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Quaternary Sea Level Change in Scotland

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Abstract

This paper summarises developments in understanding sea level change during the Quaternary in Scotland since the publication of the Geological Conservation Review volume Quaternary of Scotland in 1993. We present a review of progress in methodology, particularly in the study of sediments in isolation basins and estuaries as well as in techniques in the field and laboratory, which have together disclosed greater detail in the record of relative sea level (RSL) change than was available in 1993. However, progress in determining the record of RSL change varies in different areas. Studies of sediments and stratigraphy offshore on the continental shelf have increased greatly, but the record of RSL change there remains patchy. Studies onshore have resulted in improvements in the knowledge of rock shorelines, including the processes by which they are formed, but much remains to be understood. Studies of Late Devensian and Holocene RSLs around present coasts have improved knowledge of both the extent and age range of the evidence. The record of RSL change on the W and NW coasts has disclosed a much longer dated RSL record than was available before 1993, possibly with evidence of Meltwater Pulse 1A, while studies in estuaries on the E and SW coasts have disclosed widespread and consistent fluctuations in Holocene RSLs. Evidence for the meltwater pulse associated with the Early Holocene discharge of Lakes Agassiz-Ojibway in N America has been found on both E and W coasts. The effects of the impact of storminess, in particular in cliff-top storm deposits, have been widely identified. Further information on the Holocene Storegga Slide tsunami has enabled a better understanding of the event but evidence for other tsunami events on Scottish coasts remains uncertain. Methodological developments have led to new reconstructions of RSL change for the last 2000 years, utilising state-of-the-art GIA models and alongside coastal biostratigraphy to determine trends to compare with modern tide gauge and documentary evidence. Developments in GIA modelling have provided valuable information on patterns of land uplift during and following deglaciation. The studies undertaken raise a number of research questions which will require addressing in future work.

Key words: Carseland, continental shelf, glacial isostatic adjustment, isolation basin, relative sea level, rock shoreline, storms, tsunamis.

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Sea level changes around Scottish coasts have been remarked on for over 300 years. Accounts describe the great variety of shore features displaced above present sea levels from the raised estuarine sediments, locally known as "carse", in the "carselands" of the E and S, to the extensive raised rock platforms of the W. Important concepts in understanding the processes involved in sea level change were first identified in Scotland, for example glacio-eustasy (Maclaren 1842), glacio-isostasy (Jamieson 1865) and shoreline diachroneity (Wright 1914, 1925). Building on a rich heritage of ideas, modern studies of sea level change in Scotland owe much to J.B. Sissons, whose research (e.g. 1962, 1966, 1972, 1974a, 1981 and Sissons *et al*. 1966) greatly influenced later work. Detailed field and laboratory studies continue to disclose relative sea level (RSL) changes, while models of glacial isostatic adjustment (GIA) and shoreline-based isobase models now provide the context for such changes.

This review takes as its bench mark the Quaternary of Scotland Geological Conservation Review (GCR) volume (Gordon & Sutherland 1993). It comprises sections contributed by research scientists working in the field of Scottish sea levels. It examines developments which have taken place since 1993 in (1) methodologies and techniques; (2) studies of both offshore and onshore evidence for RSL change and extreme events; and (3) GIA modelling. Key research questions are identified. All dates are given in sidereal (calibrated) years before AD1950 (BP). Where individual dates are quoted, a 2σ range is given. Where several dates are quoted, as for a specific event, the total range and number of dates is given. Otherwise, approximate ages are expressed in thousands of years BP, thus "19ka". Altitudes are quoted with respect to Ordnance Datum Newlyn (OD), with a few unsurveyed altitudes recorded as above sea level (asl). In this paper, Late Devensian is taken as the period from the maximum of the Devensian in Scotland to the end of the Younger Dryas, or from 26ka BP, to 11.7ka BP and Lateglacial is the period of the Windermere Interstadial (15ka BP to 12.9ka BP) and the Younger Dryas (12.9ka BP to 11.7ka BP). The Holocene is divided into Early (11.7ka BP to 8.2ka BP), Middle (8.2ka BP to 4.2ka BP) and Late (4.2ka BP to present) following Walker *et al*. (2012). Locations discussed in this paper are shown in Figures 1 and 7.

1. Methodology and techniques

David Smith and Jason Jordan

1.1. Methodology

A major development which began in 1993 is the work on isolation basins. Isolation basins are closed depressions in the coastal landscape already present before changes in RSL occurred. These depressions, in rock or glacial sediments, may at different times have been either connected to or isolated from the sea by changes in RSL. Isolation basin sediments, deposited in a low energy environment, can provide information on changes in the nearshore and sometimes offshore marine environment, while the lowest elevation on the threshold or sill of the basin provides a measure of RSL altitude at the point in time when the basin was flooded by or isolated from the sea during episodes of RSL change. The methodology was probably originally developed in Sweden, where Sundelin (1917) studied basins at the margins of the Baltic Ice Lake. It was first applied in Scotland at Arisaig (Shennan *et al.* 1993) and since then has been applied at several sites in western Scotland, largely by Shennan and co-workers (e.g. Shennan *et al.* 2000a).

The study of estuaries and coastal embayments continuously connected to the sea, and with sedimentary records of RSL in low energy environments, has increased. Most such studies since 1993 have been in the estuarine carselands of eastern and south-western Scotland (e.g. Smith *et al.* 2003a, 2010), but less accessible estuarine areas and coastal embayments in northern Scotland and the Outer Hebrides have also provided information on RSL change (e.g. Smith *et al.* 2012). Together with the results of isolation basin studies, these developments have provided an increasingly detailed picture of RSL change in the Late Devensian and Holocene in Scotland. However, there are differences in approach between the two methods. Studies in carseland areas now routinely use Mean High Water Spring Tides (MHWST) from the nearest tidal station in a comparable setting as well as OD as a datum, having established that the carseland is a former saltmarsh surface, the landward margin of which approximates to MHWST (e.g. Smith *et al.* 2003a). Studies of isolation basins and coastal marshland areas on the W coast, using detailed microfossil and stratigraphical evidence, compare the horizons they date with the tidal frame in establishing a reference water level, in addition to OD (e.g. Shennan *et al.* 1993, 1994). Both approaches base graphs of RSL change on sea level index points (SLIPs), identifying transgressive and regressive overlaps as defined by Tooley (e.g. 1982) and with limiting points defining the limits of evidence for RSL in the stratigraphy (see Figs 8 and 9 below). Both approaches recognise error margins in the altitudes obtained, both in tidal frame estimates as well as in survey. In estuarine sites estimates for sediment compaction are provided. Full details of error margin estimates are given in the works quoted, notably in Shennan *et al.* (e.g. 1995a, 2000a) and

Smith *et al.* (e.g. 2003a). In registering RSL change, isolation basin sediments and estuarine sediments each have their benefits: isolation basin sediments can be more accurate than estuarine sediments provided the threshold (across which the changing RSL rose and fell) is accurately known, whereas estuarine sediments provide greater continuity. However, each method is appropriate to the topographical setting: isolation basins on W and NW coasts and estuaries mainly on SW and E coasts.

An important development since 1993 has been in the modelling of spatial patterns of GIA. Before then, glacio-isostatic uplift for Scotland as a whole was identified in terms of generalised isobase maps based upon altitude measurements of former shorelines (e.g. Sissons 1976; Jardine 1982) or modelled isobase maps for specific areas (Smith *et al.* 1969; Gray 1978). Graphs of RSL change for specific locations based upon GIA modelling (e.g. Lambeck 1991a, 1991b) were produced, but no modelled isobase maps for Scotland as a whole provided. Since 1993, GIA models based upon geophysical, rheological, water and ice loading parameters in both the near and far field (e.g. Lambeck 1993a, 1993b, 1995; Bradley *et al.* 2011; Shennan *et al.* 2012) depicting patterns of uplift for Scotland as a whole have been produced. These have been further improved in recent years with the advent of terrain correction (Shennan *et al.* 2006a), particularly important in an area with considerable local variation in topography (Fretwell *et al.* 2008). At the same time, models based upon the statistical analysis of shoreline altitudes have been produced. These models have normally involved polynomial quadratic trend surfaces (e.g. Smith *et al.* 2000, 2002) but recently a new approach employing Gaussian quadratic trend surfaces (e.g. Fretwell *et al.* 2004; Smith *et al.* 2006, 2012), provides a better fit than polynomial trend surfaces and has the additional benefit of defining a zero level for the surfaces computed. Modelling approaches to isostatic uplift in Scotland were recently reviewed by Stockamp *et al*. (2016).

1.2. Techniques

Since 1993, the study of RSL change in Scotland has seen improvements in the techniques used. Offshore, high resolution survey methods have disclosed increasing detail of the sea floor. Onshore, morphological studies supported by instrumental survey are now regularly used. Stratigraphical work is commonly more detailed than previously and has benefited from a greater concentration of boreholes in order to more accurately reconstruct underlying stratigraphy. This is exemplified by detailed work in isolation basin studies (e.g. Shennan *et al.* 1993). Powered coring systems are increasingly used, especially in the carseland areas (e.g. Holloway 2002) and in low lying machair locations of the Western Isles (e.g. Jordan *et al*. 2010). There has been increasing interest in sediment structures (e.g. Barrass & Paul 1999; Tooley & Smith 2005).

Microfossil studies now frequently employ new biological proxies in addition to pollen and diatoms, notably in isolation basin studies. Thus, Shennan *et al*. (e.g. 1996, 2000a, 2006) used dinoflagellate cysts, foraminifera and thecamoebians in reconstructing RSL change at several locations in W and NW Scotland, while Lloyd (2000) employed foraminifera and theocamoebians in order to reconstruct the majority of the Holocene sequence from Loch nan Corr in NW Scotland. Smith *et al*. (2003a) used ostracods and foraminifera in a study in the Cree valley, SW Scotland.

With the increased use of newer techniques and proxies, the need to better understand modern sedimentation and the current environmental conditions of coastal sites has led to the development of contemporary analogue studies. For example, Lloyd and Evans (2002) employed the use of contemporary analogues of foraminifera to better understand the palaeodepositional processes affecting fossil assemblages. The natural development of this mode of research has been to extend the statistical measurement of changes via a transfer function approach, as in western Scotland (e.g. Zong & Horton 1999; Barlow *et al.* 2014). Transfer functions aim to explore the relationship between tidal level and the habitat range of microfossils, which once determined, allow the former RSLs to be identified alongside radiometric dating of the relevant horizons. The determination of sedimentation rates in modern saltmarshes allows further inference to be made about the fossil structures. The use of the natural radionuclide Pb^{210} and anthropogenically produced Cs^{137} has been used in the Firth of Lorn area and Mull (Teasdale *et al.* 2011) as well as in NW Scotland (Barlow *et al.* 2014), in order to determine accretion rates.

2. Quaternary sea levels on the continental shelf

David Long

Due to surveying techniques and constraints in obtaining samples offshore the evidence used to determine former sea levels differs from that used onshore. As the volume of material available for physical examination is very small, evidence of former sea levels normally consists of indirect evidence of former water depths differing from those at present and often with limited dating control (locations discussed are shown in Fig. 1).

As global sea levels changed during the Quaternary the extensive continental shelf around Scotland has seen dramatic environmental changes. However, much of the evidence for the level and position of former shorelines has been disturbed by the last episode of coalesced British and Scandinavian Ice Sheets (Graham *et al.* 2007; Bradwell *et al.* 2008; Sejrup *et al.,* 2016) that extended in many places to the shelf edge. Beyond the shelf edge the extent of iceberg scouring provides some indication as to contemporary sea level as scouring intensity and extent of cross-cutting reflect palaeo-bathymetry. Iceberg scours have been identified to more than 500m below present on the West Shetland Slope, and around both Rockall and Hatton banks with extensive sea bed scouring by icebergs on the outer shelf and topmost slope (e.g. Jacobs 2006). By comparison with modern ice fronts this suggests sea levels more than 100m below present in the outer parts of Scotland's offshore area.

Recent detailed sea floor morphological studies show that the retreat and breakup of the last ice sheet was probably strongly controlled by sea level (Bradwell *et al.* 2008). Calving drove ice sheet retreat and Bradwell *et al*. (2008) suggested that during the abrupt RSL rise around the time of Heinrich Event 2 (24ka BP), a large marine embayment opened in the northern North Sea, as far south as the Witch Ground Basin. This marine embayment changed the entire configuration of the British and Scandinavian ice sheets forcing them to decouple rapidly along a north-south axis East of Shetland. This marine embayment terminated in the Witch Ground Basin in an area of ice scouring where differences in the morphology of a surface dated as 17– 18ka BP support a sea level between 125 and 100m below present (Stoker & Long 1984). Sejrup *et al*. (2016) recently elaborated upon the extent and process of decoupling of the British and Scandinavian ice sheets in this area.

Detailed analysis of selected offshore cores shows that significant changes in sea level have occurred. Cores examined in the St Kilda Basin, on the continental shelf west of the Outer Hebrides, show that prior to the Younger Dryas water depths were probably less than 40m at a site presently 155m below sea level (Peacock 1996).

Unlike offshore England where submerged peats have regularly been recovered from the shallow waters of the southern North Sea (Hazell 2008), there have been few instances of dateable material indicative of former exposure recovered offshore Scotland. Where they have been found they are restricted to very nearshore. For example, Hoppe (1965) reported peats dated to 7 – 5.5ka BP, recovered at Symbister, Shetland, implying sea levels more than 9m below present. He noted several other locations around Shetland where submerged peats had been recovered but not analysed.

Although undateable, the finding of a flint suggestive of anthropogenic modification in the northern North Sea at 135m water depth implies extensive former exposure. However it should be noted that the morphological setting of this find suggested that it was not *in situ* but had been transported from a nearby former exposed landscape (Long *et al.* 1986).

3. Inherited rock shorelines

Adrian Hall

3.1. Introduction

Inherited rock shorelines occur where sea level has returned to a former level and reoccupied the shoreline (Blanco Chao *et al.* 2003). In Scotland, inheritance is most readily apparent where landforms of marine erosion cut in rock can survive glaciation and be modified by glacial erosion or buried by glacial deposition (Fig. 2A, B). Such inherited coastal forms can shed light on the sea level history around Scotland. This history is examined in three time periods: the Pliocene and Early Pleistocene (5.3-0.78Ma), the Middle and Late Pleistocene (780-20ka) and the Lateglacial and early Postglacial (since 15ka BP).

3.2. Pliocene and Early Pleistocene

Throughout almost all of the Pliocene, global mean sea level was above present, reaching a maximum elevation of 22 m asl (Miller *et al*. 2012). The global variability in the elevation of observed Pliocene shorelines however is large, ranging over tens of metres, due to uncertainties over the age of the shoreline features and the influence of dynamic topography (Dutton *et al.* 2015). In the cooler Early Pleistocene, global sea level only reached a few metres higher than present during brief interglacial periods; otherwise sea level was normally between 0 and -60 m (Lisiecki & Raymo 2005). The uplift history of Scotland during the Plio-Pleistocene is poorly known, a fact that greatly complicates reconstruction of the sea level history of this period. A significant phase of uplift is identified at 15 Ma in the North Sea (Japsen 1997) and on the North Atlantic shelf (Holford *et al*. 2010), but base level rose by 500m on the Norwegian inner shelf in the early Pliocene (Løseth *et al.* 2017). Pliocene fluvial erosion and the onset of glacial erosion in the Pleistocene removed rock mass from Scotland but the elevation of peripheral planation surfaces indicates that passive unloading did not generate >100m of uplift (Hall *et al.* this volume).

Extensive areas of low elevation bedrock surfaces exist close to present sea level in the Inner Hebrides to the south of Skye and across much of the Outer Hebrides as well as on the shallow shelf to the west (Dawson 1994; Dawson *et al.* 2013a). Comparisons are compelling with the strandflat, the extensive coastal platform of western Norway (Nansen 1922; Larsen & Holtedahl 1985). In Norway, these uneven, glacially-roughened and partly submerged rock platforms are cut across diverse rock types and slope gently seawards for many kilometres from the coastal mountains (Holtedahl 1998). In western Scotland, the islands of South Uist, Benbecula and North Uist in the Outer Hebrides mostly consist of extensive low rock platforms, 3–15 km in width developed in Lewisian gneiss, which extend westwards from hills along the eastern margin of the island chain and pass below sea level west of the present Atlantic shoreline (Dawson *et al*. 2013a). On Coll and Tiree in the Inner Hebrides, survey of the platforms has shown that the strandflat includes multiple, tilted, km-wide rock platforms that rise to an inner margin against cliffs at ~30 m asl (Dawson 1994). The ubiquity of glacial and marine erosional forms on the strandflat makes clear that glacial and marine erosion have been fundamental to its recent development. Indeed, these processes must have been highly effective as, in both Norway and Scotland, erosion has maintained the strandflat close to present sea level and kept pace with Plio-Pleistocene uplift of the coastal mountains (Evans *et al*. 2002; Knies *et al.* 2014). The considerable age of the strandflat is shown by its great extent and also by its configuration, with its elimination by glacial erosion in zones of fast ice flow. The strandflat however includes inherited elements that are not of marine or glacial origin. In northern Norway, Plio–Pleistocene erosion has exhumed and lowered a deeply weathered and peneplaned surface of Triassic to Early Jurassic age (Olesen *et al*. 2013; Fredin *et al.* 2017). In the Outer Hebrides, the low basement surface included in the strandflat also retains pockets of weathered rock that formed above sea level (Godard 1956). Moreover, the development of topographic basins along the inner margin of the strandflat, for example within altered shear zones near Leverburgh on southern Harris, indicates a subaerial origin for the wider erosion surface. In the Inner Hebrides, the fragments of strandflat appear to be part of extensive, low-relief surfaces formed initially by subaerial processes in the Pliocene and later dislocated, tilted and then modified by glacial and marine erosion (Le Coeur 1988). The strandflat is a polycyclic and diachronous feature, initiated by subaerial weathering and planation close to sea level in the Pliocene, perhaps trimmed by high Pliocene sea levels (Dawson *et al*. 2013a) and substantially modified and lowered by the successive phases of glacial and marine erosion through the Pleistocene.

3.3. Middle and Late Pleistocene

The strandflat in Hebridean Scotland subsumes fragments of till-covered or striated raised rock platforms and former sea cliffs that are older than the last glaciation (Gray 1985). Similar inherited coastal features are remarkably widespread around the Scottish coast (Fig. 3A). Landforms typical of high wave-energy rock coasts have been over-ridden by the last ice sheet and striated and roughened by glacial erosion and masked by the deposition of till (Fig. 3B). On Shetland, no till plugs are reported from geos and caves but the lengths of many geos, reaching several hundred metres, coupled with the brief, ~1000-yr duration of present sea level (Figs. 4 and 6 below), suggest that these are largely inherited features. Around the Shetland Isles, cliff bases extend below -30m and indicate formation at low glacial sea levels (Flinn 1964, 1969; Hansom 2003b). On Orkney, wide rock platforms developed in Devonian flagstones and sandstones pass beneath till (Figure 3B). On the island of Hoy, raised beach gravels rest on a narrow rock platform at 6-12 m asl and are covered by till (Wilson *et al.* 1935; Sutherland 1993b). In Caithness (Crampton & Carruthers 1914) and Aberdeenshire (Walton 1959; Hansom 2003c), coastal cliffs and geos are locally encased by till. Striated and till-covered inter-tidal rock platforms also occur (Merritt *et al*. 2003; Hall & Riding 2016).

Inherited coastal forms are particularly well-developed on north-west Lewis (Fig. 3A). Here a raised rock platform lies at 7-10 m, up to 150 m wide (McCann 1968; von Weymarn 1974) and backed by low cliffs is overlain by till, organic sediments, the Galson raised beach gravels and by a further till layer (Peacock 1984; Sutherland & Walker 1984; Hall 1996). The raised rock platform predates at least two phases of glaciation and may have formed before MIS6. The warm temperatures indicated by the palynology of the organic deposit indicate a last interglacial age, implying that the Galson beach formed in the interval from MIS5-3. Raised beach gravels resting on a narrow rock platform at 5-8m OD and preserved beneath till are also present on Barra and Vatersay (Peacock 1984; Selby 1987).

The existence of till-covered rock platforms in the Inner Hebrides has long been known (Wright 1911). Platforms are developed across rock type and structure and so are distinct from other extensive low angle surfaces close to present sea level developed on resistant Palaeogene basalt lava flows and sills (Bailey *et al.* 1924). Two extensive and continuous old platforms, backed by cliffs, have been recognised on the west coasts of Islay and Jura: the High Rock Platform (32-35 m OD) (Dawson 1993b) and the Low Rock Platform (below 5 m OD) (Dawson 1980). Many smaller platform fragments also have been identified at other elevations, including a former sea cave with a till–covered floor at ~45 m OD on Ulva (Sissons 1967). Many of these platform fragments are mantled by Holocene raised shoreline deposits, but the presence of till-covered rock hollows below the shoreline deposits and records of striated and ice-roughened rock surfaces of the platforms show that some fragments predate the last glaciation (Sissons 1981; Gray 1989). In contrast, the absence of such features, together with the presence of fragile sea stacks on platform surfaces, has been used to distinguish fragments of the Main Rock Platform, which developed during the Lateglacial (Sissons 1981; Dawson 1988). Inherited rock shoreline fragments occur extensively in SW Scotland. In Kintyre, one fragment with its backing cliff stands at 13 m OD (Gray 1993) and platforms, stacks and cliffs with *in situ* or slumped till occur commonly in the southern part of the peninsula (Gray, 1978). In southern Arran, till-covered platforms have not been reported but the base of the cliff at Kildonan is mantled by till. In the inner Firth of Clyde, till-covered platforms are identified from the Kyles of Bute and Cardross (Browne & McMillan 1984). Till-covered platforms at ~10 m OD occur also on the Rhinns of Galloway (Sutherland 1993a) that may correlate with features on the opposite side of the North Channel (Stephens 1957). In western Islay, a raised rock platform at c. 10m OD is buried by a thick sequence of till and glaciomarine deposits (Benn & Dawson 1987). Extensive terraces or shorelines are developed in the deposits that rise to 70m OD. Thermoluminescence ages of 41ka – 54ka BP on clays from the glaciomarine deposits suggest formation of the rock platform before MIS 3 (Dawson *et al.* 1997). Alternatively, if the ages are in error, the glaciomarine deposits may have been deposited at a time of low sea level during early in the last deglaciation (Peacock 2008).

Inherited landforms reappear along the coastline of eastern Scotland within three broad altitudinal ranges. Remnants of till-covered high rock platforms have been described at elevations of 15 to 25 m OD North of Berwick (Rhind 1965; Sissons 1967) and at 23 m OD at Dunbar (Sissons 1967) (Figure 3C). Raised platforms standing a few metres above present sea level and the inter-tidal rock platform also retain till-filled fractures and depressions west of Torness (Hall 1989). In East Fife, the abandoned cliff line of the Main Late Glacial Shoreline turns inland at St Andrews, where its base is covered by till (Sissons 1967). The presence of dark shelly till predating the last interglacial at elevations as low as 15 m OD in Kincardineshire (Campbell 1934; Auton *et al.* 2000) implies that at least the higher raised shore platforms along this coast started to form before MIS6 (Bremner 1925).

Beyond the present-day coastline of Scotland, the sea floor retains widespread morphological evidence of low former sea levels. Off the W coast, Sutherland (1984) describes pre-Late Devensian rock platforms at -120 m off St Kilda and -155 m and -125 m off Sula Sgeir. Submerged shorelines have been identified off the Firth of Lorn (Hall & Rashid 1977). Off the East coast, submerged, low relief rock surfaces occur extensively at -70 m off Shetland and -60 m off Orkney (Flinn 1964, 1969). Submerged platforms off Stonehaven slope away from coast at 0.5 to 2.0 m/km and are separated by low irregular steps (Stoker & Graham 1985). The upper platform at -30 m is 1 km wide; the middle platform at -45 to -50 m is 4.5 km wide. Both platforms are cut in Devonian strata and covered by till. The lower platform lies at -60 to -70 m and is 7.5 km wide. It is cut across Permo-Triassic red beds and pre-Holsteinian (MIS 11) sediments and overlain by till, indicating a Middle Pleistocene age. The recent availability of high-resolution bathymetric and side scan sonar data for the sea bed around Scotland provides new opportunities to re-examine these and similar submerged platforms (Bradwell *et al.* 2007; Howe *et al.* 2012).

Viewed as an assemblage, it is clear that fragments of former rock shorelines exist between +50 and -100 m around the coast of Scotland (Fig. 4). Shore platforms are cut at sea level and when an area is not covered by glacier ice. The duration of the periods when sea level was at its present and slightly higher (+5m OD) elevation since the last deglaciation have been brief in peripheral locations but rock shorelines closer to the main Late Devensian ice centres have been reoccupied at different intervals during the Lateglacial and Holocene (Fig. 4). With the presently limited information on platform distribution and structural controls, it is appropriate to follow Sissons (1981) and view inherited shore platforms as occupying broad altitudinal zones in relation to present sea level: submerged (SBRP) (<0 m OD), inter-tidal (ITRP) (0 to 3 m), raised (RRP) (3 to 10 m) and high rock platforms (HRP) (>10 m). Comparison with the history of the British-Irish Ice Sheet (BIIS) and the global mean sea level curves for the last glacial cycle (Fig. 5) allows consideration of when these groups of platform may have formed or been reoccupied:

- SBRPs were likely extensively eroded during low sea level stands in MIS 3 and 5 (Fig. 5). The km-wide extent of SBRPs compared to the much narrower platforms found along the present coast reflects in the generally lower resistance of the sedimentary rocks found offshore, the long duration of low sea level phases in the Middle and Late Pleistocene and, perhaps also, intense winter frost action operating in the inter-tidal zone during cold intervals.
- Till-covered ITRPs at the Scottish coast (Fig. 3) have been attributed to formation in earlier interglacial periods (Wright 1911) due to the brief period that sea level has been close to the present in the Holocene (Fig. 5). The Scottish ITRPs are regarded as essentially horizontal in gradient (Dawson, 1984). Detailed surveys are few, however, and multiple platforms close to present sea level exist at localities such as Dunbar (Sissons 1974b, Hall 1989) and more widely in western Scotland (Dawson 1980). Moreover the prior occupation during the Lateglacial and Holocene of many modern shore platforms (Fig. 5) is a reminder that inherited ITRPs also may have been lowered and re-trimmed repeatedly by marine erosion before the last glaciation. Nonetheless horizontal gradients and a position near to sea level are consistent with an interglacial age for inherited Scottish ITRP fragments, with global ice volumes close to those of the present (Fig. 4).
- Inherited RRPs across Scotland may also have had complex and different erosion histories. In peripheral locations such as the Outer Hebrides, where sea level has never been above its present level since the end of the last glaciation, RRPs may relate to high interglacial sea levels. RRPs on the inner coastlines of Scotland may have developed during periods when lower global mean sea level was accompanied by crustal loading from mountain ice caps covering western Scotland. Such intervals may have included the early parts of Pleistocene stadials when the Scottish ice sheet expanded before the much larger Laurentide and Scandinavian ice sheets (Sissons 1981, 1982, 1983; Sutherland 1981b, 1984a) or periods of sustained mountain ice cap development, such as in MIS5b-d and MIS3 (Fig 4). Inherited, till-covered RRPs may date from earlier phases of rebound during the retreat of the MIS4 and MIS6 ice sheets.

- The high elevations of HRPs require profound isostatic depression by a thick ice sheet covering Scotland and so are likely to have formed only in brief phases of early ice sheet build-up and decay in MIS 4 and in late MIS 3 and 2 (Fig. 6).

Improved understanding of the origins and ages of inherited elements in the rock shorelines of Scotland must await detailed mapping, improved constraints on the exposure histories of rock platform surfaces and further dating of overlying sediments.

4. Late Devensian and Holocene relative sea levels before 2000 BP

David Smith, Callum Firth and Jason Jordan

4.1. Introduction

Evidence for RSL change in the Late Devensian and Holocene has been published from over 30 site locations involving over 90 separate sites since 1993 (see Fig. 7). Here, these locations are summarised and briefly discussed (section 4.2) following which patterns of RSLs are inferred and evidence for fault movement and shoreline dislocation is examined (section 4.3).

4.2. New site locations published since 1993

4.2.1. N Scotland: Cape Wrath – Moray Firth, and the Northern Isles (site locations 1-6, Fig. 7). In northern Scotland, research has provided new information in both the mainland and the Orkney islands, although crucially no further studies on Shetland other than research on the Holocene Storegga Slide tsunami (see section 6.2 below) have been published. In studies of Late Devensian RSLs, the work on RSLs and ice limits in the Moray Firth area reported in Gordon & Sutherland (1993) was further developed by Merritt *et al.* (1995), who recorded a fluctuating ice margin in the area but a progressive fall in RSL from 13ka BP, with a sequence of glacio-isostatically tilted shorelines. On the N coast, Auton et al. (2005) identified shoreline fragments between 27 and 15m OD in Strath Halladale and Armadale Bay (3,4, Fig.7), whilst at Loch Eriboll (1, Fig. 7), Long *et al.* (2016) traced RSL from a Lateglacial highstand at 6-8m OD at 15ka BP.

In studies of Holocene RSLs, a back barrier environment at Scapa Bay on Orkney (5, Fig. 7) (de La Vega-Leinert *et al.* 2007) records a rise in RSL from -5.4m OD at 9,675-9,277 BP to -0.6m OD at 5,603-5,306 BP. At nearby Carness (6, Fig. 7), also behind a barrier (de la Vega-Leinert *et al.* 2012), a rise in RSL in the middle Holocene between 7,570-7,339 at -3.2m OD and 6,726-5,751 BP at -1.7m OD is recorded. On the mainland, in the lower Wick River valley (2, Fig. 7), Dawson & Smith (1997) identified a sequence of three successively younger Holocene estuarine deposits in stratigraphic order with regressive overlaps dated at respectively 6,940-6,705 BP at 1m OD, 2,390-1,115 BP (range of 2 dates) at 1.6-1.3 m OD and 1,220-805 BP (range of 3 dates) at 2.4-1.3m OD (Fig. 8D). At Loch Eriboll (1, Fig. 7), Long *et al*. (2016) traced the RSL rise in the Middle and Late Holocene to reach c.1m OD between 7ka and 3ka BP before falling to present levels. They identified evidence of transgressive overlaps after the peak of Holocene RSL rise in the area, but maintained that local coastal processes may have been responsible for these later events, and hence were unable to correlate the evidence from Loch Eriboll with the evidence from Wick River Valley to the East. They argued that RSL change was broadly similar across the N coast of Scotland, implying similar ice loading across that area. The sites at Scapa Bay, Carness, Loch Eriboll and Wick collectively indicate declining isostatic uplift northwards from the northern mainland to the Orkney Islands, in broad agreement with both GIA (Bradley *et al.* 2011) and shoreline-based (Smith *et al.* 2006, 2012) models, as shown in Figures 13, 14 and 24, below.

