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Patterns of glacio-isostatic adjustment in mainland Scotland: new data from western central Scotland, proximal to the zone of maximum rebound

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The results of geomorphological mapping and survey of Lateglacial and Holocene displaced shorelines in the Clyde estuary and around Loch Lomond, western central Scotland are described. On the basis of morphology, sedimentology, altitude and radiocarbon dating, four discrete shorelines are identified and are correlated with previously identified Scottish displaced shorelines. The shoreline formerly referred to as the Main Postglacial Shoreline is renamed the Menteith Shoreline. This body of data, combined with data on displaced shorelines for Scotland as a whole has been analysed using Gaussian quadratic trend surface analysis in order to determine the centre of glacio-isostatic displacement for each shoreline. These Gaussian models of palaeo-relative sea-level suggest that the zone of greatest displacement lay NNW of Loch Lomond in the Lateglacial then moved SSE to the region of Loch Lomond during the Holocene and the Clyde in the Late Holocene. The factors responsible for the movement of the zone of greatest uplift are discussed, including temporal variations in the ice-sheet thickness, variations in water load in the adjacent sea-lochs and neotectonic processes. Comparison is made with glacial isostatic adjustment (GIA) models. A sensitivity analysis has been carried out on the use of Gaussian trend surface analysis glacio-isostatic modelling and this is included in the research evaluation, and reported in full in the Supporting Information files, along with the raw data used throughout this study.

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Substantial work has been undertaken on patterns of glacio-isostatic recovery following the wastage of the last ice sheet in Scotland (e.g. Smith *et al*. 2006, 2012; Bradley *et al*. 2009, 2011, 2023; Shennan *et al*. 2018). These patterns are critical for our understanding of the distribution of glacier ice during the Last Glaciation and the process of crustal adjustment following ice decay. Two approaches have been used in determining the patterns arising (e.g. Smith *et al*. 2019): a shoreline-based approach, in which altitudes on displaced shorelines are correlated on geomorphological and stratigraphical evidence and are modelled statistically; and a glacial isostatic adjustment (GIA) approach, in which key stratigraphical sites are used to model shoreline displacement based on earth rheology and hydrology. Both modelling approaches provide patterns of displacement of the Earth's crust that are based upon evidence of relative sea-level (RSL).

The GIA approach utilizes sea-level index points, which are dated and related to a reference water level. This allows reconstructions of RSL for any time interval associated with the data set, although the majority of index points only provide a 'limiting point' above or below which sea-level may occur. The approach has been used to combine RSL histories from sites in local areas around Scotland's coastline, to reconstruct the pattern of displacement of the palaeoRSL of a particular time period for Britain and Ireland (e.g. Bradley *et al*. 2011). Since the sites concerned are often tens of kilometres apart, complex patterns of displacement, including glacio-isostatically induced fault movement, are difficult to identify.

In contrast, the shoreline-based approach uses altitudes based on a reference water level, normally at ~50-m intervals, that extend for kilometres across the zone of glacio-isostatic displacement. On the basis of morphology, altitude and some dated sites this approach enables the identification of distinctive displaced shorelines. In some cases, a shoreline level can be traced, almost continuously, along parts of the Scottish coastline, thus enabling the identification of complex patterns of crustal displacement. The modelling of the altitudes, or sea-level index points, associated with a well-defined shoreline, illustrates the pattern of displacement of the shoreline, and enables predictions to be made of the area of greatest relative land level change, in this case uplift. On the assumption that ice-loading is the predominant driving force, this helps to define the zone of greatest ice-loading within the context of an ice sheet that is changing its dimensions over time. Indeed, in the area concerned, the ice sheet disappears and then starts to rebuild within the time period considered. The location of the zone of greatest displacement is the focus of this paper.

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In taking a shoreline-based approach to patterns of glacio-isostatic uplift, this paper identifies a shoreline as a morphological feature that formed within a given area during a period of stable relative sea-level. Thus, a shoreline is developed in an area where the rate of glacio-isostatic crustal change is equal to the rate of regional eustatic sea-level change, and will cease to develop where crustal uplift exceeds, or is less than, the change in eustatic sea-level forming, respectively, a relict uplifted or buried shoreline. Since the amount of deformation varies with the glacier load, shorelines developed within areas of glacio-isostatic deformation tend to be diachronous and can only be synchronous if eustatic sea-level falls or rises very rapidly. Where a diachronous shoreline develops the earlier sections form near the zone of greatest uplift and the later sections towards the margins (Wright 1914). Smith *et al.* (2002) measured the diachroneity of the Menteith Shoreline across a modelled glacio-isostatic uplift surface, demonstrating that the age near the centre of greatest uplift is at least 7579–7344 cal. a BP, and towards the margins of uplift the age is 7000–6300 cal. a BP. Observations show that shorelines formed within areas of glacio-isostatic deformation are well developed and may be the product of either erosional processes cutting a bench and cliffline, or depositional processes building-up beach ridges, sandflats or terraces, depending on the geodynamics of the coastal areas.

The sea-level to which shorelines have developed, has varied both temporally and spatially. Global ocean volume changes, as modelled by Lambeck *et al.* (2014) and Peltier *et al.* (2015), show a net sea-level rise of at least 60 m in the period during which the shorelines studied in this paper were formed. At the same time, regional changes in global sea-levels have occurred (Mitrovica & Milne 2003; Shennan *et al.* 2012) due to gravitational effects of different ice sheets, changes in seawater temperature and variations in the patterns of ocean currents. At the local scale, variations in tidal amplitude have also occurred (e.g. Uehara *et al.* 2006; Ward *et al.* 2016). In the present work, we have assumed that regional sea-level changes have been the same for each shoreline. In the case of tidal changes, whilst there would probably have been little difference between Middle and Late Holocene shorelines, earlier shorelines (Early Holocene and Lateglacial) would have been developed during different tidal circumstances as several studies (e.g. Ward *et al.* 2016) propose. The extent to which such changes could have influenced the results of this study are assessed in the sensitivity analysis described below.

The present work builds on previous work by the authors and colleagues, developed over many years, using a similar methodology. However, with the exception of the Forth valley, previously published observational evidence is derived from areas largely, although not exclusively, peripheral to the probable area of maximum glacio-isostatic land uplift. The present study provides new evidence using mapping and levelling of displaced shorelines in an area close to the zone of maximum glacio-isostatic uplift, along the north side of the Clyde estuary and the shores of Loch Lomond (Fig. 1) in western central Scotland.

