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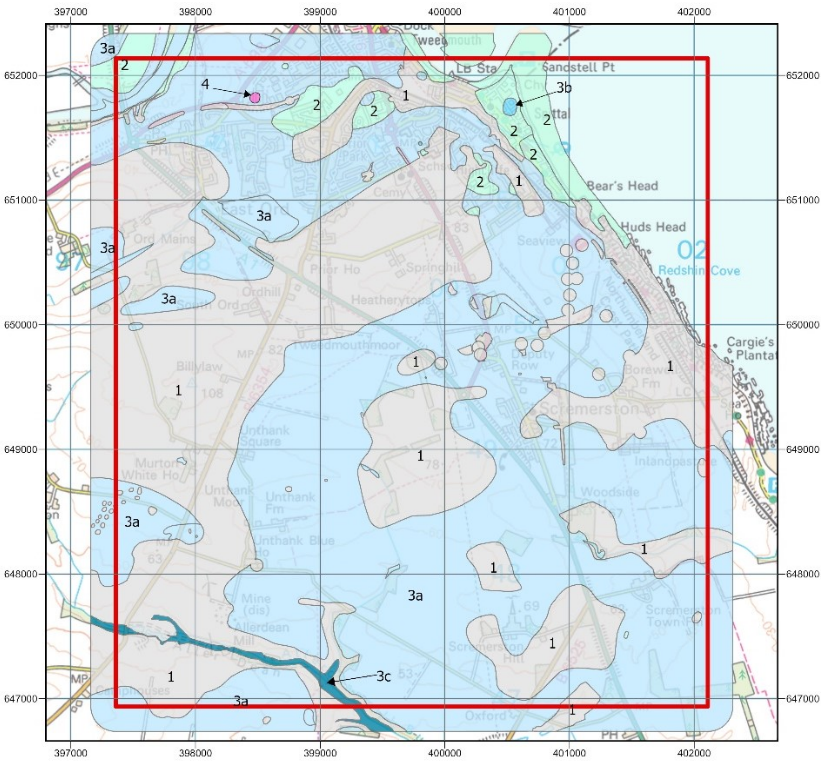
Superficial hydrogeological domains for the Spittal area - Project Groundwater Northumbria

National Geoscience Programme

Commercial Report CR/24/064



BRITISH GEOLOGICAL SURVEY

NATIONAL GEOSCIENCE PROGRAMME

COMMERCIAL REPORT CR/24/064

Superficial hydrogeological domains for the Spittal area - Project Groundwater Northumbria

H. Burke, R. Terrington, T. Reeves, B. Murphy, N. Dewald, and V. Banks

Keywords

Spittal, hydrogeology domains, superficial deposits

National Grid Reference

SW corner 397360,646935
NE corner 402110,652140

Map

Sheet 1&2, 1:50 000 scale, Berwick-upon-Tweed and Norham

Front cover

Superficial hydrogeological domains - Spittal. BGS © UKRI 2024.

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Summary

This report has been produced by the British Geological Survey (BGS) on behalf of Project Groundwater Northumbria, the Flood and Coastal Resilience Innovation Programme (FCRIP) project led by Gateshead Council. It provides background and methodological information on the development of superficial hydrogeological domains for the Spittal area (near Berwick Upon Tweed) and accompanies the delivery of datasets including a superficial hydrogeological domains map and a new superficial thickness model for the project area.

The development of the domains was undertaken through analysis of 287 boreholes. 271 boreholes were digitally coded boreholes including over 187 coded for this project. The boreholes were attributed for permeability according to previously used schemes and analysed to characterise the vertical succession of superficial deposits for classification as hydrogeological domains.

Superficial hydrogeological domains have been mapped for the area based on a schema defined through consultation with the clients and intended for characterisation of both potential recharge to, and discharge from, underlying bedrock aquifers. The domains have been characterised from the superficial thickness model using thickness thresholds as well as the attributed borehole distribution, the 1:50,000 scale geological map of the area and wider geological understanding of the region and associations of deposits.

Four primary domains were identified in the Spittal area. Domain 1 comprises areas with less than 2 m of superficial deposits, including areas where no superficial deposits are present. Domain 2 represents areas where only aquifer (permeable deposits) are present, regardless of their thickness. Domain 3 comprises areas with 2-10 m of aquitard deposits (low permeability) within the succession. Domain 3 is divided into three subunits (3a, 3b and 3c) to show differences in the vertical sequence of aquifer and aquitard units. Domain 4 covers areas with 10-30 m of aquitard in the succession.

As the borehole data was densely clustered in the north of the respective study area and there was limited borehole data in the central and southern part of the study area, artificial ground was also considered as a major contributor to the make-up of the superficial hydrogeological domains for Spittal. These included mine shafts and former quarries/open cast mines.

Future work to improve the understanding of thickness, distribution and type of the superficial deposits using non-intrusive methods such as field survey and geophysical survey (passive seismic methods) would help constrain the superficial hydrogeological domains.

1 Introduction

1.1 BACKGROUND AND SCOPE

The British Geological Survey (BGS) has mapped a set of superficial deposit hydrogeological domains (otherwise known as superficial hydrogeological domains) for the Spittal area as part of work commissioned for Project Groundwater Northumbria (PGN), part of the Flood and Coastal Resilience Innovation Programme (FCRIP) project led by Gateshead Council. These hydrogeological domains reflect spatial variations in the lithological properties of superficial deposits that are likely to influence the recharge and movement of groundwater into and out of bedrock aquifers within the underlying Lower Carboniferous aged bedrock units (cf. McMillan et al., 2000; Price et al., 2007).

The PGN project work is intended to help project partners including the Environment Agency and Gateshead Council understand both spatial variations in recharge to the bedrock aquifers and highlight areas where outflow from sandstone units or historic mine workings may raise risks of groundwater flooding and/or interact with surface water systems and shallow superficial aquifers.

This report details the methodology for the development of the revised superficial deposit thickness model and superficial hydrogeological domains and accompanies the delivery of these datasets as grids and shapefiles. The underling bedrock was not directly considered in this study as the focus was on the superficial deposits and the artificially modified ground as conduits or barriers of groundwater flow into the bedrock aquifer or aquitard.

1.2 THE DOMAINS APPROACH

Characterisation of superficial hydrogeological domains is an approach that has been developed to help understand the influence of complex superficial deposit sequences on groundwater recharge and on discharge from potential bedrock aquifers. The approach is particularly suited to complex Quaternary glacial successions which exhibit high structural and lithological variability arising from glacial and postglacial depositional environments (McMillan et al., 2000).

Superficial domains reflect areas with distinct vertical lithological profiles related to the distribution of permeable (typically sand and gravel dominated) and low permeability (typically clay dominated) deposits. Domains may be distinguished by the thickness, presence/absence and relative position of units (e.g. Price et al., 2007). For example, areas of till deposits that are overlain by sandy alluvium would be considered as distinct from areas of till deposits with buried sand lenses.

Although the focus of the domains approach is on characterising vertical successions, horizontal flow along channel structures and through sand and gravel lenses can also occur within superficial deposit sequences. For the Spittal area, faults and the contact between the superficial and bedrock geology may form specific groundwater flow paths for bedrock recharge.

The location of the Spittal project area is shown in **Figure 1** and **Figure 2** (please note that only the onshore area was considered in this project). The Spittal project area is approximately 5 km by 5 km comprising rural and coastal areas, with the main urban centre to the north in the town of Berwick-Upon-Tweed.

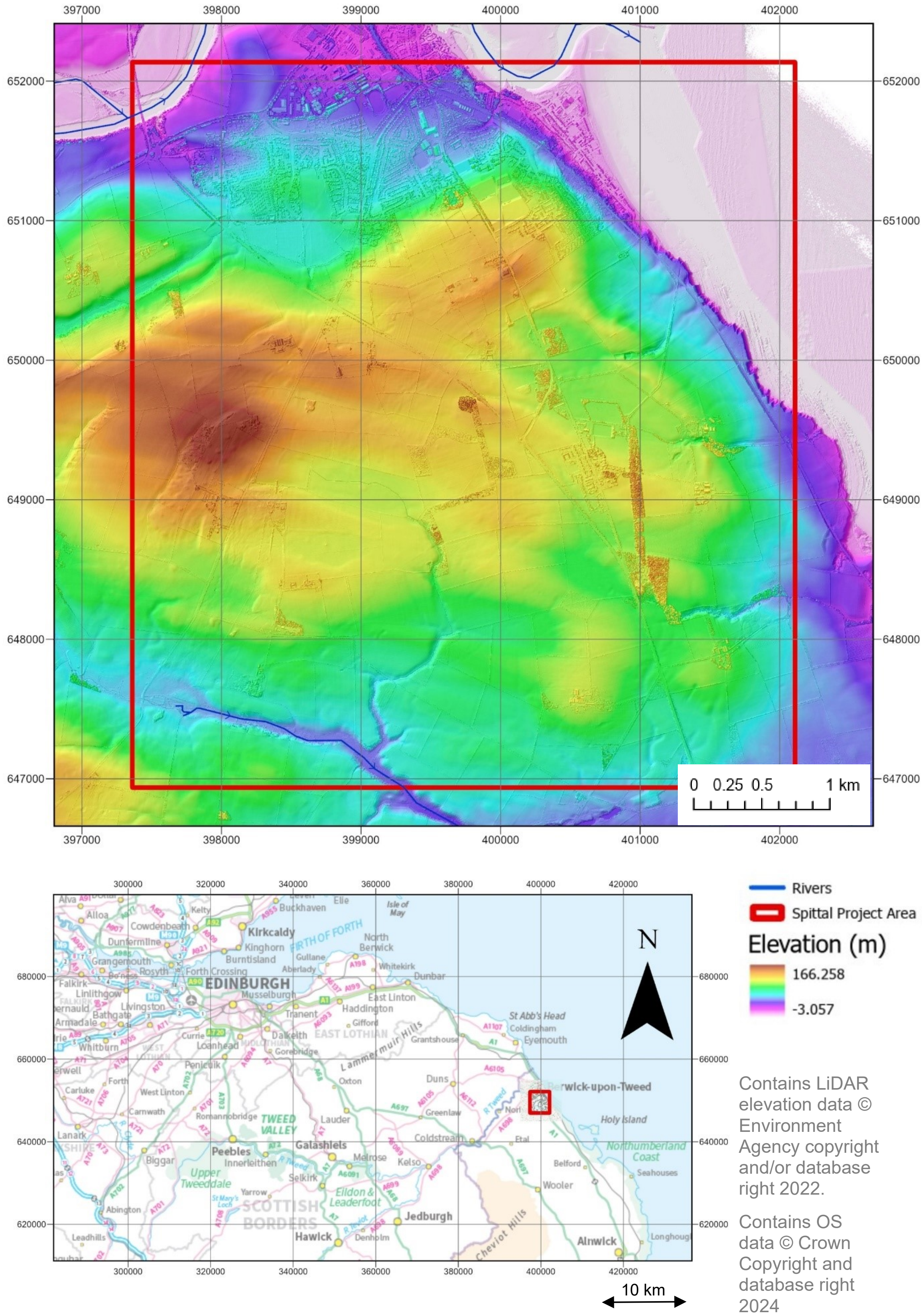

Figure 1 Location map of the Spittal project area with elevation

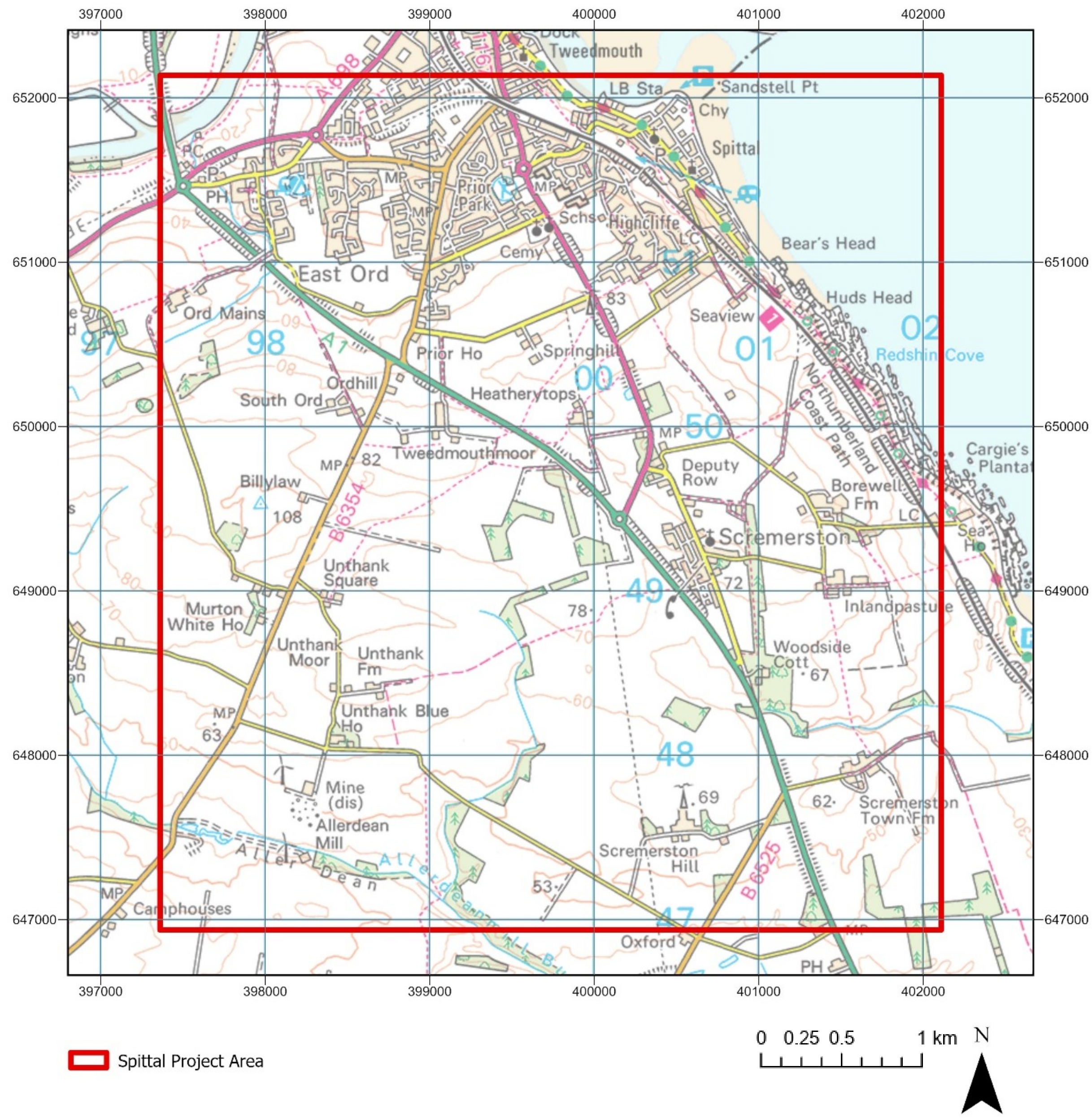

Figure 2 Spittal project area

1.3 GEOLOGICAL HISTORY OF THE AREA

The superficial geology in the study area comprises a suite of glacial and postglacial sediments deposited during and after the development and retreat of the British-Irish Ice-Sheet (BIIS) in the Late Devensian, around 27,000 to 22,000 years ago when much of Britain was covered by ice (Fowler, 1926; Stone et al, 2010). These include extensive cover of glacial till, glaciofluvial (typically sand & gravel), and glaciolacustrine (typically silt and clay) deposits. The glacial deposits are overlain by modern river terraces and alluvium along river courses. Following the glaciation, sea levels rose, leading to the formation of shoreline deposits in the area and the establishment of the modern river network.

