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# Examining the geometry, age and genesis of buried Quaternary valley systems in the Midland Valley of Scotland, UK

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Buried palaeo-valley systems have been identified widely beneath lowland parts of the UK including eastern England, central England, south Wales and the North Sea. In the Midland Valley of Scotland palaeo-valleys have been identified yet the age and genesis of these enigmatic features remain poorly understood. This study utilizes a digital data set of over 100 000 boreholes that penetrate the full thickness of deposits in the Midland Valley of Scotland. It identified 18 buried palaeo-valleys, which range from 4 to 36 km in length and 24 to 162 m in depth. Geometric analysis has revealed four distinct valley morphologies, which were formed by different subglacial and subaerial processes. Some palaeo-valleys cross-cut each other with the deepest features aligning east–west. These east–west features align with the reconstructed ice-flow direction under maximum conditions of the Main Late Devensian glaciation. The shallower features appear more aligned to ice-flow direction during ice-sheet retreat, and were therefore probably incised under more restricted ice-sheet configurations. The bedrock lithology influences and enhances the position and depth of palaeo-valleys in this lowland glacial terrain. Faults have juxtaposed Palaeozoic sedimentary and igneous rocks and the deepest palaeo-valleys occur immediately down-ice of knick-points in the more resistant igneous bedrock. The features are regularly reused and the fills are dominated by glacial fluvial and glacial marine deposits. This suggests that the majority of infilling of the features happened during deglaciation and may be unrelated to the processes that cut them.

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Published research describes a variety of palaeo-valley features that were formed by geological processes that are no longer active and are typically described as either ‘buried’ or ‘open’ depending on their physical expression relative to the contemporary land surface or seabed (Jørgensen & Sandersen 2006). In mid-latitude areas, palaeo-valleys are typically formed by: (i) subaerial fluvial incision (e.g. Dyer 1975; Swift *et al.* 1980; Rose 1989; Bozzano *et al.* 2000; Bridgland 2010); (ii) glacial over-deepening to form U-shaped valleys, which can then become partly submerged and filled by younger sediment (e.g. Holtedahl 1967; Nesje & Whillans 1994); (iii) tunnel valleys (or tunnel channels) incised by subglacial meltwater beneath glaciers and ice sheets (e.g. Ó Cofaigh 1996; Praeg 2003; Hooke & Jennings 2006; Lutz *et al.* 2009; Kehew *et al.* 2012); (iv) polygenetic palaeo-valleys that have been formed and shaped by two or more of the above processes (e.g. Huisink 2000; Huuse & Lykke-Andersen 2000; Montgomery 2002).

Buried palaeo-valleys, the focus of this paper, are of particular significance because their concealed occurrence can have significant (and often unexpected) implications for groundwater (e.g. Sandersen & Jørgensen 2003; Cloutier *et al.* 2008; Seifert *et al.* 2008; Oldenborger *et al.* 2013), hydrocarbon (e.g. Huuse *et al.* 2012) and geothermal resources (e.g. Allen & Milenic 2003; Allen *et al.* 2003) and may provide detailed archives of palaeoenvironmental and landscape change (e.g. Evans & Campbell 1995; Piotrowski 1997; Bridgland 2010; Graham *et al.* 2011; van der Vegt *et al.* 2012). Buried palaeo-valley systems have been identified widely beneath lowland parts of the UK including eastern England (Woodland 1970; Cornwell & Carruthers 1986; Rose 1994; Boreham & Rolfe 2009; Bricker *et al.* 2012), central England (Rose 1989; Bridgland *et al.* 2014; Westaway *et al.* 2015), northern England (Boswell 1937; Howell 1973; Delaney 2003), south Wales (Al-Saadi & Brooks 1973; Anderson & Owen 1979) and the North Sea (Bradwell *et al.* 2008; Stewart & Lonergan 2011; Stewart *et al.* 2012).

Despite widespread recognition of their existence, a detailed understanding of the form, long-term evolution and significance of buried palaeo-valleys in the UK remains limited due to the paucity of available sub-surface data. One area of the UK where sufficient sub-surfaceborehole data exist to reconstruct the geometry and cross-cutting relationships of the network of buried palaeo-valleys is the Midland Valley of Scotland. Here, boreholes (>100 m depth) with thick sequences of Quaternary sediments have been used to suggest the presence of buried palaeo-valley systems beneath Alva in Clackmannan (Parthasarathy & Blyth 1959), under the modern River Kelvin to the northwest of Glasgow (Browne & McMillan 1989; Rose & Smith 2008; Finlayson 2012) and under Grangemouth (Cameron 1998). Additionally, several shallower ‘drift-filled buried channels’ have been recorded in the vicinity of Irvine, Ayrshire (Monro 1999).

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Despite considerable attention, the age, genetic evolution and overall geometry of these enigmatic features in the Midland Valley of Scotland remain poorly understood. Furthermore, all of these valleys have been studied in isolation so their context within the broader evolution of the landscape is unclear. The purpose of this study is to identify and assess the geometry, relationships and fill of buried palaeo-valleys in the Midland Valley of Scotland. It will also assess the origins of these features and determine if they are all formed by the same process or a range of different processes. This study utilizes a digital database of boreholes, which penetrate the full thickness of Quaternary deposits in the Midland Valley of Scotland, and enable the morphology of the underlying bedrock surface and the sedimentary infill to be investigated.

## Regional geological background

This study focuses on the Midland Valley of Scotland (16 799 km$^2$), which is a predominantly lowland, formerly glaciated landscape between the Scottish Highlands to the north and the hills of the Southern Uplands to the south (Fig. 1).

### *Pre-Quaternary evolution of central and southern Scotland*

The Midland Valley of Scotland is largely underlain by Devonian and Carboniferous age sedimentary and igneous rocks, which are dissected by a complex network of faults (Fig. 2; Cameron & Stephenson 1985). To the north, the region is separated from the metamorphic and igneous rocks of the Highlands by the Highland Boundary Fault and to the south, from the more resistant and strongly folded rocks of the Southern Uplands by the Southern Upland Fault system (Figs 1, 2). Within the Midland Valley, volcanic rocks of Devonian and Carboniferous age form zones that are resistant to erosion forming areas of elevated relief (e.g. the Campsie Fells and Ochil hills) relative to surrounding low-relief areas underlain by sandstones, mudstones and limestones (Cameron & Stephenson 1985).

The precise 'heritage' of the landscape of central and southern Scotland is also a matter of some debate. Some have suggested that the modern landscape of central Scotland represents a remnant relief formed as a result of the Caledonian Orogeny (Nielsen *et al.* 2009) but others recognize that the region has been progressively exhumed during the past *c.* 400 Myr (Hall 1991; Persano *et al.*


*Fig. 1.* Location map for this study. The area highlighted in green is the Midland Valley of Scotland. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

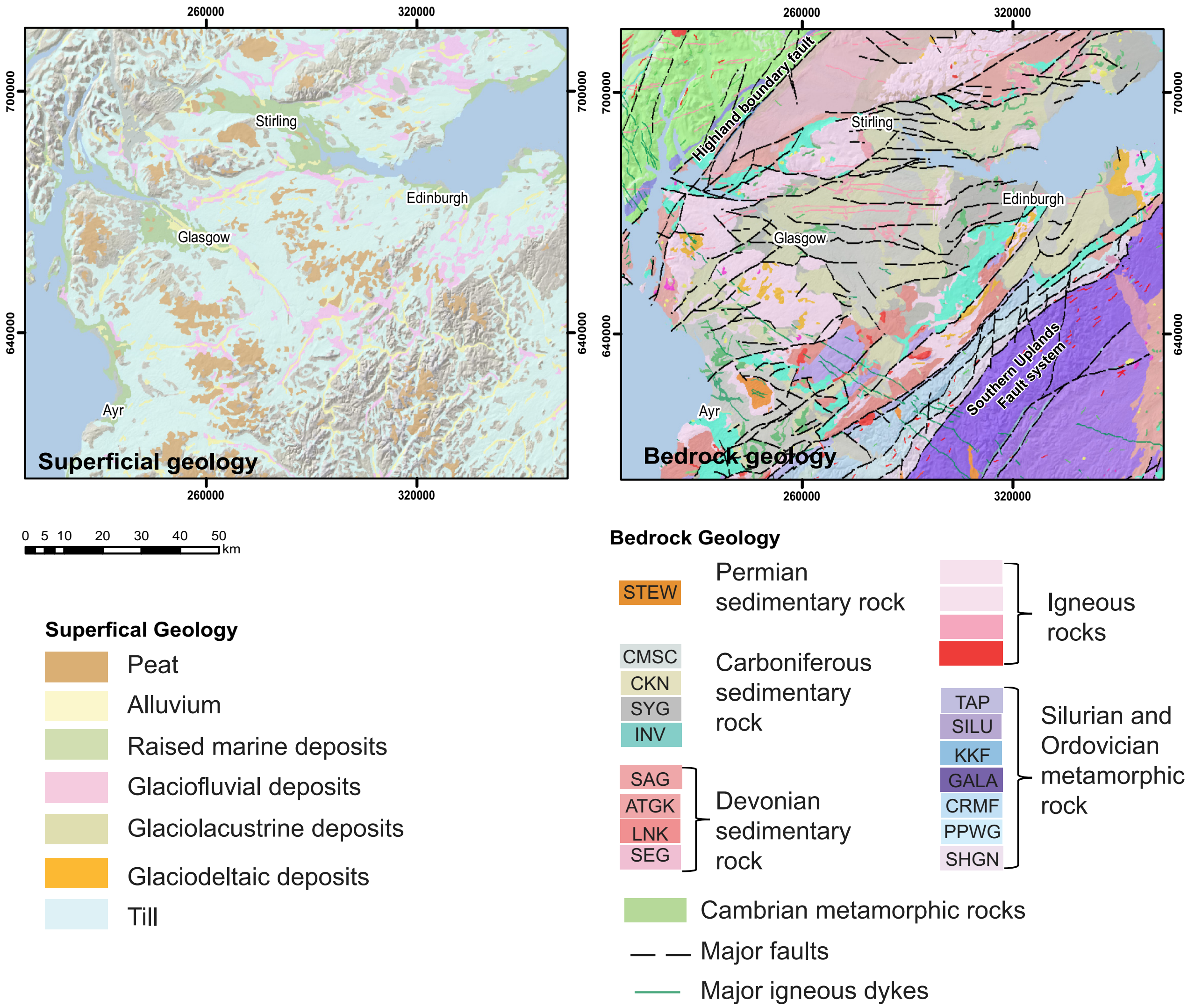


*Fig. 2.* BGS superficial and bedrock geology 1:625 000 maps for the study area. The names of the individual bedrock units are as follows: Stewartry Group (STEW), Scottish Coal Measures Group (CMSC), Clackmannan Group (CKN), Strathclyde Group (SYG), Inverclyde Group (INV), Stratheden Group (SAG), Arbuthnott-Garvock Group (ATGK) Lanark Group (LNK), Strathmore Group (SEG), Tappins Group (TAP), Silurian undifferentiated (SILU), Kirkcolm Formation (KKF), Gala Group (GALA), Crawford Group and Moffat Shale Group (CRMF), Portpatrick Formation and Glenwhargen Formation (PPWG), Shinnel Formation and Glenlee Formation (SHGN). Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

