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Quaternary Domains: Glacial Drowned Valley Estuaries

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BRITISH GEOLOGICAL SURVEY

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Quaternary Domains: Glacial Drowned Valley Estuaries

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Summary

This report provides a new interpretation of ‘Glacial Drowned Valley Estuaries’ as part of an ongoing upgrade of the BGS Quaternary Domains dataset. Glacial Drowned Valley Estuaries are major buried features found across the coastal area of GB. These features represent a fluvial landscape that has been dissected and deepened by multiple glaciations to form valleys that are in-part situated beneath modern sea-level. These buried glacial valleys have been and continue to be infilled with marine and estuarine sediment and are overlain by complex or fjord-type estuaries. They typically contain significant thicknesses of superficial sediment of up to 160 m and are often associated with major cities, ports, or industrial centres. Consequently, these features have important groundwater and engineering implications. This work uses a range of national-scale data sets to identify and map Glacial Drowned Valley Estuaries across GB. The identified Glacial Drowned Valley Estuaries are all in Scotland and occur north of the maximum known extent of Late Devensian glacial ice. The infill sequence predominantly comprises clay and silt with variable proportions of sand, gravel, and peat. The sediments are interpreted as glacial till, post-glacial marine and Holocene-aged estuarine sediments. The mapped extent of post-glacial marine sediment and key isostatically uplifted shorelines are used to define the boundary of the Glacial Drowned Valley Estuaries.

1 Introduction

Glacial Drowned Valley Estuaries are a major buried feature found across the coastal area of GB and are defined as ‘over-deepened valleys of glacial and fluvial origin that have been partially infilled by Late Quaternary to Holcene sediment’ (**Figure 1**). This definition follows Cooper *et al*., (2004), who classified Irish Estuaries based on their surface and subsurface morphology. Borehole records from these features show post-glacial and Holocene estuarine sediment thicknesses of up to 162 m (Kearsey *et al*., 2019a). Unlike other glacially-derived or modified valleys, these valleys have limited topographic expression within the modern landscape. However, due to their subsurface scale they can have important implications for the engineering and groundwater properties and behaviour of the shallow subsurface.

Previous work has focused on overdeeped features or valleys north of the Anglian ice limit. This work has examined Late Devensian surface glacial features including glacial lakes such as BRITICE (Clark *et al*., 2018), or buried valleys such as the BGS buried valleys dataset (Kearsey *et al*., 2019b). The buried valleys dataset identified numerous overdeeped features across the UK, using the BGS SOBI (Single Onshore Borehole Index) dataset. Neither work has focused on Glacial Drowned Valley Estuaries specifically. The Glacial Drowned Valley Estuaries form an important component of the Coastal, Estuary and Fluvial Province (Booth et al., 2015), however in the current dataset these features are not distinguished from estuaries with thinner estuarine infills.

This work provides the first overview and detailed mapped extent of these important features. The work uses a broad range of datasets to identify and map the extent of estuarine deposits within these features.

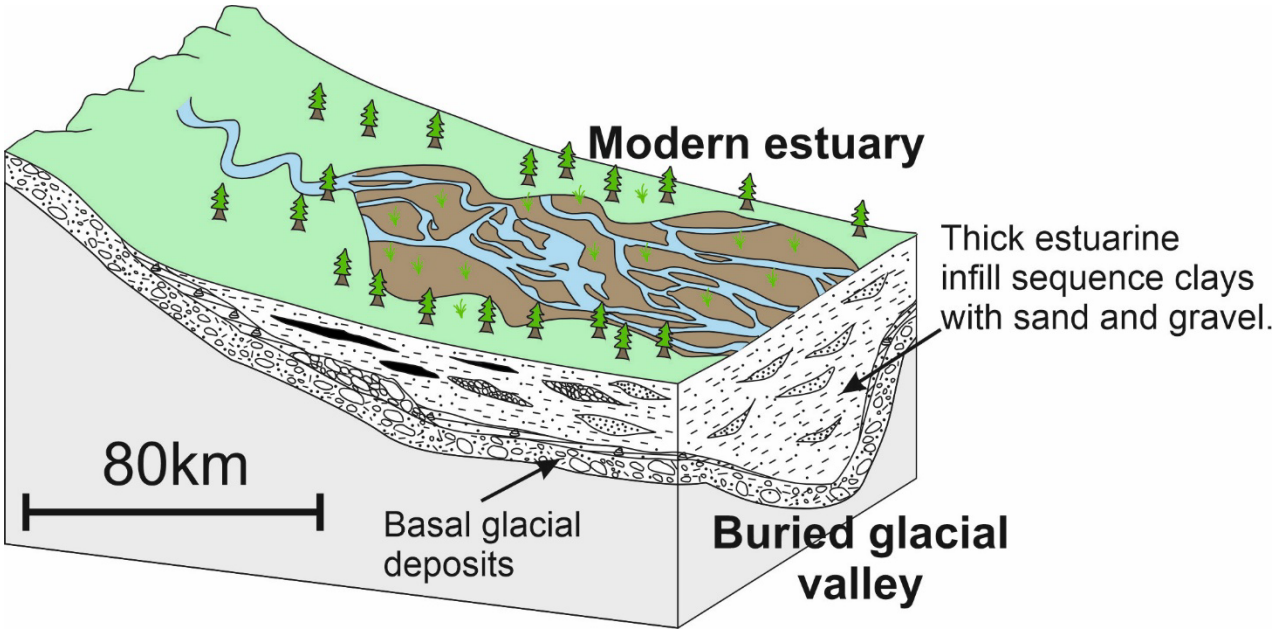


Figure 1. Overview of the surface and subsurface morphology of a Glacial Drowned Valley Estuaries.

2 Glacial Drowned Valley Estuaries across Great Britain

There are several major estuaries located around Great Britain (GB) that represent the transition from land and fresh water into the offshore setting (see Davidson *et al.,* 1991). These are important environments for nature, conservation and historically as areas of significant human development. Although most estuaries have been shaped by modern fluvial processes, several possess a complex polygenetic history (e.g. glacial and / or fluvial erosion) with their morphology and deeper sedimentary record concealed by younger estuarine sediments. Glacial Drowned Valley Estuaries are the product of a combination of pre-existing drainage networks, multiple Quaternary glaciations, bedrock lithology, and major faults (Kearsey *et al.,* 2019).

A key aspect of the development of these features is the interaction between pre-existing drainage networks and multiple Quaternary glaciations. Prior to any major glaciation, much of the onshore GB landscape was produced by progressive Cenozoic exhumation and shaped by fluvial incision, chemical and more recently by physical weathering (Hillis *et al*., 2008; Holford *et al*., 2009; Westaway, 2017).