Source of new data and methods of data collection

In Table S1, we indicate the details of 1005 data points used in the present study. In each case the elevation (m OD), reference water level in relation to mean high water spring tide (MHWST) and indicative range (potential error) have been determined. These features consist of: (i) the inner margin of a rock platform or a beach formed in front of an erosional cliffline, (ii) the inner margin of sand or estuarine flats, (iii) the highest point of a shoreline terrace and (iv) occasionally a buried estuarine deposit. All shoreline landforms were measured avoiding slope-wash or features developed at the shoreline by non-marine processes and anthropogenic disturbance.

One Lateglacial and three Holocene discrete shorelines have been recognized and comprise both depositional and erosional features. We have taken the opportunity here to rename the 'Main Postglacial Shoreline' as the 'Menteith Shoreline'. The term 'Main Postglacial Shoreline' was first used by Sissons *et al.* (1966) and was initially considered to consist of the highest Holocene displaced shoreline around Scotland's coastline. Subsequent research (Smith *et al.* 2000, 2006, 2007, 2012; Smith 2005) has demonstrated that whilst Middle Holocene relative sea levels formed the highest Holocene shoreline features near the centre of uplift, these features were buried by later Holocene shorelines further from the centre of uplift. As a consequence, features that were correlated with the Main Postglacial Shoreline in some early papers to produce isobase maps (e.g. Sissons 1967, 1976; Firth *et al.* 1993) have subsequently been associated with later shorelines (Smith *et al.* 2012). It is thus appropriate to discard the term 'Main Postglacial Shoreline'. The name 'Menteith' is used because the Main Postglacial shoreline was first described around the Lake of Menteith at the head of the Forth valley (Smith 1965; Sissons *et al.* 1966), where it is the most extensive feature and the highest raised shoreline in that location.

All shore features were mapped following the approach developed by Sissons *et al.* (1966) and reported in Rose (1980a, b, 1982, 2003a, b) and Rose and Smith (2008). Shoreline altitudes were surveyed by levelling from and to Ordnance Survey benchmarks. These altitudes relate to the inland margin of a beach, or the crest of a beach ridge, and were taken at approximately 50-m intervals, avoiding buildings or disturbed ground. All altitudes are correct to ±0.05 m, and surveys with a closing error greater than this were repeated. Elevations are given in metres above Ordnance Datum Newlyn (OD). The different morphological features

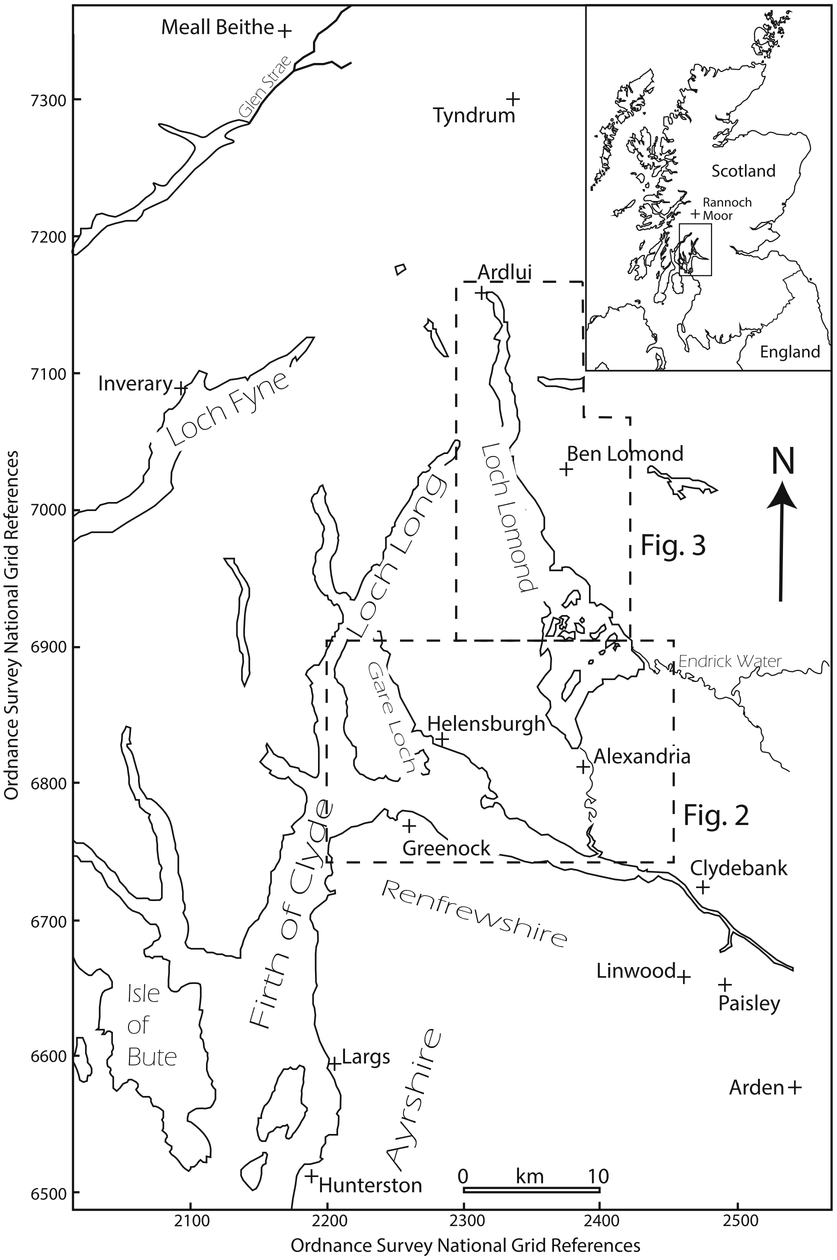

Fig. 1. Location of the study area.