2007; Holford *et al.* 2010). Progressive exhumation occurred during separate Triassic and Cretaceous phases (Holford *et al.* 2010) although punctuated by subsidence and sediment deposition (Hall 1991). The final phases of relief formation occurred during the Cenozoic driven by ongoing northwards-directed Alpine compression (Stoker *et al.* 1994) and Palaeocene–Eocene magmatic underplating linked to the Iceland Mantle Plume (Brodie & White 1994; Persano *et al.* 2007). Cenozoic exhumation occurred during three known exhumation phases (65–40, 40–25 and 15–10 Ma) (Holford *et al.* 2010) resulting in the removal of the thin Mesozoic cover-rocks (Clausen & Huuse 1999; Clausen *et al.* 1999). Studies into the burial history of the Carboniferous rocks that are currently at the ground surface suggest that they only came close to the surface in the Neogene; prior to this they were buried up to 2.5 km deep (Vincent *et al.* 2010). Therefore, the age of the broad topographic expression of central and southern Scotland is likely to be of Late Miocene age, corresponding to a wide spread unconformity that extends across much of Britain, the North Sea and Fennoscandia (Clausen & Huuse 1999; Clausen *et al.* 1999; Westaway 2010, 2017; Lee *et al.* 2017). No pre-Quaternary saprolites or sediments have been found in the Midland Valley of Scotland (Cameron & Stephenson 1985; M. Browne pers. comm. 2018). This is in contrast to Scandinavia where pre-Quaternary deep

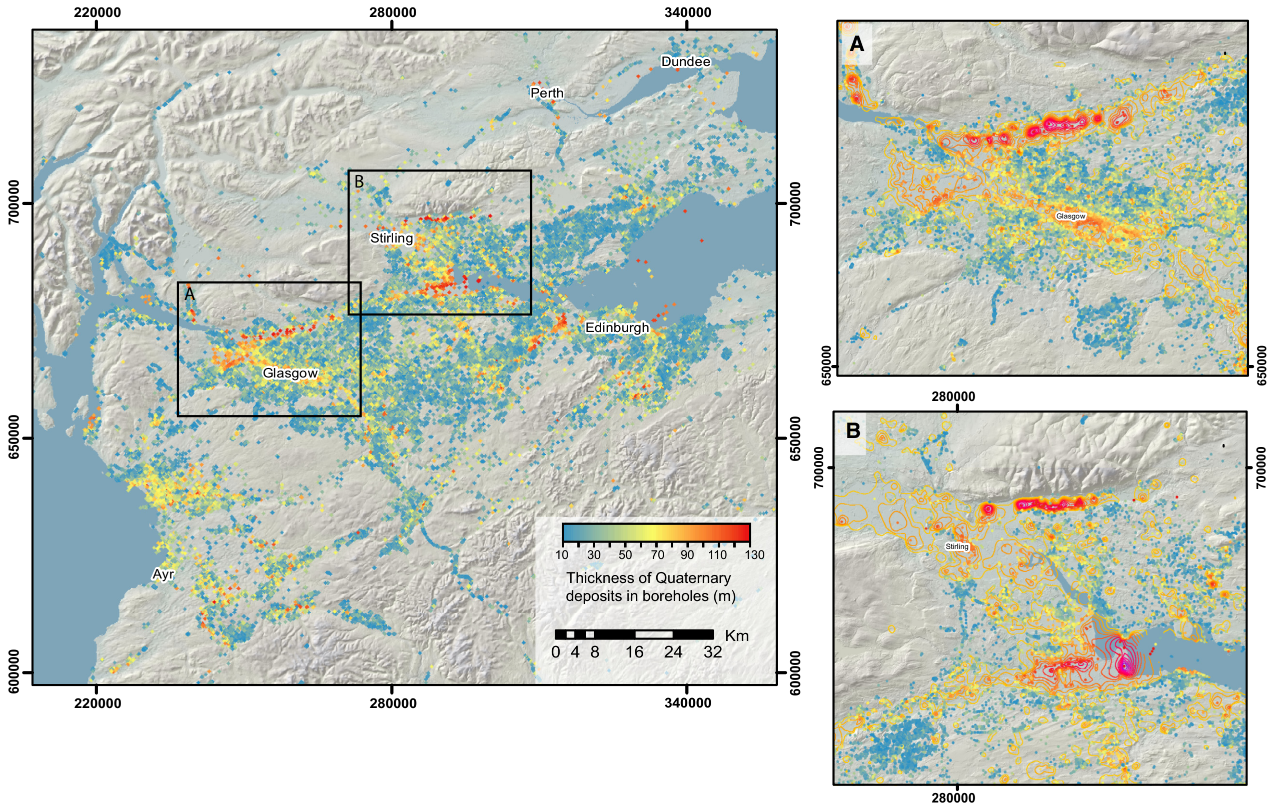


*Fig. 3.* Boreholes that show the thickness of Quaternary deposits in the Midland Valley of Scotland. Insets show details over Glasgow (A) and (B) Stirling to Grangemouth. The contours on the insets are 10-m contours of the BGS interpolated Superficial Thickness model of Lawley & Garcia-Bajo (2009). Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

weathering controlled the present relief and glacial erosion (Lidmar-Bergström *et al.* 1997).

### *Quaternary history*

Britain has a long history of glaciation, which in tandem with neighbouring Fennoscandia was initiated in the UK around the beginning of the Quaternary at approximately 2.6 Ma (Sejrup *et al.* 2005; Lee & Phillips 2011; Böse *et al.* 2012; Lee *et al.* 2012; Thierens *et al.* 2012). Evidence for these older glaciations is generally restricted to offshore basinal, shelf and shelf-edge locations (Stoker *et al.* 1994; Sejrup *et al.* 2005; Thierens *et al.* 2012) and points to the periodic growth and contraction of highland glaciers in Scotland during the Early and early Middle Pleistocene and their occasional expansion onto adjacent marine basins (Lee & Phillips 2011; Lee *et al.* 2012; Hall *et al.* 2018).

The most recent ice sheet overrode the Midland Valley sometime after 35 ka BP (Brown *et al.* 2007; Jacobi *et al.* 2009; Ballantyne & Small 2018). Geomorphological and stratigraphical evidence suggests that glaciers initially flowed southeastwards into the area from highland sources to the northwest (Finlayson *et al.* 2010, 2014). The coalescence of these highland sourced glaciers with Southern Upland sourced ice masses then led to the development of an ice divide over the western edge of the Midland Valley (Gordon & Sutherland 2012; Finlayson *et al.* 2010). This approximate configuration is thought to have persisted as the British–Irish Ice Sheet neared its maximum extent, potentially driving an ice stream eastward into the Firth of Forth (Hughes *et al.* 2014).

There are little observational data to constrain maximum ice thicknesses over the Midland Valley of Scotland. The adjacent upland areas do not possess trimlines, which have been used elsewhere to infer the altitude of former thermal boundaries (e.g. Fabel *et al.* 2012), and are likely to have remained well below former ice-sheet surfaces during maximum stages. The results from modelling investigations suggest that LGM ice surface altitudes over the Midland Valley may have been in the range of 1000–2000 m above modern sea level (Boulton *et al.* 1991; Boulton & Hagdorn 2006; Hubbard *et al.* 2009). Upon deglaciation, ice flow into the Midland valley was once more characterized by southeastward-flowing outlet glaciers of the highland icecap.

Within the Midland Valley of Scotland, there are currently no known primary deposits that pre-date the Devensian (Weichselian; MIS 4-2) cold stage (Hughes *et al.* 2011 and references therein). The oldest dated deposit is 31 ka $^{14}$C, MIS 3 (Jacobi *et al.* 2009) within the Kelvin palaeo-

*Table 1.* Bedrock palaeo-valleys and other features identified in the Midland Valley of Scotland.

| Feature number | Name | Number of boreholes within palaeo-valley | Area ($m^2$) | Average width of feature (m) | Length of feature (m) | Average depth to bedrock in borehole (m) | Max. depth to bedrock in borehole (m) | Depth: width ratio | Variance in depth to bedrock in borehole (m) | Type |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Loch Lomond palaeo-valley | 72 | 13 373 812 | 908 | 14 410 | 30 | 74 | 1:12 | 311 | Type 1 |
| 2 | Kelvin palaeo-valley | 214 | 45 855 688 | 1544 | 28 008 | 34 | 108 | 1:14 | 359 | Type 1 |
| 3 | Ochil palaeo-valley | 83 | 14 213 367 | 1085 | 12 614 | 46 | 113 | 1:10 | 957 | Type 1 |
| 4 | Livingston palaeo valley | 313 | 24 531 478 | 921 | 20 303 | 29 | 72 | 1:13 | 140 | Type 1 |
| 5 | Carron palaeo-valley | 360 | 129 722 088 | 2513 | 23 772 | 28 | 162 | 1:16 | 404 | Type 1a |
| 6 | Forth river palaeo-valley | 281 | 129 722 088 | 1950 | 36 594 | 23 | 52 | 1:37 | 86 | Type 2a |
| 7 | Tay palaeo-valley | 23 | 142 839 518 | 3778 | 26 154 | 26 | 67 | 1:56 | 466 | Type 1 |
| 8 | Earn palaeo-valley | 19 | 142 839 518 | 1239 | 14 960 | 33 | 54 | 1:23 | 118 | Type 1 |
| 9 | Lower Clyde river palaeo-valley | 2701 | 64 731 454 | 2019 | 31 547 | 27 | 52 | 1:39 | 52 | Type 2a |
| 10 | Upper Clyde river palaeo-valley | 100 | 13 187 467 | 764 | 16 900 | 25 | 53 | 1:14 | 89 | Type 2 |
| 11 | Ayrshire bedrock palaeo-valley system | 43 | 2 393 833 | 641 | 4319 | 26 | 38 | 1:17 | 25 | Type 2 |
| 12 | Ayrshire bedrock palaeo-valley system | 191 | 15 387 104 | 699 | 17 702 | 23 | 62 | 1:11 | 65 | Type 2 |
| 13 | Ayrshire bedrock palaeo-valley system | 20 | 7 744 296 | 879 | 5230 | 26 | 36 | 1:24 | 21 | Type 2 |
| 14 | Ayrshire bedrock palaeo-valley system | 127 | 9 288 916 | 998 | 4902 | 23 | 36 | 1:28 | 74 | Type 2 |
| 15 | Lanark bedrock palaeo-valley system | 22 | 2 476 933 | 480 | 5684 | 21 | 43 | 1:11 | 89 | Type 2 |
| 16 | Lanark bedrock palaeo-valley system | 10 | 20 228 821 | 847 | 13 753 | 12 | 24 | 1:35 | 48 | Type 2 |
| 17 | Lanark bedrock palaeo-valley system | 38 | 12 387 133 | 646 | 13 815 | 23 | 53 | 1:12 | 165 | Type 2 |
| 18 | New Cumnock palaeo-valley | 21 | 4 579 834 | 761 | 5892 | 28 | 55 | 1:14 | 268 | Type 2 |

