Geomorphology of the Continental Shelf

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Abstract

The continental shelf around Scotland covers an area of ~286,500 km^2, around 3.5 times the size of the Scottish landmass. This relatively shallow underwater realm (mainly <200 m water depth) boasts extremely varied geomorphology: from small individual landforms (<100 m^2) to large extensive landsystems (>1000 km^2). These landforms and landsystems relate to both past terrestrial processes, when global sea levels were >100 m lower than at present, and more recent marine processes, active since sea levels rose. This chapter outlines the main geomorphological landsystems found on the shelf, highlighting notable landform examples imaged in high-resolution digital bathymetry data. Many of the landforms have remained exceptionally well preserved since deglaciation, unlike on land, having not been subject to significant disturbance by human activity. The uniquely preserved submarine landforms and landscapes in the shallow seas around Scotland should be protected where possible, especially where they host rare or valuable ecosystems.

Keywords

Glaciation • Multibeam bathymetry • Seabed landforms • Sea-level change • Marine geoconservation

6.1 Introduction

The seabed around Scotland comprises an extremely wide range of geomorphic features and landforms that reflect a variety of environments and processes, past and present, operating over various temporal and spatial scales. These landforms have resulted from tectonic, glacial, paraglacial, mass-movement, fluid-escape, coastal, marine, biogenic and anthropogenic processes. Much of the continental shelf has been periodically covered by ice sheets and other smaller ice masses throughout the Quaternary Period (the last 2.59 Ma), with the last ice sheet reaching its maximum extent at ~30 to 24 ka (Bradwell et al. 2008, 2019a; b; Ballantyne and Small 2019; Chap. 4), during or slightly before the global Last Glacial Maximum (LGM; ~27 to 22 ka). Following ice-sheet retreat, widespread marine inundation of the continental shelf took place with the establishment of marine hydrodynamic conditions. These marine processes continue to modify the seabed environment today.

Formally defined by The Continental Shelf (Designation of Areas) Order 2013, the United Kingdom Continental Shelf (UKCS) encompasses areas of the seabed and sub-surface giving the UK exclusive rights of exploration and exploitation of natural resources within this zone. This Exclusive Economic Zone (EEZ) extends up to 200 nautical miles (370 km) offshore and includes all of the waters adjacent to the UK irrespective of depth (Fig. 6.1). Of the UK EEZ area, Scotland's seas cover ~462,263 km^2 from Mean High Water Springs out to the UKCS limit, an area 6 times the size of Scotland's landmass (Baxter et al. 2011; Scottish Government 2015). Of this vast area, the continental shelf around Scotland covers an area of 286,547 km^2, with

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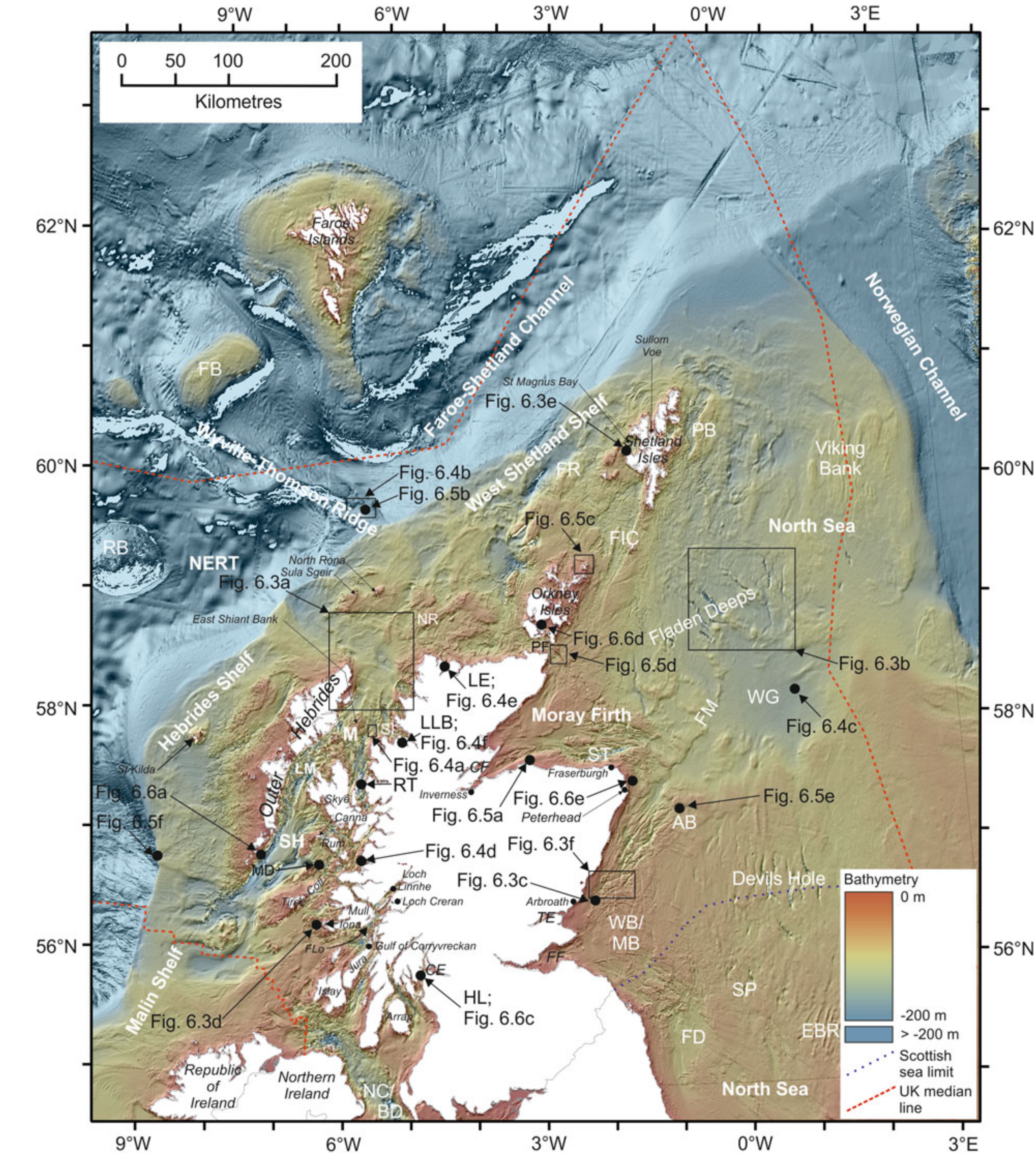

Fig. 6.1 Present-day bathymetry of the continental shelf around Scotland. AB: Aberdeen Bank; BD: Beaufort's Dyke; CE: Clyde Estuary; CF: Cromarty Firth; EBR: East Bank Ridges; FB: Faroe Bank; FD: Farne Deep; FIC: Fair Isle Channel; FM: Fladen Moraine; FF: Firth of Forth; FLo: Firth of Lorne; FR: Foula Ridge; HL: Holy Loch; LE: Loch Eriboll; LLB: Little Loch Broom; LM: Little Minch; M: The Minch; MB: Marr Bank; MD: Muck Deep; NC: North Channel; NERT: North East Rockall Trough; PB: Pobie Bank; PF: Pentland Firth; RB: Rosemary Bank; RT: Raasay Trench; SH: Sea of the Hebrides; SI: Summer Isles; SP: Swallow Pit; ST: Southern Trench; TE: Tay Estuary; WB: Wee Bankie; WG: Witch Ground

Scotland's territorial waters defined as the area within 12 nautical miles (22 km) of the coastline.

The increasing acquisition and availability of high-resolution marine geophysical data over the last two decades have enabled researchers to accurately map seafloor geomorphology, characterize seafloor substrate, identify vulnerable marine ecosystems and manage marine resources. Multibeam bathymetry echosounder (MBES) datasets, in particular, have resulted in a step-change in our understanding of NW European glacial history, and a new understanding of former ice-sheet extent and decay on the continental shelf (e.g. Bradwell et al. 2008; Dunlop et al. 2010; Clark et al. 2012, 2017; Howe et al. 2012; Bradwell and Stoker 2015a, b; Dove et al. 2015). These and other studies co-register high-resolution bathymetry datasets with legacy 2D seismic and geological (core) data to offer new insights on seafloor geomorphology, sub-seabed Quaternary geology and marine ice-sheet behaviour (Ó Cofaigh 2012; Dowdeswell et al. 2016). This chapter highlights the diverse geomorphology of the seabed around Scotland, providing exemplary landforms as case studies.

6.2 Geology, Setting and General Bathymetry

The seabed landscape of the continental shelf comprises striking differences in large-scale geomorphology and smaller-scale landform assemblages east and west of Scotland (Fig. 6.1). The North Sea occupies a shallow epicontinental basin with present water depths typically less than 100 m, generally deepening towards the northern shelf break (at ~200 to 240 m) and eastwards towards the Norwegian Channel (which descends steeply to 550 m). Seafloor depths to the east of Scotland gradually increase with distance offshore, save for a few notable localized deeps in the Moray Firth, the Fladen Ground in the northern North Sea, and offshore Shetland. The east coast of mainland Scotland is notable for the near absence of islands. By contrast, the Hebrides Shelf, to the west of Scotland, has strongly undulating relief culminating in numerous islands, skerries and submerged banks. Furthermore, water depths close to shore west of Scotland often exceed those on the open continental shelf, due to selective glacial erosion exploiting topographical, structural and lithological controls. Good examples of this occur in the Inner Minch and Sea of the Hebrides, where inshore deeps (such as the Muck Deep and Raasay Trench) locally exceed 300 m water depth, greatly exceeding water depths on the Outer Hebrides Shelf (typically 50–130 m below sea level).