4.2.2. E and SE Scotland: Moray Firth – Berwick upon Tweed (site locations 7-14, Fig. 7). In eastern and south-eastern Scotland, Peacock (1999) described pre-Windermere interstadial raised marine sediments from an area extending from St Fergus in the N to Berwick upon Tweed in the S (Fig. 10), and maintained that these were diachronous, beginning at 15ka – 14ka BP offshore and continuing to as recently as 13ka BP in the Forth estuary. Later, Peacock (2002, 2003) and Holloway *et al*. (2002) described Windermere interstadial marine deposits from the Tay and Forth areas. Peacock (2003) examined the Errol Clay Formation marine deposits at Gallowflat claypit (13, Fig. 7) and Inchcoonans (14, Fig. 7), on the Tay estuary, and concluded that the deglaciation of the middle Tay estuary occurred between 14.5ka and 14ka BP from ^{14}C and U-TH dating (Rowan *et al.* 2001). Holloway *et al.* (2002) maintained from Windermere marine deposits in the upper Forth valley that RSL may have lain at 15-20m OD in that area before falling during the Younger Dryas. Later, McCabe *et al*. (2007a) using AMS radiocarbon dates from *in situ* mono-specific foraminifera contained in marine muds at Lunan Bay (10, Fig. 7) and at Bertha Park, Perth (11, Fig. 7) maintained that the region was deglaciated before 21ka BP and proposed that there had been two readvances of the ice sheet after the LGM in eastern Scotland: the Lunan Bay Readvance, dating to sometime between 20.2ka BP and 18.2ka BP, in which RSL W of the Lunan valley reached possibly 22m OD, and the Perth Readvance, dating to between 17.5ka BP and 14.5ka BP, in which RSL reached up to 38m OD in the Stirling area. They thus reasserted the concept of the Perth Readvance, originally proposed by Sissons (1963, 1964), following Simpson (1933). Peacock *et al*. (2007) disagree, arguing that the readvance limit in the Tay valley is questionable, but McCabe *et al.* (2007a) point to the morphological and stratigraphical evidence for ice contact features and outwash merging with shoreline terraces at the readvance limit. Evidence for ice sheet fluctuations may be reflected in changes in deposition of the St Andrews Bay Member of the Forth Formation offshore eastern Scotland, showing distinct pulses in sedimentation (Stoker *et al.* 2008). The argument between Peacock *et al.* (2007) and McCabe *et al.* (2007a) reflects a contrast between the morphological and stratigraphical approach of Cullingford (1977) and Cullingford and Smith (1980) and the mainly stratigraphical and biostratigraphical approach of Browne *et al*. (1981). The issues were debated by Cullingford and Smith (1982) and Browne *et al*. (1982), and illustrate the need for an inclusive approach to RSL studies in which both morphological and stratigraphical work are seen as complementary.

Research into Holocene RSL change in the Moray Firth area has focussed on the Dornoch Firth (7, Fig. 7), where Smith *et al*. (1992) and Firth *et al*. (1995) recorded evidence for an equivalent of the Main Buried Beach in SE Scotland, which they dated at 10,708 – 11,125 BP, followed by a rapid rise during which the Holocene Storegga Slide tsunami of 8.15ka BP is registered. Further S, in the Ythan estuary (12, Fig. 7), Smith *et al*. (1999) documented a rapid rise in Early-Middle Holocene RSL. Later, Smith *et al*. (2013) attributed a noticeably rapid rise in RSL between dates of 8,637-8,445 and 8,366-8,177 BP to the release of water from pro-glacial Lake Agassiz-Ojibway in North America (e.g. Barber *et al.* 1999; Teller *et al.* 2002). This rise was followed by the Holocene Storegga Slide tsunami, dated there at sometime between 8,363 and 7,871 BP (range of two dates) (see Fig. 19 below). In the Forth lowland (8, 9, Fig. 7 and Fig. 8A), arguably the closest location studied to the centre of glacio-isostatic uplift in Scotland (Smith *et al.* 2010, 2012), Robinson (1993) identified sites disclosing Holocene RSL and provided detailed pollen, diatom and molluscan records. Near the head of the present Forth estuary, Paul *et al*. (1995, 2004), Paul & Barrass (1998), and Barrass & Paul (1999), working on sediments at Bothkennar near Grangemouth, provided a sedimentary context for much of the work on Holocene RSL change in the Forth area. In the Forth lowland and estuary, RSL fell after the Younger Dryas through three buried estuarine levels: the High, Main and Low "Buried Beaches", dated at between 11.7ka BP and 9.7ka BP to a low point achieved during a relatively short period around 9.5ka BP after which the fall in RSL was reversed and a rise occurred marked by evidence for the Holocene Storegga Slide tsunami at 8.15ka BP before culminating at 7.8ka BP at the Main Postglacial Shoreline in the

Forth valley. RSL subsequently fell further in the Forth valley to a prominent carseland terrace at 4.8ka BP, the Blairdrummond Shoreline, but this shoreline overlaps the higher feature towards the periphery of uplift (Smith *et al.* 2010, 2012).

4.2.3. SW Scotland: Solway Firth – Kintyre (site locations 15-18, Fig. 7). In SW Scotland, research since 1993 has focussed on the Holocene. In the lower Cree valley (15, Fig. 7 and Fig. 8C), Smith *et al*. (2003a) mapped three Holocene terraces across a carseland area of 20km^2, with a buried terrace locally beneath. Radiocarbon dates of 9,711-9,539 and 9,528-9,026 BP were obtained for the -1.1 to -0.5m OD buried terrace, believed to correlate with one of the "Buried Beaches". At the surface, visible terraces were correlated with later shorelines: dates of 7,560-7,251 and 7,209-6,752 BP were obtained for the Main Postglacial Shoreline, at 7.7-10.3m OD, which is confined to the head of the valley; and 5,991-5,588 BP for the Blairdrummond Shoreline, the highest Holocene RSL over most of the valley (and locally overlying deposits of the Main Postglacial Shoreline), reaching 7.8-10.1m OD at the mouth of the valley. Below these shorelines a terrace correlated with the Wigtown Shoreline measured at 5.5-8.0m OD is less securely dated at 3.1ka BP. To the E, the Nith valley (16, Fig. 7) carselands occupy over 15km^2 (Smith *et al.* 2003b). Here RSL is shown to have been rising at 8,640-8,170 (range of 4 dates) BP at 3.4-6.9m OD; briefly falling at 8,190-7,610 (range of 4 dates) BP at 4.6-7.0m OD before resuming and culminating at 6,470-6,210 BP at 9.4m OD. Subsequently RSL fell to present, possibly in stages (Smith *et al.* 2003b). From the inner Solway Firth, comparison between a site at Priestside Flow, near Annan (17, Fig. 7) on the North Shore and sites on the South shore supports differential crustal movement between the two shores (Lloyd *et al.* 1999). Along the Ayrshire coast and outer Firth of Clyde the altitudes of raised coastal features are orthogonal to the isobase pattern shown in Figures 13 and 14 (Smith et al., 2007). At Girvan (18, Fig.7 and Fig. 8B), a buried surface reaching c. 7.8m OD was dated at 7,290-6,780 BP (range of two dates) and correlated with the Main Postglacial Shoreline, which is overlapped by deposits of a higher estuarine surface, reaching 8.6m OD and dated at 4,140-3,900 BP, correlated with the Blairdrummond Shoreline (Fig. 8B). North of Girvan, where the Main Postglacial Shoreline becomes the highest Holocene shoreline, the fall in RSL is reflected in suites of terraces and barriers, notably on the Isle of Bute and the adjacent mainland.

Working at Blair's Croft in the Cree valley, Lawrence *et al.* (2016) have disclosed evidence for three rapid increases in RSL which occurred at the time of the release of meltwater from pro-glacial lake Agassiz-Ojibway in North America and dated at 8.65ka BP, 8.5ka BP and

8,231-8,163 BP. Taken with the evidence for a rapid rise in RSL from the Ythan valley (Smith *et al.* 1999, 2013) and with possible evidence for an increase in RSL at a similar time in Skye (Selby & Smith 2015, 2016) it is likely that the effects of the discharge of the lake are registered widely around the Scottish coastline.

4.2.4. W and NW Scotland: Kintyre – Cape Wrath including the Hebrides (site locations 19-34, Fig. 7). Since 1993, much research on Late Devensian and Holocene RSL change in Scotland has been concentrated on the W and NW mainland, where from the Arisaig area, Shennan *et al.* (e.g. 1993, 1994, 1995a, 1995b, 2005, 2006a) compiled the longest dated record of Late Devensian and Holocene RSL change in the UK (Figs 9D and 22(11)).

In the N of this area, isolation basin sites in Eddrachillis Bay, at Duart Bog and Loch Duart marsh (19, Fig. 7) were examined by Hamilton *et al.* (2015), who found a Holocene highstand at below 2.47±0.59m OD. They maintain that GIA models need to incorporate thicker ice in the northwest sector of the British-Irish Ice Sheet to explain the values for RSL obtained for the timing of the Late Glacial fall and early Holocene RSL rise there. Farther South, at Coigach (20, Fig. 7), N of Ullapool, Shennan *et al.* (2000a) examined coastal wetland and back barrier sites at Dubh Lochan, Loch Raa and Badentarbat, where they found the Holocene highstand reaching "no more than ~2.5m above present", the highest level having been reached at Loch Raa at 4,804-4,354 BP and slightly lower at Dubh Lochan at 6,192-5,913 BP (Fig. 9A). Farther South in Applecross (21, Fig. 7) on Loch Torridon, at Fearnbeg, an isolation basin, the Middle Holocene maximum lies below 5.7m OD, while 3km to the NW at Fearnmore, in a raised tidal marsh, the highest Holocene RSL index point was identified at 5.17m OD at 4,839-4,444 BP. At Kintail (22, Fig. 7 and Fig. 8B), Shennan *et al.* (2000a, 2006a) obtained a series of RSL index points from Loch Alsh and Loch Duich. From the head of Loch Duich at the Loch nan Corr isolation basin, with a threshold at 2.70m OD, they interpreted maximum RSL as having been achieved at 8,131-7,916 BP (range of 2 dates) and on Loch Alsh, in an isolation basin at Nostie, a date of 2.7ka – 2.1ka BP for the cessation of tidal influence at c. 6.36 - 6.56m OD (the elevation range may be greater) was obtained. At Kirkton, W of Nostie, the Late Holocene RSL fall was taking place across a surface of sand and gravel at c. 3.0 – 3.8m OD by 1,503 - 1,816 BP. Given the spread of sites, in which the head of Loch Duich lies c. 10 - 12km nearer the area of maximum glacio-isostatic uplift than Kirkton and Nostie, the graph in Figure 9B is only a general indication of RSL change over the area involved.

Farther S, at Arisaig (23, Fig. 7 and Fig. 9D), where much of the work on isolation basins in Scotland has been concentrated, a record of RSL change has been obtained in which the marine limit reached as high as 36.5±0.4m OD as early as 16,220 – 15,458 BP at Upper Loch Dubh. This was followed by an apparently uninterrupted fall (Shennan *et al*. 1996a, 1996b), thought to have continued to the early Holocene, although believed to have slowed during the Younger Dryas (12.9ka - 11.7ka BP), during which RSL remained within a narrow height range for some time (Shennan *et al*. 2000a), enabling the formation of the marked cliff and platform of that age originally identified by Sissons (1974a) as the Main Lateglacial Shoreline. The subsequent rise to the Holocene maximum was followed by an episode during which RSL is believed to have occurred within c. 1m over an extended period from 8ka – 5ka BP (Shennan *et al.,* 2000a) perhaps with a slight peak of c. 1000 years centred on 7.6ka – 7.4ka BP (Shennan *et al*. 2005). At Kentra Moss (24, Fig. 7 and Fig. 9C), a coastal marsh and peat moss where biogenic sediments overlie outwash deposits, the fall from 7.7m OD at 4,471-4,462 BP is apparently uninterrupted to present (Shennan *et al.* 1995b).

The most southerly study is from Knapdale, Kintyre (25, Fig. 7 and Fig. 9E), where from isolation basin and coastal wetland sites Shennan *et al*. (2006b) record a limiting date for falling RSL at 17,910-16,770 BP at 30.5±1.1m OD to less than 9.6±0.3m OD at c. 12,780-11,440 BP (range of 2 dates) before rising then falling after 5,650-5,490 BP at 8.0±0.6m OD or 4,830-4,530 BP at 10.1±0.2m OD to present. Shennan *et al*. (2006b) expressed some uncertainty about the oldest date, because the area is in a limestone catchment and the sample was from the base of the organic horizon dated, directly overlying inorganic material, and this appears to have been later confirmed in reconstructions of ice sheet retreat (e.g. Clark *et al.* 2012; Finlayson *et al.* 2014) which show the area occupied by ice at the time.

Apart from evidence for RSL change, sites in the Arisaig area provide information on climate and oceanic circulation changes from the foraminiferal and dinoflagellate cyst record in the context of pollen and diatom records. In a landmark study, Shennan (1999) sought to identify evidence for post-LGM meltwater pulses from the detailed record of RSL change at isolation basins in the Arisaig area. Whilst no evidence for Meltwater Pulse 1B could be inferred from the record, Shennan (1999) maintained that Meltwater Pulse 1A may be present, although no firm evidence could be found in the isolation basin sediments. Shennan (1999) provided a constraining estimate of c. 22mm/yr for the increase in RSL rise at 14ka BP, later revised to c. 30mm/year (Shennan *et al* 2005, 2006b). Globally, estimates for the rise during Meltwater

Pulse 1A range up to 80mm/yr (e.g. Liu *et al.* 2004, Deschamps *et al.* 2012; Lambeck *et al.* 2014), but the work at Arisaig indicates that at least at far field locations the rise during Meltwater Pulse 1A may have been at the lower end of the rage quoted, perhaps for near field sites half the range predicted by Fairbanks (1989, 1990).

In the Inner Hebrides, on Skye, Selby *et al.* (2000) and Selby & Smith (2007, 2015, 2016) describe evidence from both back barrier environments and isolation basins. Isolation basins on the Sleat peninsula at Inver Aulavaig (26, Fig. 7) and Point of Sleat (27, Fig. 7) provide evidence for RSL change, although the basal dates from sediments directly overlying Durness limestone, are questionable. At Inver Aulavaig, estuarine conditions already present in the basin at 9,030-7,960 BP withdrew after 6,387-6,024 BP but were reintroduced between 3,638-3,382 BP and 3,459-3,253 BP before again withdrawing. In the nearby back barrier site of Peinchorran (28, Fig. 7), estuarine conditions are replaced by a freshwater environment between 7,610-7,335 and 4,868-4,551 BP. Taken together, these sites record possibly two falls in the rising Middle-Late Holocene RSL in the area. To the E, on the mainland, a fluctuation is recorded at Loch nan Eala, Arisaig, where a brief episode of freshwater conditions replaced an estuarine environment at 7,579-7,435 BP (Shennan *et al.* 1994). In contrast, at Gruinart Flats on Islay (29, Fig. 7), Dawson *et al.* (1998) concluded that evidence supports RSL having departed little from c. 4 – 5m OD between 7ka BP (by inference from nearby Colonsay dates) and 2ka BP, although no dates from Islay supporting the start of this period are offered, and the record they quote contrasts sharply with the modelled record in Figure 22(18).

From Lismore (30, Fig. 7), Stone *et al.* (1996) obtained cosmogenic ^{36}Cl dates for the Main Rock Platform (Main Lateglacial Shoreline), which lies at 7-8m OD in that area, and is believed to have been formed during the Younger Dryas (Dawson, 1988). They obtained dates younger than expected (10,400±900 to 8,900±1,100 BP), but maintained that "shielding" of the platform by the higher Holocene RSL may explain the age obtained and estimate an age of between 12,200+1,900/-1,500 and 10,500+1,600/-1,400 BP.

In the Outer Hebrides, a rise in RSL from at least the middle Holocene to present is recorded from coastal wetland areas at Horgabost (31, Fig. 7) and Northton (32, Fig. 7), Harris (Fig 8E), where at least two transgressive overlaps at 5,450-4,861 BP at -0.5 to 1.6m OD and 3,375-1,948 BP (range of two dates) at -0.3 to 2.3m OD, respectively, and a possible extreme flooding event in the middle Holocene dated at 8,348-7,982 BP crossing a threshold at -0.1m OD occurred (Jordan *et al.* 2010). The flood could relate to the Holocene Storegga Slide tsunami or the discharge of Lake Agassiz-Ojibway, but as yet its origin is unclear.

4.3. Late Devensian and Holocene RSL changes in Scotland before 2000BP.

4.3.1. Late Devensian RSLs. Following the LGM, as decay of the British-Irish Ice sheet (the BIIS) took place, the varied topography beneath was progressively revealed. Along emerging coastal areas, irregularities in topography were occupied by sediment accumulations, while at coastal glacier margins suites of outwash terraces and related shoreline terraces formed as sea level changes occurred against the background of glacio-isostatic uplift. Shoreline sequences formed during ice recession rise in elevation towards the area of greatest uplift (e.g. Smith 1997, fig. 12.3), but research since 1993 has provided few radiometric dates which can be directly related to shorelines reached as ice retreated. The only reliable dates are those for the Wester Ross Readvance of between 14,000±1,700 and 13,500±1,200 BP (Ballantyne 2009) with which the Wester Ross Shoreline of Sissons & Dawson (1981) is closely related. Otherwise available dates for RSL change during this period are from sedimentary sequences from which RSL is inferred (e.g. Peacock 1999, McCabe *et al.* 2007), or isolation basins. Isolation basins provide the most consistent and reliable record of RSL change during this period (e.g. Shennan *et al.* 2000a, 2005), and may contain evidence of Meltwater Pulse 1A (Shennan 1999; Shennan *et al*. 2005).

The Younger Dryas (12.9ka – 11.7ka BP) is associated with RSL marked by the Main Rock Platform on the W coast and the related Buried Gravel Layer on the E coast: the Main Lateglacial Shoreline. The extent of the Main Lateglacial Shoreline, as originally shown by Sissons (1974a), Gray (1978), Dawson (1980), and Firth *et al.* (1993), together with the dates obtained by Stone (1996) and the observations that in the Arisaig area at least, RSL lay between mean tide level and MHWST for a "long period" during the Younger Dryas (Shennan *et al*. 2000a) are evidence for the significance of this feature. A Gaussian quadratic trend surface isobase model (Fretwell 2001) for the Main Lateglacial Shoreline depicts a centre of glacio-isostatic uplift in the SW Grampian Highlands (Fig. 11).

4.3.2. Holocene RSLs. Shennan *et al.* (2000a) depict the episode of consistent RSL during the Younger Dryas being exceeded by a rise in Holocene RSL in the Arisaig area, the local equivalent of the global early Holocene sea level rise (Smith *et al.* 2011). In eastern Scotland, the rise is widely recognised from the deposition of estuarine sediments across the Buried Gravel Layer (e.g. Sissons 1974a). During the subsequent fall in RSL, as glacio-isostatic uplift initially exceeded global mean sea level rise, at least three terraces, the "buried beaches" described in Gordon & Sutherland (1993) were formed. Possible equivalent horizons have been identified in the Dornoch Firth (Smith *et al.* 1992) and the Cree valley (Smith *et al.* 2003a). A marked change after the "buried beach" sequence from a falling to a rising RSL (as global mean sea level rise exceeded local uplift) took place over a relatively short period, between 9.7ka and 9.2ka BP near the area of maximum uplift (Smith *et al.* 2012). During the rise, up to three discharges from Lake Agassiz-Ojibway reached Scottish coasts (Smith *et al.* 1999; Lawrence *et al.* 2016) and following this, the Holocene Storegga Slide tsunami of 8.15ka BP occurred (see section 6.2 below). Currently available dates from the culmination of the rise in RSL in Scotland range between 6.2ka and 7.8ka BP, the older dates being generally nearer the centre of glacio-isostatic uplift, where they are associated with the Main Postglacial Shoreline (e.g. Smith *et al.* 2012), and younger dates towards the periphery of the uplifted area, as Wright's (1914) theory envisaged. At the periphery the Main Postglacial Shoreline is overlapped by two later shorelines (Smith *et al.* 2012). Dates from conformable contacts at all three shorelines cluster in groups (Fig. 11). Shoreline-based Gaussian quadratic trend surface models showing isobases for the Main Postglacial and Blairdrummond shorelines are shown in Figure 13. The separation in altitude of the shorelines decreases away from the area of greatest uplift, with the shorelines ultimately being reversed in altitude in peripheral areas. This is supported by the field evidence. Thus the Main Postglacial Shoreline in the Forth Valley lies c.4m above the next lowest shoreline (the Blairdrummond) there (Smith *et al.* 2010), but is c.1m below the Blairdrummond Shoreline in the Cree valley (Smith *et al.* 2003a), while in the Wick River valley the equivalent horizon lies below two later transgressive overlaps (Dawson & Smith 1997). From these relationships it follows that there will be a zone around the uplift centre where the shorelines merge before further away the shorelines overlap. Shennan *et al.* (e.g. 2005) remark on a "flat peak" in the RSL graph for the Middle Holocene in the isolation basin sites in western and north-western Scotland (which are not at the centre of uplift and therefore more likely to exhibit gradual change in the Middle Holocene), and interpret this "flat peak" as evidence in the global mean sea level record of a gradual, rather than sudden, end to Antarctic ice melting. The shoreline evidence is not inconsistent with this, given the close separation of shorelines away from the area of greatest uplift in the Forth valley.

Figure 14A-C shows Gaussian quadratic trend surface isobase models for the three visible Holocene raised shorelines of Smith et al. (2012) centred on a common centre and axis and Figure 14D shows areas where each of the three shorelines proposed is the highest displaced shoreline above MHWST along the Scottish coastline. The form of the shoreline-based Gaussian trend surface models for both Younger Dryas and Holocene shorelines is close to that of the GIA models of Bradley *et al.* (2011 and Figs. 23, 24 below), and implies little change in the spatial pattern of glacio-isostatic uplift at least since the Younger Dryas.

4.3.3. Uplift rates from empirical evidence. Firth & Stewart (2000) compared relative sea level graphs with regional mean sea level changes, to determine estimates of the magnitude and rate of crustal movement (Table 1). The errors associated with each element of the calculation resulted in considerable ranges for a particular period but they suggest that rates of uplift increased from 4.5-26 mm/yr during the early Lateglacial to 14.4-31.5 mm/yr later in this period. Following this, rates of uplift have been reducing, from 4.0 - 7.3 mm/yr in the Early Holocene to 0.4-4.8 mm/yr in the Middle Holocene. However, reassessment of the Holocene RSL data by Firth and Stewart (2000) to take account of the decay in glacio-isostatic uplift according to Firth *et al.* (1993, 1995, 1997) indicates that the current rates of uplift are between 0.2-1.0±0.1 mm/yr near the centre and 0.2-0.1 mm/yr near the margin.

4.3.4. Younger Dryas crustal redepression. Shoreline studies have previously been used to imply that the growth of the Younger Dryas ice mass may have retarded glacio-isostatic uplift (Boulton *et al.* 1991) or even redepressed the crust (Sutherland 1981; Firth, 1986, 1989; Firth *et al.* 1993) and shifted the centre of uplift (Gray 1983). Localised crustal redepression was proposed by Firth (1986, 1989) based on the sequence of lacustrine shorelines at the southern end of Loch Ness which indicated a 3m rise in loch level. More widespread redepression of the crust was implied from regional shoreline gradients (Sutherland 1981; Firth 1989; Firth *et al.* 1993) with certain Late Devensian shorelines having a lower regional gradient than the Younger Dryas Main Lateglacial Shoreline. However Firth & Stewart (2000) noted that the gradient of the Main Lateglacial Shoreline in the inner Moray Firth was significantly steeper than the Younger Dryas raised lacustrine shorelines around Loch Ness. They concluded that the Main Lateglacial Shoreline may be a time-transgressive feature and that its gradient was not solely the product of glacio-isostatic tilting. The widespread redepression of the crust during the Younger Dryas thus remains unproven. Indeed, GIA models for both the Younger

Dryas and Holocene suggest that the growth of ice would have had minimal impact on patterns and rates of uplift (e.g. Lambeck 1991a, 1991b, 1995; Bradley *et al.* 2011; Kuchar *et al.* 2012).

4.3.5. Fault movement and shoreline dislocation. The study of tilted shorelines has been used to suggest that localised crustal movements had taken place which involved block uplift and dislocation of marine and lacustrine shorelines (Sissons 1972; Gray 1974, 1978; Sissons & Cornish 1982; Firth 1986; Ringrose 1989). The number of dislocations and block crustal movements was limited and they tended to be associated with the reactivation of pre-Quaternary fault lines.

A more systematic assessment of Quaternary neotectonic activity was undertaken by Davenport *et al.* (1987), Ringrose *et al.* (1991), Fenton (1991) and Fenton & Ringrose (1992). Morphological mapping of pre-Quaternary faults identified neotectonic features such as: pop-up scarps, striations, fault gouges, offset surfaces (e.g. shorelines), deflected or offset drainage channels and landslides which were interpreted as evidence of recent crustal movements. The deflected/offset drainage channels were used to suggest that significant Late Devensian/Holocene lateral fault movement (15-200m displacement) had occurred at a large number of sites in the western Highlands. The scale of the movement indicated that the lateral movements would have been achieved through the repeated reactivation of the faults with each displacement associated with a major earthquake. The number of active faults implied that many of the shorelines and sea level change sites may have been affected by local crustal movements.

Firth & Stewart (2000) and Stewart *et al*. (2001) reassessed the evidence associated with a number of the proposed active faults in the Western Highlands. They concluded that the deflected/offset drainage channels could be explained by either fluvial systems exploiting the weaker rocks within the fault zone or by more limited vertical movements (1-2m displacement) associated with discrete tectonic events. They concluded that a large number of pre-existing faults were reactivated by vertical movements during deglaciation but that the scale of the displacement was limited (e.g. <3m). The reactivation appears to have been most pronounced near the margins of the Younger Dryas ice cap (Firth & Stewart 2000) and in fault aligned valleys/firths, with the valley floor, where the ice was thickest, moving upward relative to the surrounding high land, where the ice was relatively thin. It is noteworthy that historical earthquake activity mainly occurs in the Western Highlands, the Central Lowlands and around Dumfries and Lockerbie (Musson 2007). If a similar pattern of tectonic activity occurred in the past then neotectonic features may only occur in these areas.

Firth & Stewart (2000) indicated that due to the fragmentary nature of many shorelines and the variations in altitude along particular fragments, it would only be possible to identify dislocations which exceeded 0.8m on well-defined shorelines (e.g. Holocene features and the Main Lateglacial Shoreline) and which are more than 2.5m on less-well defined Late Devensian shoreline sequences. Their review of the 9 sites where local irregularities in patterns of uplift had been reported suggested that only five provided firm evidence of dislocations (Glen Roy; Forth valley; Port Donain, North Mull) or variations in patterns of uplift (Forth valley; Loch Ness; North Mull) and one (Cree estuary) required further evaluation. The Blairdrummond Shoreline in the lower Cree valley and estuary is marked by an area of increased slope southward on both sides of the valley at c. 9.5 – 8.5m in the East and c. 9 – 8m in the West (Smith *et al.* 2003a). The steeply sloping sections were initially thought to align with pre-existing faults but recent mapping in the area indicates that this is not the case, and that local patterns of sedimentation probably explain these changes.

The three dislocated marine shorelines identified by Firth & Stewart (2000) are shown in Figure 15. The dislocations coincide with pre-Quaternary faults, implying that pre-existing zones of tectonic weakness were being reactivated during glacio-isostatic uplift. The scale of the dislocations (1 – 2.7m) suggests that they resulted from one or two tectonic events (e.g. earthquakes) which occurred after the morphological feature concerned had formed. The majority of the features are associated with Younger Dryas shorelines. However the features in the Forth valley are Early to Middle Holocene in age, which indicates that differential movements continued during the Holocene. Firth *et al.* (1993) initially proposed that given the close proximity of most of the shoreline dislocations to the Younger Dryas ice margin they may be related to crustal stresses resulting from the growth of the ice cap, a view supported by the close association between rock slope failures and Stadial ice limits reported by Holmes (1984). However, neotectonic features (Kinloch Hourn, Stewart *et al.* 2001, South Raasay, Smith *et al.* 2009) and rock slope failures (Ballantyne & Stone 2013) have subsequently been identified at sites away from the margins of the Stadial ice cap. Recent studies of rock slope failures may be of value in determining the magnitude and periodicity of uplift-driven seismic events in the Lateglacial and Holocene and thus corroborative evidence of shoreline dislocation. Ballantyne *et al.* (2014) and Cave & Ballantyne (2016) have argued that many of the failures were triggered by fault reactivation caused by crustal rebound. Whilst the magnitude of the seismic events has not been quantified, it seems likely that surface faulting would have occurred particularly in the seismically active Highlands of Scotland (Musson 2007) and such events may have dislocated shorelines and displaced sea level index points.

5. Relative sea level changes during the last 2000 years

Natasha Barlow

The focus of Scottish sea level research to constrain patterns of post-LGM GIA and reconstruct the maximum extent and timing of deglaciation of the former BIIS, means that research into the evidence for sea level changes during the last 2000 years has received relatively little attention. Middle and occasionally, Late Holocene sea level index points have been used to extrapolate rates of RSL change during the last 1000-4000 years (Shennan & Horton 2002; Shennan *et al*. 2009; Gehrels 2010) though there is relatively little directly-dated evidence of sea level during this time. Ongoing late Holocene isostatic uplift around much of Scotland (see Fig. 23 below) restricts the available accommodation space for the accumulation of coastal sediment sequences that may record recent changes in sea level, further compounded in locations of hard bedrock and steep relief (e.g. NW Scotland) which do not provide much fine-grained sediment needed to accumulate at the head of lochs and sheltered bays. The few Late Holocene sea level index points from Wick (Dawson & Smith 1997), Kentra Moss (Shennan *et al*. 1995), Islay (Dawson *et al*. 1998) and NW Sutherland (Barlow *et al*. 2014; Long *et al*. 2016) along with the extrapolated rates from numerous other locations (e.g. Shennan & Horton 2002) show sea level during the last 2000 years around Scotland has generally been falling or near stable. This relative stability provided opportunity for the development of coastal sand dune systems, in particular associated with the cooling and increased storminess of the Little Ice Age (Gilbertson *et al*. 1999; Dawson *et al*. 2004; Sommerville *et al.* 2007), and coastal spit and barrier formation, for example at the Dornoch Firth (Firth *et al.* 1995).

Reconstructions of past sea level in Scotland have typically followed the framework of dating transgressive and regressive sediment overlaps which record changes in the proximity of marine conditions. For example, in the lower Wick River valley, Dawson & Smith (1997) provide evidence of a slight RSL rise from ca. AD 780 to present as a brown-grey clay containing brackish water diatoms replacing a freshwater peat in the uppermost part of the sequence. More recently, there have been efforts to develop near-continuous records of past sea level from coastal salt marsh cores, rather than discontinuous records from dated sediment boundaries, to provide a detailed picture of the spatial and temporal pattern of Late Holocene sea level changes, globally (e.g. as summarised in Kopp *et al*. 2016). Two reconstructions from Loch Laxford and Kyle of Tongue, Sutherland (site locations 33 and 34, Fig. 7), are the only ~2000-year duration continuous records of sea level from NW Europe (Barlow *et al.* 2014) (for location, see Fig. 7, above). The records are developed using a transfer function which models the relationship between the distribution of modern flora and/or fauna assemblages (in this case, diatoms) and elevation with respect to the tidal frame (Barlow *et al.* 2013, Kemp & Telford 2015). The model is then used to transform the fossil diatom assemblages recorded at numerous depths in the continuous salt marsh core into estimates of palaeomarsh surface elevation at the time of deposition, with an associated error term. This is then converted to relative sea level and plotted along aside an age-depth model.