The recent glacial history associated with the British-Irish Ice Sheet (BIIS) maximum and late Devensian retreat is evident from relatively fresh striae, as seen in the ground elevation model (**Figure 3**). West-north-west to east-south-east lineations are part of a suite of landforms recognised by Everest et al. (2008), Livingstone et al. (2012, 2015), Clark et al. (2018) and Davies et al. (2019). These have been interpreted as the product of southerly flowing ice and easterly flowing subglacial ice streams (fast flowing ice) that contributed to the southerly flowing North Sea ice lobe (Livingstone et al., 2015). Lineations in this area are related to the Tweed palaeo ice stream (Everest et al., 2008). These authors suggest that the ice stream likely extended offshore as a grounded ice lobe.

Deglaciation occurred in the context of westerly retreat of the ice characterised by ice shifts in ice-divide location and changes in internal ice-sheet dynamics associated with flow switches (Livingstone et al., 2015; Davies et al., 2019).

Figure 3 shows glacial landforms identified in the BRITICE glacial map version 2 (Clark et al. 2018), where the authors analysed a detailed terrain model. In the Spittal area the authors interpreted topographic landforms as crag and tail features, meltwater channels, subglacial lineations and a moraine that clips the south-east corner of the project area (these terms are described in the glossary).

Although there is a paucity of data pertaining to the hydrogeology of these deposits it is possible to speculate broadly on the likely properties based on typical sediment architectures in the region. The crag and tail deposits are likely characterised by a resistant bedrock core with the downstream tail comprising unconsolidated sands, gravels and silts of variable permeability and limited storage for groundwater. These features have subsequently been incised and eroded by subglacial meltwater channels draining to the south. The moraine deposits (identified just to the south of the project area) likely comprise denser sediments: sands, gravels and laminated silts that may result in locally perched groundwater. Field examination of exposed sediment would be required to confirm this in detail.

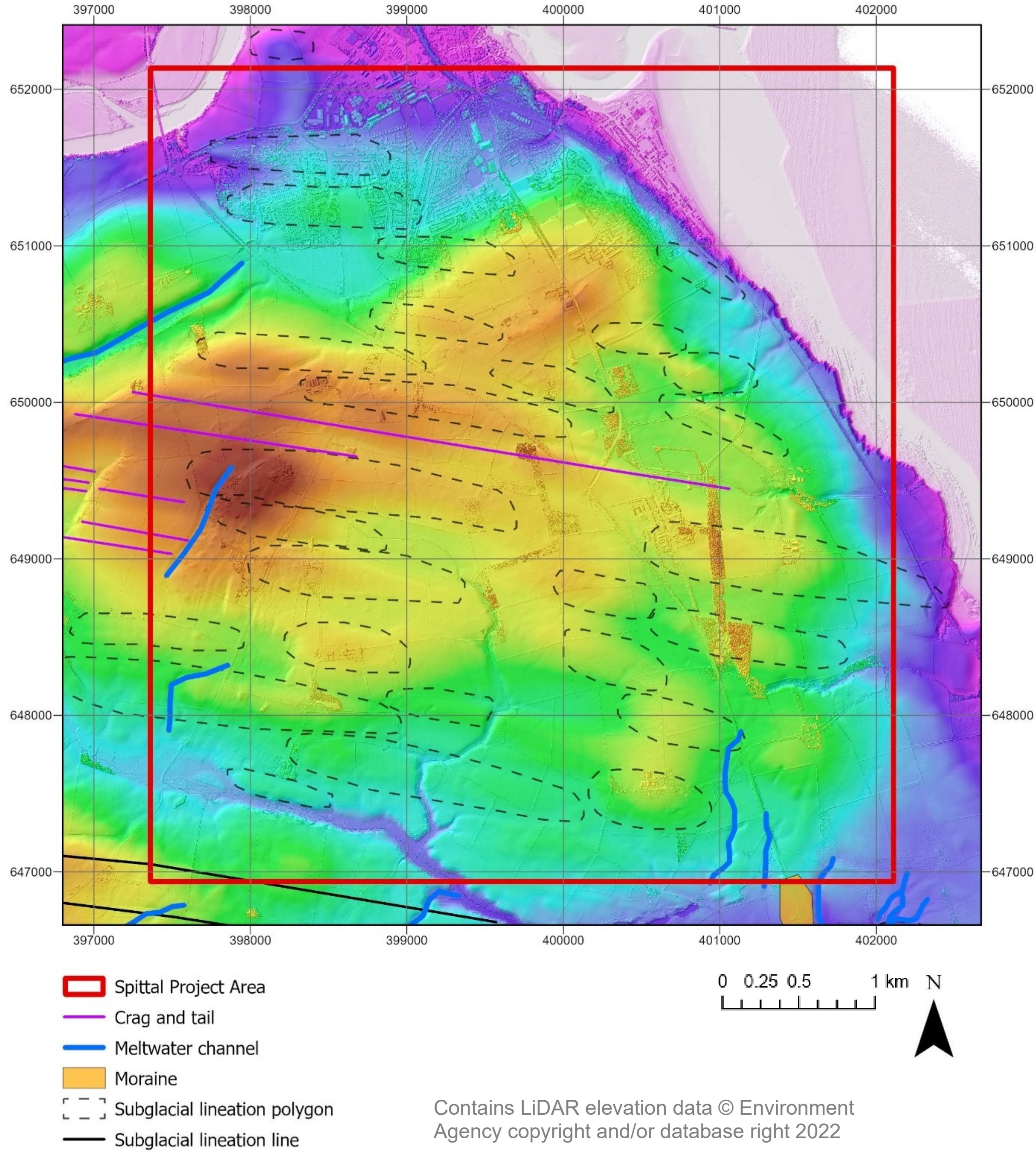

Figure 3 Glacial landforms in the project area identified in the BRITICE project (Clark et al, 2017)

1.3.1 Bedrock geology

The bedrock units in the Spittal area are Lower Carboniferous in age. The bedrock mapping of the northern half of the area was revised recently, with a re-assessment of the thickness of the Fell Sandstone Formation and greater detail added to the mapping of sandstone/mudstone dominated beds of the Fell Sandstone Formation (Kearsey et al., 2023). This new interpretation is shown in **Figure 4**, with the re-mapped area outlined in pink.

The rocks dip south-east, making the oldest rocks outcrop in the north-west and become progressively younger to the south-east. A fold axis runs roughly NW-SE through the eastern part of the project area, with the rocks to the western side having a shallow dip, whilst those on the eastern side dip much more steeply, up to 60°. The bedrock units are displaced by several

NW-SE trending geological faults, shown as blue lines in **Figure 4**. As stated, the bedrock was not directly considered, however, as much of the area is covered by a shallow thickness of superficial deposits (described further below in the report) it is important as a future input in developing the superficial hydrogeological domains further. The hydrogeology of the bedrock formations is characterised by interbedded aquifers and aquitards. Recent research on the hydrogeology for the Fell Sandstone Formation has been reported by Bianchi et al. (2023).

Table 1 lists the bedrock units in relative stratigraphic order from youngest to oldest. More information on the bedrock units can be found in the BGS Lexicon of Named Rock Units: https://www.bgs.ac.uk/technologies/the-bgs-lexicon-of-named-rock-units/

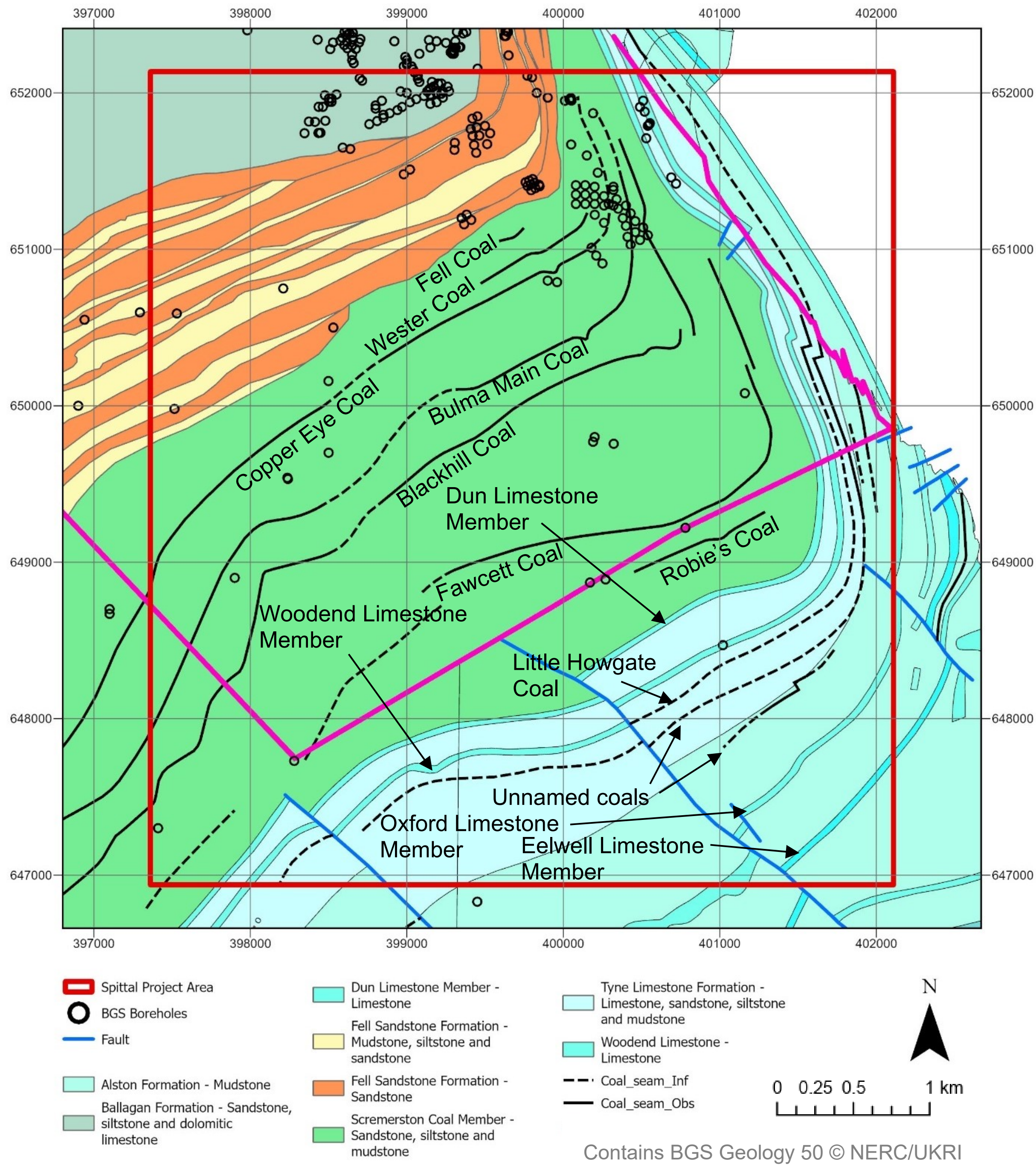

Figure 4 Bedrock geology map of the Spittal area, comprising the newly mapped area in the north (outlined in pink) and surrounding published BGS Geology 1:50,000 scale mapping (British Geological Survey, 2016b). Faults are shown as blue lines, coal seams are black solid/dashed lines. BGS © UKRI 2024

Table 1 Summary of bedrock units in the Spittal area

Unit name	Description
Alston Formation (AG-LSSM)	Youngest bedrock unit int the area. Composed of limestone, sandstone, siltstone and mudstone. Includes the Oxford Limestone Member (OXL-LMST), Eelwell Limestone Member (EWL-LMST) and an unnamed coal.
Tyne Limestone Formation (TYL-LMST)	Composed of limestone, sandstone, siltstone and mudstone. Includes Dun Limestone Member (DNL-LMST) and Woodend Limestone Member (WDEL-LMST). Includes the Little Howgate Coal and an unnamed coal.
Scremerston Coal Group (SCG-SDSM)	Composed of sandstone, siltstone and mudstone. Includes several coal named seams – Fell Coal, Wester Coal, Copper Eye Coal, Bulmer Main Coal, Blackhill Coal, Fawcett Coal and Robie's Coal.
Fell Sandstone Formation (FELL-SDST)	Bedded fine to coarse grained sandstone with siltstone, mudstone and locally developed thin coals. Divided into sandstone (SDST) and mudstone/siltstone/sandstone facies (MDSS) on the geology map.
Ballagan Formation (BGS-SSDL)	Oldest bedrock unit in the area. Composed of sandstone, siltstone and dolomitic limestone.