The pre-existing fluvial drainage networks were heavily dissected and over-deepened because of multiple ice cap and full ice sheet glaciations during the Quaternary (Godard, 1965; Hall *et al.*, 2019). Many of the coastal areas, such as the Firth of Forth and Moray Firth, were the pathways of major ice streams and were therefore areas of focused erosion. Unlike in upland areas there was limited topographic constraint of ice and therefore repeated glaciations were able to erode these valleys well below base level to form over-deepened (buried) valleys at the coastline. The features are found in a broad range of coastal settings and therefore reflect a range of glacial morphologies, including U-shaped valleys, and tunnel valleys that have been incised by subglacial meltwater and ice sheets.

The Glacial Drowned Valley Estuaries formed where glacial ice streams followed pre-existing drainage valleys, and in several coastal settings the drainage system has developed into a major estuary. The base of drowned glacial valleys are covered by a thin veneer of till or other glacial deposits (Kearsey et al., 2019), which were deposited during the most recent glaciation, covered in-turn by Late Glacial and Holocene estuarine and marine deposits. Glacial deposits from previous glaciations are rarely preserved due to erosion during the most recent glaciation. Most of the infill is typically estuarine sediments that were deposited during the Late Glacial and Holocene. A major feature of Glacial Drowned Valley Estuaries is that they are not fully infilled with sediment, and are areas of active deposition.

The Glacial Drowned Valley Estuaries are identified based on two characteristics, firstly they are modern estuaries that have been shaped by glacial processes; and secondly, modern estuarine sediments are currently infilling the over-deepened glacial valley. For the purposes of this report, we define a Glacial Drowned Valley Estuary as being an estuary during the present day, thus excluding other inland over-deepened features. There are several map and landscape-based datasets that can be used to assess the surface and subsurface aspects of estuaries across GB.

Across the GB coastline there are 155 estuaries of various scales, which can be classified into nine types of estuaries based on their surface morphology (Fairbridge, 1980), including: Fjord, Fjard, Ria, Coast plain, Bar-built, Complex, Barrier beach, Linear shore, and Embayment (**Table 1**). Glacial Drowned Valley Estuaries in GB are found to underlie major glacially influenced estuaries, which include fjord, fjard and complex types. These are estuaries that have a glacial history that has influenced their modern surface morphology. Fjord and fjard estuaries are orientated perpendicular to the coast and typically have steep slopes along their margins. Complex type estuaries are highly variable and can range from having parts that are broad and flat to parts that have steeper slopes. Estuary deposits and morphology can be assessed with the BGS 1:625 000-scale superficial maps and valley bottom flatness (derived from a digital elevation model) (Gallent and Dowling, 2003) (**Figure 2a-b**).

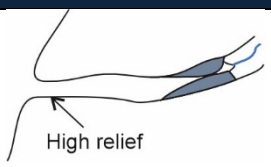
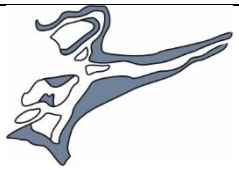
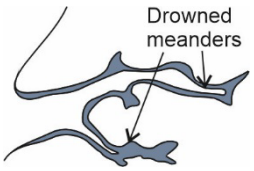
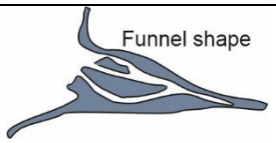
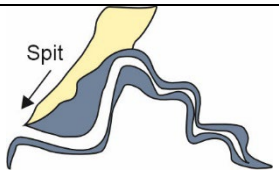
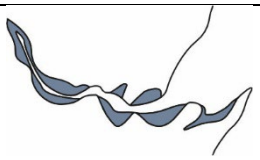
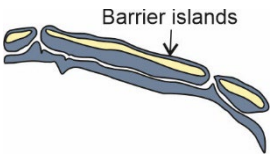
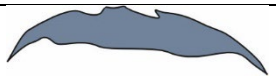
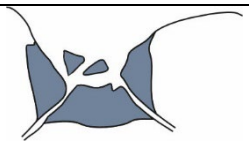
Estuary type	Description	Example morphology
Fjord	Fjords are drowned glacial troughs with bedrock or till covered bases with active deposition mainly at the head of the estuary. The edges of the estuary have steep slopes and high relief. River discharge is small relative to the overall volume of the estuary.	
Fjard	Fjards are mostly found in glacial lowlands and are structurally more complex than fjords with a more open and irregular coastline and no main channel. Occasional small islands are found at the mouth of the estuary.	
Rias	Rias are like fjords and fjards but do not have a glacial origin. They are drowned river valleys that have formed by tectonic subsidence, sea-level rise, or a combination of both. Significantly sedimentation has not kept pace with these changes in base level.	
Coastal plain	Coastal plain estuaries formed as part of the Holocene transgression through flooding of pre-existing valleys. Thus, they have a subsurface morphology of a normal valley and deepen towards their mouth. The surface morphology has a triangular funnel shape.	
Bar-built	Bar-built are also part of drowned river valleys but have had recent sedimentation which has kept pace with the changes in base level and therefore a sand bar can develop across the estuary mouth.	
Complex (polygenetic)	These are river estuaries that have a complex origin, these maybe a combination of both glacial and fluvial processes, and therefore do not easily fit into the classification. Several factors may contribute to their surface morphology including complex bedrock features, glacial history, fluvial process and eustatic sea level changes.	
Barrier beach	These are open coastal systems with soft shores in shallow water and strongly controlled by coastal processes.	
Linear shore	Linear shores are the result of little erosion of the coast and deposition parallel to the coast that was formed a convex to linear morphology.	
Embayment	Embayments form when the coastline has followed a series of rocky headlands, which provide sheltered areas for sediment to accumulate.	

Table 1. Overview of the key types of estuaries found across GB (based on Fairbridge, 1980 and adapted from Davidson *et al.,* 1991 (available under the Open Government Licence)).

A key component of the Glacial Drowned Valley Estuaries is the subsurface morphology that has been shaped by multiple Quaternary glaciations. Recent work used 113, 415 borehole records held by BGS to identify buried Quaternary Valleys across the UK (Kearsey *et al*., 2018) (**Figure 2c**). Several of these buried valley features intersect fjord and complex type estuaries (**Table 1**). Buried valley estuaries are interpreted where both glacial surface morphology and buried Quaternary valleys are identified together.

