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The Quaternary Geology of the Solway

Geology and Landscape (Scotland) Programme
Research Report RR/11/04

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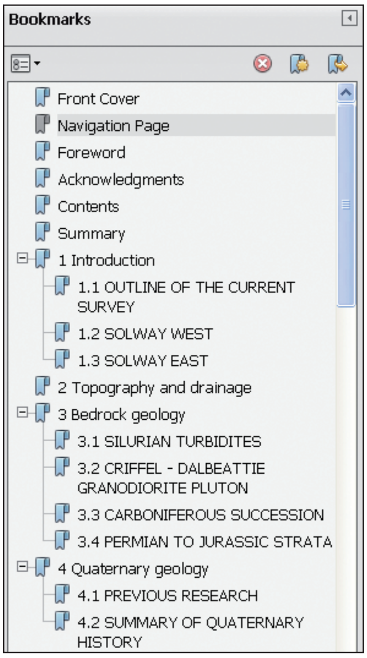

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BRITISH GEOLOGICAL SURVEY

GEOLOGY AND LANDSCAPE (SCOTLAND) PROGRAMME
RESEARCH REPORT RR/11/04

The Quaternary Geology of the Solway

A A McMillan, J W Merritt, C A Auton, and N R Golledge

Contributors
D C Entwisle, B Humphreys, C J Jordan, B É Ó Dochartaigh, E R Phillips, and C L Vye

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SW corner 290000, 550000
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Map

Sheet Solway East and Solway West, 1:50 000 scale, Special Quaternary sheets.

Front cover

Ice-wedge casts in glaciofluvial sand and gravel sheet deposits of the Kilblane Sand and Gravel Formation at Halleaths Gravel Pit [NY 0868 8344], Lochmaben. Photo A A McMillan (P774196).

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British Geological Survey offices

BGS Central Enquiries Desk
Tel 0115 936 3143 Fax 0115 936 3276
e-mail enquires@bgs.ac.uk

Kingsley Dunham Centre,
Keyworth, Nottingham NG12 5GG
Tel 0115 936 3100 Fax 0115 936 3200
e-mail sales@bgs.ac.uk

Murchison House, West Mains Road,
Edinburgh EH9 3LA
Tel 0131 667 1000 Fax 0131 668 2683
e-mail scotsales@bgs.ac.uk

BGS London, Natural History Museum, Cromwell Road,
London SW7 5BD
Tel 020 7589 4090 Fax 020 7584 8270
Tel 020 7942 5344/45 e-mail bgslondon@bgs.ac.uk

Columbus House, Greenmeadow Springs,
Tongwynlais, Cardiff CF15 7NE
Tel 029 2052 1962 Fax 029 2052 1963

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB
Tel 01491 838800 Fax 01491 692345

Geological Survey of Northern Ireland,
Colby House, Stranmillis Court, Belfast BT9 5BF
Tel 028 9038 8462 Fax 028 9038 8461
www.bgs.ac.uk/gsni/

Parent Body

Natural Environment Research Council, Polaris House,
North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

This report publishes the results of research undertaken by the British Geological Survey (BGS) as part of the resurvey of the Quaternary deposits and landforms of the Solway area (Eastern Dumfries and Galloway and Northern Cumbria). A preliminary assessment of the sea-bed geology of the Inner Solway Firth is included. The area covered includes parts of the following 1:50 000 geological sheets: Kirkbean 6W (Scotland), Annan 6E (Scotland), Thornhill 9E (Scotland), Lochmaben 10W (Scotland), Ecclefechan 10E (Scotland), Langholm 11 (Scotland), Longtown 11 (England) and Carlisle 17 (England).

The resurvey was undertaken during the period 1998–2002 as part of the Solway Project and later under the Quaternary of Southern Scotland Project. The ground was divided into two mapping areas, Solway West and Solway East which form the basis of the recently published 1:50 000 Quaternary Geology Special Sheets. Field mapping used 1:10 000 scale Ordnance Survey bases supplemented by air photo and satellite image interpretation. Clean copies (standards) were prepared at 1:25 000 scale. Solway West was surveyed by C A Auton and N R Golledge. Solway East was surveyed by J W Merritt and N R Golledge with the assistance of C L Vye. The offshore account in this report was prepared by B Humphreys. Satellite image data were processed and interpreted by C Jordan. Sediment micromorphological studies were undertaken by E R Phillips. The section on hydrogeological Quaternary domains was prepared by B É Ó Dochartaigh, and the engineering geological interpretation of the Quaternary sequences encountered in site investigations for construction of the A74M and M6 motorways was provided by D C Entwisle.

Radiocarbon (^{14}C) ages are given as 'ka BP' (1000 radiocarbon years before the present) or 'BP' (years before the present). Calibrated (calendar) radiocarbon ages are quoted in the form of '26 cal ka BP' or '11 550 cal. BP'. Descriptions from field note cards are referred to in the form CA123 (C A Auton), NRG123 (N R Golledge), and ME123 (J W Merritt).

Acknowledgments

The authors acknowledge the helpful discussions in the field with Dr M E Brookfield (University of Guelph, Ontario) who also supplied field notes. The ready co-operation of many landowners is also acknowledged.

Contents

Summary

This report describes results of a resurvey of the Quaternary landforms and deposits in the cross-border area of eastern Dumfries and Galloway and northern Cumbria, around the inner Solway Firth. The work was carried out under the BGS Geology and Landscape (Scotland) programme and predecessor programmes, by a multidisciplinary team of geologists and Quaternary specialists. The Solway Project was initiated in 1998 to resurvey the Quaternary geology of the Solway lowlands. Field Survey was undertaken between 1998 and 2000, and two special 1:50 000 sheets (Solway West and Solway East) depicting superficial deposits and simplified bedrock were published in 2005 and 2006 respectively. Prior to this survey, published Geological Survey maps of the district were based on surveys carried out in the 1880s (Dumfriesshire) and the 1920s (Cumbria), when understanding of both the Quaternary and bedrock geology was limited. It was acknowledged by the BGS that there was a requirement for up-to-date geological data for a range of applications.

1 Introduction

This report documents the results of mapping and research of the Quaternary geology of the Solway lowlands of eastern Dumfries and Galloway and northern Cumbria. Fieldwork took place between 1999 and 2002, resulting in the publication of new 1:50 000 scale Quaternary Special sheets, Solway West (BGS, 2005) and Solway East (BGS, 2006). Prior to this work, published Geological Survey maps of the district were based on the Primary Geological Survey carried out in the 1880s (Dumfriesshire) and revision mapping in the 1920s (Cumbria). Most of the published BGS maps and memoirs for southern Scotland date from the late 19th Century to the 1920s, and although the district abounds with classic examples of glacial and postglacial landforms, modern Quaternary research in southern Scotland has been relatively limited.

The new survey was designed to enhance our scientific understanding of the landforms and sediments of the Quaternary Period (approximately corresponding to the last 2.6 million years) of the Solway lowlands. A wide variety of deposits are present including glacial, marine, lake, river and hill-slope sediments. The geological output is not only of scientific value but also of use, for example, in assessments of natural aggregate (sand and gravel) resources, coastline stability and groundwater vulnerability. The research will also help to inform planning decisions concerning a range of land use issues including construction of roads and buildings, positioning of landfill sites and assessment of land stability and flood potential. In 2001, the outbreak of Foot and Mouth Disease resulted in widespread culling of livestock herds and flocks in the area, and seriously affected income from the tourist trade. Maps prepared as part of the current survey aided the BGS response to enquiries from the Scottish Environment Protection Agency and the Environment Agency regarding the geology and hydrogeology of potential burial sites for culled livestock.

1.1 OUTLINE OF THE CURRENT SURVEY

The area covered by the new survey includes parts of the following 1:50 000 geological sheets: Kirkbean 6W (Scotland), Annan 6E (Scotland), Thornhill 9E (Scotland), Lochmaben 10W (Scotland), Ecclefechan 10E (Scotland), Langholm 11 (Scotland), Longtown 11 (England and Wales) and Carlisle 17 (England and Wales).

Based on the new survey, two maps of superficial deposits and simplified bedrock geology were published for Solway West (BGS, 2005) and Solway East (BGS, 2006). Since the publication of these maps, new editions of Lochmaben (10W) bedrock (BGS, 2007) and superficial deposits and simplified bedrock (BGS, 2008) have been issued. The latter map incorporates the results of the most recent survey of the Quaternary deposits of northern part of the Lochmaben district by T Bradwell in 2002–04, together with minor revisions to alluvium boundaries shown on Solway West (BGS, 2005).

Dates and type of survey and surveyor for Solway West and Solway East 1:50 000 scale compilations are shown on Figure 1. Reconnaissance fieldwork and air photo interpretation was undertaken over much of eastern Dumfries and Galloway at 1:10 000 scale and clean copies (standards) prepared at 1:25 000 scale. The compilation of simplified bedrock geology of the onshore and offshore areas was prepared by A A McMillan, based on primary and revision surveys. Offshore, the bedrock geology was modified from the East Irish Sea 1:250 000 Special Sheet Edition (BGS, 1994), and the superficial deposits were compiled at 1:50 000 scale by B Humphreys.

1.2 SOLWAY WEST

Solway West (BGS, 2005) includes the lower catchments of the rivers Nith and Annan. Coverage extends from Southerness in the south-west to Lockerbie in the north-east, and includes the towns of Dumfries and Lochmaben. The bedrock geology compilation is based on several revision surveys. The area between New Abbey and Southerness was partially revised by A A McMillan in 1989–90 during the resurvey of Scotland Sheets 5E/6W (Lintern and Floyd, 2000; BGS, 1993). A partial revision of Scotland Sheet 6W (which includes Silloth on the English side of the Solway) was compiled by R A Hughes (Hughes, 1995; BGS, 1998). The bedrock geology of the Nith valley from Kirkconnell Flow northwards was partially resurveyed by A A McMillan and M C Akhurst for Scotland Sheet 9E in 1990–94 (BGS, 1996). Draft linework from the partial resurvey of the Scotland Sheet 10W (BGS, 2007) was also incorporated.

The superficial deposits (Quaternary) geology of Solway West was partially resurveyed by C A Auton and N R Golledge in 1998–2000 (Figure 1; Golledge, 1999, 2000). The Quaternary geology between Glencaple and Annan was partially revised by R A Hughes during 1990–94 (Hughes, 1995; BGS, 1998) and 1:10 000 scale clean copies of NY 06 NW/SW, 06 NE and 16 NW were prepared. Much of this latter revision concentrated on a re-evaluation of the distribution of modern and postglacial raised marine and estuarine sequences. However, much of the geological data from the higher ground (more than 20 m above Ordnance Datum), was not significantly altered from that shown by the primary survey (1871–74). The nature and distribution of many of the glacial deposits has required significant reappraisal. The extent of glaciofluvial deposits in particular is much more restricted than shown on the previously published 1:50 000 scale maps (Sheet 9E, Thornhill, IGS, 1980a; Sheet 6W, Kirkbean, BGS, 1998), including that covering the New Abbey–Caulkerbush area (Sheet 5E, Dalbeattie, IGS, 1981). In these cases, the earlier surveyors had considerable difficulty distinguishing between till and sand and gravel, largely because of the generally sandy nature of much of the glacial sequence.

1.3 SOLWAY EAST

Solway East (BGS, 2006) includes the lower catchments of the Kirtle Water and Rivers Annan, Esk, Eden, Wampool and Waver. Coverage extends from Abbey Town, Cumbria in the south-west to Langholm, Dumfries and Galloway in the north-east, and includes the towns of Annan, Gretna and the western parts of Carlisle. The simplified bedrock geology was compiled from published sources including Scotland Sheet 6 (primary survey of 1871–74; Sheet 6W published by BGS, 1998), Sheet 10 (primary survey of 1885), and Sheet 11 (IGS, 1968); and England and Wales Sheet 11 (resurveyed in 1925 and reprinted by IGS, 1967), and Sheet 17 (resurveyed in 1925 and reprinted by IGS, 1969). Linework was modified using other published sources including Nairn (1956) and Ivimey-Cook et al. (1995).

The superficial deposits (Quaternary) geology of Solway East was partially resurveyed by N R Golledge, J W Merritt and C L Vye in 1998–2003 (Figure 1; Golledge, 1999, 2000). Limited fieldwork was carried out on Sheet NY28. For sheets NY28NW and NY28NE are compilations of the primary survey linework modified using air photo interpretation of the 1988 All Scotland Survey flight runs. The amount of information gathered from air photos was limited. On the English side of the Solway, both the bedrock and Quaternary geology was partially resurveyed by B Young, R A Hughes and M P Boland during 1991–94 but only 1:10 000 scale clean copies of NY 15 (NW, SW and NE) were prepared. Owing to the embargo on fieldwork during 2001 as a result of the UK Foot and Mouth Outbreak, no new fieldwork was carried out in Cumbria on sheets NY15, NY25 and NY35. New 1:25 000 scale clean copies for this area are based upon the 1920s survey, supplemented by limited satellite imagery interpretation.

2 Topography and drainage

The predominantly rural Solway district, straddling eastern Dumfries and Galloway and northern Cumbria, comprises the upland areas of Criffel and Eskdale together with low-lying coastal ground and adjacent extensive estuarine flats of the inner Solway Firth (Figure 2). The main transport routes include the A75 Euroroute, the M74/M6 and the main west coast railway network, and the principal towns include Dumfries, Lockerbie, Annan, Carlisle, Wigton and Silloth. Traditionally the district has been a major centre of cattle and sheep production, and today the rural economy is largely supported by farming and tourism.

The principal rivers of the district include the Rivers Nith, Annan, Esk, and Eden. The Nith flows southwards through the low ground of the Thornhill Basin (preserving Carboniferous to Permian strata) and the Dumfries Basin (underlain by predominantly Permian rocks). Several important tributaries drain the high ground of Southern Uplands lying to the east and west of Nithsdale. The southerly flowing River Annan, sourced in Moffatdale, flows through the expansive alluvial ground concealing Permian rocks of the Lochmaben Basin (underlain by Permian strata). To the south the river cuts through strata of Carboniferous to Triassic age reaching the Solway at Annan. The River Esk and tributaries drain the high ground of the Southern Uplands (composed of Lower Palaeozoic strata) north of Langholm, before cutting through Carboniferous to Triassic rocks and entering the head of the Solway Firth south of Gretna. The River Eden flows north-westwards through the Vale of Eden and Carlisle and drains mainly Permian to Triassic ‘red bed’ strata.

3 Bedrock geology

The Solway district is underlain by rocks ranging in age from Silurian to Jurassic. The distribution of the bedrock geology is shown in Figure 3.

3.1 SILURIAN TURBIDITES

The oldest rocks within the Solway district are of early Palaeozoic (Silurian) age referred to the **Gala**, **Hawick** and **Riccarton** groups (Lintern and Floyd, 2000; McMillan, 2002). They are composed of wacke sandstones, siltstones and mudstones. These strata, which form part of the Southern Uplands Terrane, were deposited as turbidites within the Iapetus Ocean. As the ocean closed during the Caledonian Orogeny (from the late Silurian to Early Devonian) the rocks were deformed, folded and cleaved. Generally, the strata are folded and dip steeply to the north-west or to the south-east, and strike north-eastwards. In the district, these rocks crop out in an upstanding south-east trending ridge, separating the Dumfries and Lochmaben Upper Palaeozoic basins; they also form the upland across the north-eastern part of the district between Lockerbie and Langholm. Typically the wacke sandstones are hard, lithic-rich lithologies that have been glacially moulded into streamlined crags and knolls.

3.2 CRIFFEL – DALBEATTIE GRANODIORITE PLUTON

The Criffel–Dalbeattie Granodiorite Pluton of the Galloway Granitic Suite, part of which occupies the western margin of the district culminating in Criffel [NX 957 618], was emplaced within the turbidite sequence during the Early Devonian. The pluton is dated at 397 Ma and was probably unroofed during the Mid Devonian (Lintern and Floyd, 2000).

3.3 CARBONIFEROUS SUCCESSION

To the south of the Criffel–Dalbeattie Pluton, the North Solway Fault forms the northern boundary of the Solway Basin, an extensive depositional centre initiated during latest Devonian times. The Carboniferous strata generally dip south-eastwards towards the axis of the basin which is broadly coincident with the axis of the modern Solway Firth (Chadwick et al., 1995). Formational nomenclature follows that of Waters et al. (2007) (after Nairn, 1956; Lumsden et al., 1967; McMillan, 2000a; Jones and Holliday, 2006). The earliest rocks belong to the early Carboniferous **Kinnesswood Formation** (predominantly fluvial sandstones), the **Birrenswark Volcanic Formation** (basalts) and overlying **Ballagan Formation** (interbedded mudstones, siltstones, sandstones and ferroan dolostones — all belonging to the Inverclyde Group. The Ballagan Formation is succeeded by cyclical successions of sandstone, siltstone and thin beds of limestone of the **Lyne Formation** and **Fell Sandstone Formation** (Border Group), and the **Tyne Limestone Formation** and **Alston Formation** (Yoredale Group). These strata are well exposed in coastal sections lying to the west of the Nith estuary, at Kirkbean [NX 977 591], Southerness [NX 975 543] and Arbigland [NX 995 574] (BGS, 1993; McMillan, 2000a). East of the Dumfries Basin, Carboniferous rocks crop out north-eastwards from the Dalton area [NY 116 740] through Annandale, Eaglesfield [NY 230 740] and Waterbeck [NY 245 775] to Langholm [NY 365 845]. Sections are best seen in the River Annan and the Kirtle Water (Nairn, 1956), and the River Esk downstream of Langholm (Lumsden et al., 1967). South of Gilnockie Bridge [NY 386 781], near Canonbie, strata of the **Pennine Coal Measures Group** (Westphalian) and overlying **Warwickshire Group**, described by Jones and Holliday (2006), are exposed in the River Esk and extend southwards under a cover of younger Permian to Triassic rocks as the concealed Canonbie Coalfield (Picken, 1988).

3.4 PERMIAN TO JURASSIC STRATA

Permian red-bed strata occupy the basins of Dumfries and Lochmaben. Shown on Solway West as belonging to the Appleby Group, these rocks have been recently reassigned to the Stewartry Group (BGS, 2007; Akhurst and McMillan, in prep). Within the Dumfries Basin, fluviatile breccia conglomerates of the **Doweel Breccia Formation** (Brookfield, 1978) crop out on the east shore of the estuary of the River Nith near Glencaple [NX 995 685]. The formation is regarded as partly contemporaneous with and partly younger than the aeolian desert sandstones of the **Locharbriggs Sandstone Formation** (Brookfield, 1978; McMillan, 2002). Clasts comprise a variety of sedimentary rocks of mainly Lower Palaeozoic origin, together with porphyrite and granodiorite derived from the Criffel–Dalbeattie Pluton. On geophysical evidence, the thickness of Permian strata under the Nith at Glencaple is 200–400 m (Bott and Masson Smith, 1960). The maximum thickness modelled for the centre of the Dumfries Basin, under Dumfries, is more than 1.4 km. Recently acquired borehole evidence indicates that Permian rocks overlie a thin succession of early Carboniferous strata on the eastern margin of the basin (Akhurst and McMillan, in prep).

From geophysical evidence, the Lochmaben Basin is occupied by some 1000 m of sedimentary strata. West of the main basin there is evidence of early volcanicity associated with basal conglomerates. Basal strata referred to the **Hartfield Formation** crop out on the western, northern and eastern margins of the basin (Brookfield, 1978). Here, up to 170 m of red, laminated and cross-laminated silty sandstone interbedded with pebbly sandstone and lenses of breccio-conglomerate, rest unconformably on Lower Palaeozoic strata. The sandstone is medium to thick bedded, silty and medium to fine grained, with small (less than 0.5 mm) detrital mica flakes and many frosted and rounded quartz grains. Pebble-sized, predominantly tabular, platey, matrix-supported clasts are aligned parallel or near parallel to bedding. The clasts are composed of red or grey mudrock, grey micaceous wacke sandstone, cream-coloured quartzite and, locally, amygdaloidal basalt. The formation may also include interbeds of brick red, dune cross-bedded, fine- or very fine-grained sandstone without detrital mica grains. On the eastern margin of the basin near Lockerbie, the basal Permian strata comprise the **Lockerbie Breccia Member** of the Hartfield Formation (Akhurst and McMillan, in prep), with over 11 m of red-brown breccio-conglomerate interbedded with thin- to medium-bedded red sandstone. Lithic clasts have a distinctive local derivation and include reddened limestone, wacke sandstone, basic volcanic rocks, siltstone, mudstone and rounded quartz pebbles.

The **Corncockle Sandstone Formation** occupies the central part of the basin (Brookfield, 1978; Akhurst and McMillan, in prep). Where there is over 900 m of red, fine- to medium-grained, well-sorted quartz sandstone with large scale aeolian cross-bedding. Some of the best sections are seen in Corncockle Quarry [NY 085 870], north of Lochmaben, which has long supplied building stone and formerly revealed well-preserved reptilian trackway trace fossils on bedding planes. At Lochmaben [NY 081 825], these strata are overlain by the **Lochmaben Formation**, comprising over 50 m of red, irregularly-bedded siltstone and fine-grained sandstone that may be cross-bedded (Akhurst and McMillan, in prep). It includes beds of coarse-grained sandstone with well-rounded frosted grains in a fine-grained matrix, slump structures, small gypsiferous nodules, breccio-conglomerate and near-horizontal gypsum-cemented veins.

In the east-north-east-trending Carlisle Basin, strata of the Appleby Group (Permian) comprise more than 500 m of red beds of **Brockram** and **Penrith Sandstone Formation** (Holliday et al., 2001, 2004). The Brockram is typically a locally derived breccia; for example, in the Annan Sub-basin east of Annan a basal succession of about 8.5 m of limestone breccias is referred to the Kelhead Breccia Member. The overlying argillaceous and evaporite (gypsum–anhydrite) strata of the **Eden Shales Formation** (late Permian) of the Cumbrian Coast Group crop out around the margins of the Carlisle Basin. Boreholes in the Canonbie Coalfield and around Annan [NY 200 670] indicate the thickness of the Eden Shales ranges from 80 to 112 m (Holliday et al., 2001). In the Solway district, strata of the overlying **Sherwood Sandstone Group** (Permo-Triassic) have been traditionally divided into two formations, the St Bees Sandstone and the Kirklinton Sandstone. However, there is difficulty in consistently identifying, defining and mapping the Kirklinton Sandstone Formation. The principal lithological change within the Sherwood Sandstone Group is between mainly fine-grained micaceous sandstones with numerous mudstone interbeds, in the lower and middle parts of the group, and fine- to coarse-grained sandstones with rare or no mica and few mudstone partings in the top of the group. This change occurs within the Kirklinton Sandstone Formation as previously mapped. Consequently, Holliday et al. (2008) have proposed adopting the stratigraphical nomenclature presently employed in the contiguous offshore Solway Firth and Irish Sea basins (Jackson and Johnson, 1996), namely the **St Bees Sandstone** and the **Ormskirk Sandstone** formations. The St Bees Sandstone Formation is exposed in several quarries, and natural exposures occur in north Cumbria and eastern Dumfries and Galloway (Dixon et al., 1926).

The **Mercia Mudstone Group** is largely restricted to the central parts of the Carlisle Basin where it is generally poorly exposed (Dixon et al., 1926). The group comprises dominantly red-brown (locally grey-green) mudstones that are commonly silty. Cross-cutting fibrous gypsum veins are common throughout, and a bed of halite has been recorded within the succession in several boreholes (Jackson et al., 1995; Young et al., 2001). Boreholes at Silloth suggest that the group is more than 320 m thick (Holliday et al., 2004).

In the vicinity of Great Orton [NY 327 540], west of Carlisle, a small fault-bounded outlier of strata assigned to **Penarth Group** (Rhaetian, Late Triassic) and the **Lias Group** (Late Triassic to Early Jurassic) is present (Ivimey-Cook et al., 1995; Holliday et al., 2004). The Penarth Group consists of 10 to 15 m of grey mudstones, fine-grained sandstones and limestones that rest disconformably on the Mercia Mudstone Group. The Lias Group comprises more than 110 m of grey calcareous silty mudstones, siltstones, fine-grained sandstones and limestones of marine origin.

4 Quaternary geology

4.1 PREVIOUS RESEARCH

The history of Quaternary research in Galloway may be traced back to an early paper on the evidence for glaciation in Galloway by Jolly (1868). In their descriptions of the geology of Sheets 5 and 9 (Scotland), Horne (1896) and Geikie et al. (1877) emphasised evidence for recent glaciation and marine inundation in Kirkcudbrightshire and Dumfriesshire. No memoirs were produced from the primary survey of Scottish Sheets 6 and 10. In Eastern Dumfriesshire, the Langholm district was resurveyed in the 1950–60s (Sheet 11, Langholm, IGS, 1968; Lumsden et al., 1967). More recent summaries of the Quaternary geology have appeared in the 3rd edition of British Regional Geology: South of Scotland (Greig, 1971), in publications relating to the sand and gravel resources of the district (Goodlet, 1970; Cameron, 1977), and in memoirs for the Kirkcudbright–Dalbeattie and New Galloway and Thornhill districts (McMillan, 2000b; McMillan and Golledge, 2002).

Apart from the primary mapping conducted by the Geological Survey in the 1870s, the Quaternary geology of Dumfries and Galloway received little attention until J K Charlesworth published two major papers (1926a, b) on the distribution and source of erratics, the positions of moraine belts and the extent of glacial re-advances in southern Scotland. During the last fifty years the work of J B Sissons (for a review see Ballantyne and Gray, 1984) and PhD research, in particular by R J Price (Edinburgh) (Price, 1961, 1963), H D Cutler (Liverpool) (Cutler, 1979), R Cornish (Edinburgh) (Cornish, 1980, 1981), J May (Glasgow) (May, 1981) and K E Salt (Glasgow) (Salt, 2001; Salt and Evans, 2004) has revived interest in the late Devensian history of southern Scotland. Recent BGS research includes micromorphological studies of the glacial sediments from Plumpe Farm [NY 3344 6813], near Gretna (Phillips et al., 2007), and from North Corbelly [NX 9853 6337], near Dumfries (Phillips and Auton, 2008).

On the southern side of the Inner Solway Firth, Goodchild (1875, 1887) provided evidence from glacial erratics that ice sourced in the Galloway Hills flowed up the Vale of Eden, across the Stainmore Gap and towards the coast north of the Cleveland Hills. From the primary survey, Holmes (1899) described the glacial and other superficial deposits of the Carlisle district (England Sheet 17). Extensive revision survey of Cumbria by the Geological Survey in the 1920s (see Trotter, 1922, 1923) resulted in the publication of several important papers (Trotter, 1929; Hollingworth, 1931; Trotter and Hollingworth, 1932a) and memoirs (Dixon et al., 1926, Eastwood, 1930; Eastwood et al., 1931; Trotter and Hollingworth, 1932b). Recent publications including the Quaternary Research Association Field Guide to Cumbria (Boardman and Walden, 1994), the Geological Conservation Review volume for the Quaternary of Northern England (Huddart and Glasser, 2002) and the Fifth Edition of British Regional Geology: Northern England (Stone et al., 2010) provide excellent summaries of Quaternary research in the region.

The late-glacial and Holocene environment of the Solway was extensively studied by Jardine (1964, 1967, 1971, 1975, 1980, 1981; Jardine and Morrison, 1976). Pollen studies in southern Scotland include those of Moar (1969), Bishop (1963) and Bishop and Coope (1977). More recent research of Haggart (1988, 1989, 1999), Lloyd (1999), Lloyd et al. (1999), Smith et al. (2003), Wells (1999a, b), and Wells and Smith (1999) has enhanced our understanding of the history of Holocene sedimentation and relative sea level change along both sides of the Solway Firth. Evolution of the coastline south of Dumfries during medieval times has been investigated by Tipping et al. (2004) and Tipping and Adams (2007). Research at Newbie by Jardine, (1964, 1971, 1975, 1980) and Dawson et al. (1999), together with detailed studies of insect assemblages at Bigholms Burn and Redkirk Point by Bishop and Coope (1977), have thrown light upon both depositional environments and fluctuating climatic changes during the Late Pleistocene and early part of the Holocene (see also Tipping, 1999a, and the review by Sutherland in Gordon and Sutherland, 1993). The sequences at the Bigholms Burn Site of Special Scientific Interest (SSSI) [NY 316 815] (Gordon, 1993a) and at Redkirk Point [NY 301 652] (Gordon, 1993b) were ^{14}C dated in the 1960s and 1970s (see Bishop and Coope, 1977, and references therein). Deposition of the organic sediments spanned the Windermere Interstadial–Younger Dryas–Holocene transition at both sites. However, most modern published ^{14}C dating in the district has been confined to Holocene materials.

4.2 SUMMARY OF QUATERNARY HISTORY

4.2.1 Pre-late Devensian events

Biostratigraphical and oxygen isotope evidence from cored ocean floor sediments indicates that there have been at least 16 major cold events during the Quaternary (Shackleton and Opdyke, 1976; Boulton et al., 2002). Some fourteen climatostratigraphical stages of alternating glacial (cold) and interglacial (temperate) conditions are recognised in the British Isles (Catt et al., 2006). It is unlikely, however, that every one of the cold events produced extensive ice-sheets and till deposits on the British landmass.

No representative deposits predating the last interglacial (Ipswichian) are known in the district, although lenses of fossiliferous clay were found beneath till and gravel in a borehole [NY24NE2, NY 2532 4865] drilled 229 m south of Wigton Station, just to the south (Eastwood et al., 1968, p.226). The lenses occurred within red clay that rested on a bedrock depression in a buried channel at about -21 m OD, and contained the gastropod *Turritella communis* (Risso), foraminifera and ostracods (Figure 4). The fossiliferous deposits (**Wigton Marine Bed**) may be Ipswichian in age, and were possibly transported as glacial rafts from the Solway Firth during an early stage in the last glaciation, when Scottish ice flowed southwards over the Solway.

At least the early part of the Ipswichian Interglacial was warmer than any part of the Holocene. The district became cloaked in mixed deciduous forest, which included a peculiarly large proportion of hornbeam and alder in addition to birch, pine, oak and holly (Chiverrell et al., 2004a, b). The nearest known terrestrial deposit of presumed

Ipswichian age occurs at Scandal Beck [NY 742 024], at the southern edge of the Vale of Eden drumlin field (Carter et al., 1978; Letzer, 1978; Mitchell, 2002). This deposit, the **Scandal Beck Peat Bed** (Thomas, in Bowen, 1999, p.95), comprises at least 4 m of organic mud, sand, gravel and compressed peat containing pollen, coleoptera and plant macrofossils indicative of the closing stages of an interglacial. The organic sediments occur in the core of a drumlin, overlain by two till units. The stratigraphical significance of the organic sediments remains uncertain, however, because a weathered diamicton overlying the organic sediments is similar to one that underlies them, suggesting that the upper one may have been ice-rafted, but probably only a short distance.

The current chronostratigraphy for the British Quaternary places divisions between the early, mid and late Devensian substages at 50 000 years ago and 26 ka before present (BP) respectively. However, many researchers would now place the divisions at 60 000 years and at 28.6 cal ka BP, the former corresponding with the end of Marine Isotope Stage (MIS) 4, and the latter based on recent recalibration (Figure 5). The continental European record indicates that the Ipswichian (MIS 5e) was halted by climatic deterioration about 116 000 years ago. This was followed by a warmer period about 100 000 years ago (MIS 5c), which probably correlates with the Chelford Interstadial, when mixed birch, pine and spruce forest developed in the Chelford area [SJ 820 740] of the Cheshire lowlands (Worsley, 2005). Cooling recommenced about 90 000 years ago, followed by another warmer period about 80 000 years ago (MIS 5d), the so-called Brimpton Interstadial. Significant cooling then occurred until about 65 000 years ago, in MIS 4, when there may have been a significant early Devensian glaciation in northern Britain (Bowen et al., 2002), although there is little tangible evidence (Worsley, 1991). However, uranium-series dating indicates that there was low growth of speleothems between 90 000 and 45 000 years ago in caves of the Craven district [SD 570 720], implying that a non-glacial, tundra-like environment existed in north-west England throughout the period (Gascoyne et al., 1983). Peaks in speleothem growth at 76 000, 57 000 and 50 000 years ago suggest that there were three short, warmer interludes.

During the last 115 000 years, there is evidence for two major ice advances (McCabe, 1987; Bowen, 1989) in the British Isles. The earlier glaciation developed about 70 000 years ago (early Devensian), and the second at about 26 ka BP, at the beginning of the late Devensian (Rose, 1989; Boulton, 1992; Boulton et al., 1991; Gordon and Sutherland, 1993).