1.3.2 Superficial deposits

The most widespread superficial deposit in the Spittal area is till, which is composed of firm to stiff reddish clay with variable proportions of silt, sand and gravel. Glaciofluvial deposits, also of Devensian age, are mapped in a thin sliver on the eastern side of the River Tweed. In the absence of borehole evidence, these are inferred as consisting of sand and gravel, possibly with some clay. Clarke et al. (2017) identify streamlined crag and tail features and drumlins in the till topography and meltwater channels. The meltwater channels are carved into the bedrock according to the geology map as, with no mapped water-lain sediments (alluvium) or present day streams associated with them. However, they are likely to be the preferential route for present day surface drainage.

Fowler (1926) noted that the till could be divided between a lower clay with large boulders of local origin and an upper unit with finer more distally sourced gravels. He noted the variability in the thickness of the till (generally less than 3 m but with up to 8 m present at Scremerston Old Engine Pit). The occurrence of a "quicksand" below the till at Ancroft Tile Works south of the study area suggests the presence of water, at least locally.

Ridges, or drumlin features in the till were described by Fowler (1926) with reference to them comprising gravelly clay. It is also interesting to note that he suspected the material forming the ridges appeared to be more loosely aggregated than that forming the flatter areas. Locally, it was noted that there were sandy facies in the uppermost till.

Fluvial deposits mapped in the area comprise alluvium and river terrace deposits. Alluvium associated with rivers and streams is mapped in the River Tweed floodplain in the north-west and along Allerdeanmill Burn in the south. Alluvium is also mapped in isolated patches elsewhere. Two of these alluvium patches are located at the northern end of glacial meltwater channels. There is some uncertainty as to the interpretation of these alluvium patches, which may in fact be lacustrine or glaciolacustrine in origin, formed by ponding on the till surface. However, the original interpretation of alluvium has been kept until further evidence becomes available. Reinterpreting these patches as lacustrine or glaciolacustrine would not affect the hydrogeological domain because the composition would be very similar to alluvium (clay/silt dominated, which is considered an aquitard).

First order river terrace deposits are mapped on the north bank of the River Tweed in the north-west corner of the project area and are composed of sand according to the BGS Geology-50 superficial map of the area. However, a cluster of boreholes in another patch of first order river terrace deposits on the south side of the River Tweed just north of the study area describe the composition as clayey, sandy gravel.

Coastal deposits (marine & beach deposits, storm beach deposits) are mapped along the Spittal shoreline and in the River Tweed estuary (tidal river or creek deposits). Marine beach deposits are mapped along the shore at Spittal, and on both sides of the River Tweed in the north-west and north-east of the project area. Boreholes record a variable composition of sand, clayey sand gravel and cobbles. Tidal river or creek deposits are mapped in the tidal stretch of the River Tweed in the north-west corner of the project area. Like the River Tweed alluvium, these are assumed to be composed of clay underlain by sand and gravel.

Fowler (1926) stated that the town of Spittal stands on a raised or storm beach. Storm beach deposits are mapped near Spittal Point where their composition is described in boreholes as varying from sand, sand & gravel through to gravel & boulders. Decayed wood is recorded in some boreholes, and six boreholes record the presence of tar. A cluster of four boreholes that record tar is located at the former gas works on Spittal Point (although other nearby boreholes from the site do not record tar), and a further two are located at the Carr Rock slipways next to the lifeboat station (similarly, other nearby boreholes do not record tar).

Blown sand is mapped in a relatively small area on the coast at Spittal where boreholes record around 2 m of brown sand/silty sand.

A single small patch of peat is shown on the superficial geology map just outside the project area to the south. Because of a lack of boreholes in the area there is no thickness information. The peat is assumed to occupy a topographic hollow on the till surface and therefore be underlain by till.

A patch of river terrace deposits (undifferentiated) is mapped outside the project area to the west. It is shown in **Figure 5**, but falls outside the area considered for the hydrogeological domains, and is not described in **Table 2**.

The superficial deposits are described below and summarised in **Table 2**. More information on the superficial deposits can be found in the BGS Lexicon of Named Rock Units: https://www.bgs.ac.uk/technologies/the-bgs-lexicon-of-named-rock-units/

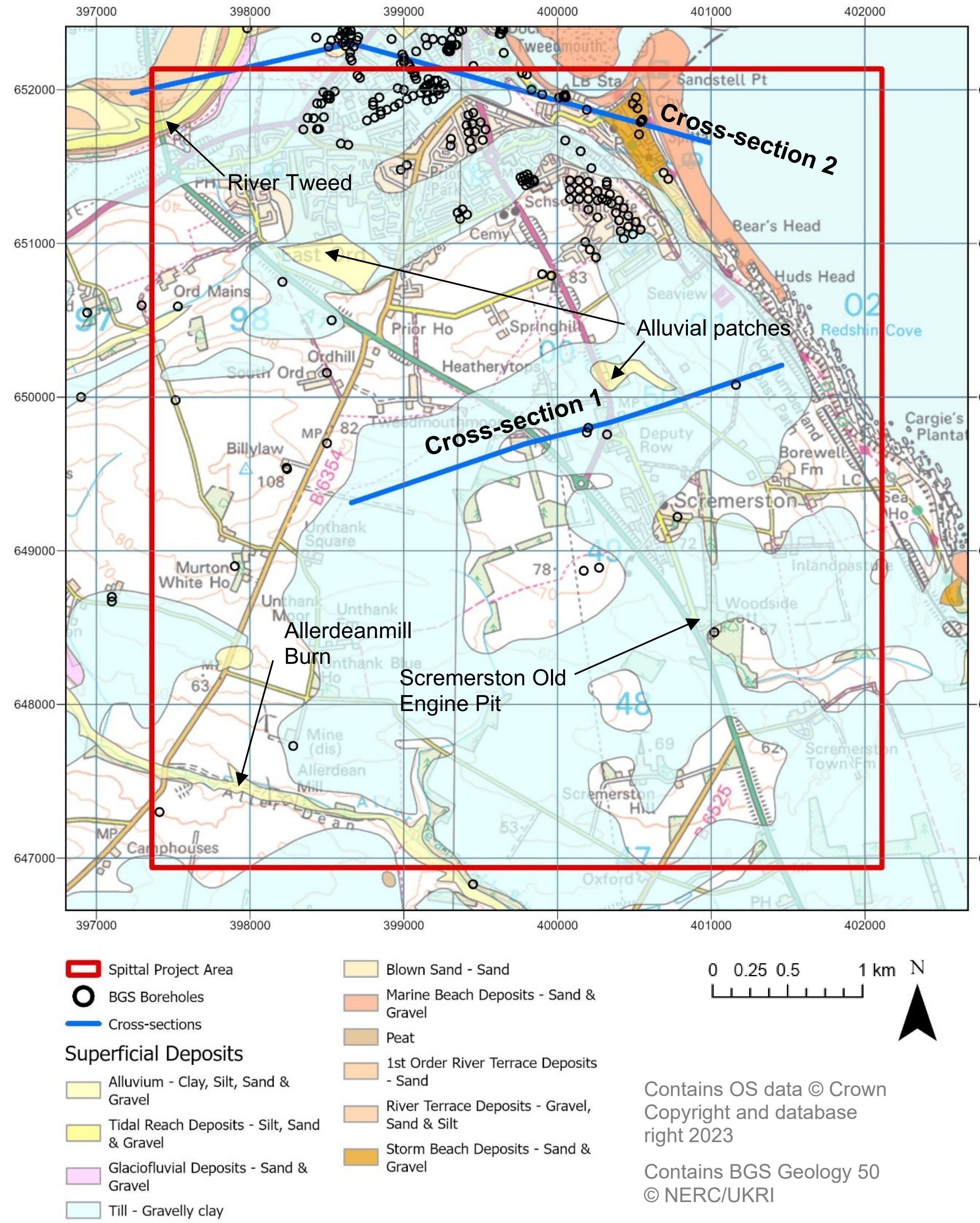

Figure 5 Published BGS Geology 1:50,000 scale geology map of the Spittal project area (British Geological Survey, 2016a). Superficial deposits are absent in areas where the topographic map is not covered by a polygon. BGS © UKRI 2024.

Two schematic cross-sections were constructed to show the inferred geometric relationships between the mapped superficial deposits and the underlying bedrock. Cross-section 1 is in the central part of the area of interest and shows the typical relationship between the till and bedrock for much of the area. The till is generally a thin veneer below the ground surface of 2 m or less in thickness, and in some areas is absent as shown through one of the 'windows' where the bedrock is exposed at surface (**Figure 6**). Cross-section 2 is in the north where the greatest variety and complexity in the superficial deposits occurs. This cross-section shows the fluvial deposits associated with the River Tweed, coastal sediments at Spittal Point, an isolated patch of alluvium, and glacial sediments around the Tweed valley (**Figure 7**) – note these are updated against the modified superficial deposit geological map with artificial ground features (**Figure 12**).

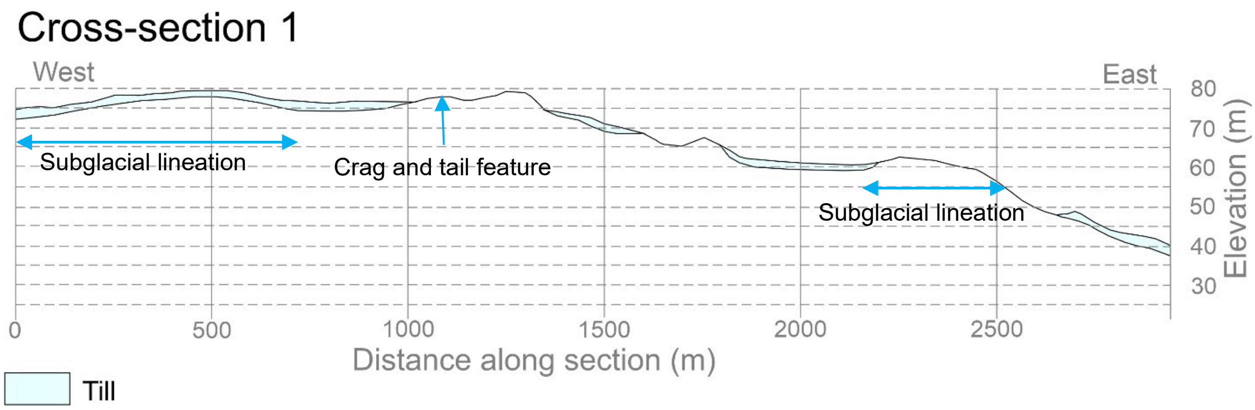

Figure 6 Schematic cross-section showing the till across the central part of the project area. Please see Table 1 for full description of units. BGS © UKRI 2024.

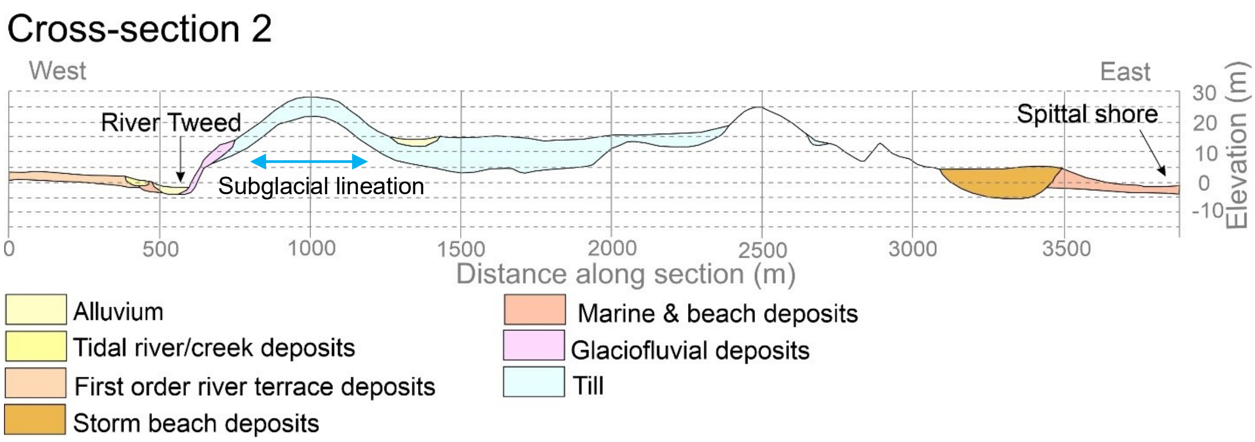

Figure 7 Schematic cross-section showing the superficial deposits in the northern most part of the project area. Please see Table 1 for full description of units. BGS © UKRI 2024

Table 2 Summary of superficial deposits in the Spittal study area.

