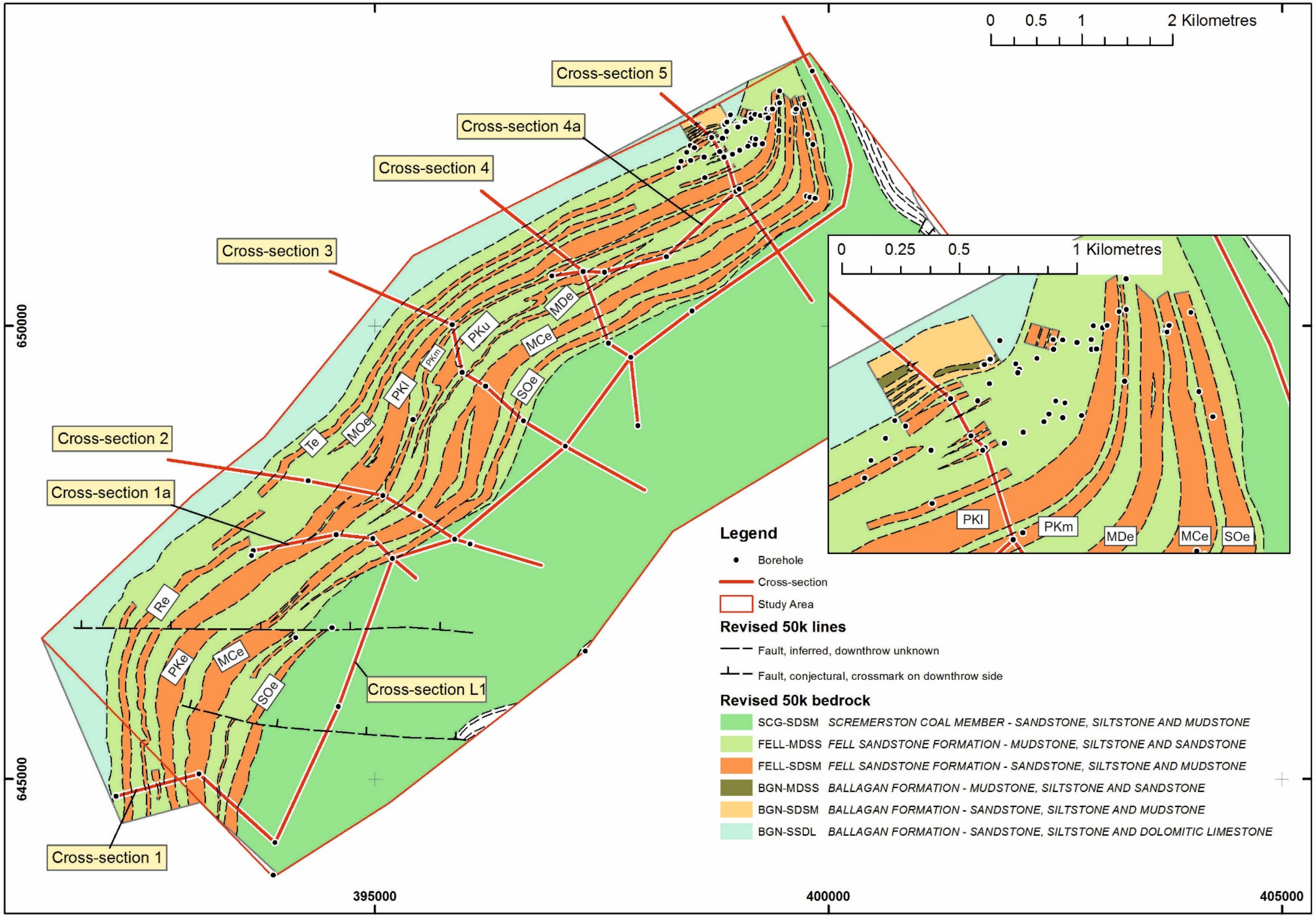

Figure 8 - Revised 1:50,000-scale bedrock geology map of the Fell Sandstone and adjacent strata. Inset map shows the area around Berwick-upon-Tweed in greater detail. Te – Thornton Park equiv., Re – Royalty equiv., MOe – Middle Ord equiv., PKl, PKm, PKu – Peel Knowe equiv. lower, middle, upper leaf, MDe – Murton Dean equiv., MCe – Murton Claggs equiv., SOe – South Ord equiv. See the digital data for attribution of the (uncoloured) units not represeented in the legend. Geological data British Geological Survey © UKRI 2019.

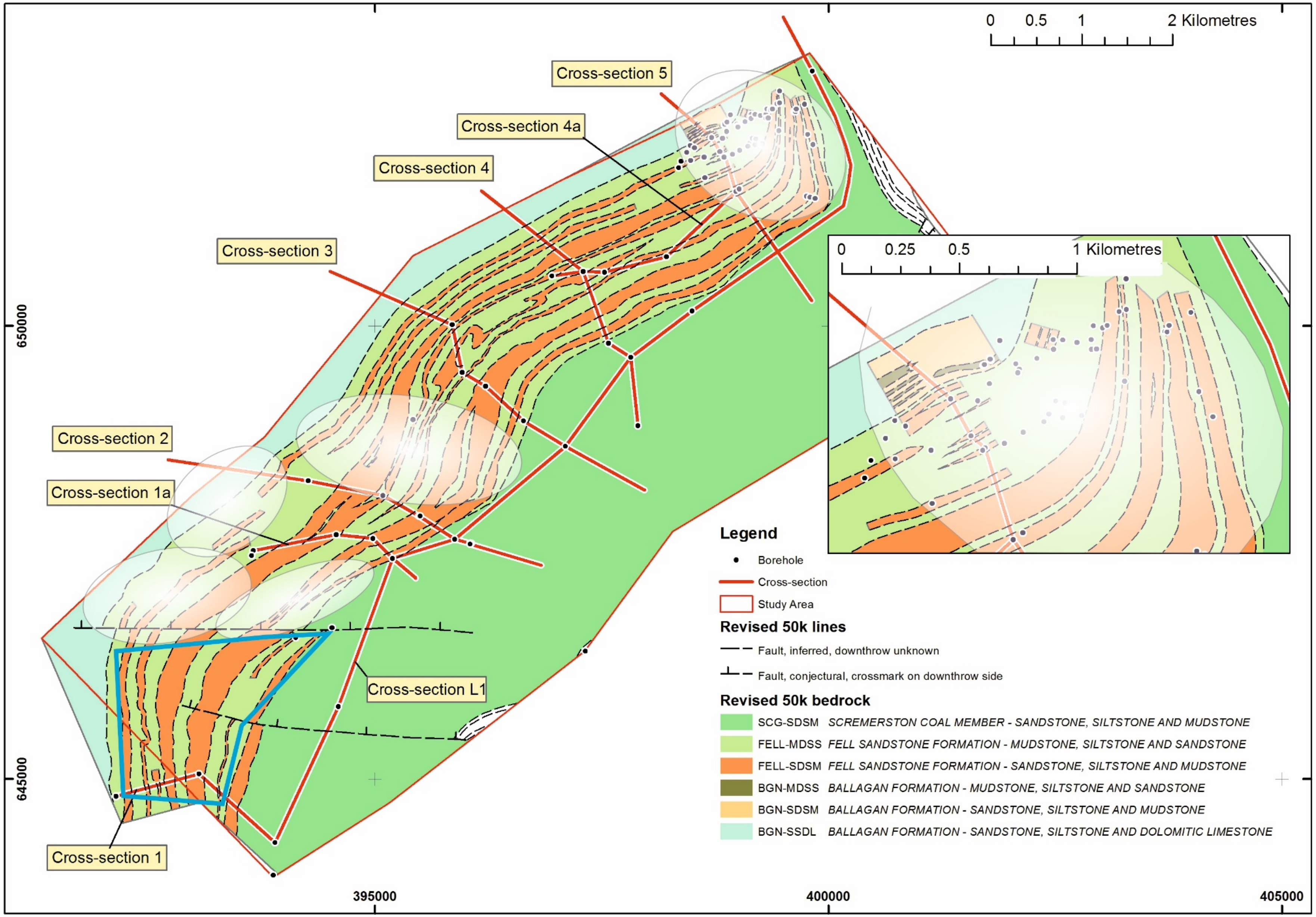

Figure 9 – Schematic indication of the relative level of confidence in the revised bedrock map. Less certain parts of the interpretation are highlighted in white. The area outlined in blue indicates the approximate coverage of field mapping carried out in 2018 as part of this study. Geological data British Geological Survey © UKRI 2019.

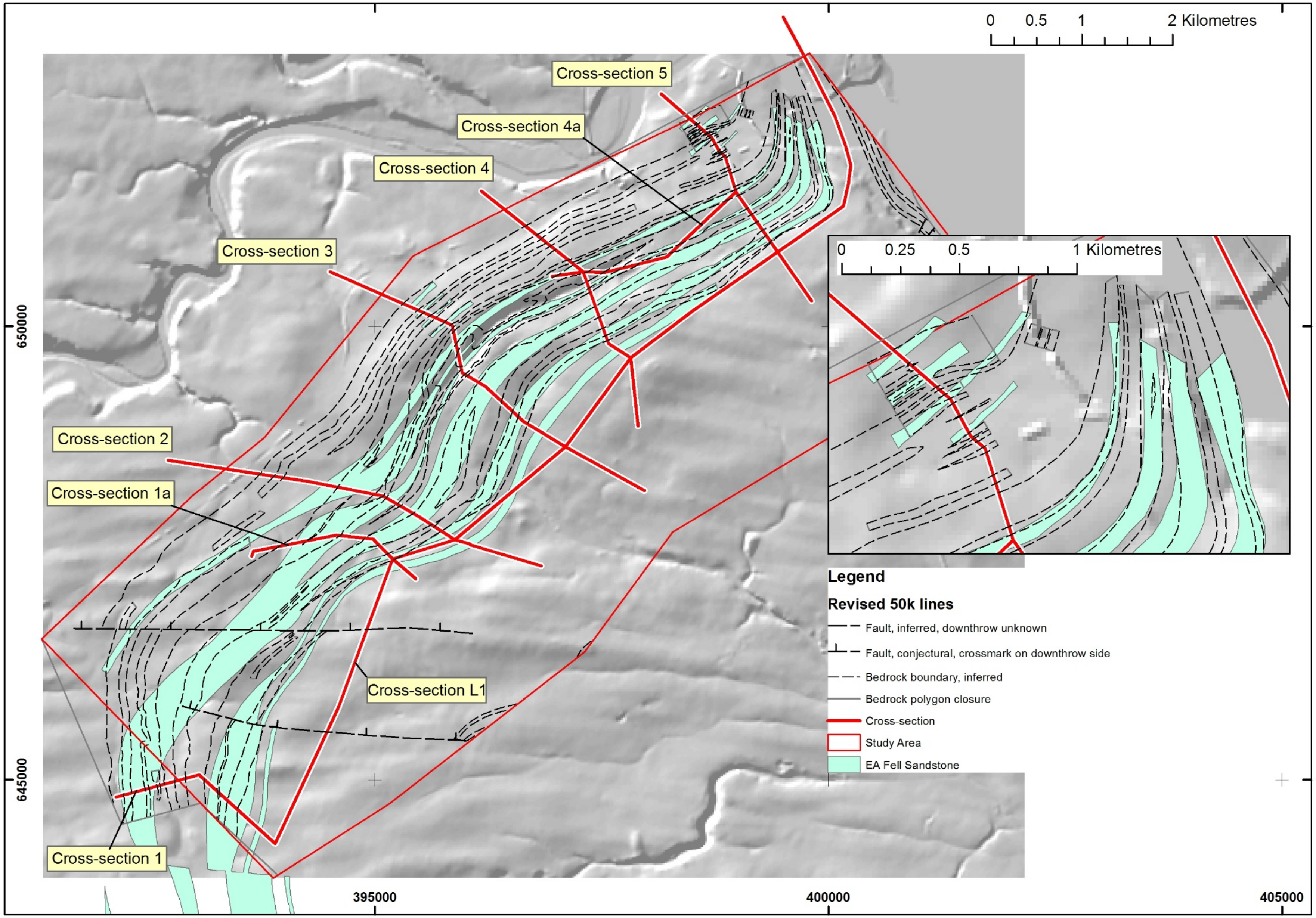

Figure 10 - Revised bedrock geology map of the Fell Sandstone (lines) showing EA bedrock interpretation (filled polygons). Hillshaded NextMap DTM courtesy of Intermap Technologies. Geological data except EA interpretation British Geological Survey © UKRI 2019.