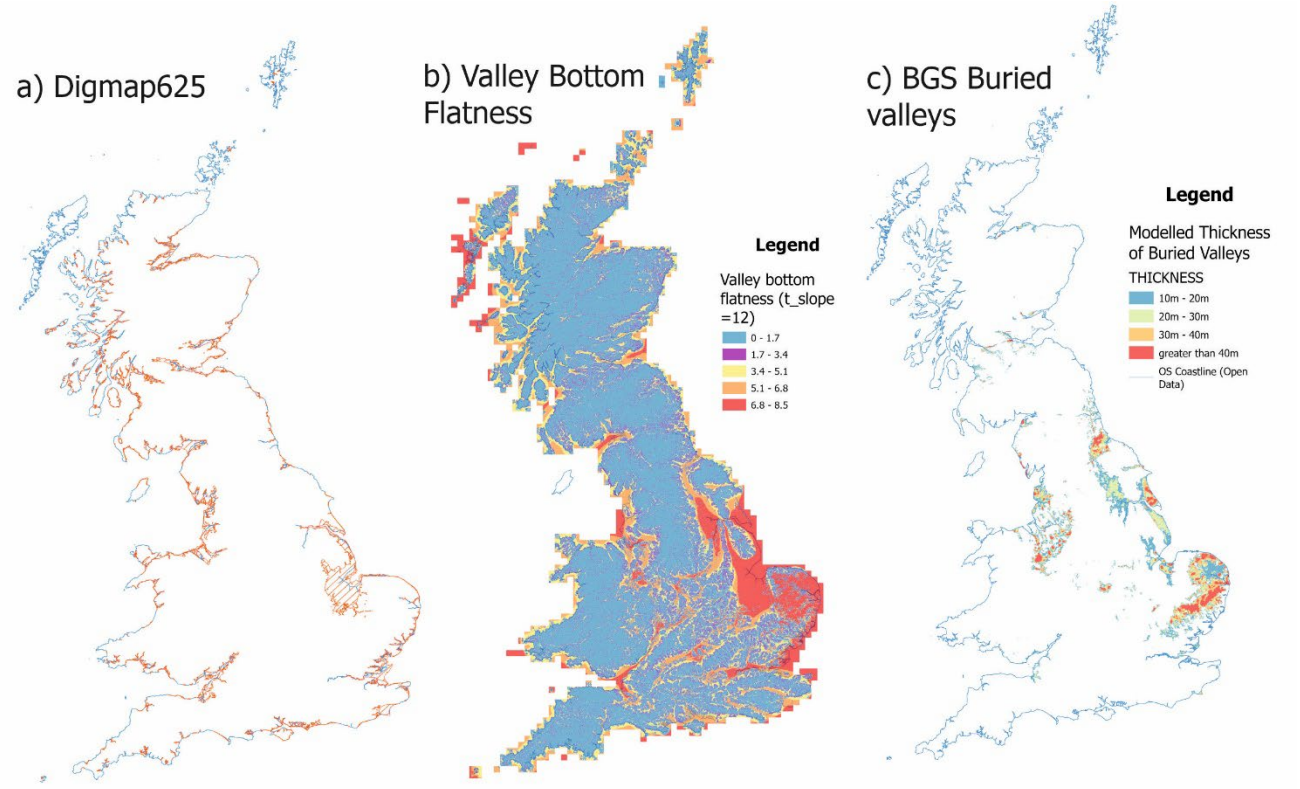


Figure 2. Key data sets used to identify Glacial Drowned Valley Estuaries across GB, include a) marine and coastal deposits from the BGS 1:625 000-scale GB superficial map; b) Valley Bottom Flatness (based on Gallant and Dowling, 2003), and c) BGS Buried Valleys dataset (Kearsey *et al*., 2018). (Contains Ordnance Survey data © Crown copyright and database rights 2010)

Using a combination of surface and subsurface morphology several Glacial Drowned Valley Estuaries have been identified based on available data, including the Firth of Forth, Firth of Clyde, Firth of Tay, Moray Firth, and Solway Firth (**Figure 3**). The five Glacial Drowned Valley Estuaries identified across GB are modern estuaries that are underlain by a partially drowned buried glacial valley. This classification does not include buried valleys that are not partially infilled by modern estuaries with estuarine sediments. Other areas of substantially thick Quaternary sediment such as the Vale of York and the Mersey and Dee estuaries, are not included as Glacial Drowned Valley Estuaries because the modern estuary has not partially infilled the buried glacial valley.