valley. Nevertheless, the longer-term Quaternary evolution of the landscape is likely to have been driven primarily by denudational and erosion (Molnar & England 1990), glacial erosion and periglacial weathering (Hall & Kleman 2014) and paraglacial response to deglaciation (Ballantyne 2002; Ballantyne & Stone 2013).

## Material and methods

### *Boreholes*

The British Geological Survey holds digital records for 230 307 boreholes in the Midland Valley of Scotland (Fig. 3). Approximately half of these (113 415) intersect the Carboniferous and Devonian bedrock surface, which lies beneath the cover of Quaternary sediment, and can be used to investigate the form of the bedrock surface. The boreholes are not evenly distributed throughout the area, but are largely focussed around the urban centres of Glasgow, Edinburgh, Stirling and former coal mining regions.

The borehole start height (the elevation relative to mean sea level of where the borehole intersects the ground surface) and bedrock surface elevation captured from these boreholes were extracted from a digital database using a database query. Two spatial data sets were developed. Firstly, a bedrock surface model was created by subtracting the depth to bedrock from a high-resolution (5 m horizontal and 1 m vertical) digital terrain model; secondly, a Quaternary thickness (isocpach) model was derived from the total thickness of Quaternary sediment recovered. Interpolation between data points was performed statistically using a natural neighbour algorithm as part of the UK Superficial Thickness Model (Lawley & Garcia-Bajo 2009) and contoured at 10-m intervals to help interpretation. The palaeo-valley features were manually interpreted from these two data sets.

For the purpose of this study a palaeo-valley is defined as any negative linear feature in the bedrock surface that is filled by Quaternary deposits >20 m thick and of over 4 km in length. This thickness was used because it is 10 m greater than the 75th percentile (9.6 m) of sediment thickness for all boreholes in the area. The minimum length of the feature is dictated by the distribution of boreholes, which is extremely variable. The use of borehole data to define these features means that the edges of the feature are often indistinct because some have little or no geomorphological representation. The topography and mapped limits of Quaternary deposits from BGS 1:50 000 mapping were used to guide the definition of the edges of the features but the Browne edges feature without geomorphological representation were controlled by borehole distribution.

### *Measurements of features*

The geometry of the palaeo-valley features was calculated by automated GIS processes to provide quantitative data on their length ($x$) and width ($y$). These were calculated in GIS by creating centrelines using the Thiessen polygon method (Roux *et al.* 2015) and edited to remove any minor tributaries. Using these centrelines the width of the features was calculated at 100-m intervals. The precision of this technique in defining palaeo-valley geometry is constrained by the borehole density and the issues of defining the edges of the features mentioned above is such that the technique will always underestimate the geometry of these features because of the poor definition of the edge.

### *Calculating the types of sediments that filled the features*

Boreholes within the palaeo-valleys were also used to investigate their sediment fill. Of the 4591 boreholes that intersected palaeo-valleys, 2886 recorded lithological variation in their Quaternary fill. In the remaining boreholes, either the driller or the core logger had not recorded the lithologies, often starting their description in the bedrock. Because the original cores from these boreholes no longer exist, borehole descriptions were accepted at face-value. This is acknowledged to be a potential source of inconsistency in the data set that we use. Initial processing of the data indicated that 147 different lithological descriptions have been used to describe the Quaternary sediments. These were rationalized to six dominant lithofacies (Clay, Diamicton, Organic deposits, Silt, Sand, Sand & Gravel) using the approach employed by Kearsey *et al.* (2015). The relative proportions of lithofacies were then calculated.

## Results

The mean thickness of Quaternary deposits recorded within the Midland Valley boreholes is 7.54 m (standard deviation 7.42 m) with a median thickness of 5.13 m. The maximum thickness of Quaternary deposits recorded was 161.54 m from a drilling platform in the Forth Estuary, with the rockhead surface situated at 165.52 m below mean sea level (m.s.l.). Eighteen palaeo-valleys in total were identified (Table 1, Fig. 4). The lowest number of boreholes within a single feature is 10 and the highest is 2701. To communicate the statistical confidence in the geometry of the palaeo-valleys, the features were sub-divided into three categories based on of the number of boreholes that identify the feature (<30 and >150 boreholes; Fig. 4). These numbers of boreholes were chosen because they are the 25th and 75th percentile of boreholes found within the features studied.

### *Occurrence and patterns of thickness of Quaternary deposits*

The palaeo-valleys in the Midland Valley of Scotland are mostly aligned northeast–southwest, although the deeper features have a more east–west alignment (Fig. 4). The modern drainage appears to be superimposed upon them. The size and depth of the palaeo-valleys appear not to be related to the catchment size of the modern rivers.

The deepest feature runs from Falkirk to Grangemouth beneath the course of the modern River Carron (Fig. 4: feature 5). It was identified by Cadell (1913) and Cameron (1998) who called it the 'Carron depression'. Onshore the valley is deepest in the east, under Grangemouth, where a Quaternary sediment thickness of 161.54 m places the bedrock surface at 165.94 m below m.s.l. Offshore, coal mine workings under the Forth Estuary have encountered the base of the palaeo-valley at 203 m below m.s.l. suggesting the valley deepens farther eastwards into the Inner Forth (Cameron 1998). The valley shallows rapidly westward where the centreline of the palaeo-valley is only 49.96 m below m.s.l. The onshore expression of this palaeo-valley is 15 km long and extends in the Firth of Forth for at least another 8 km. It has an average width of 2500 m (Table 1). It is parallel to the Kelvin and Ochils palaeo-valleys showing a broadly east–west alignment.

The Kelvin palaeo-valley (Fig. 4: feature 2) and Ochils palaeo-valley (Fig. 4: feature 3) have been identified previously (Parthasarathy & Blyth 1959; Soons 1960; Browne & Gregory 1984; Browne & McMillan 1989; Finlayson 2012). The form of the Kelvin palaeo-valley is constrained by 214 boreholes; it has a maximum depth of 107.90 m, an average width of 1500 m and a length of 26 km (Table 1). The Ochils palaeo-valley has an average width of 1085 m, a maximum depth of 113.39 m and a length of 12 km. There are similar, but north–south aligned and less well-constrained, features seen under the current course of the River Tay in Perth and under the River Leven, south of Loch Lomond (Fig. 4: features 1, 8, 7).

There are broader palaeo-valleys under the current courses of the River Forth and River Clyde, which have northwest–southeast alignments. The geometries of palaeo-valleys beneath the River Forth and the River Clyde are wider (average 1950–2019 m) and shallower (average thickness 25–27 m) than the palaeo-valleys previously mentioned. There is also a noticeable area of increased thickness of Quaternary deposits from Kilmarnock to Irvine (Fig. 4: features 11–15; Monro 1999). This consists of several discrete valleys ranging between 614–998 m in width and 36–62 m in depth. From Douglas in south Lanarkshire to Edinburgh there are a series of northeast–southwest trending features with an average depth of 20–26 m and widths of 0.9–0.48 km (Fig. 4: features 15–17) that underlie modern drainage and are filled by kame terraces sediments and other glacifluvial deposits that are found in these valleys (Eckford 1952; McLellan 1969; Huddart & Bennett 1997).

### *Variation in geometry and morphology*

The length of the palaeo-valley features varies from 4.3 km in the Ayrshire bedrock palaeo-valley system (Table 1: feature 11) to 36.59 km in the Forth River