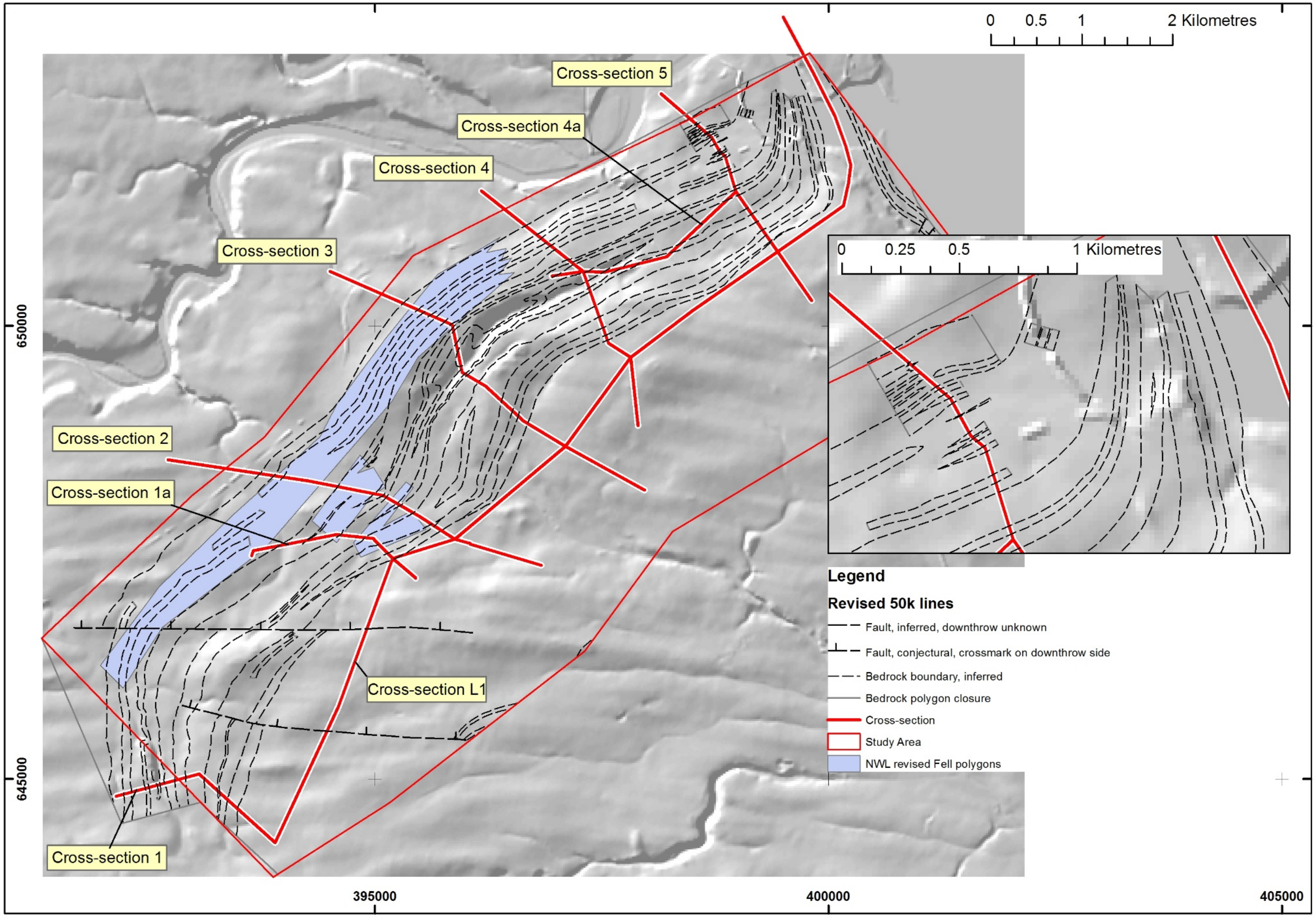

Figure 11 - Revised bedrock geology map of the Fell sandstone (lines) showing NWL revisions to EA bedrock interpretation (filled polygons). Hillshaded DTM courtesy of Intermap Technologies. Geological data except NWL interpretation British Geological Survey © UKRI 2019.

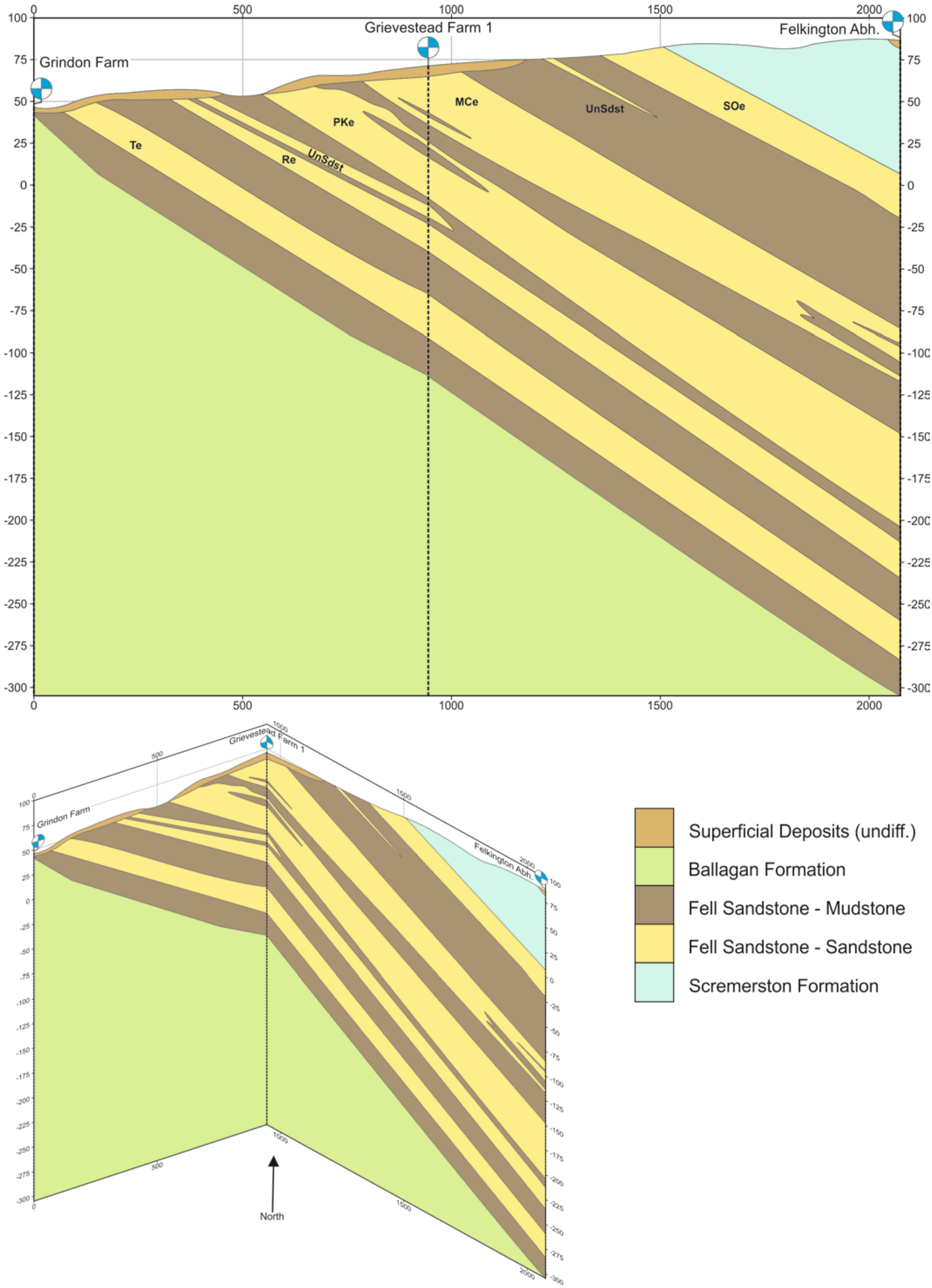

Figure 12 - Cross-section 001 shown in panel view and approximate actual orientation. Vertical exaggeration of x4 times applied. *Units in metres*.