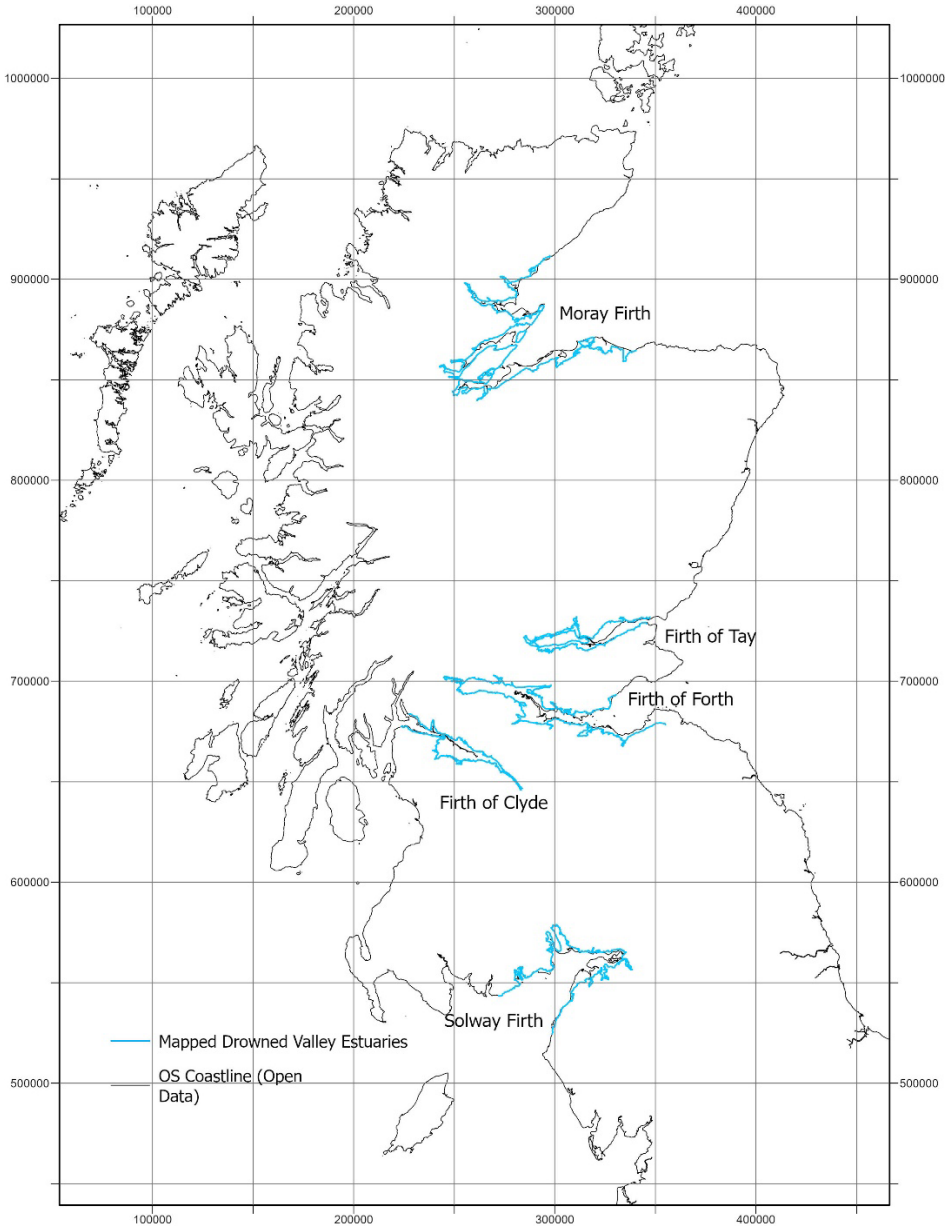


Figure 3. Overview map of the identified and mapped Glacial Drowned Valley Estuaries in GB (Contains Ordnance Survey data © Crown copyright and database rights 2010).

The five identified Glacial Drowned Valley Estuaries are all situated to the north of the maximum known Late Devensian ice extent. The majority of the identified Glacial Drowned Valley Estuaries are 'complex-type' estuaries (Davidson *et al*., 1991), often reflecting the dynamic glacial and fluvial processes that shaped them. The Firth of Clyde is the only fjord type estuary (Davidson *et al*., 1991), due to narrow overall morphology. Limited data is available on the sub-surface morphology of the drowned valley features, however, using borehole depths Kearsey *et al*. (2018) suggests a large variation in morphology across the buried valley in the Midland Valley of Scotland, reflecting the broad range of pre-existing local drainage morphology, variability in glacial erosive processes and local controls such as bedrock geology or faults. Nevertheless, the buried valleys are generally described as U-shaped valleys that have been formed through incision by subglacial meltwater.

3 Methodology

The aim of this work is to characterise the maximum extent of estuarine and post-glacial marine influence for each of the identified drowned valley estuaries. The mapping is desk-based and uses published BGS geological maps and DEM datasets to interpret the maximum extent of post glacial marine influence. This work does not include field-based remapping of estuarine deposits or landscape features but is focused on creating a national-scale dataset by using up-to-date geological and DEM data. A range of datasets will be used together to interpret and map each Glacial Drowned Valley Estuary (**Table 2**).

3.1 BACKGROUND

Ongoing work has been undertaken to interpret key deposits and features to understand local impacts of deglaciation and isostatic rebound of all the estuaries included in this report. This work uses key information on significant formations and major landscape features from each estuary. For each estuary the relevant published memoirs, regional guides and peer-reviewed journal articles will be used to assess and characterise the local setting.

Dataset	Practical Use	Accessibility
BGS Geology 50k Superficial	Superficial geology linework used to constrain the mapped presence of post-glacial marine deposits and / or estuarine sediments.	Open Access via BGS GeoIndex.
NEXTMap Britain DTM	Digital Terrain Model (DTM) used to interpret key landscape features associated with the most recent post-glacial marine incursion.	Used under licence from Intermap Technologies.
BGS buried valleys dataset	Buried Valleys dataset used BGS borehole records to identify over-deepened features across GB.	Open Access via BGS GeoIndex.
Literature: including memoirs, regional guides and peer-reviewed journals.	Overview of key sequences and landscape features for each estuary caused by local glacial and isostatic processes.	BGS publications and scientific literature are available for purchase or through subscription services.

Table 2. Datasets used in the new interpretation of maximum extent of estuarine and post-glacial marine influence of the Glacial Drowned Valley Estuaries including how the datasets were used and their accessibility.

3.2 DATASETS

The current limit of estuarine and marine influence is assessed using two factors, firstly superficial deposits and secondly, erosional landscape features. The key superficial deposits of the Glacial Drowned Valley Estuaries are the post-glacial marine and estuarine sequences, which are both included in the 1:50 000-scale GB superficial dataset. The inland limit of these deposits is used to represent the maximum known extent of estuarine and post-glacial marine influence. Across part of the estuaries there are key landscape surfaces that formed because of the Late Devensian marine incursion such as uplifted shorelines, which can be interpreted from the DEM and slope map. The height of these surfaces is different for each estuary depending on local isostatic processes and is determined from local literature. The BGS buried valleys dataset is used to identify major over-deepened valleys and their spatial extents associated with each of the mapped estuaries. Limited offshore borehole records result in significant uncertainty around the exact subsurface extents of these features in coastal settings.

3.3 SPATIAL EXTENT

The spatial extent of these Glacial Drowned Valley Estuaries will be captured at a 1:10 000-scale using the map and DEM datasets. The capture of linework will be carried out in ArcGIS using a polyline shapefile. The line will be separated into segments that represent the datasets used for interpretation and serve to highlight how the linework has been captured, which will reflect in relative terms, the level of uncertainty (**Table 3)**. Three classifications are used, firstly 'map' to represent lines that following mapped deposits on the 1:50 000-scale superficial dataset. Secondly, 'DEM' to describe lines that are interpreted based on landscape features. Finally, 'conjectural' will be used where the current data provides no constraint on the estuary boundary and where topographic contours were used to join segments of linework.

Constraint Class	Explanation
Map	'Maximum extent' is constrained by published BGS 1:50,000 superficial geological mapping.
DEM	Interpreted from landscape features that were observed on a DEM or slope model.
Conjectural	Minimal information is available to constrain the 'maximum extent'; it is interpreted based on contours derived from the DEM.

Table 3. Constraint Classes used to define how segments of the 'maximum extent' had been captured and to highlight the relative levels of uncertainty.

4 Results

The following section provides an overview of the key observations and interpretations of each of the mapped estuaries.

4.1 FIRTH OF FORTH

The Firth of Forth is a complex-type estuary that is orientated broadly east-west (**Figure 4**). The estuary starts with the River Forth which drains from Loch Ard, across Stirlingshire before joining the Firth of Forth east of Stirling and has a total length of *c.* 80 km. The Firth of Forth is a relatively narrow estuary but widens beyond Queensferry from *c.* 3 km to over *c.* 20 km wide. The estuary has gentle slopes (<5°) that make up most of its flanks, with the steepest slopes located (> 20°) near Stirling. The rivers Teith, Carron and Devon are major drainage systems that also drain into the estuary.