(saltmarsh, sandflat, sand and gravel beach, rock platform) form at a different elevation to the tidal cycle (the reference water level) and as a consequence, corrections were made based on the relationship of modern features to mean high water ordinary spring tides (MHWST) to adjust all the elevations to local MHWST level. The correction that was applied to each shoreline fragment is provided in Table S1. It is also recognized that the elevation of modern MHWST varies around the coastline and frequently rises up estuaries. As a consequence, the elevation of MHWST at the nearest tide gauge (Table 1), in a comparable situation to the shoreline fragment measured, was deducted from the corrected altitude to determine the palaeo-relative sea-level (pRSL) when the feature was formed. As noted above variations in tide levels are considered to have been limited during the period of the Holocene shorelines studied here.

Since the shorelines measured in this study occur over considerable distances (often several km) the measurements have been analysed as groups of five (i.e. distances of ~200 m for each group), and the means of each group taken, both for altitude and location (the latter based on OS grid coordinates), following similar practice

Table 1. Tidal stations quoted in this study (Admiralty Hydrographic Department 1996).

Station	Symbol used in this text	Mean high water spring tide (m OD)	Mean high water neap tide (m OD)	Mean low water neap tide (m OD)	Mean low water spring tide (m OD)
Glasgow	G	3.08	1.78	−0.02	−0.92
Port Glasgow	P	1.98	1.28	−0.62	−0.62
Bowling	B	2.00	1.30	−0.70	−1.60
Helensburgh	H	1.78	1.18	−0.62	−1.32
Rothesay Bay	R	1.98	1.38	−0.42	−1.12
Ardrossan	A	1.58	0.98	−0.52	−1.22

elsewhere (Smith *et al.* 2010). These groups are here termed 'shoreline fragments'.

Whilst the errors associated with the levelling traverses were very small the variation in elevation along shoreline fragments can be somewhat greater, as a simple function of the coastal geo-dynamics. These variations have been used to determine the indicative range of the index point for a particular region. Unlike the features studied in the Clyde and Loch Lomond region, the majority of shoreline fragments were reported in Smith *et al.* (2012) and are associated with raised estuarine silty clay deposits (known as 'carse' in Scotland). Measurements on modern-day equivalent features (saltmarshes) indicate that these features form very close to MHWST. Fragments from the Isle of Bute and the Ayrshire coastline (Smith *et al.* 2006) largely consist of sand terraces with the modern equivalent features (sandflats) forming 1.15 m below MHWST.

Along the northern coast of the Clyde estuary, the level of the shoreline measured was the break of slope at the inland margin of the feature, and considered a consistent indicator of sea-level (Andrews 1986; Jardine 1986). The results from sampled points at six locations confirm the greater uniformity of the level of the break of slope at the base of the beach (0.93±0.32 m above OD). This break of slope has a level that is, apparently, independent of position along the shoreline or the lithology into which the shoreline has been eroded. The altitudes derived from current landforms at the six locations were used to identify the reference water level associated with raised shoreline fragments in the same area.

A study of 17 sample points around Loch Lomond shows that the active shoreline break of slope is 1.09±0.34 m above the contemporary water level with a significant difference between west (+0.68±0.14 m) and east (+1.31±0.16 m) coasts of the loch, most probably reflecting wind direction and fetch during the period of shoreline formation. These variations relate to the lake level at the time of measurement and were not influenced by tidal processes. However, since the displaced shorelines measured around Loch Lomond developed during marine incursions their altitudes are considered with reference to the nearest tidal station (Bowling, in Table 1), with the reference water level for the sheltered western side being considered comparable with features in the Leven valley (MHWST −1.2 m OD) and those on the more exposed east coast 63 cm higher (MHWST −0.57 m OD).

Stratigraphical context and age ranges

Radiocarbon dates are given in both radiocarbon and sidereal (calibrated) years. Calibrations were made using Calib. 7.1 (Reimer *et al.* 2009, in conjunction with Stuiver & Reimer 1993), and where a radiocarbon date is given only as 'circa' or otherwise without any statistical qualification in the published work quoted, the equivalent calibration shown here is the mean of 2σ about the radiocarbon date, using an assumed 1σ of 100.

In the present account, the terms Early, Middle and Late Holocene follow the definitions of Walker *et al.* (2012) and terms for the latter part of the Last Glaciation are taken from Walker and Lowe (2019). Late Devensian refers to the period from the maximum of the Devensian Stage (*c.* 22 000/20 000 cal. a BP) to the end of the Younger Dryas and the base of the Holocene (11 700 cal. a BP). The Lateglacial is from 14 700 to 11 700 cal. a BP.

Previous work

In the account below, previous work is outlined before the present work is described and set in the context of models of glacio-isostatic uplift. Much work has been done recording shoreline characteristics within the region around the Clyde estuary, but this work has taken the form of very early Quaternary studies, site descriptions in field meeting reports and British Geological Survey reports along with brief analyses of radiocarbon dates (Smith 1836; Clough *et al.* 1925; Rose 1969, 1975, 1979, 1980a, b, c, 1982, 2003a, b; Bishop & Dickson 1970; Peacock 1971, 2003; Peacock *et al.* 1978; Browne & Graham 1981; Browne *et al.* 1983; Browne & McMillan 1984, 1989; Paterson *et al.* 1990). Hitherto, there had been no substantive study of shoreline development within the region.

Main Lateglacial Shoreline

The widespread Main Rock Platform (Sissons 1974), mapped along the coasts of western mainland Scotland and the islands of the Inner Hebrides by Gray (1972, 1974a, b, 1978), Dawson (1979, 1980, 1982, 1984, 1988) and Dawson *et al.* (1999), is also reported in the west and southwest of the Clyde estuary and the Loch Lomond basin (Gray 1974b, 1995; Rose 1980b, 1982, 2003a; Fretwell 2001) and has been equated with the Main Lateglacial Shoreline, and is thus of Younger Dryas age (Sissons 1974). The Main Rock Platform reaches an elevation of 4.7 m OD (2.92 m pRSL) on the Isle of Bute at the mouth of the Clyde estuary and from trend surface analysis (Gray 1974b; Fretwell 2001) may reach over 7 m pRSL in the estuary itself, while Rose (1980b, 1982) correlated a platform at ~12 m OD (~10 m pRSL) and marine deposits in the Loch Lomond basin, with the Main Rock Platform, because the platform and deposits are overlain by material deposited by the Loch Lomond Readvance (Younger Dryas). Gray and Ivanvoich (1988) sought to date the platform using U-series dating from evidence on the island of Lismore at the western end of the Great Glen, but concluded that it is a polygenetic feature, formed during the Younger Dryas but possibly modified by later RSLs. Later, Stone *et al.* (1996), using cosmic ray exposure dating, concluded that the Main Rock Platform on the island of Lismore was formed rapidly during the Younger Dryas. The dates provided by Stone *et al.* (1996) imply that the Main Rock Platform may have been abandoned towards the end of the Younger Dryas.