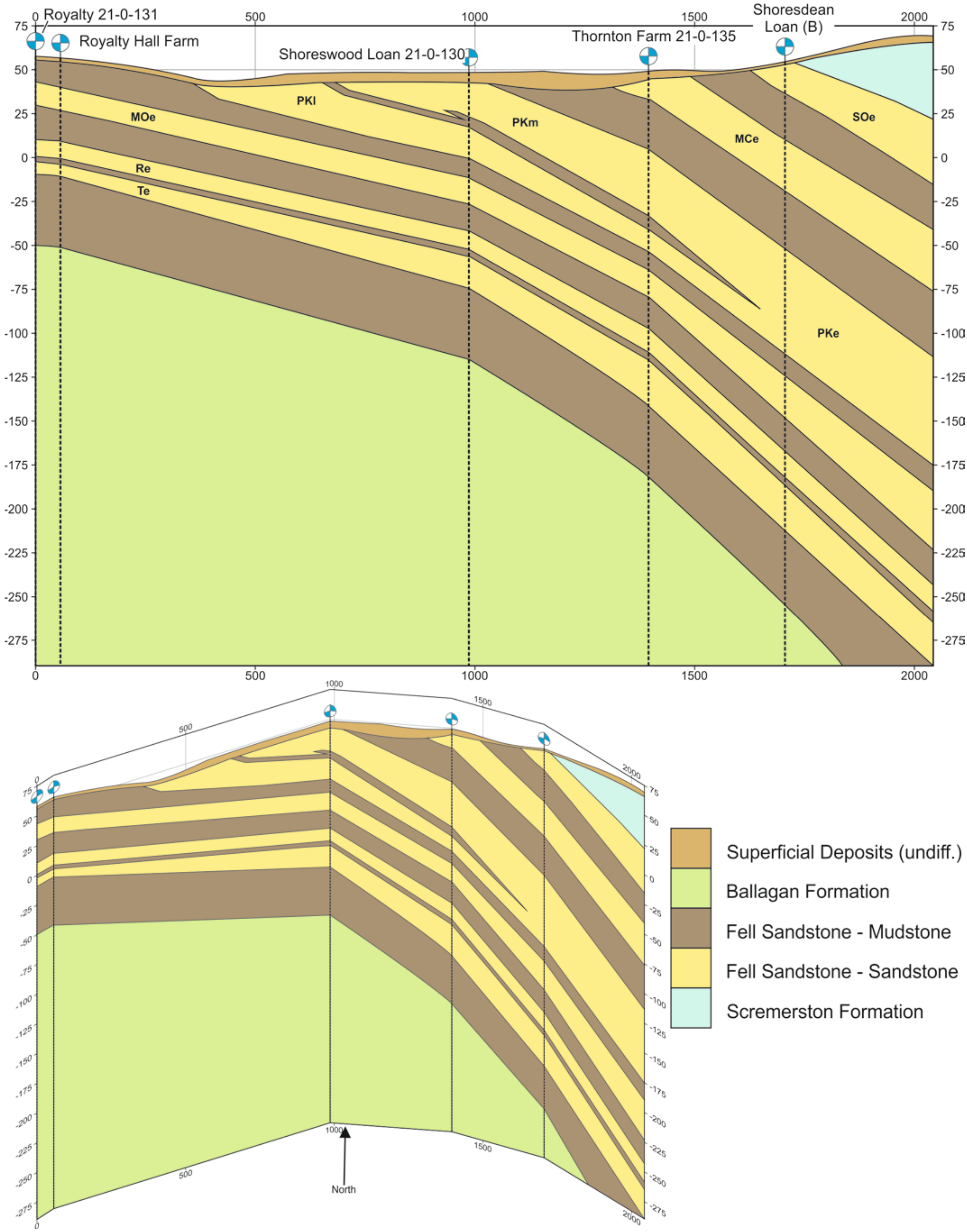

Figure 13 - Cross-section 001a shown in panel view and approximate actual orientation. Vertical exaggeration of x4 times applied. *Units in metres.*

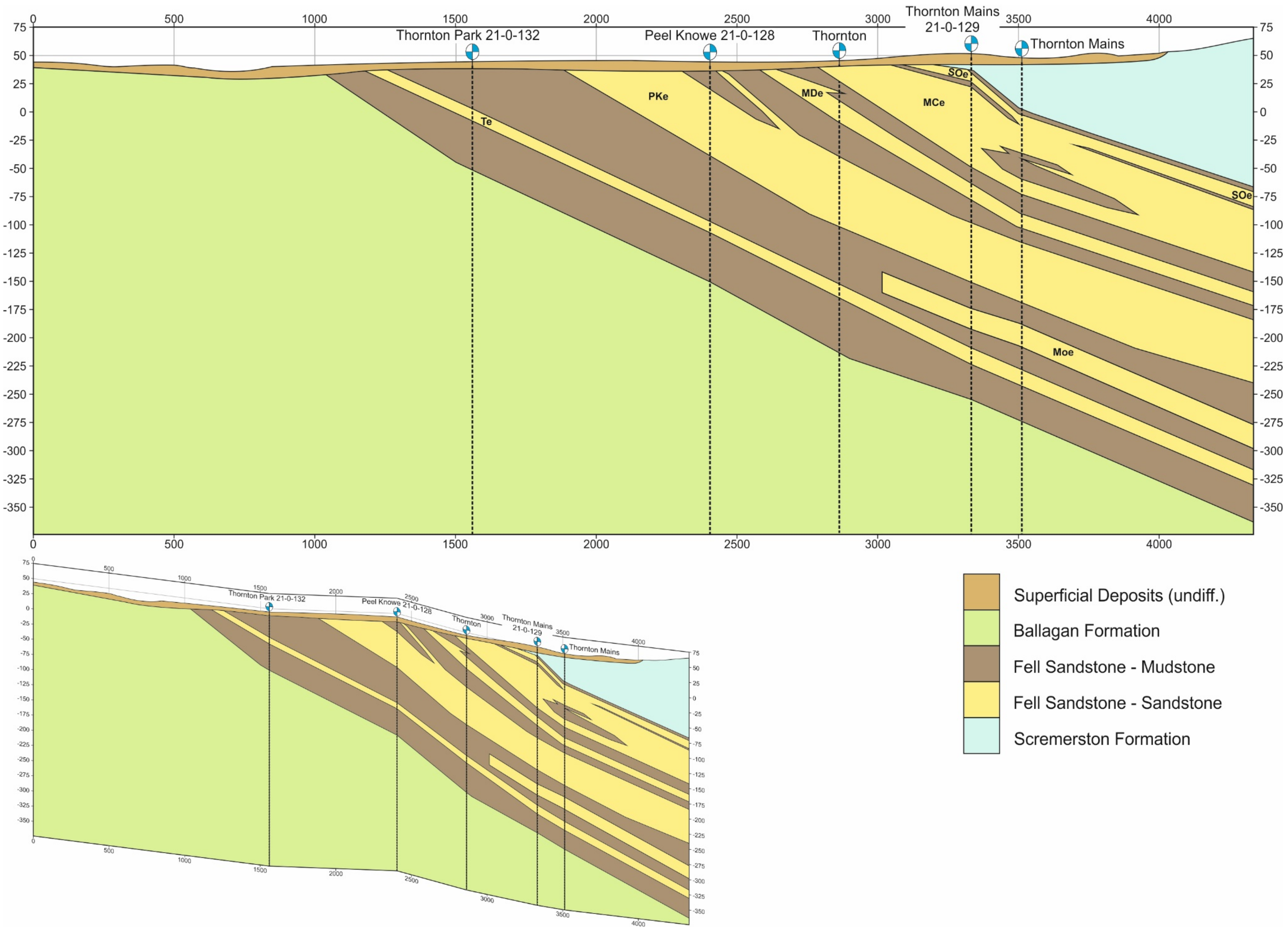

Figure 14 - Cross-section 002 shown in panel view and approximate actual orientation. Vertical exaggeration of x4 times applied. *Units in metres.*

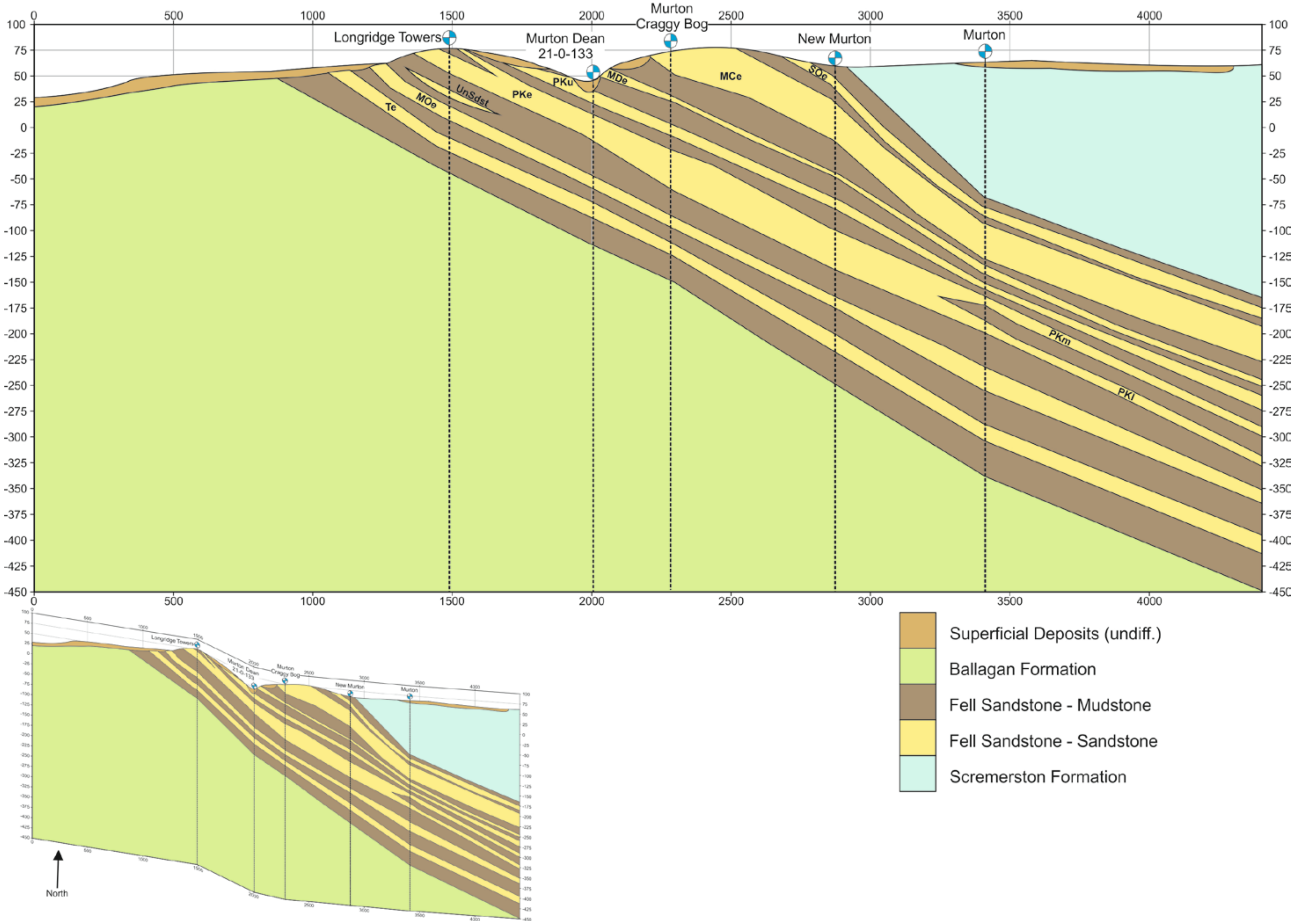

Figure 15 - Cross-section 003 shown in panel view and approximate actual orientation. Vertical exaggeration of approx. x4 times applied. *Units in metres.*