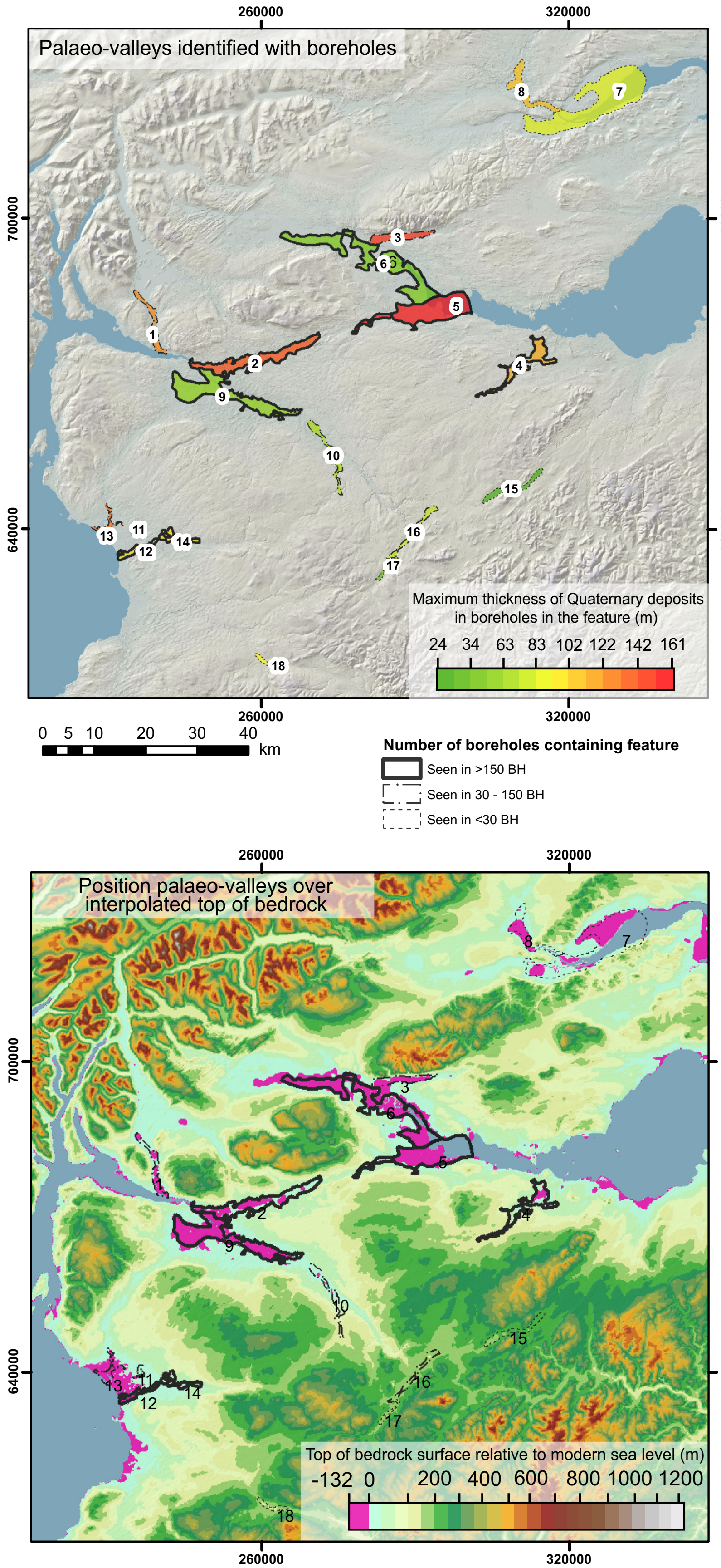
Palaeo-valleys identified with boreholes
260000
320000
700000
640000
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
Maximum thickness of Quaternary deposits in boreholes in the feature (m)
24 34 63 83 102 122 142 161
0 5 10 20 30 40 km
Number of boreholes containing feature
Seen in >150 BH
Seen in 30 - 150 BH
Seen in <30 BH
Position palaeo-valleys over interpolated top of bedrock
Top of bedrock surface relative to modern sea level (m)
-132 0 200 400 600 800 1000 1200

*Fig. 4.* Buried bedrock palaeo-valleys interpreted from borehole data. The lower image shows the bedrock elevation model (Lawley & Garcia-Bajo 2009). Numbered features: 1 = Loch Lomond palaeo-valley; 2 = Kelvin palaeo-valley; 3 = Ochil palaeo-valley; 4 = Livingston trough; 5 = Carron palaeo-valley; 6 = Forth river valley; 7 = Tay palaeo-valley; 8 = Earn palaeo-valley; 9 = Lower Clyde palaeo-valley; 10 = Upper Clyde palaeo-valley; 11–14 = Ayrshire palaeo-valley system; 15–17 = Lanark palaeo-valley system; 18 = New Cumnock palaeo-valley. Contains Ordnance Data © Crown Copyright and database rights 2018. Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

palaeo-valley (Table 1: feature 6). The average widths of the features range from 350 to 3000 m wide with the mean width being 1270 m (Table 1). There is a weak positive linear relationship between width and depth, although the Tay palaeo-valley (Fig. 5A: feature 7) is an outlier and is wider than expected based on its width. Comparing average width with length of the features shows a similar weak positive linear relationship (Fig. 5B). Maximum depth was used, rather than average depth because most geotechnical boreholes only drill down to 20–30 m (foundation depths). This produces a bias in the data set towards the boreholes that intersect bedrock at shallow depths; these generally occur on the flanks of the buried palaeo-valleys with significantly fewer boreholes in the centre of the feature drilling down all the way to the top of bedrock (see Table 1).

The cross-section geometry of the palaeo-valleys is also variable. Focusing on features constrained by >150 boreholes or by a line of boreholes orientated perpendicular to the long-axis of the feature (Fig. 6), two distinctly different valley cross-sectional geometries are identifiable, each with two sub-classes. The first valley type (Type 1) exhibits a 'U-shaped' cross-section with a valley width of between 1000–1500 m, as seen in the Kelvin and Ochils palaeo-valleys (Fig. 6). There is a variant of this type (Type 1a) that exhibits a double thalweg (e.g. the Carron palaeo-valley) with a U-shaped cross-section and a smaller secondary channel (Fig. 6) that was identified by Cameron (1998). The second valley type (Type 2) comprises of broad and shallow palaeo-valleys that can in turn be sub-divided by their scale and sediment infill. Type 2a valleys are over 2000 m wide and occur beneath the Upper and Lower Clyde, and Forth River valleys (Fig. 6). They appear to have poorly defined edges and are wider than the flood-plain of the modern rivers. Type 2b valleys (e.g. Livingston palaeo-valley, Ayrshire palaeo-valley system) are similar to Type 2a but are narrower at 500–1500 m wide and are filled with diamicton (see next section).

These types of cross-section geometries identify separate clusters in the cross-plot of maximum depth com-

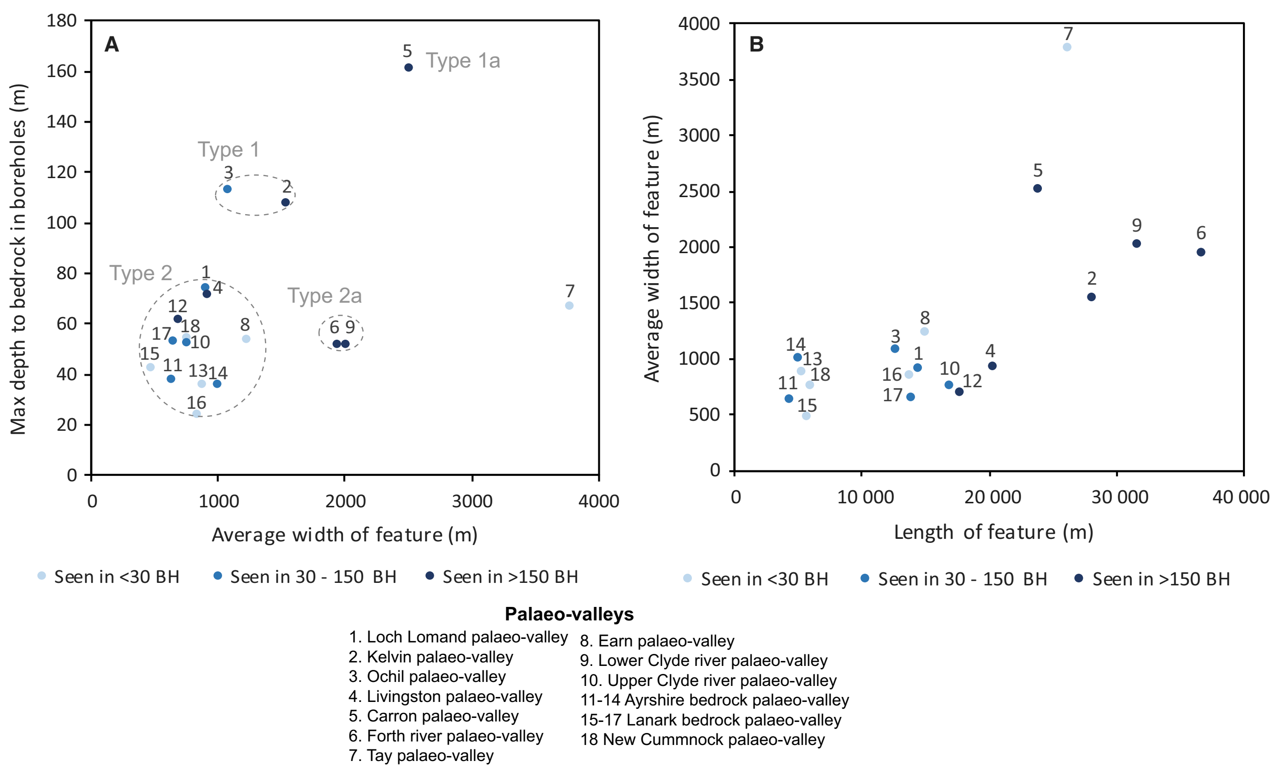


*Fig. 5.* A. Relationship between average width and maximum depth of palaeo-valleys in the Midland Valley of Scotland. B. Relationship between average width of feature and length. The colour of the points represents the number of boreholes that prove a feature and can be used as a proxy for uncertainty. [Colour figure can be viewed at www.boreas.dk]