This method has advantages over approaches which date discrete stratigraphical contacts in that it is able to provide an estimate of the former elevation of sediment deposited at any point in a core. However, there are series of statistical assumptions which can impact on the resulting reconstruction. Therefore, assessing that the results are accurate and robust is important. RSL reconstructions of this type typically have a 2-sigma uncertainty of ~10-20% of the local tidal range (Barlow *et al*. 2013). Using this approach, the results from Sutherland show that during the last 2000 years sea level has been falling or near stable (Barlow *et al.* 2014) (Fig. 15). A recent switch in the biostratigraphy at the top of the sequences means that the authors are unable to reject the hypothesis of a 20th century sea level rise outpacing the local rate of background RSL fall at this location. Teasdale *et al.* (2011) suggest similar evidence for sea level rise outpacing the rate of background land uplift from near-surface salt marsh sediments on Mull. In both cases the recorded signal is small and within the uncertainties of the methods.

Records of sea level change from the last century, with centimetre-scale uncertainties, may be obtained from instrumental tide gauge records, with 12 gauges currently operational in Scotland. In general, historic tide gauge records from Scotland are short in length and/or patchy in data coverage and not currently suitable for providing estimates of long term trends

(Woodworth *et al.* 1999; Dawson *et al*. 2013b). A composite tide gauge record from Aberdeen is the longest in Scotland covering much of the period AD 1862-present (Woodworth *et al.* 1999) and records a rate of mean sea level rise from 1901-2006 of 0.87 ± 0.10 mm yr^{-1} (Woodworth *et al.* 2009). Rising sea level along much of Scotland's coastline has also been inferred from the patterns of erosion associated with many depositional features (Firth *et al.* 1997, 2000; Firth & Collins, 2002). Understanding the spatial pattern of the rates of modern day RSL around Scotland, largely driven by ongoing solid Earth deformation following LGM deglaciation, provides an important baseline for stakeholders engaged in coastal management (Shennan *et al.* 2009; Gehrels 2010; Rennie & Hansom 2011). However, when planning for coastal change it is important to consider rates of RSL change, which comprise the total glacial rebound process, including gravitational redistribution of ice and water loads and rotational redistribution of ocean mass, rather than simply vertical land-level change (Dawson *et al.* 2013; Shennan 2013). Bradley *et al.* (2011) model present-day rates of RSL change in Scotland ranging from -0.8 mm yr^{-1} (RSL fall) at locations closest to the former LGM ice load centre (e.g. Inverness to Dumfries), up to 1.4 mm yr^{-1} (RSL rise) in northern Shetland (see Fig. 24 below) with any future rates of RSL rise imprinting over these longer term spatial patterns.

6. Extreme events

6.1. Storms

Adrian Hall and David Smith

6.1.1. Background. Quaternary RSL change and storm frequency and intensity (storminess) are closely linked, given that storminess may influence landforms and sediments that record RSL change, while changes in the rate of RSL change may influence the impact of storminess on shorelines. Storminess has always been a feature of the Scottish coastal environment, although the magnitude and frequency of storms has varied. Climate change, with associated changes in temperature, sea ice cover, and changes in the North Atlantic Oscillation (NAO), has led to changes in storm track and wave height as studies of recent trends show (e.g. Woolf & Challenor 2002; Woolf *et al.* 2002). Changes in wave climate, as modelled by Neill *et al.* (2009), would have also been influenced by RSL change.

6.1.2. Studies since 1993 of storm impacts. Many local studies since 1993 have focussed on dunes (Gilbertson *et al.* 1999; De la Vega-Leinert *et al.* 2000; Dawson *et al.* 2002; Wilson

2002; Dawson *et al.* 2004; Sommerville 2003; Sommerville *et al.* 2003; Sommerville *et al.* 2007) or on documentary evidence for historic storms (e.g. Hickey 1997; Dawson *et al.* 2007; Hansom *et al*. 2008). Dunes developed widely in the Middle Holocene (e.g. Tooley 1990), but interpretation with respect to episodes of storminess is as yet unclear. Evidence from beach ridges may yet provide information on storminess trends. Thus, in a study of beach ridges in western Jura, Dawson *et al*. (1999) found that the earlier part of the Windermere interstadial was associated with larger ridges than later, possibly implying greater storminess at that time, while at Scapa Bay, Orkney, de la Vega-Leinert *et al.* (2007) remarked on changes in ridge height which may be related to storminess.

Information on storm impacts on hard rock coasts has come from the analysis of cliff top storm deposits (CTSDs) (Hall *et al.* 2006; Hansom *et al.* 2008; Hansom & Hall 2009; Hall *et al.* 2010). CTSDs are potentially more reliable than dune stratigraphies, but so far too few locations have been studied for regional storminess to be determined. On hard rock coasts, erosional forms dominate and sediments are mainly confined to bays. In a few locations around the most exposed coasts of Scotland and Ireland, where deep water reaches close inshore, the cliff tops hold remarkable arrays of CTSDs (Hall *et al.* 2006). In Scotland, CTSDs have been described from the Atlantic and North Sea coasts but they reach their finest development on western Orkney and Shetland where they reach elevations of c.50 m asl at Eshaness, Shetland. Shorelines with CTSDs commonly show 4 distinct zones: the cliff face, the storm wave scour zone, the boulder accumulation zone and a landward zone characterised by wave-splash and air-throw debris (Fig. 17A). The cliff-top platform or ramp shows a storm wave scour zone of bare rock that lacks loose debris. Comparable features occur on stepped and ramped cliff faces on many parts of the Scottish coast, but without wave-transported boulders (Fig. 17B). Here the upper limit of exposed rock marks the maximum elevation of storm wave scour and splash on the cliff face. The boulders in CTSDs may form spreads, imbricate stacks, or ridges. Individual boulders may be of impressive size, with A-axis lengths that may exceed 3 m. The large size of the boulders has led to suggestions that CTSDs are tsunami deposits (Scheffers *et al.* 2009) but there is abundant field and documentary evidence for boulder production and movement in historic and recent storms (Hall *et al.* 2010). Wave-tank experiments and mathematical modelling have shown that when high amplitude storm waves impact the cliff face they produce a bore of green water moving at velocities capable of extracting large rock blocks from sockets on the cliff top and of transporting these blocks to the rear of the cliff top (Hansom *et al.* 2008). The zone of airthrown debris may extend for many tens of metres inland and clasts of cobble-size may be thrown or roll across turf surfaces. Vertical jets of wave water generated by high energy wave impacts at the cliff face in high winds carry spray inland (Harrison 1997) and transport marine aerosols over many tens of km from the coastline (Franzén 1990). The extent however to which sand-sized particles and marine microfossils may also be transported is uncertain.

CTSD ridges can be seen as an end-member type of storm beach, unusual in terms of altitude and calibre, but nonetheless sharing characteristics of sorting and imbrication with boulder and gravel storm beach ridges at lower elevations (Austin & Masselink 2006). Steeply seaward-facing, asymmetric boulder beaches are a remarkable feature of exposed coasts in the Hebrides, Orkney and Shetland (Steers 1973). Suggestions that some imbricate boulder ridges are tsunami deposits (Scheffers *et al.* 2009) are unsubstantiated as the burial of man-made debris, along with photographic evidence indicates instead that large boulders are mobilised in major storms. Storm beaches, together with the ponds and bogs trapped landward of beach ridges (Shennan *et al.* 1998) and the laminated sands and gravels in storm swash terraces found in bay heads (McKenna *et al.* 2012), represent a neglected archive of past storminess on high-energy coasts in Scotland.

The narrowing of shore platforms into firths and other sheltered waters around the Scottish coast confirms that storm waves are of fundamental importance in the erosion of shore platforms. Under normal tidal levels, waves break on the seaward edge of shore platforms. At astronomical high tides and under conditions of storm surge, waves may reform to cross the platform and reach the cliff or beaches at the rear (Hall 2011). Such wave currents extract blocks of rock from sockets and mobilise large boulders on the platform and quarry rock from the cliff base (Dawson *et al.* 2007; Hall 2011). A less obvious process is the lowering of the platform surface by removal of small rock fragments and by abrasion (Kirk 1977). The large height range of storm wave impacts on shore platforms and backing beaches means that there is no simple relationship between these coastal features and RSL.

6.2. Tsunamis

David Smith

Long (2015, 2017) produced a catalogue of tsunamis to have affected the United Kingdom. Of the tsunamis listed in the catalogue, only the Holocene Storegga Slide tsunami was recognised as a definite tsunami in Scotland. The Holocene Storegga Slide tsunami (Fig. 18) is undoubtedly one of the most remarkable events to have taken place along the Scottish coastline during the Quaternary. The evidence for this event was originally found in the Forth valley (Sissons & Smith 1965) but the interpretation of that evidence as from a tsunami generated by submarine mass wasting off the SW coast of Norway was first made by Dawson *et al*. (1988). Since 1993, new sites have been found at the Dornoch Firth (Smith *et al.* 1992; Firth *et al.* 1995; Shi 1995), Wick River (Dawson & Smith 1997), Strath Halladale (Dawson & Smith 2000), Shetland (Bondevik *et al.* 2003), Cocklemill Burn, Fife (Tooley & Smith 2005) and Loch Eriboll, Sutherland (Long *et al.* 2016). In 2004, Smith *et al.* (2004) reviewed the evidence from 32 sites in Scotland and NE England, showing that the tsunami had affected coastal areas in Shetland, northern, north eastern and south eastern Scotland, with sediment run-up values of over 9m at some locations on mainland Scottish coasts. Soulsby *et al.* (2007) used a mathematical model to describe the reduction in grain size and thinning of the tsunami deposit landwards at Montrose, while Smith *et al.* (2007) estimated water depths several metres above the sediment surface from particle size analyses. In more recent work, Dawson *et al.* (2011) and Bondevik *et al.* (2012) dated the event at a site in Norway at 8,110±100BP. Smith *et al.* (2013) remarked on the closeness between the age of the tsunami in Scotland and the published dates for the discharges of Lake Agassiz-Ojibway (e.g. Barber *et al.* 1999; Teller *et al.* 2002). They maintained that the Holocene Storegga Slide may have been triggered by the rapid RSL rise in the area of the slide resulting from the lake discharges, thus causing the tsunami (Fig. 19). Detailed stratigraphical work at many sites discloses the elevation at which the sand layer commonly associated with the tsunami crosses the inland limit of underlying marine sediments. The altitude of this limit, taken to be the shoreline when the tsunami struck, has been used in generating a shoreline-based isobase model which, by avoiding any diachronous element, depicts glacio-isostatic uplift from the date that the tsunami took place (Fig. 20).

The Holocene Storegga Slide tsunami may not have been the only such event to have affected Scottish coasts during the Quaternary. Bondevik *et al*. (2005), who summarised evidence for tsunami deposits on Shetland, reported evidence for a tsunami from deposits in lakes on Shetland, which they dated at 5.5ka BP, while at Basta Voe on Yell, Shetland, Dawson *et al*. (2006) described a distinctive sand layer in coastal peat, which they dated to between 1300 and 1570 BP and speculated may have been generated by a tsunami resulting from a submarine slide in the Storegga area. However, a tsunami origin for both the 1300/1570 BP and 5.5ka BP events appears uncertain. Tappin *et al.* (2015) supported evidence for the

1300/1570 BP tsunami, but did not identify a source for that event, while Long (2015) was uncertain that the event was a tsunami. Indeed, the slides dated as post-Storegga are considered as relatively small, insufficient to create a tsunami (Haflidason *et al.* 2005) and no tsunami event of similar age has been observed in Norway. Thus evidence for tsunamis in Shetland other than from the Holocene Storegga Slide tsunami remains enigmatic, especially since evidence for the possible later events has yet to be found outside Shetland. Some may be from storms, some from sliding of the peat across minerogenic sediment (Tappin *et al.* 2015) and others deposited when coastal peats were split and floated during episodes of high tidal levels or possibly increases in RSL in the manner of the "klappklei" deposits described from the North Sea coast of Germany (e.g. Behre 2004).

7. Glacial Isostatic Adjustment Models

Sarah Bradley

Glacial Isostatic Adjustment (GIA) is the term used to describe the solid Earth deformation that results from the mass redistribution between land based ice sheets and the ocean during glacial-interglacial cycles. By comparing predictions generated by GIA models, for example of relative sea level RSL with surface observations, such as sea level index points (SLIPS) information about past ice sheet history (Brooks *et al*. 2008; Shennan *et al.* 2006), global ice-volume equivalent sea level change (Shennan *et al.* 2005) and the Earths rheological properties (Lambeck 1996) can be inferred.

Over the past two decades there have been numerous GIA modelling studies for the British Isles: from the early work of Lambeck (1993a, b), through the studies of Johnston and Lambeck, 2000; Peltier, 2002, to the studies of Bradley *et al*. 2011 and Kuchar *et al.* 2012 (referred to below as the Bradley and Kuchar models respectively). These studies were motivated by the high quality SLIPs database with over 1100 data points, at over 50 sites.

A GIA model has three key inputs: (1) a reconstruction of the Late Quaternary ice history commencing at ~120ka BP; (2) an Earth model to reproduce the solid Earth deformation resulting from surface mass redistribution between ice sheets and oceans; and (3) a model of sea-level change to calculate the redistribution of ocean mass (which includes the influence of GIA-induced changes in Earth rotation) (Farrell & Clark 1976; Mitrovica & Milne 2003; Kendall *et al.* 2005; Mitrovica *et al.* 2005). These inputs are primarily constrained using

SLIPs; with longer records from the far-field tropical regions used to estimate the total volume of continental ice and timings and pattern of global ice-volume equivalent sea level change (Milne *et al*. 2002; Liu *et al*. 2016), and regional near-field databases (Shennan & Horton 2002) used to constrain the regional ice sheet history and earth model. Additionally, landform evidence from previously glaciated regions, such as trimlines (Ballantyne 2007), raised shorelines (Smith *et al.* 2006) and offshore sediment cores (Sejrup *et al.* 2009) have been used to delimit the lateral and vertical extent and temporal history of the ice sheets.

Once an initial input ice sheet history and reference earth model is chosen, the sea-level model is solved and the input Earth and ice model are then tuned to improve the agreement between observational data, such as SLIP, and GIA model predictions.

The two most recent BIIS reconstructions from GIA modelling are illustrated on Figure 21: the Bradley and Kuchar models. The construction of the BIIS in these two studies is significantly different as described below and illustrates the two main methods adopted in the generation of an input ice sheet model for GIA modelling. In both reconstructions, the regional BIIS model (which will be referred to as the local signal) was combined with the same global GIA ice model (Bradley *et al*. 2015), which was developed independently using far-field sea level data. This 'non-local model' dictates the pattern of global ice-volume equivalent sea level change and is driven by the melting of the larger global ice sheet, such as Scandinavian Ice sheet (SIS) or Laurentide Ice sheet (LIS).

The Bradley model combined two regional ice sheet reconstructions; one for the British Ice sheet (Shennan *et al.*, 2006a) and one for Irish Ice sheet (Brooks *et al.* 2008). In these reconstructions, the maximum vertical height of the ice sheet was delimited by trimline data (Ballantyne 2007) which until quite recently was thought to mark the upper erosive limit of a warm-based erosive ice sheet. The reconstruction was characterised by a two-stage glaciation of the North Sea Basin, with an initial coalescence of the BIIS and the SIS between 32-27ka BP (Fig. 21(a)), followed by a short lived retreat (26-25ka BP, Fig. 21b). Following this, the BIIS readvanced out across the North Sea basin, thickened and extended out onto the continental shelf, reaching a maximum ice thickness of ~1110m. There are two short lived ice streams, one to the Isles of Scilly (Fig. 21(c)) and one along the east coast of England (Fig. 21(d)). Deglaciation begins at 21ka BP, with rapid thinning and retreat of the Irish Ice sheet and complete retreat by 17ka BP (Fig. 21). The timings of this advance and retreat pattern were constrained primarily with sediment cores data taken from Sejrup et al., 2009. However, since the creation this BIIS reconstruction, newer evidence (Clark *et al.* 2012; Sejrup *et al*. 2016) suggests a later coalescence between the BIIS and SIS.

A second new finding has been the reinterpretation of the Scottish trimline data, as representing an englacial boundary (Ballantyne 2010), which marks the boundary between a lower zone of warm-based eroding ice asnd an upper zone of cold-based, non-eroding ice. The trimlines therefore mark the upper limit of a warm-based ice and the minimum vertical height that the BIIS reached during the glacial maximum. This revised interpretation enables the generation of a much thicker ice sheet and supports the vertical extent inferred from glaciological modelling (Boulton & Hagdorn 2006; Hubbard *et al.* 2009). The use of glaciological modelling and support for this revised trimlime interpretation is illustrated in the second BIIS GIA modelling example – the Kuchar model (Fig. 21). Note that the results shown here adopted the "minimal reconstruction" of Kuchar *et al.* (2012). In this reconstruction, the spatial and temporal history of the BIIS was generated by a glaciological ice sheet model (Hubbard *et al.* 2009). Unlike the more traditional approach of developing an input ice reconstruction using geomorphological constraints (as in the Bradley model), the key observational constraint is ice flow locations and directions. As can be seen by comparing the extent at the Last Glacial Maximum (~21ka BP) in the two reconstructions (Figs. 21(d) compared to 21(h)), this leads to a much thicker ice sheet (1965m compared to 1100m in the Bradley model), which supports the revised interpretation of the Scottish trimline data. Compared to the Bradley model, in the Kuchar reconstruction, the BIIS is more restricted spatially and vertically between 32-26ka BP, during which time the ice begins to expand outwards from the high terrain of Scotland (Figs. 21(a) compared to 21(f)). There is also a short-lived retreat-readvance as in the Bradley model, but between 28-27ka BP. By 21ka BP (Fig. 21(h)) the ice has expanded within the Irish Sea basin, and out along the NW and NE margins, but the Irish ice sheet extent is more restricted. Deglaciation begins ~21-20 ka BP (Fig 21), with the slower retreat from the offshore regions than the Bradley model (compare Fig 21(i-j) to Fig. 21(m-n)). Note not shown for either reconstruction is a short lived readvance across Scotland at 13ka and 12ka BP in Bradley and Kuchar model respectively, associated with the Younger Dryas.

Typically in regions that were once ice covered, such as Scotland, GIA model predictions are primarily driven by the isostatic response of the solid Earth due to the changes in the regional ice loading, and to a lesser extent the global ice-volume equivalent sea level signal. Therefore the predictions are highly dependent on the regional reconstructed ice-sheet history and Earth model. However, the GIA predictions across Scotland are more complicated as the RSL signal is equally sensitive to the regional isostatic response (due to the deglaciation of the BIIS) and to changes in the global ice-volume equivalent sea level signal, (driven by the deglaciation of the larger global ice sheets, such as LIS or SIS). We will term these two signals, for the 'local signal' and 'non-local' signal respectively.

To illustrate the interplay between these two signals, RSL predictions were generated at seven selected sites across Scotland using the Bradley and Kuchar models (Fig. 22). The total RSL signal from the Bradley model was separated into the contribution from the BIIS only, the "local signal" (Fig 22(a)) and the "non-local signal" separated into the contribution from the SIS only (Fig. 22(a)) and from all other far-field ice sheets (Fig. 22(b)).

These seven sites are located relatively near to the centre of ice loading, and as such the local signal (Fig. 22(a), see Table 2 for colours) drives a steady fall in RSL from between ~130-80 m above present. This is the typical RSL signal seen at near-field sites and is driven by uplift of the solid earth following the retreat of the BIIS. This local signal is overprinted by the non-local signal, where there is a near equal, but opposite, rise in RSL towards present, from ~ -135 to -110 m followed by a gradual slowdown through the mid-to late Holocene (Fig. 22(b)). This steady rise is punctuated by two periods of rapid RSL rise: at ca ~ 14 ka BP, known as Meltwater pulse 1a, and at ~ 11aBP due to an increase in global ice melting associated with the Younger Dryas. It is this non-local signal which drives the sharp inflections in the predicted RSL at all seven sites (Fig. 22). It should be noted, that although the SIS is relatively close to the BIIS, the total contribution to the RSL signal across Scotland is quite small (see dashed lines on Fig. 22(a)), with a predicted rise in RSL of ~-14m.

The Forth Valley (Fig. 22(17)), situated closest to the centre of ice loading (Fig. 23), will experience the maximum uplift and as such has the maximum RSL fall. In the Kuchar model, from the Late Devensian to 14ka BP (Fig. 23), RSL falls by over 150m (20m in Bradley), reaching +32m (14m in Bradley) by 14ka BP, with a maximum Holocene highstand of 7.4m (9.4m in Bradley). With an increased distance, away from the centre of loading, for example at Arisaig (Fig. 22(11)), the local signal is reduced (Fig. 22(a)) and as such by 11ka BP the RSL has fallen either close to (+1.8m Kuchar) or just below (-1.5m Bradley) at the present day. At Arisaig (Fig. 22 (11)), the thicker ice sheet in the Kuchar model (Fig. 21(d)) improves the fit to the older, pre 15ka BP SLIP and elevates the predicted RSL at 11ka BP. However, as seen at the Forth Valley (Fig. 22(17)), the Holocene highstand is lower, 3.9m compared to 7.4m in the Bradley model. The lower highstand produced by the Kuchar model, despite a thicker BIIS, is in part due to the different choice of input earth model (Kuchar *et al.* 2012) and due to the earlier and more rapid retreat of the ice sheet across Scotland (compare Figs. 21 (l) with 21 (p))

The influence of the varied BIIS loading history between the Kuchar and Bradley models is highlighted by comparing the difference in the predictions at the two sites from eastern Scotland: NE Scotland (Fig. 22(13)) and SE Scotland (Fig. 22 (22)). At 14ka BP, with the Kuchar model, the predicted RSL is elevated by 24m and 30m (relative to the Bradley model) at each site respectively, and at SE Scotland the increase in the local signal is such that the predictions remain elevated above present day at all times. It is the more expansive and thicker ice sheet across the East of Scotland within the Kuchar model (compare Fig. 21(i-j) with Fig. 21(m) and 21(n)) which not only increases the relative local uplift, but widens the region of relative RSL fall, displacing the centre of uplift from the NW (Bradley) to the NE (Kuchar) (compare Fig. 23(a-d) with Fig. 23(e-h)). However, at these two sites, by the mid Holocene, the non-local signal is more dominant in controlling the predicted RSL, as can be seen in the similarity in the height of the predicted highstand at each site, unlike the differences as described at Arisaig and the Forth Valley. As the SLIP records at these two sites stands, it is again not possible to discriminate between these two BIIS reconstruction predictions. A Holocene highstand is only generated at the observed sites when the local RSL fall is sufficiently large to outpace the non-local driven RSL rise. For example, at Coigach, Ullapool (Fig. 22(6)), a highstand is produced with both models, capturing the observed SLIP data. This site is located closer to the centre of uplift (Figs. 23(b) – 23(f)) and as such, the local RSL fall outpaces the non-local rise.

In the Hebrides (Fig. 22 (7)), there is no highstand with predicted RSL remaining below present from 14 ka BP to present. The results from both models are quite similar and neither captures the higher RSL seen in the observed SLIP. This similarity is due to the dominant influence of the non-local signal in driving the RSL over this period, which is the same in both models. With its more distal location from the centre of ice sheet, the local signal (Fig. 21(a)) is near equal to the non-local signal (Fig. 22(b)). We note that this is not the case for the Late Devensian to early Holocene (not shown on Fig. 22, see Kuchar et al. 2012), where in the Hebrides, the Kuchar model again results in a much higher RSL, by over 50m.

We have outlined the interplay between the local and non-local signal in driving the RSL up to the timing of the mid Holocene highstand, but these two signals are equally important in driving the ongoing present-day rate of sea level change.

As discussed in Section 5, above, and as the selection of seven sites illustrates, there are relatively few SLIPs available (less than 50) across Scotland for the last 4ka in the current database, to either constrain GIA models over this period or to estimate the on-going present day rate of sea level change. Two studies which have estimated a maximum present-day rate of sea level change from the Scottish data obtain a rate of ~ -1.7mm/yr across NW Scotland (Gehrels 2010; Shennan & Horton 2002). As Figure 24(a) illustrates, the predicted present-day rate of sea level change only reaches a maximum of -1.1mm/yr (see red circle), corresponding to the region of thickest ice sheet, lower than that inferred from the observed data. This total signal is composed of a large local signal (Fig. 24(c)) which forms a concentric pattern, reaching a maximum of -1.67mm/yr, reduced by a non-local long - wavelength signal (Fig. 24(b)), of ~ + 0.8mm/yr.

The main driving mechanism for this ongoing fall in sea level is the vertical land motion, due to the rebound of the solid earth. By comparing the corresponding predicted present-day rate of vertical land motion on Figures 24(d)-23(f), the distinct similarity is evident; where the main region of maximum uplift (+ 0.83mm/yr) coincides with the region of maximum RSL fall. The offset between the '0mm/yr' or line of zero sea level change/zero land uplift is due to the displacement of the sea (Fig 24(g)) of ~0.3mm/yr. This signal is combined with the present-day rate of vertical land motion to derive the total predicted signal.

8. Key research questions and future work

All authors

8.1 The continental shelf record

While progress has been made in determining the morphology and sediments of the continental shelf surrounding Scotland, there is room for a better understanding of the offshore Devensian and pre-Devensian record of RSL change. The record will be improved with the release of data from the BRITICE-CHRONO project. Information on submarine mass failures to help determine the likely frequency and magnitude of tsunamis on Scottish coasts is a focus of the work of the Landslide-Tsunami Consortium (Talling 2013).

8.2 Inherited rock shorelines.

The most important research question in studies of inherited rock shorelines in the Quaternary concerns their age and what information they can provide about RSL change. Understanding the distribution, morphology and age of these features will require a combination of field study, dating and modelling (Trenhaile 2014). Although in parts of the W coast and on NW Lewis, it is possible to recognise former shorelines from multiple rock platform remnants at similar elevations, at many locations platform fragments have not been surveyed in detail. Mapping should identify such fragments by the main locality at which they are found, as with stratigraphic units, thereby allowing later correlation and identification of former shorelines on the basis of altitude, overlying sediments and age. Such mapping should also differentiate between shore platforms and structural platforms developed on flat-lying rock units (Wright 1911). The advent of detailed bathymetric data for the inner shelves around Scotland (Bradwell & Stoker 2015a) and the improved understanding of offshore Pleistocene sediment sequences (Bradwell & Stoker 2015b) provides great opportunities to establish the distribution of submarine rock platforms and to constrain the age of formation from overlying, dated, sediments. Dating of buried shore platforms onshore is difficult but significant progress has been made in modelling cosmogenic isotope inventories on shore platforms (Hurst *et al.* 2016) and in dating exposed and buried rock surfaces (Choi *et al.* 2012; Branger & Muzikar 2001; Stone *et al.* 1996). The presence of till-filled caves and geos protected from glacial erosion on lee slopes indicates that more of these features await discovery. Such marine cave fills are potentially rich archives of environmental (Larsen *et al.* 1987) and even archaeological (Bailey & Flemming 2008) information from the period before the last ice sheet.

8.3 Late Devensian and Holocene RSL change.

Determination of the altitude and age of Late Devensian RSLs will help determine ice extent during deglaciation, including the extent of a separate Shetland Ice Cap. For the Holocene, more information is needed from areas peripheral to the area of greatest uplift, including the Northern Isles and Outer Hebrides. Further, since studies of isolation basins and coastal estuarine depocentres are confined to different areas, there is room for an assessment of the comparability of the record. The extent and magnitude of local crustal movements which may affect RSLs are unclear. Finally, little is known about palaeotides at Scottish coastal sites over much of the Late Devensian and Holocene, which may affect comparability of the record. Thus whilst Shennan *et al.* (2000b, 2003) estimated that there would have been little change in tidal levels on North Sea coasts during the last 6-7ka, and Uehara *et al*. (2006) estimated little change overall for the last 8ka, the effects of changes in coastal configuration in previous periods are largely unknown. Ward *et al.* (2016) modelled noticeable changes in tidal dynamics on the W coast before 8ka BP.

8.4 RSL change in the last 2000 years.

Understanding RSL changes taking place during the documentary and instrumental record is vital in determining spatial and temporal changes in the foreseeable future. Determination of recent and current RSL trends using lithostratigraphy, biostratigraphy and dating methods is essential to build up a detailed picture at both the regional and local scale. A far greater number of high-precision records than presently available are required to be able to do this. These results will help guide understanding of future changes, which is important for climate mitigation and adaptation strategies.

8.5 Extreme events.

Stratigraphical evidence for Holocene storminess has recently been improved through the study of aerosols in coastal peat mosses (e.g. Orme *et al.* 2016), and combined with studies of sand dune movement and cliff top storm deposits may provide valuable chronologies. In the case of tsunamis, the record is uncertain, with only the Holocene Storegga Slide tsunami confirmed at present. Determining the record of both storminess and tsunamis will depend upon the stratigraphic record. Research to discriminate between storm and tsunami deposits (e.g. Donnelly *et al.* 2016) is needed.

8.6 GIA modelling of patterns of crustal and RSL change.

GIA models have been greatly improved as the effect of global mean sea level change is refined with new global bathymetrical and topographical data such as was developed in the ETOPO series and as more is known about the dynamics and history of Quaternary ice sheets and of Earth geophysics. GIA models offer the best method of determining patterns of uplift, and the development of new observational data on RSL change will enable detailed validation and refinement of these models.

9. Conclusion

Since the publication of the Quaternary of Scotland GCR volume in 1993, there have been continuing developments in understanding RSL change in Scotland. While much remains to be understood about the record of RSL offshore on the continental shelf, some inferences can be made about RSL change from the morphology and features there. Onshore, some progress has been made in understanding the development and timing of inherited rock shorelines, but the picture remains complex. For Late Devensian and Holocene RSL change, the application of the isolation basin approach has provided much needed information for the coastline of W Scotland, where previously relatively little information was available, while from the estuaries of E and SW Scotland the presence of variations in Holocene RSL changes has been supported. Evidence for two global meltwater pulses is probably present at sites in Scotland. Progress in understanding RSL change in the last 2ka has received less attention, and will depend upon a wider coverage of sites and comparison with GIA models. The importance of extreme coastal flooding events is recognised, with new approaches to identifying patterns of storminess and to reconstructing the impact of the Holocene Storegga Slide tsunami. The development of GIA models is providing increasingly detailed information on rates and patterns of crustal movement, and the similarity in outline with shoreline-based numerical models of Holocene crustal movement provides support for the methodology. However, much remains to be discovered. Little is known at present about RSL changes before the Late Devensian, while for the Late Devensian itself the sequence of RSL changes during deglaciation is only known in general terms. For the Holocene, gaps in knowledge include the poor record from the Outer Hebrides and Northern Isles, the effect of local crustal movements and the timing and impact of extreme coastal floods. Resolution of such problems will enable an improved perspective on RSL change during the Quaternary in Scotland.

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11. References

Austin, M. J. & Masselink, G. 2006. Observations of morphological change and sediment transport on a steep gravel beach. *Marine Geology* **229**, 59-77.

Auton, C. A., Gordon, J. E., Merritt, J. W. & Walker, M. J. C. 2000. The glacial and interstadial sediments at the Burn of Benholm, Kincardineshire: evidence for onshore pre-Devensian ice movement in northeast Scotland. *Journal of Quaternary Science* **15**, 141-156.

Auton, C. A., Firth, C. R., Pearson, S. G. & Spencer, J. 2005. Onshore evidence for Late-Quaternary sea-level changes in the Dounreay area. *British Geological Survey Commissioned Report* CR/05/08, 106pp.