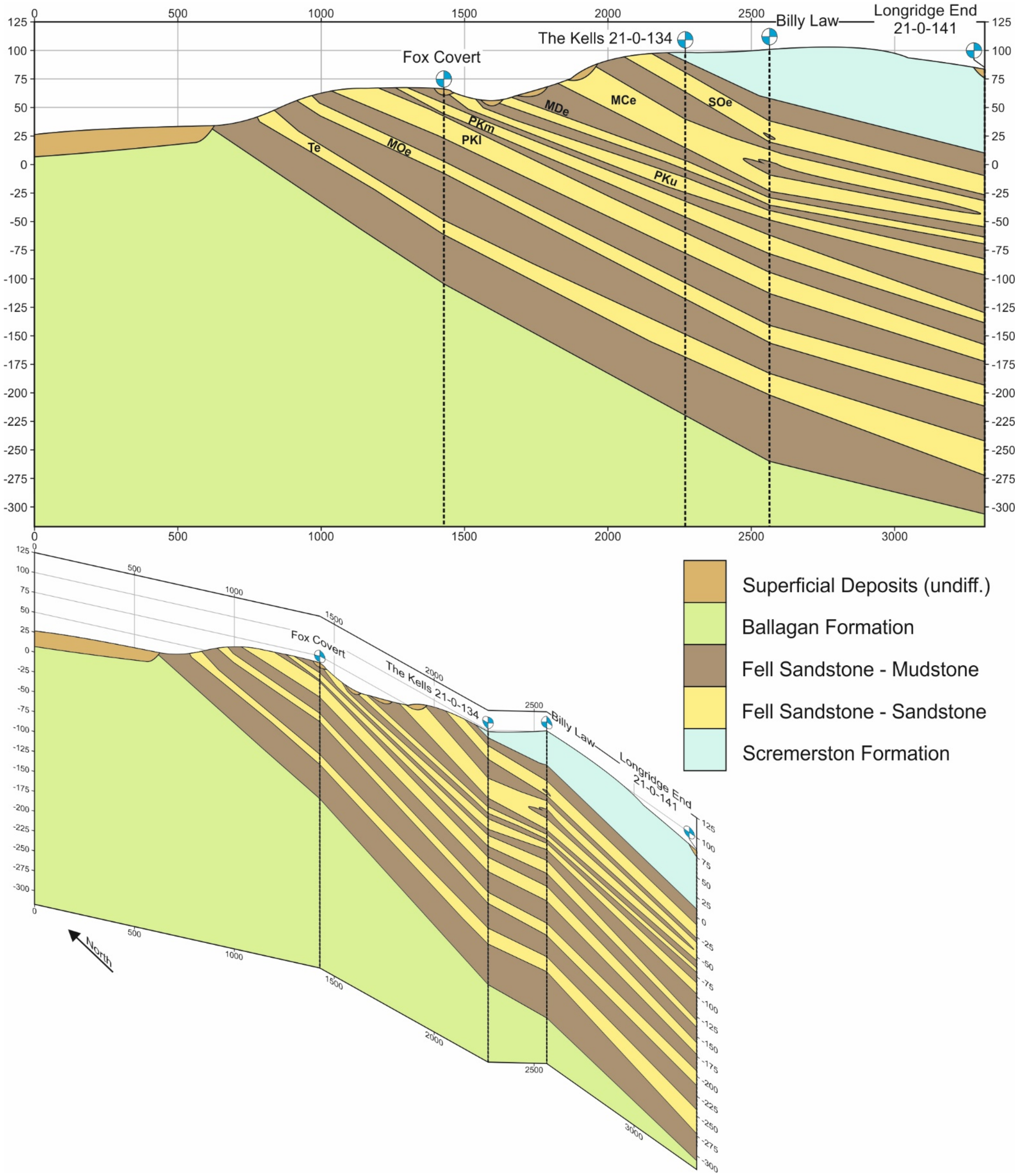

Figure 16 - Cross-section 004 shown in panel view and approximate actual orientation. Vertical exaggeration of x4 times applied. *Units in metres.*

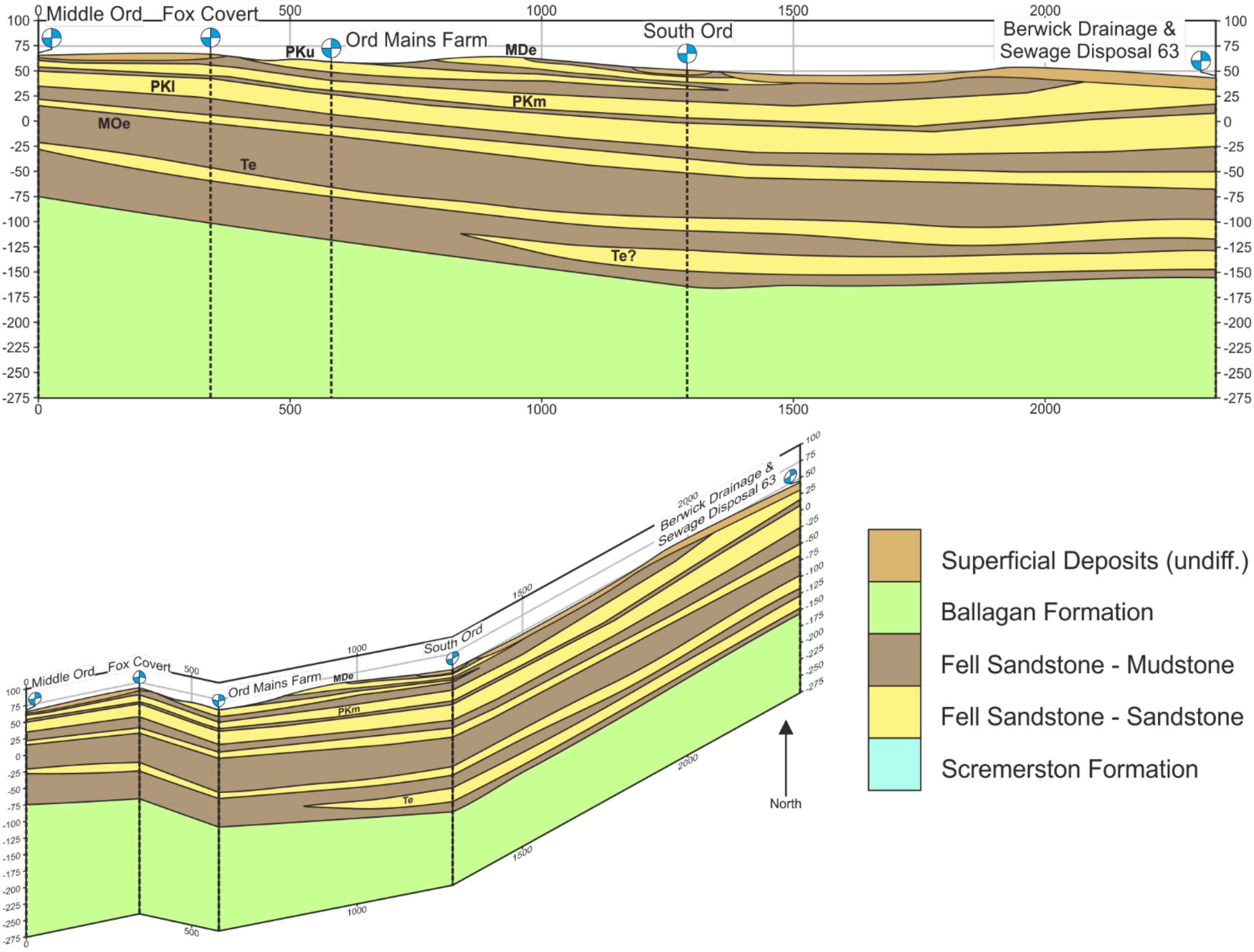

Figure 17 - Cross-section 004a shown in panel view and approximate actual orientation. Vertical exaggeration of x2 times applied. *Units in metres.*

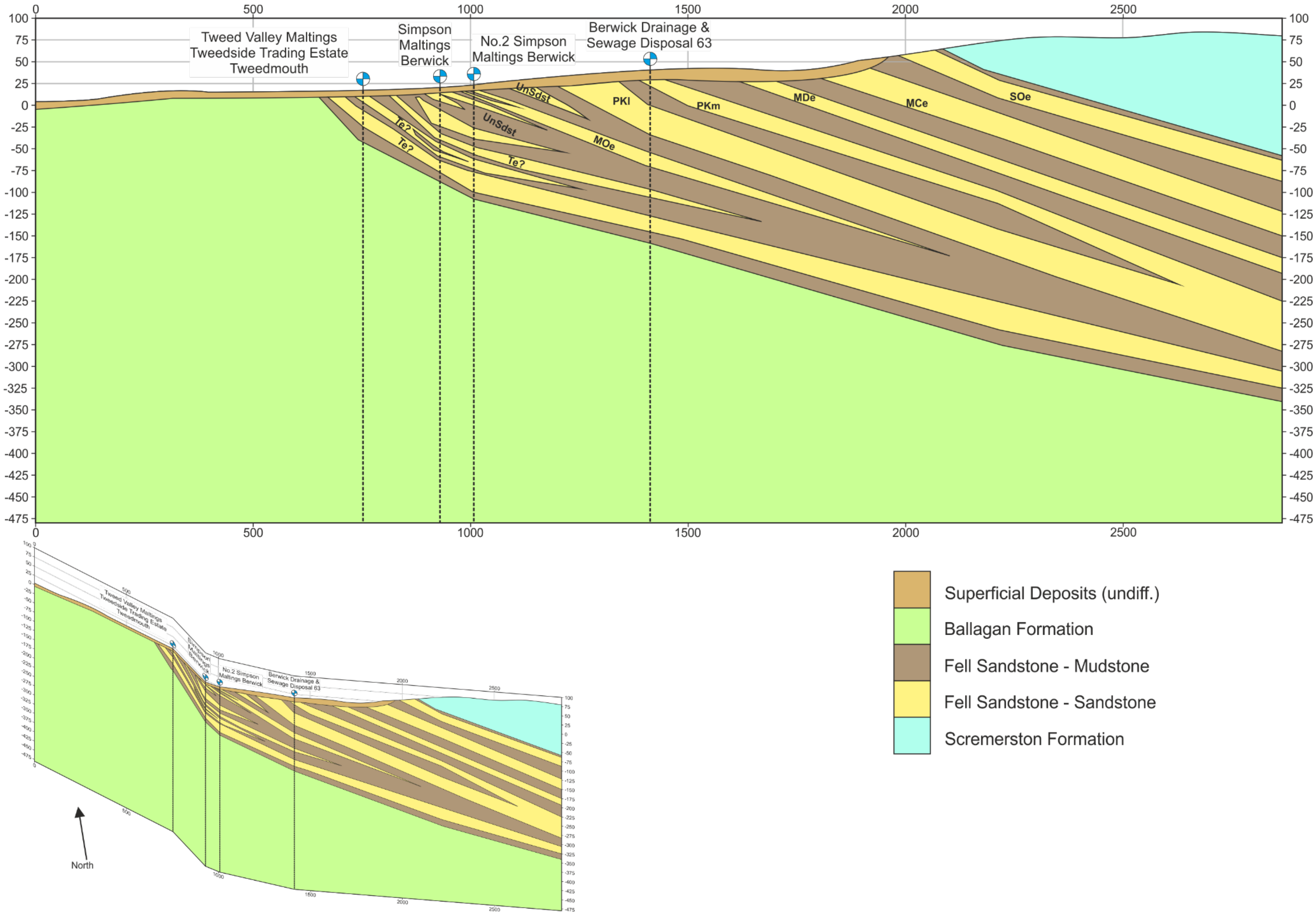

Figure 18 - Cross-section 005 shown in panel view and approximate actual orientation. Vertical exaggeration of x2 times applied. *Units in metres.*