The Inner Hebrides Shelf and Minch are confined by the Outer Hebrides in the west and the long, glacially carved coastline of the Scottish mainland to the east. The region incorporates hundreds of islands which, combined with the incised fjordic coastline, corresponds to an extremely complex offshore physiographic environment, characterized by a number of large structurally controlled basins, upstanding volcanic platforms, and glacially over-deepened sea lochs or fjords (McIntyre and Howe 2010). Water depths are variable across this high-relief area, ranging from very shallow (<10 m) to locally very deep (320 m), with a high degree of geomorphological diversity and seabed heterogeneity.

Extensive areas of bedrock occur at seabed around the islands off western Scotland (Fig. 6.1). The well-expressed structural fabric in the Inner Hebrides and The Minch is associated with a series of dominant Late Palaeozoic NNE-trending tectonic faults and basins (Fyfe et al. 1993; Smith 2012; Chap. 2), as well as a number of older and younger intersecting and conjugate faults. The submarine landscape is also punctuated by numerous elongate intrusive igneous structures (e.g. dykes), which most commonly strike NW–SE. Development of NNE-trending basins in both the Inner Hebrides and The Minch modified the pre-existing Precambrian and Early Palaeozoic terrain, with long fault networks along the eastern margin of the Outer Hebrides (Minch Fault) and the eastern margins of Tiree, Coll and Rùm controlling half-grabens that subsequently filled with Mesozoic sedimentary rocks (Fyfe et al. 1993; Stoker et al. 1993; Howe et al. 2015). Due to this tectonic complexity, a range of bedrock strata from Precambrian to Palaeogene age are now exposed at seabed. Broadly speaking, the relatively weak rocks of Mesozoic and Cenozoic age that were predisposed to erosion by repeated Pleistocene glaciation are associated with areas of increased water depth (such as the Little Minch Trough). In contrast, harder crystalline Precambrian basement rocks (e.g. Lewisian Complex), ancient (?meta)sedimentary strata (e.g. Torridonian Group) and volcanic rocks (e.g. Palaeogene volcanics), being more resistant to erosion, remain upstanding (e.g. East Shiant Bank, Nun Rock and North Rona).

Less extensive areas of bedrock crop out at seabed along the North Sea coast, generally only within 5 km of the coast away from the major estuaries around Fife (Carboniferous strata), and from Arbroath to Peterhead (predominantly Dalradian and Devonian strata). There are very few islands offshore eastern Scotland; the small cluster of islands in the Firth of Forth, the subaerial expressions of igneous intrusions, being the most conspicuous. A number of roughly NE–SW trending igneous intrusions crop out at seabed, reaching within 30 m of sea level, ~50 km off the present coastline of SE Scotland (Gatliff et al. 1994).

Holocene sediment cover is patchy and discontinuous on the shelf to the north and west of Scotland. The relative absence of marine (sediment) bedforms in these areas have been attributed to the present hydrodynamic regime, with relatively high current velocities and strong tides removing loose sediment cover and restricting the formation of modern bedforms (Fyfe et al. 1993; Stoker et al. 1993). By contrast, most of the central and northern North Sea is not subject to strong tide- or surge-dominated hydrodynamic conditions; rather, sediment mobility is through wave disturbance, with the exception of the coastal areas of the mainland where tide-dominated currents are typical (Owens 1981). In open ocean settings, such as on the continental shelf west of Scotland, surge-dominated currents predominate with complex semidiurnal tidal cycles and patterns around the intricate, deeply embayed coastline, such as the intense tidal race generated by the Gulf of Corryvreckan (Howe et al. 2015). Stronger current regimes close to the coast and between the Orkney and Shetland islands are responsible for ensuring bedrock remains exposed at seabed.

6.3 Glacial Geomorphology

The onset of the Quaternary Period (2.59 Ma) was marked by intensification of Northern Hemisphere glaciation which strengthened further during the Mid-Pleistocene Transition (~1.25 to 0.7 Ma; Chap. 4). The North Sea Basin preserves evidence for multiple glacial and interglacial cycles within thick sedimentary sequences that capture a detailed record of Northern Hemisphere environmental change (e.g. Graham et al. 2011; Lamb et al. 2017). By contrast, the shelf to the west of Scotland was dominated by glacial erosion during the Mid- to Late Pleistocene and consequently preserves only a discontinuous or partial sedimentary succession in deeper-water basins on the Hebrides Shelf (e.g. Stoker et al. 1993; Stoker and Varming 2011). The largely erosional seabed landscape offshore western Scotland is thought to reflect the impact of fast-flowing ice streams that operated within the British-Irish Ice Sheet (BIIS) on numerous occasions over the last ~1 Ma. These palaeo-ice streams, and their tributaries, dominated the flow pattern and discharge flux of the BIIS (as in present-day Greenland and Antarctica) with the distribution of streaming and non-streaming areas governing the style of subglacial erosion (and/or preservation) of the underlying bedrock landscape (e.g. Hubbard et al. 2009; Bradwell 2013).

Numerous studies have presented and reviewed the evidence for ice-sheet glaciation of the North Sea Basin during the Late Pleistocene (e.g. Gatliff et al. 1994; Graham et al. 2011). High-resolution seismo-acoustic profiles, bathymetric elevation models and shallow marine cores have contributed to a relatively good understanding of the last glacial phase (MIS 2). During this time the BIIS expanded into the central and northern North Sea, and extended to, or close to, the continental shelf edge from the Norwegian Channel and west of Shetland to the Barra–Donegal Fan, NW of Ireland (Bradwell et al. 2008; Graham et al. 2009; Clark et al. 2012, 2017; Sejrup et al. 2016). Detailed seabed mapping of glacial landforms has permitted reconstruction of the pattern of deglaciation following the LGM, at a time of rapidly rising sea levels (Bradwell et al. 2008; Dunlop et al. 2010; Bradwell and Stoker 2015a, b; Dove et al. 2015; Clark et al. 2017; Fig. 6.2). More recently, studies using geomorphological evidence strongly suggest a major dynamic switch in glacial styles on the continental shelf around northern Scotland during deglaciation, from predominantly terrestrial to strongly marine-influenced ice-sheet retreat, resulting in rapid ice-mass losses at key time intervals (Bradwell et al. 2008, 2019a, b; Clark et al. 2012; Sejrup et al. 2016).

6.3.1 Large Moraines

On the mid- and outer shelves, large moraines deposited by the BIIS take the form of broad, curvilinear, sometimes arcuate, occasionally overlapping ridges of glacigenic sediment. These moraines range in length from 5 to 20 km and width from 0.5 to 3.5 km and are typically 10–40 m high (e.g. Stoker and Holmes 1991; Stoker et al. 1993; Bradwell et al. 2008, 2019a, b; Stoker and Varming 2011). The best-preserved examples of these large Late Pleistocene end moraines and glacitectonic push moraines are located on the West Shetland and Hebrides shelves (Figs. 6.2 and 6.3a). These moraines relate to shelf-wide ice-sheet glaciation and many occur adjacent to or directly inshore of large continental slope fans such as the Foula and Rona Wedges, the Sula Sgeir Fan and Barra-Donegal Fan (Stoker et al. 1993; Bradwell et al. 2008; Bradwell and Stoker 2015a). Prominent seafloor ridges 5–40 m high and 1.5–5 km wide extend up to 200 km along the outer West Shetland Shelf (Stoker et al. 2006; Stoker and Varming 2011). Of the large moraines preserved on the Hebrides Shelf, the most distinctive occurs at the shelf edge, is 20–30 m thick, up to 4 km wide and can be traced laterally for around 70 km (Stoker and Holmes 1991; Bradwell and Stoker 2015a). Several ice-marginal moraines on the North Sea Shelf are associated with ice emanating from the Moray Firth (Hall et al. 2003; Bradwell et al. 2008; Sejrup et al. 2009). Perhaps the clearest of these, the Fladen Moraine, forms a ridge 2–6 km wide and 20–30 m high, and is thought to have formed at ~18 to 16 ka (Sejrup et al. 2015; Fig. 6.2). Other large moraines east of mainland Scotland, such as the Wee Bankie and Marr Bank moraine complexes, once thought to mark the LGM offshore ice-sheet limit (Bowen et al. 2002), are now considered to mark significant recessional stages during overall ice-sheet retreat (Golledge and Stoker 2006; Bradwell et al. 2008; Clark et al. 2012; Fig. 6.2).