Bailey, E. B., Clough, C., Wright, W., Richey, J., & Wilson, G. 1924. Tertiary and post-Tertiary geology of Mull, Loch Aline and Oban. *Memoir of the Geological Survey of Scotland, Sheet 44.* Her Majesty's Stationery Office.

Bailey, G. N. & Flemming, N. C. 2008. Archaeology of the continental shelf: marine resources, submerged landscapes and underwater archaeology. *Quaternary Science Reviews* **27**, 2153-2165.

Ballantyne, C. K. 2007. Glacial landforms, trimlines and palaeonunataks. *In* Elias, S. A. (ed) *Encyclopaedia of Quaternary Science*, 892-903. Elsevier, Oxford.

Ballantyne, C. K., Schnabel, C., & Xu, S. 2009. Readvance of the last British-Irish Ice Sheet during Greenland Interstade 1 (GI-1): the Wester Ross Readvance, NW Scotland. *Quaternary Science Reviews* 28, 783-789.

Ballantyne, C. K. 2010. Extent and deglacial chronology of the last British-Irish Ice Sheet: implications of exposure dating using cosmogenic isotopes. *Journal of Quaternary Science* **25**, 515-534.

Ballantyne, C. K. & Stone, J. O. 2013. Timing and periodicity of paraglacial rock-slope failures in the Scottish Highlands. *Geomorphology* **186**, 150-161.

Ballantyne, C. K., Wilson, P., Gheorhhiu, D. & Rhodés, Á. 2014. Enhanced rock-slope failures following ice-sheet deglaciation: timing and causes. *Earth Surface Processes and Landforms* **39**, 900-913.

Barber, D. C., Dyke, A., Hillaire-Marcel, C., Jennings, A. E., Andrews, J. T., Kerwin, M. W., Billodeau, G., McNeely, R., Southons, J., Morehead, M. D., & Gagnon, J.-M. 1999. Forcing of the cold event of 8,200 years ago by catastrophic drainage of Laurentide lakes. *Nature* **400**, 344-348.

Barlow, N. L. M., Shennan, I., Long, A. J., Gehrels, W. R., Saher, M. H., Woodroffe, S. A. & Hillier, C. 2013. Salt marshes as geological tide gauges. Global and Planetary Change **106**, 90-110.

Barlow, N. L. M., Long, A. J., Saher, M. H., Gehrels, W. R., Garnett, M. H. & Scaife, R. G. 2014. Salt-marsh reconstructions of relative sea-level change in the North Atlantic during the last 2000 years. *Quaternary Science Reviews* **99**, 1-16

Barrass, B. F. & Paul, M. A. 1999. Sedimentology and depositional history of the Claret Formation ("carse clay") at Bothkennar, near Grangemouth. *Scottish Journal of Geology* **35(2)**, 131-144.

Behre, K-E. 2004. Coastal development, sea-level change and settlement history during the later Holocene in the Clay district of Lower Saxony (Niedersachsen), northern Germany. *Quaternary International* **112**, 37-53.

Benn, D. I. & Dawson, A. G. 1987. A Devensian glaciomarine sequence in western Islay, Inner Hebrides. *Scottish Journal of Geology* **23**, 175-187.

Berry, R. J. 2000. *Orkney Nature*. Academic Press, London, 256pp.

Blanco Chao, R., Costa Casais, M, Martínez Cortizas, A., Pérez Alberti, A. & Trenhaile, A. 2003. Evolution and inheritance of a rock coast: western Galicia, northwestern Spain. *Earth Surface Processes and Landforms* **28**, 757-775.

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A. G. & Lohne, Ø. 2003. Record-breaking Height for 8000-Year-Old Tsunami in the North Atlantic. *EOS, Transactions, American Geophysical Union* **84(31)**, 289-293.

Bondevik, S., Mangerud, J., Dawson, S., Dawson, A. G. & Lohne, O. 2005. Evidence for three North Sea tsunamis at the Shetland Islands between 8000 and 1500 years ago. *Quaternary Science Reviews* **24**, 1757-1775.

Bondevik, S., Stormo, S. K. & Skjerdal, G. 2012. Green mosses date the Storegga tsunami to the chilliest decades of the 8.2ka cold event. *Quaternary Science Reviews* **45**, 1-6.

Boulton, G. S., Peacock, J. D., & Sutherland, D. G. 1991. Quaternary. *In* Craig, G.Y. (ed) *Geology of Scotland,* 503-543. The Geological Society, London.

Boulton, G. & Hagdorn, M. 2006. Glaciology of the British Isles Ice Sheet during the last glacial cycle: form, flow, streams and lobes. *Quaternary Science Reviews* **25**, 3359-3390.

Bradley, S. L., Milne, G. A., Shennan, I. & Edwards, R. 2011. An improved glacial isostatic adjustment model for the British Isles. *Journal of Quaternary Science* **26**, 541–552.

Bradwell, T., Stoker, M. S., & Larter, R. 2007. Geomorphological signature and flow dynamics of the Minch palaeo-ice stream, northwest Scotland. *Journal of Quaternary Science* **22,** 609-617.

Bradwell, T., Stoker, M. S., Golledge, N. R., Wilson, C. K., Merritt, J. W., Long, D., Everest, J. D., Hestvik, O. B., Stevenson, A. G., Hubbard, A. L., Finlayson, A. G. & Mathers, H. E.

2008. The northern sector of the last British Ice Sheet: Maximum extent and demise. *Earth Science Reviews* **88**, 207-226.

Bradwell, T. & Stoker, M. S. 2015a. Asymmetric ice-sheet retreat pattern around northern Scotland revealed by marine geophysical surveys. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh* **105(4)**, 297-322.

Bradwell, T. & Stoker, M. S. 2015b. Submarine sediment and landform record of a palaeo-ice stream within the British−Irish Ice Sheet. *Boreas* **44(2)** 245-276.

Bremner, A. 1925. The glacial geology of the Stonehaven district. *Transactions of the Edinburgh Geological Society* **11**, 25-41.

BRITICE-CHRONO. 2017. Constraining Rates and Style of Ice Sheet Decay. Natural Environment Research Council. www.britice.chrono.org

Brooks, A. J., Bradley, S. L., Edwards, R. J., Milne, G. A., Horton, B. & Shennan, I. 2008. Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. *Journal of Quaternary Science* **23**, 175-192.

Browne, M. A. E., Armstrong, M., Paterson, I. B., & Aitken, A. M. 1981. New evidence of Late Devensian marine limits in east-central Scotland. *Quaternary Newsletter* **34**, 8-15.

Browne, M.A.E., Armstrong, M., Paterson, I.B., & Aitken, A.M. 1982. New evidence for Late Devensian marine limits in east-central Scotland – a reply. *Quaternary Newsletter* **35**, 14-17.

Browne, M. A. E. & McMillan, A. A. 1984. Shoreline inheritance and coastal history in the Firth of Clyde. Scottish Journal of Geology **20**, 119-120.

Campbell, R. 1934. On the occurrence of shelly boulder clay and interglacial deposits in Kincardineshire. *Transactions of the Edinburgh Geological Society* **13**, 176-182.

Cave, J. A. S. & Ballantyne, C. K. 2016. Catastrophic Rock-Slope Failures in NW Scotland: Quantitative Analysis and Implications. *Scottish Geographical Journal* **132(2-4)**, 185-209.

Choi, K. H., Seong, Y. B., Jung, P. M. & Lee, S. Y. 2012. Using Cosmogenic 10Be dating to unravel the antiquity of a rocky shore platform on the West Coast of Korea. *Journal of Coastal Research* **28**, 641-657.

Clapperton, C. M. 1997. Greenland Ice Cores and North Atlantic Sediments: Implications for the Last Glaciation in Scotland, *In* Gordon, J.E. (ed), *Reflections on the Ice Age in Scotland*, 45-58. Scottish Natural Heritage, Edinburgh.

Clark, C. D., Hughes, A. L. C., Greenwood, S. L., Jordan, C. & Sejrup, H. P. 2012. Pattern and timing of retreat of the last British-Irish Ice Sheet. *Quaternary Science Reviews* **44**, 112-146.

Crampton, C. B. & Carruthers, R. G. 1914. *The Geology of Caithness*. Geological Survey of Scotland, Edinburgh.

Cullingford, R. A. 1977. Lateglacial raised shorelines and deglaciation in the Earn-Tay area. *In* Gray, J.M. & Lowe, J.J. (eds) Studies in the Scottish Lateglacial Environment, 15-32. Pergamon Press.

Cullingford, R. A. & Smith, D. E. 1980. Late Devensian raised shorelines in Angus and Kincardineshire, Scotland. *Boreas* **9**, 21-38.

Cutler, K., Edwards, R., Taylor, F., Cheng, H., Adkins, J., Gallup, C., Cutler, P., Burr, G. & Bloom, A. 2003. Rapid sea-level fall and deep-ocean temperature change since the last interglacial period. *Earth and Planetary Science Letters* **206**, 253-271.

Davenport, C. A. & Ringrose, P. S. 1987. Deformation of Scottish Quaternary sediment sequences by strong earthquake motions. *In* Jones, M.E. & Preston, R.M.F. (eds) Deformation of Sediments and Sedimentary Rocks. *Geological Society Special Publication* **29**, 299-314.

Dawson, A. G. 1979. *Raised shorelines of Jura, Scarba and NE Islay*. Unpublished PhD Thesis, University of Edinburgh.

Dawson, A. G. 1980. The Low Rock Platform in western Scotland. *Proceedings of the Geologists' Association* **91**, 339-344.

Dawson, A.G. 1984. Quaternary sea-level changes in western Scotland. *Quaternary Science Reviews* **3(4),** 345-368.

Dawson, A. G. 1988. The Main Rock Platform (Main Lateglacial Shoreline) in Ardnamurchan and Moidart, western Scotland. *Scottish Journal of Geology* **24**, 163-174.

Dawson, A. G. 1991. Scottish Landform Examples - 3. The raised shorelines of northern Islay and western Jura. *Scottish Geographical Magazine* **107**, 207-212.

Dawson, A. G. 1993a. North-west coast of Islay, *In* Gordon, J. E. & Sutherland, D. G. (eds), *Quaternary of Scotland*, 378-382. Chapman and Hall, London.

Dawson, A. G. 1993b. West coast of Jura, *In* Gordon, J. E. & Sutherland, D. G. (eds), *Quaternary of Scotland*, 382-388. Chapman and Hall, London.

Dawson, A. G. 1994. Strandflat development and Quaternary shorelines on Tiree and Coll, Scottish Hebrides. *Journal of Quaternary Science* **9(4)**, 349-356.

Dawson, A. G. Long, D. & Smith, D. E. 1988. The Storegga slides: evidence from eastern Scotland for a possible tsunami. *Marine Geology* **82**, 271-276.

Dawson, A. G., Benn, D. I. & Dawson, S. 1997. Late Quaternary glaciomarine sedimentation in the Rhinns of Islay, Scottish Inner Hebrides. *In* Dawson, A.G. and Dawson, S. (eds) *Quaternary of Islay and Jura*, 66-67. Quaternary Research Association. Cambridge.

Dawson, A. G., Smith, D. E., Dawson, S., Brooks, C. L., Foster, I. D. L. & Tooley, M. J., 1999. Lateglacial climate change and coastal evolution in western Jura, Scottish Inner Hebrides. *Geologie En Mijnbouw* **77**, 225-232.

Dawson, A. G., Hickey, K., Holt, T., Elliott, L., Dawson, S., Foster, I.D.L., Wadhams, P., Jonsdottir, I., Wilkinson, J., McKenna, J., Davis, N. R. & Smith, D. E. 2002. Complex North Atlantic Oscillation (NAO) Index signal of historic North Atlantic storm-track changes. *The Holocene* **12**, 363-369.

Dawson, A. G., Dawson, S. & Bondevik, S. 2006. A Late Holocene Tsunami at Basta Voe, Yell, Shetland Isles. *Scottish Geographical Journal* **122(2)**, 100-108.

Dawson, A. G., Dawson, S. & Ritchie, W. 2007. Historical climatology and coastal change associated with the "Great Storm" of January 2005, South Uist and Benbecula, Scottish Outer Hebrides. *Scottish Geographical Journal* **123**, 135-149.

Dawson, A. G., Bondevik, S. & Teller, J. T. 2011. Relative timing of the Storegga submarine slide, methane release, and climate change during the 8.2ka cold event. *The Holocene* **21(7)**, 1167-1171.

Dawson, A. G., Dawson, S., Cooper, J. A. G., Gemmell, A. M. D. & Bates, R. 2013a. A Pliocene age and origin for the strandflat of the Western Isles of Scotland: a speculative hypothesis. *Geological Magazine* **150**, 360-366.

Dawson, S. & Smith, D. E. 1997. Holocene relative sea-level changes on the margin of a glacio-isostatically uplifted area: an example from northern Caithness, Scotland. *The Holocene* **7(1)**, 59-77.

Dawson, S., Dawson, A. G. & Edwards, K. J. 1998. Rapid Holocene relative sea-level changes in Gruinart, Isle of Islay, Scottish Inner Hebrides. *The Holocene* **8(2),** 183-195.

Dawson, S. & Smith, D. E. 2000. The sedimentology of middle Holocene tsunami facies in northerm Sutherland, Scotland. *Marine Geology* 170, 69-79.

Dawson, S., Smith, D. E., Jordan, J. & Dawson, A. G. 2004. Late Holocene coastal sand movements in the Outer Hebrides, N.W. Scotland. *Marine Geology* **210**, 281-306.

Dawson, S., Powell, V. A., Duck, R. W. & McGlashan, D. J. 2013b. Dicussion of Rennie, A. F. and Hansom, J. D. 2011. Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast, *Geomorphology* **125 (1)**, 193-202. *Geomorphology* **197**, 185-186.

De la Vega-Leinert, A. C., Keen, D. H., Jones, R. L., Wells, J. M. & Smith, D. E. 2000. Mid-Holocene environmental changes in the Bay of Skaill, Mainland Orkney, Scotland: an integrated geomorphological, sedimentological and stratigraphical study. *Journal of Quaternary Science* **15(5)**, 509-528.

De la Vega-Leinert, A. C., Smith, D. E. & Jones, R. L. 2007. Holocene coastal environmental changes on the periphery of an area of glacio-isostatic uplift: an example from Scapa Bay, Orkney, UK. *Journal of Quaternary Science* **22(8)**, 755-772.

De la Vega-Leinert, A. C., Smith, D. E. & Jones, R. L. 2012. Holocene coastal barrier development at Bay of Carness, Mainland Island, Orkney, Scotland. *Scottish Geographical Journal* **128**, 119-147.

Deschamps, P., Durand, N., Bard, E., Hamelin, B., Camoin, G., Thomas, A.L., Henderson, G.M., Okuno, J., & Yokoyama, Y. 2012. Ice-sheet collapse and sea-level rise at the Bølling warming 14,600 years ago. *Nature* **483**, 559-564.

Donnelly, J., Goff, J. & Chagué-Goff, C. 2016. A record of local storms and trans-Pacific tsunamis, eastern Banks Peninsula, New Zealand. *The Holocene*, **27(4)**, 5496-508.

Dutton, A., Carlson, A., Long, A.J., Milne, G., Clark, P., DeConto, R., Horton, B., Rahmsdorf, S., & Raymo, M. 2015. Sea-level rise due to polar ice-sheet mass loss during past warm periods. *Science* **349(6244),** 4019(1-9).

Ellison, C. R. W., Chapman, M. R., & Hall, I. R. 2006. Surface and deep ocean interactions during the cold climate event 8200 years ago. *Science* **312**, 1929-1932.

Evans, D., McGiveron, S., Harrison, Z., Bryn, P. & Berg, K. 2002. Along-slope variation in the late Neogene evolution of the mid-Norwegian margin in response to uplift and tectonism. *Geological Society, London, Special Publication* **196**, 139-151.

Fairbanks, R. G. 1989. A 17,000 year glacio-isostatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. *Nature* **342**, 637-642.

Fairbanks, R.G. 1990. The age and origin of the "Younger Dryas climate event" in Greenland ice cores. *Paleoceanography* **5**, 937-948.

Farrell, W. E. & Clark, J. A. 1976. On Postglacial Sea Level. *Geophysical Journal of the Royal Astronomical Society* **46**, 647-667.

Fenton, C. H. 1991. *Neotectonics and Palaeoseismicity in North West Scotland*. Unpublished PhD Thesis, University of Glasgow.

Fenton, C. H. & Ringrose, P. S. 1992. Glacio-isostatic faulting and palaeoseismicity in the area of Glen Roy. *In* Fenton, C.H. (ed) *Neotectonics in Scotland: a Field Guide*, 41-53. University of Glasgow, Glasgow.

Finlayson, A., Fabel, D., Bradwell, T. & Sugden, D. 2014. Growth and decay of a marine terminating sector of the last British-Irish Ice Sheet: a geomorphological reconstruction. *Quaternary Science Reviews* **83**, 28-45.

Firth, C. R. 1986. Isostatic depression during the Loch Lomond Stadial – evidence from the Loch Ness area. *Quaternary Newsletter* **48**, 1-9.

Firth, C. R. 1989. Isostatic depression during the Loch Lomond Stadial – evidence from the Inner Moray Firth, Scotland. *Geologiska Foreningens i Stockholm Forhandlingar* **111**, 296-298.

Firth, C. R., Smith, D. E. & Cullingford, R. A. 1993. Late Devensian and Holocene glacio-isostatic uplift patterns in Scotland. *Quaternary Proceedings* **3**, 1-14.

Firth, C. R., Smith, D. E., Hansom, J. D., & Pearson, S. G. 1995. Holocene spit developmenton a regressive shoreline, Dornoch Firth, Scotland. *Marine Geology* **124**, 203-214.

Firth, C. R., Collins, P. E. F. & Smith, D. E. 1997. Coastal processes and management of Scottish estuaries IV – The Firth of Forth. *Scottish Natural Heritage Review* **87**. Scottish Natural Heritage, Edinburgh, 124pp.

Firth, C. R., Collins, P. E. F. & Smith, D. E. 2000. Coastal processes and management of Scottish estuaries V – The Solway Firth. *Scottish Natural Heritage Review* **93**, Scottish Natural Heritage, Edinburgh, 128pp.

Firth, C. R. & Stewart, I. S. 2000. Postglacial tectonics of the Scottish glacio-isostatic uplift centre. *Quaternary Science Reviews* **19**, 1469-1493.

Firth, C. R., Collins, P. E. F. & Smith, D. E. 2002. Coastal processes and management of Scottish estuaries VI – The Firth of Clyde. *Scottish Natural Heritage Review* **108**, Scottish Natural Heritage, Edinburgh, 130pp.

Flinn, D. 1964. Coastal and submarine features around the Shetland Islands. *Proceedings of the Geologists' Association* **75**, 321-340.

Flinn, D. 1969. On the development of coastal profiles in the north of Scotland, Orkney and Shetland. *Scottish Journal of Geology* **5**, 393–399.

Flinn, D. 1973. The topography of the seafloor around Orkney and Shetland and in the northern North Sea. *Journal of the Geological Society* **129**, 39-59.

Franzén, L. G. 1990. Transport, deposition and distribution of marine aerosols over southern Sweden during dry westerly storms. *Ambio* **19**, 180-188.

Fredin, O., Viola, G., Zwingmann, H., Sørlie, R., Brönner, M., Lie, J-E., Grandal, E.M., Müller, A., Margreth, A., & Vogt, C. 2017. The inheritance of a Mesozoic landscape in western Scandinavia. *Nature Communications* **8**, 14879.

Fretwell, P. T. 2001. *A Gaussian trend surface model of Late Devensian and Holocene isostatic uplift in Scotland based upon shoreline altitudes*. Unpublished MSc Thesis, Coventry University.

Fretwell, P., Peterson, I. R. & Smith, D. E. 2004. The use of Gaussian trend surfaces for modelling glacio-isostatic crustal rebound. *Scottish Journal of Geology* **40(2)**, 175-179.

Fretwell, P.T., Smith, D.E., Harrison, S. 2008. The Last Glacial Maximum British-Irish Ice Sheet: a reconstruction using Digital Terrain Mapping. *Journal of Quaternary Science* **23,** 241-248.

Gallagher, C., Telfer, M. W. & Ócofaigh, C. 2015. A marine isotope Stage 4 age for Pleistocene raised beach deposits near Fethard, southern Ireland. *Journal of Quaternary Science* **30(8),** 754-763.

Gehrels, R. 2010. Sea-level changes since the Last Glacial Maximum: an appraisal of the IPCC Fourth Assessment Report. *Journal of Quaternary Science* **25**, 26-38.

Gilbertson, D. D., Schwenninger, J. L., Kemp, R. A. & Rhodes, E. J. 1999. Sand-drift and Soil Formation Along an Exposed North Atlantic Coastline: 14,000 Years of Diverse Geomorphological, Climatic and Human Impacts. *Journal of Archaeological Science* **26**, 439-469.

Gordon, J. E. & Sutherland, D. G. 1993. *The Quaternary of Scotland*. Joint Nature Conservation Committee. Chapman and Hall, London, 695pp.

Godard, A. 1956. Problèmes morphologiques des Orcades. *Norois* **9**, 17-33.

Godard, A. 1965. *Recherches en géomorphologie en Écosse du Nord-Ouest*. Masson et Cie., Paris.

Graham, A. G. C., Lonergan, L. & Stoker, M. S. 2007. Evidence for Late Pleistocene ice stream activity in the Witch Ground Basin, central North Sea, from 3D seismic reflection data. *Quaternary Science Reviews* **26**, 627-643.

Granger, D. E. & Muzikar, P. F. 2001. Dating sediment burial with in situ-produced cosmogenic nuclides: theory, techniques and limitations. *Earth and Planetary Science Letters* **188(1)** 269-281.

Gray, J. M. 1974. Lateglacial and postglacial shorelines in western Scotland. *Boreas* **3**, 129-138.

Gray, J. M. 1978. Low-level shore platforms in the south-west Scottish Highlands: altitude, age and correlation. *Transactions of the Institute of British Geographers* **NS 3**, 151-164.

Gray, J. M. 1983. The measurement of shoreline altitudes in areas affected by glacio-isostasy, with particular reference to Scotland. *In* Smith, D.E. & Dawson, A.G. (eds) Shorelines and Isostasy, 97-127. Academic Press, London.

Gray, J. M. 1985. Glacio-isostatic shoreline development in Scotland: an overview. *Occasional Paper* **24**. Dept. of Geography and Earth Science, Queen Mary College, University of London, 61pp.

Gray, J. M. 1989. Distribution and development of the Main Rock Platform, western Scotland: comment. *Scottish Journal of Geology* **25(2),** 227-238.

Gray, J. M. 1993. Glenacardoch Point, *In* Gordon, J. E., Sutherland, D. G. (eds), *Quaternary of Scotland*, 313-316. Chapman and Hall, London.

GRIP Ice-Core Project Members. 1993. Climatic instability during the last interglacial period recorded in the GRIP ice core. *Nature* **364**, 203-207.

Haflidason, H., Lien, R., Sejrup, H. P., Forsberg, C.F., & Bryn, P. 2005. The dating and morphometry of the Storegga Slide. *Marine and Petroleum Geology* **22,** 123-136.

Haggart, B. A. 1986. Relative sea-level change in the Beauly Firth, Scotland. Boreas **15**, 191-207.

Hall, A. M. 1989. Pre-Late Devensian coastal rock platforms around Dunbar. *Scottish Journal of Geology* **25**, 361-365.

Hall, A. M. 1991. Pre-Quaternary landscape evolution in the Scottish Highlands. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **82**, 1-26.

Hall, A. M. 1995. Was all of Lewis glaciated in the Late Devensian? *Quaternary Newsletter* **76**, 1-7.

Hall, A. M. 1996. Quaternary geomorphology of the Outer Hebrides**.** *In* Gilbertson, D., Kent, M. and Grattan, J. (eds) *The Outer Hebrides: the last 14,000 years*, 5-12. Sheffield Academic Press.

Hall, A. M. 2011. Storm wave currents, boulder movement and shore platform development: a case study from East Lothian, Scotland. *Marine Geology* **283**, 98–105.

Hall, J. & Rashid, B. M. 1977. A possible submerged wave-cut platform in the Firth of Lorn. *Scottish Journal of Geology* **13**, 285-288.

Hall, A. M., Hansom, J. D., Williams, D. M. & Jarvis, J. 2006. Distribution, geomorphology and lithofacies of cliff-top storm deposits: Examples from the high-energy coasts of Scotland and Ireland. Marine Geology **232**, 131-155.

Hall, A. M., Hansom, J. & Williams, D. M. 2010. Wave-emplaced coarse debris and megaclasts in Ireland and Scotland: Boulder transport in a high-energy littoral environment: A discussion. *Journal of Geology* **118**, 699-704.

Hall, A. M. & Riding, J. 2016. The last glaciation in Caithness, Scotland: revised till stratigraphy and ice-flow paths indicate multiple flow phases. *Scottish Journal of Geology* **52,** 77-89.

Hamilton, C. A., Lloyd, J. M., Barlow, N. L. M., Innes, J. B., Flecker, R. & Thomas, C. P. 2015. Late Glacial to Holocene relative sea-level change in Assynt, northwest Scotland, UK. *Quaternary Research* **84**, 214-222.

Hansom, J. 2003a. Foula, Shetland, *In*: May, V. & Hansom, J. D. (eds), *Coastal geomorphology of Great Britain*, 76-80. Joint Nature Conservancy Council, HMSO, Norwich.

Hansom, J. D. 2003b. Papa Stour, *In*: May, V. & Hansom, J. D. (eds), *Coastal geomorphology of Great Britain*. Joint Nature Conservancy Council, HMSO, Norwich, 72-76.

Hansom, J. D. 2003c. Bullers of Buchan, *In*: May, V. & Hansom, J. D. (eds), *Coastal geomorphology of Great Britain*, 103-106. Joint Nature Conservancy Council, HMSO, Norwich.

Hansom, J. D., Barltrop, N. & Hall, A. M. 2008. Modelling the processes of cliff-top erosion and deposition under extreme storm waves. *Marine Geology* **253**, 36-50.

Hansom, J. D. & Hall, A. M. 2009. Magnitude and frequency of extra-tropical North Atlantic cyclones: a chronology from cliff-top storm deposits. *Quaternary International* **195**, 42-52.

Harrison, S. J. 1997. Changes in the Scottish climate. *Botanical Journal of Scotland* **49**, 287-300.

Hazell, Z. J. 2008. Offshore and intertidal peat deposits, England – a resource assessment and development of a database. *Environmental Archaeology* **13**, 101-110.

Hickey, K. R. 1997. *Documentary Records of Coastal Storms in Scotland, 1500-1991 AD*. Unpublished PhD Thesis, Coventry University.

Holford, S. P., Green, P. F., Hillis, R. R., Underhill, J. R., Stoker, M. S. & Duddy, I. R. 2010. Multiple post-Caledonian exhumation episodes across NW Scotland revealed by apatite fission-track analysis. *Journal of the Geological Society* **167**, 675-694.

Holloway, L. K. 2002. *Sedimentary environments in the western Forth valley during the Late Devensian and Holocene.* Unpublished PhD Thesis, Coventry University.

Holloway, L. K., Peacock, J. D., Smith, D. E., & Wood, A. M. 2002. A Windermere Interstadial marine sequence: environmental and relative sea level interpretation for the western Forth valley, Scotland. *Scottish Journal of Geology* **38(1)**, 41-54.

Holmes, G. 1984. *Rock-Slope Failures in parts of the Scottish Highlands.* Unpublished PhD Thesis, University of Edinburgh.

Holtedahl, H. 1998. The Norwegian strandflat puzzle. *Norsk Geologisk Tidsskrift* **78**, 47-66.

Hoppe, G. 1965. Submarine peat in the Shetland Islands. *Geografiska Annaler* **47A**, 195-203.

Howe, J. A., Dove, D., Bradwell, T., Gafeira, J. 2012. Submarine geomorphology and glacial history of the Sea of the Hebrides, UK. *Marine Geology* **315,** 64-76.

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R. & Stoker, M. 2009. Dynamic cycles, ice streams and their impact on the extent, chronology and deglaciation of the British–Irish ice sheet. *Quaternary Science Reviews* **28**, 758-776.

Hurst, M. D., Rood, D. H. & Ellis, M. A. 2016. Controls on the distribution of cosmogenic ^{10}Be across shore platforms. *Earth Surface Dynamics Discussions*. Doi: 10.5194/esurf-2016-42.

Jacobs, C. L. 2006. *An appraisal of the Surface Geology and Sedimentary Processes within SEA7, the UK Continental Shelf*. National Oceanography Centre, Southampton for DTI, 62pp.

Jamieson, T. F. 1865. On the history of the last geological changes in Scotland. *Quarterly Journal of the Geological Society of London* **21**, 161-203.

Japsen, P. 1997. Regional Neogene exhumation of Britain and the western North Sea. *Journal of the Geological Society, London* **154**, 239-247.

Jardine, W. G. 1971. Form and age of late Quaternary shorelines and coastal deposits of south-west Scotland: critical data. *Quaternaria* **14**, 103-114.

Jardine, W. G. 1977. The Quaternary marine record in southwest Scotland and the Scottish Hebrides, *In:* Kidson, C., & Tooley, M. J. (eds). *The Quaternary history of the Irish Sea*, 99-118. Seel House Press, Liverpool.

Jardine, W. G. 1982. Sea-level changes in Scotland during the last 18,000 years. *Proceedings of the Geologists' Association* **93(1)**, 25-41.

Jordan, J. T., Smith, D. E., Dawson, S. & Dawson, A. G. 2010. Holocene relative sea level changes in Harris, Outer Hebrides, Scotland, UK. *Journal of Quaternary Science* **25(2)**, 115-134.

Kemp, A. C. & Telford, R. J. 2015. Transfer functions. *In:* Shennan, I., Long, A. and Horton B. (eds) *Handbook of Sea-Level Research*, 470-499. John Wiley & Sons, Chichester.

Kendall, R. A., Mitrovica, J. X. & Milne, G. A. 2005. On post-glacial sea level - II. Numerical formulation and comparative results on spherically symmetric models. *Geophysical Journal International* **161**, 679-706.

Kirk, R. 1977. Rates and forms of erosion on intertidal platforms at Kaikoura Peninsula, South Island, New Zealand. *New Zealand Journal of Geology and Geophysics* **20**, 571-613.

Knies, J., Mattingsdal, R., Fabian, K., Grøsfjeld, K., Baranwal, S., Husum, K., De Schepper, S., Vogt, C., Andersen, N., Matthiessen, J., Andreassen, K., Jokat, W., Nam, S-I. & Gaina, C. 2014. Effect of early Pliocene uplift on late Pliocene cooling in the Arctic–Atlantic gateway. *Earth and Planetary Science Letters* **387**, 132-144.

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., Hay, C. C., Mitrovica, J. X., Morrow, E. D. & Rahmstorf, S. 2016. Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences* **113**, E1434-E1441.

Kuchar, J., Milne, G., Hubbard, A., Patton, H., Bradley, S. L., Shennan, I. & Edwards, R. 2012. Evaluation of a numerical model of the British-Irish ice sheet using relative sea-level data: implications for the interpretation of trimline observations. *Journal of Quaternary Science* **27**, 597-605.

Lambeck, K. 1991a. A model for Devensian and Flandrian glacial rebound and sea-level change in Scotland. *In* Sabadini, R., Lambeck, K. & Boschi, E. (eds) *Glacial Isostasy, Sea Level and Mantle Rheology*, 33-61. Kluwer, Dordrecht.