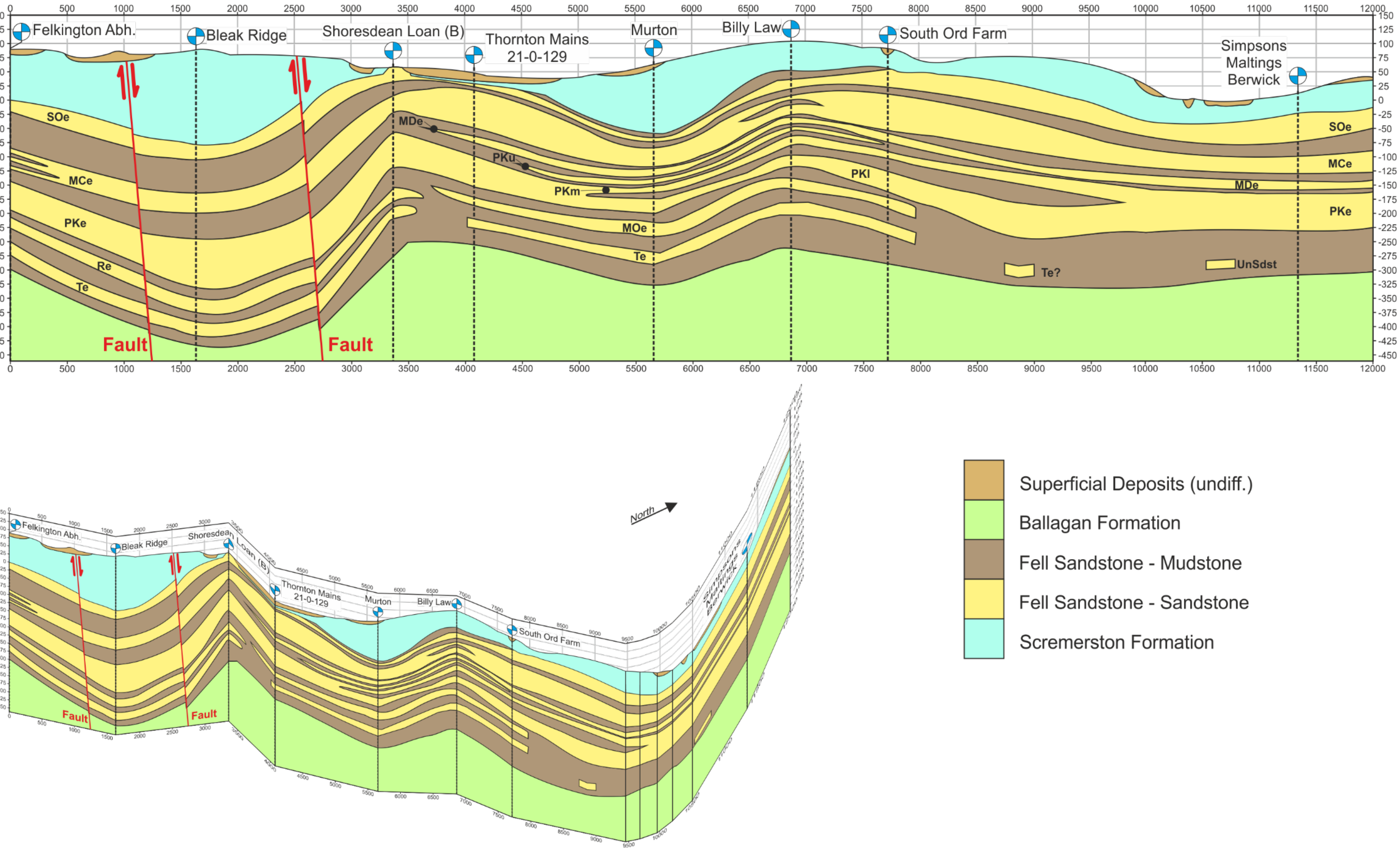

Figure 19 - Cross-section L1 shown in panel view and approximate actual orientation. Vertical exaggeration of x5 times applied. *Units in metres*.

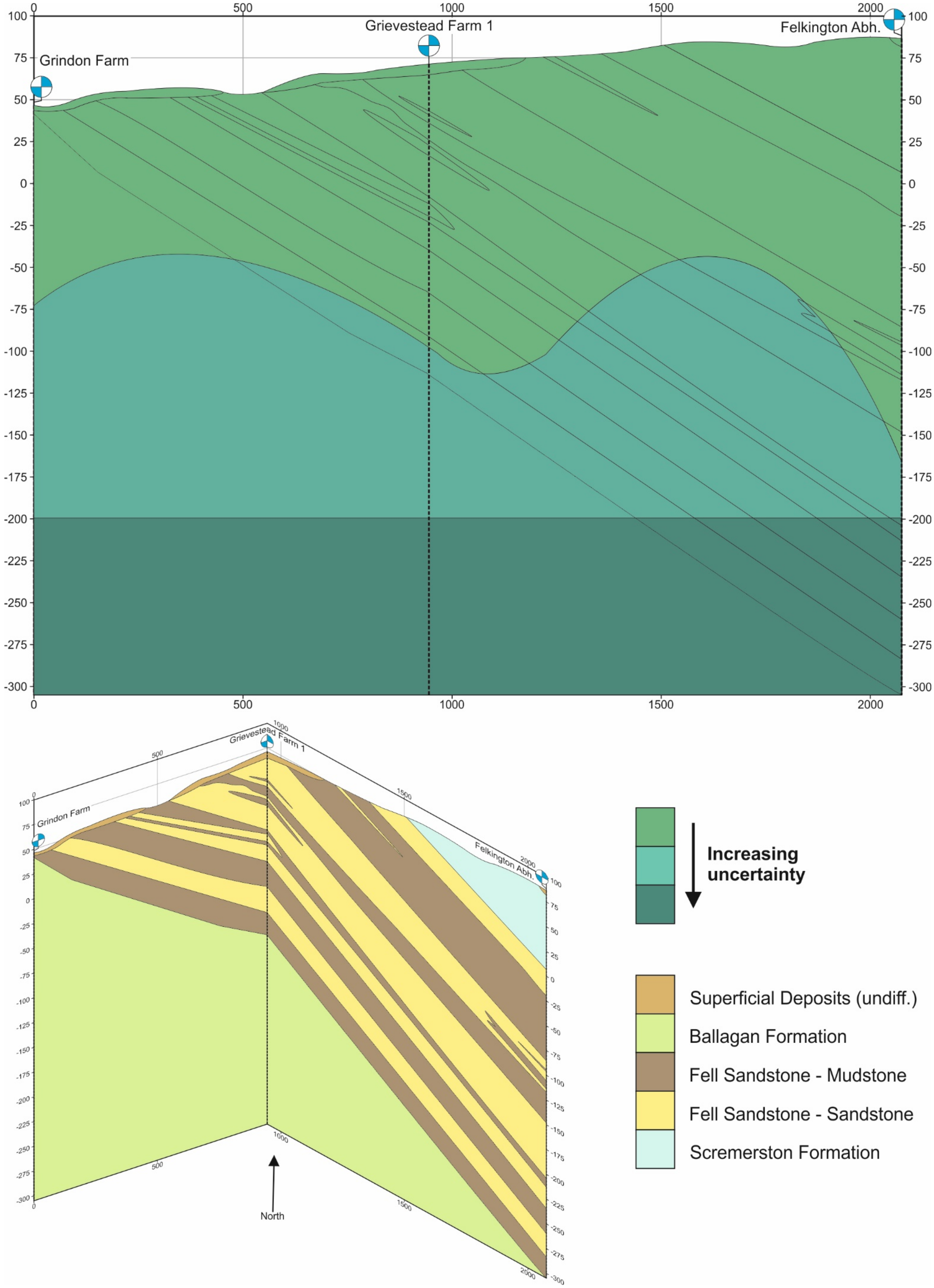

Figure 20 - Cross-section 001 showing relative confidence. Vertical exaggeration of x4 times applied. *Units in metres.*

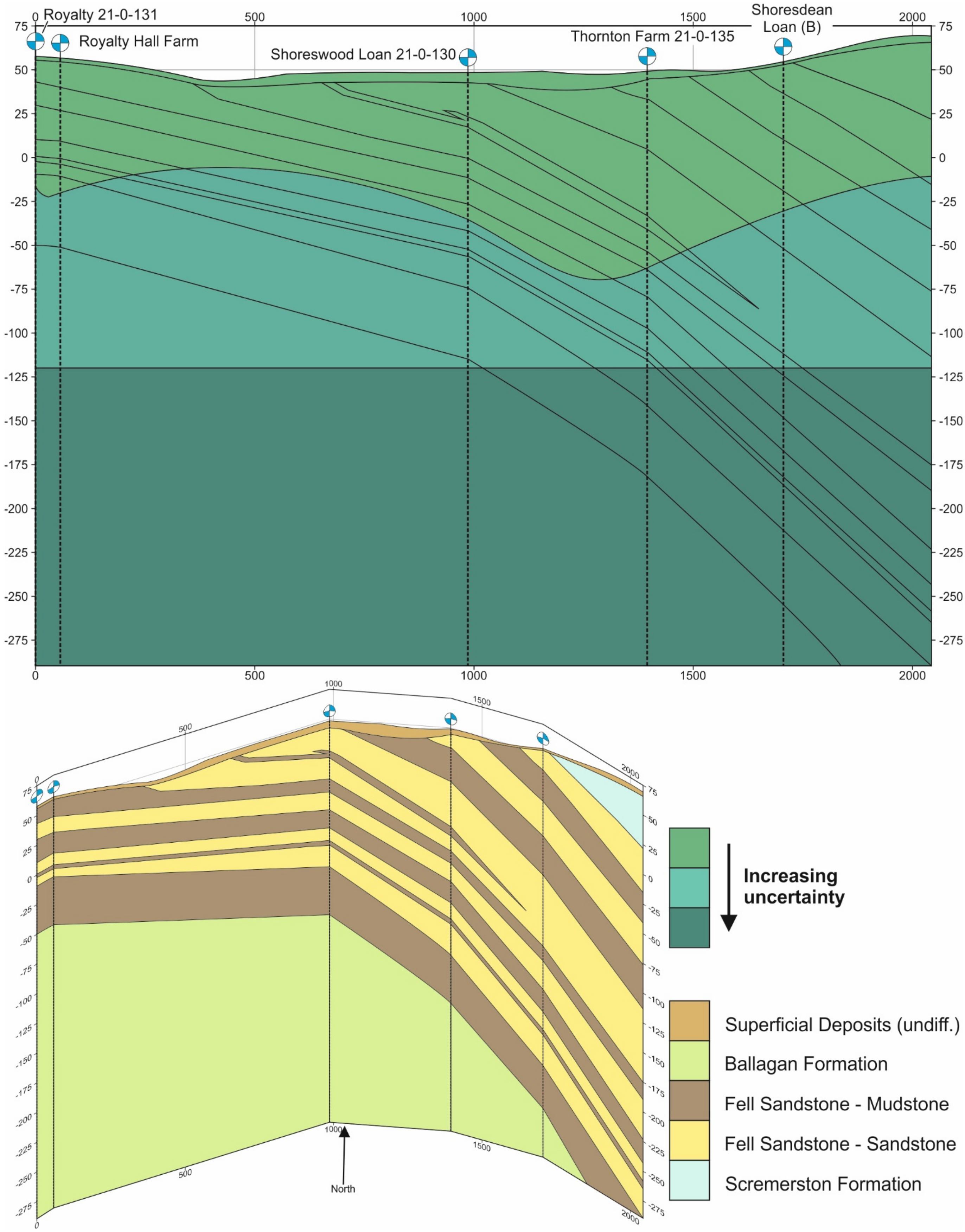

Figure 21 - Cross-section 001a showing relative confidence. Vertical exaggeration of x4 times applied. *Units in metres.*