4.2.2 Late Devensian events

During the late Devensian there have been two periods of cooling in Scotland; the first during the Dimlington Stadial from about 28.6 cal ka BP to 14.7 cal ka BP; and the second in the Loch Lomond Stadial from 12.9 cal ka to 11.7 cal ka BP. The intervening period of temperate climate has been defined as the Windermere or Lateglacial Interstadial (Figure 5). The Dimlington Stadial was associated with the build up of glaciers in the mountains of the Western Highlands of Scotland, in the western Southern Uplands, and in the central Lake District. During the first 3000 years of the Dimlington Stadial, each of these centres of ice accumulation would have nourished expanding glaciers that radiated away from their source areas. This expansion continued until Highland ice became confluent with Southern Uplands ice (Price, 1983). Thereafter, the entire landmass of Scotland was covered by a single ice-sheet that reached its greatest extent at the Last Glacial Maximum (LGM), around 22 000 cal ka BP, and which extended significantly southwards into England.

Most of the glacigenic deposits in the Solway area were laid down during the main late Devensian (MLD) glaciation, during the Dimlington Stadial (Figure 5) when the region was overwhelmed entirely by ice (Bowen et al., 1986: Catt et al., 2006; Ehlers et al., 1991; Boulton et al., 2002; Sutherland and Gordon, 1993). There is growing evidence from north-west Europe that the LGM occurred relatively early in the late Devensian, before 22 cal ka BP (Bowen et al., 2002). A period of glacial retreat followed before significant re-advances occurred shortly after 18.4 ka BP, particularly involving coastal ice streams. The supposed maximum advance of the MLD ice-sheet recorded at Dimlington (Rose, 1985, 1989), in eastern Yorkshire, therefore possibly correlates with the second of these advance events rather than the LGM (Eyles et al., 1994). In north-eastern Ireland, high precision radiocarbon dating on foraminiferids indicates that a period of ice retreat between 16.7 and 15.0 ka BP (Cooley Point Interstadial) preceded two significant re-advances between about 15.0 and 14.2 ka BP, during the Clogher Head and Killard Point stadials (McCabe, 1996, 1997; McCabe and Clark, 1998; McCabe et al., 1998; McCabe and Dunlop, 2006). The Scottish Re-advance, which is widely believed to have affected the northern tip of the Isle of Man and north-western Cumbria, was possibly contemporaneous with one or both of those events (Huddart and Glasser, 2002; Chiverrell et al., 2004a). The whole district was probably ice-free by 14.7 cal. ka BP.

Ice-sheet development during the late Devensian was complex and has been modelled only in general terms (Boulton et al., 1977, 1985, 1991; Boulton, 1990; Lambeck, 1991; Boulton and Payne, 1994). Boulton et al. (1977) estimated that at the LGM the relative elevation of the ice-sheet surface over the Southern Uplands and over the Lake District may have been in excess of 1900 m and about 1700 m respectively. However, in the Lake District, palaeonunataks have since been identified, indicating that the ice-sheet was thinner and that its surface stood at between 800–870 m above OD (Lamb and Ballantyne, 1998). Nevertheless, even the most conservative of estimates suggest that there was about 700 m of ice over the Irish Sea basin during the LGM, when Snaefell (621 m) on the Isle of Man was buried.

The sequence of events that occurred during the MLD glaciation is not fully understood despite over 150 years of research. This is due to deficiencies in geochronological control on the timing of the formation of landforms and deposits that clearly result from more than one phase of glaciation, and a stratigraphical record beset with difficulties of regional correlation. The MLD ice-sheet is now considered to have been more dynamic than previously thought, with migrating ice divides and periodically fluctuating margins that locally surged into proglacial lakes and across the sea bed (Evans et al., 2009). This resulted in multiple glacial reorganisations and local re-advances, leading to the juxtaposition of tills of markedly different provenance (Merritt and Auton, 2000). Although there are numerous references in the older literature to 'tripartite sequences' comprising 'lower' tills, 'middle' sands, silts and clays, and enigmatic 'upper' tills, the stratigraphy generally cannot be rationalised so simply.

During the latter stages of the Dimlington Stadial, sustained amelioration in climate ultimately led to complete deglaciation of the Southern Uplands by about 14.7 cal. ka BP (the beginning of the Windermere or Lateglacial Interstadial). Wastage of the ice-sheet led to extensive deposition of glaciofluvial sand and gravel. Much debate has centred on whether these deposits, which are best developed between Thornhill and Dumfries in the wide valley of the River Nith (Solway West, BGS, 2005; Stone, 1957, 1959) and in the Lochmaben Basin, were laid down by meltwaters towards the end of successive glacial re-advances. Glacial meltwater also contributed to a global eustatic rise in sea level, which was offset and periodically balanced by uplift of the land through isostatic recovery following removal of the ice load. High sea levels during the Lateglacial Interstadial resulted in the formation of raised shoreline features along the coast on both sides of the Firth. They are locally well developed south of Dumfries (McMillan, 2000b).

4.2.2.1 Other late-glacial events

The 'late-glacial' covers the period of time between the retreat of the MLD ice-sheet, which varies from area to area, and the beginning of the Holocene at 11.7 cal. ka BP. It includes the Windermere Interstadial and the Loch Lomond Stadial (Younger Dryas) (Figure 5), both periods of climatic instability. Deglaciation commenced in a cold, arid environment and high parts of the district possibly witnessed several thousand years of ice-free, periglacial conditions before the onset of rapid warming at about 14.7 cal. ka BP, prior to the beginning of the Windermere Interstadial. The abrupt amelioration in climate occurred when temperate waters of the Gulf Stream returned to the sea off the western coasts of the British Isles. River terraces and alluvial fans formed across the district by paraglacial processes, sweeping away loose glacial debris before soils became stabilised by vegetation. Raised shorelines and gravel deltas, such as those seen inland of the present coast around Carsethorn [NX 990 600] and Southerness [NX 975 550], formed during the period of high sea levels associated with the final decay of the MLD ice-sheet.

Masses of ice, which may have been buried within glacigenic sediments for hundreds of years, melted out relatively slowly to form kettleholes. Pollen, spores and the remains of beetles and midges in organic sequences preserved within kettleholes, and in small lake basins such as those at Bigholms Burn [NY 316 815] (Gordon, 1993a) and Redkirk Point [NY 301 652] (Bishop and Coope, 1977; Gordon, 1993b), provide a valuable record of environmental change. At these sites the classic 'tripartite' late-glacial sequence constitutes cold stage clastic deposits, overlain by organic or carbonate-rich interstadial sediments capped by clastic sediment representing the Loch Lomond Stadial. Palaeoenvironmental indicators show that summer temperatures rose by 7ºC within a decade or so, peaking at about 12ºC at the start of the Interstadial in southern Scotland (Brooks and Birks, 2000).

Sediment cores from raised bogs in the district, such as Bolton Fell [NY 495 695] and Walton Mosse [NY 504 667] near Carlisle (Barber et al., 1998), Burnfoothill Moss [NY 263 737] near Eaglesfield (Tipping, 1999a), and Whitrig Bog [NT 624 349] near Kelso (Mayle et al., 1997; 1999; Brooks and Birks, 2000), provide extensive palaeoenvironmental records of the Holocene. Freshly deglaciated ground was first colonised by a pioneer vegetation of open habitat, Alpine species followed by the immigration of crowberry heath, juniper and dwarf varieties of birch and willow. Eventually open birch woodland developed with juniper and isolated stands of Scots pine locally. An oscillatory climatic deterioration occurred throughout the Windermere Interstadial (Innes, in Huddart and Glasser, 2002, p.211–220) and it is possible that glaciers had already started to build up in the mountains before more sustained cooling began at about 12.9 cal. ka BP.

The Gulf Stream current retreated rapidly to the latitude of northern Portugal at about 12.9 cal. ka BP, heralding the start of the Loch Lomond Stadial and a brief return to arctic conditions. At the beginning of the stadial, Chironomid-inferred mean July temperatures declined to an average of about 7.5ºC at Whitrig Bog (Brooks and Birks, 2000), and a tundra environment became ubiquitous across southern Scotland. Glaciers re-formed in the Highlands, and at least locally in the Galloway Hills and in the Lake District to the south. During this short period, the land was subjected to periglacial arctic conditions, which locally produced patterned ground, ice-wedge casts and convolutions in the glacial and glaciofluvial deposits that had been laid down by the glaciers and their meltwaters on the lowland areas (Galloway, 1961; Watson, 1977; Ballantyne and Harris, 1994; cover photograph). Only plant communities tolerant of the arctic conditions were able to colonise the unstable soils.

Periglacial processes destroyed the immature soils that had developed during the Windermere Interstadial, creating a range of rubbly head deposits that are especially well developed in the Langholm Hills. Both fluvial and debris flow activity were enhanced, especially during springtime snowmelts, and slopes were particularly prone to failure. The sand and gravel that underlies some river terraces and floodplain alluvium in many of the larger valleys in the area was probably laid down in braided rivers during the Loch Lomond Stadial.

4.2.3 Holocene

The Holocene is considered to have commenced about 11.7 cal ka BP, and was a period of general recovery to present-day climatic conditions. It began abruptly, when the warm Gulf Stream current became re-established, providing an ameliorating influence on the climate of the British Isles. Average summer temperatures rose by about 8ºC within 100 years or so (Atkinson et al., 1987). The mildest part of the Holocene probably occurred between 9 and 8 cal ka BP, rather than during the commonly assumed mid Holocene climatic optimum between 6.5 and 6 cal ka BP (Tipping, 1999b). Radiocarbon dates of about 10 240 cal BP have been obtained by Godwin et al., (1957) on the basal parts of organic sequences from Scaleby Moss [NY 430 635], and a date of 10 300 cal BP is quoted for the lowest Holocene interval from Redkirk Point [NY 301 652] by Bishop and Coope (1977). Tipping (1999b) dates the initial colonisation of Burnfoothill Moss by birch as occurring at 10 400 cal. BP. On the upland areas, between about 7.5 and 7 ka BP, the generally wet but mild conditions led to the growth of peat bogs, extensive spreads of which blanket much of the district (Harvey and Allen, 1998). However, peat growth at Bigholms Burn only began after 6.2 cal ka BP (Bishop and Coope, 1977) and enhanced growth during a cooler, wetter climate (more typical of the present day) began about 4 cal ka. Analyses of protozoan spores, plant macrofossils and humification in peat cores from Walton Moss have identified several cyclical wetter and drier episodes since then (Barber et al., 1998; Hughes et al., 2000) (Figure 6).

Present-day rivers, which occupy most of the valleys, have laid down loamy floodplain alluvium and also cut into and reworked some of the earlier deposits to form gravelly river terraces, such as those in the valley of the River Nith, around Dumfries, and in the valleys of the Kirtle Water and the River Sark near Gretna [NY 320 670].

Although the impacts of glaciation and periglaciation remained the dominant influences on the landscape, postglacial processes superimposed subtle, but distinctive modifications on the district, particularly around the coast. Steep hillsides have been modified by gullying, landslides, soil creep and debris flows; valley floors have been sculptured by rivers and tidal inlets have become choked with muddy estuarine alluvium and salt marsh deposits.

Some of the most detailed and informative studies on Holocene climate and vegetational change in Britain have been conducted on raised, ombrotrophic bogs around the Solway (Tipping, 1999a). These include, most notably, studies of Scaleby Moss [NY 432 635] (Godwin et al., 1957), which lies immediately to the east of the district, Bolton Fell Moss [NY 495 695] and Walton Moss [NY 504 667] (Barber et al., 1998), which lie to the east of Longtown, Glasson Moss [NH 240 605] (Stoneman, 1993), to the south of the Solway, and Burnfoothill Moss [NY 262 737] (Tipping, 1999b) near Eaglesfield.

The widespread occurrence of bare, unstable soils at the beginning of the Holocene led to intense fluvial erosion and deposition, with enhanced debris flow activity on mountain sides and extensive formation of landslides as the ground thawed. The rivers were generally braided with gravelly beds. Soils gradually became more stable following the establishment of vegetation, firstly by pioneering herbs, shrubs and scrub communities similar to the succession of the Windermere Interstadial, and later by woodland.

The vegetational history of the district has been summarised by Tipping (1999a). Trees probably colonised the district from the south, at first mainly via the coastal lowlands, which were much more extensive than today owing to lower sea level in the early Holocene. A distinct phase of juniper dominance was replaced by birch and willow woodland by 9.65–9.45 cal. ka BP. Hazel became firmly established on the western fringes of the Irish Sea by about 9 cal. ka BP, possibly aided by human activity (Chiverrell et al., 2004a, b). An expansion of elm at about 8.8 cal. ka BP generally preceded oak between 8.2 and 7.5 cal. ka BP, especially in low-lying fertile areas. Pine spread into southern Cumbria between 8.5 and 8 cal. ka BP, and into the Galloway Hills. The arrival of alder at between 7.7 and 7.2 cal. ka BP broadly coincides with the transition from the drier, 'Boreal' climate period to the wetter, 'Atlantic' phase in the mid Holocene. Lime and ash were relatively common by 6.0 cal. ka BP, when all the elements of the mixed mid Holocene deciduous forest were present and dense tree cover dominated the landscape of all but the highest parts of the district. Poplar, maple, yew and beech all increased later in the Holocene, possibly as a result of human intervention. Details of anthropogenic impacts on the woodland and the prehistoric and historic record of vegetational change are also given by Tipping (1999a).

4.2.4 Sea-level change

Relative sea levels around the Solway Firth have been influenced by both 'isostatic' depression of the land under the ice load during glaciation (greatest in the western Highlands of Scotland) and by global (eustatic) sea-level changes. The latter are mainly determined by the amount of water contained within continental ice-sheets and global sea levels have risen from a low-stand of about -120 m OD some 20 000 years ago, when those ice-sheets began to melt. Former sea levels portrayed in local relative sea-level curves consequently vary considerably around the coast, especially when tidal inequalities, earth movements and the geoid configuration are taken into account. The rate of uplift was greatest during and immediately after deglaciation and this has fallen exponentially.

Two distinct sets of raised beach and estuarine deposits occur around the Solway Firth, where the amount of glacio-isostatic recovery was sufficiently great to bring about an early period of falling sea level (Wells, 1999a, and references therein) (Figure 7). The older, late Devensian ('late-glacial') set was created during, and shortly after retreat of MLD ice, whereas the younger, far more extensive set formed during the mid to late Holocene.

Only sporadic late Devensian raised marine deposits have been identified in the district; indeed some researchers do not accept that any occur at all, suggesting that ice sourced from the Southern Uplands remained until relative sea level had fallen to about its present level (Shennan and Horton, 2002). Silty clays with foraminifera and ostracods indicating boreo-arctic marine conditions have been recovered by Wells (1997; 1999b) from close to present sea level on the foreshore of Brighouse Bay [NX 630 450]. He equated the fauna with either that of the glaciomarine early late-glacial Errol Beds (about 18–13 ka BP) (Errol Clay Formation of Peacock, 1999, 2003), or the Clyde Beds (about 14–11 ka BP) (Paisley Clay and Linwood Clay Members of the Clyde Clay Formation of McMillan et al., 2011) of central Scotland. Brighouse Bay lies some 40 km to the west of the district. This evidence for 'high' late-glacial sea levels in the adjacent area accords well with data from the St Bees area of western Cumbria, some 45 km to the south (Auton et al., 1998; Auton and Merritt, 2004; Merritt and Auton, 2000). Here, a succession of silts containing a dinoflagellate assemblage indicating cold water conditions occurs at an elevation of at least 0.37 m above OD, beneath radiocarbon dated late-glacial peat and freshwater silt. Both sites suggest that sea level in the surrounding area was higher than present at times during the Windermere Interstadial. South of Dumfries and westwards along the Solway coast, BGS 1:50 000 scale maps (IGS, 1980b; 1981) show isolated deposits of gravel, sand and clay, interpreted to be raised beach and estuarine sediments of late-glacial age, now at elevations greater than 10 m OD (McMillan, 2000b). Haggart's (1999) study of an archaeological site at Pict's Knowe [NX 9538 7213] records a complex history of relative sea-level change from the late Devensian to the present. During the late Devensian sea level fell from about 11 m above OD to less than 1 m above OD, and a large palaeochannel was formed. During the Holocene the channel was filled with alternations of peat and marine clays and silts reflecting cyclical marine transgressive and regressive changes. Several other examples of late-glacial deposits have been identified during the present survey, notably gravelly raised beaches lying at between 11 and 13 m above OD between Caulkerbush [NX 927 571] and Southerness [NX 975 545]. Farther east, at Redkirk Point [NY 301 652], relative sea level had fallen to about 1 m above OD by the mid Windermere Interstadial (Wells, 1999b), as indicated by radiocarbon ages of between 12.3 and 10.3 ka BP on a bed of freshwater peat at this coastal site (Bishop and Coope, 1977).

No evidence has been found in the area to support claims by Eyles and McCabe (1989) that deglaciation of the Irish Sea basin was accompanied by widespread deposition of glaciomarine sediments by sea levels up to 150 m above OD. Extrapolated sea level curves for the Solway reveal a lowstand in the early Holocene when glacio-isostatic rebound outstripped global sea level rise (Zong and Tooley, 1996; Lambeck, 1996; Lambeck and Purcell, 2001). Levels as low as 60 m below OD may have occurred within the northern Irish Sea basin, low enough to have exposed a land bridge linking the Isle of Man to Cumbria.

Along the northern shores of the Solway, sea level rose towards a distinct mean tidal range highstand of about 3 to

4 m above OD by 7400–7700 cal. BP in the mid Holocene (Jardine, 1975; Haggart, 1989; Lloyd et al., 1999) (Figure 8). This was the Main Postglacial Transgression which created the Main Postglacial Shoreline, represented by fragmentary raised beach deposits of well-rounded shingle backed by a degraded cliffline, and extensive raised tidal flats and saltmarsh deposits locally about 9 m above OD. Peat beds and tree stumps ('submerged forests') interbedded with the estuarine deposits are periodically exposed on the foreshores, where they provide clear evidence of Holocene sea-level rise. The Holocene highstand was about 2 m lower on the southern side of the Solway owing to its greater distance from the centre of uplift in the western Highlands; the highstand also occurred later, between 7500 and 6800 cal. BP (Figure 8) (Lloyd et al., 1999).

Detailed relative sea-level curves, including several minor marine transgressions, have been determined from extensive biostratigraphical investigations conducted at many sites along the northern shore of the Solway Firth in the district, notably at Redkirk Point [NY 301 652] (Jardine, 1964, 1971, 1975, 1980; Bishop and Coope, 1977; Gordon, 1993b; Lloyd, 1999); Newbie Cottages [NY 168 649] (Jardine, 1975; Gordon, 1993c; Dawson et al., 1999); Priestside Flow [NY 123 658] (Lloyd, 1999; Lloyd et al., 1999); Pict's Knowe [NX 9538 7213] (Haggart, 1999), and at coastal locations between Southerness Point [NX 9773 5428] and Seafield [NY 2066 6461] south of Annan (Jardine, 1975, 1980). Jardine's investigations also extended along both sides of the River Nith almost to Dumfries, and across flat-lying ground between Caerlaverock National Nature Reserve [NY 050 650] and Nether Dargavel [NY 018 755] which he termed 'The Lochar Gulf', and which largely coincides with Lochar Moss. The evidence for Holocene sea-level change preserved in the Nith valley was presented more recently by Smith, et al., (2003).

4.2.5 Pattern of ice flow and glacial drainage

4.2.5.1 Ice-sheet development

Directions of ice flow have been deciphered mainly from the distribution of erratics and the orientation of striae, drumlins and other ice-moulded landforms (Sutherland, 1993). The generalised pattern of ice flow (Figure 9) has been largely corroborated by the interpretation of satellite imagery (Figure 10), NEXTmap Digital Surface Models (see section 6.1, Figure 11 and p. 27–30), air photo interpretation and field evaluation undertaken for this project (Figure 1). However, the iceflow indicators almost certainly relate to more than one glacial event (Salt and Evans, 2004), and generalised directions of ice flow commonly conflict with those inferred from detailed mapping, till fabric analysis, satellite imagery or digital terrain models.

It is clear that local centres of ice accumulation formed an important element of the MLD ice sheet, separated by zones of relatively fast-flowing, topographically constrained ice streams. Accumulation centres were positioned over the Moffat Hills, Galloway Hills, the high ground around Cross Fell and the central Lake District. The ice apparently remained relatively sluggish and possibly cold-based over the first three of these centres, depositing little till and causing relatively little glacial erosion. In contrast, relatively fast flowing, erosive ice radiated out from the central Lake District. A major linear ice divide linked the Lake District and the western Pennines across Shap Fell; it was independent of topography and its position shifted northwards during the glaciation (Mitchell, 1991; Mitchell and Clark, 1994).

Based upon evidence of glacial erratics (Goodchild, 1875, 1887), there is little doubt that at a stage prior to, or at the LGM, ice sourced in the Galloway Hills flowed southwards up the Vale of Eden, across the Stainmore Gap and towards the English coast north of the Cleveland Hills [NZ 590 010]. The Scottish ice was joined by easterly flowing Lake District ice (Trotter, 1929; Trotter and Hollingworth, 1932a, b). Only remnants of till (Gillcambon Till Formation) deposited during this episode remain in Cumbria, within bedrock depressions and the cores of some drumlins.

The shape and distribution of elongate drumlins in the Vale of Eden and around the northern edge of the Lake District, together with the composition of glacial erratics in the tills forming them, indicate unambiguously that ice subsequently flowed in the opposite direction, down the Vale of Eden, swinging to the west around the Lake District and into the Irish Sea basin. The glacial reorganisation possibly followed partial deglaciation, and is recorded between Appleby-in-Westmorland [NY 685 205] and Brough [NY 795 145]. Hereabouts the Stainmore suite of drumlins is overprinted by the younger Howgill Suite, the latter created by ice flowing northwards from the ice divide crossing the Howgill Fells (Letzer, 1978, 1981, 1987).

The Vale of Eden and Solway lowlands were clearly an extremely 'congested' sector of the former ice-sheet, for which some widely accepted glacial reconstructions in the literature are glaciologically implausible. For example, Scottish ice was thought to have flowed eastwards across the Solway lowlands and through the 'Tyne Gap' (the valley of the River South Tyne) [NY 780 650] contemporaneously with ice flowing westwards from the Vale of Eden, either adjacently (Taylor et al., 1971; Figure 9) or at different levels in the ice-sheet (Hollingworth, 1931). It is more likely that ice ceased to flow through the Tyne Gap following a major glacial readjustment resulting from changing mass balances of ice accumulation areas, possibly accompanied by partial deglaciation. The pattern of ice movement indicated by the interpretation of satellite imagery from the district is born out by both the air photo interpretation and field evaluation.

In the Dumfries and Lochmaben areas, ice flowed in a southerly direction during the last glaciation, as evidenced by glacial striae, roches moutonnées and drumlinised landforms (Figures 10 and 11). Various interpretations of the pattern of ice movement have been made by several earlier workers, notably Geikie (1901), Charlesworth (1926a), Sissons (1967a, b) and Greig (1971); for a summary of these interpretations of the regional pattern see Kerr (1982a, 1982b, 1983) and McMillan and Golledge (2002, fig.31). There is general agreement that ice radiated from a developing ice field centred on the Galloway Hills (Sutherland, 1993), but there is considerable divergence of view as to the trend of flow lines locally. To the north-east of Dumfries, for example, Sissons' reconstruction (1967a) indicates southward ice-flow, whereas the other reconstructions are in general agreement and indicate flow towards the south-east.

On the western side of the Nith Estuary, the pattern of glacial drainage, as indicated by the orientation of eskers and meltwater channels, was predominantly from north to south. At the western edge of the area, around Caulkerbush [NX 927 571], however, the pattern of both ice advance and drainage was very strongly from the north-north-east towards the south-south-west (Figures 10 and 11). This reflects the strength of particularly vigorous streams of ice, which flowed from the Dalbeattie area along the valleys which bisect Dalbeattie Forest. The initial radial pattern of ice flow from the Galloway Hills was disrupted by topography, notably by the upland massif of Mabie Forest [NX 935 710], north of Criffel [NX 957 618] and by Criffel itself. To the north of this massif, part of the ice flow was deflected eastwards towards the Dumfries area, whilst other streams flowed south-south-east across the upland along valleys now drained by the Southwick [NX 885 610], Drumcow [NX 905 615] and Kirkbean [NX 960 600] burns.

Within the Nith valley, upstream of Dumfries, both ice-flow and glacial drainage were strongly towards the south-east, parallel to the axis of the valley (Figure 10). Glacially sculpted landforms are well developed in bedrock and locally in till; glacial streamlining is particularly pronounced within the outcrop of the Criffel–Dalbeattie Pluton and on the ridge of Permian sandstone that extends south-south-eastwards from Dumfries. The development of large-scale glacial gouges and flutes, trending north to south or north-west to south-east, is particularly notable between Glencaple [NX 995 685] and Annan [NY 200 670]. More subtle fluting of till and bedrock shows that on the coastal lowland between Carsethorn [NX 990 600] and Caulkerbush [NX 927 571], ice-flow was deflected south-westwards around the upstanding mass of the central part of the Criffel–Dalbeattie Pluton.

In Annandale, a recent study of modern satellite imagery and air photographs by Bradwell (2006) demonstrates a network of strongly aligned north–south lineations. The positive features are interpreted as subglacial bedforms of drumlins up to 3 km long. The drumlins are associated with subparallel channels formed by subglacial meltwater drainage, and Bradwell concluded that the distribution of these landforms indicates that ice-sheet flow in this part of southern Scotland was convergent and faster flowing than in adjacent areas.

4.2.5.2 Deglaciation and active retreat

During the 20th century, the veracity of the concept of glacial ice-sheet re-advances during deglaciation of the MLD ice-sheet was actively debated by several researchers. In southern Scotland, Charlesworth (1926a) based his interpretation on presumed arcuate morainal systems and associated them with five proposed stages of recession. In the same paper, Charlesworth conceded that ‘some of the stages, or possibly all, would appear to mark the limits of re-advance of the ice of considerable magnitude.’ Two stages in particular, the Corrie and Kirkcowan stages, were identified as being associated with re-advances. The former equates with advance of corrie glaciers in upland areas, presumably during the Loch Lomond Stadial. During the Kirkcowan Stage (the second oldest of the five ‘Morainic Stages’) Charlesworth related re-advances of the ‘Nith Glacier’ to moraines at Dumfries (Figure 10), and connected re-advances of the ‘Annandale Glacier’ to moraines near Lockerbie. These moraines both form part of discontinuous series of predominantly gravelly kamiform deposits that Charlesworth (1926b) identified as a morainic belt which stretches westwards to the Rhins of Galloway [NX 050 540]. He referred to this belt as the Lammermuir–Stranraer Moraine and concluded that it was the product of one or more re-advances of ice following the main glaciation (LGM) (Charlesworth, 1926b).

Deposits assigned to the Kirkcowan Stage initially found favour with Sissons (1967a), who used the features identified by Charlesworth in support of his own Perth Re-advance limit in south-west Scotland. Subsequently, Sissons (1974) disputed all of Charlesworth’s stages except stage five, which can be associated with the Loch Lomond Stadial.

Trotter (1929) proposed a large scale re-advance of ice from southern Scotland into Cumbria during the late Devensian. Trotter’s model was disputed by Pennington (1970, 1978) and Sissons (1974), but it has gained support in recent years from Clark (1992, 2002) and Huddart (1994), although the latter suggested a less extensive advance than that originally proposed.

Stone (1957, 1959), in a study of part of Nithsdale, favoured a model of deglaciation by in situ downwasting of ice, and made no mention of possible re-advances. He attributed steep-sided mounds (kames) of stratified sand and gravel, much affected by small scale faulting, to a crevasse-fill, ice contact origin. Discontinuous kame terraces near Dalswinton [NX 936 854] were considered the product of proglacial deposition adjacent to the glacier. Rare small eskers were also identified occurring as sinuous, steep sided ridges, and interpreted as the product of sub-glacial deposition. Stone (1959) refuted the suggestion by Charlesworth (1926a) that ice-marginal channels are not widely developed in Nithsdale, citing numerous examples on the north-eastern side of the valley around Auchencairn [NX 980 848], an observation supported by the present mapping. However, his conclusion that the en echelon pattern of the channels shows successive stages in ice recession by downwasting rather than active retreat, is probably erroneous. Stone (1959) also described numerous small scale subglacial channels together with major proglacial meltwater channels, some of which are cut into bedrock. (for further details see Section 4.2.5.4 — Glacial Drainage).

Bishop (1963) cited the occurrence of small scale, soft sediment deformation structures around Lochmaben [NY 080 830] as evidence of overriding by ice. He attributed this to a local glacial re-advance, which was also responsible for the formation of kettle holes now occupied by Castle Loch [NY 088 815], Mill Loch [NY 077 832], Kirk Loch [NY 078 822] and Hightae Mill Loch [NY 083 803]. More recently, work carried out by Huddart (1999) outlined a model for kame formation within the Nith valley. This challenges the assumption of Stone (1959) that the kames are a product of crevasse fill within wasting stagnant ice. Sedimentological evidence is presented that suggests the Nithsdale kames are the product of actively retreating ice, which may have experienced stillstands and re-advances on a local scale. Subglacial drainage was found to be not as extensive as formerly assumed, and horizontally bedded, multiple channel-fills, and large scale trough cross-bedding recorded in the sediments implied drainage to an active ice front, which reached a stillstand position at the Kerr Moraine. In stagnant, wasting ice, the abundance of crevassing and lack of directional control exerted by the thin ice allows the high meltwater flow to occupy any number of the numerous pathways available, thus leading to the development of a non-oriented outwash network, which becomes superimposed on the underlying relief. Similar conclusions were reached by Price (1961, 1963) in a study of drainage in Peeblesshire. Thus, if an organised distribution of glaciofluvial deposits can be identified, and this used to infer former meltwater paths, it may logically be suggested that drainage was less extensive and was directed and controlled by an overburden of active ice. Active retreat in the Southern Uplands is also supported by Gray (1997), though his conclusions relate primarily to their northern margin.

4.2.5.3 Scottish re-advance

There is a recurrent conclusion in the older literature that one or more major glacial re-advances of Scottish ice occurred across the Solway lowlands and the coast of west Cumbria during the latter stages of the last glaciation (Trotter, 1922, 1923, 1929; Trotter and Hollingworth, 1932a, b). Several limits have been postulated for the main event, named the Scottish Re-advance, extending across the Irish Sea, linking with the Bride Moraine in the north of the Isle of Man and continuing into Ireland; none have proved sustainable (Pennington, 1970, 1978; Evans and Arthurton, 1973; Sissons, 1974; Thomas, 1985). However, the re-advance concept has gained renewed support from new evidence from the Solway lowlands (Huddart, 1970, 1971a, b, 1991, 1994; Huddart and Tooley, 1972; Huddart et al., 1977; Huddart and Clark, 1994; Clark, 1992), west Cumbria (Merritt and Auton, 2000), the Isle of Man (Thomas, 2004 and references therein) and Ireland (McCabe and Clark, 1998; McCabe et al., 1998).

Trotter (1929) argued that a major re-advance of Scottish ice had occurred, extending over the Carlisle Plain up to 122 m to 137 m OD and reaching eastwards to Cumwhitton [NY 505 522], Hayton [NY 508 578], Brampton [NY 530 610] and Lanercost [NY 554 638]. The ice supposedly caused no serious modification to pre-existing landforms, and laid down broad sheets and disconnected patches of till, although they were only recognisable where underlain by 'Middle Sands' of a 'tripartite' till-sand-till sequence (Figures 4 and 10). The absence of any terminal moraine, the progressive thinning of the 'Upper Boulder Clay' towards the re-advance limit, and the preservation of mostly undisturbed sequences of 'Middle Sands' towards the outer limit, suggested to Trotter that the re-advance was short-lived and of no great intensity. Huddart has consistently argued that the re-advance was much more limited in extent, reaching no farther east than Carlisle (see Huddart and Glasser, 2002 for details).

Fine-grained glaciolacustrine deposits were laid down in the Carlisle area during deglaciation, probably both before and following the Scottish Re-advance, when ice occupied the Solway Firth and blocked drainage within the Solway lowlands (Trotter, 1929; Hollingworth, 1931; Trotter and Hollingworth, 1932a, b). The levels of the resulting 'Glacial Lake Carlisle' were first determined by the heights of overflow channels within the 'Tyne Gap', many of which exploited previously formed subglacial channels, and later by ice-marginal channels to the south-west of Carlisle. Lake levels were determined as 61–67 m above OD in the Irthing valley [NY 600 650], 55 m around Wetheral [NY 465 545], 43 m around Carlisle airport [NY 485 610], and 30 m on the eastern outskirts of Carlisle [NY 430 550]. Levels at 15 m above OD and lower were inferred from occurrences of lake sediment (Great Easby Clay Formation) around Carlisle that had been truncated during the Scottish Re-advance and subsequently capped by 'Upper Till'. A misfit valley at 30–40 m above OD, linking the modern rivers Caldew and Wampool by way of the 'Dalston Gap' [NY 350 505] south-west of Carlisle, functioned as a major glacial spillway at the margin of Re-advance ice (Dixon et al. 1926, p.58) (Figures 2 and 11).