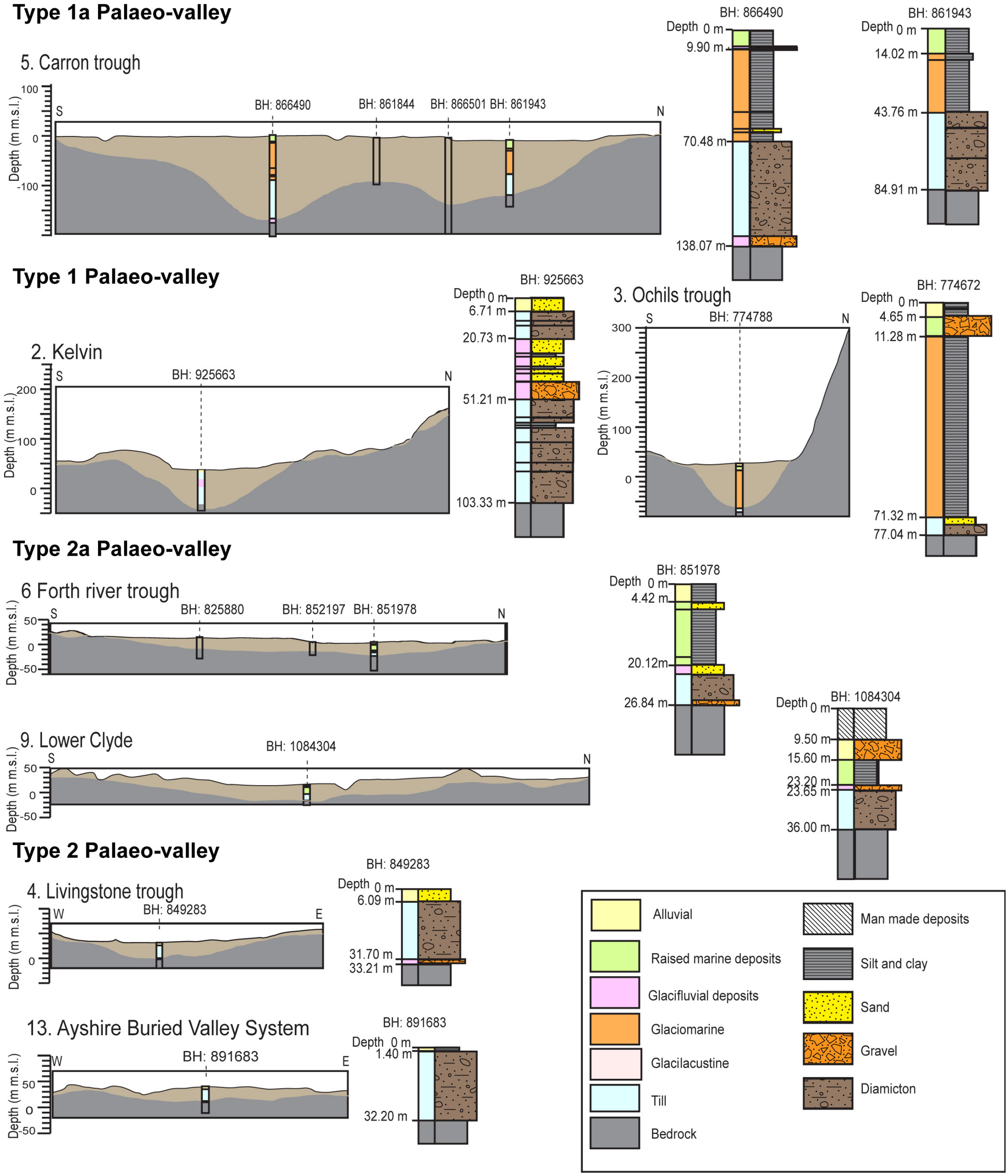


*Fig. 6.* Cross-sections showing the different geometry and fills of bedrock palaeo-valleys in the Midland Valley of Scotland. The numbers of the palaeo-valleys are the same throughout the figures and in Table 1. [Colour figure can be viewed at www.boreas.dk]

pared to average width (Fig. 5A). This suggests that the majority of the buried palaeo-valleys in the Midland Valley of Scotland fall into these classes.

The long profiles of palaeo-valleys also vary between the different types identified. The Type 2 valleys tend to have a long profile that is a consistent slope downstream, implying they were formed in subaerial conditions (Fig. 7). The Type 1 valleys have a different long profile. The Ochils palaeo-valley is over-deepened in the up-ice end of the valley and the Kelvin palaeo-valley has a very pronounced

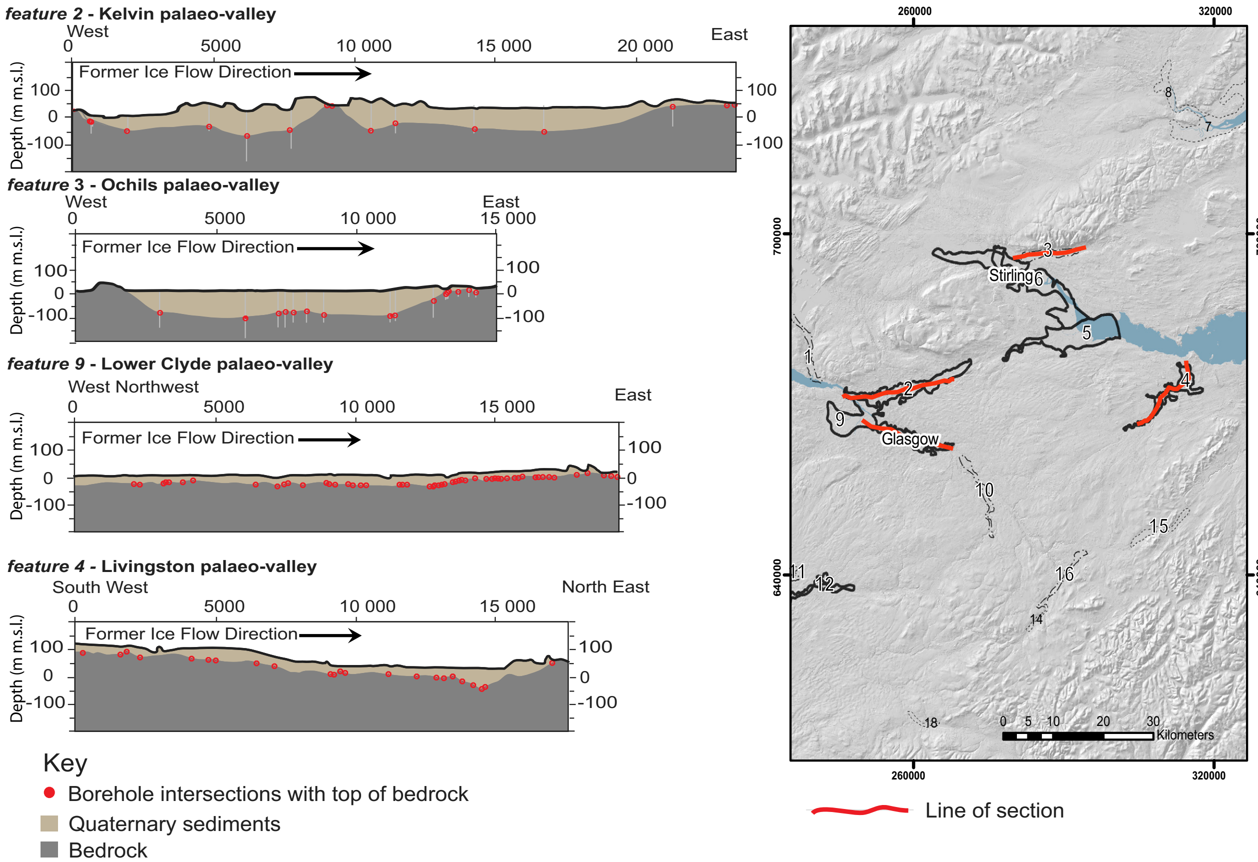


*Fig. 7.* Long profiles of key palaeo-valleys in the Midland Valley of Scotland. The numbers of the palaeo-valleys are the same throughout the figures and in Table 1. Includes NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

undulating base, implying subglacial or multi-generational formation (Fig. 7).

### *Sedimentary fill from boreholes and published descriptions*

The glacial and postglacial sediments that infill these palaeo-valleys are spatially variable and heterolithic (Fig. 8). The fills appear to be dominated by deglacial and postglacial sediments including raised marine deposits (silts and clays) or glacifluvial and alluvial deposits dominated by sands and gravels. All the features appear to have some glacigenic diamicton at their bases (Fig. 9) although this varies in thickness between features.

Within the Lower Clyde river palaeo-valley (Fig. 6: feature 9) in the west of the study area, the base of the palaeo-valley contains diamicton that forms part of the Wilderness Till Formation (Browne & McMillan 1989). Borehole logs show that the Wilderness Till Formation typically comprises a massive, matrix-supported diamicton, which has been interpreted as a subglacial till that was deposited during the Late Devensian (MIS 2; Dimlington Stadial; Rose *et al.* 1988). The till is typically overlain by glacifluvial sand and gravel deposits of the Broomhouse and Ross formations (Browne & McMillan 1989; Finlayson 2012) and in turn by lateglacial marine clays of the Paisley Formation that were deposited prior to the Loch Lomond Stadial re-advance (Browne & McMillan 1989). The Paisley Formation is overlain by Holocene-age fluvial sand and gravels of the Gourock Formation (Browne & McMillan 1989).

Within the Forth river palaeo-valley west of Stirling (Fig. 6: feature 6) the Wilderness Till Formation is overlain in boreholes by laminated clays that contain shell fragments. These are interpreted to be the equivalents of the glaciomarine Abbotsgrange and Kinneil Kerse formations in Falkirk (Browne & Gregory 1984; Cameron 1998). Overlying this are mud and sand beds and dark muds, interpreted to be equivalent of the Claret and Grangemouth beds (Browne & Gregory 1984; Cameron 1998; Smith *et al.* 2010) and deposited under marine conditions during the Holocene (Barras & Paul 1999).

The Carron palaeo-valley possesses a similar fill to the Forth river palaeo-valley (Fig. 6). The fill consists of ~7 m sand, gravel and boulder lag comprising clasts of sandstone and dolorite of unknown age, which may represent a weathering profile of the underlying dolorite bedrock. This is overlain by 60 m of diamicton (correlated with the Wilderness Till) and in turn by over 60 m of glaciomarine