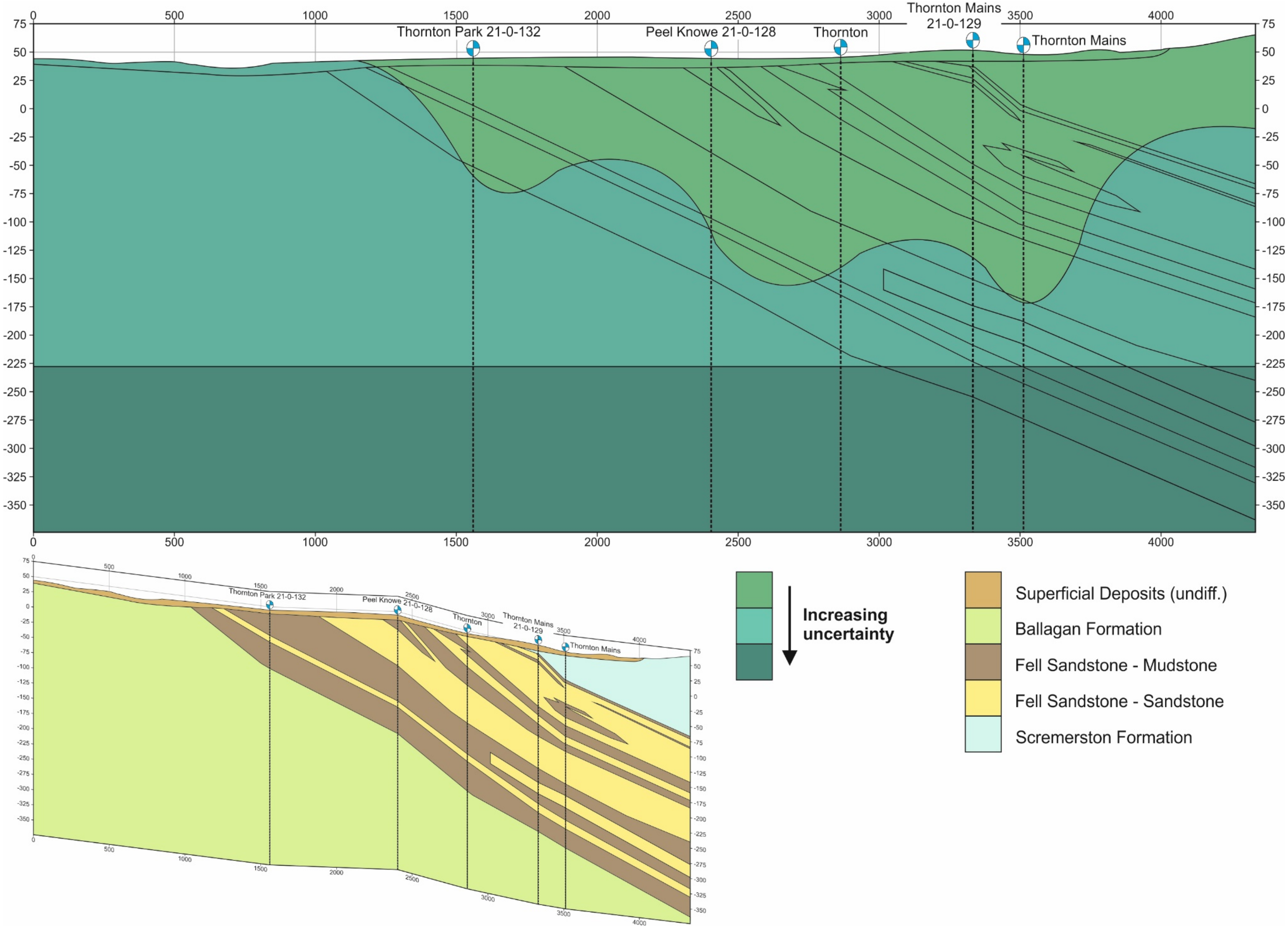

Figure 22 - Cross-section 002 showing relative confidence. Vertical exaggeration of x4 times applied. Units in metres.

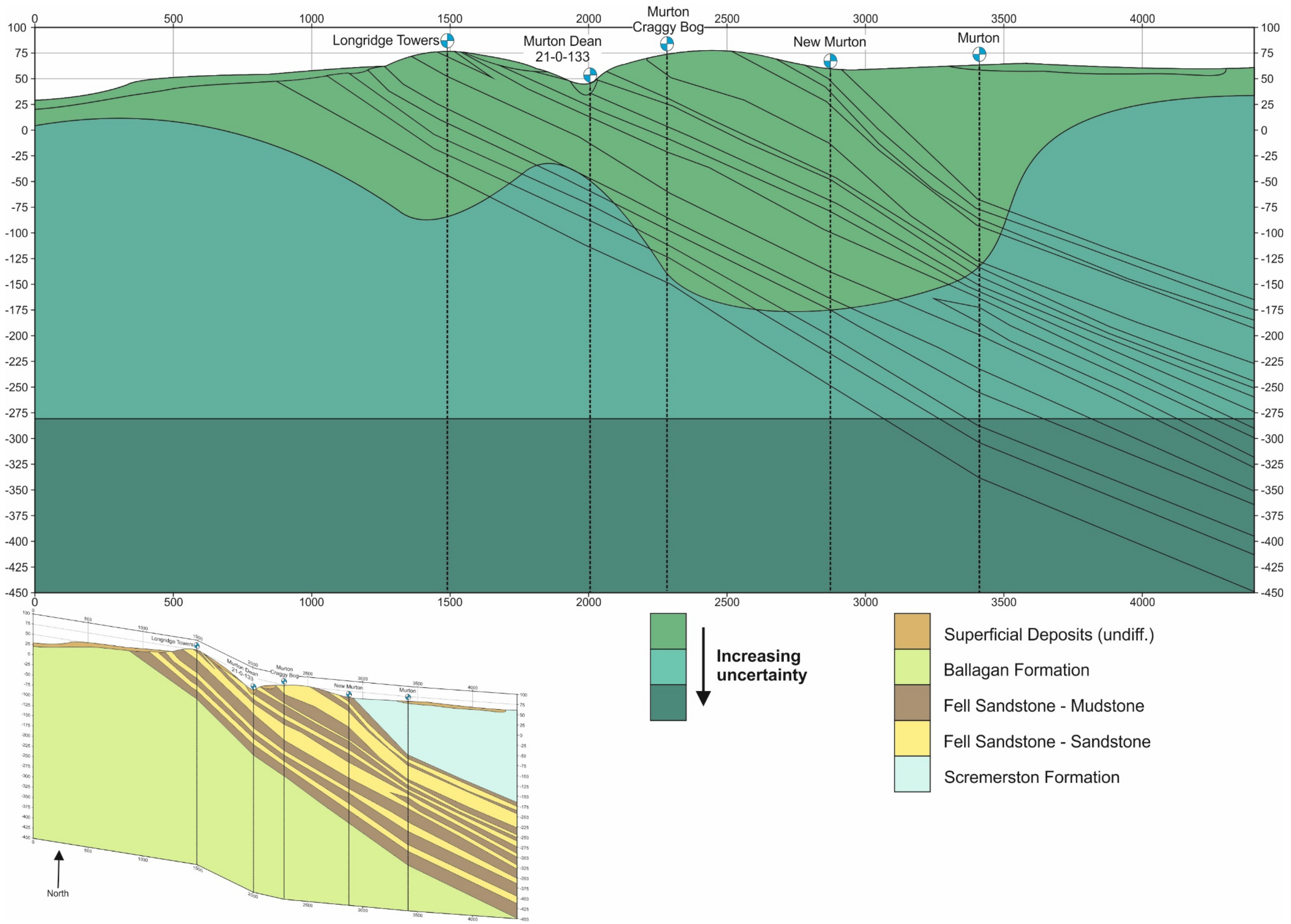

Figure 23 - Cross-section 003 showing relative confidence. Vertical exaggeration of approx. x4 times applied. *Units in metres.*