Lambeck, K. 1991b. Glacial rebound and sea-level change in the British Isles. *Terra Nova* **3**, 379-389.

Lambeck, K. 1993a. Glacial rebound of the British Isles – I. Preliminary model results. *Geophysical Journal International* **115**, 941-959.

Lambeck, K. 1993b. Glacial rebound of the British Isles – II. A high-resolution, high-precision model. *Geophysical Journal International* **115**, 960-990.

Lambeck, K. 1995. Late Devensian and Holocene shorelines of the British Isles and North Sea from models of glacio-hydro-isostatic rebound. *Journal of the Geological Society of London* **152**, 437-448.

Lambeck, K., Rouby, H., Purcell, A., Sun, Y. & Sambridge, M. 2014. Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences* **111(43)**, 15296-15303.

Larsen, E. & Holtedahl, H. 1985. The Norwegian strandflat: A reconsideration of its age and origin. *Norsk Geologisk Tidsskrift* **65**, 247-254.

Larsen, E., Gulliksen, S., Lauritzen, S-E., Lie, R., Lovlie, R. & Mangerud, J. 1987. Cave stratigraphy in western Norway; multiple Weichselian glaciations and interstadial vertebrate fauna. *Boreas* **16**, 267-292.

Lawrence, T., Long, A. J., Gehrels, W. R., Jackson, L. & Smith, D. E. 2016. Relative sea-level data from southwest Scotland constrain meltwater-driven sea-level jumps prior to the 8.2kyr BP event. *Quaternary Science Rev*iews **151**, 292-308.

Le Coeur, C. 1988. Late Tertiary warping and erosion in western Scotland. *Geografiska Annaler* **70A**, 361-368.

Lisiecki, L. E. & Raymo, M. E. 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ18O records. *Paleoceanography* **20**: PA1003.

Liu, J.P., Milliman, J.D., Gao, S., Cheng, P. 2004. Holocene development of the Yellow River's subaqueous delta, North Yellow Sea. *Marine Geology* **209**, 45-67.

Liu, J., Milne, G. A., Kopp, R. E., Clark, P. U. & Shennan, I. 2016. Sea-level constraints on the amplitude and source distribution of Meltwater Pulse 1A. *Nature Geoscience* **9**, 130-134.

Lloyd, J. M. 2000. Combined foraminiferal and thecamoebian environmental reconstruction from an isolation basin in NW Scotland: Implications for sea-level studies. *Journal of Foraminiferal Research* **30 (4)**, 294-305.

Lloyd, J. M., Shennan, I., Kirby, J. R. & Rutherford, M. M. 1999. Holocene relative sea-level changes in the inner Solway Firth. *Quaternary International* **60**, 83-105.

Lloyd, J. M. & Evans, J. R. 2002. Contemporary and fossil foraminifers from isolation basins in northwest Scotland. *Journal of Quaternary Science* **17(5-6)**, 431-443.

Long, A. J., Barlow, N. L. M., Dawson, S., Hill, J., Innes, J. B., Kelham, C., Milne, F. D. & Dawson, A.G. 2016. Late Glacial and Holocene relative sea-level changes and first evidence for the Storegga tsunami in Sutherland, Scotland. *Journal of Quaternary Science* **31,** 239-255.

Long, D., Wickham-Jones, C. R. & Ruckley, N. A. 1986. A flint artefact from the northern North Sea. *In:* Roe, D.A. (ed) *Studies in the Upper Palaeolithic of Britain and Northwest Europe*, 55-62. British Archaeology Reports, International Series **296**.

Long, D. & Wilson, C. K. 2007. *A catalogue of tsunamis in the UK*. British Geological Survey Marine, Coastal and Hydrocarbons Programme, Commissioned Report CR/07/077, 28pp.

Long, D. 2015. *A Catalogue of tsunamis reported in the UK.* British Geological Survey Internal Report IR/15/043, 63pp. http://nora.nerc.ac.uk/id/eprint/513298

Long, D. 2017. Cataloguing tsunami events in the UK. *In:* Scourse, E. M., Chapman, N. A., Tappin, D. R. & Wallis, S. R. (eds) *Tsunamis: Geology, Hazards and Risks.* Geological Society, London, Special Publications **456**. https://doi.org/10.1144/SP456.10

Løseth, H., Kyrkjebø, R., Hilde, E., Wild, R.J., & Bunkholt, H. 2017. 500m of rapid base level rise along an inner passive margin – Seismic observations from the Pliocene Molo Formation, mid Norway. *Marine and Petroleum Geology* **86,** 268-287.

Maclaren, C. 1842. The Glacial Theory of Prof. Agassiz. *American Journal of Science and Arts*, **42(2)**, 346-365.

McCabe, A. M., Clark, P. U., Smith, D. E. & Dunlop, P. 2007a A revised model for the last deglaciation of eastern Scotland. *Journal of the Geological Society of London* **164**, 1261-1262.

McCabe, A. M., Clark, P. U., Smith, D. E. & Dunlop, P. 2007b Reply. *Journal of the Geological Society of London* **164**, 1261-1263.

McCann, S. B. 1968. Raised shore platforms in the Western Isles of Scotland. *In:* Bowen, E. G., Carter, H. & Taylor, J. A. (eds), *Geography at Aberystwyth*, 22-34. University of Wales Press, Cardiff.

McKenna, J., Cooper, J. A. G. & Jackson, D. W. 2012. Storm swash terraces: a previously overlooked element of the cliff-shore platform system. *Journal of Sedimentary Research* **82**, 260-269.

Merritt, J. W., Auton, C. A. & Firth, C. R. 1995. Ice-proximal glaciomarine sedimentation and sea-level change in the Inverness area, Scotland: a review of the deglaciation of a major ice stream of the British Late Devensian ice sheet. *Quaternary Science Reviews* **14**, 289-329

Merritt, J. W., Auton, C. A., Connell, E. R., Hall, A. M. & Peacock, J. D. 2003. *Cainozoic geology and landscape evolution of north-east Scotland*. Memoir of the British Geological Survey, Sheets 66E, 67, 76E, 77, 86E, 87W, 87E, 95, 96W, 96E and 97 Scotland. NERC, Keyworth.

Miller, K. G., Wright, J. D., Browning, J. V., Kulpecz, A., Kominz, M., Naish, T. R., Cramer, B.S., Rosenthal, Y., Peltier, W.R. & Sosdian, S. 2012. High tide of the warm Pliocene: Implications of global sea level for Antarctic deglaciation. *Geology* **40**, 407-410.

Milne, G. A., Mitrovica, J. X. & Schrag, D. P. 2002. Estimating past continental ice volume from sea-level data. *Quaternary Science Reviews* **21**, 361-376.

Mitrovica, J. X. & Milne, G. A. 2003. On post-glacial sea level: I. General theory. *Geophysical Journal Internationa*l **154**, 253-267.

Mitrovica, J. X., Wahr, J., Matsuyama, I. & Paulson, A. 2005. The rotational stability of an ice-age earth. *Geophysical Journal Internatio*nal **161**, 491-506.

Musson, R. M. W. 2007. British earthquakes. *Proceedings of the Geologists' Association* **118**, 305-337.

Nansen, F. 1922. The strandflat and isostasy. *Videnskapsselskapets Skrifter 1. Math.-Naturw. Klasse.* **192**, 1-11, Kristiana.

Neill, S. P., Scourse, J. D., Bigg, G. R. & Uehara, K. 2009. Changes in wave climate over the northwest European shelf areas during the last 12,000 years. *Journal of Geophysical Research* **114 (C6)**, C06015.

Neill, S. P., Scourse, J. D. & Uehara, K. 2010. Evolution of bed shear stress distribution over the northwest European shelf seas during the last 12,000 years. *Ocean Dynamics* **60(5)**, 1139-1156.

Olesen, O., Kierulf, H. P., Brönner, M., Dalsegg, E., Fredin, O. & Solbakk, T. 2013. Deep weathering, neotectonics and strandflat formation in Nordland, northern Norway. *Norsk Geologisk Tiddskrift* **93**, 189-213.

Orme, L. C., Reinhardt, L., Jones, R. T., Charman, D. J., Barkwith, A., & Ellis, M. A. 2016. Aeolian sediment reconstructions from the Scottish Outer Hebrides: Late Holocene storminess and the role of the North Atlantic Oscillation. *Quaternary Science Reviews* **132**, 15-25.

Paul, M. A., Peacock, J. D. & Barrass, B. F. 1995. Flandrian stratigraphy and sedimentation in the Bothkennar-Grangemouth area. *Quaternary Newsletter* **75**, 22-35.

Paul, M. A., Barras, B. F., & Mein, J. E. 2004. Geotechnical properties of British estuarine clays: towards a geological framework. *In:* Jardins, R.J., Potts, D.M., Higgins, K. (eds) *Advances in Geotechnical Engineering; Proceedings of the Skempton Conference,* 568-579. Thomas Telford, London.

Paul, M. A. & Barrass, B. F. 1998. A geotechnical correction for post-depositional sediment compression: examples from the Forth valley, Scotland. *Journal of Quaternary Science* **13(2)**, 171-176.

Peacock, J. D. 1984. Quaternary Geology of the Outer Hebrides. *Report of the British Geological Survey* **16**, 1-26.

Peacock, J. D. 1996. Marine molluscan proxy data applied to Scottish late glacial and Flandrian sites: strengths and limitations. *In*: Andrews, J. T., Austin, W. E. N., Bergsten, H. and Jennings, A. E. (eds) Late Quaternary Paleoceanography of the North Atlantic Margins. *Geological Society of London Special Publication* **111**, 215-228.

Peacock, J. D. 1999. The Pre-Windermere Interstadial (Late Devensian) raised marine strata of eastern Scotland and their macrofauna: a review. *Quaternary Science Reviews* **18**, 1655-1680.

Peacock, J. D. 2002. Macrofauna and palaeoenvironment of marine strata of Windermere Interstadial age on the east coast of Scotland. *Scottish Journal of Geology* **38(1)**, 31-40.

Peacock, J. D. 2003. Late Devensian marine deposits (Errol Clay Formation) at the Gallowflat claypit, eastern Scotland: new evidence for the timing of ice recession in the Tay Estuary. *Scottish Journal of Geology* **39(1)**, 1-10.

Peacock, J. D., Armstrong, M., Browne, M. A. E., Golledge, N. R. & Stoker, M. S. 2007. Discussion on a revised model for the last deglaciation of eastern Scotland. *Journal of the Geological Society of London* **164**, 1261-1262.

Peacock, J. D. 2008. Late Devensian palaeoenvironmental changes in the sea area adjacent to Islay, SW Scotland: Implications for the deglacial history of the island. *Scottish Journal of Geology* **44**, 183-190.

Peltier, W. R., Shennan, I., Drummond, R. & Horton, B. 2002. On the postglacial isostatic adjustment of the British Isles and the shallow viscoelastic structure of the Earth. *Geophysical Journal International* **148**, 443--475.

Rennie, A. F. & Hansom, J. D. 2011. Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast. *Geomorphology* **125**, 193-202.

Rhind, D. W. 1965. Evidence of sea level changes along the coast north of Berwick. *Proceedings of the Berwickshire Naturalists' Club* **37**, 10-15.

Ringrose, R. S. 1989. Recent fault movement and palaeoseismicity in western Scotland. *Tectonophysics* **163**, 305-314.

Ringrose, R. S., Hancock, P. L., Fenton, C., & Davenport, C. A. 1991. Quaternary Tectonic activity in Scotland. *In:* Foster, A., Culshaw, M. G., Cripps, J. C., Little, J. A. & Moon, C. F. (eds) Quaternary Engineering Geology. *Engineering Geology Special Publication* **7**, 679-686.

Robinson, M. 1993. Microfossil analyses and radiocarbon dating of depositional sequences related to Holocene sea-level change in the Forth valley, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **84**, 1-60.

Rowan, J. S., Duck, R. W. & Black, S. 2001. Calcareous concretions yield the first U/Th date for the Late Devensian raised marine strata of eastern Scotland. *Scottish Journal of Geology* **37(2)**, 73-78.

Scheffers, A., Scheffers, S., Kelletat, D. & Browne, T. 2009. Wave-emplaced coarse debris and megaclasts in Ireland and Scotland: boulder transport in a high-energy littoral environment. *Journal of Geology* **117**, 553-573.

Sejrup, H. P., Nygård, A., Hall, A. M., & Haflidason, H. 2009. Middle and Late Weichselian (Devensian) glaciation history of south-western Norway, North Sea and eastern UK. *Quaternary Science Reviews* **28**, 370-380.

Sejrup, H. P., Clark, C. D. & Hjelstruen, B. O. 2016. Rapid ice sheet retreat triggered by ice stream debuttressing: Evidence from the North Sea. *Geology* **44**, 355-358.

Selby, I. C. 1987. Glaciated shorelines in Barra and Vatersay. *Quaternary Newsletter* **53**, 16-22.

Selby, K. A., Smith, D. E., Dawson, A. G. & Mighall, T. M. 2000. Late Devensian and Holocene relative sea level and environmental changes from an isolation basin in southern Skye. *Scottish Journal of Geology* **36(1)**, 73-86.

Selby, K. A. & Smith, D. E. 2007. Late Devensian and Holocene relative sea-level changes on the Isle of Skye, Scotland, UK. *Journal of Quaternary Science* **22**, 119-139.

Selby, K. A. & Smith, D. E. 2015. Holocene relative sea-level change on the Isle of Skye, Inner Hebrides, Scotland. *Scottish Geographical Journal* **132**, 42-65.

Selby, K. A. & Smith, D. E. 2016. Raised shorelines and relative sea level change on Skye. In: Ballantyne, C. K. & Lowe, J. J. (eds.) *The Quaternary of Skye*, 89-111. Field Guide, Quaternary Research Association, London.

Shennan, I. 1999. Global meltwater discharge and the deglacial sea-level record from northwest Scotland. *Journal of Quaternary Science* **14(7)**, 715-719.

Shennan, I. 2013. Discussion of Rennie, A. F. & Hansom, J. D. 2011. Sea level trend reversal: Land uplift outpaced by sea level rise on Scotland's coast *Geomorphology* **125 (1)**, 193-202.

Shennan, I., Innes, J. B., Long, A. J. & Zong, Y. 1993. Late Devensian and Holocene relative sea-level changes at Rumach, near Arisaig, northwest Scotland. *Norsk Geologisk Tiddskrift* **73**, 161-174.

Shennan, I., Innes, J. B., Long, A. J. & Zong, Y. 1994. Late Devensian and Holocene relative sea-level changes at Loch nan Eala, near Arisaig, northwest Scotland. *Journal of Quaternary Science* **9(3)**, 261-283.

Shennan, I., Innes, J. B., Long, A. J. & Zong, Y. 1995a. Late Devensian and Holocene relative sea-level changes in northwestern Scotland: new data to test existing models. *Quaternary International* **26**, 97-123.

Shennan, I., Innes, J. B., Long, A. J. & Zong, Y. 1995b. Holocene relative sea-level changes and coastal vegetational history at Kentra Moss, Argyll, northwest Scotland. *Marine Geology* **124**, 43-59.

Shennan, I., Green, F., Innes, J., Lloyd, J., Rutherford, M. M. & Walker, K. J. 1996a. Evaluation of Rapid Relative Sea-Level Changes in North-West Scotland During the Last Glacial-Interglacial Transition: Evidence from Ardtoe and Other Isolation Basins. *Journal of Coastal Research* **12(4)**, 862-874.

Shennan, I., Rutherford, M. M., Innes, J. B. & Walker, K. J. 1996b. Late glacial sea level and ocean margin environmental changes interpreted from biostratigraphic and lithostratigraphic studies of isolation basins in northwest Scotland. *In:* Andrews, J. T., Austin, W. E. N., Bergsten, H. & Jennings, A. E. (eds) *Late Quaternary Palaeoceanography of the North Atlantic Margi*ns. Geological Society Special Publication **111**, 229-244.

Shennan, I., Tooley, M., Green, F., Innes, J., Kennington, K., Lloyd, J. & Rutherford, M. M. 1998. Sea level, climate change and coastal evolution in Morar, northwest Scotland. *Geologie en Mijnbouw* **77**, 247-262.

Shennan, I., Tooley, M. J., Green, F. M. L., Innes, J. B., Kennington, K., Lloyd, J & Rutherford, M. M. 1999. Sea level, climate change and coastal evolution in Morar, northwest Scotland. *Geologie en Mijnbouw* **77**, 247-262.

Shennan, I., Lambeck, K., Horton, B., Innes, J., Lloyd, J., McArthur, J., Purcell, T. & Rutherford, M. M. 2000a. Late Devensian and Holocene records of relative sea-level changes in northwest Scotland and their implications for glacio-hydro-isostatic modelling. *Quaternary Science Reviews* **19(11)**, 1103-1135.

Shennan, I., Lambeck, K., Flather, R., Horton, B., McArthur, J., Innes, J., Lloyd, J., Rutherford, M. M. & Wingfield, R. 2000b. Modelling western North Sea palaeographies and tidal changes during the Holocene. *In* Shennan, I. & Andrews, J. T. (eds) *Holocene Land-Ocean Interaction and Environmental Change around the North Sea*. Geological Society of London, Special Publication **166**, 299-319.

Shennan, I. & Horton, B. P. 2002. Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science* **17**, 511-526.

Shennan, I., Peltier, W. R., Drummond, R. & Horton, B. 2002. Global to local scale parameters determining relative sea-level changes and the post-glacial isostatic adjustment of Great Britain. *Quaternary Science Revie*ws **21**, 397-408.

Shennan, I., Coulthard, T., Flather, R., Horton, B., Macklin, M., Rees, J. & Wright, M. 2003. Integration of shelf evolution and river basin models to simulate Holocene sediment dynamics of the Humber estuary during periods of sea-level change and variations in catchment sediment supply. *The Science of the Total Environment* **314-316**, 737-754.

Shennan, I., Hamilton, S., Hillier, C. & Woodroffe, S. 2005. A 16,000-year record of near-field relative sea-level changes, northwest Scotland, United Kingdom. *Quaternary International* **133-134**, 95-106.

Shennan, I., Bradley, S., Milne, G., Brooks, A., Bassett, S. & Hamilton, S. 2006a. Relative sea-level changes, glacial isostatic modelling and ice-sheet reconstructions from the British Isles since the Last Glacial Maximum. *Journal of Quaternary Science* **21**, 585-599.

Shennan, I., Hamilton, S., Hillier, C., Hunter, A., Woodall, R., Bradley, S., Milne, G., Brooks, A. & Bassett, S. 2006b. Relative sea-level observations in western Scotland since the Last Glacial Maximum for testing models of glacial isostatic land movements and ice-sheet reconstructions. *Journal of Quaternary Science* **21(6)**, 601-613.

Shennan, I., Milne, G. & Bradley, S. 2009. Late Holocene relative land-and sea-level changes: providing information for stakeholders. *GSA Today* **19**, 52-53.

Shennan, I., Milne, G. & Bradley, S. 2012. Late Holocene vertical land motion and relative sea-level changes: lessons from the British Isles. *Journal of Quaternary Science* **27(1)**, 64-70.

Shi, S. 1995. *Observational and theoretical aspects of tsunami sedimentation*. Unpublished PhD Thesis, Coventry University.

Simpson, J. B. 1933. The late-glacial readvance moraines of the Highland border west of the River Tay. *Transactions of the Royal Society of Edinburgh* **57**, 633-645.

Sissons, J. B. 1962. A re-interpretation of the Literature on Late-glacial Shorelines in Scotland with Particular reference to the Forth Area. *Transactions of the Edinburgh Geological Society* **19(1)**, 83-99.

Sissons, J. B. 1963. The Perth Readvance in Central Scotland, Part I. *Scottish Geographical Magazine* **79**, 151-163.

Sissons, J. B. 1964. The Perth Readvance in Central Scotland, Part II. *Scottish Geographical Magazine* **80**, 28-36.

Sissons, J. B. 1966. Relative Sea-Level Changes between 10300 and 8300 BP in Part of the Carse of Stirling. *Transactions of the Institute of British Geographers* **39**, 19-29.

Sissons, J. B. 1967. *The evolution of Scotland's scenery*. Oliver and Boyd, Edinburgh.

Sissons, J. B. 1972. Dislocation and non-uniform uplift of raised shorelines in the western part of the Forth Valley. *Transactions of the Institute of British Geographers* **55**, 149-159.

Sissons, J. B. 1974a. Late-glacial marine erosion in Scotland. *Boreas* **3**, 41-48.

Sissons, J. B. 1974b, The Quaternary of Scotland: a review. *Scottish Journal of Geology* **10**, 311-337.

Sissons, J. B. 1976. *The Geomorphology of the British Isles: Scotland*. Methuen, London, 150pp.

Sissons, J. B. 1981. British shore platforms and ice-sheets. *Nature* **291**, 473-475.

Sissons, J. B. 1982. The so-called high 'interglacial' rock shoreline of western Scotland. *Transactions of the Institute of British Geographers* **N.S 7**, 205-216.

Sissons, J.B. 1983. Shorelines and isostasy in Scotland. *In* Smith, D. E. & Dawson, A. G. (eds) *Shorelines and Isostasy*, 209-225. Academic Press, London.

Sissons, J. B. & Smith, D. E. 1965. Peat bogs in a post-glacial sea and a buried raised beach in the western part of the Carse of Stirling. *Scottish Journal of Geology* **1**, 247-255.

Sissons, J. B., Smith, D. E. & Cullingford, R. A. 1966. Late-glacial and Post-glacial shorelines in South-East Scotland. *Transactions of the Institute of British Geographers* **39**, 9-18.

Sissons, J. B. & Dawson, A. G. 1981. Former sea-levels and ice limits in part of Wester Ross, northwest Scotland. *Proceedings of the Geologists' Association* **92(2)**, 115-124.

Sissons, J. B. & Cornish, R. 1982. Differential glacio-isostatic uplift of crustal blocks at Glen Roy, Scotland. *Quaternary Research* **18**, 268-288.

Smith, D. E. 1997. Sea level change in Scotland during the Devensian and Holocene. *In:* Gordon, J. E. (ed) *Reflections on the Ice Age in Scotland*, 136-151. Scottish Natural Heritage, Glasgow.

Smith, D. E. 2005. Evidence for secular sea surface changes in the Holocene raised shorelines of Scotland, UK. *Journal of Coastal Research, Special Issue* **42**, 26-42.

Smith, D. E., Sissons, J. B., & Cullingford, R. A. 1969. Isobases for the Main Perth raised shoreline in South East Scotland as determined by trend-surface analysis. *Transactions of the Institute of British Geographers* **46**, 45-52.

Smith, D. E. & Cullingford, R. A. 1982. New evidence for Late Devensian marine limits in east-central Scotland – some comments. *Quaternary Newsletter* **35**, 12-14.

Smith, D. E., Firth, C. R., Turbayne, S. C. & Brooks, C. L. 1992. Holocene relative sea level changes and shoreline displacement in the Dornoch Firth area, Scotland. *Proceedings of the Geologists' Association* **103**, 237-257.

Smith, D. E., Firth, C. R., Brooks, C. L., Robinson, M. & Collins, P. E. F. 1999. Relative sea-level rise during the Main Postglacial Transgression in NE Scotland, UK. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **90**, 1-27.

Smith, D. E., Cullingford, R. A. & Firth, C. R. 2000. Patterns of isostatic land uplift during the Holocene: evidence from mainland Scotland. *The Holocene* **10(4)**, 489-501.

Smith, D. E., Firth, C. R. & Cullingford, R. A. 2002. Relative sea-level trends during the early-middle Holocene along the eastern coast of Scotland, UK. *Boreas* **31(2)**, 185-202.

Smith, D. E., Wells, J. M., Mighall, T. M., Cullingford, R. A., Holloway, L. K., Dawson, S. & Brooks, C. L. 2003a. Holocene relative sea levels and coastal changes in the lower Cree valley and estuary, SW Scotland, UK. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **93**, 301-331.

Smith, D. E., Haggart, B. A., Cullingford, R. A., Tipping, R. M., Wells, J. M., Mighall, T. M. & Dawson, S. 2003b. Holocene relative sea-level change in the lower Nith valley and Estuary. *Scottish Journal of Geology* **39(2)**, 97-120.

Smith, D. E., Shi, S., Cullingford, R. A., Dawson, A. G., Dawson, S., Firth, C. R., Foster, I. D. L., Fretwell, P. T., Haggart, B. A., Holloway, L. K. & Long, D. 2004. The Holocene Storegga Slide tsunami in the United Kingdom. *Quaternary Science Reviews* **23**, 2291-2321.

Smith, D. E., Fretwell, P. T., Cullingford, R. A. & Firth, C. R. 2006. Towards improved empirical isobase mdels of Holocene land uplift for mainland Scotland, UK. *Philosophiocal Transactions of the Royal Society A* **364**, 949-972.

Smith, D. E., Cullingford, R. A. Mighall, T. M. & Fretwell, P. T. 2007. Holocene relative sea level changes in a glacio-isostatic area: new data from south-west Scotland, United Kingdom. *Marine Geology* **242**, 5-26.

Smith, D. E., Foster, I. D. L., Long, D. & Shi, S. 2007. Reconstructing the pattern and depth of flow onshore in a palaeotsunami from associated deposits. *Sedimentary Geology* **200**, 362-371.

Smith, D. E., Stewart, I. S., Harrison, S. & Firth, C. R. 2009. Late Quaternary neotectonics and mass movement in South East Raasay, Inner Hebrides, Scotland. *Proceedings of the Geologists' Association* **120 (2-3)**, 145-154.

Smith, D. E., Davies, M. H., Brooks, C. L., Mighall, T. M., Dawson, S., Rea, B. R., Jordan, J. T. & Holloway, L. K. 2010. Holocene relative sea levels and related prehistoric activity in the Forth lowland, Scotland, United Kingdom. *Quaternary Science Reviews* **29(17-18)**, 2382-2410.

Smith, D. E., Harrison, S., Firth, C. & Jordan, J. T. 2011. The early Holocene sea level rise. *Quaternary Science Reviews* **30**, 1846-1860.

Smith, D. E., Hunt, N., Firth, C. R., Jordan, J. T., Fretwell, P. T., Harman, M., Murdy, J., Orford, J. D. & Burnside, N. G. 2012. Patterns of Holocene relative sea level change in the North of Britain and Ireland. *Quaternary Science Reviews* **54**, 58-76.

Smith, D. E., Harrison, S. & Jordan, J. T. 2013. Sea level rise and submarine mass failures on open continental margins. *Quaternary Science Reviews* **82**, 93-103.

Sommerville, A. A. 2003. *Optically stimulated luminescence dating of wind blown sands from an archaeological site in Northern Scotland*. Unpublished PhD Thesis, University of Glasgow.

Sommerville, A. A., Hansom, J. D., Sanderson, D. C. W. & Housley, R. A. 2003. Optically stimulated luminescence dating of large storm events in Northern Scotland. *Quaternary Science Reviews* **22**, 1085-1092.

Sommerville, A., Hansom, J., Housley, R & Sanderson, D. 2007. Optically stimulated luminescence (OSL) dating of coastal aeolian sand accumulation in Sanday, Orkney Islands, Scotland. *The Holocene* **17**, 627-637.

Soulsby, R. L., Smith, D. E. & Ruffman, A. 2007. Reconstructing tsunami run-up from sedimentary characteristics – a simple mathematical model. In Kraus, N. C. and Rosati, J. D. (eds.) Coastal Sediments '07. *Proceedings of the 6th International Symposium on Coastal Engineering and the Science of Coastal Sediment Processes. American Society of Civil Engineers, Volume* ***2***, 1075-1088.

Steers, J. A. 1973. *The Coastline of Scotland*. University Press, Cambridge.

Stephens, N. 1957. Some observations on the 'Interglacial' platform and the early Post-glacial raised beach on the east coast of Ireland. *Proceedings of the Royal Irish Academy Series B* **58**, 129-149.

Stewart, I. S., Firth, C. R., Rust, D. J., Collins, P. E. F. & Firth, J. A. 2001. Postglacial fault movement and palaeoseismicity in western Scotland: A reappraisal of the Kinloch Hourn fault, Kintail. *Journal of Seismology* **5**, 307-328.

Stockamp, J., Bishop, P., Li, Z., Petrie, E. J., Hansom, J. & Rennie, A. 2016. State-of-the-art in studies of glacial isostatic adjustment for the British Isles: a literature review. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh,* 1-26.

Stoker, M. S. & Long, D. 1984. A relict ice-scoured erosion surface in the central North Sea. *Marine Geology* **61**, 85-93.

Stoker, M. S. & Graham, C. C. 1985. Pre-late Weichselian submerged rock platforms off Stonehaven. *Scottish Journal of Geology* **21**, 205-208.

Stoker, M. S., Golledge, N. R., Phillips, E. R., Wilkinson, I. P. & Akhurst, M. C. 2008. Lateglacial-Holocene shoreface progradation offshore eastern Scotland: a response to climatic and coastal hydrographic change. *Boreas* **38**, 292-314.

Stone, J., Lambeck, K., Fifield, L. K., Evans, J. M., & Creswell, R. G. 1996. A Lateglacial age for the Main Rock Platform, western Scotland. Geology **24(8)**, 707-710.

Sundelin, U. 1917. Fornsjöstundier inom Stångåns och Svartåns vattenområden, med särskild hänsyn till den sen- och postglaciala klimatutvecklingen. Akademisk Avhandling, Uppsala, Matematisk-Naturvetenskapliga Sektion. *Sveriges Geologiska Undersökning Series Ca*. **16**, 291pp.

Sutherland, D. G. 1981a. *The Raised Shorelines and Deglaciation of the Loch Long/Loch Fyne area, western Scotland*. Unpublished PhD Thesis, University of Edinburgh.

Sutherland, D. G. 1981b. The high-level marine shell beds of Scotland and the build-up of the last Scottish ice sheet. *Boreas* **10,** 247-254.

Sutherland, D. G. 1984a. The Quaternary deposits and landforms of Scotland and the neighbouring shelves: a review. *Quaternary Science Reviews* **3**, 157-254.

Sutherland, D. G. 1984b. The submerged landforms of the St Kilda archipelago, western Scotland. Marine Geology **58**, 435-442.

Sutherland, D. G. 1993a. Port Logan. *In:* Gordon, J. E. and Sutherland, D. G. (eds) *Quaternary of Scotland*, 593-594. Chapman and Hall, London.

Sutherland, D. G. 1993b. Muckle Head and Selwick, *In:* Gordon, J. E., Sutherland, D. G. (eds), *Quaternary of Scotland*, 74-76. Chapman and Hall, London.

Sutherland, D. G. & Walker, M. J. C. 1984. A late Devensian ice-free area and possible interglacial site on the Isle of Lewis, Scotland. *Nature* **309**, 701-703.

Talling, P. 2013. Waves on the horizon. *Nature Climate Change* **3**, 179.

Tappin, D. R., Long, D. L. & Carter, G. D. O. 2015. Shetland Islands Field Trip May 2014 – Summary of Results. *British Geological Survey Open Report, OR/15/017. NERC Open Research Archive.* 48pp.

Teasdale, P. A., Collins, P. E. F., Firth, C. R. & Cundy, A. B. 2011. Recent estuarine sedimentation rates from shallow inter-tidal environments in western Scotland: implications for future sea-level trends and coastal wetland development. *Quaternary Science Reviews* **30**, 109-129.