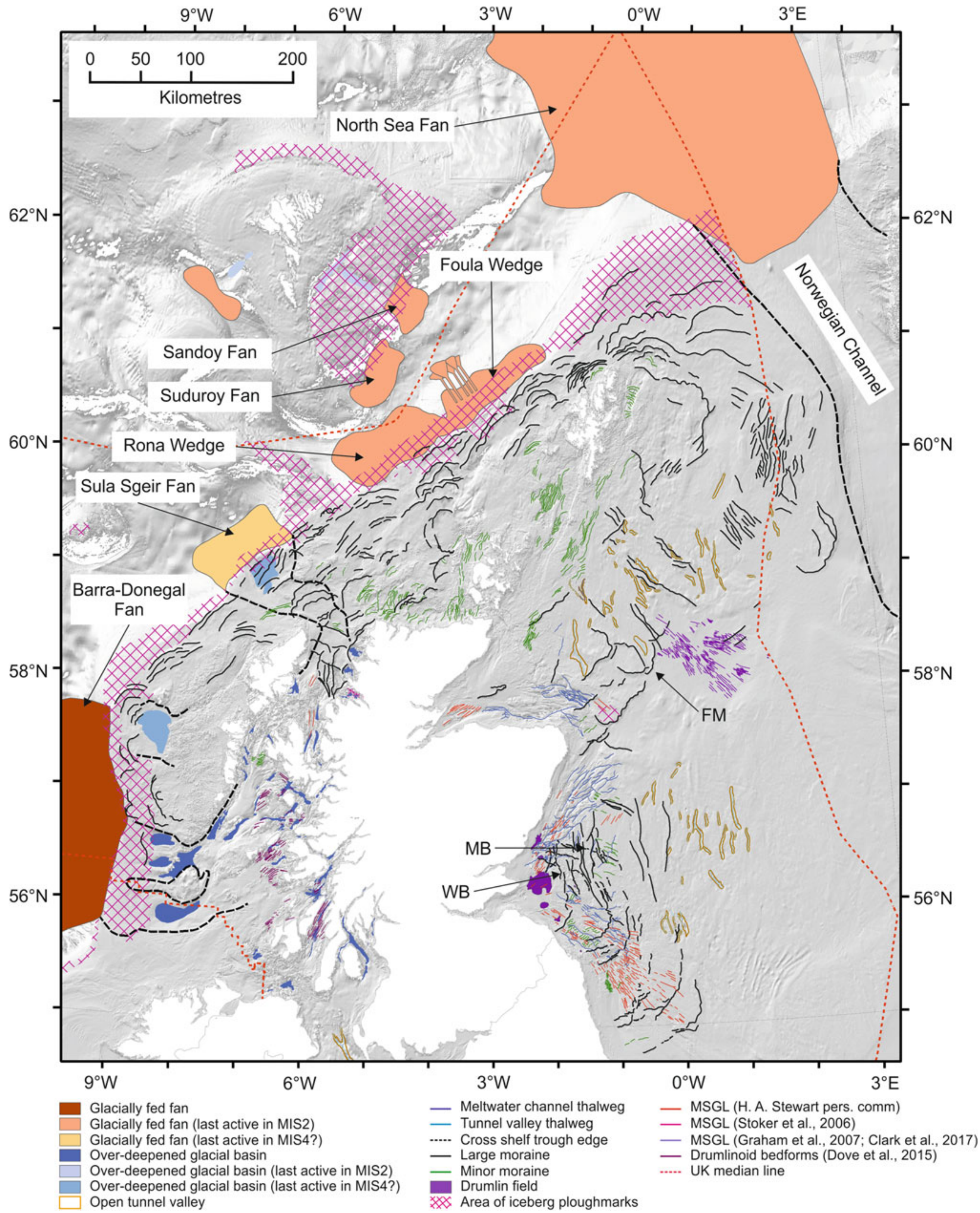

Fig. 6.2 Large-scale subglacial landforms on the continental shelf around Scotland, including: tunnel valleys and streamlined bedforms; ice-marginal landforms represented by large moraines; glacimarine landforms such as trough-mouth fans and iceberg ploughmarks; and glacifluvial landforms such as meltwater channels. MSGL: mega-scale glacial lineation

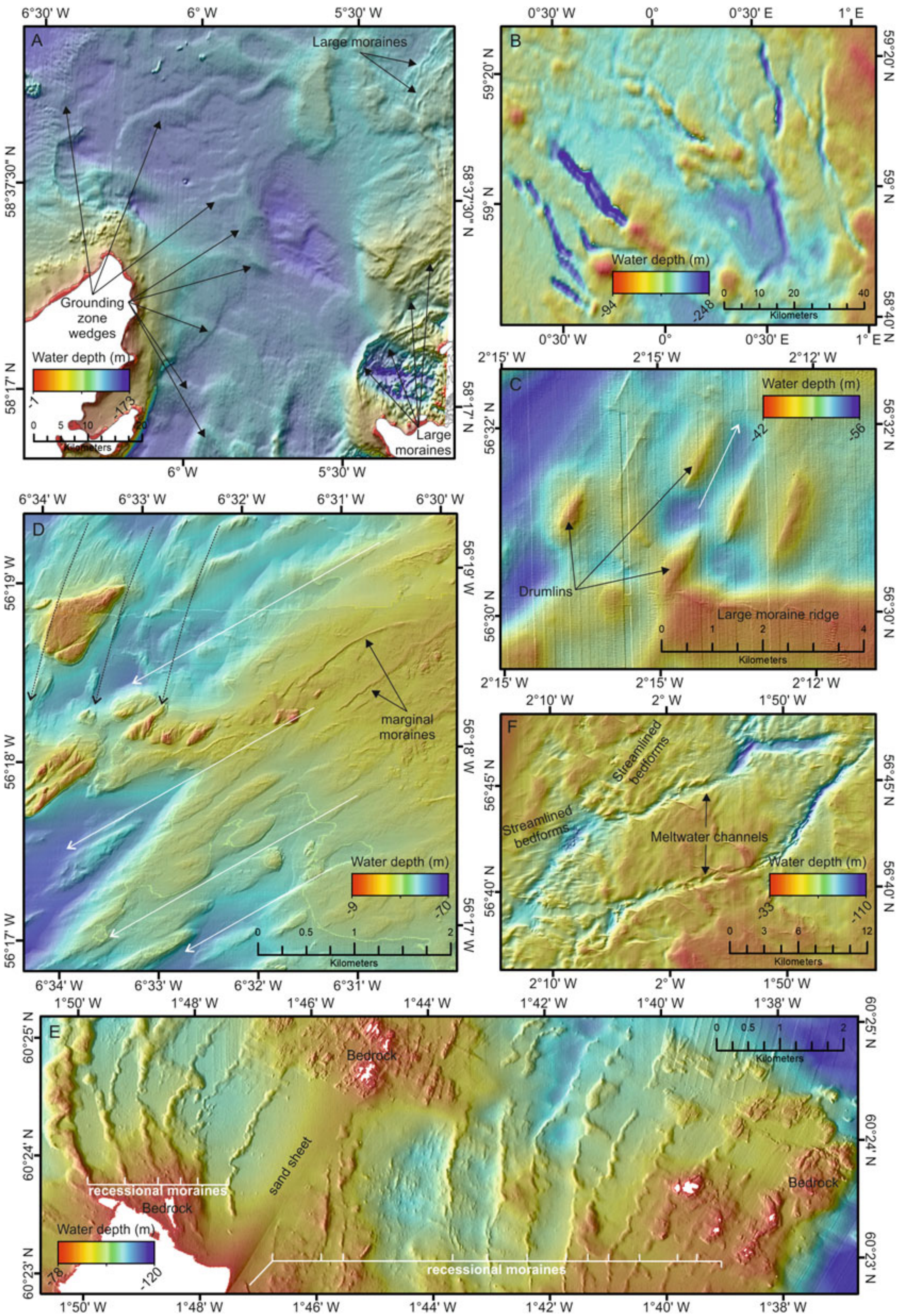

Fig. 6.3 Glacial geomorphology of the seafloor. **a** Example of grounding zone wedges (GZWs) recording grounding-line positions during retreat of the Minch Ice Stream and large moraines mapped in the Minch. **b** The morphology and distribution of a number of large tunnel valleys from Fladen Deeps incised into the seabed, northern North Sea. **c** Drumlin field, part of the offshore expression of the Forth-Tay Ice Stream indicating flow in a NE direction (white arrow). **d** Example of cross-cutting flowsets of streamlined bedforms from the Hebrides Ice Stream, offshore the west coast of Iona. The dominant SW-oriented flow set (white arrows) is superimposed by a later, SSW-directed flow set (black dashed arrows) controlled by local topography. **e** Around 20 recessional moraines demonstrating the stepped eastward retreat of a tidewater ice-margin, St Magnus Bay, west of Shetland. **f** Meltwater channels incised into glacigenic deposits offshore Montrose, eastern Scotland

6.3.2 Grounding-Zone Wedges

Within cross-shelf troughs west of Scotland, broad transverse ridges of glacigenic sediment with very low-angle, asymmetric cross profiles have been mapped as grounding-zone wedges (GZWs; Callard et al. 2018; Bradwell et al. 2019a). GZWs form by the accumulation of glacigenic sediment in the cavity between the ice-sheet grounding line and the projecting (floating or buoyant) ice shelf. Modern examples occur within the tracks of ice streams that have receded, for example on the inner West Greenland Shelf and in the Amundsen Embayment, West Antarctica (Dowdeswell et al. 2016).