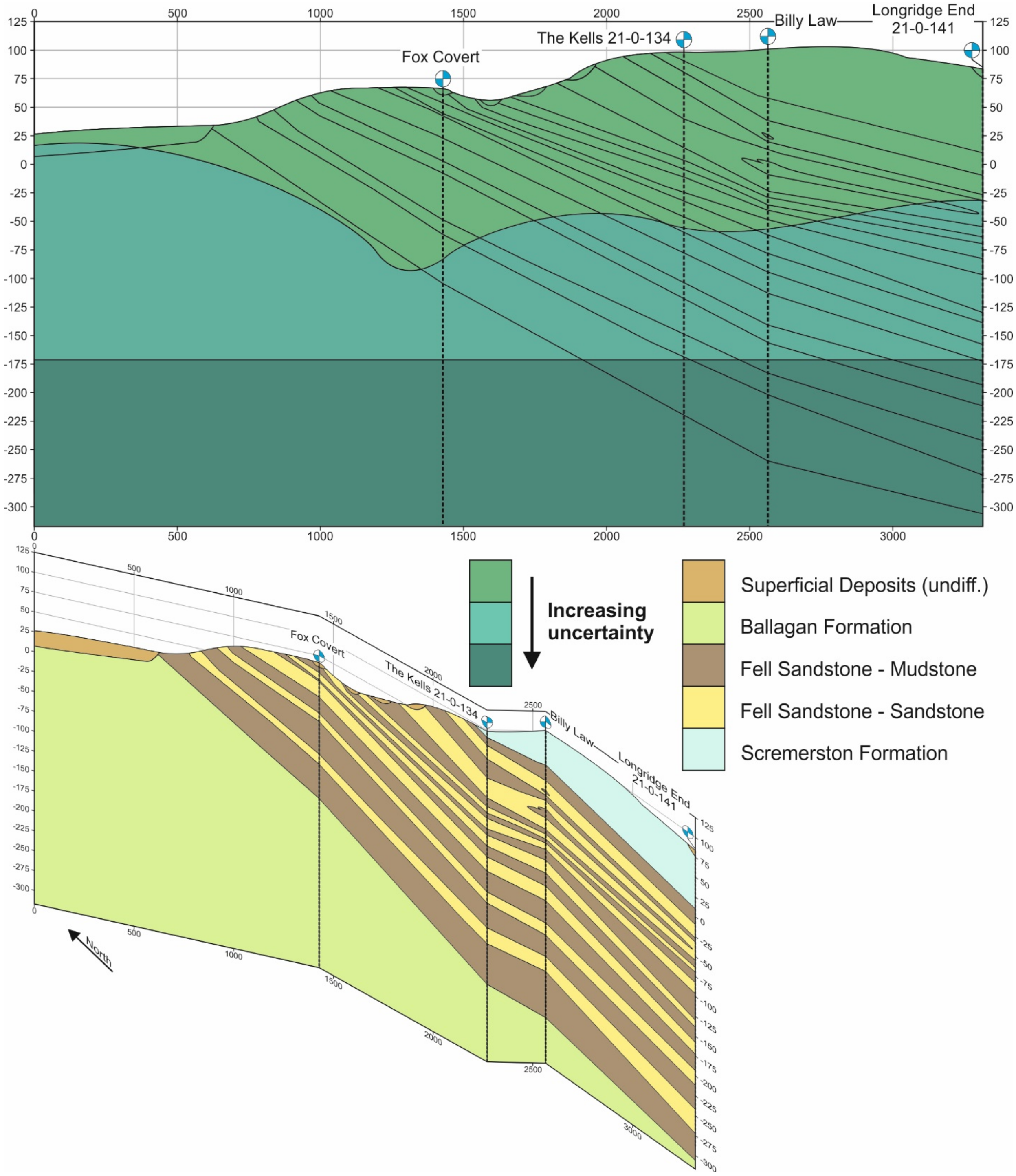

Figure 24 - Cross-section 004 showing relative confidence. Vertical exaggeration of x4 times applied. *Units in metres.*

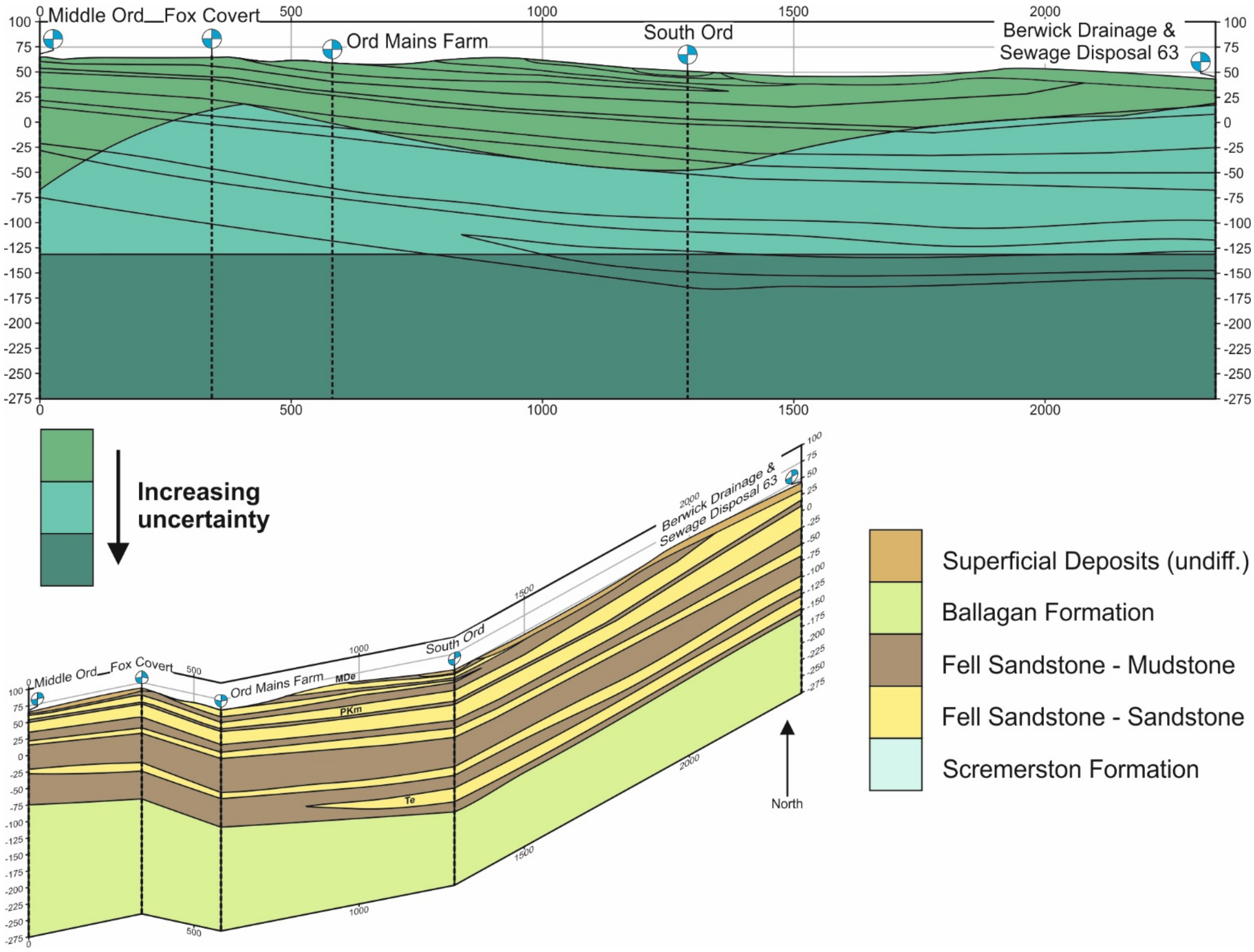

Figure 25 - Cross-section 004a showing relative confidence. Vertical exaggeration of x2 times applied. *Units in metres.*

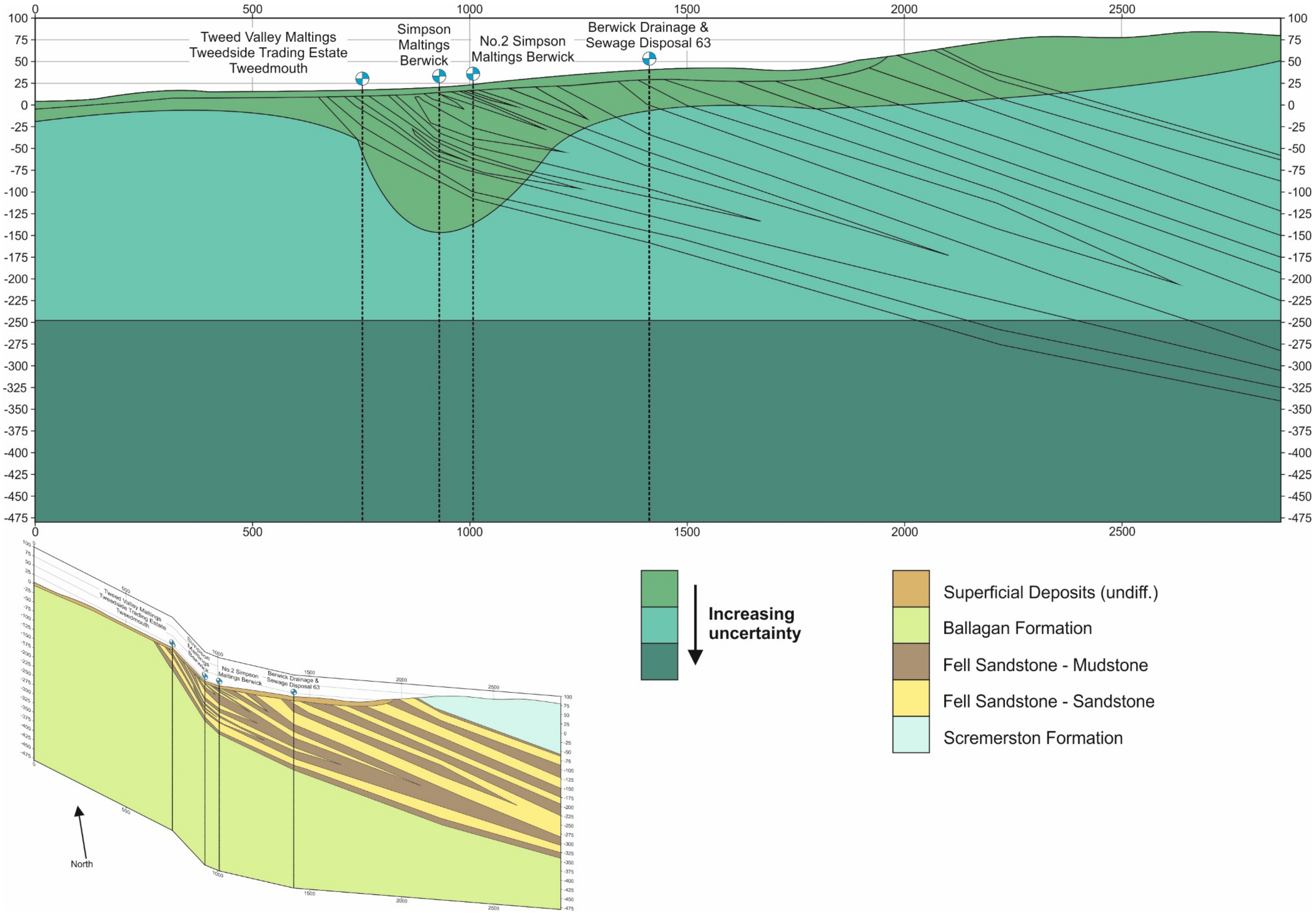

Figure 26 - Cross-section 5 showing relative confidence. Vertical exaggeration of x2 times applied. *Units in metres.*