Teller, J. T., Leverington, D. W. & Mann, J. D. 2002. Freshwater outbursts to the oceans from glacial Lake Agassiz and their role in climate change during the last deglaciation. *Quaternary Science Reviews* **21**, 879-887.

Tooley, M. J. 1982. Sea-level changes in northern England. *Proceedings of the Geologists' Association* **93**, 43-51.

Tooley, M.J. 1990. The chronology of coastal dune development in the United Kingdom. *Catena Supplement* **18**, 81-88.

Tooley, M. J. & Smith, D. E. 2005. Relative sea-level change and evidence for the Holocene Storegga Slide tsunami at a site in Fife, Scotland, United Kingdom. *Quaternary International* **133-134**, 107-119.

Trenhaile, A. S. 2014. Modelling the effect of Pliocene-Quaternary changes in sea level on stable and tectonically active land masses. *Earth Surface Processes and Landforms* **39**, 1221-1235.

Uehara, K., Scourse, J. D., Horsburgh, K. J., Lambeck, K. & Purcell, A. P. 2006. Tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present. *Journal of Geophysical Research* **111**, C09025, 15pp.

von Weymarn, J. A. 1974. *Coastline development in Lewis and Harris, Outer Hebrides, with particular reference to the effects of glaciation.* Unpublished PhD Thesis, University of Aberdeen.

Walker, M. J. C., Berkelhammer, M., Björck, S., Cwynar, L. C., Fisher, D. A., Long, A. J., Lowe, J. J., Newnham, R. M., Rasmussen, S. O. & Weiss, H. 2012. Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). *Journal of Quaternary Science* **27(7)**, 649-659.

Walton, K. 1959. Ancient elements in the coastline of Northeast Scotland, *In*: Miller, R. & Watson, J. W. (eds). *Geographical Essays in Memory of Alan G. Ogilvie*, 93-109. Nelson and Sons, London.

Ward, S. L., Neill, S. P., Scourse, J. D., Bradley, S. L. & Uehara, K. 2016. Sensitivity of palaeotidal models of the northwest European shelf seas to glacial isostatic adjustment since the Last Glacial Maximum. *Quaternary Science Reviews* **151**, 198-211.

Wilson, G. V, Edwards, W., Knox, J., Jones, R. C. B. & Stephens, J. V. 1935. *The geology of the Orkneys*. Memoir of the Geological Survey of Scotland, Edinburgh.

Wilson, P. 2002. Holocene coastal dune development on the South Erradale peninsula, Wester Ross, Scotland. *Scottish Journal of Geology* **38,** 5-13.

Wilson, P., McGourty, J. & Bateman, M. D. 2004. Mid-to late-Holocene coastal dune event stratigraphy for the north coast of Northern Ireland. *The Holocene*, **14**, 406-416.

Woodworth, P. L., Tsimplis, M. N., Flather, R. A. & Shennan, I. 1999. A review of the trends observed in British Isles mean sea level data measured by tide gauges. *Geophysical Journal International* **136**, 651-670.

Woodworth, P., Teferle, F., Bingley, R., Shennan, I. & Williams, S. 2009. Trends in UK mean sea level revisited. *Geophysical Journal International* **176**, 19-30.

Woolf, D. K. & Challenor, P. G. 2002. Variability and predictability of North Atlantic wave climate. *Journal of Geophysical Research* **107**, C10, 3145.

Woolf, D. K., Cotton, P. D. & Challenor, P. G. 2002. Measurements of the offshore wave climate around the British Isles by satellite altimeter. *Philosophical Transactions of the Royal Society A*, **361**, 27-31.

Wright, W. B. 1911. On a pre-glacial shoreline in the Western Isles of Scotland. *Geological Magazine* **48**, 97-109.

Wright, W. B. 1914. *The Quaternary Ice Age.* Macmillan, London, 478pp.

Wright, W. B. 1925. Three short papers on isostasy. *Geological Magazine* **62**, 227-234.

Zagwijn, W. 1989. The Netherlands during the Tertiary and the Quaternary: a Case History of Coastal Lowland Evolution. *Geologie en Mijnbouw* **68**, 107-120.

Zong, Y. & Horton, B. P. 1999. Diatom-based tidal-level transfer functions as an aid in reconstructing Quaternary history of sea-level movements in the UK. *Journal of Quaternary Science* **14(2)**, 153-167.

Figures

Figure 1. Scotland, showing its location on the continental shelf off NW Europe adapted from Google Earth.

Figure 2A. Actively eroding rock shoreline. LWM: Low water mark; HWM: High water mark.

Figure 2B. The same shoreline in 2A after a period of glaciation. 1: Direction of ice flow. 2: Till. 3: Bevelled cliff edge. 4: Stump of former wall. 5: Crag and tail. 6: Roche moutonnée with striated surface. 7: Stump of former stack with striated surface. 8: Beach gravel preserved below till.

Figure 3. A. Inherited elements of rock coasts in Scotland: The Galson Beach at Melbost Borve, Lewis. 1. Modern ITRP – note the irregularity of the platform surface developed in closely-fractured Lewisian gneiss. 2. Modern storm beach. 3. Shallow weathering of basic dykes in the gneiss. 4. Raised shore platform at ~6 m O. D., locally covered by patches of red

brown till with Torridonian and Cambrian glacial erratics derived from the North-West Highlands. 5. Sub-horizontally bedded cobble to boulder gravels of the Galson Beach. 6. Late Devensian till. B. Inherited elements of rock coasts in Scotland: Start Point, Sanday, Orkney. ITRP developed in dipping Devonian flagstones, with many glacial erratics incorporated into the storm beach on its surface. The platform is 600 m wide where it passes beneath the eastern tip of the Point. C. Inherited elements of rock coasts in Scotland: Tantallon, East Lothian, showing a mix of inherited and dynamic landforms in a rock coastline. 1. Till-covered HRP at ~20 m asl. 2. Modern cliff developed in Carboniferous volcanic tuff and agglomerate. At Seacliff, 1-2 km to the south of Tantallon, the cliff line is degraded and fronted by beaches of the Main Postglacial Raised Shoreline (MPS). East of Tantallon towards North Berwick, however, parts of the cliff-line appear to be locally plastered with till and to be mainly inherited features. 3. Remnants of the shore platform of the MPS, preserved in resistant rock units. 4. Modern ITRP. In weak Carboniferous sandstones and marls, the ITRP is being lowered at rates of ~1 mm/yr (Hall 2011). At a few nearby locations south and west of Tantallon, however, the ITRP and the raised platform beneath the MPS retain till patches (Hall 1989).

Figure 4. Distribution and elevation of inherited elements in the coastline of Scotland.

1. Cliff. 2. Rock platform. 3. Till cover. 4. Glacially-striated or roughened surface. 5. Raised beach gravel below till. Data sources: Shetland (Flinn 1969, 1973; Hansom 2003a, 2003b). Orkney (Berry 2000). Buchan (Walton 1959; Merritt *et al.* 2003). Angus (Bremner 1925; Stoker & Graham 1985; Auton *et al*. 2000). Outer Forth (Rhind 1965; Sissons 1967; Hall 1989). Galloway (Jardine 1971; Jardine 1977; Sutherland 1993a). Kintyre (Gray 1978, 1993). Islay (Dawson 1979, 1980; Benn & Dawson 1987; Dawson 1991, 1993a, 1993b). Mull (Wright 1911; McCann 1968). Barra (Peacock 1984; Selby 1987). St Kilda (Sutherland 1984b). North Lewis (Peacock 1984; Sutherland & Walker 1984; Hall 1995). Also unpublished data from Hall.

Figure 5. Time intervals for formation of rock platforms in the Inner and Outer Hebrides. Greenland GRIP-2 ice core data (from GRIP Ice-Core Project Members 1993). Global sea level curve for the last glacial cycle from Cutler *et al*. (2003). Glaciation curve based on estimates of ice extent derived from ice core data by (Clapperton 1997) and projected onto the SW-NE oriented main ice dome of the last ice sheet in Scotland. IS Ice sheet in Scotland extends onto neighbouring shelves. MIC: Largely land-based mountain ice cap.

Figure 6. Duration of occupancy of the shoreline in the last 15ka at mean sea levels of 0 ± 2m and 5 ± 2m O. D. The periods of occupancy are from Shennan *et al.* (2006).

Figure 7. Site locations onshore from which evidence for Late Devensian and Holocene RSLs has been published since 1993.

Figure 8. Graphs of MHWST with OD equivalent for estuarine locations in the western Forth valley (A), Girvan (B), the Cree valley (C), Harris (D) and Wick (E), based on data from Dawson & Smith (1997), Smith *et al.* (2003a, 2007, 2012) and Jordan *et al.* (2010). Local dates for the Holocene Storegga Slide tsunami are not plotted on these graphs. Altitudes are referenced to OD and the local equivalent present MHWST. Error margins are explained in the references quoted. See Section 1.2 above for definitions of the points plotted.

Figure 9. Graphs of RSL (relative to the reference water level identified) for isolation basin and coastal wetland sites at Assynt and Coigach (A), Loch Alsh and Loch Duich, Kintail (B), the Arisaig area (C), Kentra Moss (D) and Knapdale, Kintyre (E), based on data from Shennan *et al.* (2000, 2006) and Hamilton *et al.* (2015). Equivalent OD values and error margins are explained in the references quoted. See Section 1.2 above for definitions of the points plotted.

Figure 10. Distribution of the Late Devensian, pre-Windermere Interstadial marine strata and associated glacigenic deposits and the adjacent sea area (the “Red Series” and Wee Bankie Formation), based on Peacock (1999).

Figure 11. Isobases in metres MHWST for the Main Lateglacial Shoreline based upon a shoreline-based Gaussian quadratic trend surface, with a mean absolute residual of 0.97m, from Fretwell (2001) with permission.

Figure 12. Graph of radiometric dates for Holocene shorelines in Scotland (except for the Holocene Storegga Slide tsunami shoreline). The dates cluster in three groups, although dates for the Wigtown Shoreline are so few that the age of this feature can only be regarded as provisional. Reprinted from *Quaternary Science Reviews* 2012, vol. 54: Patterns of Holocene relative sea level change in the North of Britain and Ireland. With permission from Elsevier. For full details, see references.

Figure 13. Isobases in metres MHWST for the Main Postglacial (A) and Blairdrummond (B) shorelines based on shoreline-based Gaussian quadratic trend surfaces with mean absolute residuals of respectively 0.39m and 0.32m. Reprinted from *Quaternary Science Reviews* 2012, vol. 54: Patterns of Holocene relative sea level change in the North of Britain and Ireland. With permission from Elsevier. For full details, see references.

Figure 14. Isobases in metres MHWST for the Main Postglacial (A), Blairdrummond (B) and Wigtown (C) shorelines according to shoreline-based Gaussian quadratic trend surface models based on a common axis and centre, with mean absolute residuals of respectively

0.50m, 0.44m and 0.33m based on Smith *et al.* (2012), and (D) areas where the Main Postglacial, Blairdrummond and Wigtown shorelines are the highest visible shoreline, based on the models in A-C. Shaded bands about the shoreline overlaps are derived from the range of 95% of residual values of the surface altitudes computed.

Figure 15. Shoreline dislocations and the Younger Dryas ice cap in the Highlands. Limits of the Younger Dryas derived from numerous sources. Shoreline gradients derived by linear regression from data plotted along the directions indicated. Based on Firth & Stewart (2000).

Figure 16. 2000 year continuous salt-marsh reconstruction from Kyle of Tongue and Loch Laxford, Sutherland, plotted with 2σ age and altitudinal errors (adapted from Figure 9 in Barlow *et al.* 2014).

Figure 17. A. Origins and morphology of cliff-top storm deposits. B. Zones of cliff-top storm deposits.

Figure 18. Sites where evidence for the Holocene Storegga Slide tsunami has been found. Based on Smith *et al*. (2004), with additional information from Tooley & Smith (2005), Jordan *et al*. (2010), Selby & Smith (2015) and Long *et al*. (2016). The sites on Harris and at Talisker Bay are unconfirmed at present.

Figure 19. RSL graph for the Ythan estuary, showing the change in RSL thought to mark the impact of the Lake Agassiz-Ojibway flood, with the age of the Holocene Storegga Slide tsunami from sediments in the estuary area. Reprinted from *Quaternary Science Reviews* 2013, vol. 82: Sea level rise and submarine mass failures on open continental margins. With permission from Elsevier. For full details, see references.

Figure 20: A, Shoreline-based Gaussian trend surface showing isobases in metres MHWST for the shoreline of the Holocene Storegga Slide tsunami, based on an axis and centre in common with later Holocene shorelines (see Fig. 14), with a mean absolute residual of 0.69m (after Smith *et al*., 2012). B, Section from Fullerton, Montrose, showing the inferred shoreline at the time of the Holocene Storegga Slide tsunami.

Figure 21. Ice Thickness maps of the reconstructed British-Irish Ice sheet at various times presented in Bradley *et al*. 2011 (a-d) (i-l) and the "minimal reconstruction" of Kuchar *et al*. 2012 (e-h) (m-p).

Figure 22. Predicted RSL for the seven sites (Table 2) due to the BIIS only (solid line) and the SIS only (dashed line) (panel a) and Far-field ice sheets only (panel b): Coigach (green): NE Scotland (Blue): Arisaig (light blue): SE Scotland (yellow): Forth Valley (orange): Islay (dark green): Hebrides (purple). In the remaining seven panels is the predicted RSL at the seven sites from the Bradley (red line) and Kuchar (black line) model compared to the

observed primary sea level index points; blue circles: basal index points, black circles: intercalated points and red limiting data.

Figure 23. Predicted RSL for the Bradley (a-d) and the Kuchar (e-h) model at a range of time steps. Labelled is the location of the seven RSL sites shown on Figure 22.

Figure 24. Predicted present day rate of sea level change (a-c) and vertical land motion (d-f) using the Bradley model due to: All ice sheets (a) and (d); All other ice sheet apart from BIIS (b) and (e); and BIIS only (c) and (f). Panel (g) is the predicted present day rate of change in the sea surface, where over several decades this approximates the ocean geoid. Contour interval of 0.4m, apart from panel (g) 0.02m. Labelled is the location of the seven RSL sites in Figure 22. The red circle highlights the location of maximum uplift /maximum RSL fall.

Table 1. Estimates of rates of crustal uplift (mm/yr) for selected sites in Scotland, based on Firth & Stewart (2000). Rates of uplift for Arisaig are based on a RSL graph from Shennan *et al.* (1995, 1996). Rates for other sites based on estimates from Sissons 1974; McCabe *et al.* 2007; Smith *et al.* 2012. Uncertainties relating to the ages of Late Devensian features and global mean sea level changes result in the large ranges in the estimates.

Shoreline and age, BP	**Location**					
	Arisaig	**Stirling**	**Dunbar**	**Inverness**	**Dornoch**	**Islay**
EF1-Main Perth, 18,500/17,000-15,500-16,000	-	5.6-26.0	4.5-22.5	-	-	-
Main Perth-Main Lateglacial, 15,500/16,000-12,500/12,800	14.3-26.7	22.0-31.5	14.4-29.4	19.0-28.0	-	-
Main Lateglacial–Main Buried Beach, 12,500/12,800-10,500-11,000	12.9-13.0	6.4-11.0	-	8.1-12.2	-	9.5-15.4
Main Buried Beach-Main Postglacial, 10,500/11,000-6,800/7,400	4.0-4.4	4.8-6.4	-	5.1-7.0	5.4-5.8	5.2-7.3
Main Postglacial-Blairdrummond, 6,800/7,400-3,700/4,400	1.4-2.4	1.2-4.8	0.4-3.5	1.0-5.0	1.1-2.8	0.4-3.3
Blairdrummond-Present, 3,700/4,400-0	0.8-1.3	2.1-3.9	1.1-2.7	0.8-2.0	1.1-2.0	0.9-2.0

Table 2. Summary table of the observed SLIPs illustrated in Figure 22.

				Primary SLIP				
Site.No	Name	Latitude	Longitude	Basal	Intercalated	Limiting Data	References	Colour
						⊥(max); ⊤(min)		Fig.22
6	Coigach	58.05	-5.36		7	1	Shennan et al., 2000a	Green
7	Hebrides	57.51	-7.55	1	1	1	Ritchie 1985	purple
11	Arisaig	56.91	-5.85	39		8	Shennan et al., 1993; 1994; 1995b;	Light Blue
							Shennan et al., 1999; Shennan et al., 2000a	
13	NE Scotland	57.66	-1.98	8	11	5	Smith et al., 1982	Blue
17	Forth Valley	56.12	-4.15	2	19		Robinson, 1993	Orange
18	Islay	55.81	-6.34	10			Dawson et al., 1998	dark green
22	SE Scotland	56.03	-2.69	1	2		Robinson, 1982	Yellow

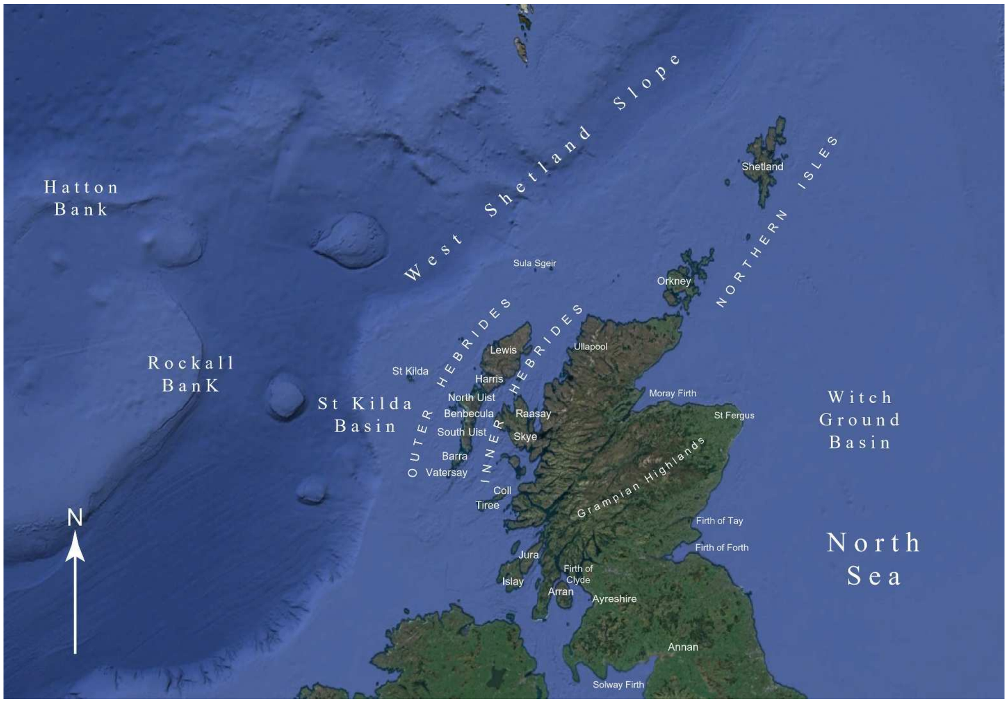

Figure 1

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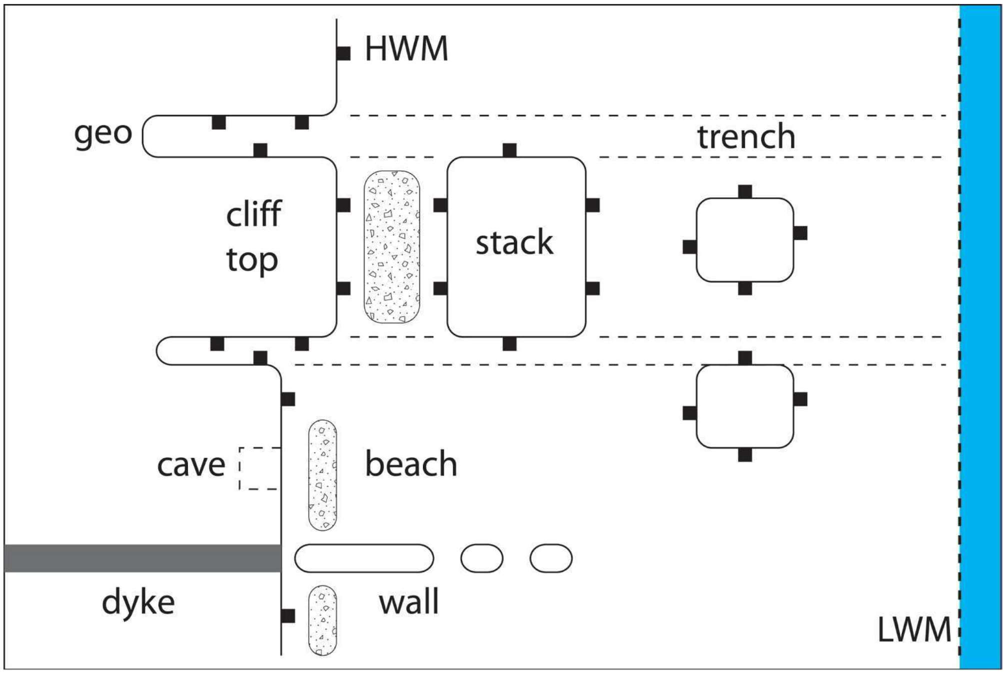

Figure 2A

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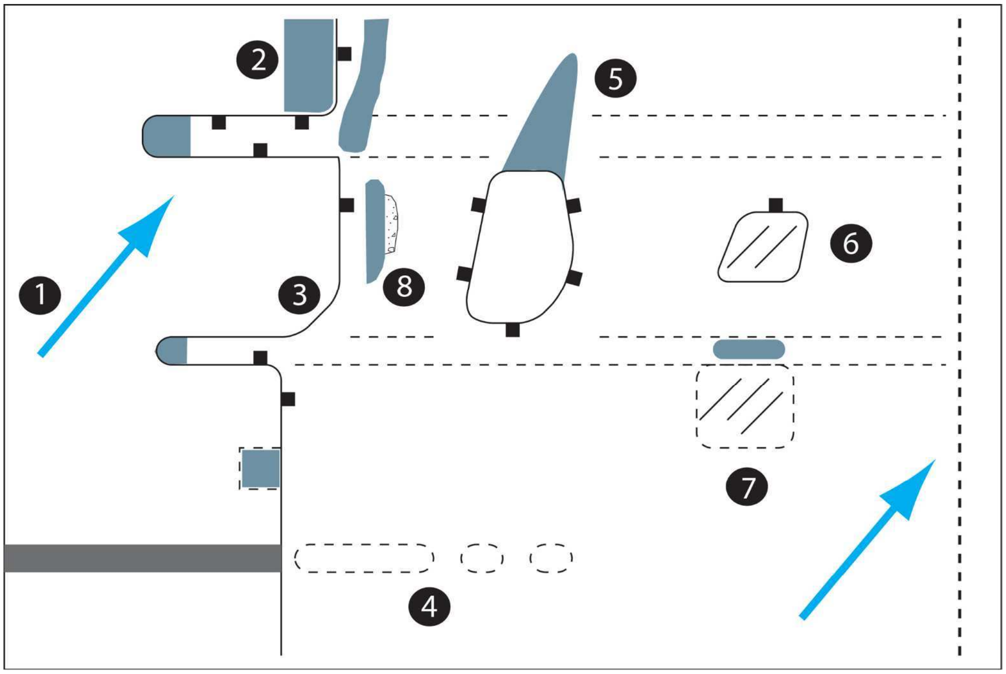

Figure 2B

183x122mm (300 x 300 DPI)

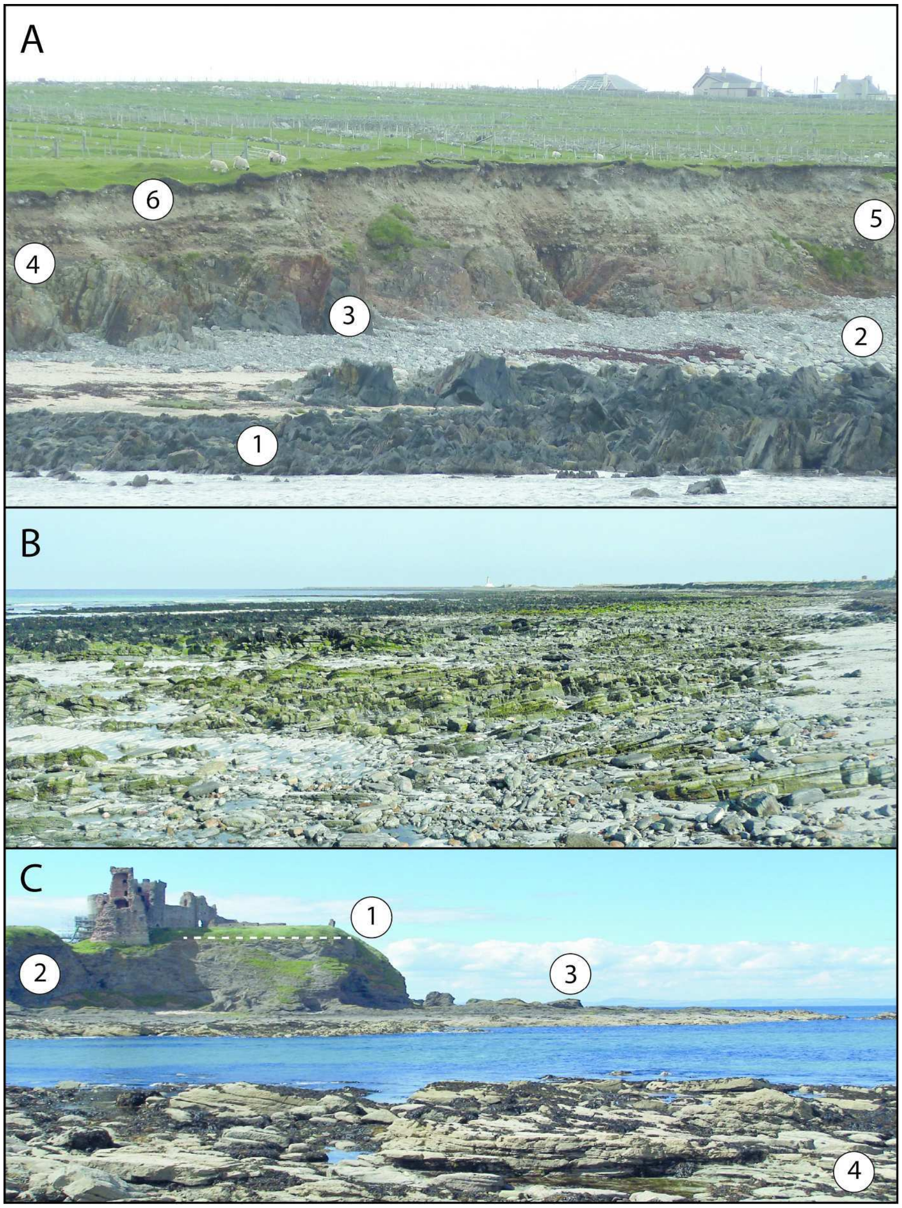

Figure 3

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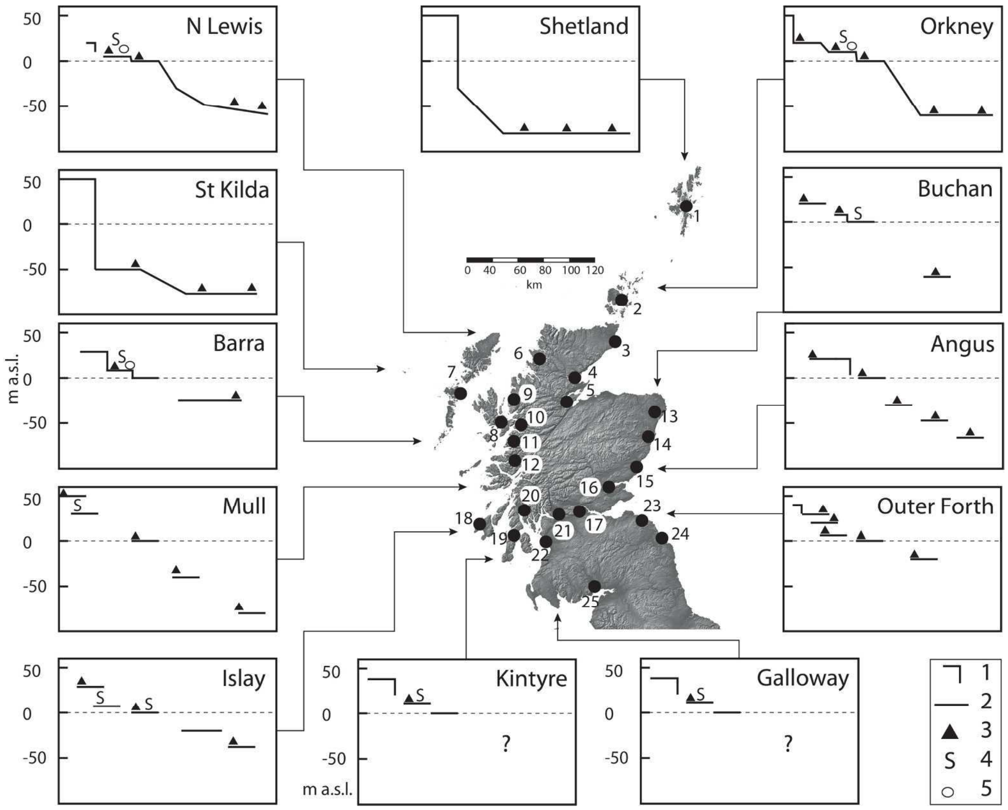

Figure 4

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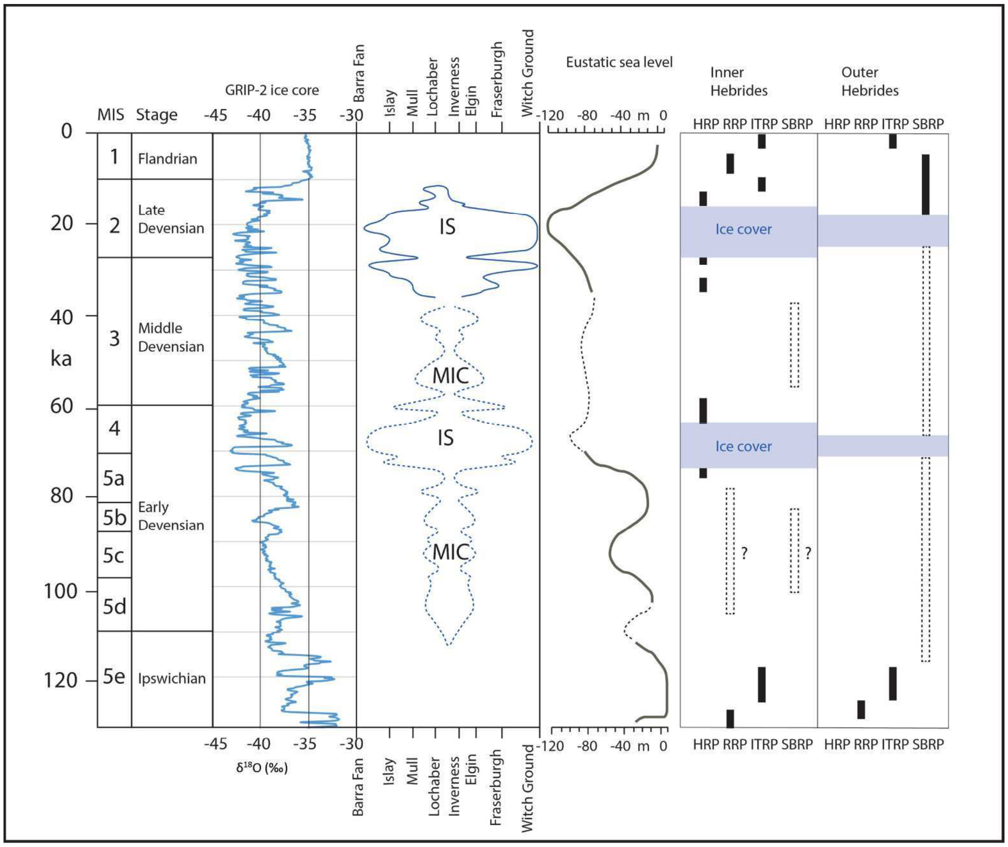