Seventeen GZWs (or hybrid forms) have recently been identified within the path of the former Minch Ice Stream off NW Scotland (Bradwell et al. 2019a; Fig. 6.3a). The distribution of GZWs within the Minch ice-stream trough suggests punctuated or episodic recession of the grounding line during overall ice-stream retreat. Bradwell et al. (2019a) related an abrupt reduction in size of GZWs to the geological transition from a soft/weak sediment bed on the outer- and mid-continental shelf to a hard/strong bedrock bed within the Inner Minch. Other GZWs have been identified in the path of the former Hebrides (or Barra-Donegal) Ice Stream on the Malin Shelf, marking episodic retreat of the BIIS from its maximum LGM extent at ~26.7 ka (Arosio et al. 2018; Callard et al. 2018). Fewer GZWs have been identified in the North Sea Basin, possibly owing to the shallower water depths, though a well-developed GZW has been identified by Sejrup et al. (2015) offshore NE Scotland, west of Fladen Ground, indicating ice sourced from the east. Additionally, putative GZWs have recently been identified offshore SE Scotland within the track of the former North Sea Lobe ice stream (Roberts et al. 2019). Although their offshore signature is predominantly beyond Scotland's seas, the most northerly of these GZWs, charting retreat towards the Firth of Forth, is within Scotland's marine realm.

6.3.3 Tunnel Valleys

Tunnel valleys are generally considered to form beneath ice sheets, roughly perpendicular to the ice-sheet margin during deglaciation, and their orientations have been used to infer approximate ice-flow directions (Ó Cofaigh 1996). Tunnel valleys preserved on the seafloor around Scotland (Fig. 6.2) are interpreted as belonging to a single 'generation' relating to LGM ice-sheet deglaciation and MIS 2 flow re-configurations (Stewart 2016).

The most conspicuous bathymetric features within the central and northern North Sea are the Fladen Deeps and Devil's Hole Deeps (Stewart 2016; Fig. 6.1). The Fladen Deeps (Fig. 6.3b) comprise 21 elongate or linear channel-like incisions, the farthest east of which are oriented roughly north–south, whereas the western deeps are oriented roughly NW–SE. The Fladen Deeps range in length from 6.5 to 35 km and are 2–5 km wide; individual channels are incised 50–100 m (maximum 150 m) below the surrounding seabed, attaining maximum water depths of up to 290 m. The Devil's Hole Deeps are located further south and comprise 13 roughly north–south, linear incisions that reach a maximum of ~190 m water depth, incised up to 110 m below the surrounding seabed. The Devil's Hole Deeps range from 10 to 45 km in length and are 2–3.5 km wide.

The largest tunnel valley preserved on the seafloor of the North Sea region is the Southern Trench, in the Moray Firth, which is ~60 km long and up to 210 m deep. The Southern Trench and adjacent east–west oriented deeps close to the Moray and Buchan coasts cut down into Mesozoic bedrock and have been linked to catastrophic meltwater discharge during Late Pleistocene ice-sheet retreat (Long and Stoker 1986). Farther inshore, another seafloor channel oriented roughly NE–SW, located in the Inner Moray Firth, is believed to be an eastward continuation of the Beauly and Ness valleys near Inverness (Chesher and Lawson 1983).

Although clearly defined tunnel valleys are absent from the continental shelf west of Scotland, a number of overdeepened troughs with tunnel-valley-like characteristics are present in the submarine landscape of the Inner Hebrides, most notably west of Muck and north of Rùm (Howe et al. 2012), and Beaufort's Dyke in the North Channel of the Irish Sea between SW Scotland and NE Ireland (Callaway et al. 2011). These tunnel-valley-like glacial overdeepenings have exploited structural weaknesses in the bedrock but, unlike true tunnel valleys, may have formed over more than one glacial cycle.

6.3.4 Streamlined Bedforms

Large, elongate streamlined landforms, comprising sediment- and bedrock-dominated drumlins, crag-and-tail features and mega-scale glacial lineations (also described as mega-flutes and mega-grooves in bedrock) are interpreted to have formed subglacially beneath relatively fast-flowing but firmly grounded ice. The orientation (or long axis) of streamlined forms reflects the former ice-flow direction. Well-preserved examples of streamlined subglacial bedforms offshore Scotland are found in The Minch (Bradwell and Stoker 2015a; Bradwell et al. 2019a), the Inner Sea of the Hebrides (Howe et al. 2012; Dove et al. 2015), offshore eastern Scotland (Golledge and Stoker 2006; Sejrup et al. 2016), in the North Channel (Gandy et al. 2019) and to a lesser degree around Shetland (Bradwell et al. 2019b). Offshore eastern Scotland, highly elongate, flow-parallel, mega-scale glacial lineations and shorter-elongation, flow-aligned drumlins (Fig. 6.3c) are indicative of fast-flowing and persistent ice-sheet flow from both the Forth-Tay and Strathmore Ice Streams during MIS2 (Golledge and Stoker 2006).

Dove et al. (2015) attributed the distribution of streamlined bedforms on the seafloor around the Inner Hebrides to the onset zone of the Hebrides (Barra-Donegal) Ice Stream that drained ~5 to 10% of the BIIS at its maximum extent. The majority of the mapped streamlined bedforms associated with the Hebrides Ice Stream indicate former ice flow to the southwest, although locally bedform orientations can be more variable reflecting topographic and structural influences (Dove et al. 2015). In places, such as off the west coast of Mull and Iona, cross-cutting bedform flowsets suggest ice-sheet re-organization as the dominant SW-directed flow regime evolved into a weaker later-stage SSW-directed flow (Fig. 6.3d).

6.3.5 Smaller (Recessional) Moraines

Suites of similar-sized, relatively small, transverse ridges of glacigenic sediment on the seafloor are interpreted as recessional moraines formed by an intermittently retreating, marine-terminating ice-sheet margin. Typically these more delicate features are <15 m high and 30–200 m wide with fairly regular spacing between ridges (Fig. 6.3e). Often these features are De Geer moraines (a type of recessional moraine), recording the incremental retreat of a grounded tidewater glacier-front over time. The moraines locally overprint streamlined bedforms, thus confirming a deglacial origin and late-stage timing. Where mapped on the continental shelf around Scotland, these suites of recessional (or De Geer) moraines provide important insights into the retreat pattern and style of individual sectors within the last BIIS (Bradwell et al. 2008, 2019b). Comparable modern examples are found at the termini of retreating tidewater glaciers, such as those in the fjords of west Spitsbergen (Ottesen and Dowdeswell 2008; Dowdeswell et al. 2016).

A well-preserved suite of 40–50 recessional De Geer moraines traverse bathymetric highs and deeps and are draped on larger (older) moraines in the vicinity of the Summer Isles in NW Scotland. Identified from high-resolution MBES data (Stoker et al. 2006), these small moraines are indicative of ice-frontal deposition or sediment squeezing during oscillatory retreat of a lightly grounded marine-terminating ice-sheet margin (Bradwell and Stoker 2015a, b, 2016; Chap. 13). Morphologically similar fields of recessional moraines have been identified in the shallow waters around Orkney and Shetland and in the Fair Isle Channel (Bradwell et al. 2008, 2019b; Bradwell and Stoker 2015b). An excellent, well-preserved suite of 20 recessional moraines in St Magnus Bay, west of Shetland (Fig. 6.3e), charts the punctuated retreat of a partially grounded or buoyant tidewater ice-margin during the final stages of ice retreat towards the Shetland mainland at ~18 to 17 ka (Bradwell et al. 2019b). Farther south, discontinuous recessional moraines that occur preferentially on bedrock highs within the Sound of Jura in the Inner Hebrides, are thought to have been deposited following the demise of the Hebrides Ice Stream as tidewater glaciers receded inshore (Dove et al. 2015).

6.3.6 Meltwater Channels

Meltwater channels incised during ice-sheet retreat are relatively common on the Scottish North Sea continental shelf but are less common offshore western Scotland. Such meltwater channels differ from tunnel valleys (Sect. 6.3.3) in that they are subaerial networks of anastomosing channels formed by high water and sediment discharge from a former ice margin, causing incision into both soft/weak sediment beds and hard/strong bedrock beds. Some of the most striking examples trend roughly parallel to the Scottish east coast from Arbroath in the south to Peterhead in the north (Fig. 6.3f). Many are incised into the Marr Bank and Aberdeen Bank glacigenic formations and relate to melting during the later stages of ice-sheet retreat (Golledge and Stoker 2006). This extensive meltwater channel network covers an area that extends ~100 km from south to north and ~85 km from west to east; individual channels range from 200 m to 2.5 km in width, with depths ranging from 10 to 75 m into the surrounding seabed. Other prominent dendritic meltwater channel networks are present 27–40 km northwest of Fraserburgh and elsewhere in the outer Moray Firth.