Trotter and Hollingworth's evidence for proglacial lakes in Cumbria and farther afield was challenged by Carruthers (1953, and references therein), who considered that much of the ponding occurred subglacially. Huddart (1970, 1981, 1991) also disputed that the lakes were proglacial, concluding that all but the lowest levels of lake had been ice-walled and had formed amidst stagnating ice. This helped explain the absence of well-developed lake shorelines. Furthermore, Huddart concluded that the lakes had all formed prior to the Scottish Re-advance. He also suggested that the occurrences of 'Upper Till', previously reported by Trotter and Hollingworth, beyond his re-advance limit, were flow tills and not formed subglacially. Huddart also deduced that the Dalston Gap overflow channel was initiated subglacially and that it subsequently drained the 30 m lake during ice-sheet retreat. He did not think that the re-advance ice was sufficiently thick to hold up lakes in the Carlisle Plain. However, some of the sedimentological evidence cited by Huddart is capable of alternative interpretation in the light of advances in our understanding of glacially overridden sediments, and more work is clearly required to elucidate the sequence of events in this area.

Evidence for a subsequent, minor re-advance of Scottish ice has been found in the form of a striated boulder pavement that is intermittently exposed at low tide on a boulder scar [NY 125 645] located 500 m south of the shoreline at Nethertown, west of Powfoot (Brookfield, Personal Communication, 2008). The pavement consists of a single layer of interlocking bullet- and flatiron-shaped boulders up to 50 cm in length. The clasts are composed predominantly of wacke sandstone with some red Triassic sandstone and sparse granodiorite derived from Criffell, some 15 km to the west. The flatirons have smoothed and striated upper surfaces and both the long axes of the boulders and the striations show a consistent west north-west to east-south-east alignment. The simplest explanation is that the pavement formed subglacially beneath wet-based ice that flowed east-south-east across previously deposited till and glaciofluvial deposits. The presence of granodiorite boulders from Criffell in till locally overlying the pavement, but not below it, is compatible with a late stage re-advance of ice splaying out into the Solway Firth from Nithsdale and Annandale.

4.2.5.4 Glacial drainage

There are numerous glacial drainage channels around the Vale of Eden, including a splendid series that descend northwards obliquely down the western slopes of the North Pennine Escarpment. Most channels formed in the vicinity of the ice margin at transitory positions of actively retreating ice (Trotter, 1929; Hollingworth, 1931; Trotter and Hollingworth, 1932a, b). They record progressive lowering of the ice surface in conjunction with frontal retreat, which led to eventual separation of Lake District and Scottish sourced ice, and to formation of intervening lakes (the higher levels of Trotter and Hollingworth's Glacial Lake Carlisle). These channel systems have been reinterpreted by Letzer (1978, 1981, 1987), Arthurton and Wadge (1981) and Huddart (1981, 1991) as having formed subglacially beneath stagnating ice, in which steady-state, dendritic meltwater channel systems developed.

A prominent suite of south-eastward draining meltwater channels is present north of the valley of the Mein Water, between Kirtleton [NY 270 800] and Lockerbie [NY 135 815]. It records progressive westward retreat of the Southern Uplands ice towards Dumfries. Other notable groups of ice marginal channels were identified by Stone (1959) in mid Nithsdale around Auchencairn [NX 980 848] (see 4.2.5.2 above) and on the south-eastern side of the valley of the Water of Ae, west of Parkgate [NY 017 876]. These are related to the active late-stage retreat of glaciers in the Nith and Ae valleys respectively. Ice-marginal channels associated with retreat of the Nith glacier are also present in the northern Dumfries suburbs of Heathhall [NX 995 795] and Marchfield [NX 980 775], where they dissect glacial outwash gravels associated with the Marchfield Moraine.

Deposits of glaciofluvial sand and gravel were laid down during the final retreat of Scottish ice from the district, including several parallel eskers created by meltwaters that flowed subglacially towards an ice margin in the vicinity of the Dalston Gap overflow channel (Huddart, 1991)

(Figure 10). They are draped on drumlins formed earlier by ice that flowed in the opposite direction. Trotter and Hollingworth (1932a, b) concluded that east-south-east orientated eskers in the vicinity of Gretna [NY 320 670] and Cummertrees [NY 143 665] formed following the advance.

The most extensive spreads of glaciofluvial sand and gravel in the district lie between Thornhill and Dumfries (Figure 11), in the wide valley of the River Nith and in the Lochmaben Basin. On the western side of the Nith Estuary, the pattern of glacial drainage as indicated by the orientation of eskers and meltwater channels, was predominantly from north to south. Eskers and meltwater channels between New Abbey [NX 962 662] and Kirkbean [NX 977 591] trend southwards. They follow the fluted topography formed by fast moving ice from the Nith, Culden Water and Cargen Water valleys that flowed south-westwards towards the Irish Sea Basin. However, at the western edge of the area around Caulkerbush [NX 927 571], the pattern of both ice advance and drainage was very strongly from the north-north-east. This reflects the strength of particularly vigorous streams of ice, which flowed from the Dalbeattie area along the valleys that bisect Dalbeattie Forest.

5 Lithostratigraphy and distribution of the Quaternary deposits (onshore)

5.1 CLASSIFICATION OF DEPOSITS

The two special 1:50 000 scale Quaternary maps described herein, covering the ground surrounding the inner Solway Firth (Solway West and Solway East; BGS, 2005, 2006), show deposits that have been classified in two ways. The traditional BGS morpho-litho-genetic scheme was used with its familiar symbols and standard colours. This method of classification has proved to be a practical means of mapping deposits cropping out at the surface and it is particularly appropriate for rapid mapping techniques relying heavily on air photo interpretation. However the morpho-litho-genetic scheme does have some failings. For example, it does not easily accommodate complicated sequences of deposits or bodies of sediment that contain a mix of lithologies. It also does not allow families of deposits with common attributes to be easily depicted. To overcome these difficulties, many of the deposits on these maps have also been classified lithostratigraphically in accordance with the Quaternary lithostratigraphical framework for Great Britain defined by McMillan (2005) and McMillan et al. (2005, 2011).

In order to embrace both classification schemes, the Superficial Deposits symbols have been embellished, such that lithostratigraphical map codes appear as superscripts, lithological codes as prefixes, chronostratigraphical qualifiers as subscripts and inferred depositional environments as suffixes.

5.2 LITHOSTRATIGRAPHY

Lithostratigraphy involves the description, definition and naming of rock units. Individual units are normally described and defined using their gross lithological characteristics, by their inter-relationships with adjacent units, and on the basis of their unconformable bounding surfaces. The units are ranked in a formal hierarchy of Bed, Member, Formation, Subgroup and Group. The Formation is generally the basic mappable unit in the hierarchy. All units established by the BGS have been entered into the BGS Lexicon of Named Rock Units and the Index of Computer Codes (downloadable from http://www.bgs.ac.uk/).

The lithostratigraphical framework adopted for classifying the Quaternary deposits of the Solway (Table 1) is based on the 'top–down' scheme outlined by McMillan (2005) and McMillan et al. (2005, 2011). The glacigenic deposits (glacial, glaciofluvial, glaciolacustrine) are the product of the Devensian stage glaciations. Formations established for these deposits are assigned to two subgroups of the **Caledonia Glacigenic Group**, namely the **Irish Sea Coast Glacigenic Subgroup** and the Southern Uplands Glacigenic Subgroup. The broad distribution of these and other subgroups in northern England and southern Scotland is based upon the distribution of defining formations of till (Figure 12). Late-glacial, Devensian and Holocene fluvial deposits (including lithogenetically defined units of alluvium, alluvial fan and river terrace deposits) are assigned to the **Solway Catchments Subgroup** of the **Britannia Catchments Group**. Lacustrine deposits, together with peat and head are also assigned to the Britannia Catchments Group. Intertidal, saltmarsh, marine, estuarine, blown sand, beach and raised marine deposits are assigned to the **British Coastal Deposits Group**.

5.3 CALEDONIA GLACIGENIC GROUP

5.3.1 Irish Sea Coast Glacigenic Subgroup

The deposits of the Irish Sea Coast Glacigenic Subgroup (Figure 12) include material derived from south-west Scotland, the Solway lowlands, the Cumbrian mountains and the west Cumbrian coast, together with glaciomarine sediments from the Irish Sea Basin. The matrices of the tills are predominantly reddish brown where derived mainly from Permo-Triassic 'red beds'. The deposits were laid down from ice that flowed around the north-western side of the Lake District to merge with ice that flowed southwards across the Irish Sea basin from southern Scotland.

5.3.1.1 Tills

The tills of the Irish Sea Coast Glacigenic Subgroup, which in part subsumes the West Cumbria Drift Group defined in Akhurst et al. (1997) and Merritt and Auton (2000), are predominantly reddish brown with matrices composed of variable proportions of clay, silt and fine-grained sand. Gravel content is also variable. The tills are generally very compact, poorly stratified, matrix-supported diamictons, containing angular to rounded clasts up to boulder size. The most abundant clasts are generally wacke sandstones and siltstones from the Southern Uplands, with smaller proportions of red sandstone and vivid red to purple siltstone from the local Permo-Triassic outcrops. Rarer lithologies include granodiorites and granites from the Criffel–Dalbeattie Pluton and other plutons of the Galloway Hills respectively, more locally derived Permian and Carboniferous basalts (mainly from the Birrenswark Volcanic Formation), and dolerite from dykes. Tills containing blocks of locally derived Carboniferous limestone are also present in the district (Dean, 1999). Tills overlying outcrops of Carboniferous sedimentary rocks are commonly yellowish brown in colour and contain much yellow and white sandstone. Large angular blocks of underlying strata are common towards the base of tills.

The tills range up to about 25 m in thickness, but probably average about 5 m. In general they become increasing compact and more homogeneous downwards. The uppermost few metres are commonly crudely stratified, and vary considerably in lithology and compactness over distances of a few metres (both horizontally and vertically). Lensoid beds of sand, gravel, silt and clay are common towards the surface, but locally there are thicker and more laterally persistent beds that represent mappable units within the local glacigenic sequence.

Most known tills of the Irish Sea Coast Glacigenic Subgroup in the district have been assigned to the **Gretna Till Formation**. The type section is a coastal cliff exposure at Dornockbrow [NY 2331 6517] (registered section ME 264), near Eastriggs, where 5 m of till comprising a stiff red stony clayey diamicton, is exposed beneath raised beach deposits (see also section 5.5.1.1). Many clasts in

Table 1 Quaternary lithostratigraphy of the Solway district.

Eastern Dumfries and Galloway and North Cumbria			British substage	Approx. MIS correlation	British/European stage
BRITANNIA CATCHMENTS GROUP (BCAT) *SOLWAY CATCHMENTS SUBGROUP (SYDR)*: **Solway Esk Valley Formation (MIS 1 to 2) (SESKV)**; ***Un-named lithogenetic units:*** Alluvium; Alluvial fan deposits; River Terrace deposits ***Un-named lithogenetic units:*** Lacustrine deposits Head: Landslide deposits **Blelham Peat Formation (MIS 1-2) (BHPT)** *Racks Peat Member* *Healy Hill Organic Mud Member* *Bigholms Burn Gravel Member* Bigholms Burn Peat Bed (BIGP) *Redkirk Point Peat Member*	**BRITISH COASTAL DEPOSITS GROUP (COAS)** ***Un-named lithogenetic units:*** Blown sand Tidal river and creek deposits Saltmarsh deposits Intertidal deposits Marine beach deposits Raised tidal flat deposits Raised marine beach deposits (MIS 1-2) Raised storm beach deposits **Carse Clay Formation (CARCL)** *Newbie Silt Member* *Rigfoot Silt Member*		Holocene	1	Holocene
			Loch Lomond Stadial	2a	Devensian/ Weichselian
			Windermere Interstadial	2b	
CALEDONIA GLACIGENIC GROUP (CALI) *SOUTHERN UPLANDS GLACIGENIC SUBGROUP (SUDR)*: **Kirkbean Sand and Gravel Formation (KN)** **Mouldy Hills Gravel Formation (MOHI)** **Dalswinton Moraine Formation (DSMO)** **Langholm Till Formation (LHTI)** *New Abbey Till Member (NATI)*	*IRISH SEA COAST GLACIGENIC SUBGROUP (ISCG)*: **Kilblane Sand and Gravel Formation (KBSG)** **Cullivait Silts Formation (CUS)** **Kerr Moraine Formation (KEMO)** **Gretna Till Formation (GRET)** Plumpe Bridge Till Member (PLBT) **Plumpe Sand and Gravel Formation (PLSG)** Plumpe Farm Sand Member (PFS) Loganhouse Gravel Member (LOGG)	**Great Easby Clay Formation (GECL)**	Dimlington Stadial	2c	
	Chapelknowe Till Formation (CHAK)	**Gillcambon Till Formation (GCBTI)**		2d	
Hoghill Gravel Bed (HGGR)				3	
				4	
		Scandal Beck Peat Bed (?glacial raft) (SBPT)		5a-d	
		Wigton Marine Bed (?glacial raft) (WIGM)	Ipswichian	5e	Ipswichian/ Eemian
No known deposits				Pre-5e	

the diamicton are rounded suggesting that they have been derived from glacially overridden gravel deposits.

Well-exposed sections in the Gretna Till Formation include those on the north bank of the River Eden at Rockcliffe [NY 3490 6190], where about 30 m of stiff, red-brown till with wacke sandstone clasts rests on weathered red sandstone of the Sherwood Sandstone Group (Triassic). Stiff, unstratified, subglacial red-brown till (stony sandy clay diamicton) rests directly on Permian and Carboniferous bedrock in the district west of Annan, between Kelhead [NY 146 696] and Clarencefield [NY 092 686]. In this area the till contains significant amounts of Permian material, as well as the ubiquitous wacke sandstones and siltstones from the Southern Uplands. It is well exposed in Kelhead

Quarry at [NY 1497 6934] (CA1453), where the unit is 2 to 5 m thick and rests directly on limestone breccia of the Brockram (Appleby Group). The bedrock is glacially smoothed and striated (azimuth 190° at [NY 1511 6932], ME267) (Figure 13). The till is a vivid red-brown, poorly stratified, matrix-supported diamicton, which is weathered in its uppermost 0.25 m. It contains widely scattered cobbles of wacke sandstone and some tabular blocks of the underlying breccia. Micromorphological examination by Phillips (2002) of a sample taken near to its base, showed the lower part of the unit to be a poorly sorted, immature, matrix-supported diamicton, with a matrix of silty sand. The till is also exposed in the flanks of a deep (more than 15 m) glacial drainage channel at Glenstuart [NY 1294 6757] (CA 1456), where it exceeds 5 m in thickness.

5.3.1.2 The 'tripartite' sequence

As previously described (see 4.2.5.3 above), the early 20th century concept of several glacial re-advances across the Solway lowlands during the MLD glaciation, has gained renewed support in recent decades. The 'tripartite' re-advance model was developed by Trotter and Hollingworth (1932a), who concluded that at least one major re-expansion of Scottish ice occurred that laid down a suite of deposits quite distinct from those formed during the main glaciation ('Lower Till'). Glaciofluvial and glaciolacustrine sediments ('Middle Sands') were laid down in the coastal lowlands of west Cumbria during the initial deglaciation, later to be overridden during glacial re-advances. Each re-advance caused minimal recognisable subglacial erosion, yet laid down a thin, widespread mantle of diamicton ('Upper Till' of Trotter et al. 1937).

The upper part of the 'tripartite' sequence identified by Trotter in the Gretna area has been confirmed in a section behind a cowshed at Plumpe Farm [NY 3344 6813] (ME 262–263) (Figure 14) and at a a temporary section nearby at [NY 3273 6842] (ME 259). It appears to be confined to a buried valley lying to the east of Gretna [NY 320 670] and Gretna Green. Here crumbly red sandy till overlies a thick sequence of red fine-grained sands and silts resting on gravel, which in turn rests on a stiff, red, clayey 'lower' till (according to the farmer). The upper till is patchy and very variable in lithology. The underlying sequence has been glacitectonised to a varying degree at Plumpe Farm.

The upper till at Plumpe Farm is named formally as the **Plumpe Bridge Till Member** of the Gretna Till Formation (Figures 4, 14 and 15). The underlying sands are referred to the **Plumpe Farm Sand Member** of the **Plumpe Sand and Gravel Formation**. Plumpe Farm is the type locality of both units. Five soft sediment block samples from the exposure at Plumpe Farm (Figure 14) indicate that the glacitectonised sequence is orientated normal to the overall eastward ice-flow direction. Thin sections of the samples, which were collected across the boundary between the Plumpe Farm Sand Member and the Plumpe Bridge Till Member, were described and analysed by Phillips et al. (2007). The thin sections showed that the Plumpe Farm Sand Member is composed of laminated fine-grained sand, silt and clay. Some of the thicker sand laminae are normally graded and preserve a low-angle cross-lamination. Apart from some minor soft-sediment deformation and associated liquefaction structures, localised faulting and rare recumbent folding, the sediments are essentially undeformed.

The two samples from near the base of the Plumpe Bridge Till are composed of a stratified, poorly sorted, sandy diamicton, containing layers of highly disrupted laminated silt and clay. The clay-rich layers within the till are lithologically similar to those within the underlying laminated sediments, and stratification within the diamicton becomes less pronounced and more diffuse away from its base. A single sample was taken to intersect the gradational boundary between the till and the underlying laminated sediments. It showed that this boundary zone comprised alternating layers of laminated silt and clay and sandy diamicton. The silt and clay layers are variably deformed and disrupted. In the least deformed layers, the lamination is contorted by small scale disharmonic folds, recumbent rootless folds and flame structures. These structures are cross-cut by thin veinlets and lenticles of clay cutan. The silt laminae are variably homogenised, with liquefaction leading to the overprinting of earlier developed structures. In more highly deformed layers, broken angular fragments of laminated clay occur within a homogenised silty or silty clay matrix. These disrupted layers also contain rounded to elongate till pebbles of similar composition to the adjacent layers of diamicton.

Although the Plumpe Farm Sand Member has been overridden by ice, the absence of significant glacitectonic deformation suggests that conditions at the ice–sediment interface were such as to impede the transmission of shear to any significant depth within these finely laminated sediments. The bulk of the deformation was concentrated within the gradational boundary between the Plumpe Farm Sand Member and the overlying Plumpe Bridge Till Member. The microstructures within the stratified base of the till, such as disharmonic folds and flame structures, coupled with the liquefaction and homogenisation of the silty laminae, are consistent with the sediment having had high water content during its deposition and deformation (Phillips et al., 2007).

The lack of pervasive deformation in the glacially overridden laminated sands and silts at Plumpe Farm may, at least in part, be a result of the regional palaeogeography at the time of the Scottish Re-advance. During this re-advance, glacier ice flowed over the flat-lying glaciofluvial/glaciolacustrine sediments and encountered a number of ice-marginal lakes ponded against high ground to the east (Trotter, 1929; Hollingworth, 1931). The water-saturated nature of these sands and silts aided movement of the ice, which locally would have occurred on a water-lubricated surface, and this dramatically reduced the amount of shear translated into the underlying sediments (Phillips et al., 2007).

Two red tills separated by 5 m of dense gravel are seen in a section in the 'tripartite' sequence in the valley of the Logan Burn [NY 3110 7181] (ME 300), south of Chapelknowe (Figure 16). The gravel, of probable glaciofluvial origin, is named as the **Loganhouse Gravel Member** of the Plumpe Sand and Gravel Formation. The underlying till apparently represents the lower till of the sequence, and is named the **Chapelknowe Till Formation**. The Loganhouse Gravel Member has been identified upstream in a section at [NY 296 734], and also crops out in the valley of Closses Burn at [NY 3852 7610] (ME 304), where both the overlying and underlying tills are exposed (Figure 17); a similar sequence was formerly exposed at Englishton [NY 334 731].

The tripartite sequence of Plumpe Farm has also been identified, at least in part, at Logan Burn near Smallholms Farm [NY 2973 7339] (NRG108). Here, a stream cutting reveals about 0.3 m of gravel overlying a 0.4–1.5 m-thick glacitectonite layer of reddish brown (Munsell Soil Colour 5YR 5/4), shear-hardened, silty, sandy clay, which itself overlies about 2 m of matrix-supported gravel. The glacitectonite exhibits a well-developed fissility and boudin structures. The unit is homogenous and no clasts were seen.

Traces of highly disrupted bedding were seen in places in the section, whilst elsewhere silt and sand appeared as small and discrete irregular pods. Some gravel stringers occur in the glacitectonite near the lower contact with the underlying gravel, which is poorly sorted and matrix-supported. The matrix is coarse sand and locally variable, with about 0.3 m shear-hardened in the upper part of the unit. Some of the pods of sand preserve traces of their original bedding. The unit is mostly clast-rich in the middle of the section, and the clasts show no obvious preferred orientation. Clasts are subangular, subrounded and rounded, up to 0.3 m diameter and mainly of sandstone or greywacke with occasional quartzite cobbles. Some of the clasts are cracked in half, in situ, which may suggest that significant loading has occurred. Weathered clasts are common, either displaying pitted surfaces or disaggregating when moved. The gravel is thought to rest on till, although high water prevented verification. The section most probably represents a basal MLD till (Chapelknowe Till Formation) with associated outwash (Loganhouse Gravel Member of the Plumpe Sand and Gravel Formation) that has been subsequently overridden from the south-west by ice associated with the of Scottish Re-advance at about 14 cal. ka BP. Borehole SE10672/T071/03R at [NY 2922 7365] proved 0.7 m of silty sandy clay over 2 m of red and purple silty sand. The former unit may be correlated with the glacitectonite, and the latter with the Plumpe Farm Sand Member.

The 'tripartite' sequence found in the Gretna area has been traced as far west as Annan, and in the Esk valley at least as far north as Langholm. It has been identified at several new localities in the Esk valley downstream of Langholm, and in many boreholes drilled for the A7 Canonbie bypass (Figure 15). Red sand correlated with the Plumpe Farm Sand was worked in a borrow pit for the new A7 road at [NY 3859 7364] (ME 297) and it crops out in the vicinity of Batenbush [NY 378 715]. Farther north, the sequence crops out in the valley of Closses Burn (see above), and in the valley of the Byre Burn in the vicinity of Greenburn [NY 395 800]. Clusters of boreholes prove the sequence north-west and south of Canonbie [NY 395 765].

The northernmost known occurrence of the 'tripartite' sequence is in the valley of the Byre Burn, north of Claygate [NY 395 791]. Here, yellowish brown sand correlated with the Plumpe Sand and Gravel Formation overlies very stiff reddish brown stony diamicton assigned to the Chapelknowe Till Formation. The sand crops out on the western side of the valley in the vicinity of Greenburn [NY 395 800], where a north-north-easterly orientated drumlin has been partially dissected to expose the sequence. The sand unit extends into the hillside (the drumlin) beneath till assigned to the Gretna Till Formation.

The Plumpe Farm Sand Member is locally predominantly fine grained and laminated. At Brockwoodlees [NY 383 781], near Hollows, several boreholes drilled into a north-east orientated drumlin (which is partially dissected by the River Esk) record red sandy till overlying greyish brown, laminated silt and clay up to 7 m thick. The laminated deposits rest on brown or reddish brown till, and appear to pass into the drumlin beneath till. A borehole [NY 3934 7538] south of Canonbie penetrated 10.3 m of laminated silt and clay below 6.2 m, resting on 3 m of reddish brown till. However, most boreholes in the vicinity record sand and gravel between the two till formations. The laminated deposits described at these localities were initially identified as belonging to the **Cullivait Silts Formation** (see section 5.3.1.5) on Solway East (BGS, 2006) but are more likely to be correlatives of the Great Easby Clay Formation into which they pass laterally.

The **Great Easby Clay Formation** is interpreted to have been deposited in 'Glacial Lake Carlisle', formed when ice occupied the Solway Firth and blocked drainage within the otherwise deglaciated Solway lowlands. The formation includes dark reddish brown clays, silts and very fine-grained sands that are generally thinly laminated and locally varved (McMillan et al., 2011). The deposits, which are more widespread around Carlisle (Figure 4), contain sparse dropstones, convolute bedding, slump and water-escape structures, and are commonly disturbed glacitectonically and capped by red diamicton of the Gretna Till Formation (see Dixon et al., 1926; Trotter, 1929). In the valley of the River Caldew, south of Carlisle (Solway East, BGS, 2006), the Great Easby Clay Formation appears to underlie west-north-west-orientated drumlins of the North Lake District Suite (section 6.1.1.2). This relationship suggests that the deposits here were laid down during a deglaciation prior to that drumlin-forming event, and not during the subsequent Scottish Re-advance. Huddart (1970) argued that stagnant ice remained in this valley during the Re-advance, stopping Scottish ice from invading the area.

A 2.4 m-thick lensoidal mass of stiff, reddish brown, clay was formerly exploited for more than 200 years for making bricks, tiles and pipes at Tarrasfoot [NY 381 809], south of Langholm. Although this deposit was reported to be interbedded with sand (Lumsden et al., 1967), the apparent lack of surface expression of the clay indicates that it might form part of the Plumpe Farm Sand Member and crop out beneath till.

The origin and patchy distribution of the 'tripartite' sequence has been difficult to explain satisfactorily in the past. Indeed, many have not been convinced of its integrity and even of its existence. There can no longer be any doubt that locally two discrete units of red till are separated by a sequence of red sands and gravels. The Plumpe Farm section demonstrates that the uppermost diamicton was deposited subglacially and that it results from at least a local glacial re-advance of a wet-based glacier (Phillips et al., 2007). The preservation of the Plumpe Sand and Gravel Formation within major southward trending valleys, such as the Esk, probably results from the likelyhood that the final flow of ice was directed towards the east, as clearly indicated by the well-defined, west–east glacial streamlining seen on Landsat satellite images (see insets on Solway maps, BGS, 2005, 2006) and NEXTmap (see Chapter 6). In contrast, the preservation potential of such deposits within the valley of the Nith would be relatively low, because the final flow of ice was through, and not across, that valley.

It is also apparent that the full 'tripartite' sequence is commonly preserved within drumlins, for example, as cited above around Hollows [NY 384 769] to the north-west of Canonbie. The bodies of silt, clay, sand and gravel within these drumlins have probably become attenuated through the process of 'extensional subglacial glacitectonism' (Hart and Boulton, 1991), leaving the upper and lower tills in contact on the flanks of the features. Between drumlins, the upper till commonly lies directly on bedrock because the rest of the sequence has been eroded away through the process of 'excavational subglacial glacitectonism'.

5.3.1.3 Morainic deposits

These hummocky deposits are highly variable in lithology and include complex interdigitating beds of diamicton, boulder gravel, sand, silt and clay. Most deposits are constructional moraines that formed at the ice-sheet margin during 'active' glacial retreat. They were deposited by several processes, including dumping of debris flows from the glacier surface and 'bulldozing' of loose debris at the ice front during forward movement of the ice.

A suite of recessional moraines with eskers at right-angles have been mapped on Solway East (BGS, 2006), indicating that the ice margin generally retreated towards the west-north-west, at right-angles to most eskers. The ridges are generally 3–5 m high and composed of rubbly diamicton. They are particularly common across outcrops of the Carboniferous sandstones, where the deposits consist largely of boulders and blocks of white and yellow sandstone in a matrix of yellowish brown sandy clay. For example, many morainic mounds and ridges occur between Bloch [NY 3285 8130] and Ryehills [NY 3460 7860].

Many morainic ridges are closely associated with ice-marginal glacial drainage channels, particularly on west-facing hillsides. Good examples of such related features are found in the vicinity of Kerr Height [NY 338 800], where southward flowing meltwater at the westward retreating ice margin cut a series of interconnecting channels down the valleyside. The channels abut ridges, one of which includes a kettlehole where a block of ice formerly incorporated within the sediment melted out. This area is the type locality of the **Kerr Moraine Formation**, which includes most morainic deposits of the Irish Sea Coast Glacigenic Subgroup.

Another complex of ridges and channels of similar aspect to those at Kerr occurs in the vicinity of Howgillcleuch [NY 396 817] (ME 310), on the eastern margin of the sheet. The ice was receding towards the west-north-west when these features were formed.

A large recessional moraine on the south eastern side of the River Nith, forming discontinuous mounds and ridges typically rising 10–15 m above glaciofluvial sand and gravel deposits that crop out in the northern Dumfries suburbs of Heathhall [NX 992 793] and Marchfield [NX 983 777], corresponds in part with the 'kettle moraines about Dumfries' identified by Charlesworth (1926a). He ascribed the moraine to a prolonged stillstand during the active retreat of the Nith Glacier. Simliar morainic mounds rise up to 22 m above the glaciofluvial deposits on the western side of the valley of the river Nith, near Maxwelltown [NX 966 757] and around Cargenbridge [NX 953 748]. These indicate that moraines of both areas form part of a recessional limit extending across the valley through the centre of the Dumfries urban area, and which has been bisected by the present river.

Records of boreholes drilled in the vicinity of Marchfield House, for the A75 Dumfries bypass, show that the morainic deposits exceed 12 m in thickness and comprise an interbedded sequence of reddish brown sandy diamicton, dark brown sand and gravel, pinkish brown clayey diamicton, clayey silt and cobble gravel. Elsewhere, glacitectonised, interbedded, fine-grained, light brown sands and reddish brown silts, with anastomosing water-escape conduits infilled with clayey silt, were present in temporary exposures (CA 1325–26) associated with new housing developments south of The Grove [NX 985 786]. All of these deposits are ascribed to the **Marchfield Moraine Member** of the Kerr Moraine Formation, which are generally made of finer-grained sediment than those comprising the remainder of the formation. In particular, the sediments visible in the temporary exposures at [NX 987 783] appear to be glacitectonised equivalents of the glaciolacustrine Cullivait Silts that are exposed beneath glaciofluvial gravels at Lochabriggs Sand and Gravel Quarry [NX 993 808], some 2.7 km to the north-east (see section 5.3.1.5). This suggests that minor re-advances of the snout of the Nith glacier took place during its recession, and resulted in the intercalation of proglacial lake deposits within the Marchfield Moraine sequence.

5.3.1.4 Glaciofluvial deposits

The glaciofluvial deposits of the Irish Sea Coast Glacigenic Subgroup are composed of a similar range of rock types to the tills, except that clasts of red sandstone are more abundant. Most of the deposits were laid down during the final deglaciation, either subglacially as eskers or proglacially as glacial outwash fans and deltas (sandar). Three morpho-litho-genetic categories of glaciofluvial deposit have been mapped: 'sheet' deposits (terraced), 'ice-contact' deposits (generally moundy) and esker ridges. These categories are defined as informal members within the **Kilblane Sand and Gravel Formation**, to which most of the surficial glaciofluvial deposits are assigned. The deposits of this formation are variable in thickness and form; they generally overlie the Gretna Till Formation or bedrock. Glaciofluvial deposits are widely developed in the Solway West area, notably on the low lying ground within the Lochmaben Basin, around Dalton [NY 116 740], on both sides of the valley of the Lochar Water and within the Nith Valley. They are much more sparsely developed in the Solway East area, although notable spreads occur around Gretna [NY 320 670] and Annan. In this district, glaciofluvial deposits occurring lower in the glacigenic sequence have been assigned to the Plumpe Sand and Gravel Formation (see above, section 5.3.1.2).

Sheet deposits

The most extensive sheets of glaciofluvial sand and gravel occur as low-level spreads flanking the alluvium of the River Annan, and its tributary the Water of Ae, around Lochmaben [NY 084 825]. At Halleaths Quarry [NY 087 735] east of Lochmaben, ice-wedge casts (cover photograph) are preserved in interbedded coarse gravel and sand, indicative of a cold tundra environment during the Loch Lomond Stadial (see section 4.2.2.1). Higher level kame terraces around the village of Dalton [NY 116 740] formed as outwash from ice in the Annan Valley, when early meltwaters flowed southwards along the valley now drained by the Pow Burn to reach the present coast at Cummertrees [NY 143 665]. The deposits, which are typically cobble and pebble gravels, are sparsely developed near the mouth of the Pow Water. The lower-lying spreads are generally younger and many were formed when the later glacial drainage from the Lochmaben basin was directed eastwards along the Annan valley.