Figure 5

189x159mm (300 x 300 DPI)

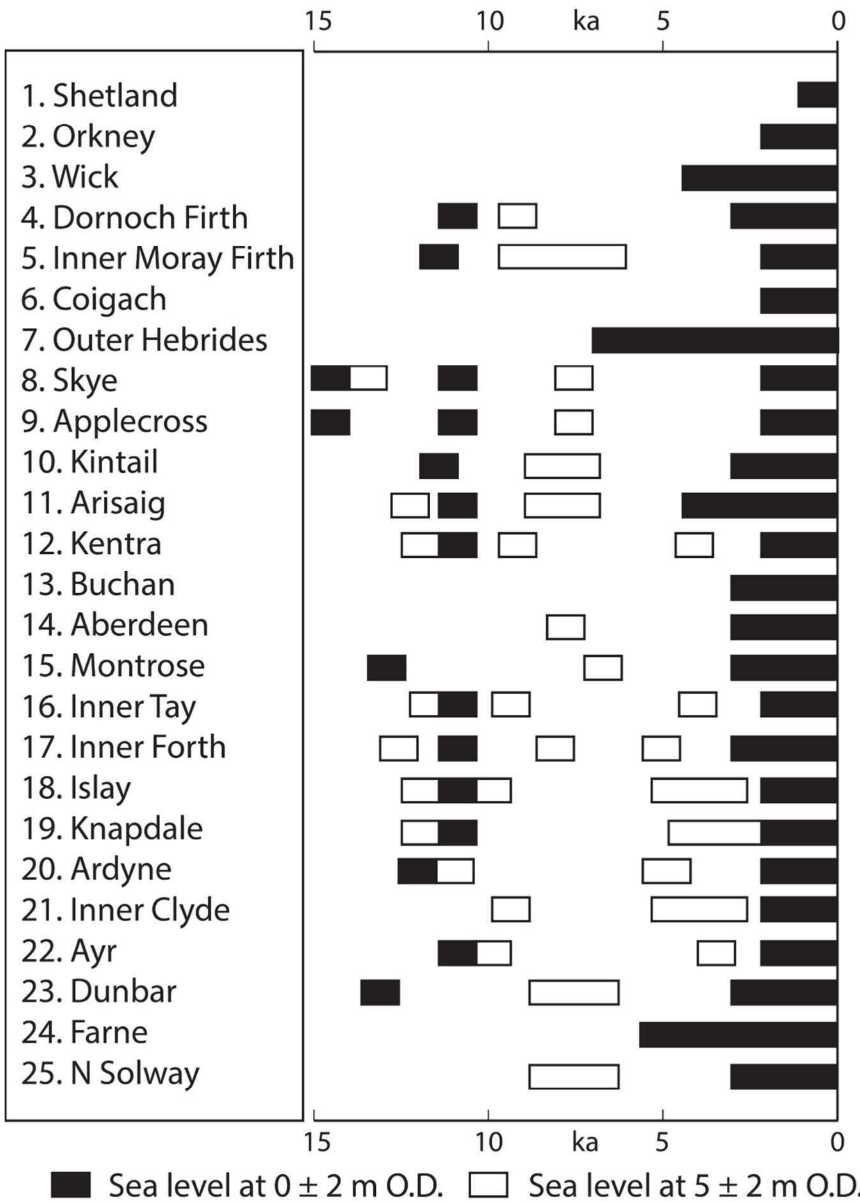

Figure 6

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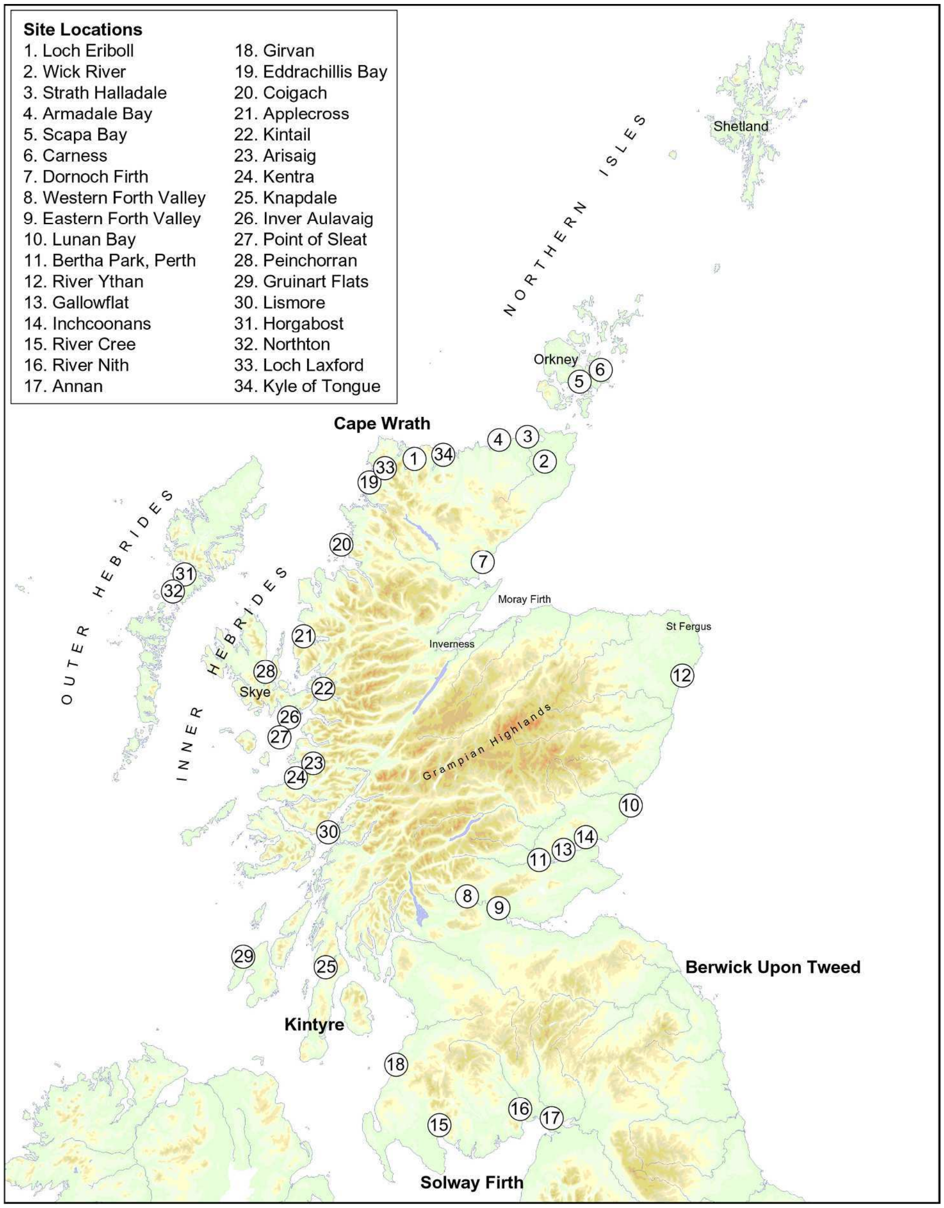

Figure 7

189x242mm (300 x 300 DPI)

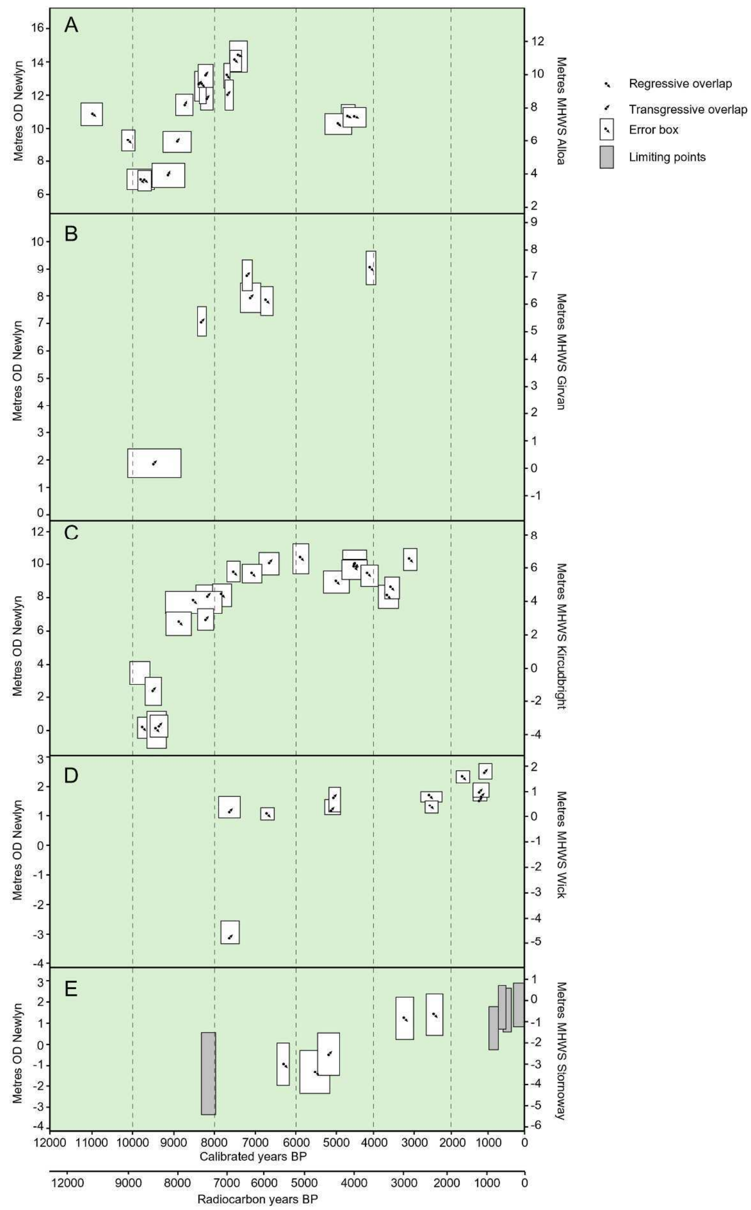

Figure 8

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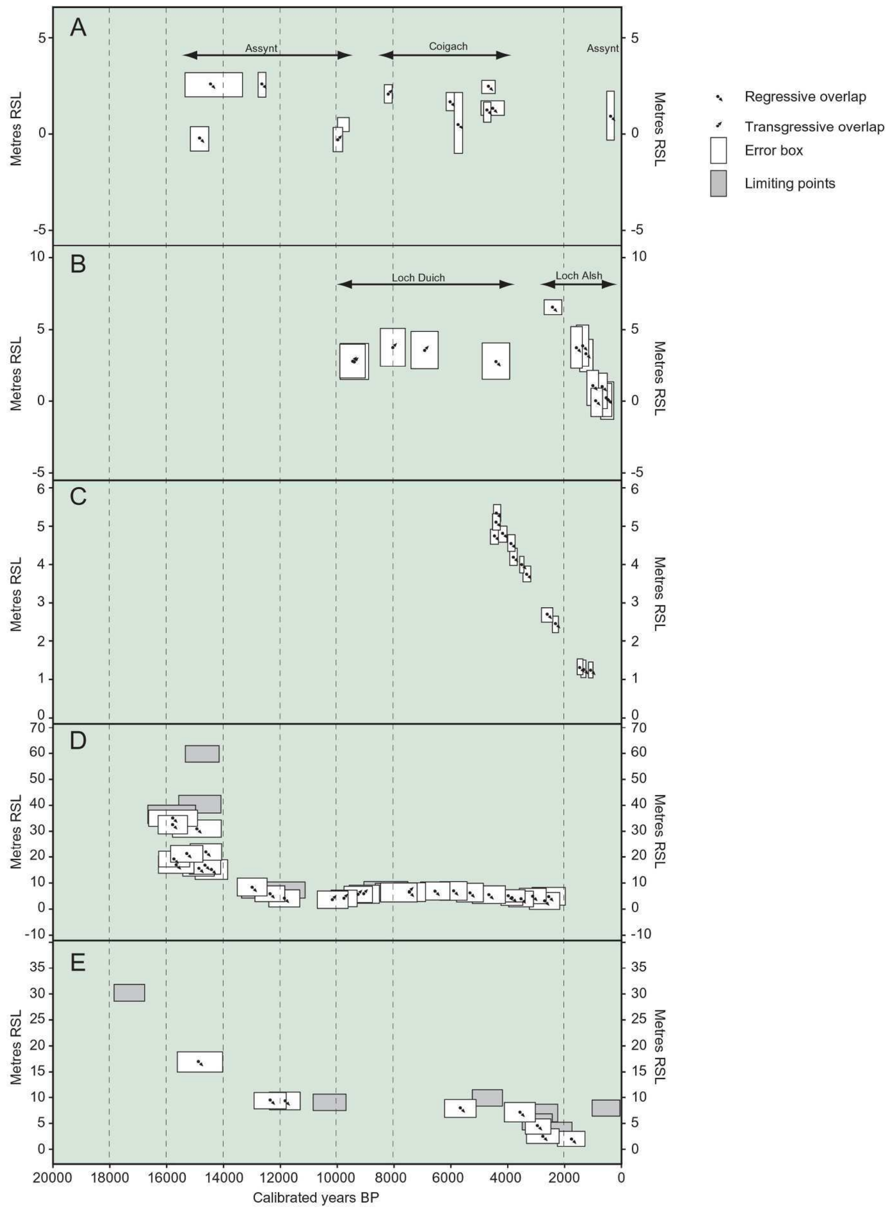

Figure 9

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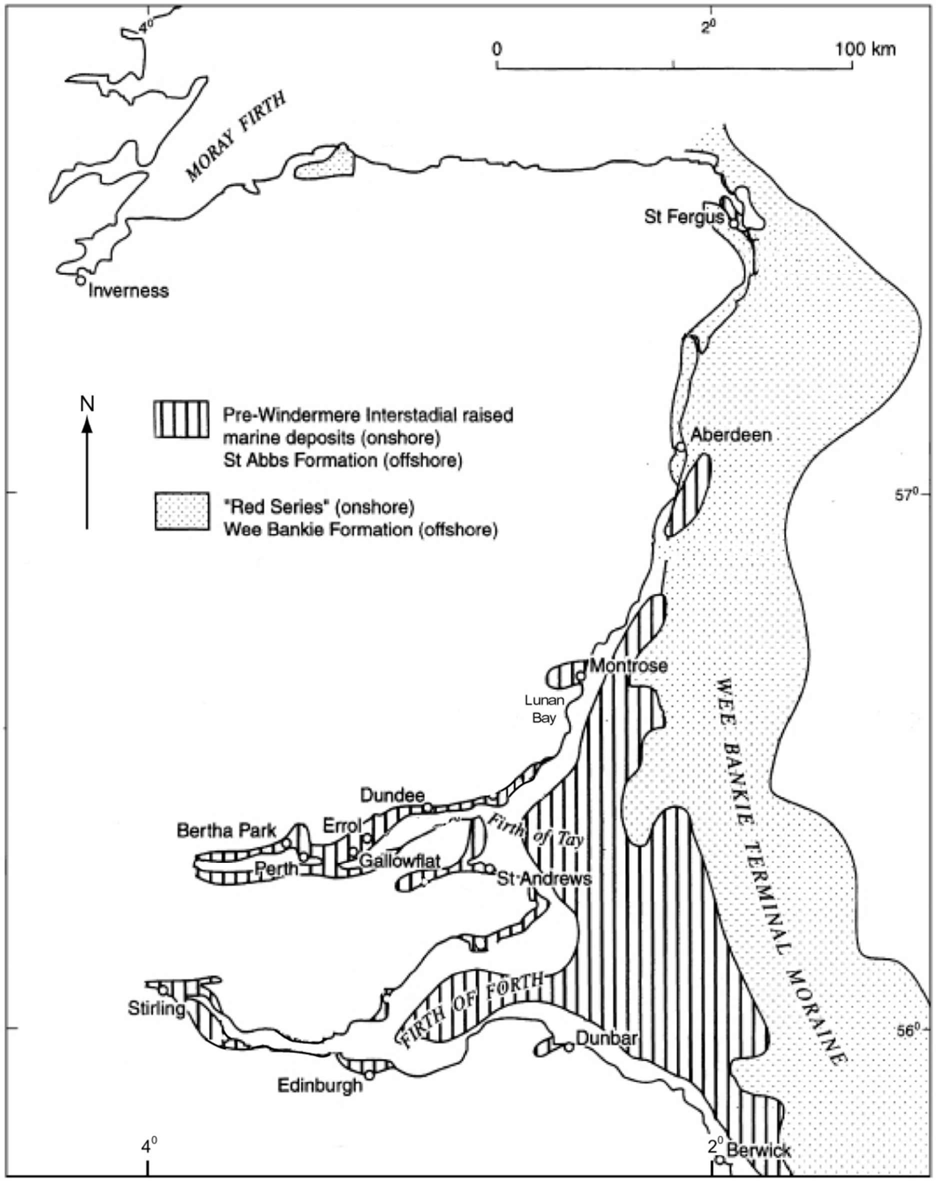

Figure 10

97x122mm (300 x 300 DPI)

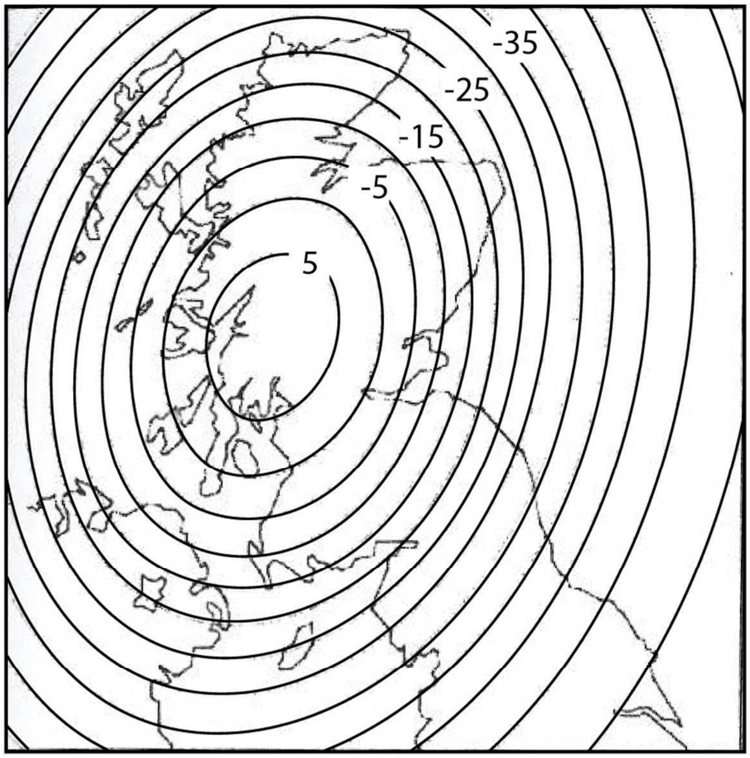

Figure 11

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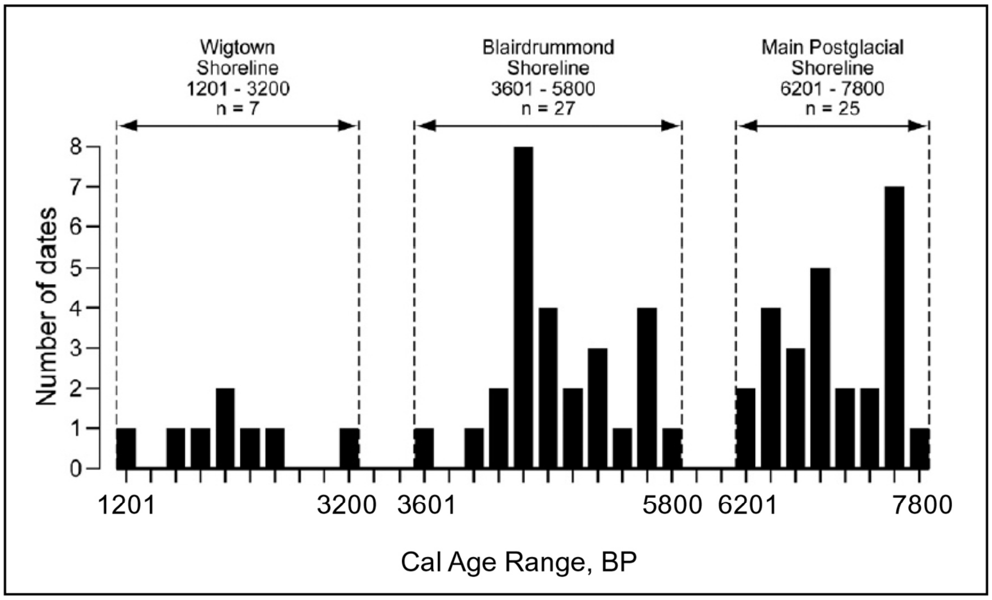


Figure 12

153x93mm (300 x 300 DPI)

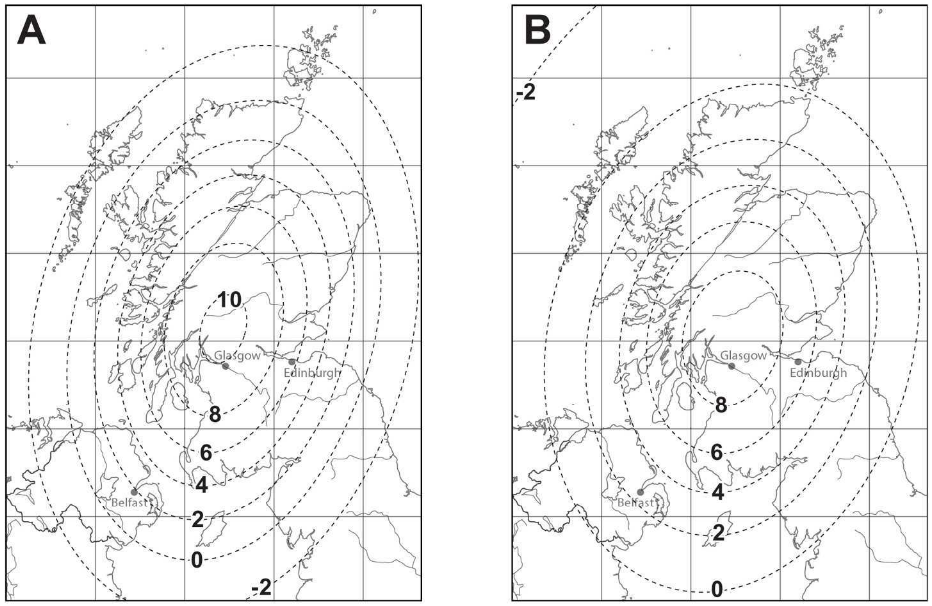


Figure 13

175x105mm (300 x 300 DPI)

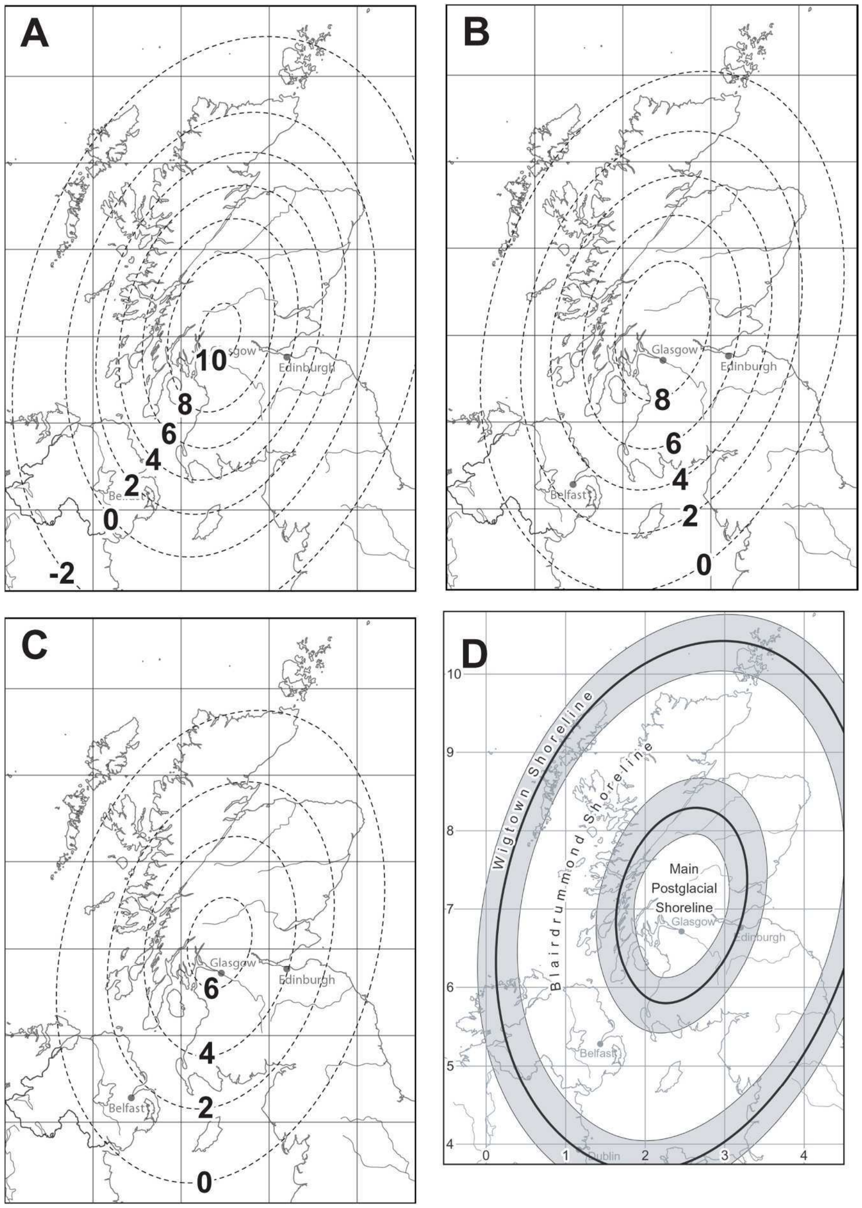


Figure 14

150x210mm (300 x 300 DPI)

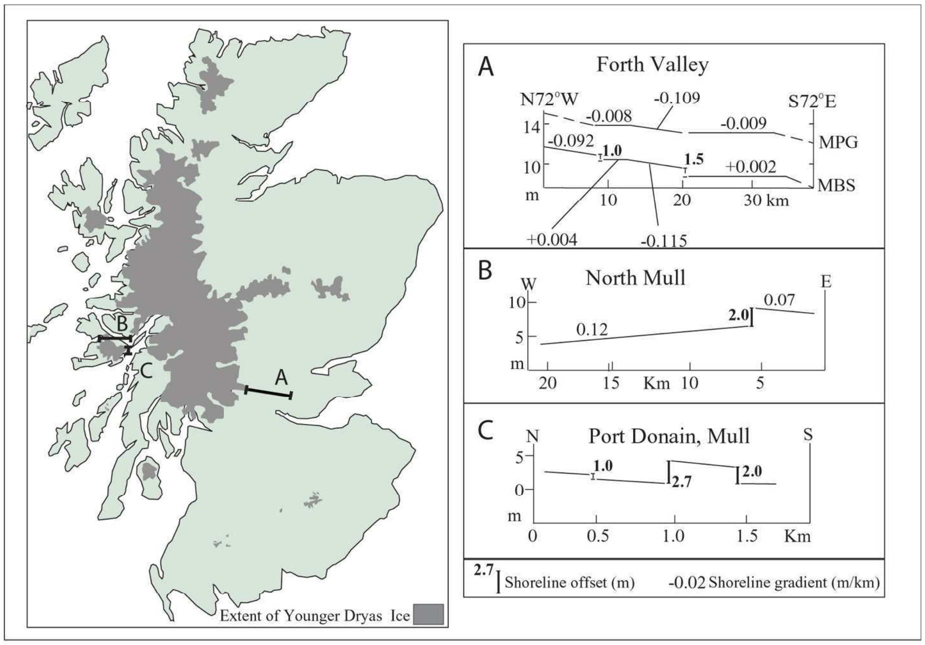


Figure 15

174x153mm (300 x 300 DPI)

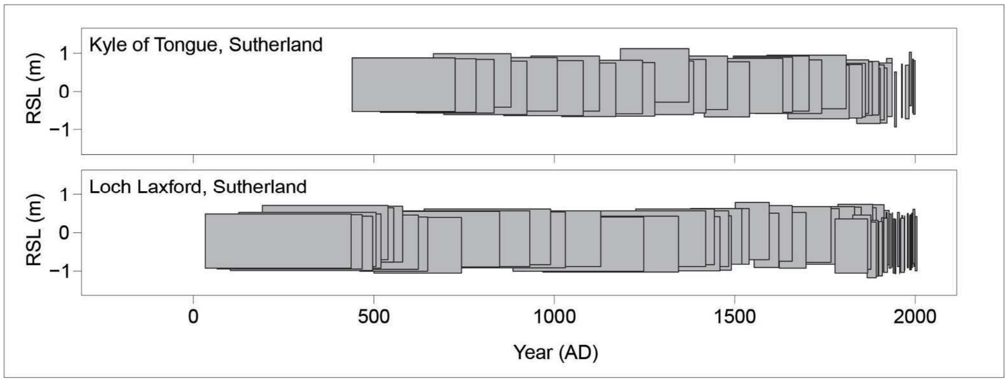


Figure 16

180x67mm (300 x 300 DPI)