Unit name	Description
Blown sand	Mapped along the coast at Bear's Head. Boreholes record around 2 m of brown sand/silty sand.
Peat	Mapped as a single isolated patch just outside the area to the south, assumed to be underlain by till.
Alluvium	R. Tweed - two boreholes just north of the area record 2 m of sandy silty clay over 2.1 m of firm laminated clay with a thin sand & gravel in between. A gravel lag is recorded beneath the clay to 6.1 m where the borehole terminates. Allerdeanmill Burn - there is no borehole evidence to confirm the composition of alluvium along Allerdeanmill Burn. This is inferred to consist of clay, silt and sand, possibly with some gravel and/or peat. Patches – the only borehole in a patch of alluvium is just north of area and records 'firm mottled red brown silty clay' underlain by 'soft-firm slightly laminated silty clay with a little gravel', with 'soft brown

Unit name	Description
	sandy clay' underneath. The borehole ends at 3.5 m without reaching the base of the clay.
Tidal river or creek deposits	Mapped in the north-west corner of the area along the River Tweed. Assumed to have a very similar composition to alluvium - two boreholes at the mapped boundary between alluvium and tidal river or creek deposits just to the north of the area record 2 m of brown to grey-orange mottled sandy silty clay with a thin clayey sand and gravel (0.15 m thick) at the base. This is underlain by 2 m of firm to stiff brown laminated clay. A gravel lag at the base consists of sandy gravel, at least 2 m thick (base of gravel not reached).
Marine beach deposits	Variable composition of sand, gravelly sand to sandy/clayey gravel, cobbly in places. One borehole records evidence of pollution: 'sand stratified with tar'. Recorded to a maximum depth of 9.15 m in a borehole without reaching the base.
Storm beach deposits	Variable composition of sand, sand & gravel, gravel & boulders with decayed wood in some locations. Several boreholes record evidence of pollution e.g. 'sand saturated with tar'. Recorded to a maximum depth of 22 m in a borehole without reaching the base.
River terrace deposits	Sand and gravel, locally with lenses of silt, clay or peat.
First order river terrace deposits	Mapped as sand but boreholes record fine to coarse gravel with a little gravel in a matrix of clay, around 1.5 m thick.
Till	Boreholes describe the till as firm to stiff reddish silty/gravelly/sandy clay with a maximum thickness recorded in boreholes of 7m.
Glaciofluvial deposits	In the absence of borehole evidence, this is interpreted as sand and gravel, possibly with a variable component of clay.

2 Methodology

2.1 BOREHOLE CODING

A total of 271 coded boreholes were collated, including 187 boreholes coded for the project along with boreholes and rockhead (base of the superficial deposits) picks from the BGS borehole database. Every single borehole available was considered in the Spittal study area, and no filtering was done based on borehole density or depth because of the clustered and sparse nature of the borehole coverage (described below). The vast majority are located around Spittal and the coverage elsewhere is sparse, especially in the south (**Figure 9**). Boreholes were coded into the BGS borehole geology database using the BGS coding scheme for superficial deposits (Cooper et al., 2006). The level of detail recorded in the logs varies enormously, from very detailed lithological descriptions through to only a generic description of the superficial deposits using terms such as ‘drift’. Some 16 boreholes could not be used include those as they provided no geological information or descriptions that commence below ground (beneath the superficial deposits, probably from old mines).

The lithologies in the borehole data are recorded as lettered codes referring to a specific sediment type and the first letter indicating the primary lithology (see Appendix 1). For example, the code ‘CSV’ indicates a clay (C) containing sand (S) and gravel (V) in order of decreasing relative proportions. Each individual combination of letters, i.e. each lithology code was assigned a permeability class as either ‘permeable’ or ‘low permeability’. This classification is based on the BGS Guide to Permeability Indices (Lewis et al., 2006) and previous work conducted in the Vale of York (Ford et al., 2003). The assignment for this project was based on the first two letters in the lithology code, to ensure that the presence of substantial amounts of clay within the matrix of mixed deposits was accounted for in the permeability attribution. Lewis et al. (2006) was the preferred schema for assigning a permeability class. However, lithologies that were not included in their classification were attributed according to Ford et al. (2003). In general, units containing clay or silt as a primary or secondary component are classified as having a ‘low permeability’, whereas units that are predominantly sand, gravel or larger are defined as ‘permeable’.

The above classification system was only applied to superficial sediments, i.e. bedrock and artificial layers are not considered in this analysis (although artificially modified ground was considered from mapped data). Boreholes recording undifferentiated superficial deposits (e.g. “drift”) were used to constrain the depth of rockhead (interpreted top of bedrock) but were excluded from the analysis of hydrogeological properties.

To reduce the number of coded layers into manageable divisions, the individual layers of the borehole data were summarised into units of the same permeability attribution (**Figure 8**). Such permeability units are referred to as either ‘aquifer’ or ‘aquitard’ – depending on their permeability attribution – in the following sections and form the basis for further analysis to inform the hydrogeological domain classification (see section 2.3).

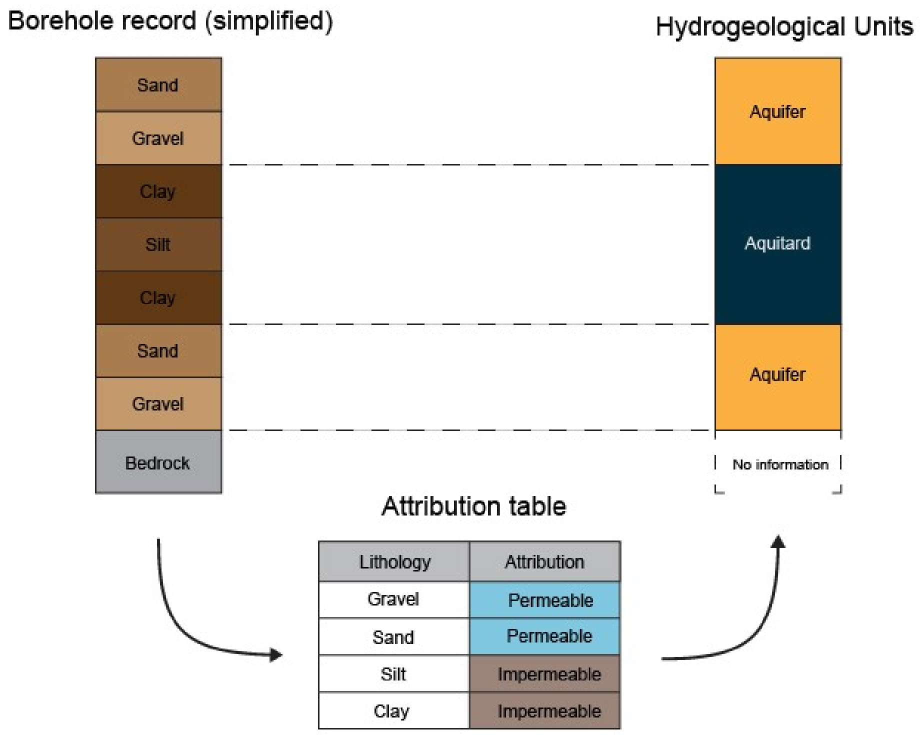

Figure 8 Illustration of the permeability attribution process for borehole data. BGS © UKRI 2024

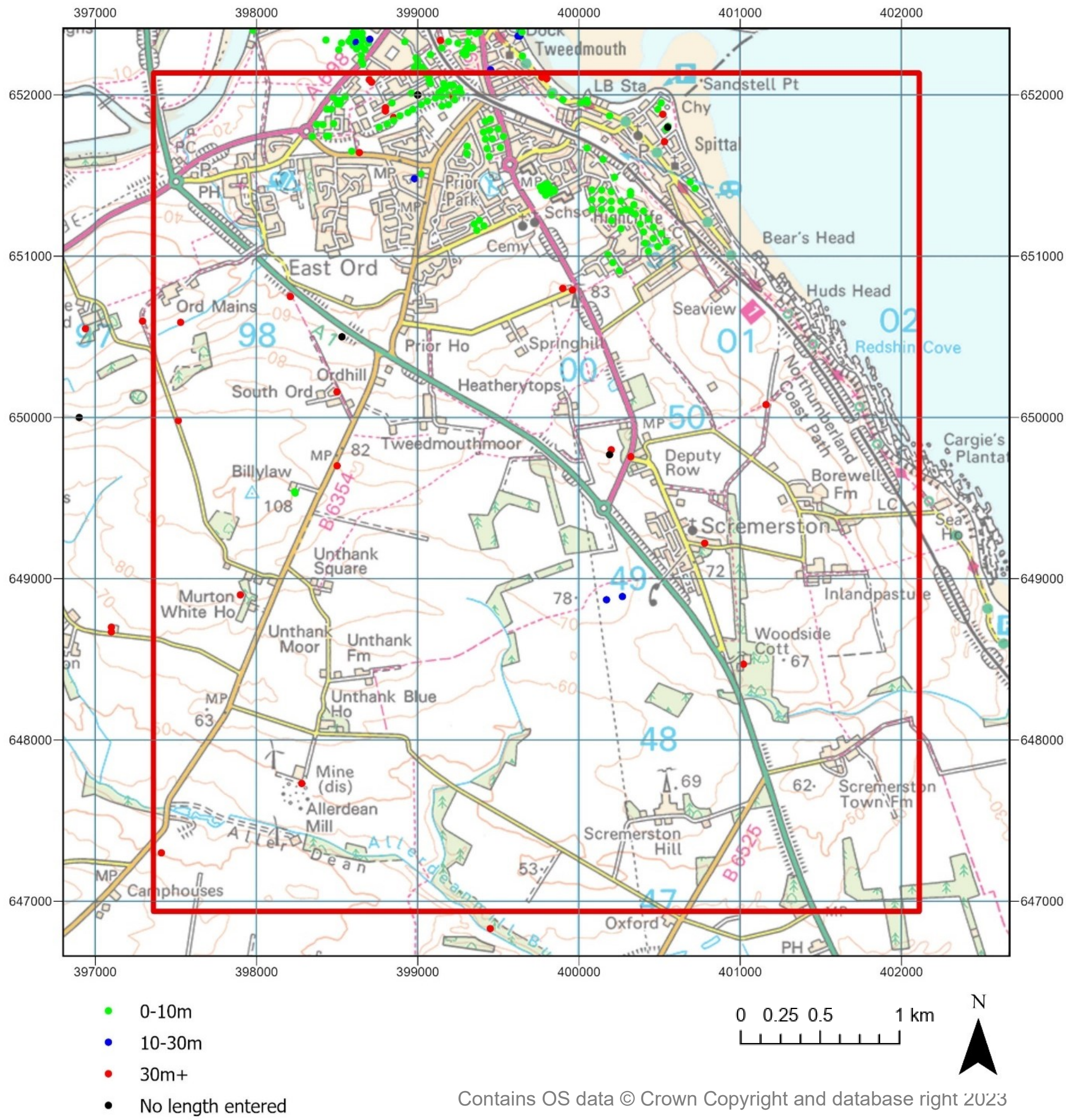

Figure 9 Map of boreholes in the Spittal area, colour coded according to drilled length. BGS © UKRI 2024

2.2 ARTIFICIAL GROUND CAPTURE

Artificially modified ground is defined as human made changes to the land level, either by removing material from the ground or placing material on it. BGS geology maps subdivide artificial ground into five categories: Worked Ground (WGR), where the land level has been lowered, e.g. quarries, road/railway cuttings; Made Ground (MGR), where the land level has been raised, e.g. road/railway embankments; Infilled Ground, i.e. worked & made ground (WMGR), where material has been removed from the ground and subsequently backfilled, e.g. infilled quarries; Landscaped Ground (LSGR), where the land has been engineered and the areas of cut and fill are difficult to separate out, e.g. site levelling for sports fields and industrial developments; and Disturbed Ground (DDGR), such as areas of bell pits where areas of worked/made/infilled ground are difficult to separate (**Figure 10**).

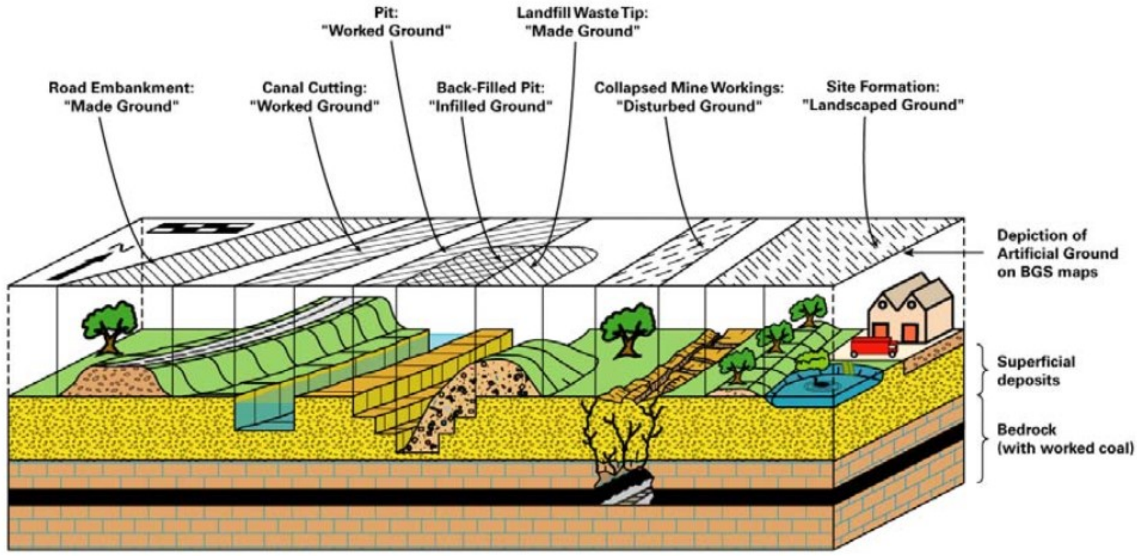

Figure 10 BGS artificial ground classification system (from Ford et al, 2006). BGS © UKRI 2024

Artificially modified ground information was captured specifically for the project. It is not included on the published geological maps and there was a lack of borehole data in large parts of the area. The lack of borehole data limits the depth to which the superficial hydrogeological domain classification at depth can be applied with confidence. Potential connectivity of the artificially modified ground with the sub-surface as indicated in **Figure 10** was the basis of the rationalisation for incorporation of the modified ground component of the project. The main source for artificially modified ground information is historic Ordnance Survey (OS) maps dating from 1866 to 1938, plus modern OS maps, aerial photographs, and the EA LiDAR terrain model. Surface workings such as coal pits are shown on historic OS maps, many of which have been backfilled and little evidence of them remains in the landscape (**Figure 11**). As well as surface coal workings, road and railway cuttings are included in the artificially modified ground layer, plus a clay pit associated with a former brick & tile works. Open pits are captured as WGR and backfilled workings are classed as WMGR. Areas of MGR, e.g. road/railway embankments and LSGR, e.g. levelled playing fields were also captured.