Sissons (1974) correlated the Main Lateglacial Shoreline with a distinct break of slope at the inland margin of a gently rising erosional surface that underlies the Bothkennar Gravel Formation in the Forth estuary in eastern Scotland (Peacock 1998). Whilst the origin of the Bothkennar Gravel Formation is debated, both Peacock (1998) and Sissons (1974) indicate that the underlying erosional surface is equivalent to the Main Rock Platform, and they suggest a Younger Dryas age for the feature. A buried erosional surface of Younger Dryas age was also identified in the Beauly Firth (Sissons 1981; Firth 1984; Firth & Haggart 1989). The erosional features are overlain by deposits of Younger Dryas (High Buried Beach) and Early Holocene (Main and Low Buried Beaches) shorelines (Sissons *et al.* 1966; Rose 1980b, 1982; Firth & Haggart 1989; Dawson *et al.* 1999).

Given that the feature formed as a result of coastal erosion under a periglacial environment there are no modern equivalent features currently being developed around the Scottish coastline. Studies from modern periglacial environments in the Lofoten Islands (Moller & Sollid 1972), Finnmark (Sollid *et al.* 1973) and NE Norway (Rose 1978) suggest the inner margin of the platforms develops close to high tide and as a consequence a reference water level of MHWST has been adopted for this feature. It is clear that a period of rapid erosion occurred around Scotland's coast during the Younger Dryas, and it seems appropriate that the inner margin of the erosional features (rock platform and buried erosional surfaces) were formed by the same process.

Holocene shorelines

Evidence for former Holocene RSLs is present in the Clyde estuary area, although detailed published information is sparse. Sedimentary evidence for former Holocene RSLs in Loch Lomond was published by Dickson *et al.* (1978) and later by Stewart and Stenhouse (1987). Dickson *et al.* (1978) reported two borehole records through ~4.9 m of Holocene sediments at the southern end of the loch at depths of 24 and 26 m below the loch surface. Radiocarbon dates were obtained at intervals from the organic fraction within sediment core samples of core LLRD1. From the sequence of radiocarbon dates compared against the sedimentary record, dates for the onset and termination of marine conditions were interpolated. It was concluded that marine waters were present in the Loch Lomond basin for a period of *c.* 1450 radiocarbon years between ~6900 BP (7759 cal. a BP) and ~5450 BP (6214 cal. a BP). From a core 25 km north of core LLRD1, Stewart and Stenhouse (1987) reported a marine phase in Loch Lomond, lasting from ~7230 BP (8078 cal. a BP) to ~5485 BP (6204 cal. a BP) with a short freshwater interval (inferred from an absence of dinoflagellate cysts) at ~6375 BP (7248 cal. a BP). The principal evidence from Stewart and Stenhouse (1987) is that the marine episode began earlier but ended at a similar time to that indicated by Dickson *et al.* (1978). The evidence from the studies of Dickson *et al.* (1978) and Stewart and Stenhouse (1987) would seem to indicate that marine conditions were present in the Loch Lomond basin from at least ~7200 BP (*c.* 8100 cal. a BP) to ~5500 BP (~6200 cal. a BP), although we note that the dates from Dickson *et al.* (1978) were interpolated, not measured, while those from Stewart and Stenhouse (1987) are from an unrefereed conference paper. If Loch Lomond lies near the centre of glacio-isostatic uplift in Scotland (where shoreline ages would have been near their maxima), it seems likely from this evidence that the Menteith and possibly the Blairdrummond shorelines should be present around the shores of the loch, notwithstanding the uncertainties surrounding the dates reported.

Haggart (1988), in a review of radiocarbon dates on peat and wood from Holocene coastal sedimentary deposits in Scotland, recorded several dates from an embayment in the Clyde valley at Linwood near Paisley, some of which could relate to former RSLs. More detailed studies were made by Bishop and Coope (1977) and Boyd (1982) from the same area, and Bishop and Coope (1977) describe up to 21 m of clays containing the bivalve *Arctica islandica* overlain by unfossiliferous silts with a surface elevation at 12 m OD (10.02 m MHWS, P). This is, in turn, overlain by peat, the base of which was dated at 9231±96 BP (10 227–10 618 cal. a BP) indicating terrestrial conditions by this date. However, the relationship between the *Arctica islandica* sample and RSL at the time is uncertain, and the date on peat may not define RSL, given the lack of marine fossils in the underlying silt. Thus, this date is of uncertain provenance other than indicating that RSL had fallen below 12 m OD (10.02 m MHWS, P) by this time. Bishop and Coope (1977) also record dates of 3572±62 BP (3694–4079 cal. a BP) from wood and 3513±56 BP (3641–3958 cal. a BP) from peat overlying silt at 8.22 m OD (6.24 m MHWST, P) and argue that although RSL had fallen from *c.* 12 m OD, a slight rise in RSL subsequently took place between 8000 BP (*c.* 8900 cal. a BP) and 4000 BP (*c.* 4500 cal. a BP), implicitly assuming that the silt may be of marine or estuarine origin. Boyd (1982) maintained that the maximum Holocene RSL reached around 8.5 m OD (6.52 m MHWST, P) to 12.5 m OD (10.52 m MHWST, P) in the general area of Ayrshire and Renfrewshire including the Linwood–Paisley embayment, at a time between ~7000 and ~4000 radiocarbon years BP, given as 5000 BP (5736 cal. a BP).

Shennan and Horton (2002), in modelling RSL changes for sites across Great Britain, produced a sea-level curve for the Clyde estuary for the last 16 000 years in which they quote dates from Haggart (1988). Shennan *et al.* (2018) produced a graph for the Clyde estuary for the last 20 000 years. Shennan *et al.* (2018) show 18 marine limiting dates in their graph (although they quote a total of 27 marine limiting and 5 freshwater and high marsh dates from the Clyde area in the Britain and Ireland Database) (Kahn *et al.* 2019), but no sea-level index points. Given the uncertainties about the evidence from Linwood discussed above and the limited information from the Database it is clear that published information on RSL change in the Clyde estuary is at best uncertain.