The Firth of Forth is infilled with up to *c.* 160 m of marine and estuarine sediment (Kearsey *et al.*, 2018). The estuary was drowned by a post-glacial marine incursion resulting in the deposition of the Errol Clay Formation that was subsequently uplifted to form the 'Main Perth Shoreline' (Sissons and Smith, 1965; Peacock, 2003; Palamakumbura *et al.*, 2018). The 'Main Perth Shoreline' generally occurs at an elevation of 30-40 m above OD (Ordnance Datum), and gently dips towards the North Sea located to the east.

The mapped shoreline follows the mapped limit of the Errol Clay Formation, which is described from east of Edinburgh and inland to Stirling, particularly in the central part of the estuary (**Figure 4**). The western limit of the estuary follows the 30-40 m OD contour to provide a boundary of the inland component of the 'Main Perth Shoreline'. The steeper parts of the estuary boundary, between Grangemouth and Queensferry, follow a surface that was interpreted from the slope map.

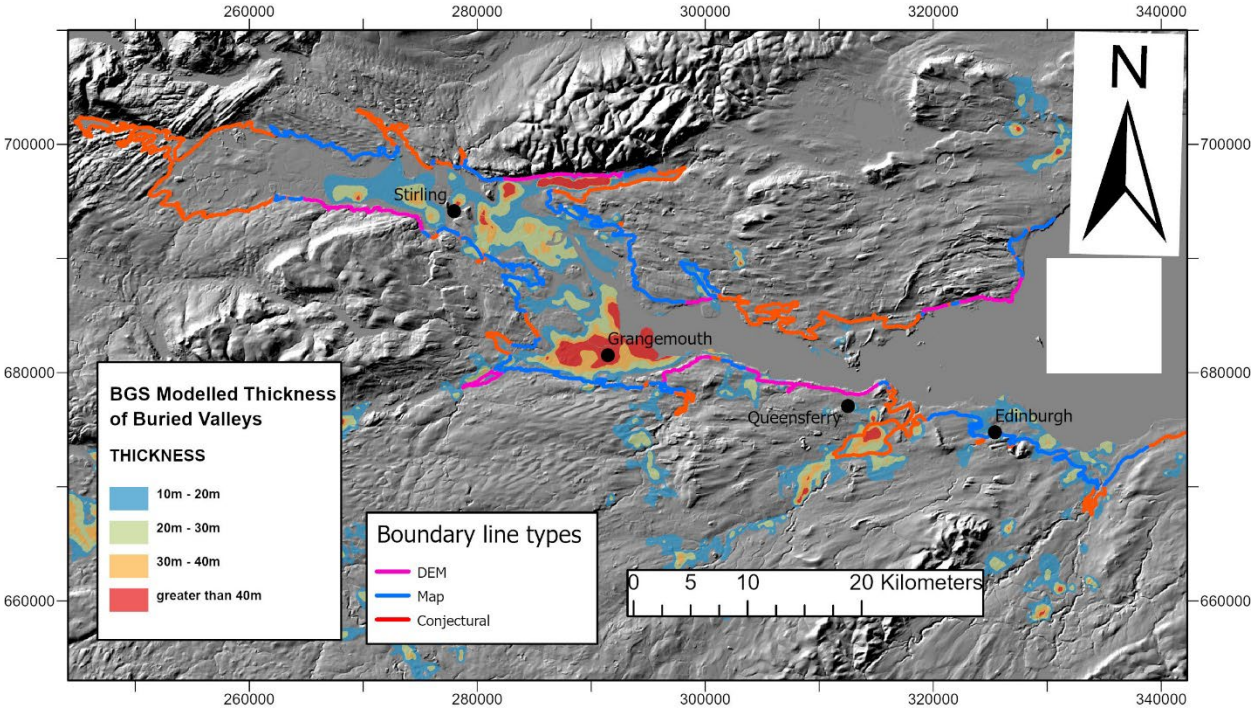


Figure 4. 1:10 000-scale map of the Firth of Forth Glacial Drowned Valley Estuary with lines that are coloured based on the datatype used. (NEXTMap Britain elevation data from Intermap Technologies).

Two major buried features are interpreted at Grangemouth and to the east of Stirling, called the Carron and Ochills troughs, respectively (Kearsey *et al*., 2018). The mapped marine boundary of the Firth of Forth continues across these features as part of the marine incursion. The Carron and Ochills troughs are both buried U-shaped valleys. The deepest known buried valley in GB is the Carron Trough with a depth to bedrock of up to 162 m (Kearsey *et al*., 2018). The Carron Trough represents the convergence of two valleys, the Carron and the Forth, forming a double valley morphology in the subsurface. The Carron Trough continues south-westwards beneath the River Carron towards the Firth of Clyde, however, the current data does not suggest a continuous trough and therefore the estuary boundary follows the mapped marine limit and DEM surface inland around Grangemouth. The Ochills Trough is broadly orientated east-west and continues along the base of the Ochills for *c.* 10 km and is over 70 m deep. The feature occurs at the boundary between the harder Ochil Volcanic Formation and the softer Carboniferous-aged limestones, hence a strong bedrock control on the position of this feature (Kearsey *et al*., 2018).

4.2 FIRTH OF CLYDE

The Firth of Clyde is a fjord-type estuary that corresponds to the mouth of the River Clyde, a major river which runs through the City of Glasgow. The estuary is orientated southeast to northwest and has a major inland component of marine influence with a total length of *c*. 70 km. The main modern estuary is situated between Greenock and Erskine (**Figure 5**), which is a narrow (2-6 km wide) region with steep valley flanks (up to 20°) and an open water setting. Inland of Erskine the drowned valley at surface is covered by the River Clyde floodplain, which is up to 15 km wide. The region narrows at Motherwell and continues to Lanark.

The main post-glacial marine incursion is represented by a sequence of marine and tidal sequences (Browne and McMillan, 1991), which are mapped as 'Late Devensian Raised Tidal Flat Deposits' in the 1:50 000-scale BGS Superficial mapping. These mapped deposits provide a constraint on the inland extent of post-glacial marine influence. These deposits are discontinuous and at a variable height of between 10-40 m OD. The in-land extent of the post-glacial influence at Lanark and Balloch follows either the nearest deposit or landscape feature, which continued along similar height contours.