Flat-topped spreads of cobble gravel form kame terraces on both sides of Nithsdale. A particularly fine example occurs on the north-eastern side of the valley, south of Castlehill [NX 975 840] where, in places, it rises some 20 m above the floodplain. It is associated with a suite of north-west to south-east trending ice-maginal drainage channels (Huddart, 1999). Less prominent examples occur on the south-eastern side of the valley in the vicinity of Broadford [NX 914 841], near Summerhill [NX 949 818] and around Broom Rig [NX 970 792]. Well-stratified, flat-topped spreads of pebble and cobble gravel also underlie much of the Dumfries urban area, where they are seen to contain almost equal proportions of sandstone and wacke sandstone clasts. In some exposures, notably those at Brownfield Farm [NX 9851 8002] (CA 1330) and [NX 9852 8018] (CA 1331), well-developed trough cross-bedded cobble and pebble gravels occur.

Ice-contact and esker deposits

Between Dumfries and Annan moundy ice-contact deposits are much more widespread, notably along the flanks of the Pow Burn, and in a small working at Ryehill [NY 1450 6567] (CA 1455) where they overlie fine-grained sand with partings of red-brown silt. This belt of moundy sand and gravel extends in an arc from Edge Hill [NY 116 699], reaching the coast near Powfoot [NY 150 658]. West of Powfoot the sand and gravel forms moundy topography, which marks the limit of marine transgression in both late-glacial and postglacial times. Prominent esker ridges are well developed on the northern edge of the arc of glaciofluvial deposits. Particularly good examples are visible from the B724 road between Cummertrees [NY 143 665] and Newfield [NY 112 688]. The railway line from Annan to Dumfries occupies cuttings within the Hurkledale Esker, which forms a natural embankment across boggy ground between Cummertrees and Summerfield [NY 112 680]. The esker sediments, which coarsen upwards from fine-grained silty sands into well-stratified, silty pebble and cobble gravels, are well exposed in a small pit at [NY 1304 6697] (CA1457). Similar esker gravels were formerly worked in several small pits around Powfoot, near Flosh [NY 116 679], and at Edge Hill [NY 116 699].

East of Powfoot, the glaciofluvial sand and gravel forms a discontinuous ridge that backs the Holocene raised beach. Sections in the ridge (ME 271) reveal interbedded reddish brown to orange-brown, fine- to medium-grained sand, with variably sorted, subrounded to well-rounded gravel. A south-westward palaeocurrent is indicated by both cross-bedding and imbrication, which accords more with the ridge feature being a moraine rather than an esker. Convolute bedding and collapse structures are common towards the top of the sections. Adjacent to the ridge, sections seen in a gravel pit within the former MOD grounds at Broom [NY 1570 6565] (ME 266, 270–271) show some complicated relationships between units (Figure 18). These include sag structures, horizontal folds, vertical to overturned bedding, shearing, extensional microfaulting and local inclusion of frost-shattered gravel. In a small pit beneath flatter ground to the north-east [NY 1583 6575] (ME 270), about 1 m of well-sorted, frost-shattered gravel rests on over 2 m of poorly sorted cobble gravel (Figure 19). The origin of all these deposits is not clear on present evidence. On balance, although the ridge is depicted on the maps as an esker, it is more likely to have formed at the margin of an active glacier that lay within the Solway Firth.

The most extensive glaciofluvial deposits on Solway East (BGS, 2006) lie in the vicinity of Gretna [NY 320 670], with former sand and gravel extraction at [NY 303 687] and near Floshend [NY 312 678]. The deposits generally form undulating ‘rolling’ topography studded with kettleholes and including isolated rounded ridges. The deposits are at least 10 m thick locally, reddish brown and very variable in composition, including clay-bound, poorly sorted gravel, clean cross-bedded (probably deltaic) pebbly sand, and laminated silt and clay. The orientation of ridges and glacial drainage channels suggests that the deposits were laid down by meltwaters flowing southwards around the margin of an ice-sheet that was retreating south-westwards. However, several boreholes prove units of till within the glaciofluvial sequence, resting on thick deposits of silty sand similar to those of the Plumpe Sand and Gravel Formation (see above, section 5.3.1.2). Hence, some of the deposits were laid down at an earlier stage and are not directly related to the present topography (as seen on a cross-section following the line of the A74M road depicted on Solway East, BGS, 2006).

Terraced glaciofluvial deposits lie immediately to the south of Gretna [NY 320 670], where up to 7.6 m of brown sand and relatively well-sorted and rounded gravel have been proven. Similar deposits were formerly worked near Kirtleside Holding [NY 295 673]. A large mound of sand has been identified near Beechgrove House [NY 212 652], south-west of Annan, but the feature could be formed of decomposed red sandstone.

Numerous isolated mounds and spreads of glaciofluvial sand and gravel lie to the north of Gretna. Noteworthy deposits are centred on Barnglieshead [NY 324 786], where deposits of red sand and gravel up to about 20 m thick form an undulating north to south orientated plateau studded with kettleholes. The plateau links with a prominent east to west orientated, discontinuous esker (Solwaybank Esker), at the eastern end of which some 8 m of moderately well-sorted gravel and sand is exposed in a small pit [NY 3224 7835] (ME 301). The gravel contains few cobbles, and is composed of subrounded to rounded clasts of red and white sandstone with some wacke sandstone. Fine pebbles are predominantly platy in shape and composed of siltstone.

The Solwaybank Esker was deposited within a subglacial tunnel by eastward-flowing meltwaters; these debouched at the ice margin to lay down the deposits forming the plateau. Similar landform–sediment associations occur elsewhere in the vicinity. At Tower-of-Sark [NY 333 750] for example, a broad, elongated, east–west orientated ridge of sand and gravel leads eastwards towards moundy deposits, with cross-bedding indicative of an eastward palaeocurrent [NY 3452 7506] (ME 299). In the ridge of Macrieholm Knowe, a small pit [NY 3321 7920] (ME 302) reveals ripple cross-laminated sand indicating a palaeocurrent towards the east-south-east, parallel to the feature.

Numerous mounds of sand and gravel occur in the vicinity of Tarcoon [NY 361 777], where there was formerly a commercial gravel pit (now landscaped). Deposits may be as much as 25 m thick locally, particularly at Torbeck Hill [NY 350 787] and Bulman’s Knowe [NY 371 771]. Many of the deposits are probably deltaic in origin, fining downwards from gravel to silt and clay, with red, fine-grained sand being most abundant.

Apart from moundy deposits of sand around Broomieknowe [NY 397 800], there are few glaciofluvial deposits in the Langholm area.

5.3.1.5 Glaciolacustrine deposits

Fine-grained sand, silt and clay deposited in standing water form part of many glaciofluvial sequences in the district, but only those that are sufficiently extensive have been identified separately as being ‘glaciolacustrine’. These deposits are commonly laminated and contain dropstones, and were mainly deposited in ice-marginal, proglacial or ice-walled lakes. These formed in the upper reaches of valleys during ice-sheet deglaciation whilst the lower reaches were blocked by ice.

The glaciolacustrine deposits within the Irish Sea Coast Glacigenic Subgroup are assigned to the Cullivait Silts Formation. The partial type section for this unit is at Locharbriggs Sand and Gravel Pit. Here, BGS Registered Section CA1320 (August 1999) [NX 9956 8138], about 250 m south-east of Cullivait House, records interbedded, moderate reddish brown, fine-grained sand and laminated clayey silt with dropstone cobbles, beneath kettled kame terrace gravel (Kilblane Sand and Gravel Formation).

Glaciolacustrine deposits of the Cullivait Silts Formation were mapped north-east of Claygate [NY 3975 7945] in the Esk valley (BGS, 2006), where deposits of reddish brown waxy clay underlie a valley-side terrace, and rest on sand.

Laminated deposits of red or greyish brown silt and clay crop out on the western flanks of the Esk valley, in the vicinity of Brockwoodlees [NY 382 780] near Hollows. However, it is apparent from borehole evidence that most of the deposit is capped by till, and hence may be more appropriately assigned to the Great Easby Clay Formation (see 'Tripartite Sequence' section 5.3.1.2 above; part of the Plumpe Sand and Gravel Formation).

Extensive spreads of laminated, very fine-grained sand, silt and clay of glaciolacustrine origin underlie low-lying ground to the east of the Solway Firth, where they were supposedly deposited in 'Glacial Lake Carlisle' at its several, descending levels (Dixon et al., 1926; Trotter, 1929). The youngest and lowest-lying of these occur beneath alluvium and river terrace deposits, and are assigned to the Cullivait Silts Formation. (Figure 4). Older units underlying glaciofluvial sand and gravel and, locally, till, are assigned to the Great Easby Clay Formation. The relationships are illustrated by a cross-section following the line of the A74M road (Solway East, BGS, 2006), which identifies a probable buried valley beneath Mossband Viaduct filled with fine-grained, laminated deposits (Great Easby Clay Formation) (see section 8.6).

5.3.2 Southern Uplands Glacigenic Subgroup

The common attribute of deposits assigned to the Southern Uplands Glacigenic Subgroup (Figure 12) is that the constituent clasts are predominantly wacke sandstones, siltstones and other rocks forming the Southern Uplands, including granite and granodiorite. The principal centres of ice dispersion were the Galloway Hills and the Moffat Hills. Granitic or granodioritic rocks are predominant locally, as seen in the vicinity of Criffel [NX 957 618]. The southern boundary of the Southern Uplands Glacigenic Subgroup roughly follows the southernmost outcrops of Ordovician and Silurian strata.

5.3.2.1 Tills

The tills of the Southern Uplands Glacigenic Subgroup are mainly assigned to the Langholm Till Formation and largely comprise stiff, sandy, silty, clayey diamictons, with rock fragments up to boulder size. Locally over 10 m thick, they are typically yellowish brown or greyish brown and composed predominantly of greywacke sandstone and siltstone, becoming very gravelly downwards and locally clast supported.

The type section of the Langholm Till Formation is the valley of the Hoghill Burn [NY 3820 8905] (ME 312), a tributary of the Ewes Water north of Langholm. Here, the sequence is capped by over 2 m of very stiff, pale yellowish brown to pale grey, massive, matrix-supported, stony, sandy silty clay diamicton (Dmm) containing subangular to subrounded clasts of wacke sandstone and siltstone. The deposit underlies a glacially smoothed landscape and is similar to most exposures of till in the vicinity. This diamicton passes downwards into about 8 m of less consolidated, more gravelly, crudely horizontally bedded material that is largely clast supported. This unit might be interpreted as a head deposit, but the majority of clasts are ice scratched and the more matrix-supported layers are fissile, suggesting subglacial deposition. Many clasts have reddened surfaces that are typical of frost-shattered wacke sandstone outcrops in the area. The basal 2 m of the till are matrix-supported and extremely stiff (Figure 20). As described during the primary survey, it either grades down (over 10 cm) into, or rests on, a basal reddish brown till that contains subrounded to rounded clasts of red sandstone and granite.

Beneath the red till at the base of the wacke sandstone-rich Langholm Till, a very dense 2.5 m-thick clast-supported diamicton comprises angular to subangular clasts in a pale yellowish brown, silty sand matrix (Figure 20). The unit is named the Hoghill Gravel Bed, and the clasts are predominantly composed of siltstone with a tabular to platy shape and crude imbrication, with clasts dipping toward the axis of the valley of the Hoghill Burn. The imbrication, close packing of clasts, absence of scratch marks, and dominant 2–32 mm size range, all suggest that the deposit formed as gelifractate (scree)/talus, probably in an ice-free, cold period prior to the last major glaciation. If this interpretation is correct, the sparse clasts of red sandstone and granite in the unit must have been recycled from an older deposit of till bearing those rock types.

The base of the Hoghill Gravel Bed is not exposed at the type section, but other exposures within 100 m (e.g. ME 312) suggest that it overlies a unit of vivid reddish brown, extremely stiff, massive, matrix-supported, stony, sandy silty clay diamicton (Dmm). The till includes clasts of yellow and red sandstone and large boulders of pink granite. It also includes deformed masses of vivid reddish brown laminated clay. The age of this red diamicton and its stratigraphical relationships are not entirely clear on present evidence; it is tentatively correlated with the Chapelknowe Till Formation (Figures 15 and 16). However this solution leaves the status of the red diamicton at the base of the till overlying the Hoghill Gravel in question; it could represent material reworked from the lower red till during a later glacial advance, or it might equate with the Chapelknowe Till Formation, with the lower red till representing an older, perhaps pre-Devensian glaciation. There are no known occurrences of such red tills to the north of the Hoghill Burn valley (Lumsden et al., 1967).

At other localities the base of yellowish brown wacke sandstone-rich till passes downwards into reddish brown till, containing clasts of red, yellow and white sandstone, volcanic rocks and grey granite, in addition to wacke sandstone. The transition is usually gradational over about 10 cm. The basal red tills are common in the valley of the Logan Water, west of Langholm, for example at Cleuchfoot Cottages [NY 3169 8235] (ME309), where over 2 m are exposed in the riverbank (Figure 21). Red tills with red sandstone clasts have also been found at the base of sequences beneath thick, wacke sandstone-rich tills in the valley of the Wauchope Water at [NY 3238 8191] and [NY 3325 8226], and in the valley of the Glentenmont Burn [NY 3035 8290].

All of the red basal tills of the Solway district are assigned tentatively to the Chapelknowe Till Formation of the Irish Sea Coast Glacigenic Subgroup (Figure 16). They were possibly laid down during the LGM, when ice was forced to flow from the Solway north-eastwards, uphill towards the Tweed Basin. This flow event is probably recorded by the Canonbie–Liddesdale Suite of drumlins (see Figure 10 and section 6.1.1.7), and equates with the 'First Glaciation' of Lumsden et al. (1967). Interestingly, G I Lumsden recorded red till on brown till on field map NY38NW in the valley of the Tarras Water, at [NY 3922 8280] south-east of Langholm, which may represent a local, late stage re-advance of Solway ice.

On the western side of the Nith estuary, the Langholm Till Formation is generally more bouldery and sandy than it is on Permian bedrock to the east. Till with clasts predominantly of Ordovician, Silurian and Carboniferous rocks is widespread along the coast, where its composition closely reflects the nature of the underlying bedrock. This type of till was well exposed in excavations for new farm buildings at North Corbelly [NX 9853 6337] (CA 1417) (Phillips and Auton, 2008). In the New Abbey area, the **New Abbey Till Member** (Langholm Till Formation) contains a preponderance of granodiorite clasts derived from the Criffel–Dalbeattie Pluton. It is generally pale grey to yellow brown in colour, with a very sandy and gritty matrix (Phillips and Auton, 2008). Its type section occurs at Townhead Sawmill, New Abbey [NX 9595 6623] (CA 1416).

5.3.2.2 Hummocky morainic deposits

Recessional moraines are not particularly common across much of the area, but where they have been identified they indicate that the ice-sheet retreated ‘actively’, periodically bulldozing material into ridges at the ice margin.

Near Dalswinton, about 8 km north-west of Dumfries, two large linear ridges are interpreted as large lateral moraine ridges with an intervening glacial drainage channel about 30 m deep at its maximum development. They occupy the north-western flank of the valley of the River Nith between [NX 935 856] and [NX 960 840] rising 10–20 m above the level of the floodplain. The deposits are referred to the **Dalswinton Moraine Formation**, and are composed of poorly exposed glacial bouldery, silty and sandy diamicton.

In the Esk valley north of Hollows [NY 384 769] and in the valley of the Ewes Water, a distinctive suite of morainic deposits, is assigned to the **Mouldy Hills Gravel Formation**. The type section is a road cutting [NY 3695 8313] near Mouldy Hills, where 7 m of the gravels are capped by 1.5 m of head gravel. The deposits form valley-side spreads that thicken toward the valley axes, but are not particularly moundy. They typically comprise yellowish brown, very poorly-sorted, clayey gravel, with lensoidal beds of silty sand and stratified sandy diamicton. Clasts are typically angular to subrounded and composed of wacke sandstone and siltstone, although yellow and white sandstones predominate towards the south. Boulders and blocks are scattered through the deposits, but clasts (particularly the wacke sandstone) are generally less than 15 cm in diameter. The deposits are over 20 m thick to the south of Langholm where they occur in rare sections in steep banks on the western side of the valley. Lumsden et al. (1967) concluded that the morainic deposits had been laid down during retreat of their ‘Second Glaciation’.

5.3.2.3 Glaciofluvial deposits

The glaciofluvial deposits of the Southern Uplands Glacigenic Subgroup include the same range of morpho-litho-genetic types as those described above for the Irish Sea Coast Glacigenic Subgroup. Moundy ice-contact landforms predominate, and several eskers trending north-west to south-east occur in the vicinity of Kirkbean [NX 977 591]. The best exposed sequence of sands and gravels occurs in Kirkbean Quarry [NX 9793 5892] (CA 1418) at the south-east edge of the village, and form the type sections for glaciofluvial deposits of the **Kirkbean Sand and Gravel Formation** to which all glaciofluvial deposits of Southern Uplands derivation within the Solway district are assigned. Here, esker gravels of two types are worked: gravel in the lower part of the succession contains a significant proportion (about 15 per cent) of granitic clasts, whereas the upper part of the gravel sequence contains only trace amounts of granitic material. Wacke sandstone, siltstone and mudstone clasts predominate in both units, however, indicating their deposition by meltwaters from Southern Uplands ice.

5.4 BRITANNIA CATCHMENTS GROUP

5.4.1 Solway Catchments Subgroup

The Solway Catchments Subgroup is defined by a series of fluvial lithogenetic units, comprising alluvium, alluvial fan deposits and river terrace deposits of all rivers draining to the Solway Firth (McMillan et al., 2011). As shown on Solway West (BGS, 2005) and Solway East (BGS, 2006), the subgroup also includes widely distributed deposits of superficial peat, blown sand and head. The deposits are of late-glacial and Holocene age, and the subgroup partially subsumes the former Solway Drift Group defined in the Sellafield area of west Cumbrian coast (Merritt and Auton, 2000).

5.4.1.1 Fluvial deposits

The most extensive fluvial deposits (alluvium and river terrace deposits) are confined within the valley floors of the major rivers of the district, including the rivers Nith, Annan, Esk, Eden, Wampool, Waver, Ellen and Derwent. However, only river terrace deposits within the Esk valley and tributary valleys have been formally named as the **Solway Esk Valley Formation** (Solway East, BGS 2006; McMillan et al., 2011).

The alluvial deposits in the district include fluvial deposits underlying the floodplains and low-lying terraces of rivers, river terrace deposits, sediments within enclosed basins and lacustrine alluvium.

Alluvium of floodplains and low-lying river terraces

Ribbons of alluvium flank the courses of the major rivers in the district, forming low-lying ground potentially liable to flooding. River bank sections commonly reveal clast-supported gravel (shingle), capped by ‘overbank deposits’ consisting of one or two metres of laminated, humic, micaceous, silty sand (loam), locally intercalated with peat. In general, the clasts forming the gravel are subangular to well rounded, and reasonably well sorted. The faster flowing rivers in the district, such as the Esk and Ewes Water, have gravelly beds and most have cultivated floodplains. Meander belts are common in the lower reaches of the Esk and Lyne, at the head of the Solway Firth, and the rivers Nith and Annan.

Thicknesses of alluvium are difficult to generalise as they are very variable, both within, and between catchments. Downstream of Langholm, the coarse, gravelly alluvium of the River Esk is probably on average about 5 m thick, and possibly as much as 10 m locally. Gravel has been dredged from the river bed downstream of Canonbie as a source of aggregate. In the lower reaches of the Esk and Lyne the alluvial gravels commonly overlie fine-grained glaciolacustrine deposits.

Alluvium of basins

Alluvium has been mapped in numerous small, poorly drained, enclosed, or semi-enclosed basins across the district. Some of the basins are kettleholes (e.g. around Lochmaben), but the majority are subglacially sculptured hollows occurring between drumlins, as for example, to the west of Carlisle. The basins are probably generally floored by up to about 3 m of thinly-bedded, gravelly silty sand. Peat formerly occupied most of these depressions before being cut by man and drained artificially.

Lacustrine alluvium

Flat-lying spreads of interbedded humic sand, silt and clay occur in some poorly drained, enclosed basins. These previously contained lochans before being drained artificially, but in many instances it is difficult to distinguish between lacustrine alluvium and the alluvium of enclosed basins described above.

Alluvial fan deposits

Since deglaciation, fans composed of sand, gravel and gravelly diamicton have accumulated where tributary streams with relatively steep gradients debouch into more major river valleys. The most notable examples occur in the catchment of the River Esk upstream of Langholm.

River terrace deposits

Dissected remnants of former floodplains flank the alluvium of the rivers Esk and Eden, but are not common elsewhere in the district. River terraces slope gently down-valley, and are typically underlain by several metres of stratified, clast-supported gravel or sandy gravel. The gravel is commonly overlain by spreads of sand and silt up to about 2 m thick, laid down as 'overbank' deposits during the waning stages of periodic flood events. These fine-grained sediments are widespread on the broad terraces of the River Esk, where they produce well drained, light sandy soils.

Three terraces have been mapped in the lower reaches of the River Esk and are described by Dixon et al. (1926). These are formally defined as members of the Solway Esk Valley Formation. The Third Terrace is typically underlain by brown sand and gravel (less than 5 m thick), locally resting on reddish brown, pebbly silty sand (locally less than 10 m thick). The Second Terrace is underlain by well-sorted brown sand and gravel, locally resting on reddish brown, pebbly silty sand (less than 10 m thick), on reddish brown, clayey sand and gravel. The First Terrace is typically underlain by grey, pebbly sand (less than 3 m thick), on reddish brown, interbedded silty sand, silt and clay (less than 4 m thick), on reddish brown clayey sand and gravel.

The terraces of the River Esk were formerly exploited for aggregate in several operations near Longtown [NY 380 685]. Terraces of the Sark were exploited in the vicinity of Springfield [NY 323 684].

Most river terraces in the district are judged to have formed during ice-sheet deglaciation, and consequently have been mapped as glaciofluvial sheet deposits. These terraces are kettled locally and commonly merge into spreads of moundy ice-contact glaciofluvial deposits.

5.4.1.2 Organic deposits

Peat

Although not shown as such on the Solway maps, all peats and organic silts and gravels of the district are assigned to the **Blelham Peat Formation** (definition extended and modified after Thomas in Bowen, 1999, p.96; see McMillan et al., 2011). Remnants of organic deposits of Windermere Interstadial to Loch Lomond Stadial age are present at the Bigholms Burn SSSI [NY 3141 8131] (ME 306), 6 km west of Langholm (Figure 22) (Gordon, 1993a). Here, organic muds (**Healy Hill Organic Mud Member**) dated at 9590 ± 170 BP and 9470 ± 170 BP, overlie organic gravels (**Bigholms Burn Gravel Member**) containing blocks of clay and peat dated at 10 820 ± 170 BP, resting on 0.32 m of sedge peat (**Bigholms Burn Peat Bed**) dated at 11 820 ± 180 BP and 11 580 ± 180 BP (Godwin and Willis, 1964; Godwin et al., 1965; Bishop and Coope, 1977; Gordon, 1993a, Sutherland in Bowen, 1999, p.107). The late Devensian succession at Bigholms Burn is overlain by early to mid Holocene sedge, woody and blanket bog peat assigned to the **Racks Peat Member**, defined at Racks Moss [NY 040 732], near Racks, Dumfries (after Nichols, 1967).

On the Solway coast at Redkirk Point [NY 301 652], the **Redkirk Point Peat Member** (after Sutherland, in Bowen, 1999, p.107) comprises 0.3 m of carbonaceous silt and fine sand overlying a highly compacted peat (Bishop and Coope, 1977). The assemblage of fossil Coleoptera in this basal peat bed, the base of which is dated at 11 205 ± 177 BP (Shotton et al., 1968), closely resembles that of the Bigholms Burn Peat Bed. The Redkirk Point Peat Member is overlain by bedded silt and fine sand (Rigfoot Member of Sutherland, in Bowen, 1999, p.107), the Racks Peat Member and the Newbie Silt Member (Carse Clay Formation: see section 5.5 below).

Woody peat deposits of the Racks Peat Member may have been extensively developed around the coasts of the Solway Firth in the early to mid Holocene, prior to the 'Main Postglacial Transgression', when most were destroyed by coastal erosion. However, some material has survived within raised saltmarsh and estuarine deposits, such as at Powfoot [NY 150 658], Newbie Cottages [NY 167 650] and Redkirk Point [NY 302 651] (see section 5.5), where roots and branches of this so-called 'Boreal Forest' are exposed occasionally on the foreshore.

Deposits of basin peat in the district mostly occur within the sites of former lochans or abandoned estuaries. The peat commonly contains tree boles and other woody fragments, as well as the partially decomposed, acidic remains of sedges, reeds, rushes, Spaghnum and heather. The most extensive spreads of low-lying blanket peat in the district rest on particularly clayey and impermeable deposits. These include till beneath Solway Moss [NY 345 695] near Longtown, and Holocene raised tidal flat deposits beneath several large expanses of peat to the south of the Solway, for example Bowness Common, Glasson Moss, Drumburgh Moss and Wedholm Flow (Dixon et al., 1926).

The district formerly included many raised peat mosses, but most are now a fraction of their original size because of peat cutting for fuel in historical times and more recent commercial exploitation. For example, Solway Moss near Longtown, and both White Moss [NY 270 672] and Nutberry Moss [NY 265 680] near Eastriggs, are presently being harvested on a large scale for domestic fuel and horticultural purposes (Figure 23). Today, many mosses barely average even one metre in thickness, but they remain waterlogged and would partially regenerate in time. Many peaty hollows have been partly, if not completely infilled with boulders carted off fields, or have provided sites for dumping waste materials.

Most of the mosses of the coastal lowlands to the north of the Solway occupy ice-sculptured basins lying between low, elongate drumlins. South-east of Dumfries the extensive Lochar Gulf is defined (sensu Jardine, 1975) between Racks Moss and the Solway Firth, where boreholes at Sandyknowe Ridge [NY 017 776], Nether Locharwoods [NY 056 668] and Midtown [NY 118 657] proved peat overlying Holocene marine and brackish water sediments (Jardine, 1975).

Hill peat is most extensive on the hilltops in the north-east of the district, but it is generally thin and patchy.

5.4.1.3 Mass movement deposits

Head

Head deposits are poorly sorted and poorly stratified sediments, mainly formed as a result of the slow, viscous, downslope flow of waterlogged soils (solifluction and gelifluction), soil creep and hillwash (Ballantyne and Harris, 1994). Solifluction was most active whilst periglacial conditions pertained in the district during the latter part of the MLD glaciation and the Loch Lomond Stadial. It occurred during the summer months, when the uppermost 0.5 to 1 m of the soil (the so-called 'active layer') thawed whilst the ground below remained permanently frozen. The thickness and potential mobility of active layers depends very much upon the cohesiveness of the sediments affected, hence the thickest head deposits tend to occur where thoroughly decomposed rocks, clayey tills and fine-grained glaciolacustrine deposits have been remobilised.

Head deposits are ubiquitous across the district, but generally it has not been practical to map them out. They are especially well developed in the hills formed of Palaeozoic wacke sandstone and siltstone in the north-east of the district. For example, good sections have been examined in the vicinity of Shaw [NY 306 831] (ME 307), and are probably typical of those developed on wacke sandstones and siltstones (Figures 24 and 25). The deposits consist of crudely bedded, compact, rubbly, clast-supported diamicton, formed of angular, tabular to platy-shaped clasts in a pale grey, silty clayey, fine-sandy matrix. The diamictons are locally interbedded with loose, clast-supported, matrix-poor, angular gravel (scree) formed by gelifraction, and they typically grade downwards into frost-shattered rock.
Head deposits derived from weathered granite typically consist of clayey, coarse-grained sand, as, for example, on the slopes of Criffel [NX 957 618].

5.5 BRITISH COASTAL DEPOSITS GROUP

Intertidal, saltmarsh, marine, estuarine, blown sand, beach and raised marine deposits are assigned to the British Coastal Deposits Group. Most deposits are referred to on the Solway maps as lithogenetic units. Sutherland in Bowen (1999) assigned the onshore marine, estuarine and organic deposits of the district to the Redkirk Formation, named after Redkirk Point [NY 301 652]. Exposures are currently poor at this locality because of the erection of sea defences; for details see Jardine (1964, 1971, 1975, 1980); Bishop and Coope (1977); Gordon (1993b) and Lloyd (1999). As indicated above (section 5.4.1.2), all of the organic units of Sutherland's Redkirk Formation are now assigned by the BGS to the Blelham Peat Formation. Sutherland's Rigfoot Member and Newbie Member have been retained as the **Rigfoot Silt Member** and the **Newbie Silt Member** of the **Carse Clay Formation** (McMillan et al., 2011).

5.5.1 Raised beach and marine deposits

In addition to present-day coastal sediments, two distinct sets of raised marine deposits are present in the district. The sets were formed during periods of relatively high sea level, in late-glacial times and in the mid Holocene. Sea level was appreciably lower than it is today between these periods. The younger set of deposits is capable of being divided lithologically into 'shoreface and beach deposits' (mainly shingle and sand), and quiet-water sedimentary facies formed in tidal-flat, brackish lagoon and estuarine environments (mainly fine-grained sand and silt).

5.5.1.1 Late devensian raised marine deposits

The recognition of late-glacial raised beaches, composed of subhorizontally interstratified pebble gravels and coarse sands, is perhaps the most significant discovery made during the mapping of eastern Dumfries and Galloway (BGS, 2005). Prior to this survey, only Holocene raised marine and estuarine deposits had been described in the academic literature, although deposits assigned by the 19th Century primary surveyors, to the uppermost 'third' alluvial 'terrace', were subsequently described as 'raised beach laid down in late-glacial times' on Sheet 9E (IGS, 1980a), and as 'late-glacial estuarine alluvial deposits' on Sheet 5E (IGS, 1981).

Gently sloping features with planar (unkettled) upper surfaces, underlain by a mixture of pebble gravel, medium-grained sand and silty pebbly sand, were identified at 10 to 15 m above OD south of Dumfries during the 1999 survey, between Maxwelltown [NX 965 765] and Cargenbridge [NX 954 748]. These features were tentatively interpreted as late-glacial glaciomarine deltas. Similar gently sloping spreads of silty sand and gravel are commonly seen at the mouths of tributary valleys of the River Nith in the vicinity of New Abbey [NX 962 662], These are also ascribed a glaciomarine origin and early late-glacial age. The ruins of Sweatheart Abbey, New Abbey [NX 965 662] stand on perhaps the best example.

The features described above differ from the flat-topped spreads of gravel and planar-bedded sand, at 15 m above OD, that flank the landward margin of the carse between Southerness [NX 975 545] and Caulkerbush [NX 927 571]. The coastal position of the latter deposits (exposed to the maximum fetch along the Solway Firth), their near horizontal stratification, pronounced upward coarsening cyclicity and well-developed shape sorting of clasts, all suggest a littoral origin. Their similarity to nearby Holocene raised beach deposits, exposed at 9–10 m above OD in cliffs at South Carse [NX 9936 5946] (CA 1419), serves to reinforce the interpretation of the origin of the Southerness–Caulkerbush gravels as beach deposits.

The raised beach gravels at more than 10 m above OD have consequently been assigned to an early late-glacial highstand, which must have occurred towards the end of the MLD deglaciation of the district. They are well exposed in an intermittently worked small gravel pit at Southerness [NX 9728 5497] (CA 1424), and in a small disused pit [NX 9485 5636] (CA 1425) west of Cowcorse. Similar gravels form a flat-topped ridge at 10–15 m above OD that flanks the inland margin of the carse between Priestfield Flow [NY 12 66] and Longbridge Muir [NY 05 70]. The gravels are also well exposed in small workings south of Comlongon Castle at [NY 0757 6828] (CA 1460) and at [NY 0778 6820] (CA 1461).

The identification of late Devensian raised marine deposits around the estuary of the River Nith is supported by detailed biostratigraphical investigations in the vicinity of Pict's Knowe [NX 9538 7213] reported by Haggart (1999). Some 26 km to the east, another possible late-glacial raised beach gravel is exposed at Dornockbrow [NY 2331 6517] (ME 264), resting on an erosion surface cut in till (Gretna Till Formation) about 6 m above sea level. The gravel contains involutions attributed to periglacial activity, and therefore is very unlikely to be of Holocene age (Figure 26).

5.5.1.2 Holocene (Flandrian) raised marine deposits

Offshore sea-bed sediments of the Solway Firth are described in Chapter 7.