Beyond the mouth of the estuary, along the coast of the Firth of Clyde and on the island of Bute, Smith *et al.* (2007) identified Holocene marine terraces at three separate levels with the upper two being correlated with the Menteith and the Blairdrummond shorelines (Table 2). At Hunterston, the Menteith Shoreline was found to slope southwards from a maximum level of 12.7–13.5 m OD (12.27–13.07 m pRSL, A) while beneath it the Blairdrummond Shoreline was found to descend southwards from 10.5–8.5 m OD (9.56 m–8.09 m pRSL, A). The work of Smith *et al.* (2007) therefore suggests that the highest Holocene shoreline in this area of the Clyde is the Menteith Shoreline. An age of 6170±100 BP (6793–7274 cal. a BP) was obtained for the Menteith Shoreline from Girvan in Ayrshire, the nearest site to the Clyde where this shoreline has been dated (Smith *et al.* 2007).

Present work

Field evidence and interpretation

On the north side of the Clyde estuary, below the Lateglacial shoreline sequence (Fig. 2), four Holocene shorelines occur up to an elevation of 13 m OD. The Holocene shorelines in the Vale of Leven occur up to 14 m OD, with some features modified by human disturbance and fluvial activity. To the SW, along the Firth of Clyde and on the Isle of Bute, Smith *et al.* (2007) identified only three visible Holocene terraces, probably because these areas are further from the area of maximum uplift (where lower features would descend close to or intersect the present shoreline). The two highest features along the Clyde estuary are comparable with the highest of the three terrace levels identified by Smith *et al.* (2007), and on this basis are correlated with the Menteith Shoreline and the Blairdrummond Shoreline.

Table 2. Age, extent and characteristics of the displaced shorelines studied in this paper.

Shoreline	Main Lateglacial[1]	Menteith[2]	Blairdrummond[2]	Wigtown[2]
Characteristics	Landward margin of rock platform, adjusted to MHWST. In E Scotland: landward margin of erosion platform beneath Bothkennar Gravel Layer, adjusted to MHWST	Landward margin of former saltmarsh, sandflat and erosional surfaces, adjusted to MHWST. See text for additional features	Landward margin of former saltmarsh, sandflat and erosional surfaces, adjusted to MHWST. See text for additional features	Landward margin of former saltmarsh, sandflat and erosional surfaces, adjusted to MHWST. See text for additional features
Age	Younger Dryas, i.e. 12 900–11 700 cal. a BP[1], but could have started forming earlier	Middle Holocene, 7800–6201 cal. a BP[2]. The shoreline is oldest nearer the area of maximum uplift[2]	Middle–Late Holocene, 5800–3601 cal. a BP[2]. The shoreline is oldest nearer the area of maximum uplift[2]	Late Holocene, 3200–1201 cal. a BP[2]. No trend in age can be seen given that there are few data points[2]
Extent	Mainly W and NE coast of Scotland and Firth of Forth	Widely present on Scottish, N Irish and adjacent N English coasts	Widely present on Scottish, N Irish and adjacent N English coasts	Widely present on Scottish, N Irish and adjacent N English coasts

[1] Main Lateglacial Shoreline is defined in Sissons (1974), Gray (1978), Sissons (1981), Dawson (1984), Stone *et al.* (1996) and studies cited therein.

[2] Menteith (Main Postglacial), Blairdrummond and Wigtown shorelines as defined in Smith *et al.* (2006, 2012, 2019). Ages are from Smith *et al.* (2012).

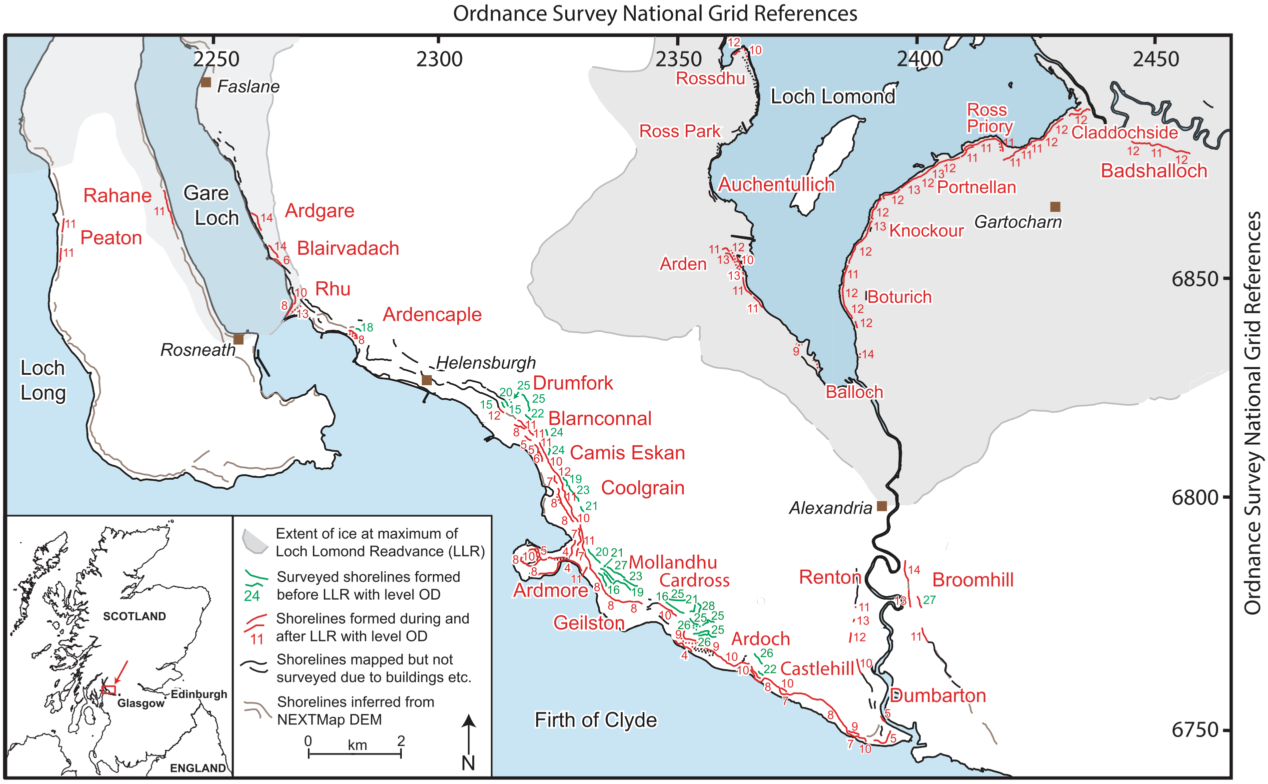

Fig. 2. Inner Clyde and southern Loch Lomond shoreline fragments.