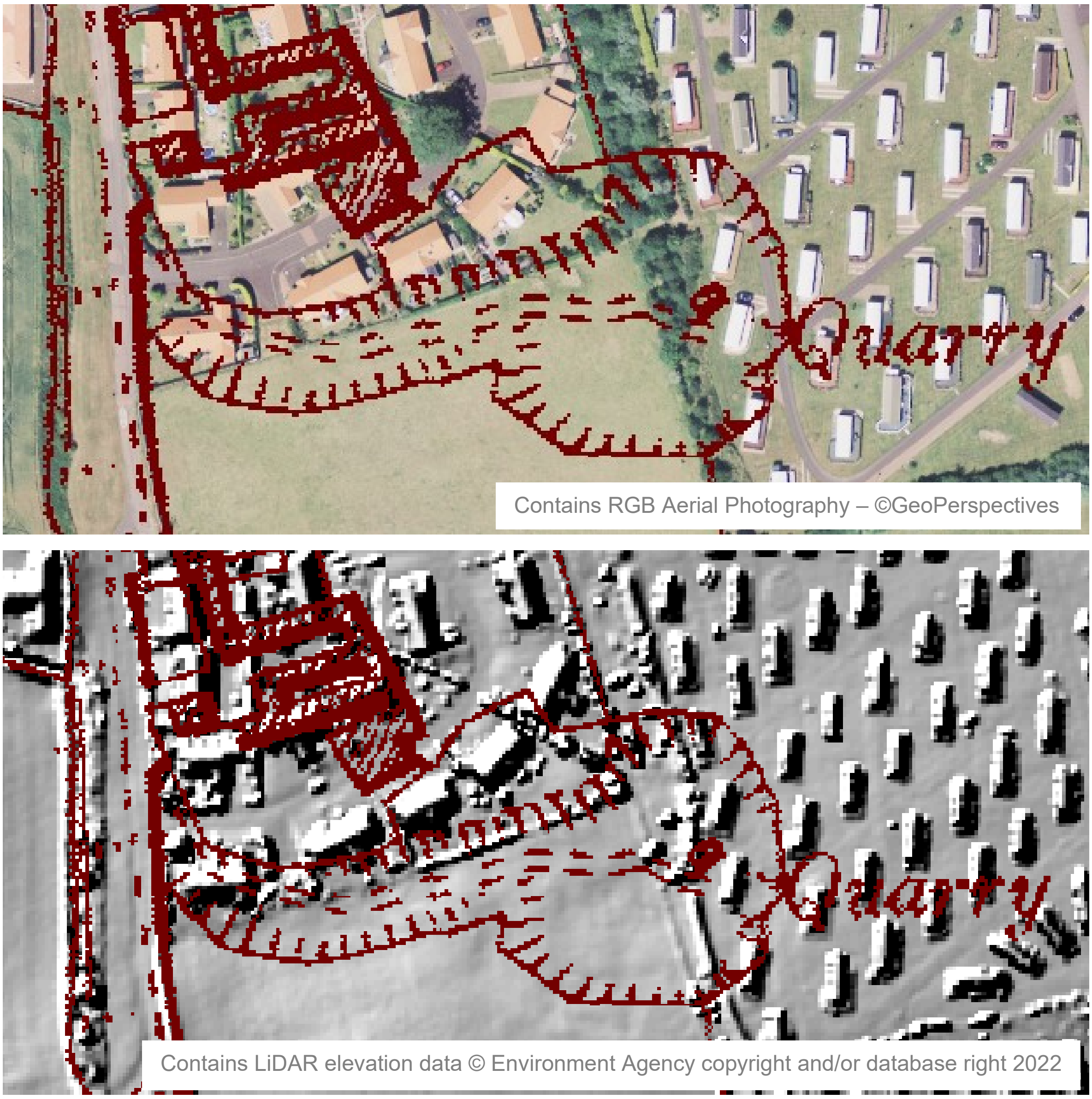

Figure 11 A quarry on historic map Northumberland 003 SE-03 1899 was captured as infilled ground because it is not shown on aerial photographs (top image) or LiDAR (bottom image)

Shafts associated with underground coal mining were captured from historic and modern OS maps, including air shafts because they may be old mine shafts. The shafts were captured as points and buffered by 50 m to allow for inaccuracies in the spatial registration of the historic OS maps. The buffered shafts were added to the artificial ground layer and classed as WGR.

The superficial geology map of the area was modified slightly using field slips and EA LiDAR to better match the topography and original lines. The hydrology analysis on the boreholes was used to modify the superficial deposits, for example, to extend the till into an area previously mapped as bedrock where a borehole recorded more than 2 m of an impermeable superficial unit. Areas of superficial deposits were removed where they coincide with WGR or WMGR in the artificial ground layer, including the buffered shafts to ensure these previously unmapped 'bedrock windows' are represented (**Figure 12**).

The artificially modified ground captured above, shows areas in which the superficial deposits have been altered or removed. For areas of Made Ground, Worked and Made Ground, and Landscaped Ground, the nature and make up of these are unknown and would need further investigation to establish the relationship between the superficial deposits and underlying bedrock. However, for the areas of Worked Ground (including shafts, open pits), an artificial conduit for the groundwater has been developed directly into the bedrock, and will directly impact the superficial hydrogeological domains in the Spittal area.

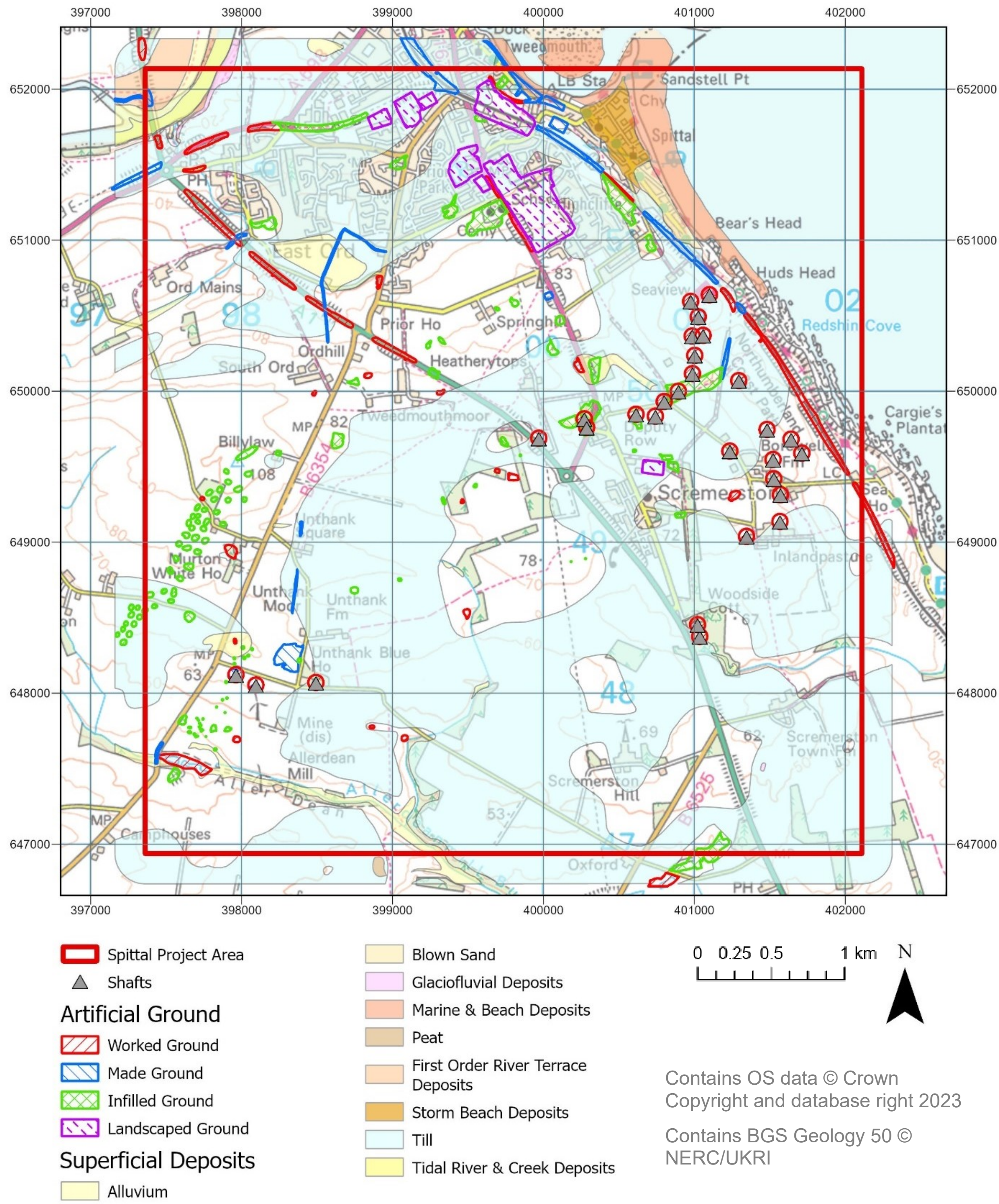

Figure 12 Map of artificial ground and mine shafts captured in the Spittal area. Superficial deposits that coincide with areas of Worked Ground and Infilled Ground were removed to represent previously unmapped 'bedrock windows'. BGS © UKRI 2024

2.3 SUPERFICIAL THICKNESS MAPPING

A superficial thickness model for the Spittal project area was derived from available borehole records in the project area. Additionally, input points with a thickness of zero were manually added to areas with no mapped superficial deposits on BGS Geology 1:50 000 scale maps to constrain areas with rock at the ground surface. These boreholes from the BGS database include both the coded records and those that have summary codes for undifferentiated superficial deposits.

These boreholes, together with the manually added '0' thickness points, were used to derive a preliminary interpolation which was compared to the remaining boreholes that did *not* reach rockhead (RH). Boreholes that did *not* reach RH were identified as having thicker superficial deposits than predicted by the preliminary interpolation. The terminal depth of these boreholes, with an additional 1 m added to reflect a conservative estimate of the true thickness, was used to constrain the final interpolation. In these areas, the true thickness of superficial deposits may be greater than predicted by the superficial thickness model. The model therefore reflects a minimum thickness of superficial deposits. In areas where there was a lack of borehole data to constrain the base of the superficial deposits, but superficial deposits were identified from geological maps, a minimum thickness of 2 m was applied. In reality the thickness could be less or more than that, nearer 1 m on the thinner side and potentially over 5 m in thickness on the thicker side but there is no other data to confirm this. The final interpolation was carried out in Esri ArcPro 3.2 using a Natural Neighbour algorithm with a cell size of 50 m.

2.4 HYDROGEOLOGICAL DOMAINS CHARACTERISATION

The same methodology used in the Gateshead area (Whitbread et al, 2024) was applied to generate the hydrogeological domains in Spittal. In Gateshead a classification scheme of six principal hydrogeological domains was developed to characterise the superficial deposits with respect to their potential for groundwater flow connectivity, four of which are present in the Spittal area. One of these was further divided into subdomains (For the final classification (domain 4), the combined data from the predominant borehole class and current superficial geological maps were considered, whereby the classes of the superficial deposit hydrogeological domains correspond to the classification applied to the borehole data. In areas where the superficial mapping shows one unit, but the boreholes show multiple hydrogeological classes, the superficial polygons were subdivided, and each part was allocated a corresponding hydrogeological domain classification. To delineate areas with a principal domain classification of 1, a maximum threshold of 2 metres was applied to the superficial deposits recorded in the boreholes. Superficial deposits less than 2 m thick and artificial ground of any thickness were considered to be permeable.

The hydrogeological domain classes are shown in **Table 3** and illustrated in **Figure 13**. To characterise the superficial deposits with respect to their potential for groundwater flow connectivity, the project area was subdivided into four principal domains, one of which is further subdivided into three subdomains. This classification was based on a combination of factors including thickness, predominant composition and sequence of boreholes in the respective area.

This classification was developed in consultation with project partners to reflect the need to assess both recharge to, and discharge from, underlying aquifers. It is based on a combination of unit thickness, predominant composition and the vertical sequence of strata.

Domain 1 is defined where superficial deposits are less than 2 m thick. Effectively 2 m is considered as the thickness below which any superficial deposits may be reasonably assumed to be permeable. Previous domain studies in the region (e.g. Price et al., 2007) have specified a 5 m threshold. However, the 2 m thickness threshold used in this study was defined following consultation and reflects a balance between the need for local understanding of recharge-discharge dynamics and the resolution of geological data.

The 2 m threshold for **Domain 1** is considered conservative given uncertainty in both the borehole depths (often due to uncertainty in the ground surface elevation), and the superficial deposits mapping. The latter is limited to deposits greater than ~1 m thick and may generalise areas where the coverage of thin deposits is patchy. The 2 m threshold is also reflective of typical weathering profiles, which may increase permeability in the upper 1 – 2 m of surface deposits, and relevant for typical depths of subsurface sewerage and water infrastructure.

Domain 2 was included to account for areas where thicker developments of permeable superficial deposits are present overlying bedrock. These areas have no aquitard (defined as more than 2 m of continuous low permeability deposits) present in the succession. Low permeability deposits (clay-dominated lithologies) less than 2 m thick may be present, but these thinner deposits are considered likely to be laterally discontinuous with a correspondingly higher likelihood of vertical and lateral continuity.

Where an aquitard comprising more than 2 m of continuous low permeability deposits is present in the deposits, the classification scheme differentiates zones based on the maximum thickness of continuous aquitard present (**domains 3 - 4**), and the relationship between the aquitard and an associated aquifer (> 2 m continuous thickness of higher-permeability deposits) if present. This approach was used to classify regions with no perched aquifer (sub-domain **3a**), an unconfined perched aquifer (sub-domain **3b**) and one or more confined perched aquifers (sub-domain **3c**).