Holocene raised marine deposits are well developed along the northern shore of the Solway Firth, particularly around the estuary of the River Nith, and between Powfoot [NY 150 658] and Gretna [NY 320 670] (for reviews of the literature see Cressey et al., 1998, and Tipping, 1999a). These flat-lying deposits, which are backed by discontinuous, degraded clifflines at about 10 m above OD, formed during the Main Postglacial Transgression in the mid Holocene. Raised beaches formed of sand and pebble gravel commonly occur towards the cliffline, but elsewhere the beaches are buried by extensive raised tidal flat and saltmarsh deposits (carse or merse) formed mainly of mud and very fine-grained sand, with lenses of peat and tree stumps. Low storm beach ridges formed of shingle are preserved on the raised beach in the vicinity of Nethertown [NY 122 653], 3 km west of Powfoot.

Much of the area underlain by Holocene raised marine deposits to the east of Powfoot has been extensively modified in connection with the storage and testing of munitions over the years. Until recently, most MOD installations were not shown on Ordnance Survey base maps of the area. Good exposures of the raised marine sequence, belonging to the Newbie Silt Member of the Carse Clay Formation, occur in soft, rapidly eroding cliffs and on the foreshore in the vicinity of Broom Knowes [NY 160 654] and Newbie Cottages [NY 168 649], east of Powfoot. Several metres of pale to dark grey, clayey silt, with horizontal lamination and inclusions of peat, roots and logs, form a raised tidal flat behind the coast at 7–8 m above OD (Jardine, 1975; Gordon, 1993c; Dawson et al., 1999). A borehole positioned on the raised tidal flat nearby at Newbie Mains proved the following (downward) sequence, that is probably typical: grey silt (2 m), blue-grey organic clay (2 m), laminated peat and wood (1.3 m), grey silt (2.1 m), peat and wood (0.6 m), grey sand and gravel (4.6 m), red sand and gravel (4.1 m) on red sandstone. The uppermost metre or so is typically mottled grey brown and orange and stiffer than the underlying fine-grained sediments, which are generally firm to soft and contain beds of ‘running sand’.

The mapped extent of Holocene Carse is little changed from that shown on the previously published maps. However, augering, limited natural and man-made exposures and conversations with local landowners, all indicate that the deposits underlying the carse, especially between Glencaple and Powfoot, are mainly sandy silts and clays, rather than sands as shown on the current edition of Sheet 6W (BGS, 1998; Hughes, 1995). Marshall (1962) and Bridson (1980) described the accretion and erosion of the extensive saltmarsh of the Caerlaverock National Nature Reserve [NY 035 650]. On the western side of the Nith estuary the seaward limit of the Holocene raised marine and estuarine sediments forms a notable break of slope, and locally a cliffline about 5 m in height. This cliffline feature is well developed in the vicinity of Maxwell Bank [NX 9847 6905] (CA 1413), where the Holocene carse abuts modern saltmarsh deposits. Haggart (1999) reported detailed biostratigraphical investigations into the Holocene sequence in the vicinity of Pict’s Knowe [NX 9538 7213]. Low storm beach ridges formed of shingle associated with a Holocene raised beach lie across the estuary of the New Abbey Pow at Ingleston [NX 986 653]. Degraded sand dunes conceal Holocene raised tidal flat and beach deposits to the north-west of Southerness [NX 975 545], where they provide an ideal setting for a golf course.

6 A reinterpretation of the sequence of glacial events

6.1 NEXTMAP DSM ANALYSIS OF THE VALE OF EDEN AND SOLWAY LOWLANDS

Apart for some ground lying to the east of Gretna [NY 320 670], around Longtown, no new mapping was undertaken south of the border, either on, or adjacent to the area covered by the Solway maps described here. That area was last surveyed in the 1920s and 1930s and is fully described elsewhere (Dixon, et al., 1926; Eastwood, 1930, Trotter and Hollingworth, 1932b; Eastwood et al., 1931, 1968). Since that revision survey, satellite imagery has greatly increased our knowledge about the regional flow pattern of ice around the Solway (see Figure 10, and Solway maps, BGS, 2005, 2006), but it has been of insufficient resolution to elucidate the final glacial events within the Solway lowlands, particularly, the limits of the enigmatic Scottish Re-advance. However, the recent acquisition of NEXTMap Britain elevation data from Intermap Technologies (Figures 11, 27 to 30), with its greater resolution and functionality compared to satellite imagery, has provided a valuable opportunity to re-investigate the subdued landforms of this low-lying area.

A preliminary analysis of NEXTMap data has been undertaken for the area in and around the Solway lowlands, in which seven distinct suites of drumlins have been observed (Figures, 11, 27 to 30). Other significant features revealed by this analysis include glacial drainage channels, eskers and ice-marginal glaciofluvial deposits.

6.1.1 Subglacially streamlined features

6.1.1.1 Tyne Gap Suite

This suite forms a strong, west to east convergent flow set within the Tyne Gap, where there is much ice-scoured bedrock. The evidence supports the generally agreed conclusion of Trotter (1929) that Scottish ice merged with ice from the Vale of Eden and the Lake District to flow through the gap into Northumberland.

6.1.1.2 North Lake District Suite

The suite comprises a very prominent and coherent set of elongated drumlins that arc around the north of the Lake District from the Caldew Valley, south of Carlisle, towards the Irish Sea coast at Maryport. The drumlins occur on ground up to at least 344 m above OD at Faulds Brow [NY 300 407], fading northwards, at about 50 m above OD, along a narrow, flattish zone that arcs west-north-west from Dalston [NY 370 505], via Great Orton Airfield (now Watchtree Reserve) [NY 310 540] to Kirkbride [NY 230 570]. This suite of drumlins was described by Eastwood (1930), Hollingworth (1931), Eastwood et al. (1931, 1968), and Embleton and King (1968).

6.1.1.3 Carlisle Suite

The Carlisle suite forms a complicated zone of symmetrical drumlins passing north-west of Carlisle into transverse forms (rogen moraines) bearing east–west flutings (Hollingworth, 1932; Huddart, 1970). The former direction of ice flow is not clear, but the steeper slopes of the transverse features face eastwards, suggesting flow towards the west-north-west. The rogens fade southwards into the narrow, flattish zone that borders the North Lake District Suite (described above), where the two suites appear to merge, representing a continuum. The northern boundary of the Carlisle Suite is not clear because the ground is mostly covered by alluvial deposits, but there is a hint that the transverse forms swing around to the north-east into another flattish zone, mirroring the one described to the south, but in a symmetrically opposite disposition. Three suites of drumlins were recognised in this area by Huddart (1971b) and both he and Trotter (1929) described remoulded drumlins. Rogen moraines appear not have not been reported hitherto.

6.1.1.4 Inglewood Forest Suite

This suite of low, south–north orientated, elongated drumlins, lies within the catchments of the rivers Caldew and Petterill in western Edenside, constrained by the Permian Sandstone escarpment to the east and relatively high ground to the west of the River Caldew. In previous reconstructions (e.g. Figure 9) the drumlins hereabouts were considered to pass imperceptibly into those sweeping around the northern slopes of the Lake District.

6.1.1.5 Vale of Eden Suite

This suite includes the classic 'basket of eggs' belt of south-east to north-west orientated drumlins described by Letzer (1978, 1981, 1987), and occupying the southern part of the Vale of Eden, south-east of Penrith. These drumlins may have originally merged with the North Lake District Suite before the emplacement of the Inglewood Forest Suite.

6.1.1.6 Annan–Gretna Suite

The low-lying ground to the north of the Solway Firth is weakly drumlinised by low, elongated forms that arc south-eastwards and then eastwards towards the Tyne Gap (see Solway East, BGS, 2006). They fade eastwards towards the Brampton Kame Belt [NY 500 620], and are distinct from the better-developed, similarly orientated forms on the higher ground within the Tyne Gap. Previous authors have directly linked these two suites of features implying that they formed synchronously (Figure 9), but this is probably not the case.

6.1.1.7 Canonbie–Liddesdale Suite

This suite of poorly developed drumlins and ice-moulded bedrock features is well displayed on Landsat imagery (Figure 10). The features arc north-eastwards, from Canonbie around the relatively weakly glacierised Langholm Hills towards the Tweed Basin and the North Sea coast. The suite is cut by, and hence predates the Annan–Gretna Suite. This relationship is supported by lithostratigraphical evidence of red, sandstone-rich tills sourced from the south-east, occurring beneath wacke sandstone-rich tills sourced from the Langholm Hills to the north (Lumsden et al., 1967) (see Langholm Till Formation and Hoghill Gravel Bed, section 5.3.2.1 above).

6.1.2 Ice-marginal features

6.1.2.1 The Brampton Kame Belt

This well-documented, ice-marginal, glaciofluvial complex (Figure 11) is bounded by ice-contact slopes that face west or north-west, suggesting that ice was withdrawing towards Scotland (Trotter, 1929; Huddart, 1981; Huddart and Glasser, 2002). However, the glaciofluvial deposits were largely laid down by meltwaters that debouched from a suite of 'ice-marginal' drainage channels to the south, flowing towards overflow channels cutting across the Tyne Gap.

6.1.2.2 The Wreay–Buckabank Moraine

This hitherto unreported feature to the south of Carlisle is a low, arcuate, south-facing bank linking Wreay [NY 436 489] and Buckabank [NY 372 490] in the Petterill and Caldew valleys respectively (Figure 11). The Pow Beck, which possibly began as an ice-marginal glacial drainage channel, lies at its foot. A secondary, parallel bank lies to the north. These features clearly truncate the Inglewood Forest Suite of drumlins lying to the south and are interpreted here as a moraine. They coincide with the feather-edge of the 'Upper Till', mapped by Trotter (1929) to the north and attributed by him to the Scottish Re-advance.

6.1.2.3 Holme St Cuthbert Complex

A large plateau of glaciofluvial sand and gravel around Holme St Cuthbert [NY 110 470] includes deltaic deposits that formed as a fan at the margin of Scottish ice lying to the north-west (Figure 11). Huddart (1970, 1991) concluded that the deposits record the maximum extent of the Scottish Re-advance hereabouts.

6.1.2.4 Caldew–Wampool Overflow Channel

During deglaciation, Scottish ice blocking the Solway lowlands at the mouth of the River Caldew, in the vicinity of Carlisle, diverted water westwards to create this prominent misfit valley of the River Wampool (Dixon et al., 1926; Trotter, 1929; Hollingworth, 1931; Eastwood, 1930; Eastwood et al., 1968). At an earlier stage in the deglaciation, meltwaters probably flowed more directly towards the Irish Sea basin to the north of Allonby [NY 080 447], via the misfit valleys of the Colmire Sough [NY 230 505], Holme Dub [NY 155 475] and Black Dub [NY 110 450]. The Bampton Beck [NY 265 545] occupies a channel that formed subsequently, when ice had retreated farther towards the north-west, but whilst meltwaters were still constrained to flow towards Allonby, possibly for a while via the misfit valley occupied by Wedholme Flow [NY 215 521]. Trotter (1929) and Hollingworth (1931) both concluded that the channels were created following the Scottish Re-advance, but Huddart (1970) considered it more likely that they formed earlier, during MLD deglaciation.

6.1.2.5 Wiza Beck Channels

The origin of this system of arcuate, 'in-out' channels to the south of Wigton (Figure 11) has caused particular controversy. Dixon et al. (1926), Trotter (1929), and Hollingworth (1931) concluded that they had been dissected sequentially in an ice marginal setting during deglaciation. Huddart (1970), Letzer (1978), Arthurton and Wadge (1981) have since argued that channels of this kind formed subglacially, as part of a regional, steady-state subglacial system, not necessarily during deglaciation. However, although channel floors do undulate locally for various reasons, on balance, the cross-cutting relationships of channels such as these indicate that they did form sequentially close to, if not strictly at, an ice margin. The Wiza Beck channels [NY 260 455] therefore indicate that the ice front retreated towards the north or north-west during their formation. This is puzzling, because drumlins of the North Lake District Suite in the vicinity indicate that ice flowed from the east-south-east. Dixon et al. (1926) reasoned that the channels must therefore have formed following the Scottish Re-advance, when ice retreated in the direction from which it had come, but that the advance had caused minimal modification of the landscape. Huddart (1970) agreed with Trotter (1929) and Hollingworth (1931) that the channels formed prior to the Scottish Re-advance during ice-sheet recession. This would have occurred as the ice responsible for creating the Northern Lake District Suite of drumlins withdrew from the northern slopes of the Lake District towards lower ground during deglaciation.

6.1.2.6 Southern Dumfriesshire Channels

Several channels may be observed arcing towards the south-east, away from higher ground to the north of Dumfries (see Solway West, BGS, 2005; Figure 11). These channels indicate that the last ice to occupy this sector of the Solway Lowlands was sourced to the west-north-west and withdrew in that direction. The orientation of several eskers including the Cummertrees [NY 143 665] system support ice retreat towards this direction.

6.1.3 Eskers

Although they generally are not obvious from NEXTmap, the presence of several eskers has important implications in unravelling the history of deglaciation.

6.1.3.1 Hallbankgate Esker

This prominent esker links with the Brampton Kame Belt, and records subglacial drainage through the Tyne Gap before the creation of overflow channels (Trotter, 1929; Huddart, 1981; Huddart and Glasser, 2002).

6.1.3.2 Thursby Eskers

These are parallel eskers created by meltwater flowing east-south-east towards an ice margin in the vicinity of the Caldew–Wampool overflow channel [NY 350 507], but draped on drumlins apparently formed by ice flowing in the opposite direction. Following Trotter (1929) and Hollingworth (1931), Huddart (1981) concluded that these eskers, and others nearby, formed following the Scottish Re-advance, and that the advance caused minimal modification of the landscape. Several parallel eskers to the north-west of Thursby were created by subglacial meltwaters that flowed east-south-east towards an ice margin in the vicinity of the Caldew–Wampool overflow channel hereabouts (Huddart, 1973). This is an unusual setting because the eskers have been draped across drumlins that were formed beneath ice flowing in the opposite direction. Huddart followed Trotter and Hollingworth in deducing that the eskers formed during the Scottish Re-advance and that the advance caused minimal modification of the landscape. Other esker systems at Sowerby Wood [NY 365 520] and Fingland [NY 255 570] formed similarly, but not contemporaneously (Huddart, 1970).

6.1.4 Conclusions

- Seven distinct sets of glacially streamlined features are recognised in and around the Solway lowlands. They can be related to three major stages of glaciation (Figures 10, 27 to 29), which are broadly as proposed by Letzer (1978).
- Stage 1 requires an ice divide to have become established linking the Lake District and Galloway Hills, which forced Scottish ice up the Vale of Eden and over Stainmore, rather than into the Irish Sea

basin. This stage is associated with the greatest accumulation of ice and probably occurred during the Last Glacial Maximum, by about 22 cal. ka BP.

- Stage 2 involves the breaching of the ice divide in the Solway, possibly as a result of headward scavenging of an active Irish Sea ice stream. The 'draw down' towards the Irish Sea basin ultimately resulted in reversal of ice flow in the Vale of Eden and creation of the dominant North Lake District suite of drumlins. It probably halted the flow of Scottish ice through the Tyne Gap.
- Stage 3 witnessed another glacial reorganisation, resulting in re-advance of Scottish ice into the Solway Lowlands. Scottish ice flowed predominantly from the Dumfries Basin rather than the Langholm Hills during stages 2 and 3.
- There is a northward progression from spindle shaped drumlin forms to elongate drumlins to transverse asymmetrical forms (rogen moraines) within the North Lake District and Carlisle suites. This may indicate that during Stage 2 rates of flow diminished northwards towards the centre of the Solway Basin where ice was thickest (Embleton and King, 1968).
- The presence of the Inglewood Forest Suite of drumlins on the floor of the Vale of Eden indicates that ice remained active there after it had retreated from higher ground to the west, where it had previously formed the North Lake District set.
- The abrupt termination of the Inglewood Forest Suite of drumlins south of Carlisle supports the local Scottish Re-advance limit proposed by Trotter (1929).
- The absence of new evidence to better constrain the limits of the Scottish Re-advance across north-west Cumbria suggests that in the Solway lowlands this may have been a relatively minor, late-stage re-advance of ice from the Dumfries Basin resulting from glacial readjustment, rather than an event of regional extent as proposed by Huddart. The most likely limit follows the Caldew–Wampool overflow channel, as proposed by Trotter (1929).
- Known occurrences of 'Middle Sands' reported by Dixon et al. (1926) and Trotter (1929) (including laminated silt and clay) are either preserved within palaeovalleys trending at acute angles to ice-flow, as at Plumpe Farm, or within the cores of drumlins. Importantly, in the vicinity of Carlisle, these drumlins appear to belong to a suite that is linked with Stage 2. If correct, it follows that units of 'Middle Sand' preserved within them predate this phase of glaciation. Much of the field evidence cited by Trotter, Hollingworth and Huddart supporting the Scottish Re-advance in this area may therefore relate to an earlier, significant deglacial event and re-advance that occurred possibly between Stages 1 and 2.

7 Offshore sea-bed sediments and landforms

7.1 BACKGROUND INFORMATION ON SEDIMENTATION IN THE SOLWAY FIRTH

The Solway Firth is a shallow estuary, with water depths generally less than 20 m and large areas lying within the intertidal zone. The funnel shape of the inner Solway Firth heightens the tidal range to 8.4 m, and the maximum velocity of the flood current is greater than the maximum velocity of the ebb current. The ebb and flood tidal currents follow different courses in the estuary, resulting in a complex and constantly evolving pattern of channel courses and shifting sandbanks. The inner Firth is an area of extensive intertidal sandflats, with sandbanks exposed during the ebb tide. Saltmarsh occurs along the flanks of the inner Firth, and is expanding in some places, but is being eroded in others where shifting channel courses cut into the high intertidal flats.

The Firth is a net sink for sediment, and much of the sediment may have been sourced from Quaternary deposits in the northern Irish Sea (Perkins, 1974). Longshore drift is carrying sand and gravel farther into the estuary. Rivers entering the Firth now contribute little sedimentary material, apart from some mud at times of flood.

Despite numerous studies on the ecology and sedimentology of the intertidal flats and banks, little is known about the thickness of sediments within the Firth, or the Quaternary sediment fill of the Firth. No seismic surveys have been undertaken in the inner Firth.

7.1.1 Distribution of sediments within the Solway Firth

Grain size variations within the estuary have been established by laboratory analysis of samples collected by hovercraft during a MAFF (now DEFRA) investigation of radionuclide distribution in the north-west Irish Sea. These data supplement grab samples collected during mapping for the BGS 1:250 000 Series Lake District Sheet 54°N–04°W, Sea-Bed Sediments and Quaternary Geology (IGS, 1983). These data provide a broad guide to the relationship between grain size and sedimentary facies within the Firth, and are useful for indicating the likely occurrences of mud-rich sediment and gravel within the estuary.

The sand fractions are dominantly fine grained and very fine grained. Locally, medium-grained sand can form up to 38 per cent of the total sand fraction. Coarser sand grades are unusual. Cores through the estuary sediments record units of parallel lamination and low amplitude wave and current ripple cross-lamination, consistent with the overall fine-grained nature of the sediments and their common reworking by tidal currents. Carbonaceous particles, and to a lesser extent mica flakes, are common components within the sand.

Mud drapes and silty mud partings occur within the intertidal and supratidal sequences along both the English and Scottish shores of the estuary, especially in sheltered embayments where rivers enter the estuary. A greater proportion of mud is present in the sediments along the northern shore, particularly in the intertidal areas offshore from Caerlaverock Nature Reserve [NY 040 640] and just east of the River Annan [NY 200 640], where it can locally form up to 70 per cent of the sediment. On the southern side of the Firth, patches of mud occur along the flanks of Moricambe Bay [NY 160 560]. However, reworking of sediment during high tides means that there are common but localised changes in the distribution of the finer, muddy sediments deposited from suspension.

The high sand flats of Solway Firth consist of fine- to very fine-grained sands, interspersed with occasional laminae of clayey silt and silty clay. Just beneath the salt marshes, the muddy laminae become more plentiful, but these decimetre-scale mud beds rarely exceed the amount of very fine sand present (Allen, 1989). The salt marshes are well drained and readily dry out.

The sediments of the high intertidal flats also contain significant shell material, including bivalves in their life position, as well as disarticulated and broken valves strewn across the sediment surface, as reported by Wilson (1967) from Carse Sands [NY 000 600] to the west of the Nith Estuary. The broken shells are almost entirely due to bird predation rather than abrasion. Reworking of the tidal flat sediments can produce localised shell banks. Thin shell banks accumulate on the sand flats where they have been concentrated by the action of tidal currents, and lags of predominantly convex-upwards valves also occur on the floors of shifting ebb tidal channels. These shell beds are also found buried within the sand flats.

Of the natural occurrences of gravel in the inner Firth, the most conspicuous is the gravel beach extending from the lifeboat ramp at Silloth towards Grune Point [NY 143 568], resulting from a natural north-easterly directed longshore movement of gravel along the southern flank of the Firth. At Grune Point the shingle has prograded north-east over the sandflats to form a spit. The gravel appears to have been sourced mainly from winnowed till deposits. Sand dunes cover the higher parts of the spit. A similar but smaller scale gravel spit-like feature has developed at Barnkirk Point [NY 192 643], near Annan on the north shore of the Firth. Artificial boulder defences have been installed in front of Newbie Villa [NY 173 645].

Gravel is also likely to be found on the floor of major channels and tidal creeks within the Firth. This gravel is probably sourced from till that formerly existed in the Firth or on the adjacent shores. Large boulders from the till are scattered across the foreshore south of Silloth [NY 102 534], and longshore drift may have carried the finer gravel fraction into the Firth.

Gravel and larger rock clasts, together with miscellaneous brick and concrete debris and occasional rounded pieces of coal, are locally found mixed with sandy sediment along the margins of the estuary, particularly in the vicinity of Annan [NY 198 650] and Bowness-on-Solway [NY 224 628]. Much of this mixed gravel debris may have been emplaced by construction activities or sourced by erosion from man-made structures around the Firth. For example, part of the foundation of a small car park at Annan Common Ground [NY 209 648] comprises loose pebbles which would be easily washed onto the saltmarsh during high storm tides. The remains of the abandoned rock-supported pillars of the railway bridge and embankment at Seafield, Annan [NY

206 645], and also on the southern side of the Firth at Herd Hill [NY 212 627], may have been a further source of gravel components in the estuary.

7.1.2 Frequent reworking of sediments

The position and morphology of bedforms show frequent modification due to strong tidal influence. Comparison of the various datasets for the year 2000 show that the position of intertidal sandbanks varies considerably, with morphological changes reflecting the frequent and significant movement of sediment around the margins of the banks. However datasets are rarely obtained at the lowest ebb tides when the limits of each bank might best be established. There was some lateral movement of the channel positions within the innermost part of the estuary during 2000, but no significant switching of channel courses. All maps produced of the bedforms within the estuary therefore capture just a moment in time.

Despite evidence from the estuary margins of a rich burrowing fauna on the intertidal flats, sediment cores from the Firth show an overall paucity of bioturbation structures, with parallel and ripple cross-lamination predominating. The frequent reworking of sediments on the intertidal flats and banks obliterates most burrow traces, with infauna concentrated along the margins of the estuary where sediments are comparatively stable.

In the Nith estuary, the sediments are so mobile that frequent shifts of the main channel accompanied by the movement of millions of tonnes of sediment are known to occur; here the infauna are washed out into the bed of the Nith channel and transported into the main estuary.

It is also likely that gravel lags may be periodically hidden and subsequently exposed along the estuary margins due to the shifting sediments.

8 Applied Quaternary geology

8.1 AQUIFERS

The Solway district includes several Permo-Triassic groundwater aquifers, including those in the Dumfries Basin and the Lochmaben Basin. The Dumfries Basin aquifer supports groundwater abstraction for public supply, agriculture and industry (Robins and Buckley, 1988; BGS, 1990; Robins and Ball, 2006; Akhurst et al., 2006). Abstraction is concentrated in the western part of the basin, where falling groundwater levels and deteriorating water quality both reflect the effects of intense pumping. In the Dumfries Basin there are two bedrock units: a predominantly breccia–coarse sandstone sequence (Doweel Breccia Formation) in the west, interfingering with a predominantly sandstone sequence (Locharbriggs Sandstone Formation) in the north-east and east. The basin is bounded by weakly permeable Lower Palaeozoic rocks, and is largely concealed by variable superficial deposits. Surface water flows onto the basin from the surrounding catchment via the Nith and the Lochar Water and their respective tributaries. Direct rainfall recharge occurs via superficial sands and gravels, especially in the north, and discharge is predominantly to the rivers in the central area rather than the sea. A picture is developing of two main aquifer types within the basin: the high-transmissivity western sector underlain by a fracture-flow system with younger water, active recharge and high nitrate content, and an eastern sector where groundwater residence times are longer and the storage capacity is higher.

Away from the Permo-Triassic basins, the Carboniferous sedimentary sequence along the coast forms a moderately productive aquifer, with a relatively complex, multilayered hydrogeology that is as yet poorly studied. Sandstone units are likely to act as discrete aquifers, separated by finer-grained, lower permeability units. Boreholes abstract groundwater from the aquifer for domestic, agricultural and recreational use.

The Silurian rocks form a low productivity aquifer, in which groundwater storage and flow is almost entirely via fractures, and groundwater flow paths are likely to be relatively shallow, short and localised. Although individual borehole yields are low, there are a number of abstractions from the aquifer across the region, primarily for domestic and farm use.

The thickest and highest permeability Quaternary deposits in the district, largely glaciofluvial deposits and associated alluvium, can form highly productive local aquifers.

8.2 QUATERNARY DOMAINS

The Quaternary superficial deposits in the Solway area can be subdivided into 3D domains that enable the role of the superficial deposits on hydrogeological issues to be evaluated, in particular recharge potential and aquifer vulnerability. Each domain represents a specific sequence of deposits that in turn can be related to the vertical flowpaths for infiltrating water (recharge) moving down to a bedrock water table. The vertical transmission of water to the underlying bedrock aquifers occurs more readily through thin, permeable Quaternary deposits such as sands and gravels, rather than through thick, low permeability clay, silt or peat. The deposits in each of the domains have not been given quantitative hydraulic conductivity values, but are classed in terms of relative permeability. For comparison, the deposits with the lowest permeability in the Solway area are marine and tidal flat clays, which are likely to have a hydraulic conductivity of 10–6 to 10–3 md^{-1}; deposits with the highest permeability are glaciofluvial sand and gravel, which are likely to have a hydraulic conductivity ranging from 101 to 103 md^{-1}. In total, eleven domains, including four sub-domains (Table 2; Figure 31) have been identified in the Solway area, based on the origin, sequence, layering, thickness and permeability of the Quaternary deposits.

8.3 HYDROGEOLOGY

In the Solway area, the majority of the alluvial, glaciofluvial, raised beach, shoreface and deltaic deposits, and the Langholm Till Formation, are granular with minor clay content, and are therefore likely to be moderately to highly permeable. The majority of the tidal flat, intertidal and saltmarsh deposits, and the glaciolacustrine deposits, are all typically dominated by clay and are likely to have low permeability. The Gretna Till Formation, with its compacted nature and significant proportion of clay, is also likely to have low permeability. Peat deposits similarly have low permeability.

Quaternary deposits are likely to inhibit recharge to the underlying bedrock aquifer, as on such deposits run-off to surface water courses is increased at the expense of vertical recharge. Highly permeable deposits such as sand and gravel have the highest recharge potential, but this can be moderated if the deposits are very thick, as groundwater infiltrating through thicker deposits has more time to flow laterally, and may discharge directly to surface water courses without reaching the underlying bedrock aquifer. However, the dominant control on recharge potential is the lowest permeability deposit in the Quaternary sequence. The Quaternary hydrogeological domains have been interpreted in terms of recharge potential, as shown in Figure 32. Note that Domain 5, comprising raised beach, shoreface, deltaic and sandflat deposits, is almost entirely below current sea level, which should be born in mind when interpreting the map of recharge potential.

8.4 ENGINEERING PROPERTIES

The engineering geological assessment of the superficial deposits in the area covered by Solway West and Solway East (BGS, 2005, 2006) is based on site investigation data reports, borehole and pit logs for engineering purposes and geologists' descriptions. Much of the information is from major road schemes, such as the M74, A74, A74M, A7 Canonbie bypass and A75 improvements at Annan, Carrutherston and Dumfries. A detailed assessment of the geotechnical and engineering geological characteristics of the site investigations between M6 junction 44 [NY 388 601] and M74 junction 22 [NY 280 707] is given by Entwisle (2007).

Table 2 Quaternary hydrogeological domains in the Solway district.

Domain	Mapped materials	Thickness	Permeability	Recharge potential	Named units
1. Alluvium, alluvial fan and river terrace deposits	Largely sand and gravel; also sand, silt and clay	>10 m	High	High	
2. Glaciofluvial ice contact and morainic deposits, sheet deposits, and undifferentiated	Clay, silt, sand and gravel; gravel; sand, gravel and boulders; diamicton, sand and gravel	>=10 m	High	High	Kerr Moraine Formation, Dalswinton Moraine Formation, Kilblane Sand and Gravel Formation and Kirkbean Sand and Gravel Formation, Loganhouse Gravel Member, Mouldy Hills Gravel Formation, Plumpe Farm Sand Member and Plumpe Sand and Gravel Formation (at outcrop)
3. Largely fine-grained, clayey till — 3a. Thin	Diamicton (red, very fine-grained, compact, often clayey, poorly drained sand; occasional isolated sand and gravel lense between upper, more compact till and lower, clayier but possibly more fractured till).	<=5 m generally	Low	Low	Gretna Till Formation and Chapelknowe Till Member; Plumpe Farm Sand Member and Plumpe Sand and Gravel Formation (in subcrop)
3. Largely fine-grained, clayey till — 3b. Thick	Diamicton (red, very fine-grained, often clayey, poorly drained sand); occasional isolated sand and gravel lense between upper, more compact till and lower, clayier but possibly more fractured till).	5–15 m	Low	Low	Gretna Till Formation and Chapelknowe Till Member; Plumpe Farm Sand Member and Plumpe Sand and Gravel Formation (in subcrop)
4. Largely coarse grained, gravelly till — 4a. Thin	Diamicton (largely coarse-grained, gravelly and stony)	<=5 m generally	Moderate–high	High	Langholm Till Formation
4. Largely coarse grained, gravelly till — 4b. Thick	Diamicton (largely coarse-grained, gravelly and stony)	5–15 m	Moderate–high	Moderate	Langholm Till Formation
5. Flandrian and Late Devensian raised beach, shoreface and deltaic deposits; intertidal sandflat deposits	Sand and gravel; gravel; sand; gravelly sand; gravel, sand and silt	High	High		
6. Modern and Flandrian tidal flat, intertidal, raised tidal flat, saltmarsh and warp deposits	Clay and silt; sand, silt and clay; silt; silt, sand, clay and gravel	30 m + in west Dumfries Basin	Low	Low	
7. Peat			Low	Low	
8. Peat on raised tidal flat deposits, on glaciofluvial sand and gravel and till	Peat over clay, silt and fine sand with interbedded peat, over sand and gravel, over laterally discontinous till	5–30 m	Low (at ground surface); High (at depth)		
9. Glaciolacustrine and lacustrine deposits	Silty clay; sand, silt and clay. Tectonised outwash around Dumfries: very mixed deposit		Low	Low	Cullivait Silts Formation
UNK. Superficial deposits not mapped					

The geological materials have been classified on the basis of their engineering geological behaviour (Dearman, 1991) with regard to land use and construction. The primary divisions are based on the principal soil type (British Standard Institution, 1999), i.e. 'fine-grained' (clay and silt) and coarse-grained (sand and gravel). A category of 'mixed soils' (fine and coarse) indicates units that comprise combinations of discrete bodies of fine and coarse material. 'Organic' soil includes both lowland and upland peat and forms part of the fine-grained soil type. A secondary division is made based on the description of strength, and density, the latter determined from standard penetration test (SPT) results.

General information on the engineering geological description and engineering considerations (i.e. foundations, excavations, suitability as engineering fill and comments on site investigation) for each engineering class are given for fine, coarse and mixed materials in Table 3, Table 4 and Table 5 respectively. Additional information is given in the following sections.

8.4.1 Glacial till (Langholm, Chapelknowe and Gretna Till formations)

The tills are classified as mixed soil and their lithology and geotechnical properties vary widely. They are generally gravelly, sandy clays or fine-grained silts with occasional cobbles and boulders. The fine material is of low to medium and occasionally high plasticity. Weathering may occur

Table 3 Engineering geological description and engineering considerations for organic and fine soils of the Solway district.