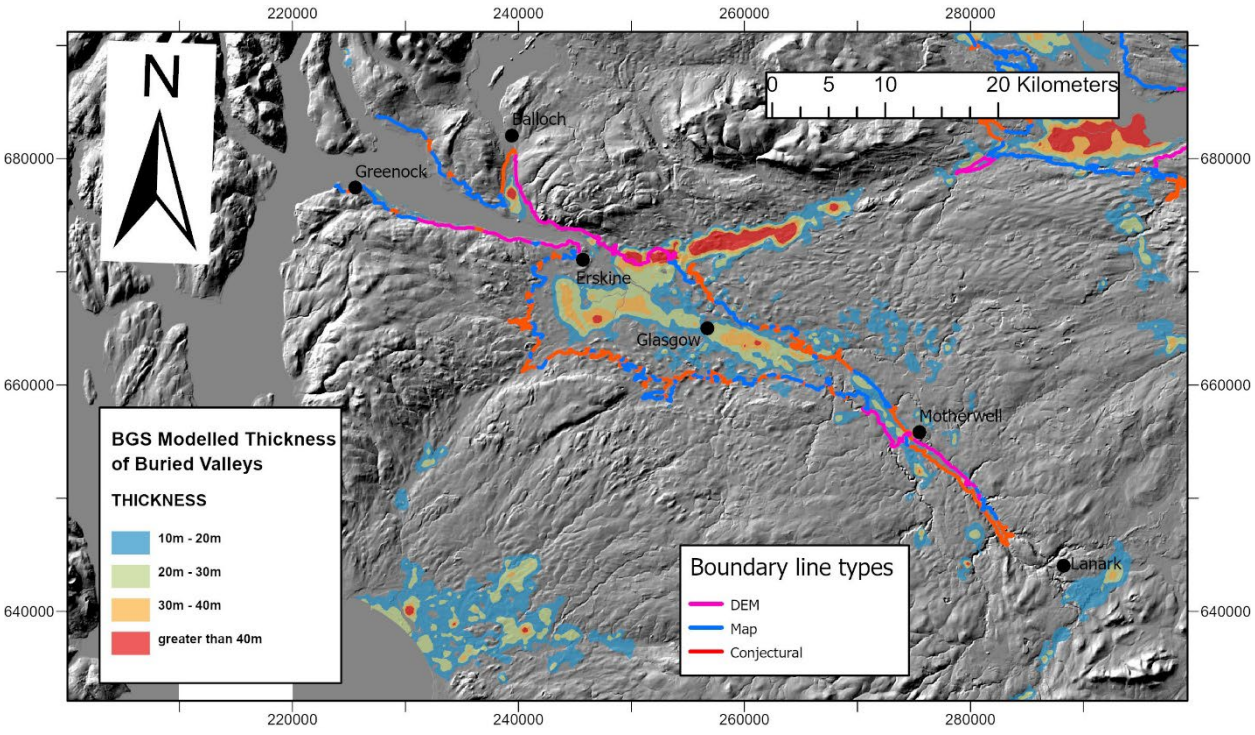


Figure 5. 1:10 000-scale map of the Firth of Clyde Glacial Drowned Valley Estuary with lines that are coloured based on the datatype used. (NEXTMap Britain elevation data from Intermap Technologies).

The main buried valley identified between Erskine and Glasgow, narrows and continues eastwards towards Motherwell. This buried valley is likely to continue beneath the main estuary towards Greenock, however there are currently no available borehole records to show this. The Carron Trough that connects the Clyde to the Firth of Forth is also observed in this area, however as before, this not a continuous feature and therefore the post-glacial marine limit is used here.

4.3 FIRTH OF TAY

The Firth of Tay is located on the east coast of Scotland and is the main outputs of the rivers Tay, Almond and Earn, which drain from the north, northwest and east, respectively. The estuary is a complex-type, with a narrow mouth (<2 km wide), inland it ranges from 3 to 8 km wide and has a total length of *c.* 65 km (**Figure 6**). The margins of the estuary vary from steep topography to open flood plains.

The region represents the type-area for the Errol Clay Formation (Peacock, 2003), which are the marine deposits associated with the Late Devensian post-glacial marine incursion. Mapping of the Errol Clay Formation around Perth provides an accurate representation of the maximum known marine limit in this area. Between Peth and Dundee, the steep topography limits the inland extent of marine influence, hence the boundary follows the 'Main Perth Shoreline' (Sissons and Smith, 1965) that is visible on the DEM. In land of Perth towards Crieff there is limited mapped Errol Clay Formation, therefore the estuary boundary mostly follows the 'Main Perth Shoreline' at 30-40 m above OD height in this area.

The western part of the estuary is a large area of high ground, between Perth and Crieff, which is included as a window within the estuary. This window reflects a major area that is topographically higher than the marine limit within the main estuary and is covered by a significant amount of glacial till and exposed bedrock. The high ground is separated by the River Tay to the north and the River Earn to the south. Marine deposits are mapped within the catchments of both rivers.

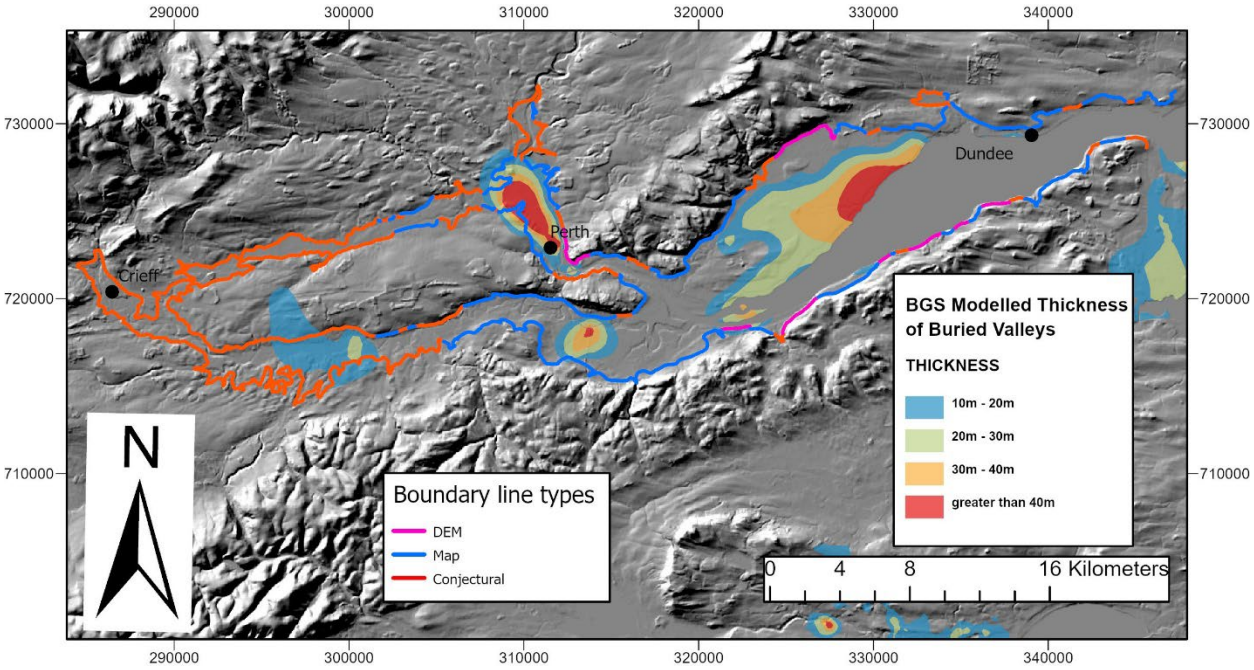


Figure 6. 1:10 000-scale map of the Firth of Tay Glacial Drowned Valley Estuary, with lines that are coloured based on the datatype used. (NEXTMap Britain elevation data from Intermap Technologies).