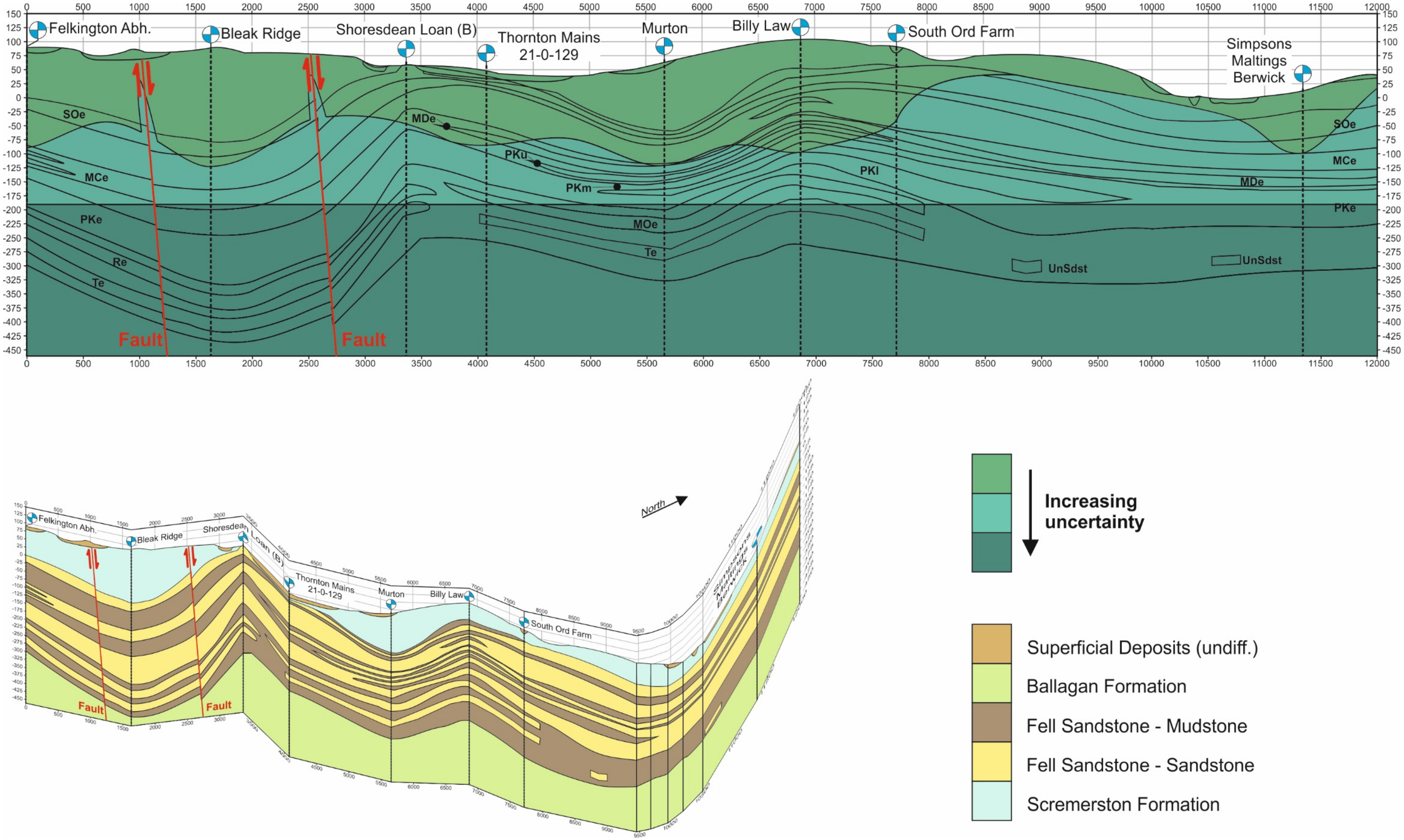

Figure 27 - Cross-section L1 showing relative confidence. Vertical exaggeration of x5 times applied. Units in metres.

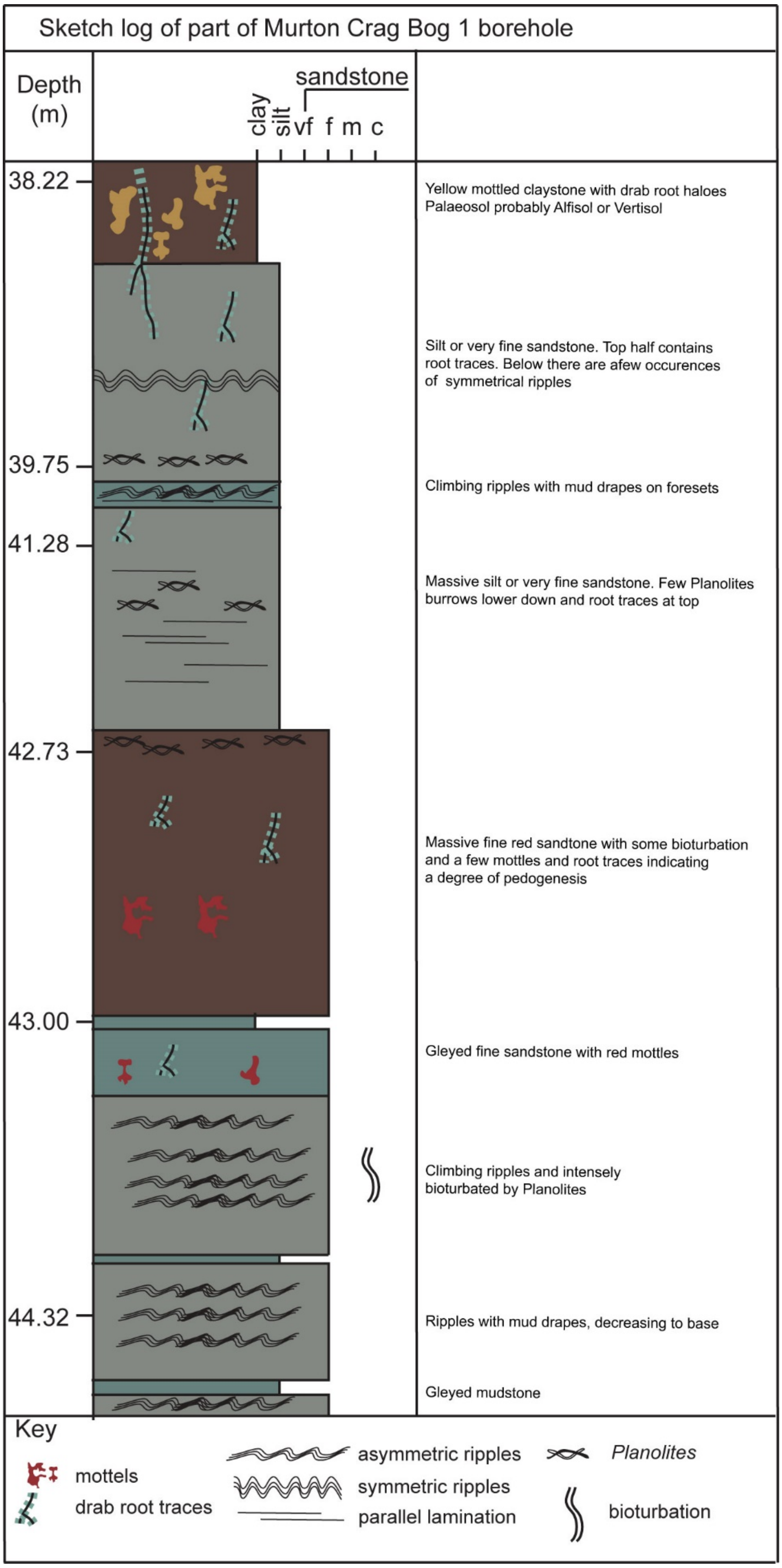

Figure 28 - Sketch log of the interval between 38 – 44m in Murton Crag Bog 1 borehole.

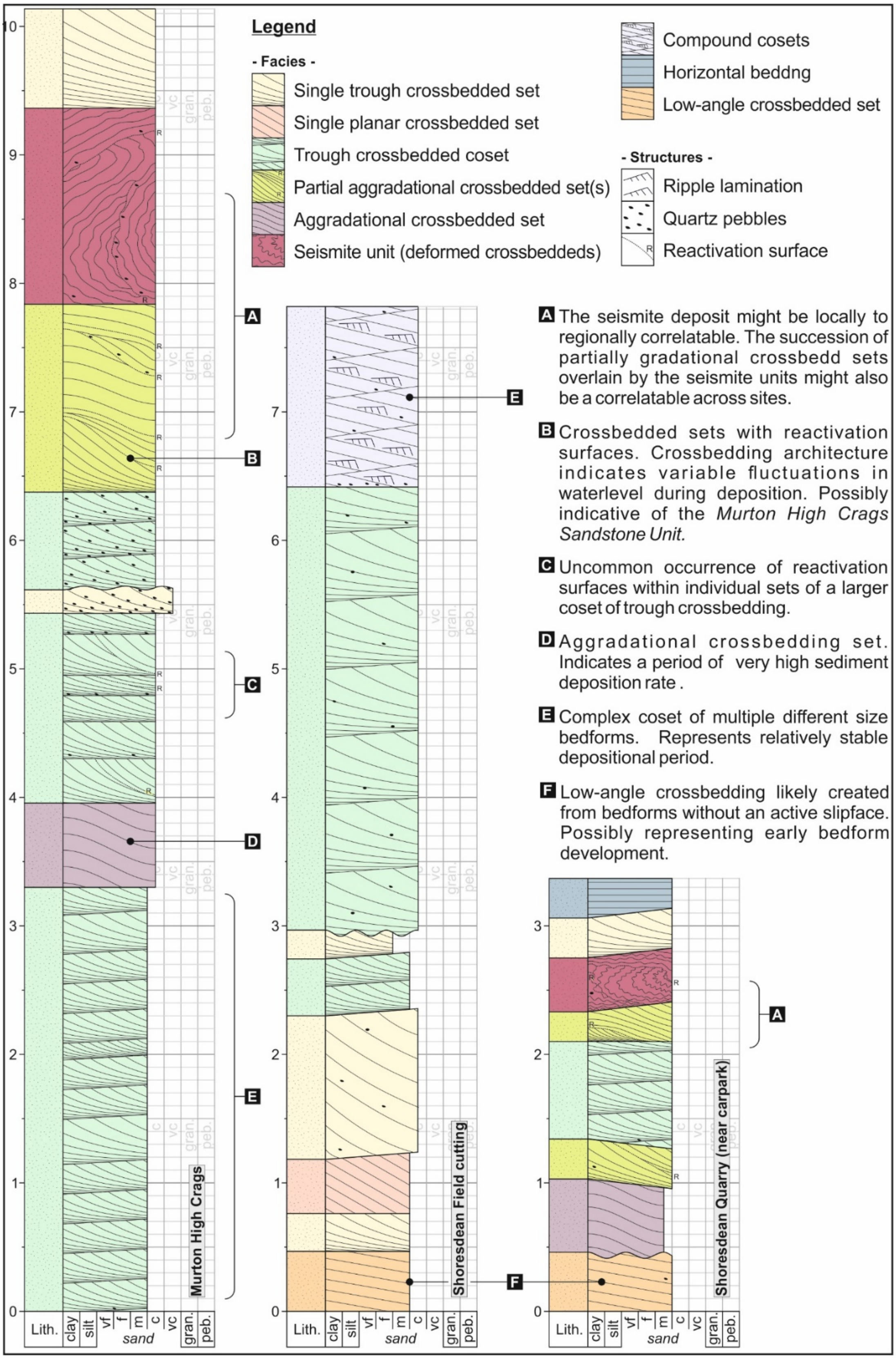

Figure 29 – Sedimentary Logs constructed from field outcrops at Murton High Craggs, and Shoreswood.

Plate 1 - An example of a palaeosol from Murton Craggy Bogs Observation Borehole 1 with yellow mottles