Engineering geological unit	Characteristics	Geological unit	Description/ characteristics	Engineering considerations			
				Foundations	**Excavation**	**Engineering fill**	**Site investigation**
Organic deposit	Highly compressible organic deposits	Peat	Fibrous and spongy, sometimes amorphous, may be clayey or occasionally sandy.	Unsuitable. Highly compressible, even light foundations will be subject to variable and considerable settlement over long periods.	Diggable. Generally poor stability particularly below the water table. Dewatering will result in shrinkage.	Unsuitable	Determine extent and depth and type of peat.
Fine grained	Soft to firm	Alluvium (fine-grained), warp, tidal river and creek deposits, raised tidal flats	Very soft to firm, stiff near surface; sometimes organic; CLAY usually red-brown, sometimes dark brown or green-grey SAND, SILT and CLAY. High saline water table.	Foundations specially designed. Top metre or so may be stiff or firm but soft beneath.	Diggable. Generally poor stability particularly below the water table.	Generally unsuitable	Determine the depth, extent and lithological and strength variation.
		Salt marsh, intertidal deposits (fine-grained)	Very soft to soft, organic, CLAY, occasional gravel beds. High saline water table.	Unsuitable	Diggable, unstable	Unsuitable	Determine depth, extent.
	Soft/firm, uncompact, loose	Lacustrine deposits, Cullivait Silts Formation, Great Easby Clay Formation	Soft–firm, thinly to thickly laminated CLAY and uncompact SILT, with some loose SAND laminae, occasional subangular to rounded fine to medium, rarely coarse, gravel. Generally firm near top and soft at depth.	Foundations must be carefully designed. Upper part often firm but variable in depth. Likely to consolidate fairly rapidly.	Diggable. Poor stability. Running conditions in silt and sand below water table.	Generally unsuitable.	Determine depth and extent particularly of soft, compressible zones.

to several metres depth, tending to increase plasticity and reduce strength. Wet weather is likely to soften the surface, which may need removing prior to construction. Compaction of low plasticity till requires tight control of emplacement moisture content, as these materials are sensitive to moisture content and may show resilience against compaction.

Coarse beds also occur within the tills. They are particularly well developed in the Plumpe Sand and Gravel Formation. Water bearing sand and gravel lenses and beds may result in unpredictable ground water conditions, most notably in excavations and natural exposures. Water seepage from coarse layers will lead to softening of the adjacent clay, perhaps leading to long-term slope failure. Seepage from sand layers may lead to cavities within the layer (Hughes et al., 1998). The proportion, strength, and size of the coarse particles, in particular cobbles and boulders, may make undisturbed sampling very difficult or impossible, impede emplacement of casing in deeper investigations, and require larger plant when excavating in till. Foundations settlement directly above a boulder will be less than the rest of the building, which may lead to differential settlement.

8.4.2 Glaciofluvial sands and gravels (Kilblane Sand and Gravel and Kirkbean Sand and Gravel formations)

Glaciofluvial sand and gravel is generally loose to moderately dense, clayey or silty angular to rounded sand and gravel, with cobbles and boulders. Thin pockets or layers of uncompact silt or firm clay, up to 2 m thick, may be present. During site investigation, care must be taken to identify fine-grained deposits and loose deposits that may occur below dense material. Differential settlement may occur in large buildings founded on materials of different densities or dense coarse material and firm fine-grained material.

8.4.3 Glaciolacustrine deposits (Cullivait Silts and Great Easby Clay formations)

Glaciolacustrine deposits consist mainly of soft to firm or uncompact, thinly to thickly laminated clay and silt, with thin beds of loose sand and occasional gravel. They are generally low to intermediate, and occasionally high plasticity. The laminations result in large differences in vertical and horizontal properties. For example, horizontal permeability along silt and sand laminations is much greater than vertical permeability, and the horizontal strength along clay laminae will be less than the vertical strength across laminae. Moisture content and strength tend to be greatest in the upper part. Foundation design should take into consideration the strength variation and relatively rapid settlement that is typical of these deposits. The sides of excavations will be unstable especially below the water table.

8.4.4 Alluvium

The alluvium in the lower reaches of rivers tends to be soft to firm clay or sandy clay, or uncompact silt or loose sand.

Table 4 Engineering geological description and engineering considerations for coarse soils of the Solway district.

Engineering geological unit	Characteristics	Geological unit	Description/ characteristics	Engineering considerations			
				Foundations	**Excavation**	**Engineering fill**	**Site investigation**
Sand	Very loose/ loose (dry)	Blown sand, storm beach,	Very loose to loose fine SAND, may be mobile (unstable dunes). Near shore may contain sodium chloride, less so further inland.	Specially designed foundations. In general must be stable.	Diggable but sides unstable	Suitable but of restricted use. May need to be blended with other materials	Determine depth and extent and identify if still mobile.
Sand	Very loose/ loose (wet)	Intertidal sandflat, intertidal sandbank	Very loose fine to medium, sometimes coarse SAND, high water table, saline.	Generally unsuitable, specialist foundations in marine situation	Diggable but sides unstable	Suitable but may need to be washed to remove salt.	Determine depth and extent.
Sand	Medium dense to very dense	Plump Farm Sand Member	Medium dense to very dense, reddish brown or brown, occasionally gravelly, sometimes silty or clayey, fine to medium SAND, sometimes with layers or bands of silt and clay and gravel.	Suitable.	Diggable, unstable below water table	Generally suitable.	Determine depth and extent, density, variability and water levels.
Sand and gravel	Loose to medium dense (dense)	Alluvium (coarse), river terrace deposits, raised marine beach deposits, raised storm beach deposits, Kilblane Sand and Gravel Formation	Generally medium dense to dense sand and gravel with occasional silt or clay layers and cobbles.	Generally suitable but loose deposits may require foundation changes.	Diggable. Poor stability. High rate of water inflow below water table.	Sand and gravel suitable.	Determine depth, extent and nature of the deposit including density and particle size distribution.
Sand and gravel	Medium dense to very dense	Plumpe Sand and Gravel Formation (undifferentiated), Loganhouse Gravel Member, Kirkbean Sand and Gravel Formation, Mouldy Hills Gravel Formation	Generally medium dense to very dense sand and gravel, with occasional silt or clay layers and cobbles occasional boulders in some formations.	Generally suitable	Diggable. Poor stability below water table. Boulders may need breaking	Suitable may need grading	Determine depth and extent, density and particle size distribution.

However, further up stream it is a loose to medium dense, slightly silty sand and gravel. Cable percussion drilling may produce ‘blowing’ conditions in saturated silty sand if the water balance is not maintained, and may reduce the measured in situ relative density values. Foundation design should take into consideration the local changes in the character of this deposit.

8.5 ENGINEERING CONSIDERATIONS

8.5.1 Foundations

Foundation conditions on superficial deposits are mixed due to their variability of lithology, density, strength or compactness.

8.5.1.1 Organic deposits

Peat and organic soils are generally very soft to firm, very or extremely plastic, have high moisture and are highly compressible. They provide poor foundation condition; building on these materials requires specialised foundations. These soils are usually avoided or removed prior to construction.

8.5.1.2 Fine-grained deposits

The suitability of clays and silts will depend on the strength or compactness and settlement characteristics. In general, these deposits have a thin upper crust of firmer material above softer material. If the stresses are transmitted to the softer material, foundation design in the firm crust must take into consideration settlement and strength of material below. Trenches for infrastructure may be unstable below the water table. Alluvium will tend to have near surface water tables and may be prone to flooding.

8.5.1.3 Coarse-grained deposits

In general loose, uniform dune sands must be stablised before construction. Old, stable dunes may be suitable but the foundations may need to be specially designed.

Loose to moderately dense granular deposits provide generally good foundation conditions; however, local density variation may result in differential settlement particularly in long buildings. The denser deposits are generally good for foundations unless they contain boulders, which may produce an uneven foundation surfaces and differential settlement.

Table 5 Engineering geological description and engineering considerations for mixed, fine and coarse soils of the Solway district.

Engineering geological unit	Characteristics	Geological unit	Description/ characteristics	Engineering considerations			
				Foundations	**Excavation**	**Engineering fill**	**Site investigation**
Fine and coarse mix	Firm – loose	Landslide deposits	Firm and loose to moderately dense generally derived from till formations	Unsuitable	Diggable. Stability and safety must be considered.	May be suitable see for tills below.	Determine depth, extent, shear planes and stability.
	Stiff/dense	Gretna Till Formation, Chapelknowe Till Formation, Langholm Till Formation	Firm to very stiff, occasionally laminated, sometimes fissured near surface, red or reddish brown sandy CLAY or sometimes compact SILT, with fine to coarse angular to rounded gravel, sometimes with cobbles. May contain beds of sand and gravel. Strength of cobbles and boulders variable	Generally good, but may be impaired if soft at surface or if there are water bearing lenses or layers. Possible uneven settlement if variable.	Diggable. Ponding of water. Short-term stability may be good but poor where highly fissure or in saturated silt and sand. Water-bearing coarse beds may reduce long-term stability	Generally suitable if moisture content is controlled. Cobbles and boulders will generally be screened out or crushed	Determine depth and extent, presence of sand and silt layers. Drilling difficult where cobbles and boulders are present. Base may be difficult to identify between boulders and bedrock.
Fine and coarse mix or fine and coarse	Firm to stiff. Moderately dense to dense	Kerr Moraine Formation, Dalswinton Moraine Formation	Moderately dense to dense sand gravel, compact silt, gravelly or sandy silt or clay, occasional and some cobbles and boulders	Generally good. Possible differential settlement because of boulders	Diggable, large boulders may need breaking	Generally suitable, large particles may need to be screened out or crushed	Determine depth, extent and variability. Drilling may be difficult where cobbles and boulders are present. Base may be difficult to differentiate from bedrock if boulders present.

8.5.1.4 MIXED DEPOSITS

Most of the mixed deposits provide a suitable foundation base. The softened, near surface interval of tills may have to be removed prior to construction. The landform of some deposits such as esker ridges and some moraine deposits may be unsuitable for building on unless levelled.

8.5.2 Excavation

All the superficial deposits are diggable, but excavation may be very difficult in the high permeability coarse material, and in the soft, fine-grained deposits below the water table. Loose, fine-grained sand will also form unstable sides. All manned excavations greater then 0.8 m deep require support, and loose coarse-grained and soft fine-grained soils may require support as they are dug. Dewatering may be needed to stablise or allow work in excavations, but consideration should be given to potential shrinkage of soft clay and peat caused by water lowering. Boulders may require breaking prior to removal.

8.5.3 Engineering fill

Most of these materials are generally suitable for use as fill. However, those containing organic matter i.e. peat, salt marsh and parts of alluvium are not suitable. Deposits from the estuary will contain salt, and whilst sand and gravels can be washed, it may not be practical to desalinate clays and silts. Selection, grading or mixing may be needed depending on the fill requirement.

8.5.4 Site investigation

It is important to ascertain the extent, depth and variation of each deposit on site, and the likely zone influenced by the construction. In some areas, meltwater channel and glacial gouge may deepen the expected depth of investigation (see BGS, 2005, 2006). Cable percussion and pitting are generally used to drill and sample superficial deposits. Larger diameter tools may be required if cobbles are likely. Very coarse particles in mixed deposits may impede cable percussion drilling, and emplacement of casing in deeper investigations may require larger plant. Boulders may require breaking and can be confused with bedrock, which may compromise construction. Pits will provide good near surface indication of lithological variability, but in soft and loose deposits the sides of these excavations are likely to be unstable particularly if beneath the water table.

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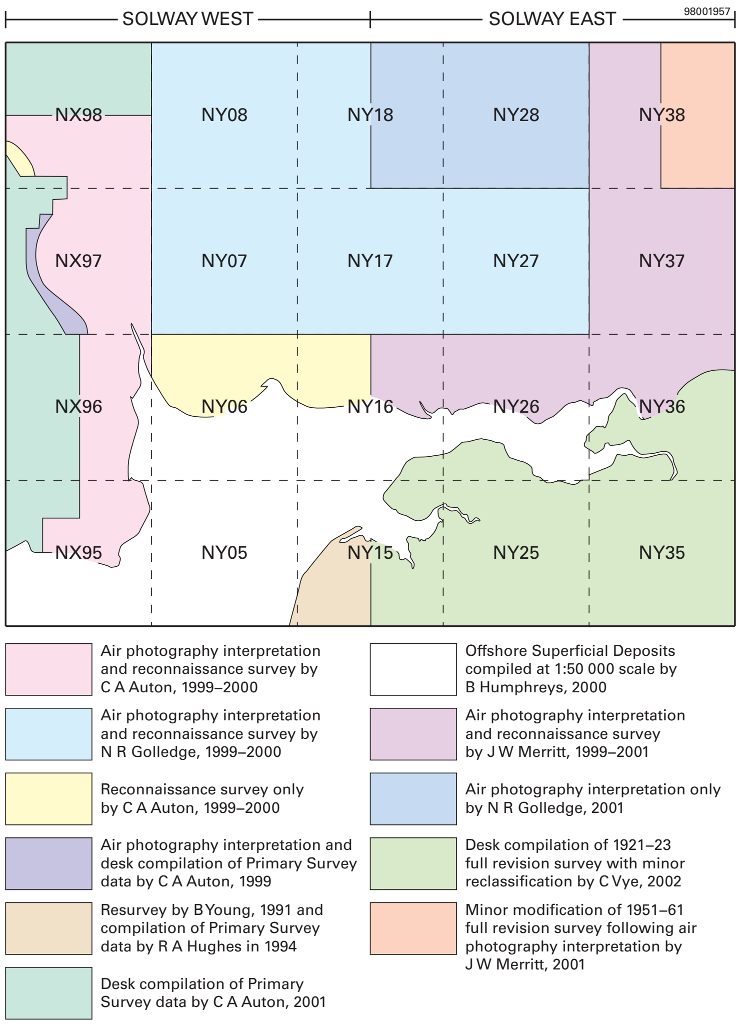
Figure 1 Sources used in the compilation of the published maps for the Solway area.



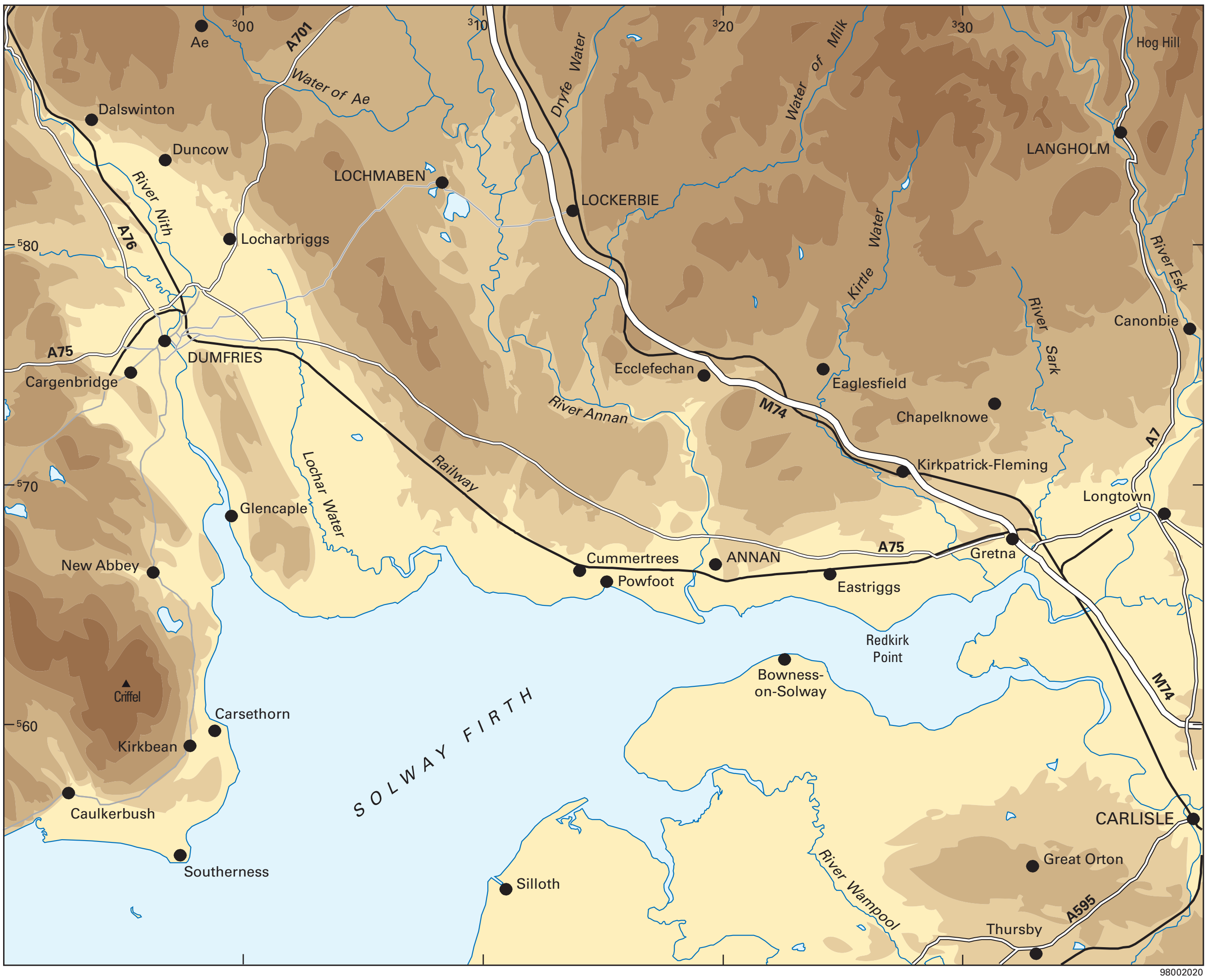
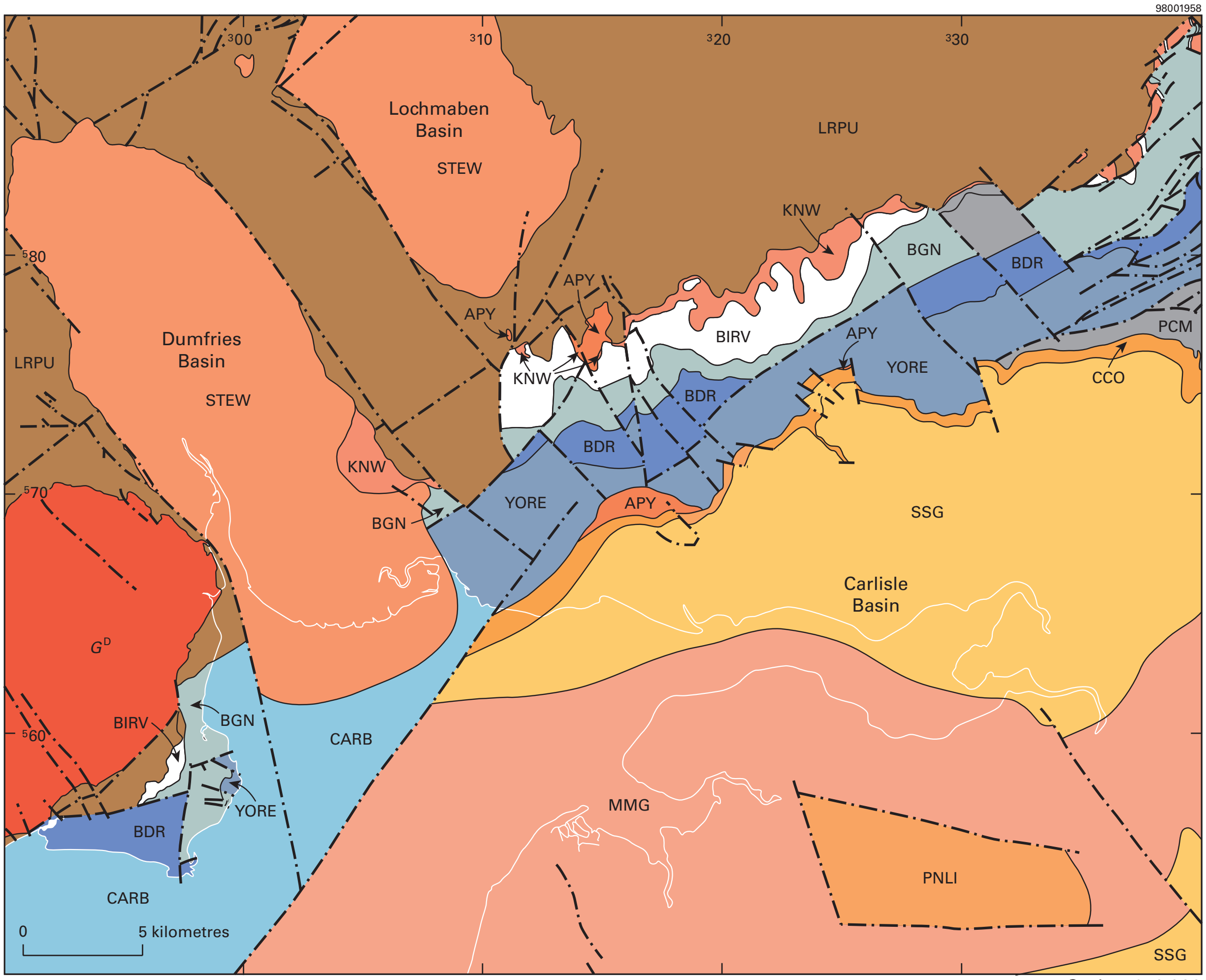


Figure 2 Topographical map showing main localities and physiography.



Scale 1:250 000

SEDIMENTARY ROCKS

TRIASSIC–JURASSIC

PNLI	Lias and Penarth groups Mudstone and thin muddy limestone beds
MMG	Mercia Mudstone Group Mudstone and siltstone, red, grey and green
SSG	Sherwood Sandstone Group Sandstone, red and grey with partings of red mudstone
CCO	Cumbrian Coast Group Mudstone and sandstone, red and grey

PERMIAN

APY	Appleby Group Sandstone and breccia
STEW	Stewartry Group Sandstone and breccia

CARBONIFEROUS

PCM	Pennine Coal Measures Group Mudstone, siltstone, sandstone and coal
YORE	Yoredale Group Mudstone, siltstone, sandstone, limestone and coal
BDR	Border Group Sandstone, siltstone and mudstone
BGN	Ballagan Formation Sandstone, siltstone, limestone and dolostone (Inverclyde Group)
BIRV	Birrenswark Volcanic Formation Basalt (Inverclyde Group)
KNW	Kinnesswood Formation Sandstone (Inverclyde Group)
CARB	Sedimentary rocks undifferentiated

SILURIAN

LRPU	Riccarton, Hawick and Gala groups Tectonostratigraphic formations comprising wacke, siltstone and fissile mudstone

IGNEOUS ROCKS

DEVONIAN

G^D	Granodiorite, Criffel–Dalbeattie Pluton (Galloway Granite Suite)

Major fault

Bedrock boundary

Figure 3 Bedrock geology of the Solway area.

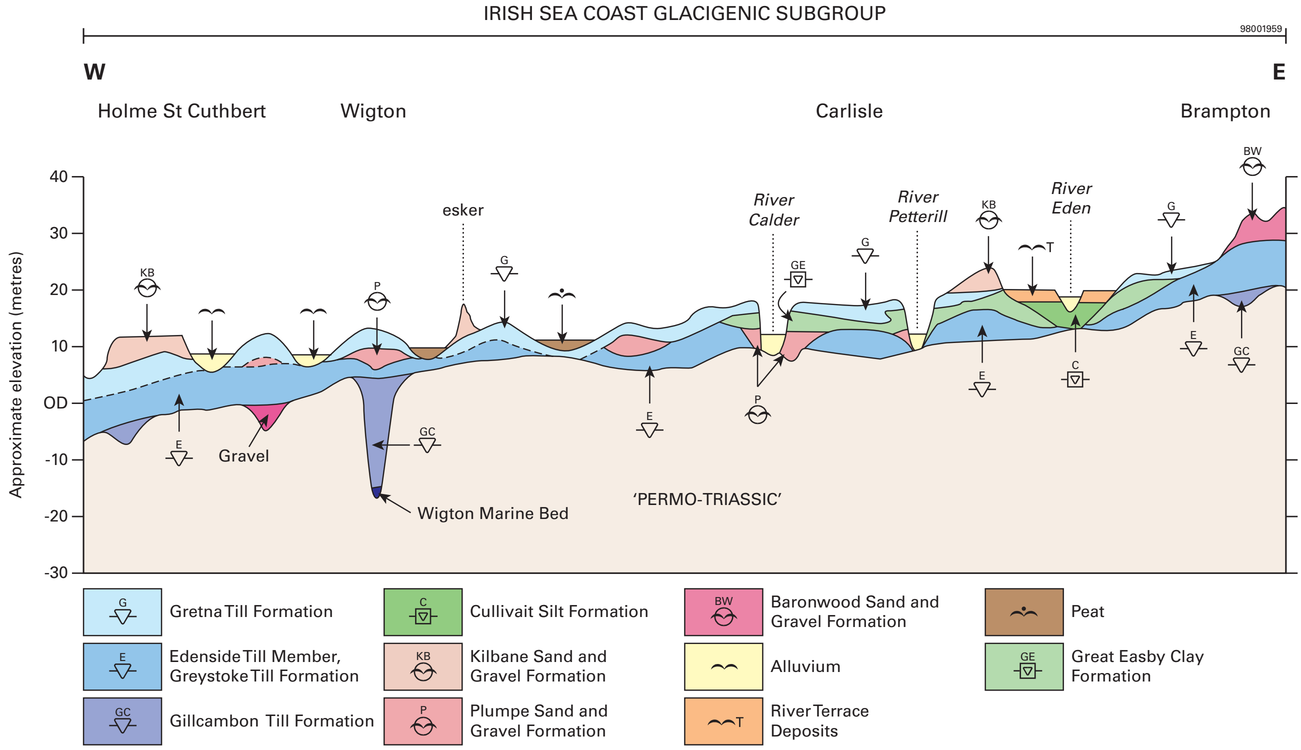


Figure 4 Schematic section across the Solway lowlands and Carlisle showing lithostratigraphical relationships.

Figure 5 British Quaternary chronostratigraphy and marine oxygen isotope stages (MIS).

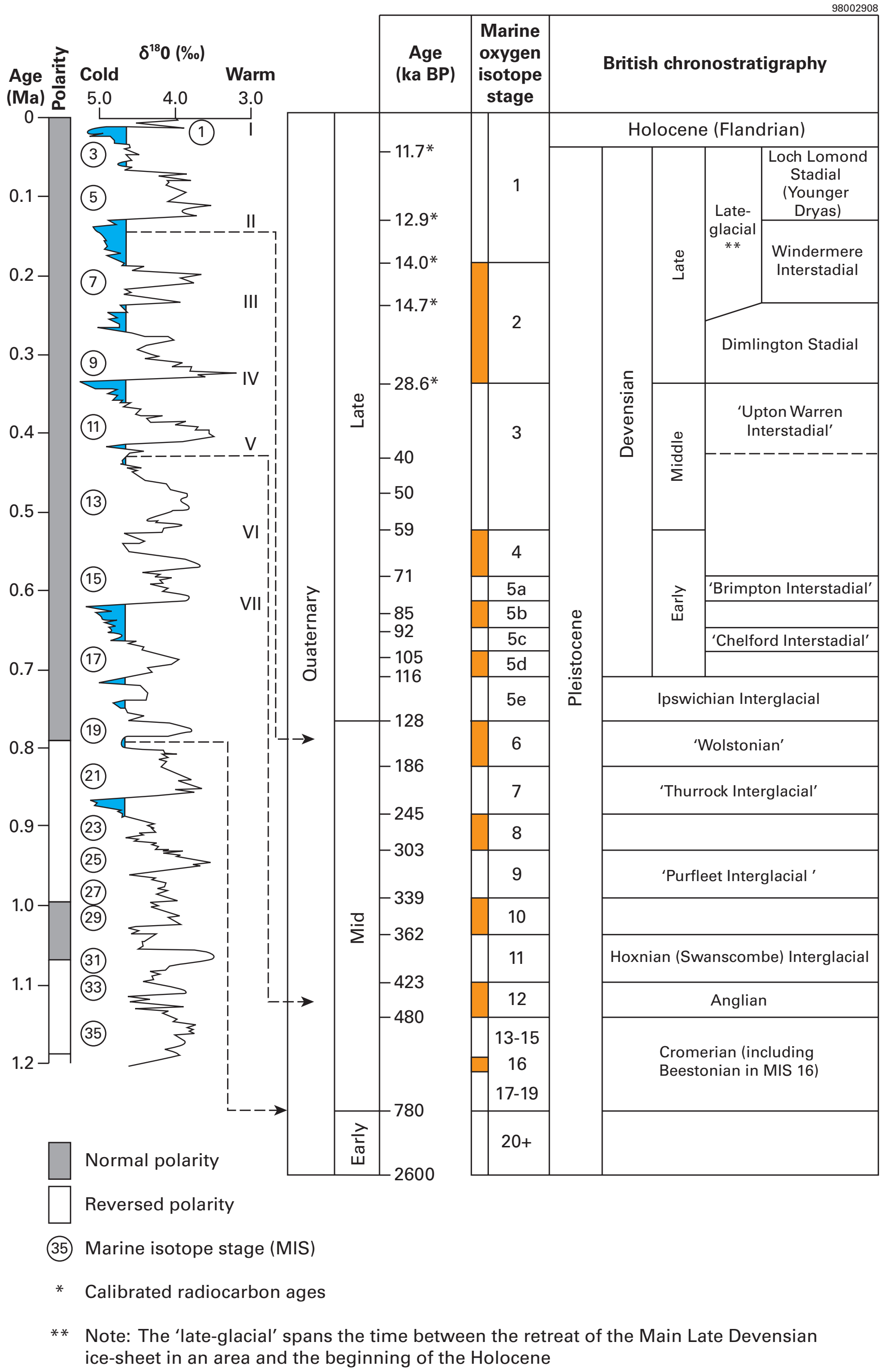
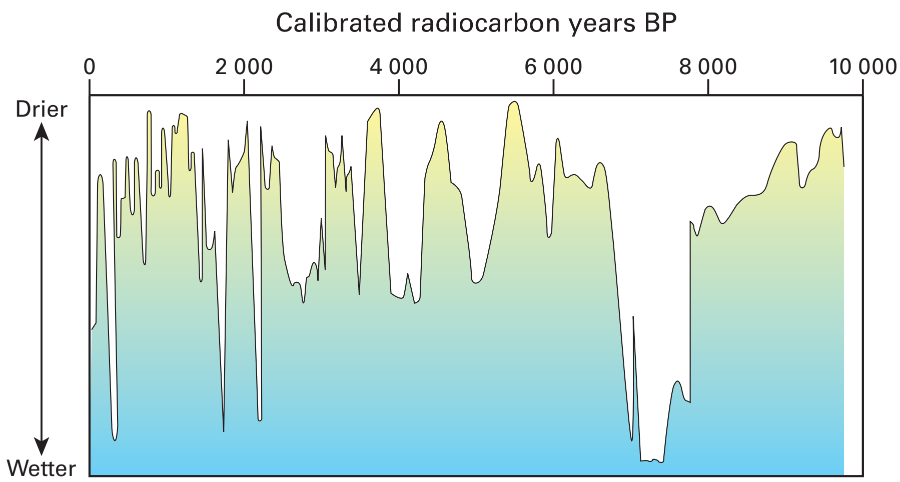


Figure 6 Changes in mire surface wetness and implied rainfall during the Holocene at Walton Moss, Cumbria (after Hughes et al., 2000).