Limited borehole data is available from the Firth of Tay, but several records do indicate that parts of the estuary are underlain by over 40 m of estuarine and marine sediments. The thickest deposits are found near Perth and Dundee, and south of Perth at the River Earn. The multiple drainage pathways into the estuary are likely to be associated with erosive ice stream paths, therefore a more complex, multi-valley subsurface morphology.

4.4 BEAULY FIRTH, CROMARTY FIRTH AND DORNOCH FIRTH (MORAY FIRTH)

The area collectively known as the Moray Firth is located in the northeast of Scotland encompassing drainage from the rivers Spey, Findhorn, Ness and Kyle of Sutherland. Inverness lies towards the centre along the line of the over-deepened valley occupying the Great Glen fault. Overall, the Moray Firth has a total length of *c*. 60 km. Last glaciated during the Late Devensian, subsequent changes in sea level and glacial isostatic rebound have created relict coastal features up to 34 m above present ordnance datum (Merritt *et al.,* 2017).

Raised marine deposits, raised beach deposits and tidal flat deposits are mapped in areas previously inundated by marine conditions, this has been used to inform landward limits of estuarine regions where possible and the NEXTmap topographic data has been used in areas where geological deposits are not present (**Figure 7**).

Buried valleys are interpreted along the southern coast of the estuary, however the limited available borehole data only shows discontinuous features, and their sub-surface morphology cannot be easily resolved. Borehole records between Inverness and Nairn indicate a buried trough of over 40 m thickness.

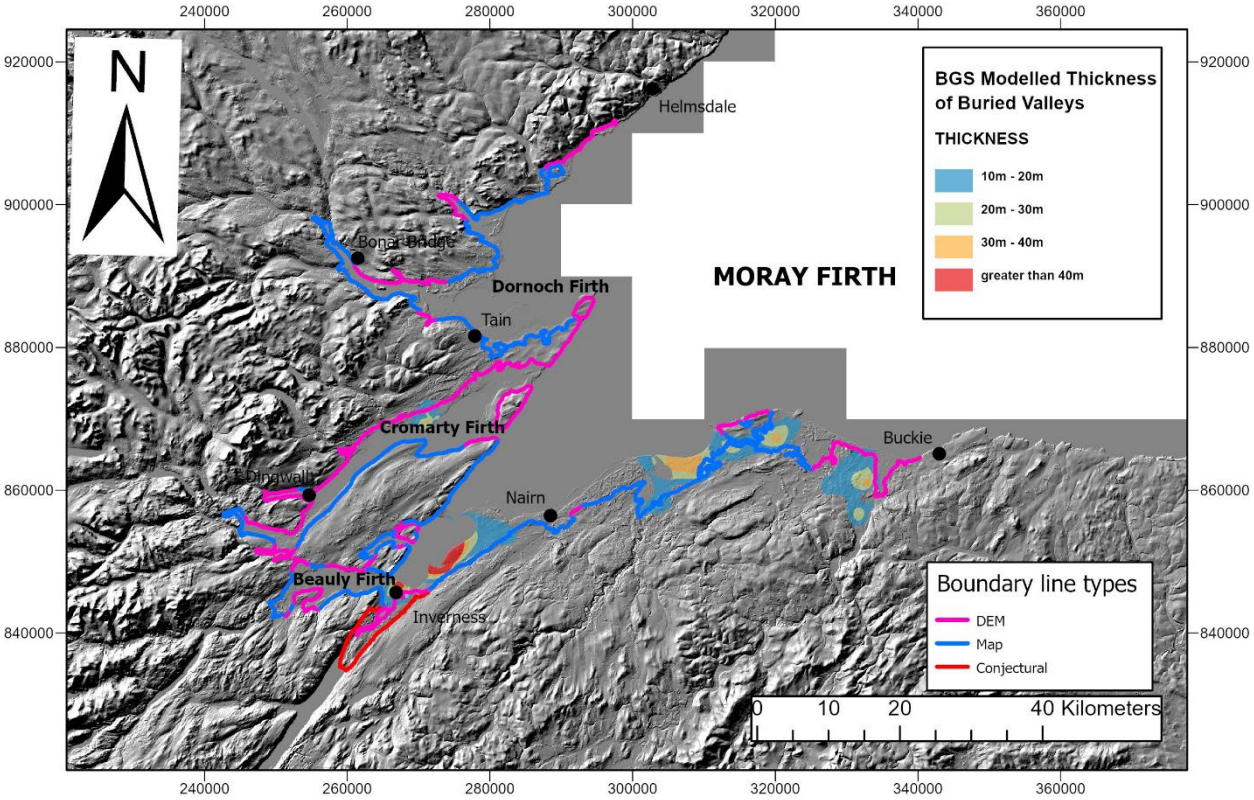


Figure 7. 1:10 000-scale map of the Beauly Firth, Cromarty Firth and Dornoch Firth Glacial Drowned Valley Estuary, with lines that are coloured based on the datatype used. (NEXTMap Britain elevation data from Intermap Technologies).

4.5 SOLWAY FIRTH

The Solway Firth is a complex-type estuary that is the main output for the rivers Eden and Esk, and broadly orientated northeast-southwest. Unlike the other drown valley estuaries the Solway Firth has a wide mouth (*c.* 32 km) and narrows to < 8 km near Carlisle over a relatively short distance (*c.* 40 km) (**Figure 8**). The northern edge of the estuary, between Kirkcudbright and Dumfries is characterized by steeper topography, whereas the rest of the estuary, from Dumfries to Whitehaven, has gentle rolling topography.

The region has experienced a major post-glacial marine incursion resulting in a sequence of marine, beach, deltaic and tidal sediments (McMillan *et al*., 2011). The raised marine deposits are mapped around the mouth of the estuary (**Figure 8**) providing an accurate constraint on the maximum known extent of marine and estuarine influence. Further inland, near Carlisle and Gretna, the raised marine deposits are more scarce, and therefore the estuary limit is based on contour height and landscape features. Limited borehole data is available from the Solway Firth; however, several coastal boreholes indicate that parts of the estuary contain over 40 m thickness of superficial sediment.