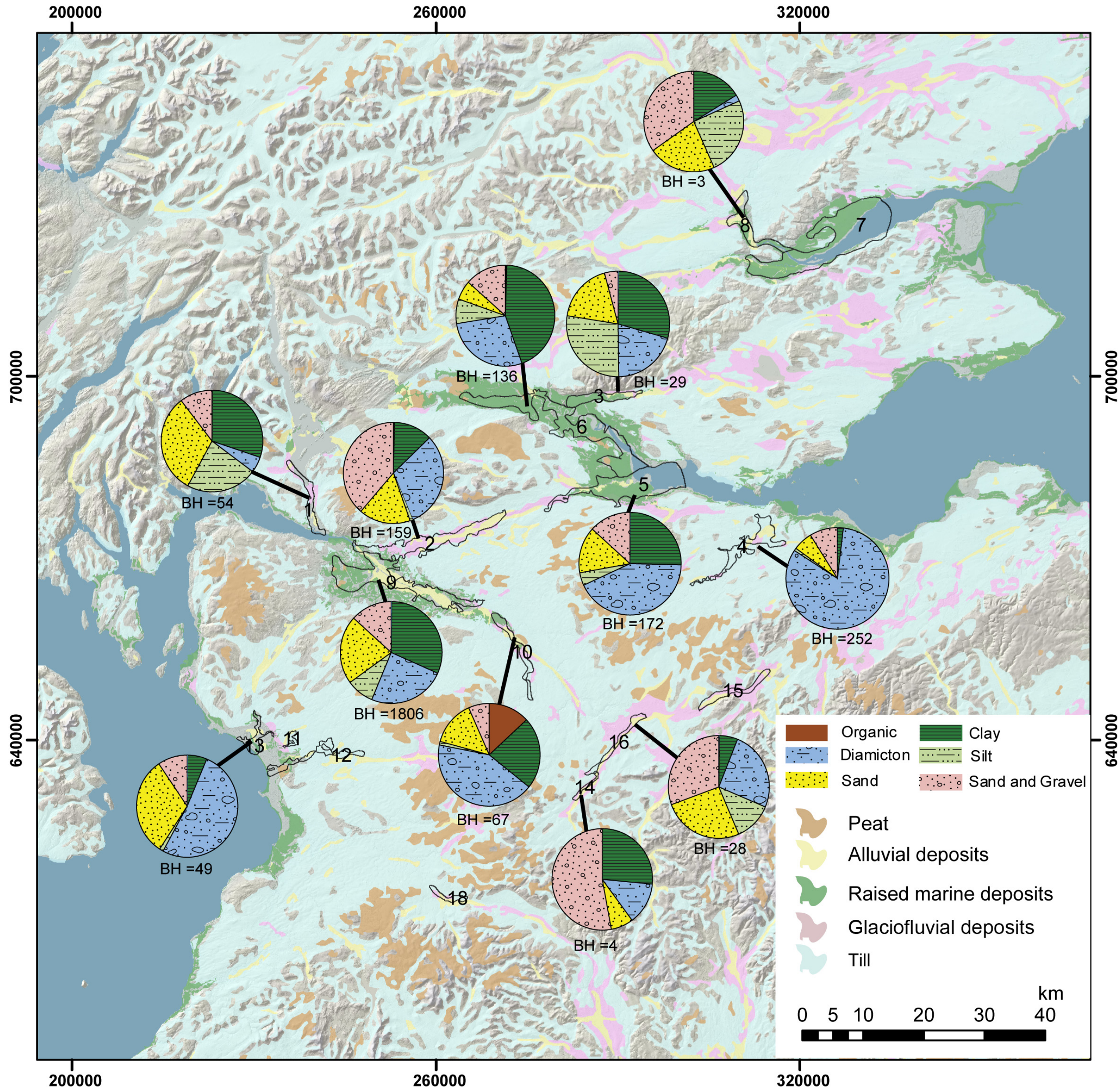


*Fig. 8.* Piecharts showing the lithologies that infill the palaeo-valley features. Mapping shows the BGS 1:625 000 superficial mapping. Contains Ordnance Data © Crown Copyright and database rights 2018 . Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

clay of the Abbotsgrange and Loanhead formations. These were deposited when sea level was ~31 m above present, although the area has undergone isostatic rebound with the deposits believed to have accumulated after 14 750 a BP based on the gradient of the extrapolated position of the EF-6 shoreline (Cameron 1998). Marine deposits are overlain by the Bothkenner Gravel Formation, which caps an erosional surface formed at the time of the Loch Lomond Stadial (Browne & Gregory 1984; Cameron 1998). Finally, the sequence is capped by 10 m of clays belonging to the Claret and Grangemouth formations.

The fill of the Ochils palaeo-valley is similar to the Carron palaeo-valley (Fig. 6). In borehole BGS ID 774788 there is 6 m of diamicton at the base of the palaeo-valley, which becomes increasingly sand-rich towards the top. The diamicton is overlain by over 60 m of laminated glaciomarine clay (Parthasarathy & Blyth 1959). This is overlain in turn by raised beach deposits and Holocene-age alluvium (Parthasarathy & Blyth 1959). These units have not been formally correlated with the Carron or Forth palaeo-valleys (cf. Browne & Gregory 1984; Cameron 1998) but show a similar succession of marine clays that overlie glacial tills,

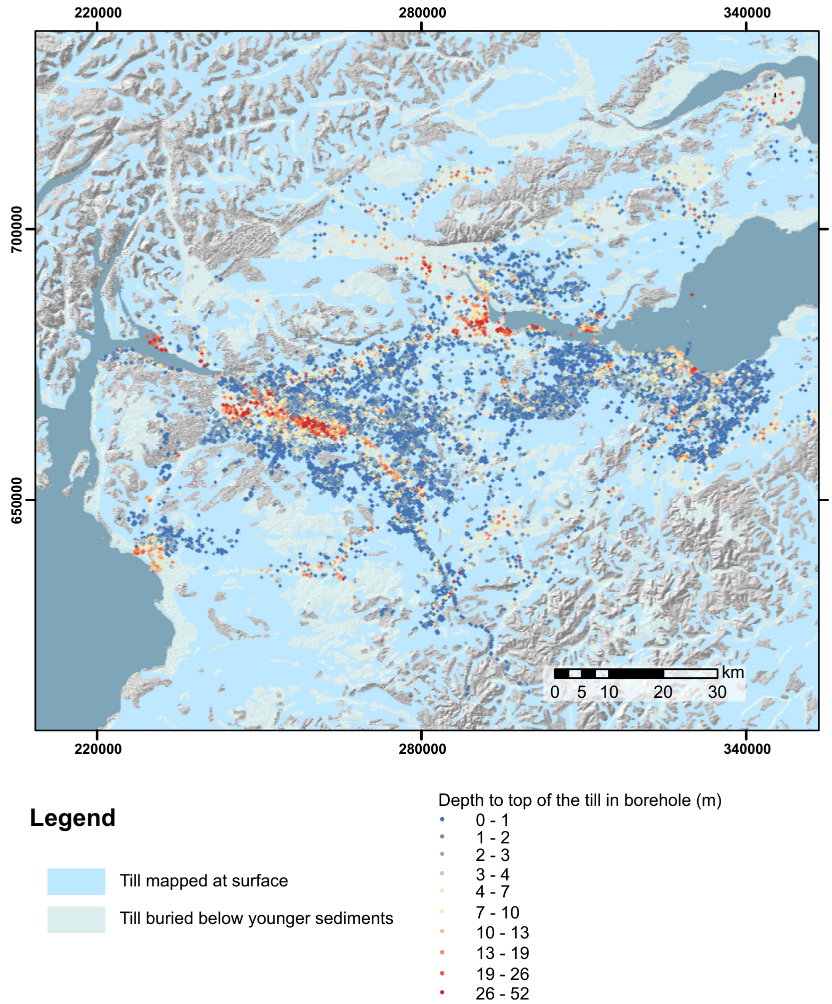


*Fig. 9.* The mapped extent of glacial till from the BGS 1:625 000 superficial mapping and the depth to the top of till in boreholes in those areas where it is covered by younger sediments. Contains Ordnance Data © Crown Copyright and database rights 2018 . Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

suggesting that all three of these features were filled when a Holocene marine incursion covered much of the low-lying ground from Falkirk and to the west of Stirling (Smith *et al.* 2010).

The Kelvin palaeo-valley, although a similar shaped feature to the Ochils palaeo-valley, possesses a very different fill (Fig. 6). This fill comprises two diamicton units – the Baillieston Till Formation (lower) and Wilderness Till Formation (upper) separated by sands and gravels. The sands and gravels belong to the Cadder Formation and contain woolly rhinoceros molars within the deposit that have been dated to 31 140±170 cal. $^{14}$C a BP (Jacobi *et al.* 2009). The age of the lower diamicton beneath the Cadder Formation remains undated and it could correspond to a pre-Devensian glacial event (Browne & McMillan 1989; Finlayson 2012).

The Cadder Formation is thought to be outwash sediments deposited as the ice advanced over the valley (Finlayson 2012). The Wilderness Till overlying the Cadder Formation in the Kelvin palaeo-valley is drumlinized, indicating that the Kelvin palaeo-valley was infilled and did not act as a tunnel valley during the Late Devensian glaciation (Finlayson 2012; Fig. 10).

## Discussion

The studied palaeo-valleys, as non-genetically defined here, are diverse and not all cut or filled by the same processes. Eighteen features were identified in the Midland Valley of Scotland and these can be divided into two broad groups based on their geometries; those with U-shaped profiles and undulating long profiles (Type 1, features 1, 2, 3, 5, 7, 8) and those with dish-shaped profiles (Type 2, features 6, 9, 10, 11–14, 15–17, 18). The former are most likely to have been formed by glacial processes, but whether these are subglacial tunnel valleys (e.g. Ó Cofaigh 1996; Praeg 2003; Hooke & Jennings 2006; Lutz *et al.* 2009; Kehew *et al.* 2012) or infilled glacial over-deepened

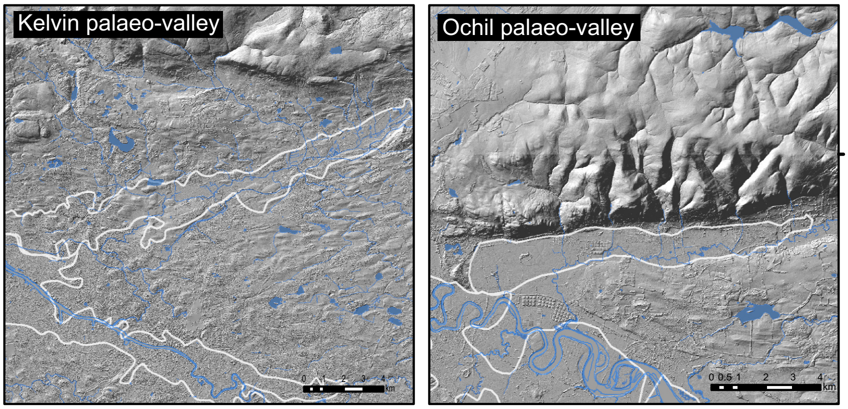


*Fig. 10.* The different surface geomorphologies above the Kelvin and Ochil palaeo-valleys (marked in white). Note that the Kelvin palaeo-valley has drumlins above it while the Ochil palaeo-valley is filled with marine deposits. Contains Ordnance Data © Crown Copyright and database rights 2018 . Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

valleys (e.g. Holtedahl 1967; Nesje & Whillans 1994) remains to be determined.

Kehew *et al.* (2012) recognize four criteria for identifying tunnel valleys: (i) that they are parallel to ice flow; (ii) they have an undulating convex upward long profile; (iii) they terminate close to or near former ice margins and they are associated with eskers and/or other types of subglacial landforms. This is an idealized list and studies such as those of van der Vegt *et al.* (2012) and Livingstone & Clark (2016) rely more on the morphology of the valleys themselves. Livingstone & Clark (2016) suggest that tunnel valleys often start and end abruptly and the up-glacier end of tunnel valley tends to be rounded. In the Midland Valley of Scotland, the Kelvin and Ochils palaeo-valleys (Fig. 7: features 2 and 3) show this morphology. The depth:width ratio of tunnel valleys has often been found to be close to 1:10 (van der Vegt *et al.* 2012); however, such analysis can only be accurately undertaken on features that are well constrained by subsurface data. The Loch Lomond palaeo-valley, Kelvin palaeo-valley, Ochil palaeo-valley and Carron palaeo-valley have depth:width ratios close to this value (Table 1), have undulating bases and are often over-deepened in the up-ice direction (Fig. 7). The Carron palaeo-valley and Tay palaeo-valleys also possess U-shaped profiles but do not fulfil the other tunnel valley geometric criteria. These features are partially filled with raised marine deposits (Browne & Gregory 1984; Cameron 1998) suggesting that they may be partially filled glacial fjords.