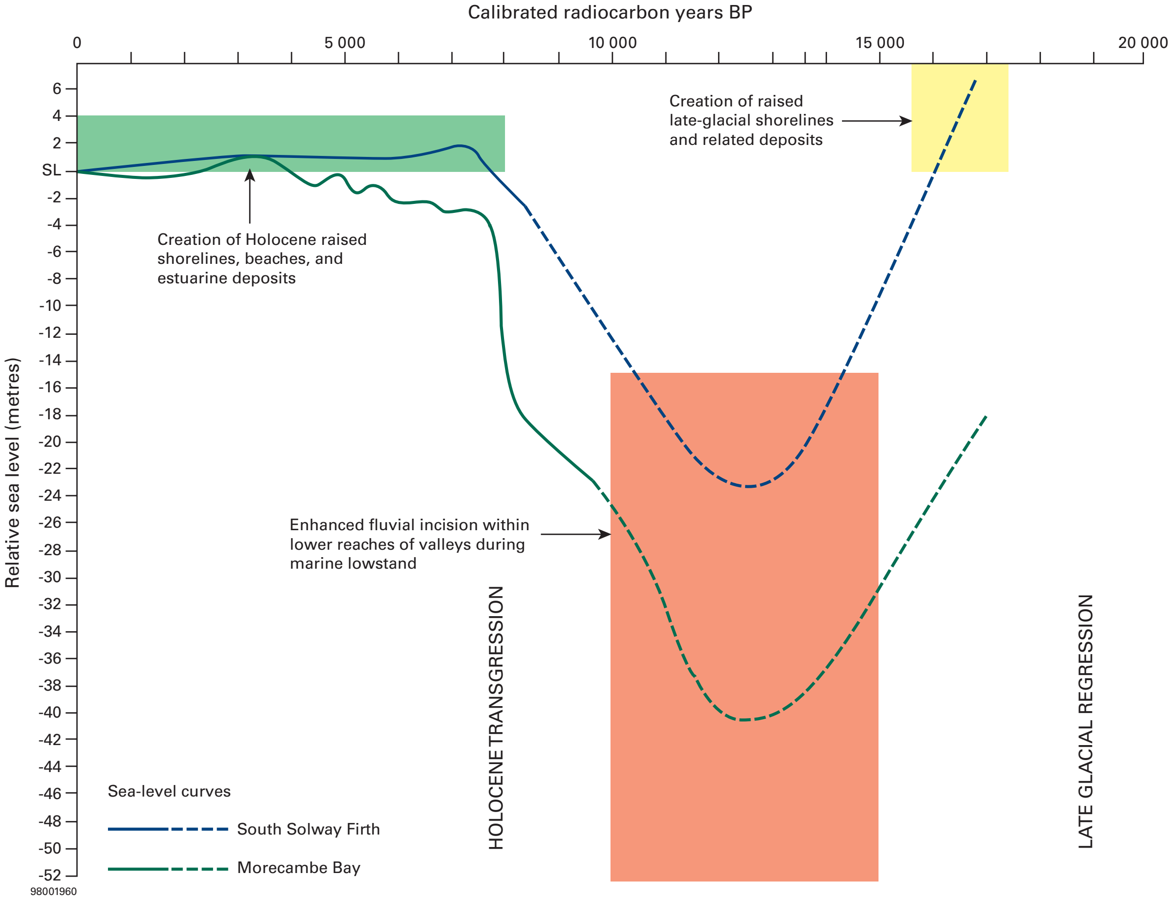
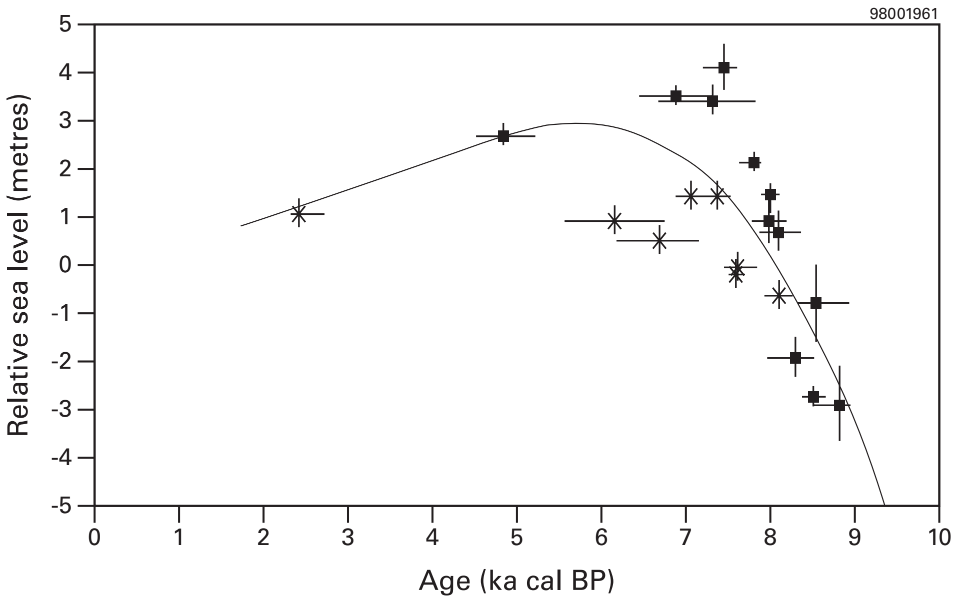


Figure 7 Representative relative sea-level curves for the late-glacial and Holocene. Solid lines are based on detailed biostratigraphical evidence (after Zong and Tooley, 1996); broken lines are based on predictive glacio-hydroisostatic modelling (after Lambeck and Purcell, 2001).

Figure 8 Detailed Holocene relative sea-level curve for the inner Solway Firth (after Lloyd et al., 1999). Squares denote index points on the northern shore; stars those on the southern shore.



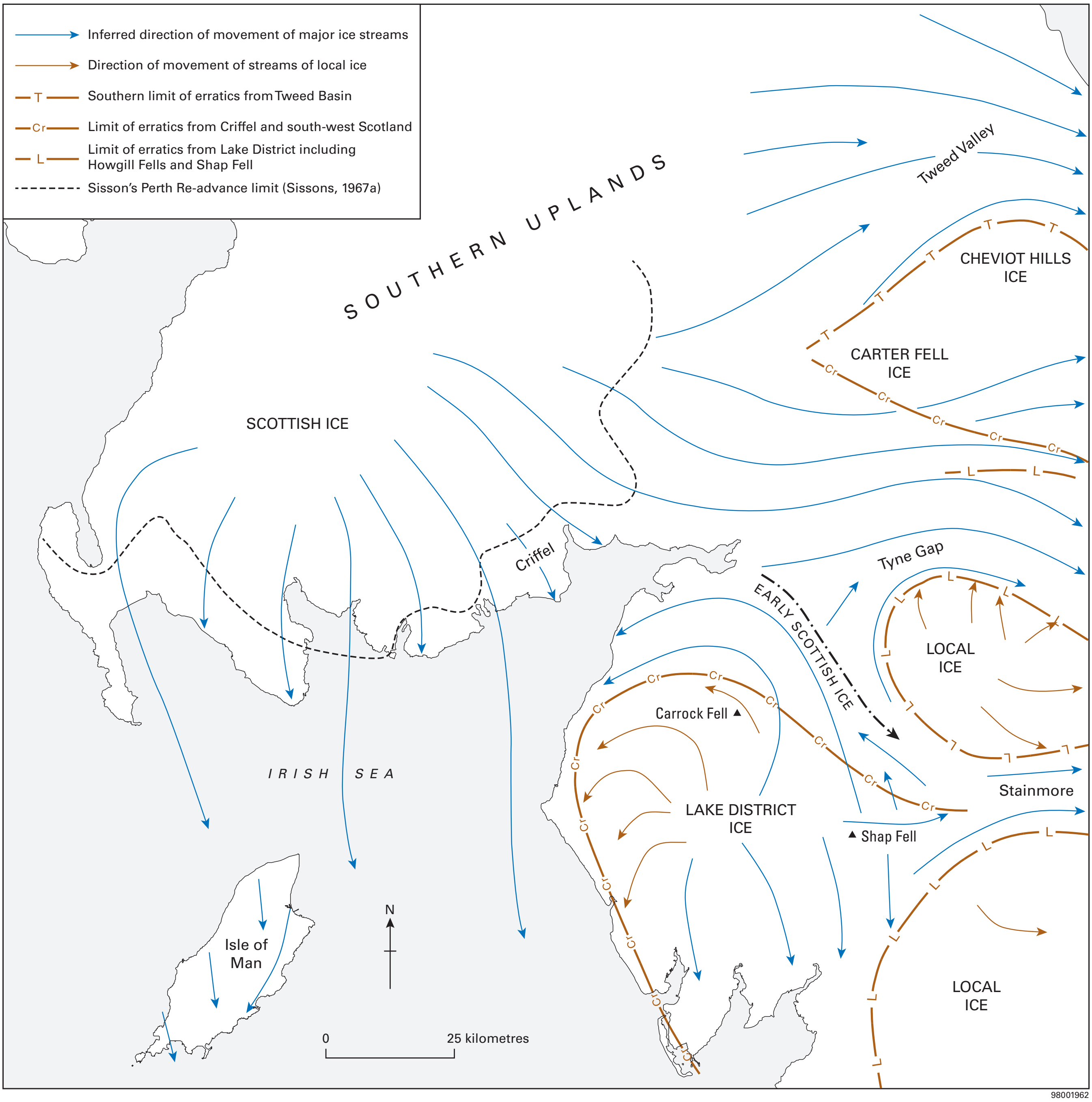


Figure 9 General pattern of ice flow around the Solway Firth during the last glaciation (after Taylor et al., 1971).

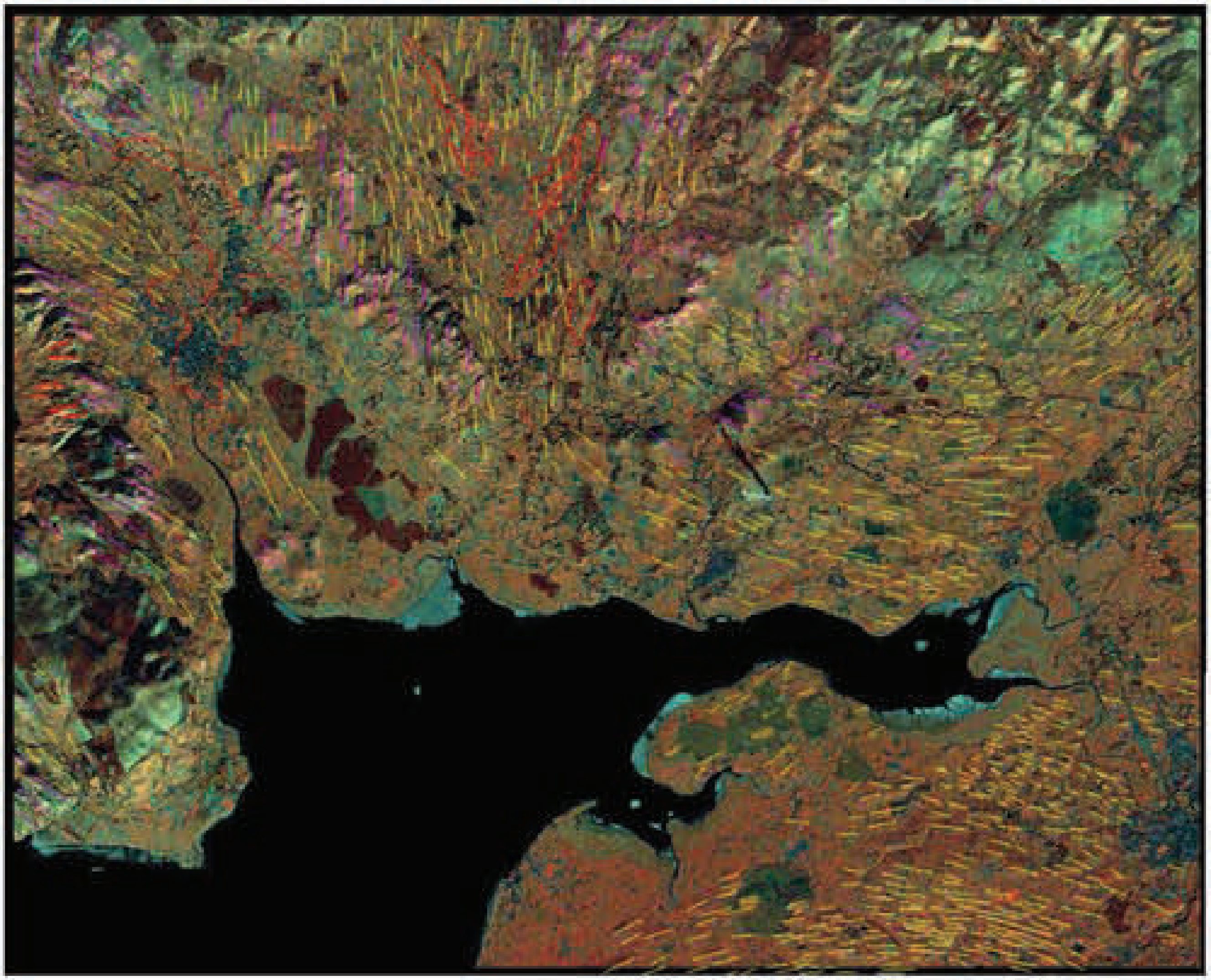


Figure 10 Winter Landsat-5 Thematic Mapper satellite image of the Solway district (comprising bands 4, 5 and 7), reprocessed and interpreted by C J Jordan (BGS Remote Sensing Unit). Field of view is about 25 km across. Purple lines - crag and tail; yellow lines - drumlin crest; red polygons - hummocky ground; red lines - roche moutonnées. *Enhanced imagery © BGS NERC.*

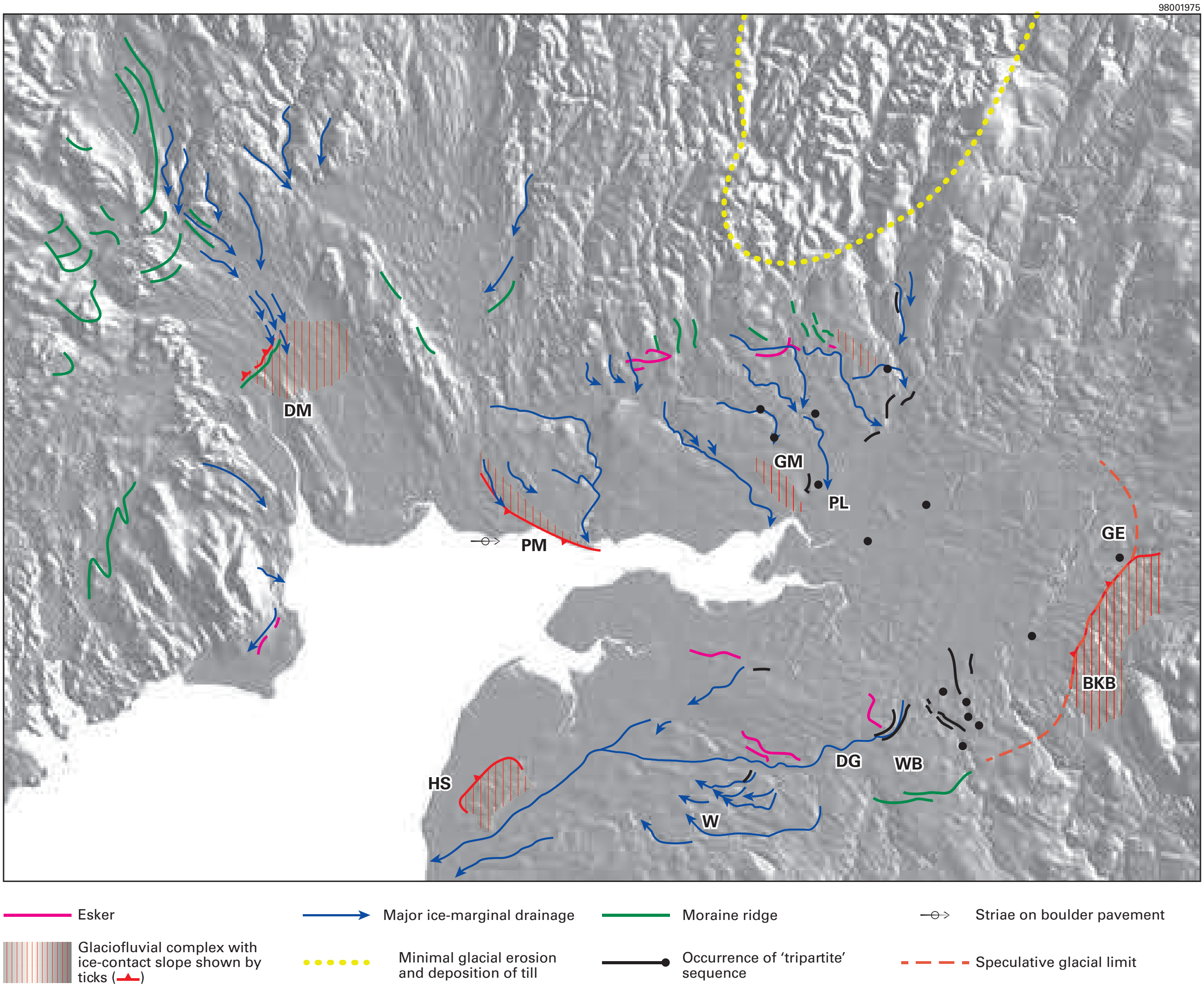


Figure 11 Evidence for the pattern of deglaciation following the Scottish Re-advance in the Solway district together with localities revealing a 'tripartite' sequence. BKB, Brampton Kame Belt; DG, Dalston Gap; DM, Dumfries Moraine of Charlesworth (1926a, b); GE, Great Easby site; HS, Holme St Cuthbert fan; GM, Gretna Moraine; PL, Plumpe Farm site; PM, Powfoot Moraine of Charlesworth (1926a, b); W, Wizza Beck channels; WB, Wreay–Buckabank limit. *NEXTMap Britain elevation data from Intermap Technologies.*

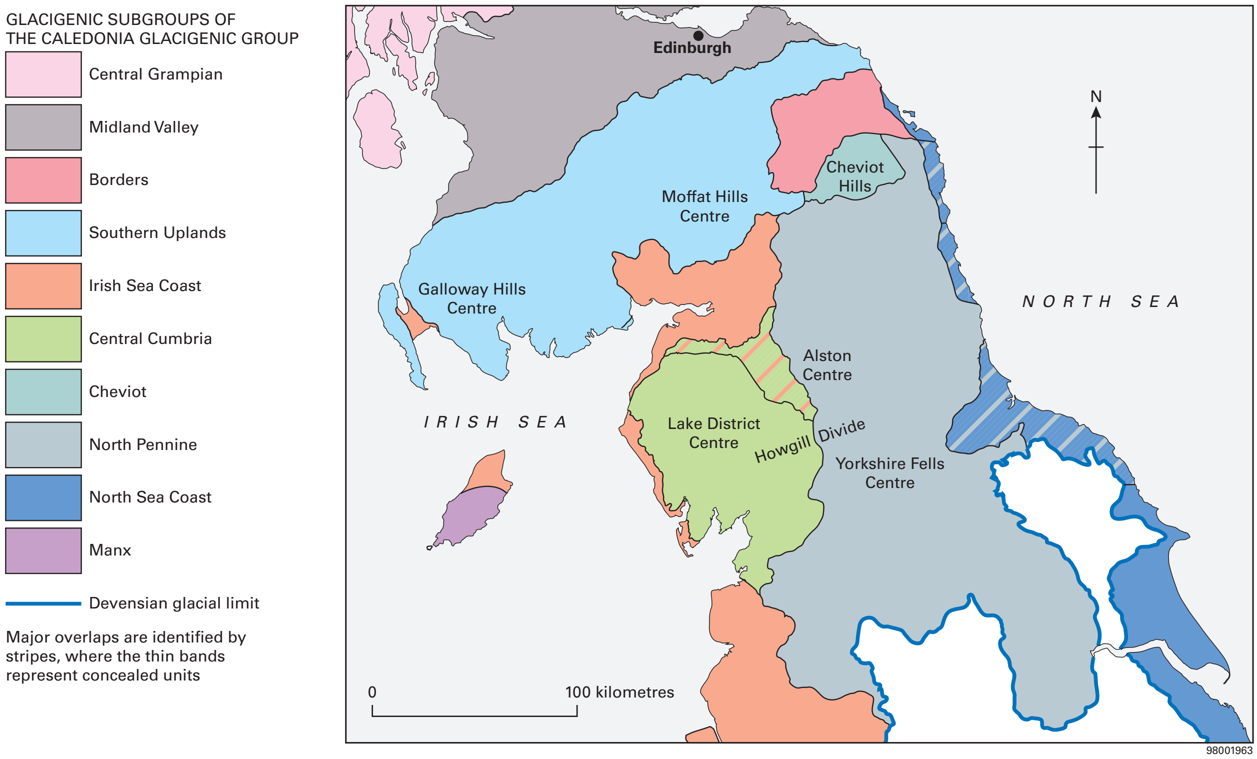


Figure 12 Distribution of glacigenic subgroups. The geographical boundaries beyond the study area are approximate, but will be refined as knowledge of the distribution of defining formations of till is improved (see McMillan, et al. 2005; 2011).

Figure 13 Glacial striae on limestone breccia exposed in Kelhead Quarry [NY 1511 6932] (ME 267), 5 km north-west of Annan. The striae (azimuth 190º) are overlain by up to 5 m of moderate reddish brown, stony sandy clay diamicton (**Gretna Till Formation**) and were presumably created by southward flowing ice (P543572).

Figure 14 Section behind cowshed at Plumpe Farm [NY 3344 6813] (ME 263), 2 km north-east of Gretna.

The section (a) is capped by 1.5 m of reddish brown, matrix-supported, clayey, fine-sandy diamicton (**Gretna Till Formation**). The presence of shear planes and the relatively low dispersion of clasts in the diamicton suggest that it is a deformation till. This interpretation is reinforced by the presence below of a 0.5 m thick unit (above the spatula) of 'glacitectonite' formed of very compact, interlaminated sand, silt, clay and diamicton. The laminae within this unit are laterally discontinuous, have gradational contacts, some are highly attenuated, yet ripple cross-lamination occurs locally together with some soft sediment deformation structures. Wet based subglacial deformation is implied. The glacitectonite grades down (beneath the spatula) into over 2.5 m of reddish brown, silty, fine-grained sand that coarsens downwards (**Plumpe Farm Sand Membe**r of the **Plumpe Sand and Gravel Formation**). Blocks of sediment (b) were collected within 10 cm square aluminium Kubiena tins from the base of the till and through the glacitectonite for micromorphological analysis (Phillips et al., 2007). Spatula is about 30 cm long. P543597 and P543823.

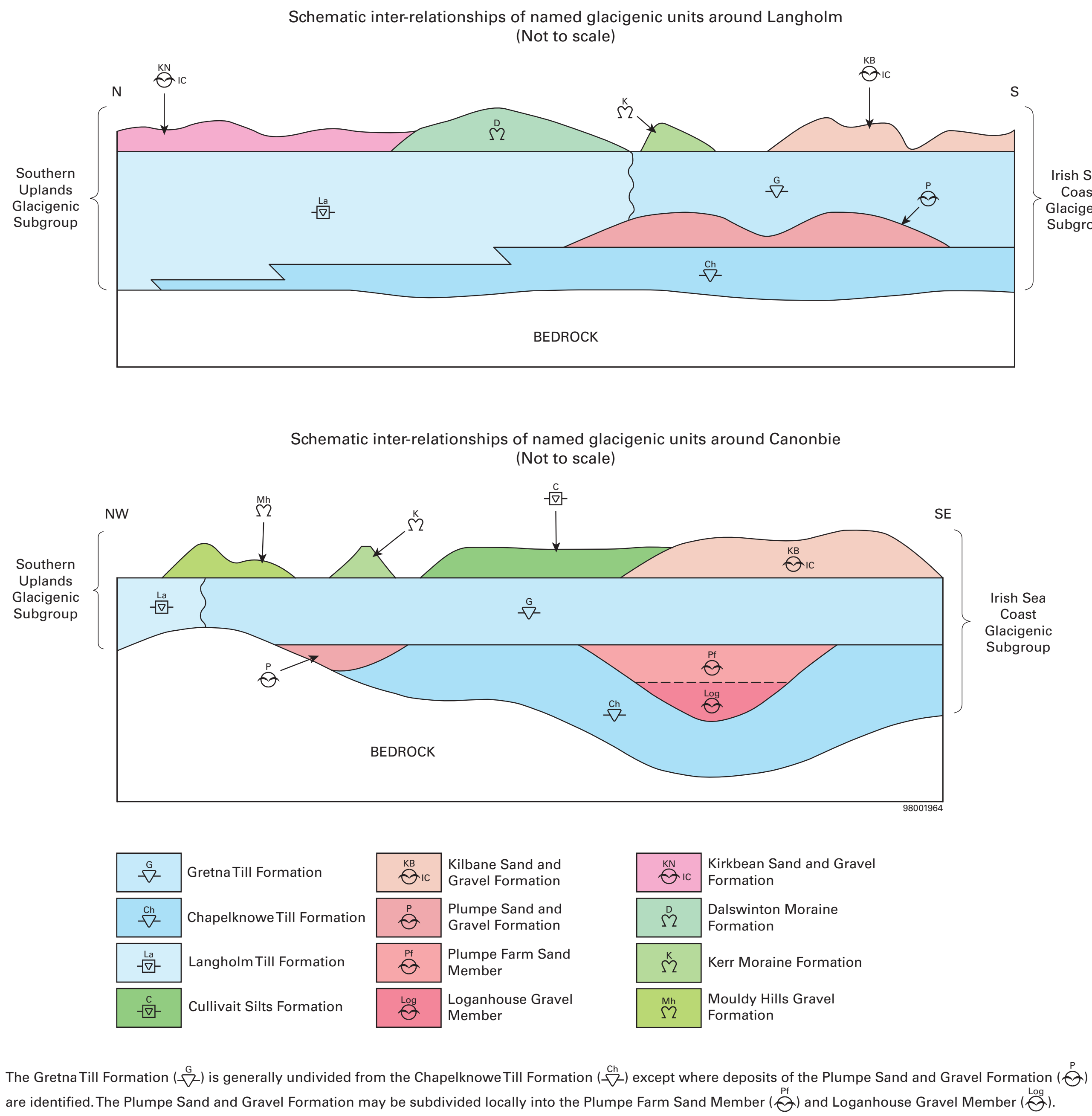


Figure 15 Schematic cross-sections depicting 'tripartite sequences' in the Langholm and Canonbie areas (from BGS, 2006a).

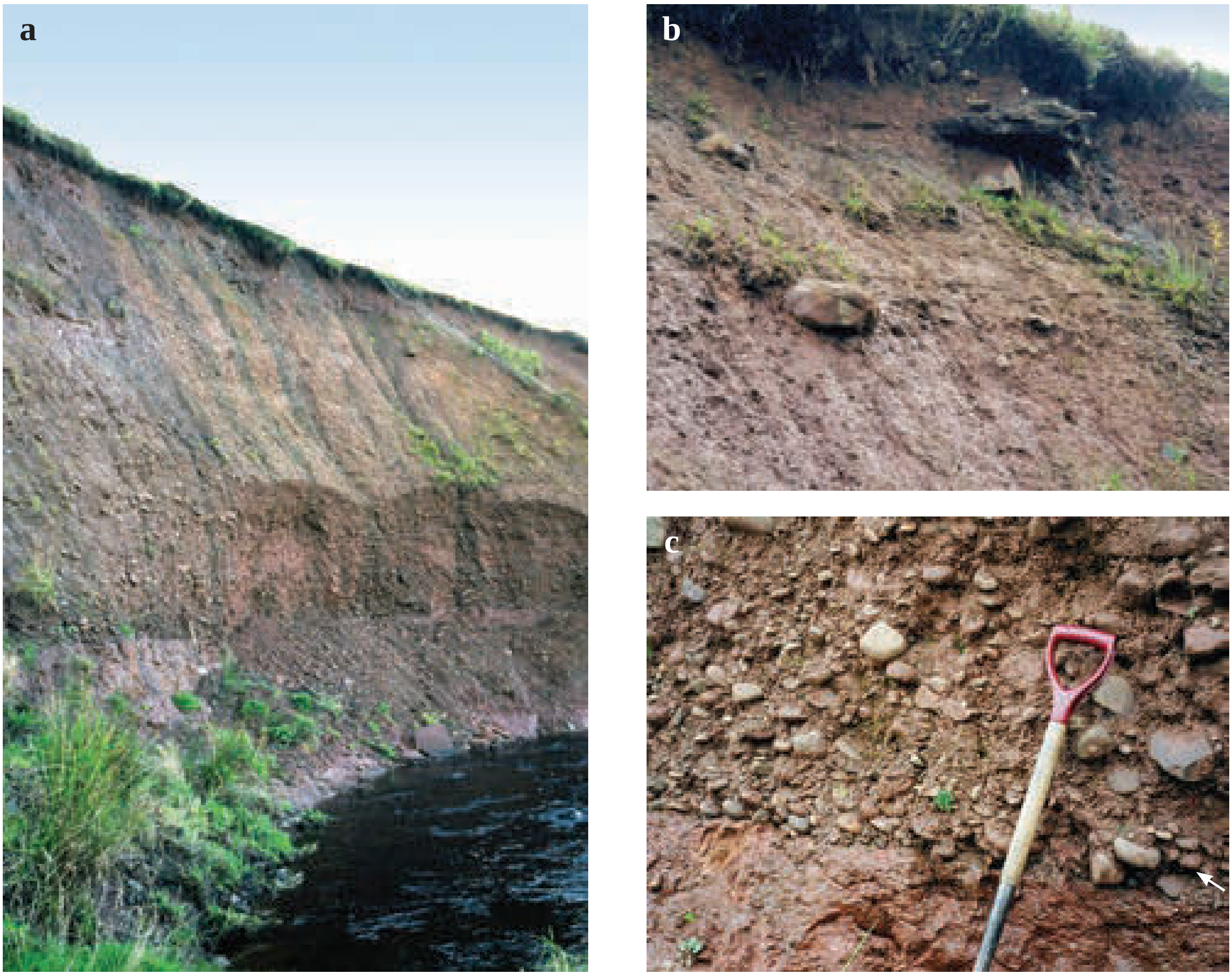


Figure 16 River cliff section of the Logan Burn [NY 3110 7181] (ME 300), 2 km south of Chapelknowe, exposing a 'tripartite sequence'.

The 7 m-high section (a) is capped by 2.5 m of very stiff, reddish brown, massive to crudely stratified, matrix-supported, sandy silty clay diamicton with some large boulders and slabs of red sandstone (**Gretna Till Formation**). The till (b) grades down into very dense, clast-supported gravel with a matrix of reddish brown, clayey, fine to coarse-grained sand and secondary infillings of red clay (**Loganhouse Gravel Member** of the **Plumpe Sand and Gravel Formation**). The gravel (c) rests unconformably on over 2 m of extremely stiff, reddish brown and orangey yellow mottled, massive, fissile, matrix-supported, sandy silty clay diamicton (**Chapelknowe Till Formation**). Many clasts of siltstone and amygdaloidal lava in the lower till are weathered. Spade 0.9 m long. P543828, P543825 and P543826.

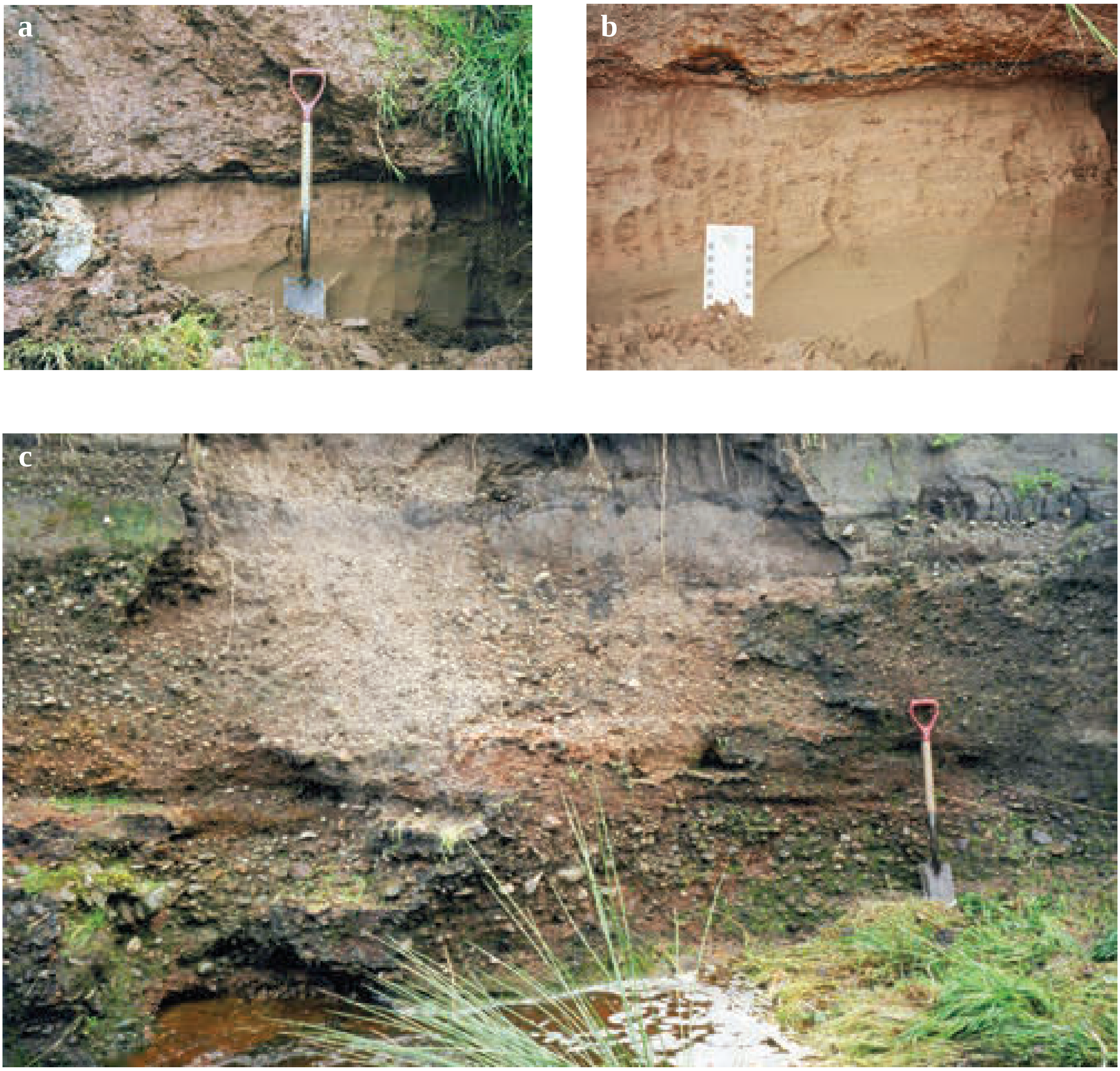


Figure 17 River cliff section of the Closses Burn [NY 3852 7610] (ME 304), 1 km west of Canonbie.