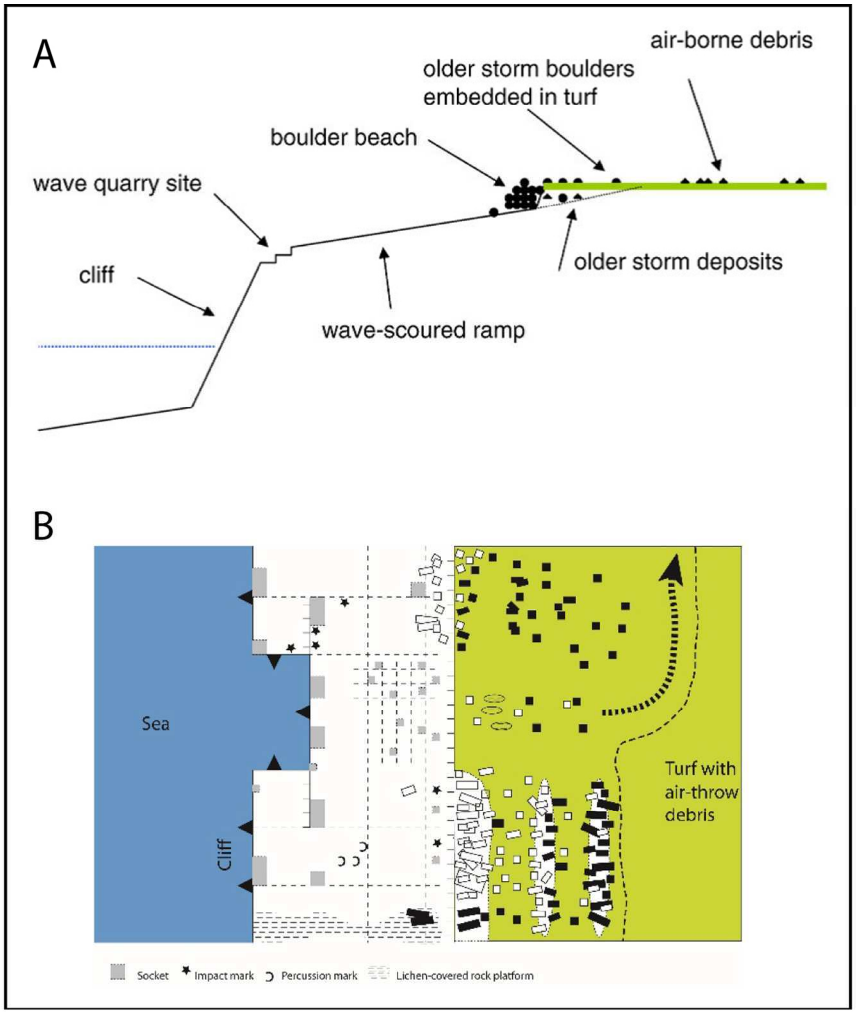


Figure 17 A & B

119x120mm (300 x 300 DPI)

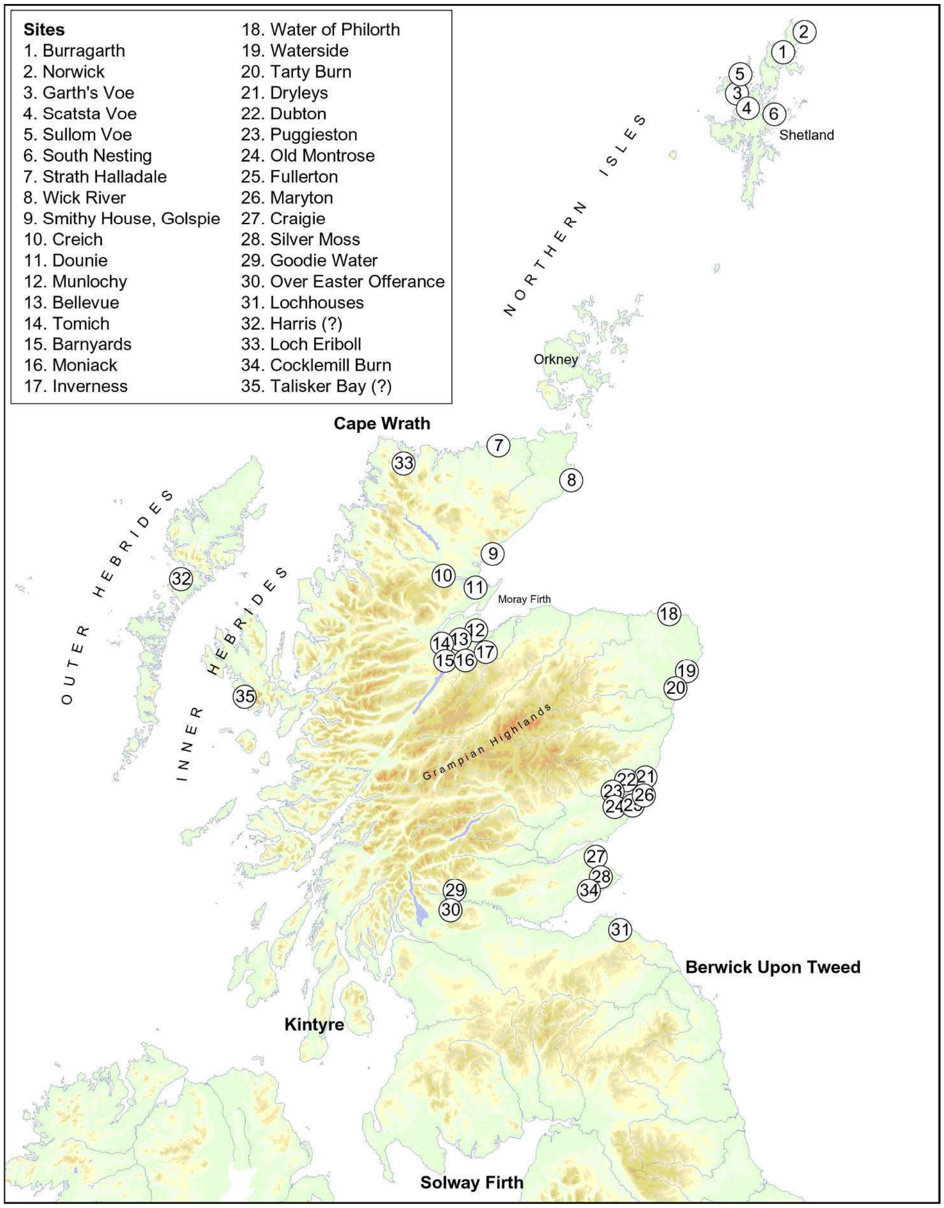


Figure 18

189x242mm (300 x 300 DPI)

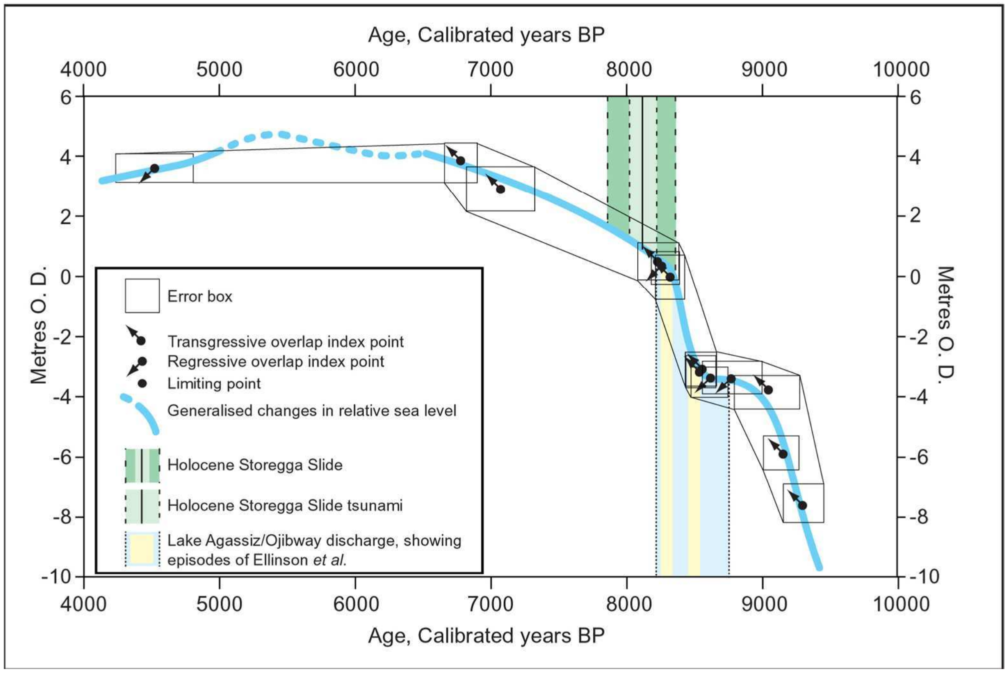


Figure 19

145x97mm (300 x 300 DPI)

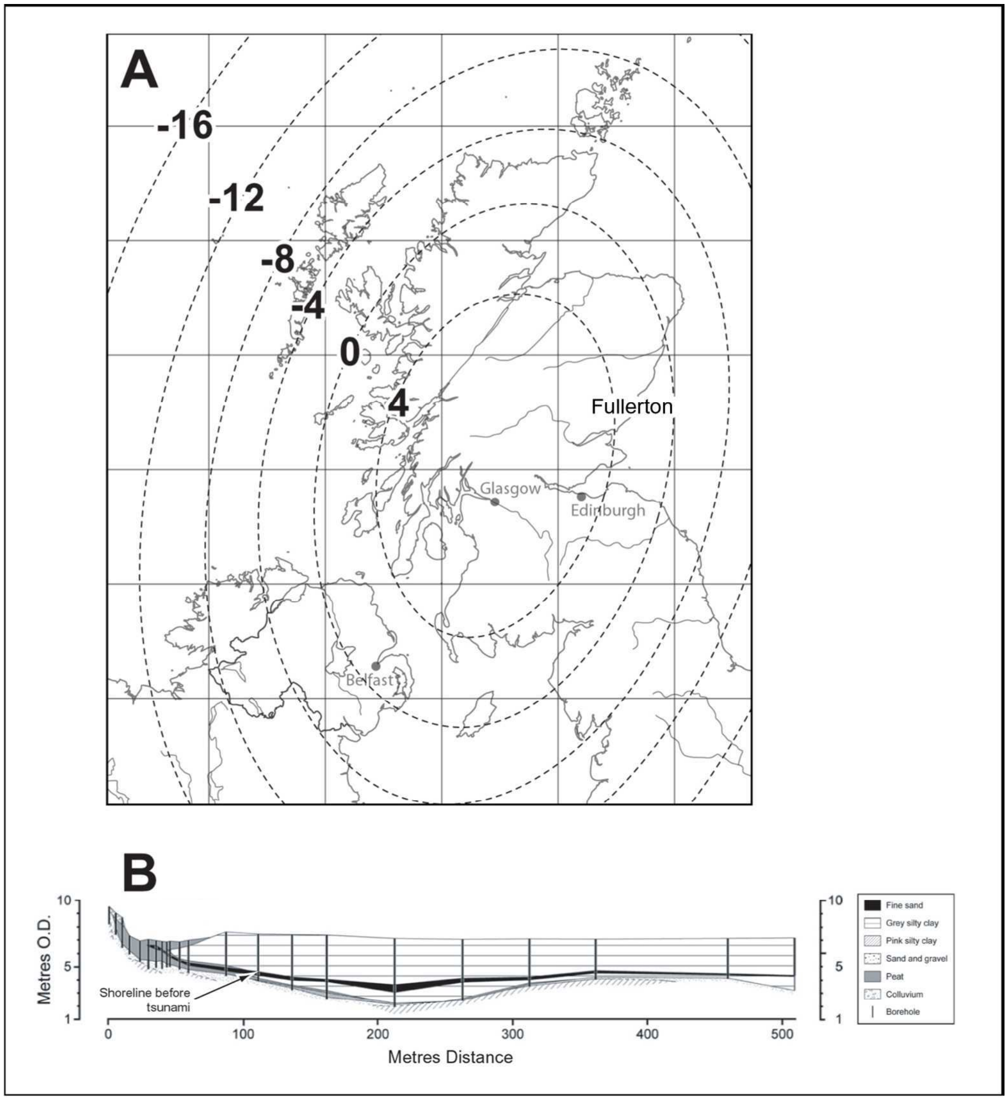
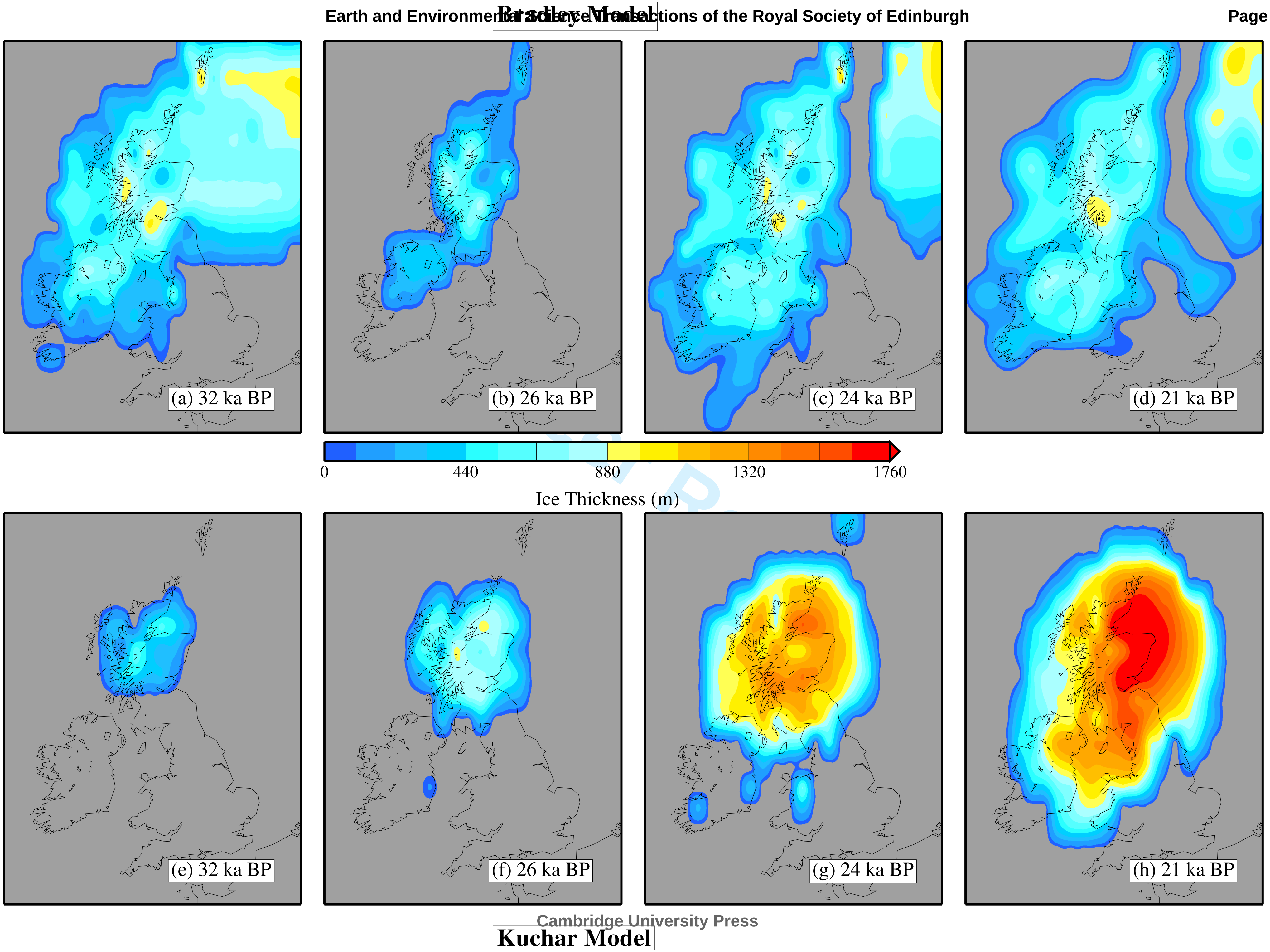
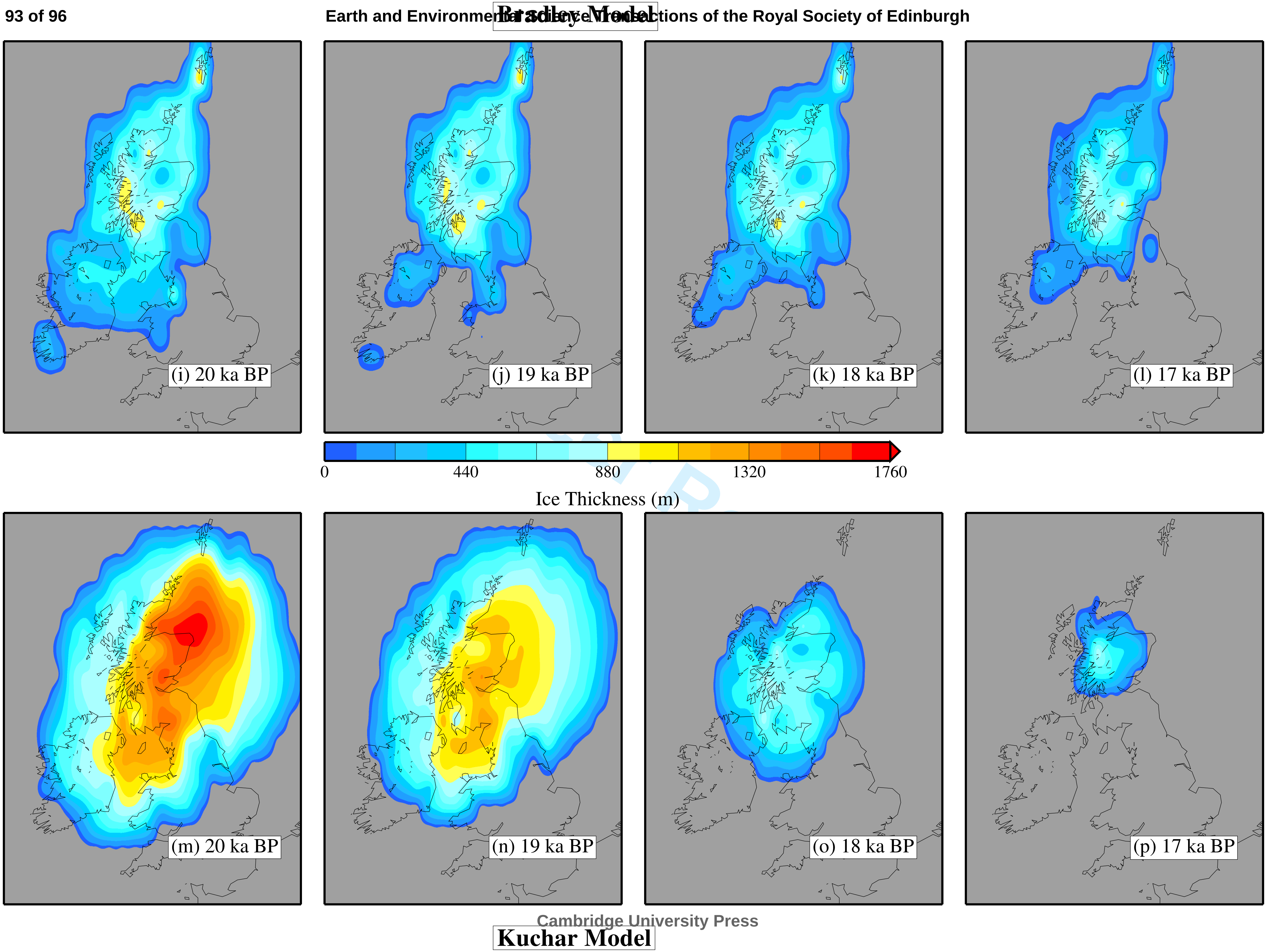
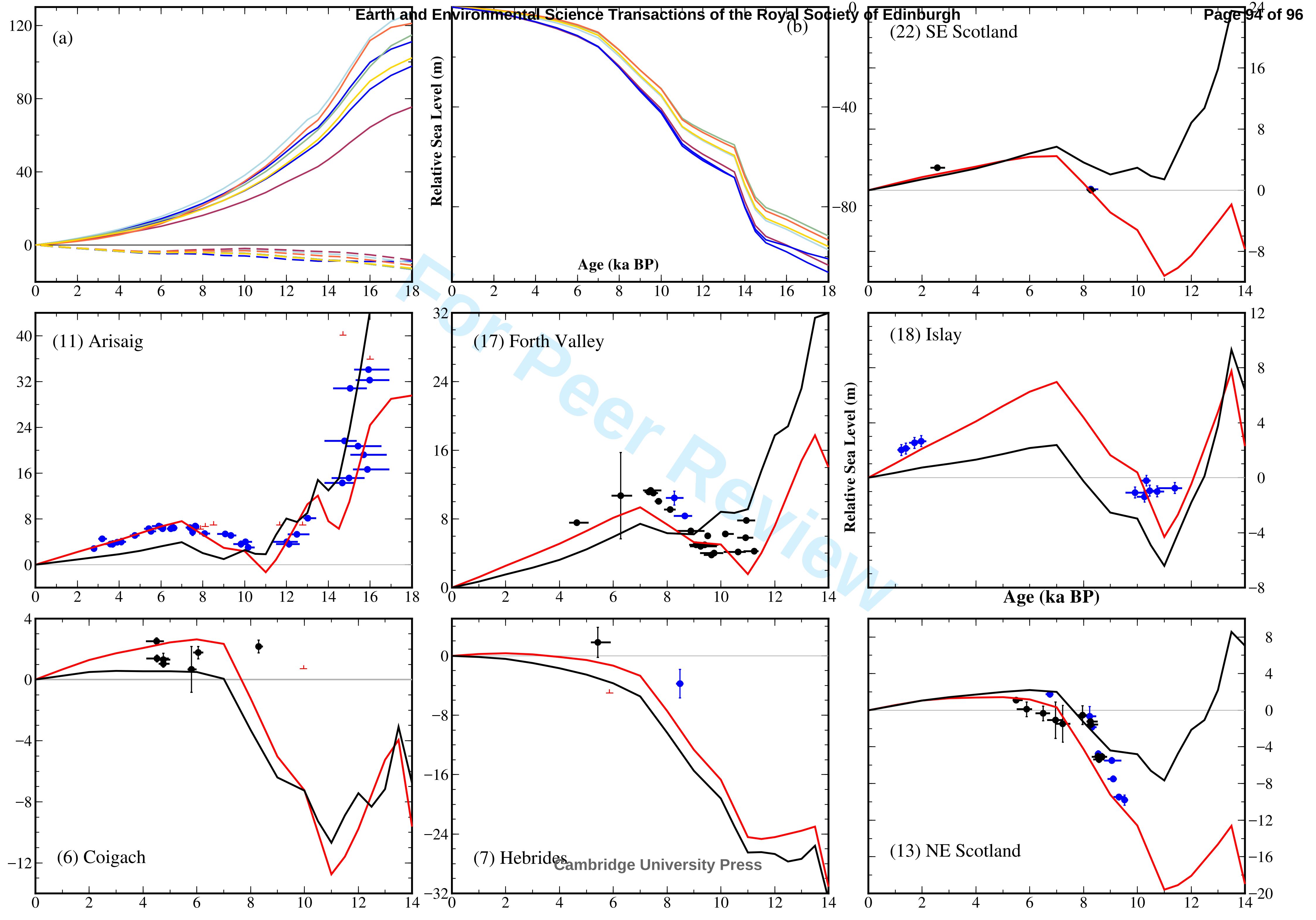


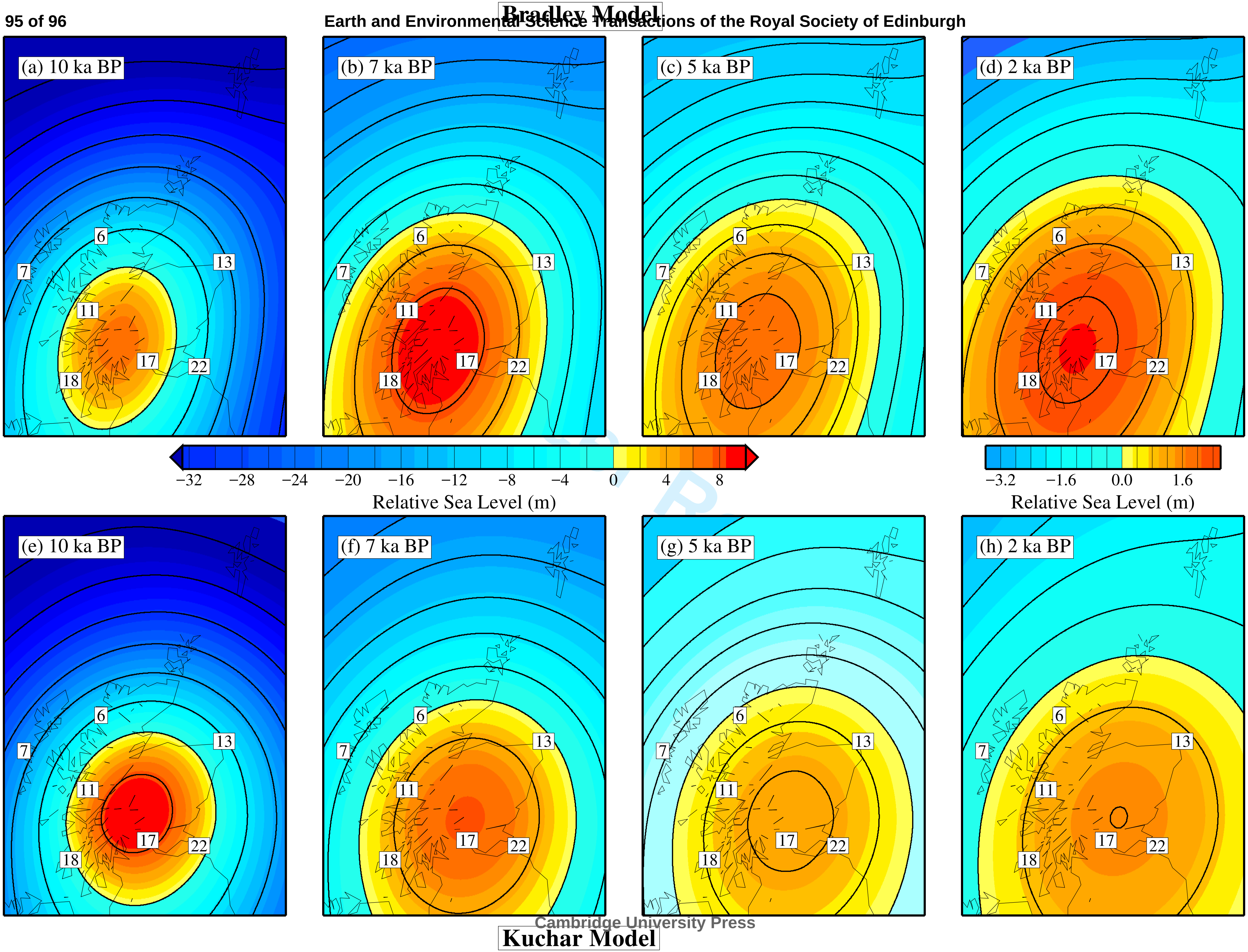
Figure 20

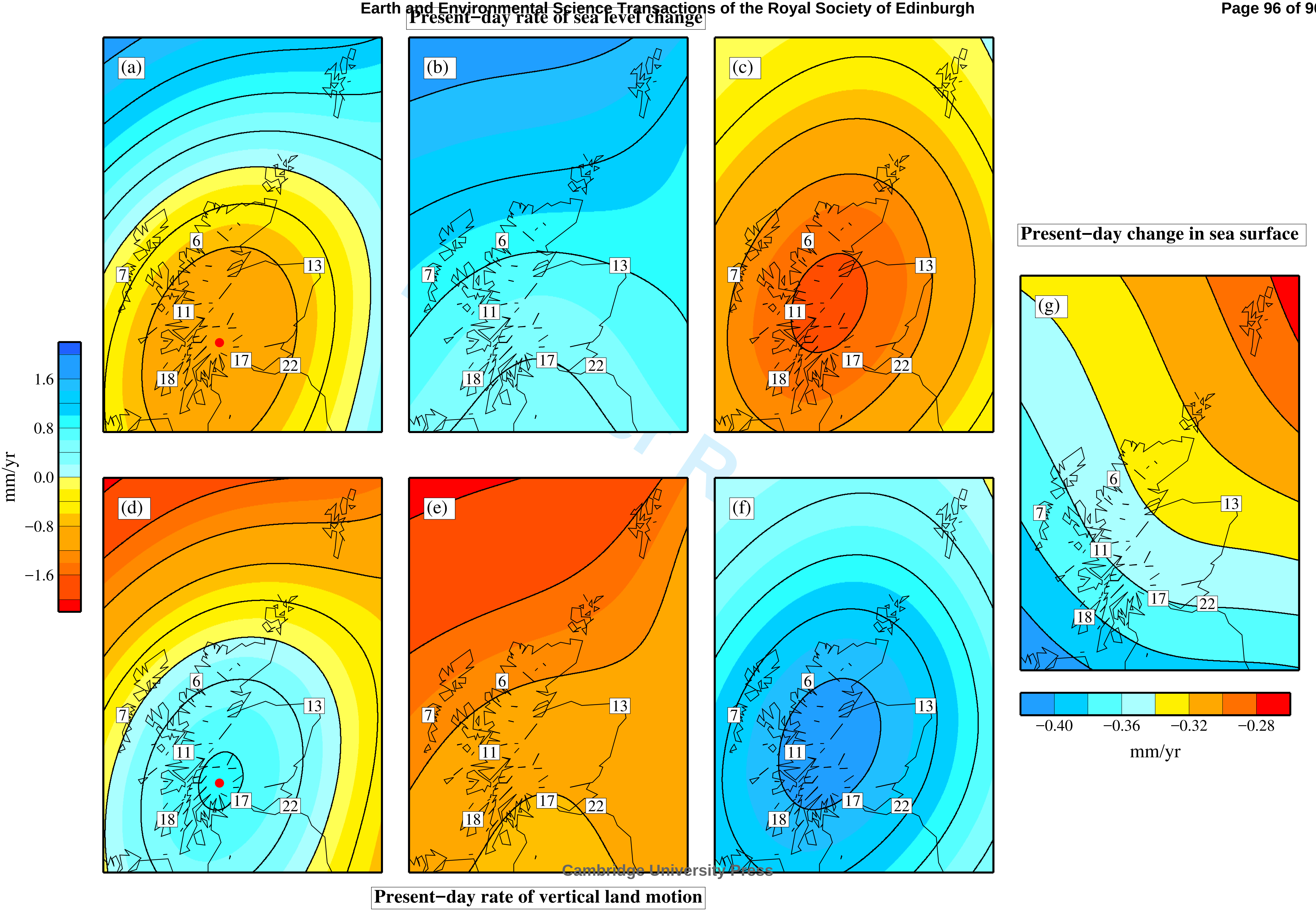
133x145mm (300 x 300 DPI)


Bradley Model
(a) 32 ka BP
(b) 26 ka BP
(c) 24 ka BP
(d) 21 ka BP
0
440
880
1320
1760
Ice Thickness (m)
(e) 32 ka BP
(f) 26 ka BP
(g) 24 ka BP
(h) 21 ka BP
Kuchar Model


Bradley Model
(i) 20 ka BP
(j) 19 ka BP
(k) 18 ka BP
(l) 17 ka BP
0
440
880
1320
1760
Ice Thickness (m)
(m) 20 ka BP
(n) 19 ka BP
(o) 18 ka BP
(p) 17 ka BP
Kuchar Model


(a)
(b)
Relative Sea Level (m)
Age (ka BP)
(22) SE Scotland
(11) Arisaig
(17) Forth Valley
(18) Islay
(6) Coigach
(7) Hebrides
(13) NE Scotland
For Peer Review


Bradley Model
(a) 10 ka BP
(b) 7 ka BP
(c) 5 ka BP
(d) 2 ka BP
6
7
11
13
17
18
22
−32
−28
−24
−20
−16
−12
−8
−4
0
4
8
Relative Sea Level (m)
−3.2
−1.6
0.0
1.6
Relative Sea Level (m)
(e) 10 ka BP
(f) 7 ka BP
(g) 5 ka BP
(h) 2 ka BP
Kuchar Model


Present−day rate of sea level change
(a)
(b)
(c)
(d)
(e)
(f)
(g)
6
7
11
13
17
18
22
1.6
0.8
0.0
−0.8
−1.6
mm/yr
Present−day change in sea surface
−0.40
−0.36
−0.32
−0.28
mm/yr
Present−day rate of vertical land motion