Along the southern shore of Loch Lomond an extensive shore platform and backing cliff have been identified (Rose 1980b; Gordon 1993) lying below the current loch level and in places covered in till associated with the Younger Dryas Loch Lomond Readvance. At Claddochside the cliff is cut in Old Red Sandstone bedrock and the junction between the cliff and platform lies at ~12 m OD (~10 m pRSL). This platform is correlated with the Main Lateglacial Shoreline and the altitude of its inner margin whilst approximate, is used in the current analysis of the data.

Around Loch Lomond, two prominent shorelines are present above the present shoreline, which lies at 8.3–9.0 m OD (7.5–8.2 m pRSL, B). Near the head of the loch and at intervals to the south, shorelines are fragmentary and composed of sand and locally fine gravel (Fig. 3), while at the southern end of the loch shorelines are continuous and composed of sand and gravel overlying Devonian (Old Red Sandstone) bedrock or till. At the valley mouths of the Fruin and Endrick Water valleys the beaches overlie, or are cut into, river and glacifluvial sands and gravels. Two levels of these shorelines are recorded. The lower of these is the most extensive, having been levelled at 243 points above the present loch level and above the present delta and floodplain of the Endrick Water valley (21 points) where it lies at 10.7–13 m OD (9.3–11.77 m pRSL, B). The higher but more fragmented level at the head of the loch and at several locations to the south (22 points) is recorded at 13.1–15.9 m OD (12.27–14.57 m pRSL, B).

It is noteworthy that the upper two Holocene marine shorelines along the northern shore of the Clyde estuary are higher than the current level of Loch Lomond and as a consequence, marine waters would have been able to enter Loch Lomond along the Leven valley (Vale of Leven). On the basis of altitude, the highest Holocene terraces around Loch Lomond are consistent with the highest Holocene marine terraces along the northern Clyde estuary (the Menteith Shoreline), whilst the more extensive lower shoreline can be correlated with the shoreline fragments associated with the Blairdrummond Shoreline. Mean age ranges for northern Britain and Ireland of the Menteith Shoreline (6201–7800 cal. a BP) and Blairdrummond Shoreline (3601–5800 cal. a BP) (Smith *et al.* 2012, 2019) compare relatively closely with the dates for the episodes of marine influence in the loch reported by Dickson *et al.* (1978) and Stewart and Stenhouse (1987), given that older dates for the shorelines would be more likely nearer the zone of greatest glacio-isostatic uplift.

The sequence of palaeo-RSL changes in the Clyde area during the Younger Dryas and Holocene therefore begins with the Main Lateglacial Shoreline, reached around 10 m OD during the Lateglacial. By ~8200 cal. a BP, pRSL was rising, reaching ~12–14.6 m OD in the Loch Lomond basin and Clyde estuary to reach two shorelines: the Menteith and Blairdrummond. Subsequently, RSL continued to fall towards present levels, vacating the Loch Lomond basin as the Wigtown and a later shoreline were formed.

The modelling approach

The shoreline data used here to determine likely patterns of glacio-isostatic uplift across mainland Scotland have a number of attributes. They were collected using similar methods developed over 60 years; are referenced to the same datum; and are related to the same reference water level (MHWST). Although the data distribution is variable across the lengthy Scottish coastline, the long chains of measurements, sometimes several kilometres in length, provide continuity along stretches of coastline, both across and along possible isobase directions. Plainly, there are extensive coastal areas without data, but it is argued that this problem is common in geoscience and not confined to shoreline studies. Similar characteristics apply to stratigraphically based RSL studies and the study of crustal loading by ice. It is maintained here that the mutually supportive effect of long chains of measurements, made to a similar method, provide as reasonable an indication of glacio-isostatic displacement as can be obtained with the data presently available.

In order to determine patterns of displacement of the pRSL shoreline index points, the shoreline height data were analysed statistically, using Gaussian quadratic trend surface analysis. Early attempts to map the pattern of shoreline displacement used quadratic trend surface analysis (e.g. Cullingford *et al*. 1991; Firth *et al*. 1993), but the surfaces increased in slope towards the limit of the data, and beyond the limit, they descended to infinity. Fretwell (2001) and Fretwell *et al*. (2004) developed an alternative method, which is more appropriate to the nature of the trends in a glacio-isostatically uplifted area. This method is Gaussian quadratic trend surface analysis, in which the surface computed does not descend to infinity beyond the data analysed, but rather descends to a base value (zero level) that is input into the model. This approach has now been used in a number of models of glacio-isostatic uplift in Britain (e.g. Fretwell *et al*. 2004; Smith *et al*. 2006, 2012). The analysis was undertaken by utilizing an Excel workbook (see Table S2) and the base level (zero value) was adjusted so that the coefficient of determination (R^2) was maximized. An alternative approach of setting the zero level to the ice-equivalent (eustatic) sea-level when the shoreline formed was undertaken but discounted because the data relate to diachronous shorelines and the changes produced were not significant. The analysis fits a mathematical model to the data set and will produce a symmetrical surface represented by a circular or elliptical dome that descends to the zero value that is input into the model. It provides a generalized model of the pattern of shoreline displacement that illustrates the zone of maximum uplift. Where an elliptical figure is produced, the orientation of the dome is illustrated.

In the present work, shoreline heights were analysed in fragments, as described above. The fragments were assigned to shorelines on the basis of age and altitude with reference to previous work in adjacent areas and to observation in the present study. For the purposes of analysis, the measured altitude of each shoreline fragment was adjusted to bring it up to local MHWST. The value of the current local MHWST was then deducted to produce the pRSL value.