The logged sequence includes over 1.2 m of very stiff, moderate reddish brown, matrix- supported, sandy silty clay diamicton with abundant clasts of red sandstone (**Gretna Till Formation**). The till has a sharp, planar, gently undulating contact with an underlying 0.6 m thick unit of yellowish brown, fine- to medium-grained sand (a). The uppermost 0.3 m of the sand becomes increasingly sheared, silty and clayey upwards parallel to the base of the till and is interpreted as a glacitectonite formed during the emplacement of the overlying till (b). The sand rests on over 2 m of dense, partially cemented, well stratified, clast-supported gravel (c) (**Loganhouse Gravel Member** of the **Plumpe Sand and Gravel Formation**). P543814, P543811 and P543812.

Figure 18 Exposures in linear, east-south-east orientated ridges of glaciofluvial ice-contact deposits [NY 1570 6565] (ME 266), 1 km east of Powfoot.

(a) Localised disturbance of otherwise mainly horizontally-bedded, relatively well-sorted and rounded sand and gravel, looking east. Note poorly sorted, frost-shattered, angular gravel has been dragged down at the margin of the central basin and the monoclinal structure to the south, which is formed of sheared silty pebbly sand cut by an extensional system of overturned conjugate microfaults. Section about 2.5 m high. (b) Sheared, overturned, silty fine-grained sand and well sorted granule gravel, looking north-west. Beds of well-sorted gravel and laminated silty sand lie to the right, dipping steeply towards the north-east. Spade 0.9 m long. The structures displayed in these adjacent sections were probably formed at the northern margin of an active glacier that splayed out into the Solway from the valley of the Nith. P543582 and P543580.

Figure 19 Section in terraced glaciofluvial deposits [NY 1583 6575] (ME 270), 1 km east of Powfoot, adjacent to the ridges exposed in the previous figure.

The exposure (a) reveals gravel with many angular, frost-shattered clasts resting on gravel that is more poorly sorted, but containing fewer angular clasts. Close-ups (b) and (c) are to the left and right of the 0.9 m-long spade respectively. P543586, P543585 and P543584.

Figure 20 . Sections towards the base of the Pleistocene sequence exposed in the valley of the Hoghill Burn [NY 3820 8905] (ME 312, 313), 5 km north of Langholm.

The **Hoghill Gravel Bed** (a) at its type locality, a gelifractate formed of angular, unabraded fragments of local wacke sandstone and siltstone. The bed lies beneath 12 m of clast- to matrix-supported, wacke-dominated diamicton (**Langholm Till Formation**) that becomes reddish brown towards its base. Section about 90 m downstream (b), apparently stratigraphically below the Hoghill Gravel Bed, revealing pale yellowish brown, extremely compact, wacke-dominated, clast- to matrix-supported diamicton with a boulder pavement at its top. Spade 0.9 m long. P543798 and P543796.

Figure 21 Red till exposed in a river cliff of the Logan Water [NY 3169 8235] (ME 309), 5 km south-west of Langholm, exposing the base of the **Langholm Till Formation**.

This very stiff, moderate reddish brown diamicton contains boulders of yellow and white Carboniferous sandstone, grey granodiorite and pink granite in addition to wacke sandstones and siltstones, which become dominant higher in the till sequence in the area. In this section the till is truncated and overlain by gravel of a river terrace. Boulder is about 0.5 m long. P543800.

Figure 22 The Bigholms Burn Site of Special Scientific Interest [NY 3141 8131] (ME 306), 6 km south-west of Langholm.

The main section (a), looking north-east, is cut into a raised peat bog and associated deposits of the **Blelham Peat Formation**. It currently exposes up to 2.2 m of fibrous peat with stumps and branches of birch (**Racks Peat Member**). The peat rests on up to 1.5 m of mainly clast-supported, trough cross-stratified gravel (b) containing lenses of grey, clayey, fine-medium-grained sand and sandy silt (**Bigholms Burn Gravel Member**). These lenses include organic laminae and beds of peat up to 5 cm thick. The gravel rests on firm to stiff, pale grey sandy silt containing disseminated organic material and compressed peat. The gravel formed during the Loch Lomond Stadial and it incorporates organic material of Windermere Interstadial age reworked from the underlying unit (Gordon, 1993a). P543810 and P543806.

Figure 23 Commercial peat extraction at Nutberry Moss [NY 264 684], 3 km north-east of Eastriggs. P543569.

Figure 24 Slope deposits exposed at Shaw [NY 3081 8354] (ME 307), 5 km west-south-west of Langholm.

(a) Peaty soil overlies up to 0.8 m of loose, angular, clast-supported fragments of wacke siltstone. The unit is interpreted as a gelifractate, but with evidence of post-depositional soil creep. The underlying unit, up to 0.9 m thick, is composed of very compact, crudely stratified, clast-supported diamicton containing angular fragments of wacke siltstone and a matrix of pale grey, silty, clayey fine-grained sand. The material grades down into frost-shattered or hydrofractured wacke siltstone and is probably primarily of subglacial origin, although partially redistributed downslope. Close-up (b), overlapping to right, reveals the two units separated by up to 0.4 m thick lenses of massive, clast- to matrix-supported diamicton (above 0.9 m-long spade in lower photo) with a pale yellowish brown, silty, clayey fine-grained sand matrix. These lenses were probably emplaced as cohesive debris flows (gelifluctate). Although deposits such as those illustrated here are widespread on hillsides within the Southern Uplands, it has generally proved impractical to map Head deposits. P543804 and P543802.

Figure 25 Head gravel (gelifractate) exposed in a river cliff of the Logan Water [NY 3102 8302] (ME 308), near Shaw, 5 km west-south-west of Langholm.

This 2 m-thick deposit overlies over 8 m of pale yellowish brown diamicton of the Langholm Till Formation at this section. P543801.

Figure 26 Possible late Devensian raised beach deposits at Dornockbrow [NY 2331 6517] (ME 264), 1.5 km south-west of Eastriggs.

The cliff section (a) is capped by up to 1 m of very dense, partially cemented, clast-supported, poorly sorted gravel with angular and subrounded to rounded clasts, and lenses of fine- to medium-grained sand. Platy to tabular clasts predominate, suggesting good shape sorting, indicative of beach processes. The cliff cuts into a bench feature, possibly a raised shoreline, standing at about 6 m above the modern beach. The rest of the cliff is cut into reddish brown stony diamicton assigned to the **Gretna Till Formation**. The gravel rests on an undulating erosion surface, which is mostly cut into a 0.5–1 m thick unit of reddish brown pebbly clay. The latter is probably a periglacial deposit, because it contains vertical fissuring, convolutions and oversteps across both till and some broad channels cut into till, up to 1.5 m deep, filled with very poorly sorted cobble gravel. This gravel is more rounded than the supposed beach gravel above, and is probably glaciofluvial in origin. The convolution structure (b), in which the supposed beach gravel has sagged into the underlying pebbly clay unit, measures 0.8 m wide and 1 m deep. P543591 and P543590.

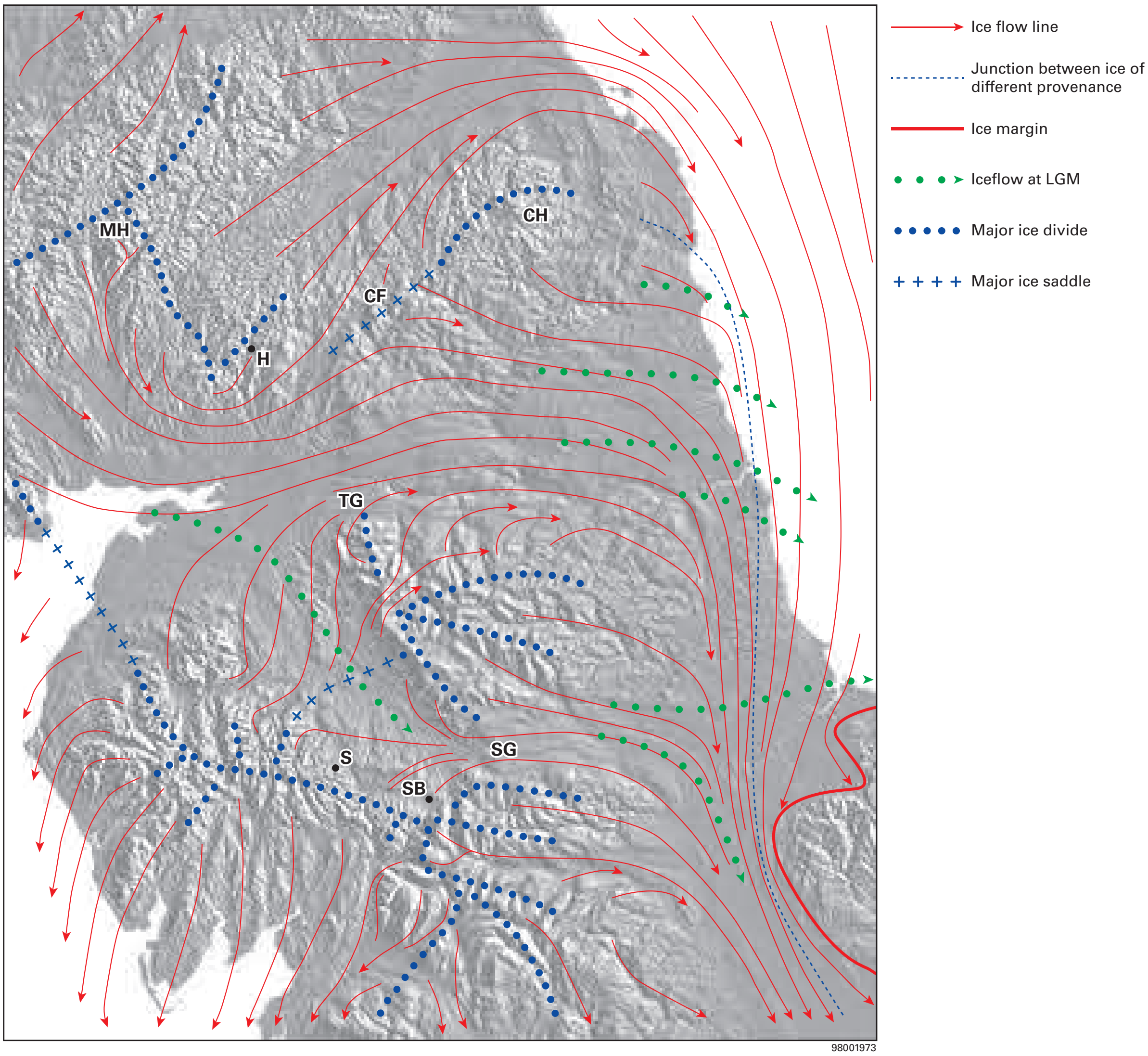


Figure 27 Speculative reconstruction of the last ice-sheet at about the Last Glacial Maximum (LGM), when Scottish ice had ceased flowing across Stainmore and Scandinavian ice had advanced into the central North Sea Basin, forcing ice from the Pennines and Tweed basin to flow into the Vale of York (after Stone et al., 2010). CF, Carter Fell; CH, Cheviot Hills; H, Hoghill Burn site; MH, Moffat Hills; S, Shap; SB, Scandal Beck site; SG, Stainmore Gap; TG, Tyne Gap. *NEXTMap Britain elevation data from Intermap Technologies.*

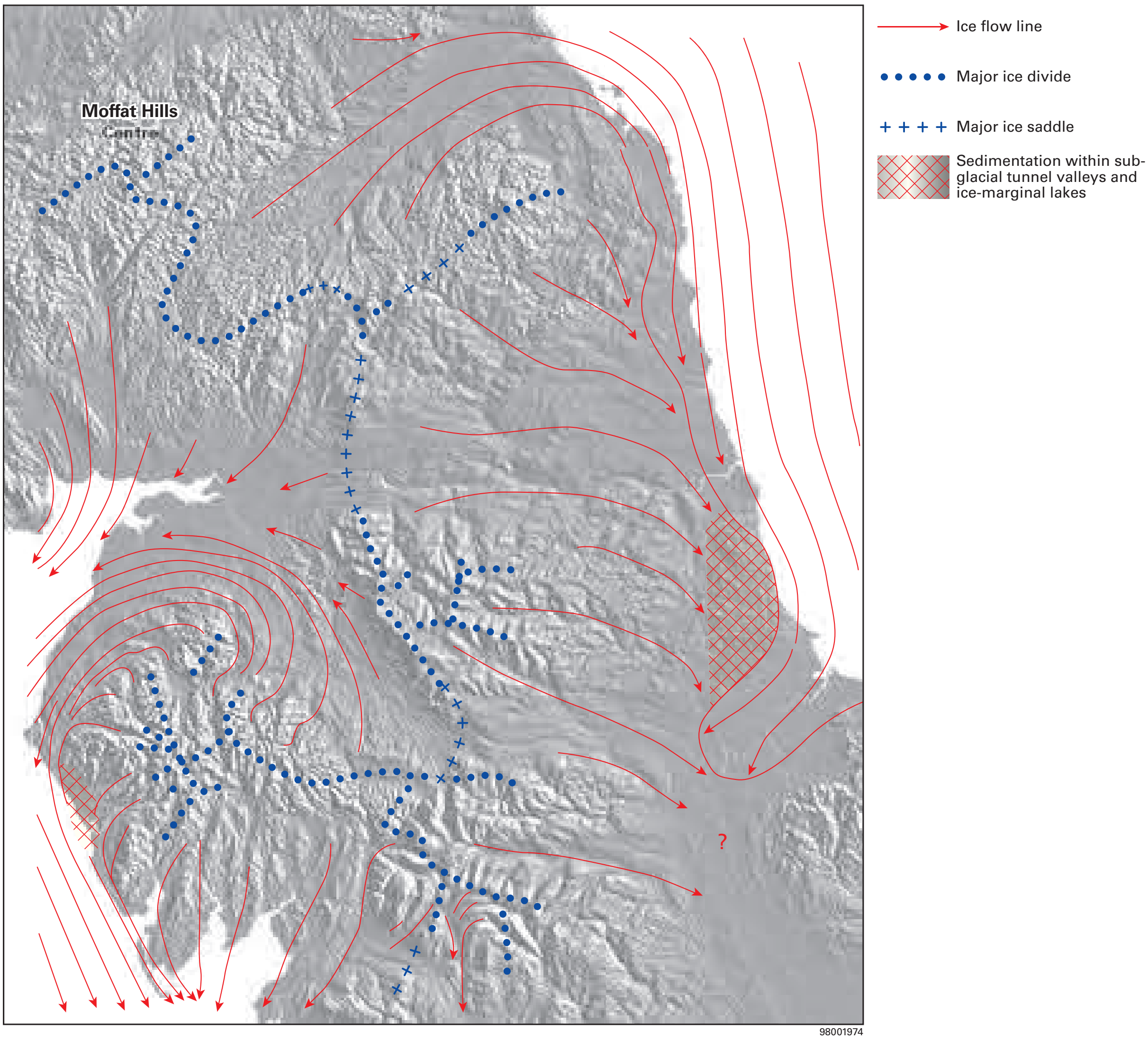


Figure 28 Speculative reconstruction of the last ice-sheet after a major glacial reorganisation that allowed drawdown of the Irish Sea ice stream and headward scavenging from ice covering the Solway Lowlands and Vale of Eden (after Stone et al., 2010). Exact correlation of events across the Pennines is unknown, but North Sea ice pushed farther into the Teesside lowlands once ice from the Lake District ceased flowing across Stainmore. Subglacial glaciofluvial deposition probably occurred within tunnel valleys beneath the Durham lowlands prior to the creation of Glacial Lake Wear. *NEXTMap Britain elevation data from Intermap Technologies.*

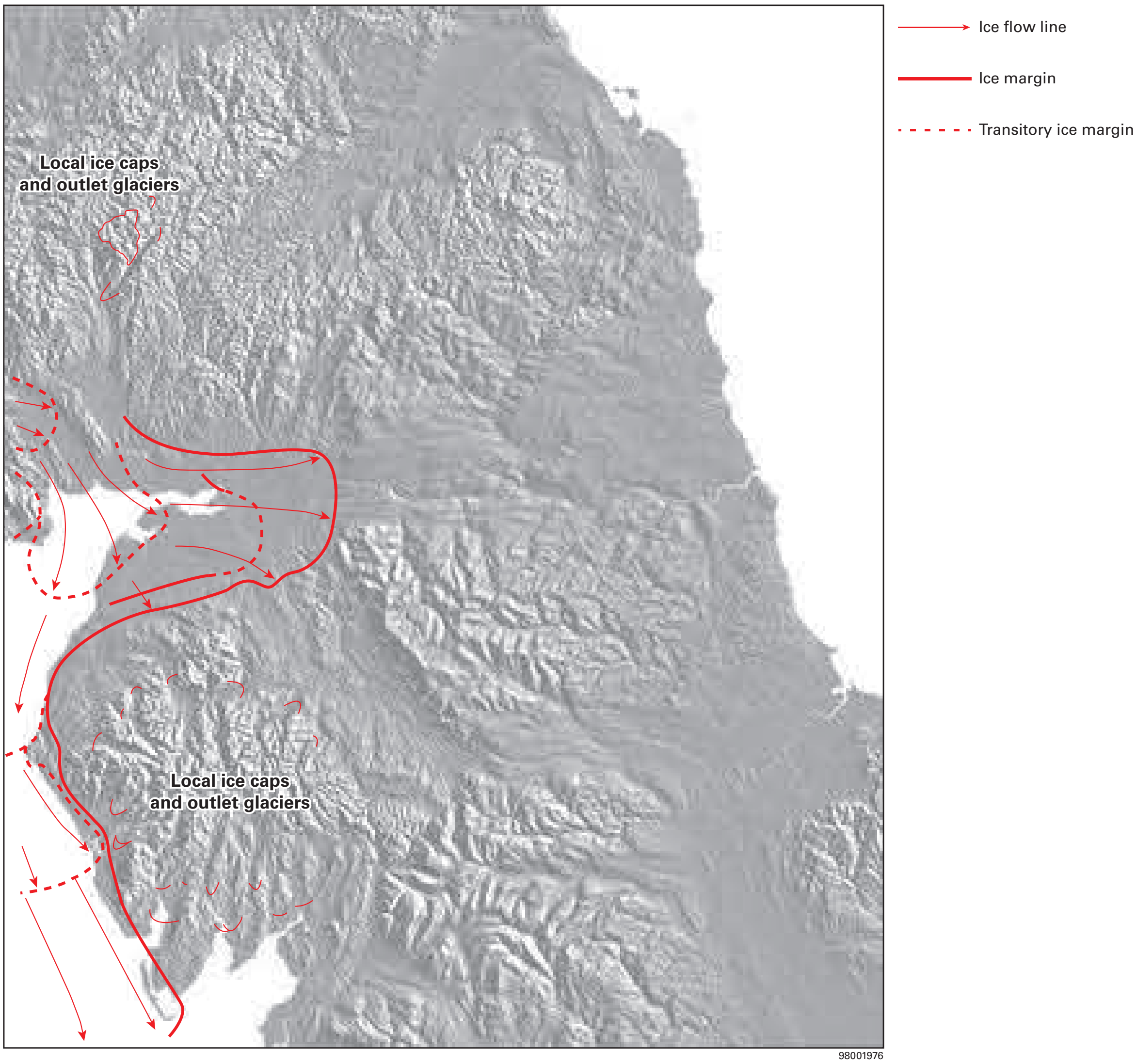


Figure 29 Speculative reconstruction of the last ice-sheet when multiple re-advances of ice sourced in the Galloway Hills affected the Solway Basin and the west Cumbrian coast. *NEXTMap Britain elevation data from Intermap Technologies.*

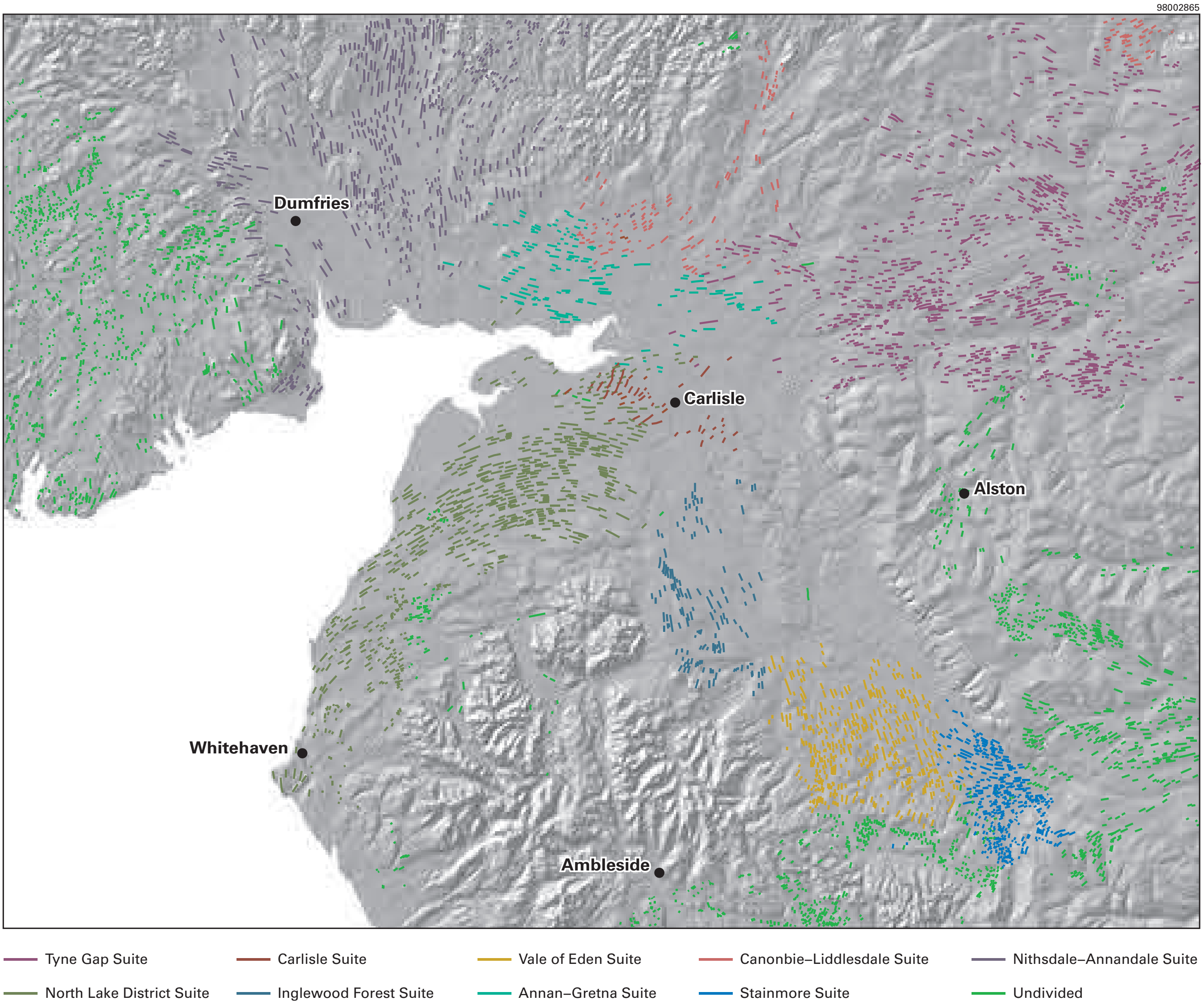


Figure 30 Flow sets of glacially streamlined landforms and other glacigenic features in and around the Solway Lowlands. *NEXTMap Britain elevation data from Intermap Technologies.*

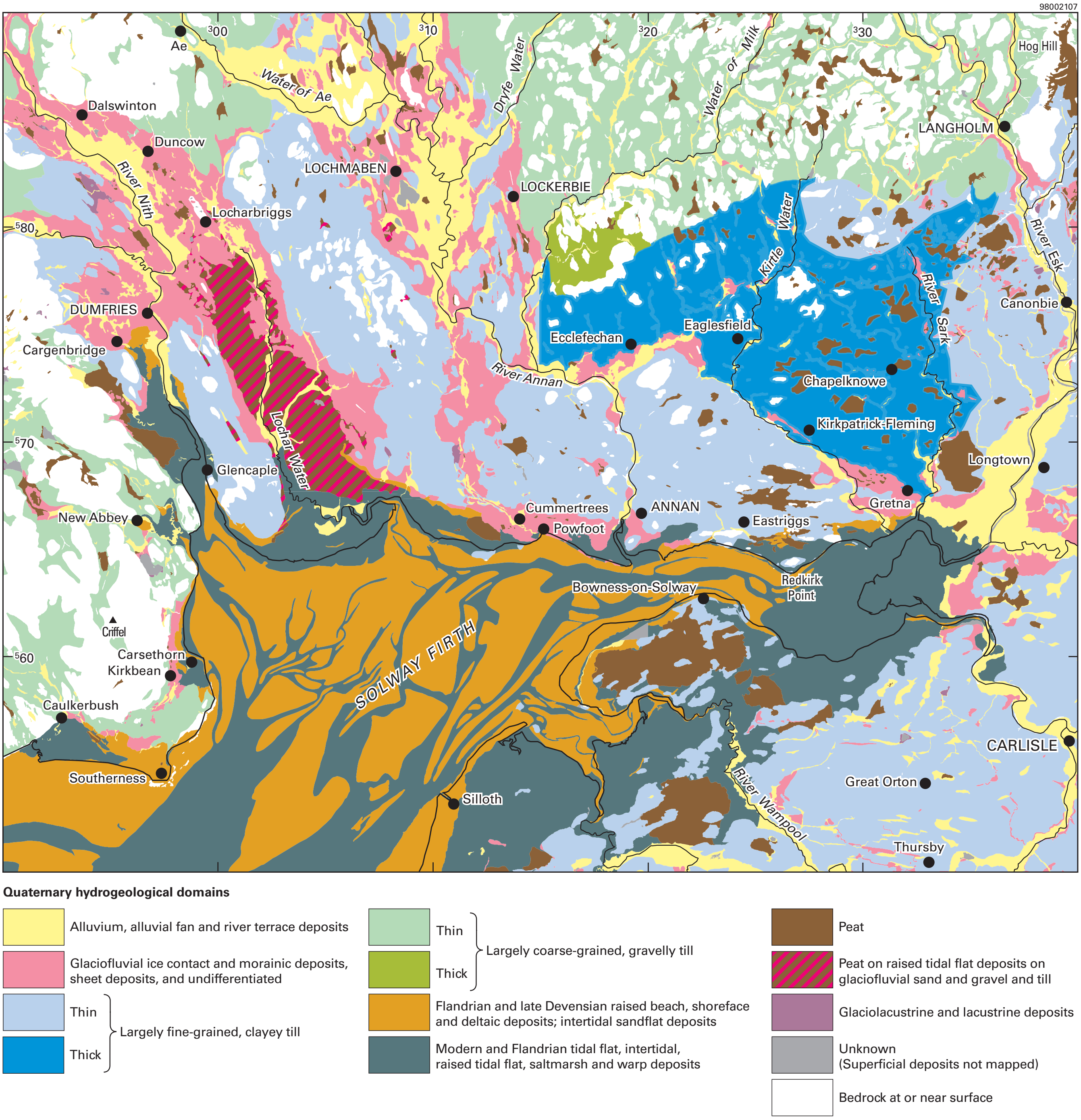


Figure 31 Quaternary hydrogeological domains in the Solway area.

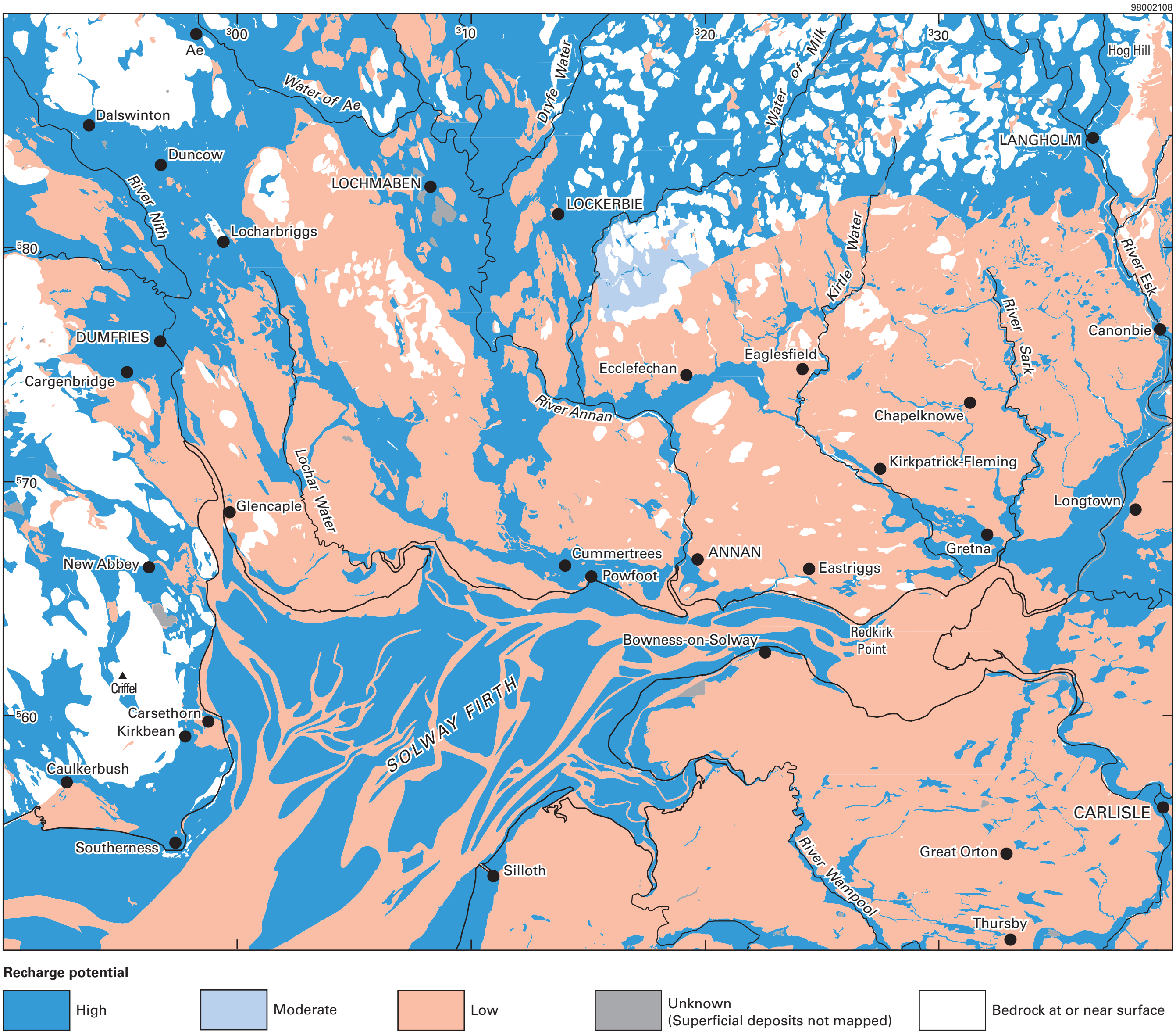


Figure 32 Potential recharge distribution derived from Quaternary hydrogeological domains.