Within the Sea of the Hebrides, around Rùm and Canna, meltwater channels of complex or composite origin are eroded into both bedrock and sediment. These features, interspersed with drumlinoid bedforms, take the form of weakly sinuous to curvilinear channels 1–6 km long and 200–500 m wide, and are incised 10–50 m below the surrounding seabed. They are thought to have been carved by the flow of both subglacial and proglacial meltwater (Howe et al. 2012). Similar channel features, with complex genesis, occur on the seabed in the vicinity of the Summer Isles and in the eastern Minch (Stoker et al. 2006).

6.4 Glacimarine Geomorphology, Fluid-Escape and Mass-Movement Landforms

Glaciation has left clear geomorphological hallmarks on the seafloor around Scotland (Sect. 6.3). However, the waning of ice masses has also physically modified the submarine landscape in other ways.

6.4.1 Iceberg Ploughmarks

Iceberg ploughmarks are formed where the keels of drifting icebergs gouge and scour the seabed, and may reflect former ocean currents and/or dominant wind patterns. They are usually randomly organized and overlapping in plan view, and have limited water-depth ranges. Individual ploughmarks typically follow an approximately straight or slightly curved course, although 'wandering', sinuous and contorted forms have all been observed on the seafloor in Scottish seas (Long et al. 2011).

Iceberg ploughmarks are found in deep-water localities such as the Malin Shelf (Dunlop et al. 2010), and elsewhere on the tops of topographic highs, on submarine banks, and on the crests of large moraines and GZWs (Bradwell and Stoker 2015a, b; Fig. 6.4a). Large fields of iceberg ploughmarks have also been identified on the outermost portions of the Hebrides and West Shetland shelves (Stevenson et al. 2011; Cotterill and Leslie 2013; Bradwell et al. 2019b; Fig. 6.4b), but are less common on the seafloor of the North Sea, probably due to a paucity of deep-water basins.

Individual ploughmarks typically consist of raised ridges, or berms, separated by shallow depressions generally 20–80 m wide and averaging 1–3 m deep (Long et al. 2011; Stevenson et al. 2011), though exceptionally ploughmarks can exceed 10 m in depth (e.g. Cotterill and Leslie 2013; Stewart and Long 2016). Ploughmarks varying in width and depth, and locally exceeding 100 m from berm to berm, can indicate where icebergs have lodged in the seafloor, forming meltout iceberg pits (Long et al. 2011). Unusually wide (>200 m) linear ploughmarks with shallow U-shaped (width: depth ratio >100:1) or multi-bermed cross profiles have been taken to indicate very large ice-shelf generated icebergs, thought to result from ice-shelf breakup events during retreat of the Minch Ice Stream (Bradwell et al. 2019a).

6.4.2 Pockmarks

Seabed pockmarks are typically formed by the focused expulsion of biogenic or thermogenic fluids from within sub-seabed sediments, resulting in the removal of fine-grained sediments and the creation of a shallow, circular or elliptical depressions in the seafloor (Judd and Hovland 2009). Pockmarks are found sporadically on the continental shelf and in nearshore waters around Scotland, predominantly in muddy, organic-rich sediments. Good examples of large pockmarks occur in deeper mud-laden basins within west coast fjords or sea lochs, or adjacent to fjord mouths (Stoker et al. 2006; Howe et al. 2012; Audsley et al. 2019). Morphometric analysis has shown these large west coast pockmarks range from 100 to 300 m in diameter and are up to 15 m deep (below the surrounding seabed). Some pockmarks form discrete chains, whereas others are elongate depressions thought to be the result of preferential bottom currents (Fig. 6.4c). The age and activity status of pockmarks in Scottish fjordic settings remains uncertain, although some deep pockmarks (>10 m) appear to have been active over a prolonged period judging by the degree of Holocene hemipelagic sedimentation surrounding them (Audsley et al. 2019).

The mud-dominated sediments of the Witch Ground Formation and the fine-grained Flags Formation occur extensively at seabed across much of the central and northern North Sea, and are known to be significant shallow gas-bearing units (Long 1992). This area of the North Sea Basin, near the eastern margin of the UK EEZ, exhibits an unusually high concentration of small pockmarks (30 km^{-2}), typically less than 50 m in diameter. Mapping studies have shown a reduction in pockmark density (<5 km^{-2}) and an increase in pockmark diameter (100–150 m) close to the basin edge (Gafeira et al. 2018). The vast majority of pockmarks within the Witch Ground Basin are less than 3 m deep (Gafeira et al. 2018) and may represent periodic gas-escape activity over at least the last 8 ka (Judd and Hovland 2009). Additionally, several unusually large pockmarks with diameters of up to 450 m and depths of 15–18 m are found in isolation or form pockmark complexes (Fig. 6.4d). These include the 'Scanner', 'Scotia', 'Challenger' and 'Alkor' pockmark complexes, located close to the margins of the Witch Ground Basin, and are thought to have been created during catastrophic gas-escape events (Long 1992; Gafeira et al. 2018; Böttner et al. 2019).

Pockmarks are rare across the mid- to outer West Shetland and Hebrides shelves, although an area ~55 km NE of North Rona hosts a small number of (possibly relict) pockmarks (Stoker et al. 1993) at 80–150 m water depth, and >50 pockmarks have been identified west of Orkney. Other isolated pockmarks have been observed in sub-bottom profiler data from mud-dominated basins east and west of Shetland.

6.4.3 Submarine Landslides

Submarine landslides are associated with a variety of triggering mechanisms, including dynamic loading of contouritic horizons in deeper water, changes in sedimentation

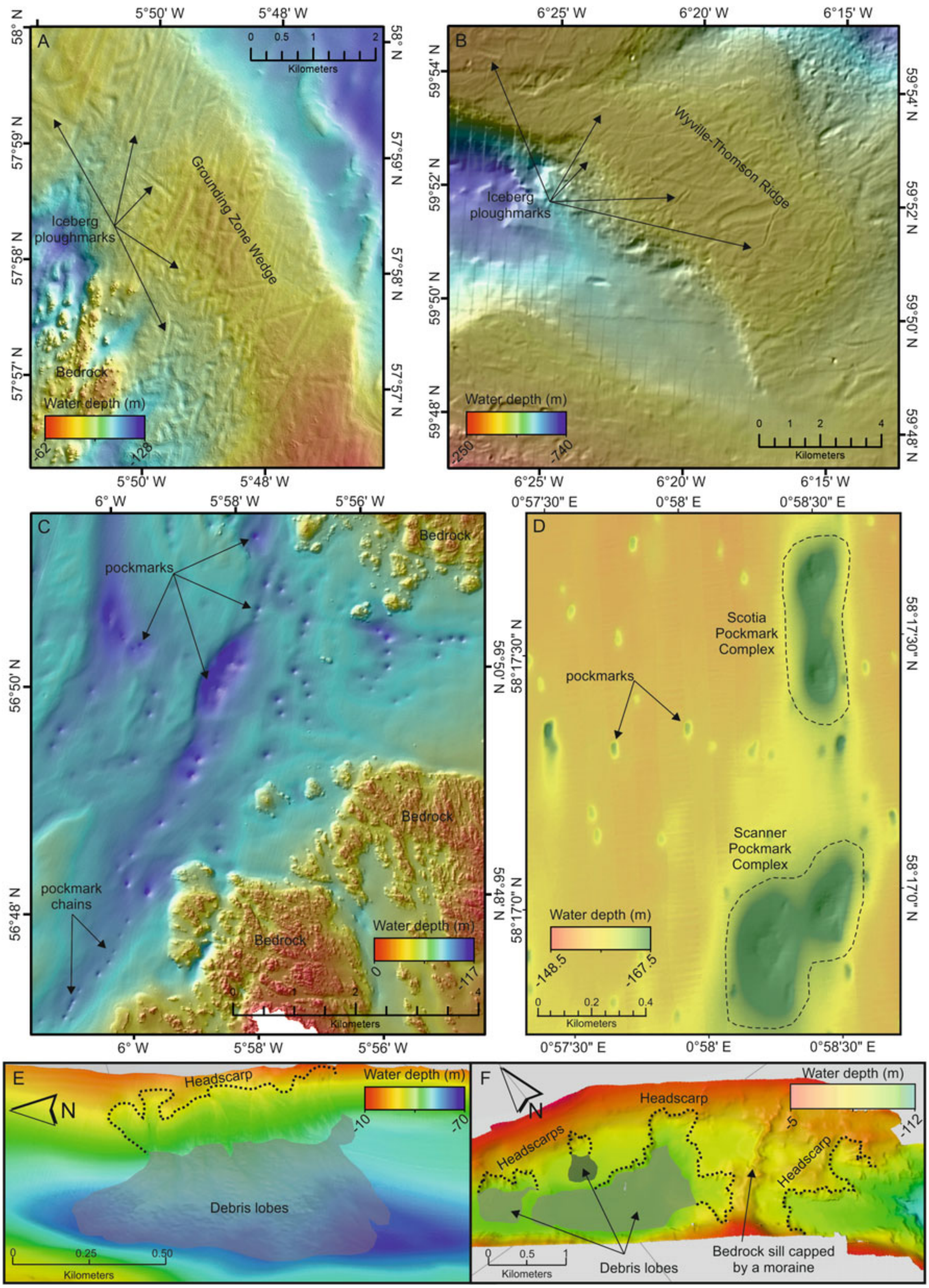

Fig. 6.4 Glacimarine geomorphology, fluid-escape and mass-movement landforms of the seafloor. **a** Iceberg ploughmarks located on the crest of a grounding zone wedge located within The Minch. **b** Iceberg ploughmarks on the Wyville-Thomson Ridge. **c** Example of pockmarks from nearshore fjordic environments and fjord approaches, east of Rùm and near Arisaig. **d** The Scotia and Scanner pockmark complexes. **e** Example of debris lobes, Loch Eriboll. **f** The Little Loch Broom paraglacial slope failures (Scoraig, Carnach, Rireavach and Badcaul slides)

style related to glacial and interglacial cycles, seismicity triggered by glacio-isostatic unloading, and instability due to gas escape.