The features that possess a dish-shaped profile tend to be shallower than the U-shaped features (Fig. 6). Depth-width analysis (Fig. 5) identifies differences between these features too. Data separate out features that are: (i) on average 2000 m wide, and (ii) <1000 m width. The Clyde and Forth River palaeo-valleys (features 6 and 9) fall within the first category with their fill dominated by glacifluvial and raised marine deposits (Fig. 6). These features are interpreted as overfilled river valleys. In the context of this paper, this term is used to describe a buried palaeo-valley that has been completely infilled by glacial sediments and exerts no morphological control on modern drainage. This is supported by the long profiles of these features, which show a fluvial morphology (Fig. 7). The second group cluster under 1000 m wide and are on average 40 m deep. All of these features are either partially infilled or completely infilled with diamicton (e.g. Figs 6, 9: features 4 and 13) demonstrating that the features were eroded before the last deglaciation.

The different types of palaeo-valley described above appear to be formed by different processes. The Type 1 features have been eroded or modified by subglacial processes, while the Type 2 features are less modified by subglacial processes and still show morphologies associated with subaerial fluvial processes, although these may be glacifluvial processes rather than preglacial fluvial. The fact that all of these Type 2 features are filled with diamicton suggests they must pre-date or were formed in, at least the Devensian glaciation. However, whether they are relicts of pre-Quaternary features or formed in the interglacials depends on the cross-cutting relationships and alignments.

### *Ice-flow alignment and timing*

The palaeo-valleys identified in the Midland Valley of Scotland show cross-cutting alignments. The deepest features (100–180 m deep) have a strong east–west alignment (Figs 4, 5, 11). These features are all U-shaped and include the probable tunnel valleys. They are also concentrated in the centre of the Midland Valley. The overfilled river valleys cross-cut these features with a northwest to southeast alignment. The shallowest features (<40 m deep) have a different southwest to northeast alignment.

The east–west alignment of the deepest palaeo-valleys appears to align with the reconstructed ice-flow directions associated with an extensive ice-sheet configuration during the Main Late Devensian glaciation in the Midland Valley

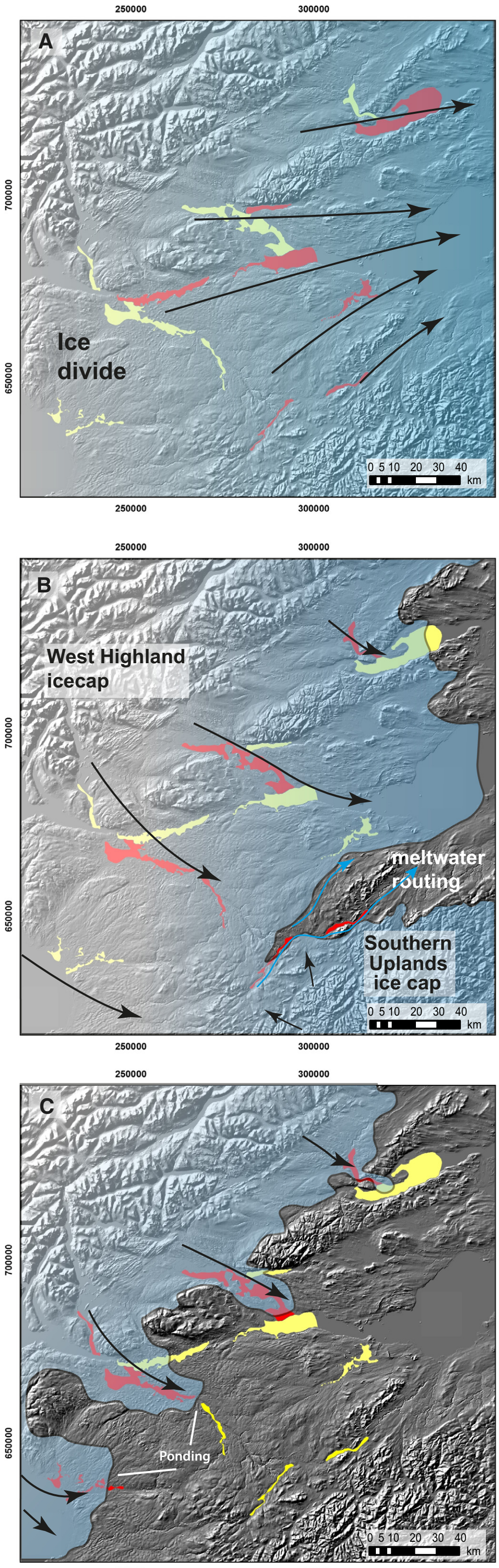


*Fig. 11.* A. Main Late Devensian glaciation. B. Ice sheet breaks into separate caps. C. Ice-sheet retreat stage. Cross-cutting alignments and depths of palaeo-valleys with associated ice-flow directions suggesting they may have formed at different times by different processes. Includes NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

(Fig. 11; Finlayson *et al.* 2010, 2014). Glacial bedforms (drumlins and crag-and-tails) and erratic distributions provide evidence for this focused eastward flow direction, which Hughes *et al.* (2014) have tentatively linked to ice-stream activity through the Firth of Forth. The other palaeo-valleys are more closely aligned to the reconstructed ice-flow directions under a smaller ice sheet or icecap. Such a configuration would have existed during growth and retreat phases of the ice-sheet cycle (Fig. 11), and may also have been a dominant 'restricted' glacial mode for earlier parts of the Quaternary, particularly prior to 1.1 Ma BP (Lee *et al.* 2012). We note that Fig. 11 presents three suggested end members; however, transitional stages would have occurred where all of the palaeo-valleys may have been subjected to active ice flow.

It is likely that the deepest features (100–180 m deep) represent valleys that are significantly long lived and may have been eroded several times during maximum stages of older pre-Late Devensian glaciations. Indeed, dated sediments (31 ka $^{14}$C, MIS 3; Jacobi *et al.* 2009) within the Kelvin palaeo-valley indicate the sedimentation occurred during the Last Interstadial and therefore the palaeo-valley itself must pre-date the deposition. Furthermore, erosion of any of these features within a single glacial cycle would require exceptional erosion rates, exceeding those calculated in most modern glacial settings (Hallet *et al.* 1996).

The longevity of preglacial drainage systems and preservation of pre-Quaternary weathering profiles are well documented in the Scottish Highlands (Hall 1991; Hall & Bishop 2002; Hall & Gillespie 2017; Merritt *et al.* 2017). Less is known in the Midland Valley of Scotland. There are no known records of preserved pre-Quaternary weathering profiles in the Midland Valley. Therefore, unlike Sweden (Lidmar-Bergström *et al.* 1997), there is no evidence of the preglacial land surface preserved.

In the western North Sea, provenance studies on Quaternary glacigenic sediments exhibit a signature consistent with the bedrock of the Midland Valley of Scotland (Davies *et al.* 2011). This suggests that there has been significant glacial erosion in the Midland Valley through successive glaciations. It is assumed that the preglacial drainage ran broadly from the west to the east (Hall 1991), which does coincide with the Type 1 features. However, these have been modified and over-deepened by glacial processes (Fig. 12) to such an extent that it is now impossible to definitively determine if they may have had preglacial origins. The double thalweg in the Carron palaeo-valley may hint at the preservation of some preglacial valley morphologies at the base of some of these deeper structures.

### *Effect of the substrate*

The present-day topography within the Midland Valley of Scotland is strongly influenced by the bedrock geology. The topographic highs are all underlain by Palaeozoic igneous rocks and are, on average, 90 m higher than the surrounding areas underlain by Palaeozoic sedimentary

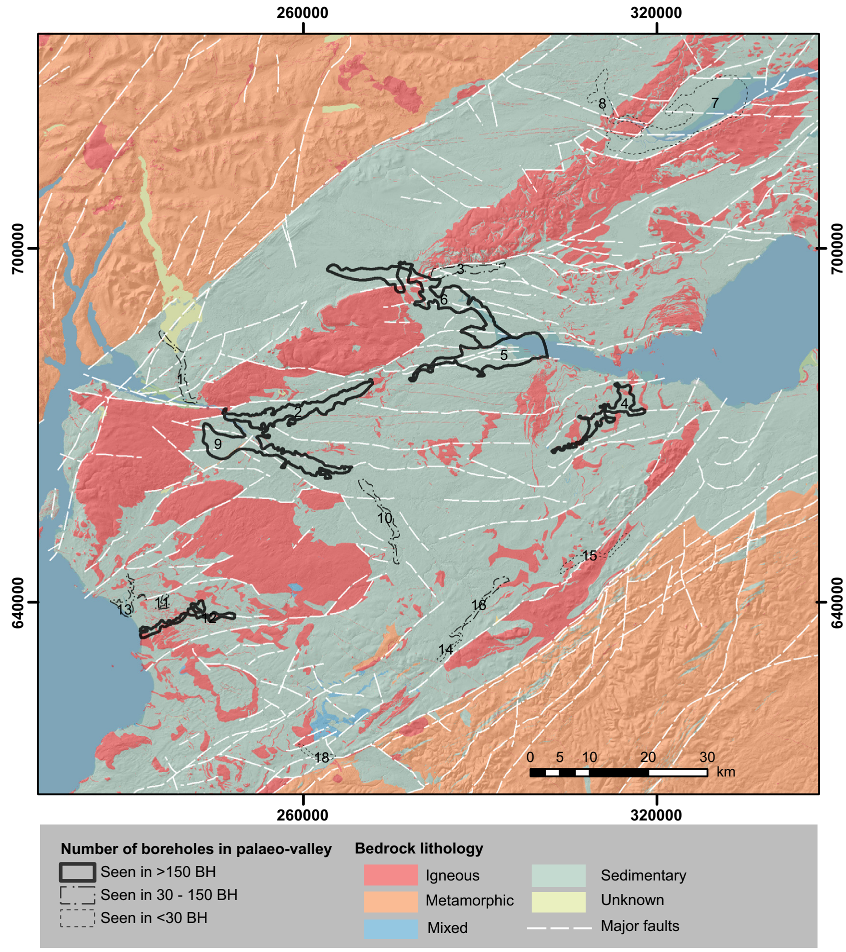


*Fig. 12.* Palaeo-valleys overlain on a simplified bedrock map of Scotland. Note many of the palaeo-valleys are aligned to the boundaries between igneous and sedimentary rocks. Contains Ordnance Data © Crown Copyright and database rights 2018 . Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

rocks. It has been suggested that buried valleys are rare outside areas underlain by poorly consolidated Mesozoic and Cenozoic sediments (Huuse & Lykke-Andersen 2000). However, detailed analyses undertaken as part of this study and others (Lee *et al.* 2015; Livingstone & Clark 2016) have shown this not to be the case.