Sand-dominated beds and lenses may vary in thickness from a few centimetres to tens of metres, with many less than 1 m thick. This high variability combined with limited borehole density means that in many areas it is not possible to correlate sand bodies laterally. The use of a 2 m thickness threshold to define an aquifer reflects a pragmatic balance between the vertical detail of a borehole and the lateral continuity of the respective units. Thinner units are more likely to be discontinuous and therefore a threshold of 2 m was selected as the lower limit for the domain mapping.

For the final classification (**Domain 4**), the combined data from the predominant borehole class and current superficial geological maps were considered, whereby the classes of the superficial deposit hydrogeological domains correspond to the classification applied to the borehole data. In areas where the superficial mapping shows one unit, but the boreholes show multiple hydrogeological classes, the superficial polygons were subdivided, and each part was allocated a corresponding hydrogeological domain classification.

To delineate areas with a principal domain classification of 1, a maximum threshold of 2 metres was applied to the superficial deposits recorded in the boreholes. Superficial deposits less than 2 m thick and artificial ground of any thickness were considered to be permeable.

Where no borehole information is available, the lithological information associated with the mapped unit was used to inform a bulk permeability attribute for each geological unit wherever it occurs in the project area. For geological units that are not covered by boreholes an assumed permeability was assigned based on the lithological information used in the BGS Geology superficial deposit layer (British Geological Survey, 2016). For example, the composition codes for till and alluvium are dominated by clay & silt, which is classed as an aquitard, whereas glaciofluvial deposits are classed as an aquifer because the lithology code in BGS Geology is sand & gravel.

Table 3 The superficial hydro-domains classification scheme. Rows are principal domains (1-4) based on total thickness of superficial deposits and thickest aquitard. Columns are subdomains (a-c) based on the sequence of permeability units as observed within individual boreholes (left units in column title are above right units). Note that subdomain classification a-c only applies to principal domain 3. Additional aquifers and aquitards in subdomain b and c are only considered if they equal or exceed 2 m in thickness. The thickest aquitard in subdomain c can be either the lower or upper aquitard in the sequence.

	Aquitard Glacial till Alluvium Peat	Aquifer | Aquitard Clay layer at the base of the storm beach deposits	Aquitard | Aquifer | Aquitard Alternating clay/gravel layers Allerdeanmill Burn
Superficial deposits < 2 m	1		
Superficial deposits > 2m no **aquitard** > 2 m	2		
Thickest **aquitard** 2 – 10 m	3a	3b	3c
Thickest **aquitard** 10 – 30 m	4		

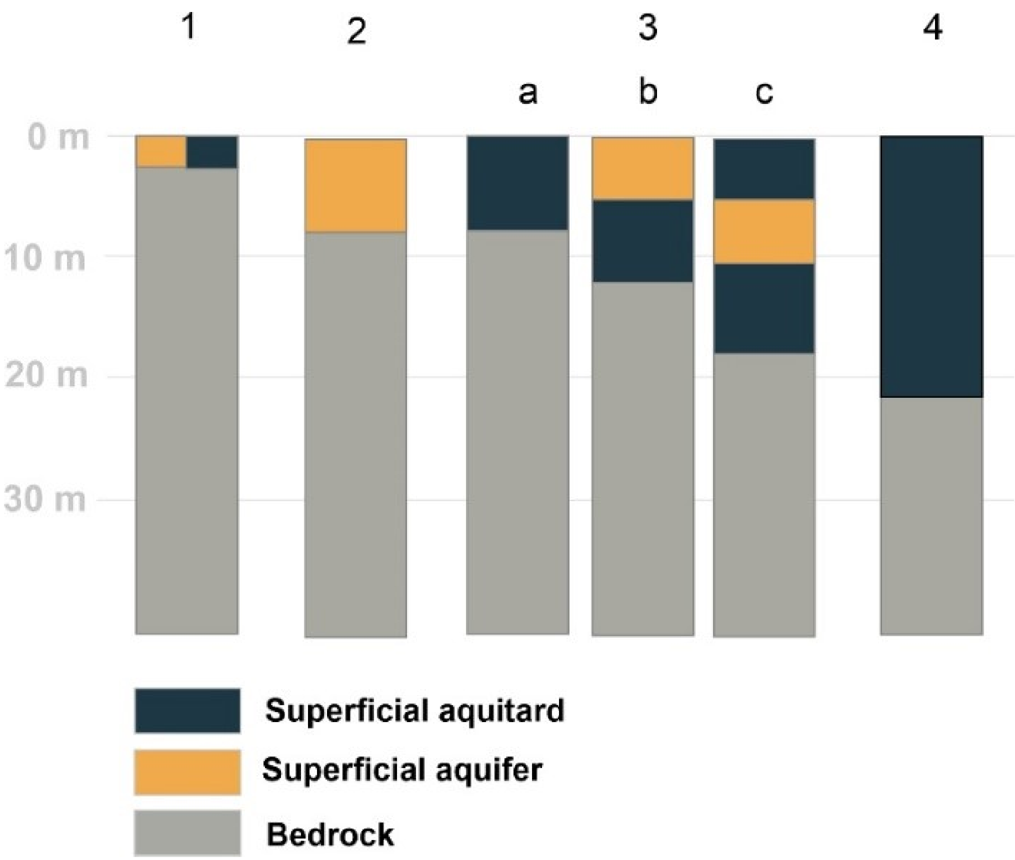

Figure 13 Schematic boreholes representing the hydrogeological domains in the Spittal area. BGS © UKRI 2024

2.5 HYDROGEOLOGICAL DOMAIN MAPPING

As illustrated in Whitbread et al (2024), boreholes were classified by domain. The same domains have also been mapped across the Spittal study area where applicable (shown in **Figure 16**) based on the combined data from the predominant borehole class, superficial geological maps, and regional geological understanding. The workflow used in the Gateshead area was followed to generate the hydrogeological domains, but the superficial thickness model was not used because of the uneven borehole distribution in the Spittal area. The process for mapping the domains is illustrated in **Figure 14**.

Areas in which superficial deposits are absent or thinner than 2 m correspond to domain 1. The area of domain 1 was delineated using a maximum threshold of 2 m applied to the updated superficial thickness model (**Figure 14**, steps 1-3). Note that areas where superficial deposits are absent can be identified from the BGS superficial geological map.

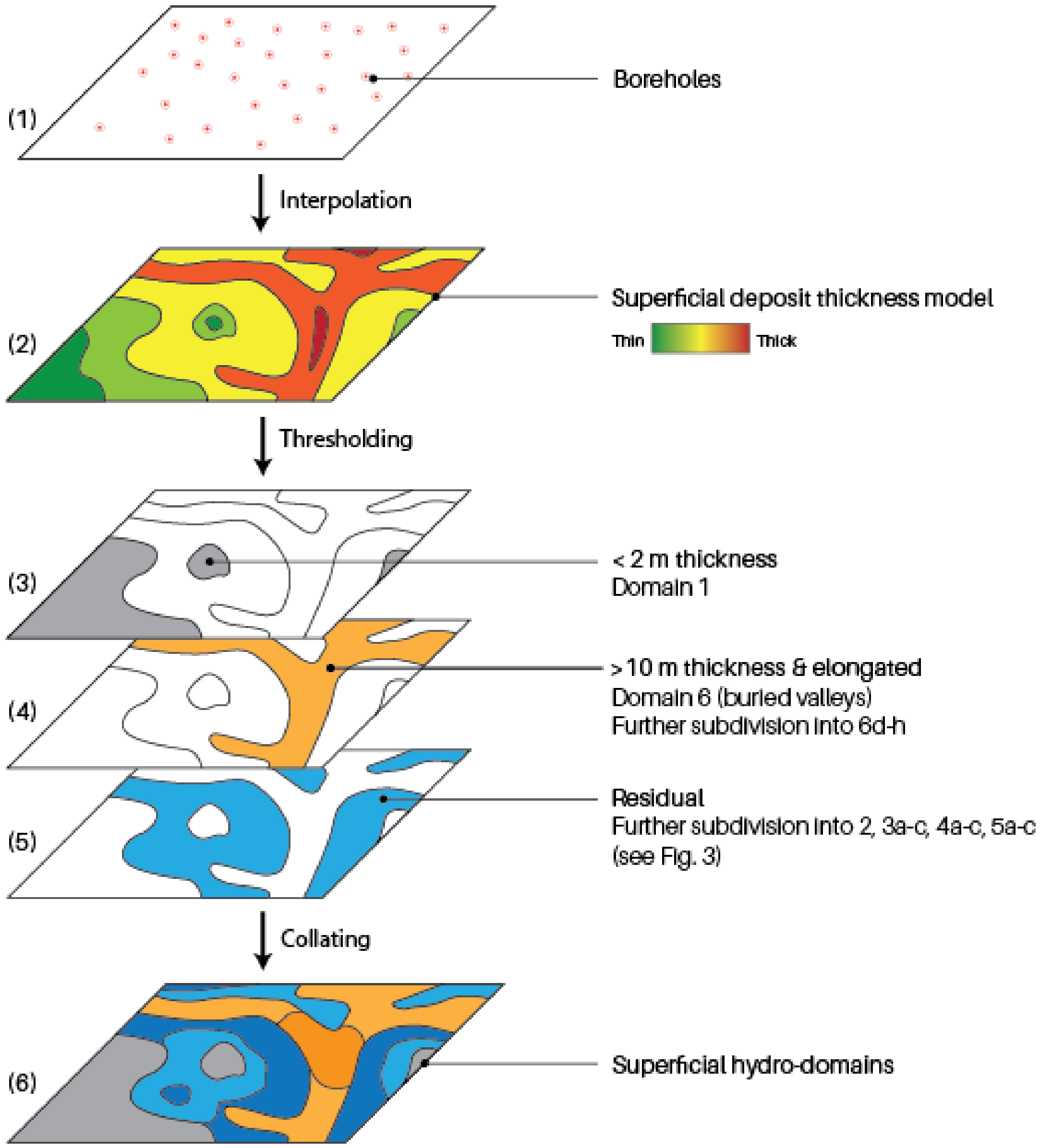

Figure 14 – Methodology for mapping the superficial hydrogeological domains (Whitbread et al, 2024). BGS © UKRI 2024.

3 Hydrogeological domains

3.1 SUPERFICIAL DEPOSIT THICKNESS MODEL

Modelled superficial deposit thicknesses vary from 1 to 20 m across the study area (**Figure 15**). The thickness sequences of superficial deposits were found in the northern parts of the Spittal study area coincident with the large borehole cluster in this area. Here they have a maximum thickness of 20 m, which coincides with the area of mapped storm beach deposits. Elsewhere the superficial thickness model is unreliable because the borehole data is sparse (**Figure 15**).

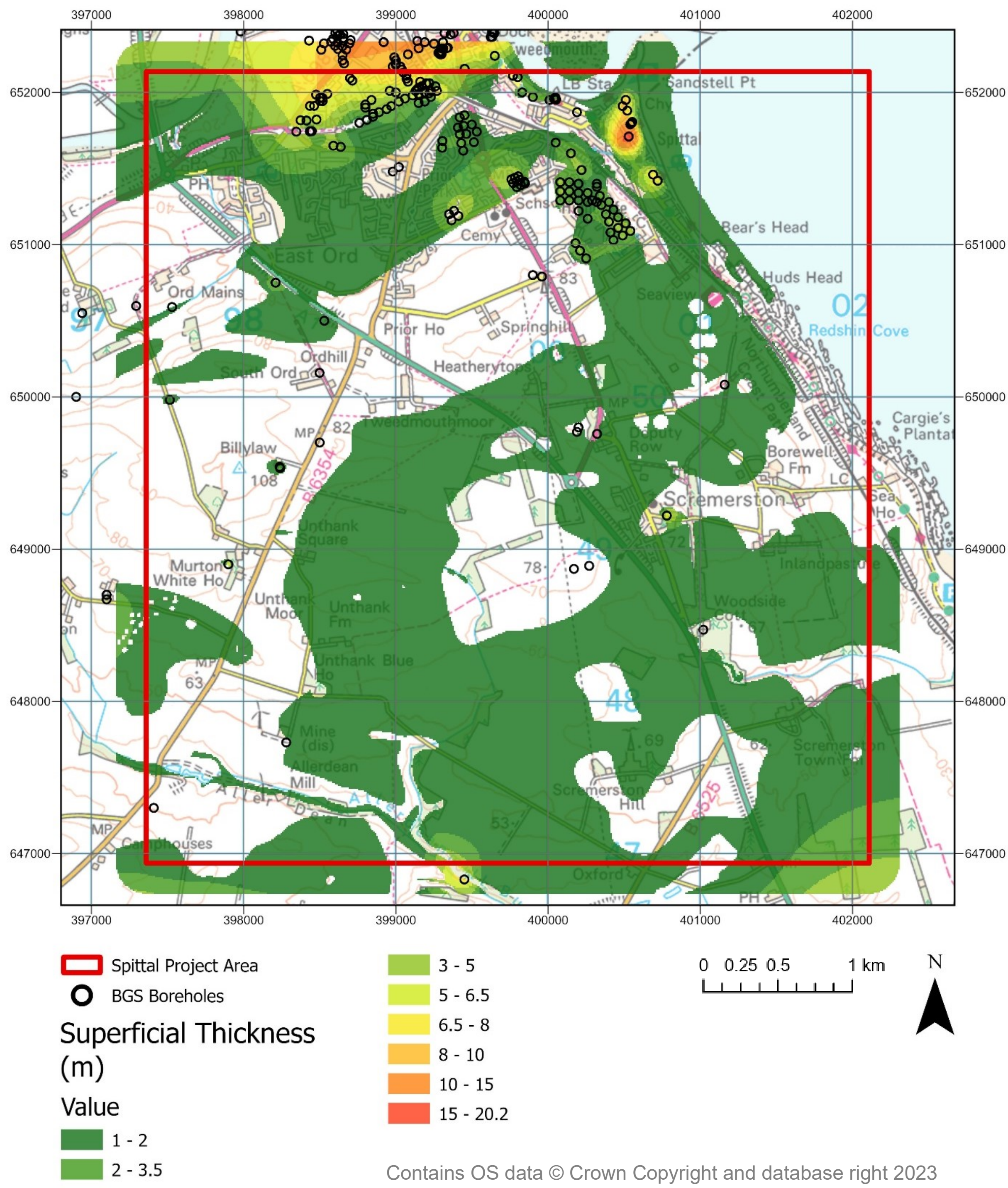

Figure 15 Superficial thickness model for the Spittal area with BGS borehole data. BGS © UKRI 2024

Due to the sparsity and clustered nature of the borehole data there was limited heterogeneity in the superficial thickness model found to inform the superficial hydrogeological domains directly across the whole of the Spittal study area. However, there are areas where the borehole data has informed the superficial hydrogeological domains, particularly for **Domains 3C** and **4 (Figure 16).**

3.2 SUPERFICIAL DOMAINS

Four main hydrogeological domains have been mapped in the Spittal area, with domains 1 and 3a being the most widespread (**Figure 16**).