Submarine slopes have been undergoing periodic readjustment since MIS2 ice-sheet deglaciation, through the Lateglacial period and into the Holocene. The retreat of the BIIS resulted in high sedimentation rates on slopes with thick accumulations of unconsolidated glacimarine and morainic sediments. Ice-sheet loss also radically changed the stress fields in the shallow crust of Scotland and the surrounding continental shelf, resulting in differential unloading and glacio-isostatic uplift rates, with the greatest rebound near the former ice-sheet centre (Smith et al. 2019; Chap. 4). Unsurprisingly, submarine mass-movement features on the continental shelf are mainly confined to steeper slopes within the more neotectonically active areas, such as the fjords of western Scotland.

In NW Scotland, along the eastern submarine slope of Loch Eriboll, a series of submarine debris flows have resulted in multiple scars in soft glacimarine sediments and the build-up of debris lobes up to 4 m thick (Fig. 6.4e). The lack of post-failure sediment cover on the debris lobes indicates a relatively recent event, probably Holocene in age (Carter et al. 2020). More complex submarine mass-wasting features have been identified farther south in the fjords of Wester Ross. Carter et al. (2020) have described several subaqueous mass-movement scars and deposits exhibiting translational, rotational and planar debris-flow failures in the steep-sided fjord of Little Loch Broom (Fig. 6.4f). The large translational and rotational failures of the Little Loch Broom Slide Complex and the Badcaul Slide occurred at ~15 to 13 ka BP, shortly after deglaciation of the fjord (Stoker et al. 2010). Comparable submarine slope failures, evident in MBES data, have been noted in the Sound of Mull, Firth of Lorn, Loch Linnhe and Holy Loch along their steeper glacially modified slope sections. Although undated, these features postdate deglaciation and are very probably Holocene in age (Carter et al. 2020).

In deeper waters, seabed-headwall and slip-surface scars are mainly confined to the continental slopes beyond the West Shetland and Hebrides shelves, and the Rockall Trough. The majority of these mass-movement features have been attributed to the Pleistocene or earlier, including the Sula Sgeir Fan debris-flow deposits along the Hebrides Slope (pre- or Early Devensian), and the multi-event Peach Slide Complex of Late Devensian to Early Holocene age on the northern slopes of the Barra-Donegal Fan (e.g. Evans et al. 2005; Long et al. 2011). On the West Shetland Slope two distinct headwall scars and associated debris-flow deposits are located ~100 km northwest of Shetland. The Afen Slide affects an area of ~40 km^2 and displaced ~0.2 to 0.4 km^3 of sediment; morphological relationships show four stages of failure indicating different modes of sediment transport (hydroplane flows and block slides; Wilson et al. 2004). The Walker Slide is a small (~0.002 km^3) mass movement scar at a similar water depth (850 m) to the Afen Slide but ~17 km to the northeast (Long et al. 2011).

6.5 Marine Landforms and Bedforms

Erosional submarine landforms generated by the action of the sea in the (former) littoral zone are typically cut into bedrock; whereas marine bedforms in the littoral or sublittoral zone are accretionary, mobile and composed of sediment.

6.5.1 Submerged Platforms

Evidence for relative changes in sea level is preserved at seabed around Scotland, primarily in the form of eroded rock platforms that are broadly horizontal with a steep seaward edge, or gently seaward sloping, in water depths of up to 120 m, and potentially up to 155 m. In contrast to the well-studied terrestrial record of relative sea-level change in Scotland (Smith et al. 2019), there have been relatively few investigations of the now-drowned continental shelf.

Smith et al. (2019) have synthesized geomorphic evidence of sea-level change from around Scotland, with prominent submerged platforms identified within the Firth of Lorn (Hall and Rashid 1977), as well as offshore Shetland and Orkney (Flinn 1969; Chaps. 7 and 8). These features are largely eroded across bedrock, where the base level of erosion is a function of the interplay between eustasy, glacio-isostasy and potentially neotectonics. The identification of these features is difficult without high-resolution MBES data and developing chronological constraints is a considerable challenge. Stoker and Graham (1985) have provided the only relative age control on submerged platforms in Scottish waters by ascribing ages to the underlying and overlying strata (through seismostratigraphic analysis), bracketing formation between MIS11 and MIS2. Smith et al. (2019) predicted that with the increased application of MBES data, further submarine evidence of sea-level change is likely to be identified; indeed, recent work around Orkney has identified a pronounced sequence of bedrock platforms or terraces probably relating to former sea levels (Dove et al. 2021).

6.5.2 Sandy Bedforms

Mobile (and relict) marine bedforms, such as sand waves, megaripples, and sand ribbons, are mainly found in areas of sandy seabed on the inner shelf, in shallow estuarine or nearshore settings (e.g. Fig. 6.5a) where the present hydrodynamic conditions are conducive to the movement of clastic sediments.

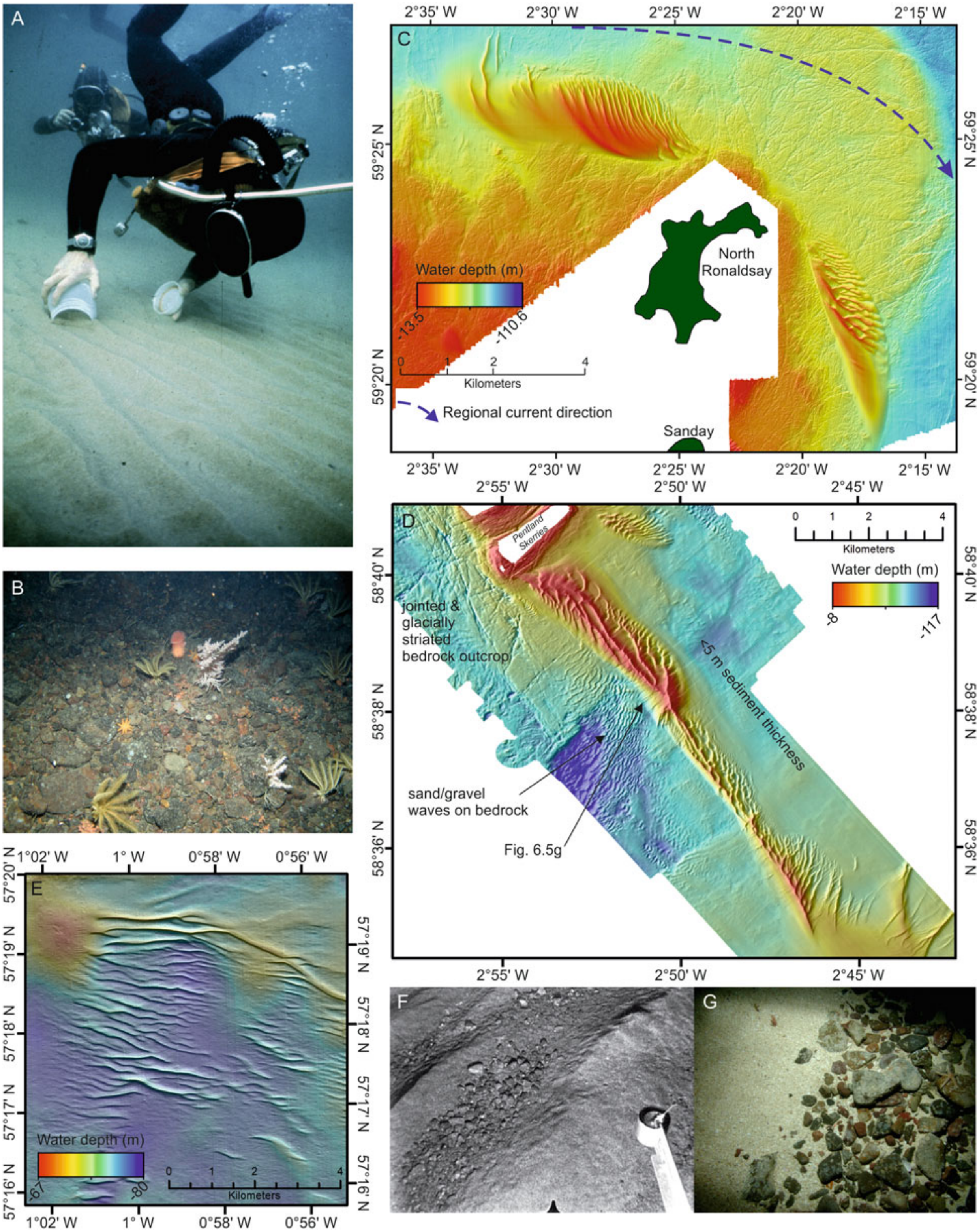

Fig. 6.5 Postglacial marine bedforms of the seafloor. **a** Seafloor photograph of sand ripples offshore Lossiemouth. **b** Cobble gravel on the outer Hebridean Shelf. **c** Well-defined sandbanks located to the north and east of North Ronaldsay, Orkney; the sand waves measure up to ~12 m in height with 200–500 m wavelengths. **d** Sandy Riddle, a large gravel and sandbank located immediately east of the Pentland Firth. **e** Large, relict sand waves in ~75 m water depth, ~50 km offshore eastern Scotland. **f** Parallel linear ripples with gravel-rich troughs on the Outer Hebrides Shelf (after Stow et al. 2002, courtesy of the Geological Society of London). **g** Seafloor photograph showing sediment wave migration, Sandy Riddle. For location see Fig. 6.5d