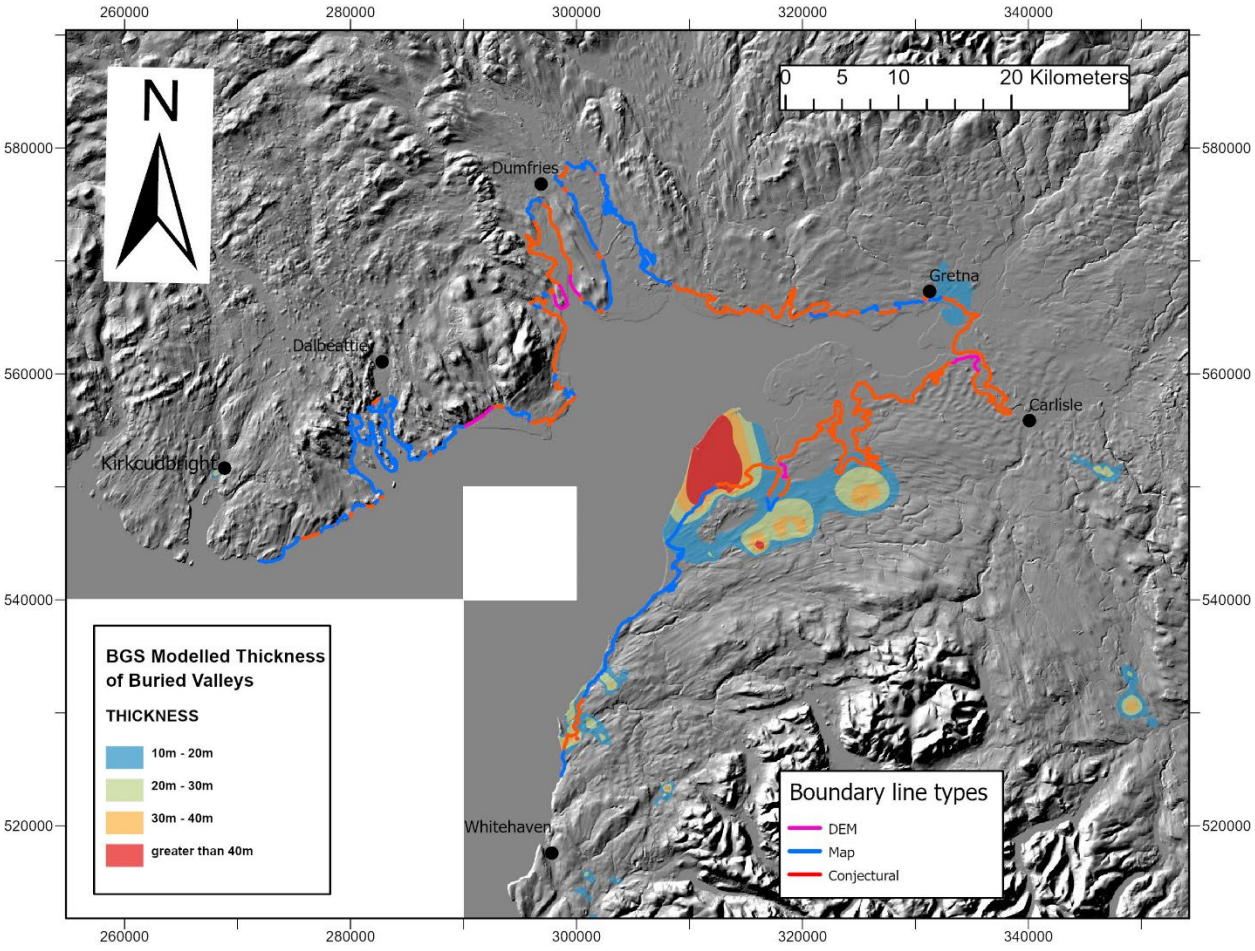


Figure 8. 1:10 000-scale map of the Solway Firth Glacial Drowned Valley Estuary with lines that are coloured based on the datatype used. (NEXTMap Britain elevation data from Intermap Technologies).

5 Conclusions

This report provides a new interpretation of Glacial Drowned Valley Estuaries as part of the ongoing reassessment of the Quaternary Domains model (Booth *et al*., 2015). The newly mapped boundaries of the Glacial Drowned Valley Estuaries will be used to create a new domain to represent these important features.

Glacial Drowned Valley Estuaries were carved out by the interaction of fluvial and glacial erosive processes and have been partially infilled by marine and estuarine sediments. A key aspect of these features, is that glacial erosion along pre-existing drainage pathways has resulted in over-deepened features below base level near the coast. A significant thickness of marine and estuarine sediments has partially infilled these features during the Holocene. Importantly, sedimentation has not fully-infilled the available accommodation space, hence they are areas of active deposition. In the present day the surface morphology of these features is classified as complex or fjord-type estuaries. These features typically contain superficial sediment thicknesses of over 40 m, with the largest known thickness of 162 m.

This work uses a range of national-scale data sets including the BGS 1:625 000-scale superficial map, the BGS buried valley dataset (Kearsey et al., 2019a) and Valley Bottom Flatness (Gallant and Dowling, 2003) to identify major Glacial Drowned Valley Estuaries. Five major Glacial Drowned Valley Estuaries have been identified across GB, including:

1. Firth of Forth;
2. Firth of Clyde;
3. Firth of Tay;
4. Moray Firth; and
5. Solway Firth.

The identified Glacial Drowned Valley Estuaries are situated to the north of the maximum known extent of Late Devensian glacial ice. Their superficial infill is dominated by post-glacial marine and Holocene-aged estuarine sediments. Typically, the infill is predominantly clay and silt with variable proportions of sand, gravel, and peat. The current spatial extent of each of the buried features is not fully known due to the clustered spatial nature of subsurface data. The buried valleys are mostly U-shaped valleys in morphology that have most recently been shaped by glacial erosion prior to a marine incursion. The 1:50 000-scale mapped extent of post-glacial marine sediment and key isostatically uplifted shorelines are used to define the boundary of the Glacial Drowned Valley Estuary. Most Glacial Drowned Valley Estuaries are classified as complex-type estuaries, reflecting the impact of local differences in regional drainage systems and local glacial history.

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The British Geological Survey Library holds most of the references listed below and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at https://of-ukrinerc.olib.oclc.org/folio/. Full guidelines for reference lists are available in *Notes for Authors* (BGS house style guide).

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