Concerns associated with trend surface analysis are well established particularly with the use of higher order surfaces, with boundary issues (predictions near and beyond the limits of the data set) and where the data are clustered or auto-correlated (e.g. Robinson 1970). An ideal data set would consist of independent data points with a random margin of error, evenly spread across the area of study. In contrast, the distribution of shoreline fragments is far from evenly spread and is frequently

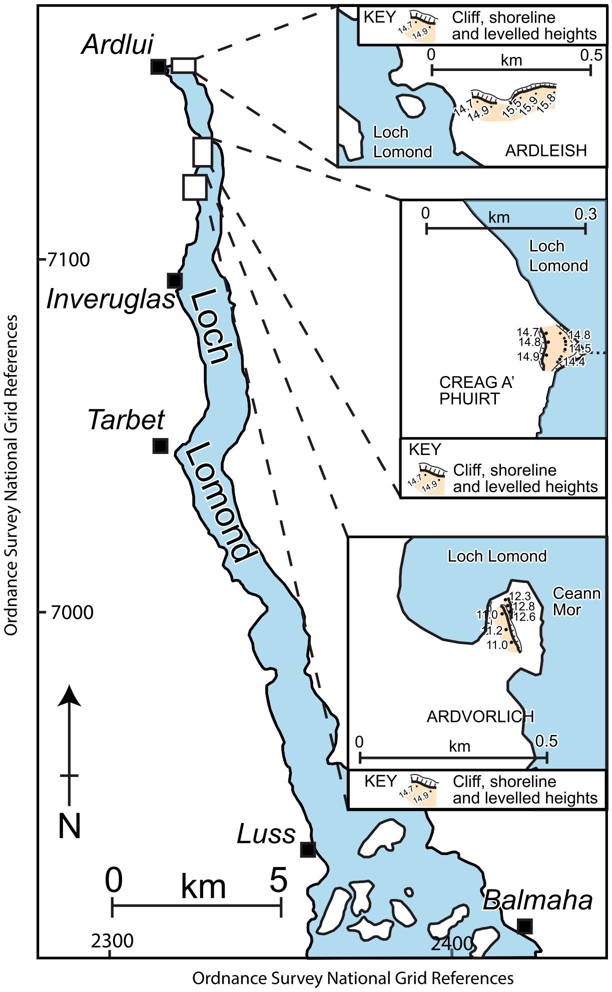

Fig. 3. Northern Loch Lomond shoreline fragments.

Table 3. Potential variation (km) of the centre of the pRSL displacement dome derived from the Gaussian trend surface model associated with different factors.

Sensitivity factor	Main Lateglacial (km)	Menteith (km)	Blairdrummond (km)	Wigtown (km)
Zero value	0.04–3.5	0.39–5.3	0.16–1.15	0.28–1.31
Morphological correction value		0.59–0.76	0.58–1.41	1.28
Clustering	0.30–0.45	2.68–3.39	2.15–3.30	5.81–7.90
Data distribution	1.09	2.02	2.02	1.27
Uniform change (±indicative range)	1.17–1.23	0.81–2.21	2.04–2.09	0.10–3.64
Systematic change (±indicative range)	4.63–8.9	8.49–12.85	8.16–18.34	23.09–33.78
Systematic change (±indicative range/4)	1.22–2.04	1.95–3.39	2.12–4.44	6.54–7.60

clustered. The division of long shoreline fragments into sub-fragments results in auto-correlation and, as a consequence, the coefficient of determination (R^2) will be enhanced. It must however be stressed that the trend surface analysis is not being used to confirm the correlation of the shoreline fragments, but to identify the pattern of displacement, and the zone of greatest displacement that lies within the heart of the data set. Similarly, restricting the analysis to the low-order quadratic surface provides a generalized model of displacement. An analysis of the residuals associated with the model will highlight where there is a poor fit to the data and where more complex patterns of displacement are likely to be found. It is however recognized that the centre of uplift and the orientation of the dome could be influenced by the zero value selected in the Gaussian model, the correction factors applied to standardize the data to pRSL, the clustering of data points and the distribution of the points. The potential variation in elevation of individual data points associated with 'errors of measurement' (indicative range) could also influence the results of the analysis. The impact of each of these factors was assessed for each shoreline by undertaking sensitivity analysis, and the results are summarized in Table 3 and Fig. 4, with the detailed results provided in Data S1.

The sensitivity analysis indicated that the above factors had a limited impact on the orientation of the displacement dome of each shoreline, all of which varied by ±5° or less. Similarly, factors such as the selected zero value, morphological correction factors, data clustering and the contrasting spatial distribution of the data altered the modelled centre of uplift of each shoreline by ±8 km or less. In contrast, the sensitivity analysis indicated that the centre of uplift was susceptible to significant change if it contained extreme errors (e.g. all index points along the east coast raised by their indicative range (error) whilst the west coast points are reduced by their indicative range). The Wigtown Shoreline was most susceptible to these errors (±23–34 km) and the Main Lateglacial Shoreline (±4.6–9 km) the least sensitive. Systematic errors of this nature and scale have an unknown origin and a reduced error range (indicative range/4) is considered more appropriate with the Wigtown centre moving by ±6.5–7.6 km and the Main Lateglacial centre by ±1.2–2.0 km. It is also noteworthy that the movement of the centre of displacement associated with the Holocene shorelines is confined to a narrow NE–SW aligned ellipse rather than a circle (Fig. 4).