An abundance of sand waves and megaripples occurs on the seabed in the vicinity of Orkney and Shetland (Stoker et al. 1993). Farrow et al. (1984) reported three large (30 m high, 10 km long and 0.5 km wide) shelly carbonate sand (and gravel) banks northeast of Orkney (Fig. 6.5c). They attributed these conspicuous marine bedforms to the influence of islands and headlands on the local hydrodynamic regime. The orientation of smaller sand waves on these sandbanks, here and in the wider Orkney region, suggests a west to east (broadly clockwise) direction of sediment transport, with storm waves probably playing an important role in sediment mobility. Radiocarbon dates obtained from these sand wave sediments indicate a pre-Holocene age, likely to reflect recycling of older shelly material within the sediments (Farrow et al. 1984).

Farther south, at the eastern entrance to the Pentland Firth, between Caithness and Orkney, is the large 'Sandy Riddle' banner bank (Fig. 6.5d). This large, complex marine bedform consists of an asymmetric sandbank, 10–12 km long, 1–2 km wide and ~60 m high, formed of calcareous coarse sand and gravel mainly deposited during the Holocene. However, the sandbank may have formed atop a core of pre-existing glacigenic sediment (Fairley et al. 2015). Active mobile sand waves and megaripples, up to 10 m high and 80–200 m in wavelength, are superimposed on the flanks of Sandy Riddle. Smaller but equally active sand wave fields, west of Stroma within the Pentland Firth, have wavelengths of up to 400 m, and occur in medium to coarse sands. Tidal currents here average 2.0 m s^{-1} and can exceed 5.0 m s^{-1}, one of the strongest tidal streams in European waters (Fairley et al. 2015).

Large sand waves (with heights of up to 17 m and wavelengths of 200 m) occur in shallow coastal waters around Peterhead, often with smaller sand waves or climbing megaripples on their stoss sides (Gatliff et al. 1994). Farther offshore (~50 km east of Peterhead) there are large sand waves 8 m high, with 160–270 m wavelengths, in water depths of 60–80 m. This area presently experiences surface tidal currents of only 0.3–0.5 m s^{-1}, and the sand waves are thought to be relict features that are now mobile under extreme storm conditions or perhaps relate to a period of low relative sea level (>10 m below present) during the Early Holocene (Owens 1981; Gatliff et al. 1994; Fig. 6.5e).

West of Scotland, on the Hebrides Shelf, the direction of sediment transport is generally from south to north (Inall et al. 2009). Asymmetric sand waves occur as isolated features or clustered in fields closer to shore, for example in the Sound of Harris and off the west coast of Lewis. Long sand ribbons are present around many of the Outer Hebrides islands, where tidal currents are consistently high (>1.0 m s^{-1}) and locally focused (Stoker et al. 1993). Sand streaks, sand ribbons and longitudinal sand patches are widespread on the West Shetland and Hebrides shelves where they range in size from several metres up to several hundreds of metres in width and up to a few kilometres in length (Stevenson et al. 2011; Cotterill and Leslie 2013). In places, these thin mobile bedforms overlie gravel lags or have gravel-rich troughs within them (Fig. 6.5f, g).

6.5.3 Gravel Bedforms

Gravel-dominated bedforms are rarer on the continental shelf, but gravel lags (Fig. 6.5b) are not uncommon across the shelf, especially in shallower waters around large mid-shelf bathymetric highs such as Sula Sgeir, North Rona and the Outer Hebrides Platform. In general, the terrigenous gravelly sediments offshore Scotland have been winnowed from the underlying Pleistocene deposits (e.g. glacial diamict) during the Lateglacial to Early Holocene marine transgression. This has resulted in the formation of lag deposits consisting of poorly sorted, subangular to subrounded lithic clasts of gravel grade (Fig. 6.5b, f). On the outer continental shelves, characterized by iceberg ploughmarks, irregular gravel ridges are prevalent, slightly raised above the general level of the otherwise sandy seafloor.

The seabed on much of the Orkney-Shetland Platform exhibits winnowed gravel lag accumulations, as do the isolated bathymetric highs of the Pobie Bank and Viking Bank where gravel deposits are common. Farther south, in the eastern North Sea, bathymetric highs such as the Marr Bank and Aberdeen Bank are also covered in extensive gravel lag deposits (Johnson et al. 1993; Gatliff et al. 1994). Wewetzer et al. (1999) reported abundant gravelly sand dunes, 0.5 m in height and 2–10 m in wavelength, in the middle Tay estuary in water depths of <10 m.

The North Channel between SW Scotland and NE Ireland is an area of high peak-tidal currents in excess of 1.5 m s^{-1}. The seabed here hosts transverse gravel ridges draped on bedrock. These low-relief gravel bedforms are 1 m wide, up to 0.6 m high, and reach 1.25 km in length (Fyfe et al. 1993).

6.6 Reefs as Biogenic Landforms

Biogenic seabed structures are created by the marine flora and fauna in the benthic zone (Gordon et al. 2016), potentially comprising the organism itself (e.g. maerl beds, horse mussels beds and *Sabellaria* spp.), or arising from the organism's activities (e.g. whale feeding marks) or the effects of biota on other hydrodynamic and sedimentation patterns (e.g. cold-water coral sediment mounds). Very few biogenic structures in extra-tropical oceans are large enough to be classed as submarine landforms in their own right. However, cold-water coral reefs function as 'ecosystem engineers', trapping sediments, altering local oceanographic currents and providing a refuge for other organisms. A rare example of an extensive cold-water coral reef within Scotland's territorial waters is the Mingulay Reef Complex in the Sea of the Hebrides, which comprises several areas supporting reef mounds preferentially located on bedrock highs. De Clippele et al. (2017) delineated over 500 *Lophelia pertusa* 'mini-mounds' between 13 and 60 m wide and up to ~100 m long located on one ridge named 'Mingulay Reef 01' (Fig. 6.6a, b). Cold-water coral reefs are both long-lived and slow-growing, and are therefore vulnerable to damage from fishing activities and climate change.

Large spreads of seabed gravel with abundant sessile (attached) and mobile biota may technically fall within the definition of 'reefs' as specified in the UK, European and International legislation. Areas of coarse gravel, or stony reef, provide important seabed habitats, for example as spawning areas for fish, and form areas for encrusting organisms to attach. Bivalve fragments tend to dominate the biogenic sands and gravels west of Orkney and the Outer Hebrides, whereas barnacles and attached serpulid worms form the larger component in inshore waters around Shetland (Gatliff et al. 1994).

6.7 Marine Geoconservation

Disturbance to seabed geomorphology from human activities takes many forms arising, for example, from fishing, dredging, anchoring of vessels and platforms, hydrocarbon exploration and offshore renewable-energy installations. The impact of recreational moorings on local biogenic reefs is evident in Loch Creran, Argyll, where damage has intensified in recent decades. Industrial platforms used in the hydrocarbon industry are fabricated and serviced in the Cromarty Firth and Clyde estuary, leaving 'spud can' footprints and mooring scours on the seafloor.

Perhaps the best-documented anthropogenic seabed landforms are those within Holy Loch, Argyll. Holy Loch was used as a naval base during World War II, and then as a US Navy submarine base for more than 30 years until 1992 (Miller et al. 2000). Evidence of this naval activity is still visible on the seafloor (Fig. 6.6c), where linear scour marks created by heavy mooring chains secured to the floating naval docks are visible in MBES data. It is reasonable to assume that in a relatively compact, shallow inlet like Holy Loch, vessels would have made contact with the seafloor numerous times, particularly in the nearshore zone.

Physical anthropogenic structures on the seafloor, such as shipwrecks (Fig. 6.6d), pipelines (Fig. 6.6e) and cables, may alter the local hydrodynamic regime, resulting in scour and remobilization of sediments, but can also form a substrate or refuge for marine organisms, such as the artificial reefs in Loch Linnhe. Since hydrocarbon exploration began in earnest in the North Sea Basin in the 1960s, extracted hydrocarbons have been transported to onshore terminals such as at St Fergus, north of Peterhead (Fig. 6.6e), and Sullom Voe in Shetland. At these terminals, a number of pipelines converge and make landfall in the nearshore zone, sometimes resulting in their unplanned burial, exposure or suspension as a result of disturbance to sediment transport pathways.