Domain 1 has less than 2 m superficial thickness and bedrock at surface. Domain 1 includes a 50 m radius around coal mine/air shafts, where the superficial deposits have been removed to extract coal underneath, and areas where the superficial deposits themselves have been worked (e.g. clay pits for brick and tile making).

Domain 2 represents superficial deposits that are over 2 m thick but comprise only sand or sand & gravel (i.e. no aquitard). This includes areas mapped as storm beach deposits, river terrace deposits, marine beach deposits and blown sand. Domain 2 also includes some areas currently mapped as till, which is typically clay dominated (and would therefore be classed as an aquitard), but boreholes indicate localised sand & gravel dominated lithologies (aquifer).

Domain 3 is divided into three subdomains (**3a**), (**3b**), and (**3c**). **Domain 3a** is defined by aquitards with a thickness range of 2-10 m. This corresponds with areas mapped as till and alluvium, which are typically clay dominated, and a patch of peat just south of the study area. In the south of the area where boreholes are absent the till and alluvium have been given an assumed thickness of more than 2 m, but in reality these deposits may be thinner in places.

Domain 3b is characterised by an aquifer overlying an aquitard, where the aquitard is 2-10 m thick. **Domain 3b** only occurs in two isolated areas: a patch within the area of mapped storm beach deposits, constrained by several boreholes. A second very small patch occurs in the till at Highcliffe, constrained by a single borehole, on the edge of a cluster, but there are no other boreholes to the north or east. This second patch of **Domain 3b** at Highcliffe is coincident with the bedrock that has been remapped for the Fell Sandstone Formation (**Figure 17**).

Domain 3c is composed of multiple aquifer/aquitard layers where the thickest aquitard is 2-10 m thick. This domain only occurs in one area, which corresponds with the mapped alluvium along Allerdeanmill Burn. This classification is based on a single borehole and there may be lithological variation in reality.

Domain 4 consists of a vertically continuous aquitard with a thickness range of 10-30 m. This domain only occurs in one isolated area associated with a single borehole where till is mapped. This domain is reasonably well constrained, with other boreholes located within 100 m to the south, west and north.

Table 4 Summary of domain descriptions

Sub-Domain	Domain Name	Summary description of domain	% coverage
1	Superficial deposits < 2 m	**Limited superficial cover.** Less than 2m of superficial deposits regardless of deposit type. Includes areas where rock is at surface and areas with till / glaciofluvial deposits / other deposits where they are less than 2m.	40%
2	Superficial deposits > 2m no **aquitard** > 2 m	**No superficial aquitard.** Areas where superficial deposits exceed 2 m but no aquitard greater than 2m thick is present. This occurs in an area were glaciofluvial deposits and glacial till are mapped but the till is locally described in boreholes as comprising sand & gravel or sand & boulders.	5%
3a	2 – 10 m **aquitard**	**Moderate thickness of superficial aquitard, no superficial aquifer.** Areas where 2 - 10 m continuous thickness of clay-dominated deposits, but no sand-dominated deposits greater than 2 m thick, are present. This predominantly includes areas of thicker glacial till.	54%
3b	**Aquifer** > 2 m overlying **aquitard** 2 – 10 m	**Superficial aquifer at surface, above a moderate thickness of superficial aquitard.** Areas where 2 - 10 m continuous thickness of clay-dominated deposits are overlain by sand-dominated deposits greater than 2 m thick. This predominantly includes areas of glaciofluvial deposits or sandy alluvium overlying till.	< 1%
3c	**Aquifer** > 2 m between **aquitard** 2 – 10 m	**Superficial aquifer within superficial aquitard of moderate thickness.** Areas where sand-dominated deposits (aquifer) greater than 2 m thick are present within a clay-dominated sequence where a continuous sequence of 2 - 10 m aquitard is present below the aquifer, and >2m aquitard occurs above. This reflects perched aquifers glaciofluvial deposits within or between layers of glacial till.	< 1%
4	**Aquitard** 10 – 30 m	**Thick superficial aquitard, no superficial aquifer.** Areas where 10 – 30 m continuous thickness of clay-dominated deposits, but no sand-dominated deposits greater than 2 m thick, are present. This predominantly includes areas of thicker glacial till.	< 1%

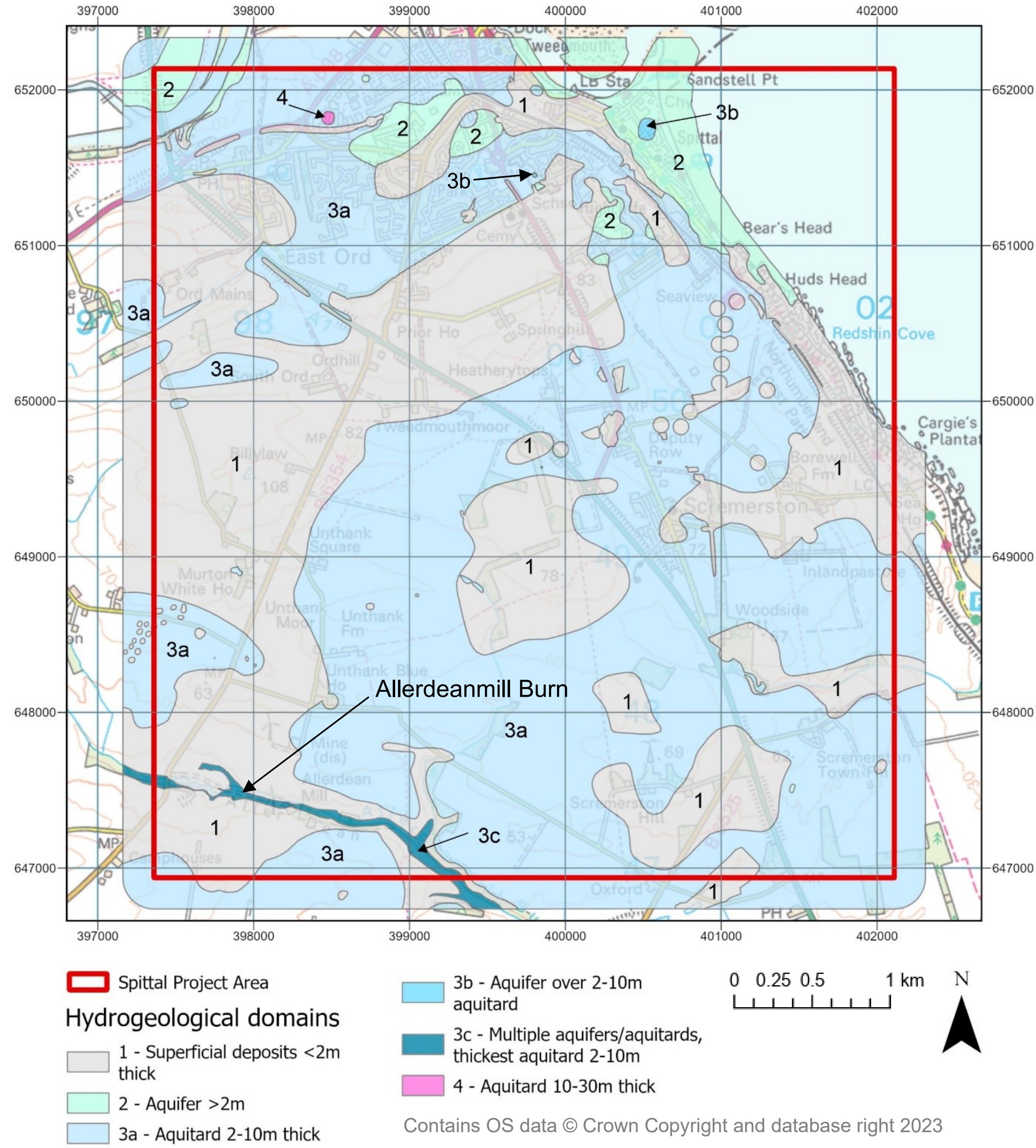

Figure 16 Hydrogeological domain map for the Spittal area. BGS © UKRI 2024

4 Limitations

Hydrogeological parameterisation

The boreholes are attributed for permeability following a binary attribution (Appendix 2). This is a considerable simplification of the very wide permeability range of porous geological media (e.g., Fetter 2018). Any analysis is highly dependent on the initial classification scheme, i.e. the outcomes presented here might change even if only small changes were made to the attribution.

Borehole records and descriptions

Borehole data used in this study is largely third-party data supplied to BGS, with records ranging from over 100 years old to the present day. The quality of the descriptions of lithologies are variable. In addition, the inclusion of AGS boreholes with engineering geological logs means that definitions of sediment types differ from standard geological descriptions. Differences between geological and engineering geological logs affect the attributions of boreholes used to inform the analysis. This has been considered in the interpretation and mapping of the domains, but still represents a limitation of the current study.

- **See recommendations 1 and 2**

Borehole coverage and geological complexity

Boreholes are concentrated in the Spittal area and are very sparse elsewhere, particularly in the south. This makes it difficult to extrapolate any lithological and thickness information or hydrogeological interpretations between the boreholes. Therefore, some of the hydrogeological domains appear to be very localised to honour the data but may extend further in reality.

- **See recommendations 3**

Geological maps

The age of the geological maps places considerable uncertainty on the accuracy of superficial and bedrock mapping in the area. The last geological survey of the area was carried out in 1851-1860 at six-inch scale (pre–National Grid). Spittal is also covered by 1:50,000 scale map Berwick-upon-Tweed and Norham (sheets 1&2), published in 1977 but based on the original six inch maps. The mapping of till in particular is uncertain; the Berwick-upon-Tweed memoir states that the till is difficult to map and the boundaries shown on the geological maps are approximate (Fowler, 1926). There is also some uncertainty as to the interpretation of the alluvial patches, which may in fact be lacustrine or glaciolacustrine in origin. Where superficial deposits are mapped with certainty it can be assumed that the ‘one metre rule’ has been applied, where a deposit is included on a geological map where it reaches a minimum thickness of 1 m.

The river terrace deposits, glaciofluvial deposits and alluvium do not have any corresponding boreholes to prove their composition or thickness. For these units an assumed permeability was applied using the primary lithology attribute in BGS Geology 50K superficial, e.g. aquifer for sand/gravel dominated glaciofluvial deposits and river terrace deposits, and aquitard for clay/silt dominated alluvium.

Where borehole data is absent the superficial deposits are given an assumed thickness of at least 2 m. In reality a feather edge would be present around the margin of the superficial deposits where they pinch out, but it is impossible to determine how far from the edge the deposits start to thin.

- **See recommendation 4**

Integration of other data sources

Integration of other hydrogeological factors such as the distribution of bedrock aquifers, mining information, and local hydrology such as springs and topographic focussing of flow was beyond the scope of this work. Bedrock hydrogeological properties (aquifers and aquitards) and structure (geological faults) have not been considered in the hydrogeological domains. However, in areas where the superficial deposits are thin the bedrock may influence the domain response. In addition, only the superficial deposits that occur onshore have been considered in this project.

- **See recommendations 3 and 5**

Artificially modified ground

Artificial modified ground is only considered where it has a direct impact on the superficial deposits, i.e. where the superficial deposits have been removed through mineral workings or road/railway cuttings. Boreholes record the presence of made ground elsewhere (coded as undifferentiated artificially modified ground in the BGS borehole database) and the composition information is stored as free text. This reveals the presence of aquifers (e.g. ash) and aquitards (e.g. clay) within the made ground that overlies the superficial deposits/bedrock. However, this was not considered in the superficial hydrogeological domains.

- **See recommendations 3 and 6**

5 Recommendations

The following recommendations reflect opportunities for future data acquisition and further work to better characterise the extent and connectivity of sand bodies, improve the hydrogeological attribution and reduce uncertainty in the mapping of the domain areas.

Relatively low-cost work to reduce uncertainty and enhance the mapping of superficial hydrogeological domains could be undertaken by combining some or all of recommendations 2, 3, 4, 5 and 6.

Recommendation 1: Future cored drilling of the superficial deposits to allow for detailed geological logging of the superficial sequence would be highly beneficial for constraining the hydrogeological parameterisation of the deposits and providing a basis for evaluating the descriptions provided in existing borehole data.

Recommendation 2: Detailed sedimentary logging and hydrogeological characterisation of sections in the field would provide high quality descriptions of key geological units to better constrain the range of lithological variability and hydrogeological properties in key units such as glacial till and glaciofluvial deposits.