Phillips *et al.* (2010) identify the link between bedrock lithology and the velocity and/or location of faster flowing zones in the overriding ice streams. They recognize that less-durable sedimentary bedrock (relative to more resistant igneous lithologies) acts as a focus for preferential glacial erosion. When the spatial distribution of palaeo-valley features in the Midland Valley of Scotland is shown relative to the bedrock lithology (Fig. 12), many palaeo-valley features occur immediately down-ice of 'knick-points' in the resistant Palaeozoic igneous bedrock. This seems to be particularly true of the probable tunnel valleys (Fig. 12: features 2, 3). Livingstone & Clark (2016) note that tunnel valleys form downstream of areas of subglacial meltwater ponding. In Denmark tunnel valleys are more common in areas where the ice is underlain by low-permeability substrata because meltwater drainage through the sediments is impeded, leading to the formation of a channelized subglacial drainage system (Sandersen & Jørgensen 2012). Compared to Denmark the Midland Valley of Scotland is all underlain by low-permeability strata (Sandersen & Jørgensen 2012; Ó Dochartaigh *et al.* 2015), which should mean that tunnel valley formation is likely. However, the Devonian and Carboniferous igneous and volcanic rocks have a significantly lower permeability than the surrounding sedimentary rocks (Fig. 12; Ó Dochartaigh *et al.* 2015). This introduces lateral permeability barriers into the substrata, which restrict and block subglacial drainage promoting possible subglacial meltwater ponding with meltwater flow and erosion being focussed into areas where the lavas were either thin or absent.

The bedrock of the Midland Valley is cut by many major strike slip faults that first formed in the Late Carboniferous (Underhill *et al.* 2008). It might be expected that these may act as areas of weakness along which palaeo-valleys would form. However, only the Type

1 features appear to form parallel to the major faults. The Type 2 palaeo-valleys, such as the Forth River palaeo-valley, cut across several major faults (Fig. 13) suggesting the faults have little control over these features.

The vertical positions of the major faults in the Midland Valley are well understood as a result of seismic data (Monaghan 2014). However, when the individual palaeo-valleys are investigated (Fig. 13), the thalwegs are not coincident with the position of the faults, which would be expected if they were exploiting the damage zones of the faults. Instead faults are often found close to the margins of the palaeo-valleys (Fig. 13) bounding the

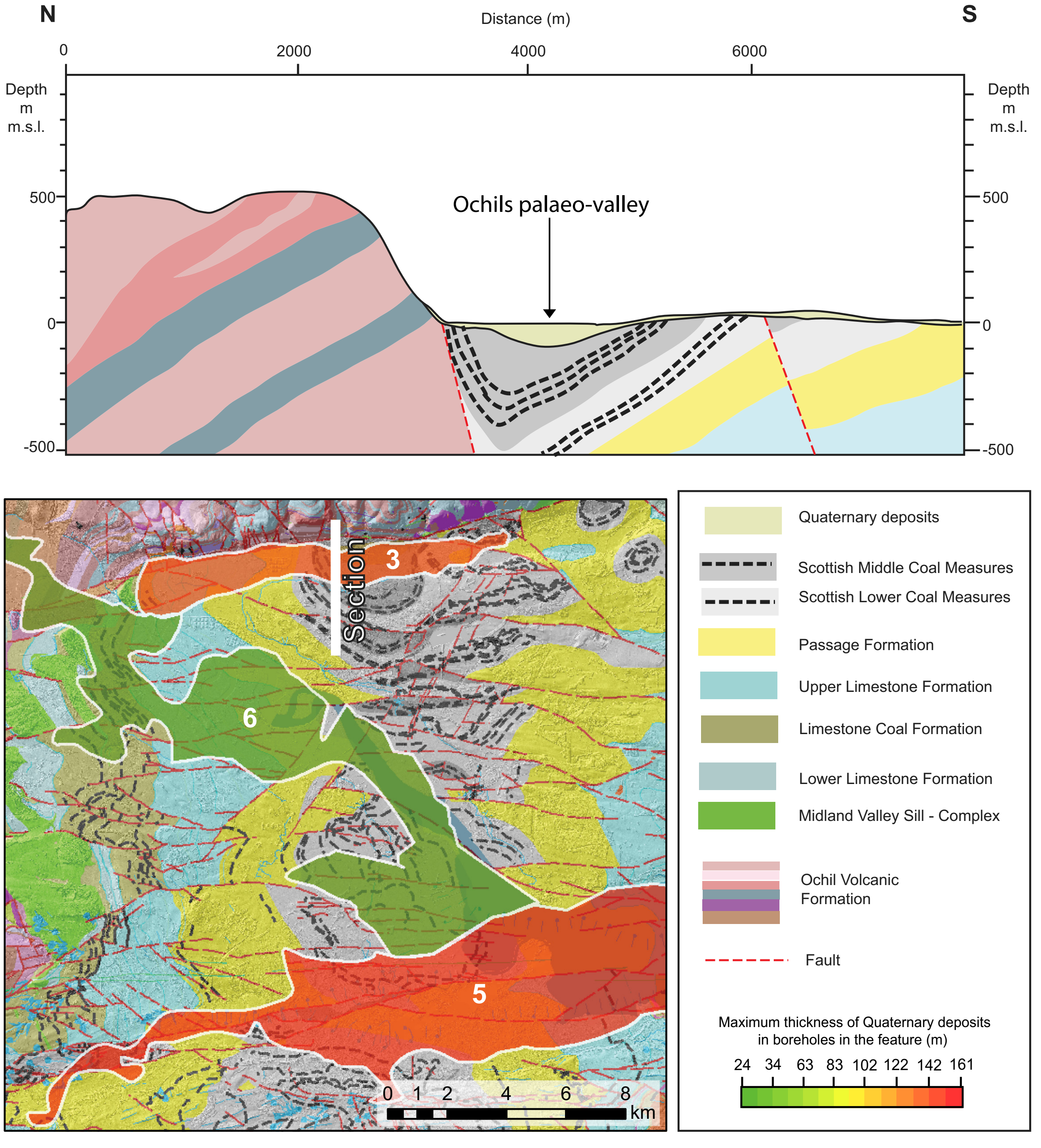


*Fig. 13.* Cross-section and map showing the relationship between the Ochils palaeo-valley and bedrock geology. Note how the thalweg of the valley is offset from the major faults. Includes mapping data from BGS DiGMap 1:50 000 bedrock mapping and licensed from Ordnance Data © Crown Copyright and database rights 2018 . Ordnance Survey Licence no. 100021290 and NEXTMap Britain elevation data from Intermap Technologies. [Colour figure can be viewed at www.boreas.dk]

features. This supports the idea that it is the lithological contrast that may control the position of some of the palaeo-valleys and the roll of the faults is juxtaposing different lithologies.

### *Valley infill*

The fills of all the palaeo-valley features seen in the Midland Valley of Scotland are very heterolithic (Fig. 8). The fills can be subdivided into primary and secondary valley fills. The primary fill is generally interpreted to have been deposited subglacially (van der Vegt *et al.* 2012) when the hydraulic regimes either reduced dramatically or shut down enabling sediment preservation (e.g. Fisher *et al.* 2003; Fielding 2006; Lang & Winsemann 2013; Lee *et al.* 2015). Diamicton is the primary fill at the base of all of the palaeo-valleys and the average diamicton thickness (9.60 m) is typically greater than that in adjacent areas (5.8 3 m). In the U-shaped palaeo-valleys the diamicton (Figs 5, 6, 9) often comprises up to half of the infill, suggesting they were not fully filled by subglacial processes. Many of the shallower features (Type 2), such as the Livingston palaeo-valley and Ayrshire system, are almost entirely filled by diamicton (Figs 5, 6, 9).

The Kelvin palaeo-valley contains two separate till fills, which are separated by glacial outwash deposits. Radiocarbon dates from the outwash deposits indicate that the lower till corresponds to a pre-Dimlington Stadial glacial event (Browne & McMillan 1989; Jacobi *et al.* 2009; Finlayson 2012). This suggests that some of the Type 1 features have been reused by multiple glaciations,

Secondary non-glacial fills appear to be very common. In the east of the Midland Valley, the secondary fills are dominated by glaciomarine deposits (Figs 5, 6, 8), demonstrating that the current area of the Forth was isostatically depressed following deglaciation (Smith *et al.* 2010). To the west, within the Clyde palaeo-valley, the secondary fill is more variable indicating a more complex interplay between isostatically depressed sea-level and subaerial conditions (Browne 1987; Browne & McMillan 1989; Finlayson *et al.* 2010; Finlayson 2012). The palaeo-valleys in the south against the Southern Uplands are buried by glacifluvial sands and gravel deposits and alluvium. This suggests that most of the palaeo-valleys in the Midland Valley of Scotland have been overfilled by glacial and glacial fluvial process and the modern river systems do not have enough energy to remove this sediment.

## Conclusions

The main conclusions from this research are as follows:

- The palaeo-valleys of the Midland Valley of Scotland were created by a range of processes including: glacial over-deepening to form U-shaped valleys; tunnel valleys (or tunnel channels) that may have been incised by subglacial meltwater beneath glaciers and ice sheets; and polygenetic palaeo-valleys that have been formed and shaped by subaerial and subglacial processes.
- The east–west features align with the ice flow at maximum ice-sheet configurations. The shallower features appear more aligned to ice-flow direction during ice-sheet retreat, and were therefore probably incised under more restricted ice-sheet configurations.
- The features are regularly reused and the fills are dominated by glacial fluvial and glacial marine deposits. This suggests that the majority of infilling of the features happened during deglaciation and may be unrelated to the processes that cut them.
- In the Midland Valley of Scotland the bedrock lithology, in which faults juxtapose igneous and sedimentary rocks, influences and enhances the position and depth of palaeo-valleys. The deepest palaeo-valleys occur immediately down-ice of knick-points in the resistant Palaeozoic igneous bedrock. In other lowland glaciated terrains with similar heterolithic bedrock similar features and bedrock control would be expected.

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