Scotland's National Marine Plan (Scottish Government 2015) provides an overarching legislative framework for the implementation of the Marine (Scotland) Act 2010 and the Marine and Coastal Access Act 2009, both in protecting the marine environment and enabling sustainable development of existing and emerging marine industries. It requires a holistic approach that values both geodiversity and biodiversity and the interactions between them (Gray et al. 2013). In 2018, the Scottish Marine Protected Area (MPA) Network covered approximately 22% of Scotland's seas, comprising 231 sites that will deliver the Scottish Government's vision of clean, healthy, safe, productive and biologically and geologically diverse marine and coastal environments (Scottish Government 2018).

Increased knowledge of seafloor geomorphology and submarine landscapes around Scotland, coupled with research into seabed substrate integrity and biodiversity, has resulted in marine geoconservation rising in prominence at national, European and international levels (Gordon et al. 2016, 2018). A number of the seafloor geomorphological features described in this chapter reside within the existing MPA network, for example the Firth of Forth Banks Complex MPA (Wee Bankie moraine), Central Fladen MPA (tunnel valleys), the Wester Ross MPA (subaqueous De Geer moraines, submarine landslides and pockmarks) and the Scanner Pockmark Special Area of Conservation (Gordon et al. 2016). However, given the exceptional preservation of this integral part of Scotland's geoheritage and the direct linkages between geodiversity and biodiversity, there is scope for future inclusion of other geoheritage features. This is especially important within Scotland's seas where glacial processes have shaped much of the current seabed topography and glacial deposits generally determine seabed sediment composition, both of which fundamentally impact the benthic community composition and distribution.

6.8 Conclusions

The seabed around Scotland hosts an extremely wide range of landforms, from steep-sided fjords and broad sandy beaches across the highly varied terrain of the continental shelf to the deep water of the continental slope. The broad-scale geomorphology of the submarine continental shelf, 3.5 times

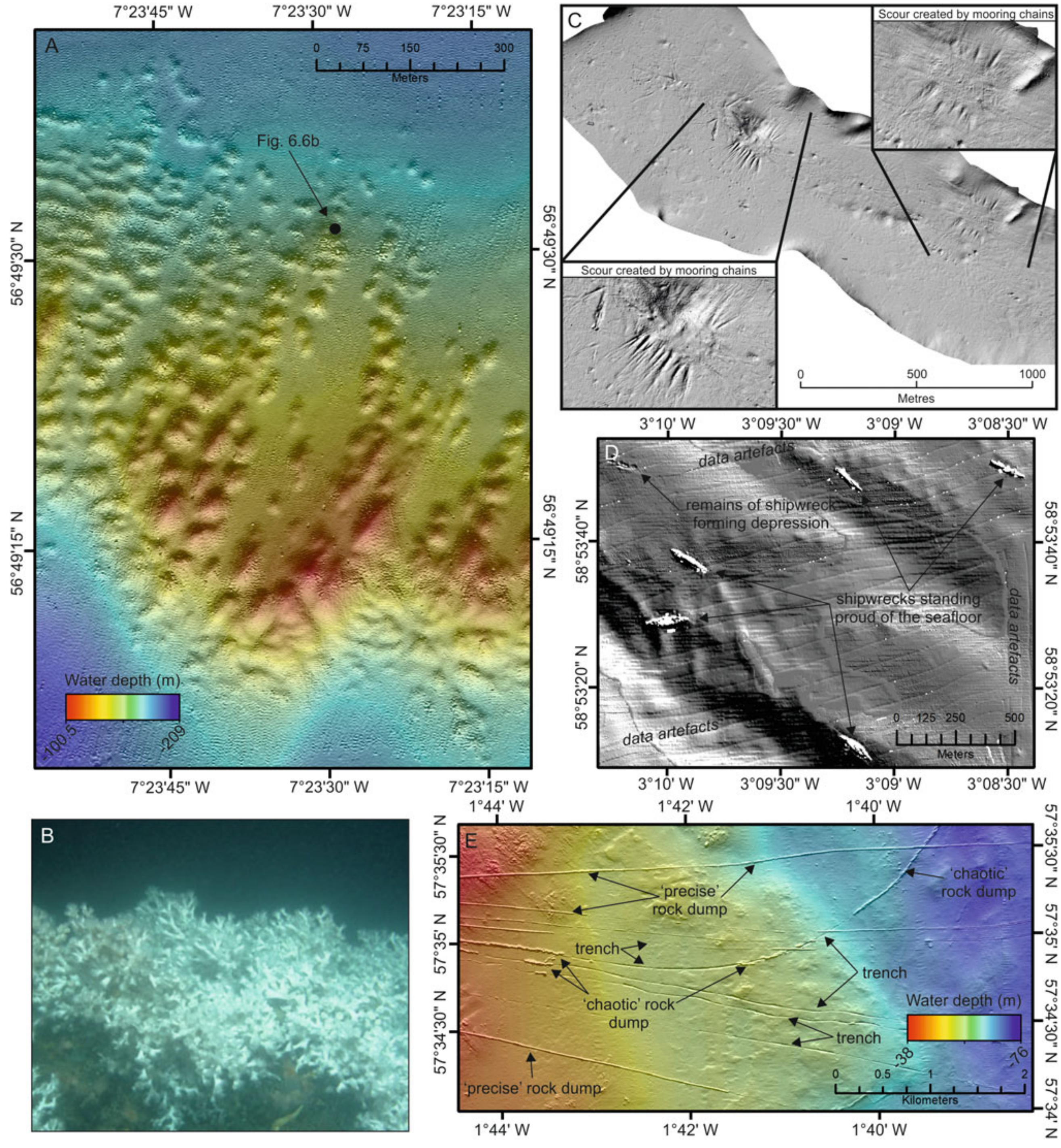

Fig. 6.6 Biogenic and anthropogenic landforms of the seafloor. **a** Part of the Mingulay Reef Complex ('Mingulay Reef 01') showing numerous biogenic sediment mounds. **b** Seafloor photograph of live coral colony from the 'Mingulay Reef 01'. For location see Fig. 6.6a. **c** Image highlighting areas of anthropogenic activity on the floor of Holy Loch (after Carter et al. 2020). **d** A small selection of shipwrecks in Scapa Flow, Orkney. **e** Pipelines making landfall at St Fergus Gas Terminal, NE Scotland

the size of the Scottish landmass, owes much to the Cenozoic geological history of NW Europe. Superimposed on this, at a smaller scale, is a vast, varied and largely well-preserved array of submarine landforms recording key global and regional events spanning the last ~1 Ma. These events include the onset, flow pattern and retreat of the last ice sheets; ice-shelf breakup and iceberg trajectories; Quaternary sea-level change and crustal movements;

earthquake-induced submarine slope failures; temporal changes in hydrodynamic regime; and episodic natural gas venting. Some of the landforms described here are amongst the best examples of their kind in Europe, with many remaining exceptionally well-preserved since deglaciation. However, human disturbance of the seabed has been increasing over the last 50–60 years, with geomorphological evidence of the commercial fishing, hydrocarbon extraction and renewable energy industries all clearly evident on the seabed. In the last decade, offshore activities have been geographically restricted with the introduction of government legislation ('The Marine Acts' (2009, 2010) and the Scottish National Marine Plan (2015)) and the subsequent establishment of the Marine Protected Areas network—now covering around 22% of Scotland's seabed. In the coming decade, further conservation of Scotland's unique submarine geoheritage and seabed geomorphology should be encouraged, especially where these landforms host rare or valuable ecosystems.

Acknowledgements Regional bathymetry data displayed in Figs. 6.1, 6.2, 6.3a, b are derived from the EMODNET Digital Terrain Model for European Seas (www.emodnet-hydrography.eu). MBES data presented in Figs. 6.3c–f, 6.4a, c, 6.5c, e, 6.6d, e were acquired as part of the Civil Hydrography Programme (CHP) on behalf of the Maritime and Coastguard Agency (MCA) and made available to the British Geological Survey (BGS) through an agreement with the MCA. MBES data displayed in Figs. 6.4e, f and 6.6c were acquired by the BGS. Acquisition of MBES data and photographs shown in Figs. 6.4d, 6.5d, g was funded by the Department for Business, Energy and Industrial Strategy's Offshore Energy Strategic Environmental Assessment programme areas 5 and 2; Crown Copyright, all rights reserved. The collection of MBES data and photographs shown in Figs. 6.4b and 6.5b was funded by the Department for Business, Energy and Industrial Strategy's Offshore Energy Strategic Environmental Assessment programme area 7 and the Department for Environment, Food and Rural Affairs through their advisors, the Joint Nature Conservation Committee, and the offshore Special Areas for Conservation programme; Crown Copyright, all rights reserved. MBES data shown in Fig. 6.6a were acquired as part of the MINCH project on board the RV *Lough Foyle*. Photograph Fig. 6.6b was collected during the Changing Oceans Expedition 2012 (Cruise JC073) University of Edinburgh. BGS authors publish with the permission of the Executive Director of the BGS (United Kingdom Research and Innovation).

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