Recommendation 3: Targeted acquisition of borehole records from third parties (e.g. the EA, Gateshead Council, local contractors etc including offshore data), particularly in the complex areas identified in this study, and where high-quality lithological logs down to rockhead are available. Mine records and other legacy data not held by the BGS could also help fill in some of the gaps in the Spittal study area where there is a lack of borehole data. This may give depth to rockhead as well as details on the lithological variation found within the superficial deposits.

Recommendation 4: A field survey to re-map the superficial deposits would provide greater detail on their distribution, composition and geometric relationships. This would also consider borehole data, and revisions could be made where the lithology recorded in boreholes contradicts the geological map. Alongside, non-invasive geophysical methods (e.g. passive seismic using a Tromino device) could be used to better estimate the depth of the superficial deposits and give a clearer indication of the superficial deposit geometry close to bedrock outcrop.

Recommendation 5: The superficial hydrogeological domains can be combined with analysis of the distribution of mine workings, and sandstone units within the underlying bedrock to generate full groundwater system domains. In addition, information relating to groundwater levels and springs could be integrated to provide further analysis of the groundwater system. This may be particularly useful in focus areas where groundwater flooding or mine water discharge are known to occur. This is particularly relevant for Allerdean Burn, where water samples taken from the upper reaches of the burn have a different chemical signature to the deeper groundwater, indicating a shallow aquifer source or a perched aquifer reaching the ground surface. Further consideration could be given to the hydrogeological properties of the bedrock, such as whether they behave as aquifers or aquitards, and the relationship between the superficial deposits and the bedrock. There seems to be a correlation between the superficial deposit limits and the depiction of the superficial hydrogeological domains in the northern part of the area which would warrant further investigation of the study if it was to be extended into the bedrock. This occurs at the southern limits of the outcrop of the Fell Sandstone Formation between domains **1** and **3a** (**Figure 17**).

Recommendation 6: Significant areas of artificially modified ground have been identified across the Spittal study area. A re-analysis of the BGS borehole data and third-party data (see Recommendation 3) may reveal the detailed composition of the artificially modified ground akin to what you would find in a borehole with superficial deposits logged. This may adjust the thickness and lithological variation of the deposits above the underlying bedrock, and would be reflected in a new superficial hydrogeological domain classification in the Spittal study area.

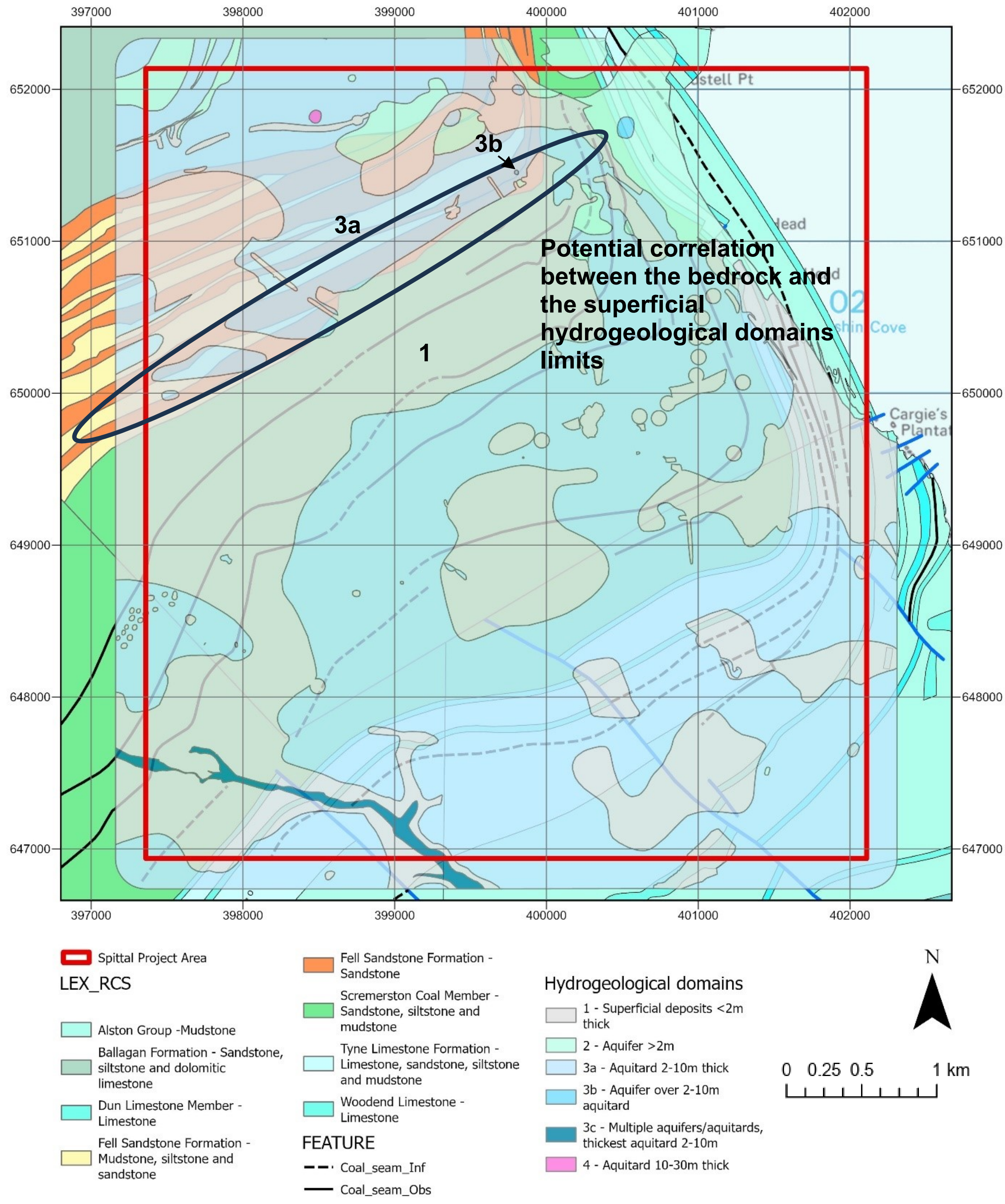

Figure 17 Superficial hydrogeological domains and bedrock correlation. BGS © UKRI 2024

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Glossary

Alluvial – deposits associated with rivers and streams

Diamicton – a general term used to describe poorly-sorted sediment containing a wide range of particle sizes

Crag and tail – a streamlined ridge or hill resulting from glaciation, consisting of a ‘crag’ of resistant bedrock with an elongate body (the ‘tail’) of more erodible bedrock on the leeward side. The long axes are roughly parallel to the ice movement direction

Drumlin – an elongated hill consisting of unconsolidated material and commonly occurring in swarms. Drumlins can reach 60 m in height and several hundreds of metres in length. They form under ice sheets or very broad valley glaciers. The long axes are approximately parallel to the direction of ice movement, and are typically steepest and highest at the end that faced the advancing ice, and slope gently in the direction of movement

Glacial till – a deposit formed under glaciers through the deposition of material eroded and entrained within moving ice. It is commonly firm to stiff and poorly-sorted, with gravel, cobbles and boulders embedded in a matrix comprising variable amounts of clay, slit and sand.

Glaciofluvial – this term is used for landforms and deposits created by the action of streams sourced directly from the melting of glacier ice

Glaciolacustrine – this term refers to landforms and deposits associated with lakes created adjacent to or beneath glaciers

Laminated - refers to the presence of fine layers developed within a rock or sediment deposit which are typically less than 1mm to several mm in thickness

Meltwater channel – valley-like feature that forms as glacial meltwater flows over the land surface and erodes the underlying rocks/sediments. Meltwater channels form close to glacier ice margins either below the ice or close to the edges. They can vary in size, but are typically U-shaped

Moraine – an accumulation of rock material that has been carried or deposited by a glacier. It ranges in size from boulders to sand, and shows no bedding or sorting. Different types of moraine are classified according to the nature of the landform

Subglacial lineation – streamlined landforms such as drumlins and crag and tails that form underneath ice sheets or glaciers. They can be metres to tens of kilometres in length and their long axes align parallel to the ice movement direction

Appendix 1 Lithological codes for superficial deposits

The coding scheme for unlithified deposits from Cooper et al. (2006), with examples illustrating the construction of composite codes.

Lithology	Code
Clay	C
Silt	Z
Sand	S
Gravel	V
Cobbles	C
Boulders	B
Peat	P
Examples of composite codes	
Clayey SAND	SC
Silty SAND	SZ
Gravelly, silty SAND	SZV
Silty sandy CLAY	CSZ

Appendix 2 Lithological attribution used for borehole data

Lithology code	Primary Lithology	Attribution
B	B	permeable
BC	B	permeable
BCS	B	permeable
BL	B	permeable
BLC	B	permeable
BLS	B	permeable
BLV	B	permeable
BLVC	B	permeable
BS	B	permeable
BSC	B	permeable
BV	B	permeable
C	C	low permeability
CB	C	low permeability
CL	C	low permeability
CLAY	C	low permeability
CLB	C	low permeability
CLGV	V	low permeability

CLSA	S	low permeability
CLSGV	V	permeable
CLVS	C	low permeability
CP	C	low permeability
CPS	C	low permeability
CPSV	C	low permeability
CPV	C	low permeability
CS	C	low permeability
CSB	C	low permeability
CSL	C	low permeability
CSLB	C	low permeability
CSP	C	low permeability
CSV	C	low permeability
CSVB	C	low permeability
CSVBL	C	low permeability
CSVL	C	low permeability
CSVLB	C	low permeability
CSZ	C	low permeability
CSZV	C	low permeability
CSZVB	C	low permeability
CSZVLB	C	low permeability
CV	C	low permeability
CVB	C	low permeability
CVBZ	C	low permeability
CVL	C	low permeability
CVLB	C	low permeability
CVLS	C	low permeability
CVP	C	low permeability
CVS	C	low permeability
CVSB	C	low permeability
CVSL	C	low permeability
CVSLB	C	low permeability
CVSZ	C	low permeability
CVZ	C	low permeability
CVZS	C	low permeability
CZ	C	low permeability
CZB	C	low permeability
CZL	C	low permeability
CZP	C	low permeability
CZS	C	low permeability
CZSB	C	low permeability
CZSL	C	low permeability
CZSV	C	low permeability
CZSVB	C	low permeability
CZSVL	C	low permeability
CZSVLB	C	low permeability
CZV	C	low permeability

CZVS	C	low permeability
GRAV	V	permeable
L	L	permeable
LB	L	permeable
LBC	L	permeable
LBCS	L	permeable
LBV	L	permeable
LBVS	L	permeable
LC	L	permeable
LCS	L	permeable
LCSV	L	permeable
LCV	L	permeable
LSC	L	permeable
LSV	L	permeable
LV	L	permeable
LVB	L	permeable
LVC	L	permeable
LVCS	L	permeable
LVS	L	permeable
LVSC	L	permeable
LVSZ	L	permeable
P	P	low permeability
PC	P	low permeability
PCS	P	low permeability
PECL	C	low permeability
PESA	S	permeable
PSC	P	low permeability
PSV	P	low permeability
PV	P	low permeability
PZ	P	low permeability
PZC	P	low permeability
PZS	P	low permeability
S	S	permeable
SACL	C	low permeability
SAGR	S	permeable
SANDU	S	permeable
SB	S	permeable
SC	S	low permeability
SCB	S	low permeability
SCL	S	low permeability
SCLB	S	low permeability
SCPV	S	low permeability
SCV	S	low permeability
SCVB	S	low permeability
SCVL	S	low permeability
SCVLB	S	low permeability
SCZ	S	low permeability

SICL	C	low permeability
SILT	Z	low permeability
SL	S	permeable
SLV	S	permeable
SNDGVI	V	permeable
SP	S	permeable
SPV	S	permeable
SV	S	permeable
SVB	S	permeable
SVC	S	permeable
SVCL	S	permeable
SVCLB	S	permeable
SVCZ	S	permeable
SVL	S	permeable
SVLB	S	permeable
SVLZ	S	permeable
SVZ	S	permeable
SVZC	S	permeable
SVZL	S	permeable
SVZLB	S	permeable
SZ	S	permeable
SZB	S	permeable
SZC	S	permeable
SZCV	S	permeable
SZL	S	permeable
SZP	S	permeable
SZV	S	permeable
SZVL	S	permeable
SZVLB	S	permeable
V	V	permeable
VB	V	permeable
VBC	V	permeable
VC	V	low permeability
VCB	V	low permeability
VCL	V	low permeability
VCLB	V	low permeability
VCS	V	low permeability
VCSL	V	low permeability
VCSLB	V	low permeability
VCZ	V	low permeability
VCZL	V	low permeability
VCZS	V	low permeability
VL	V	permeable
VLB	V	permeable
VLBC	V	permeable
VLBCS	V	permeable
VLBSC	V	permeable

VLC	V	permeable
VLCS	V	permeable
VLS	V	permeable
VLSC	V	permeable
VLSCB	V	permeable
VLSZ	V	permeable
VS	V	permeable
VSB	V	permeable
VSC	V	permeable
VSCB	V	permeable
VSCL	V	permeable
VSCLB	V	permeable
VSL	V	permeable
VSLB	V	permeable
VSZ	V	permeable
VSZC	V	permeable
VSZL	V	permeable
VSZLB	V	permeable
VZ	V	permeable
VZC	V	permeable
VZS	V	permeable
VZSL	V	permeable
XCS	C	low permeability
XCSV	C	low permeability
XCZ	C	low permeability
XCZS	C	low permeability
XSC	S	low permeability
XSV	S	permeable
XSZ	S	low permeability
XZC	Z	low permeability
Z	Z	low permeability
ZC	Z	low permeability
ZCS	Z	low permeability
ZCSV	Z	low permeability
ZCV	Z	low permeability
ZP	Z	permeable
ZS	Z	low permeability
ZSC	Z	low permeability
ZSCV	Z	low permeability
ZSV	Z	low permeability
ZSVL	Z	low permeability
ZSVLB	Z	low permeability
ZV	Z	permeable