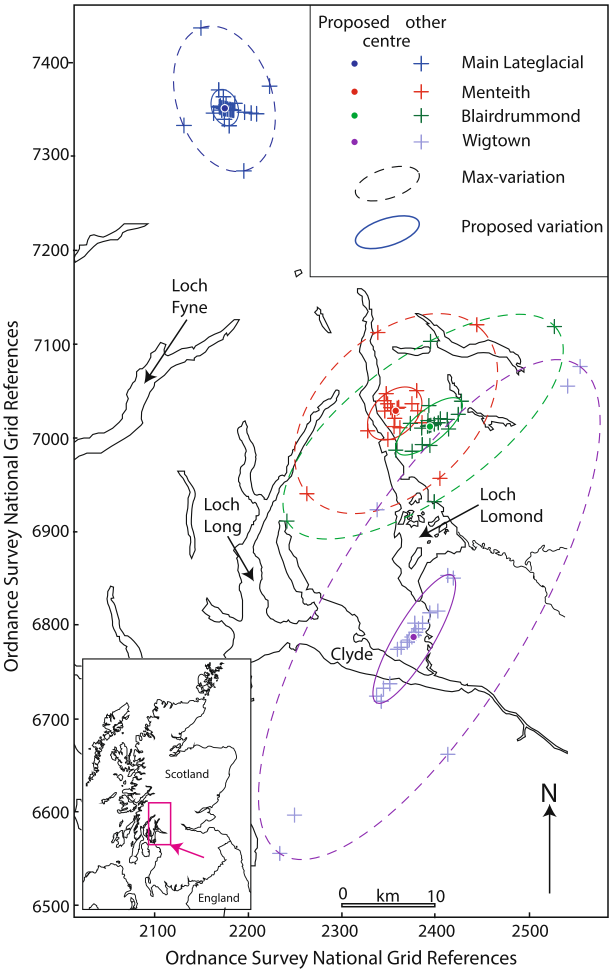

Fig. 4. Spread of the centre of the Gaussian trend surface model for each shoreline when key parameters are varied and the influence of potential known/unknown errors associated with the data set. Dots indicate the centres of uplift derived from current Gaussian trend surface models. Crosses represent alternative centres of uplift when key factors are adjusted.

Patterns of pRSL displacement in mainland Scotland indicated by the shoreline data

Using shoreline data from the Clyde area combined with shoreline data for Scotland as a whole from Smith *et al.* (2012), we show Gaussian quadratic trend surface models for the Main Lateglacial, Menteith, Blairdrummond and Wigtown shorelines in Fig. 5. Summary statistics for these models are shown in Table 4.

Assessing the shoreline-based models: analysis of residuals

The quality of the models was assessed by reviewing the pattern of residuals associated with each shoreline; with particular attention being given to notable outliers (the residuals that are ±2 standard deviations from the mean, and are surrounded by index points with high residual values) and to regions where all the residuals are either positive or negative (Table 5). Locations noted in the text are shown on Fig. 5.

The outlier in Loch Lomond is the largest residual, with the pRSL index point lying 4.05 m above the modelled surface. Index points from the Cowal region to the west lie 1 m above the modelled surface whilst nearby index points from the inner Clyde and the Forth valley are dominated by negative residuals. The residual suggests that the southern end of Loch Lomond may have been influenced by neotectonic activity or some other form of displacement. Observed shoreline altitudes near Connal and NE Islay (Fig. 6) are higher than those predicted by the model, whilst those from Ardnamurchan are lower and this may reflect complex patterns of uplift and dislocations that have been described from other sites in western Scotland (Gray 1974a, b; Firth & Stewart 2000). The residuals associated with the inner Clyde–Ayr coastline, and the Firth of Forth suggest the shoreline declines at a shallower gradient than represented by the model given that negative residuals dominate in the inner Firths and positive residuals in the outer Firths (Figs 5, 6).

Residuals associated with the Menteith Shoreline indicate that all the shoreline fragments from the inner Clyde, Loch Lomond basin, western Forth valley and eastern Solway Firth are positive whilst those from the eastern Forth valley are negative (Figs 5, 6). The inner Clyde also contains a large number of positive outliers. The residuals associated with the Forth valley (Fig. 6) highlight the complex patterns of displacement that were reported by Sissons (1972). The residuals from the Forth valley and Beauly Firth (Fig. 6) suggest the shoreline may decline at a steeper gradient than represented by the model, given positive residuals dominate closer to the centre of uplift and negative residuals further away.

All of the outliers associated with the Blairdrummond Shoreline are located in the inner Clyde or Loch Lomond basin, but some are negative and others positive. Whilst the majority of residuals from the southern end of Loch Lomond are positive there is no clear pattern and no evidence that the modelled shoreline gradient is steeper than represented by the actual data (see Figs 4, 5).

The model for the Wigtown Shoreline generated three outliers, one at the head of the Solway Firth and the others from the inner Clyde and inner Moray Firth. There was a tendency for many of the regions to have either mainly negative (e.g. Beauly Firth, Tay, Luce Bay, Dunbar) or mainly positive (e.g. Forth) residuals but once again no clear patterns were present.

The large number of positive residuals and outliers associated with two shorelines (Menteith and Blairdrummond) from the inner Clyde could indicate that the reference water levels identified for the features in this area are incorrect. However, if this were the case then a similar pattern would be identified in the Wigtown Shoreline. Examination of the patterns of residuals for each shoreline indicates that whilst statistically the models are a good fit (as Table 4 indicates), there are noticeable variations in the data that indicate that more complex patterns of uplift are present at regional levels. At several locations, the regional slope of the pRSL index points is greater or shallower than predicted by the model and this indicates that the dome of displacement is probably asymmetrical. The residuals also highlight where individual index points or clusters of index points are markedly different from those in surrounding areas, which may indicate sites where neotectonic activity has occurred.

Patterns of glacio-isostatic uplift for mainland Scotland revealed by the shoreline-based models

The models in Fig. 5 show broadly similar patterns, each with a zone of greatest uplift in the SW Grampian highlands. However, in detail noticeable differences are evident. The pRSL isobases associated with the Main Lateglacial Shoreline suggest a N-S aligned elongate uplift dome centred on the NW slopes above Glen Strae, 250 m SW of Meall Beithe (Fig. 1), while the isobases for the Holocene shorelines suggest a NNE–SSW aligned elongate uplift dome with the centre further towards the southeast and south (Menteith: 1.3 km E of Ben Lomond; Blair Drummond: 3.1 km SE of Ben Lomond; Wigtown: 2 km SE of Alexandria and 4 km SSE of the outlet of Loch Lomond). The sensitivity analysis indicates that the zone of greatest displacement is influenced by a number of factors, with the Holocene shorelines being more sensitive to possible systematic errors in the data. Once these variations are considered (Fig. 4) it appears that the zone of greatest displacement shifted SSE between the Lateglacial and the Holocene. However, if the potential unknown errors are smaller, then the zone of greatest displacement appears to move towards the south during the Holocene. This is apparent

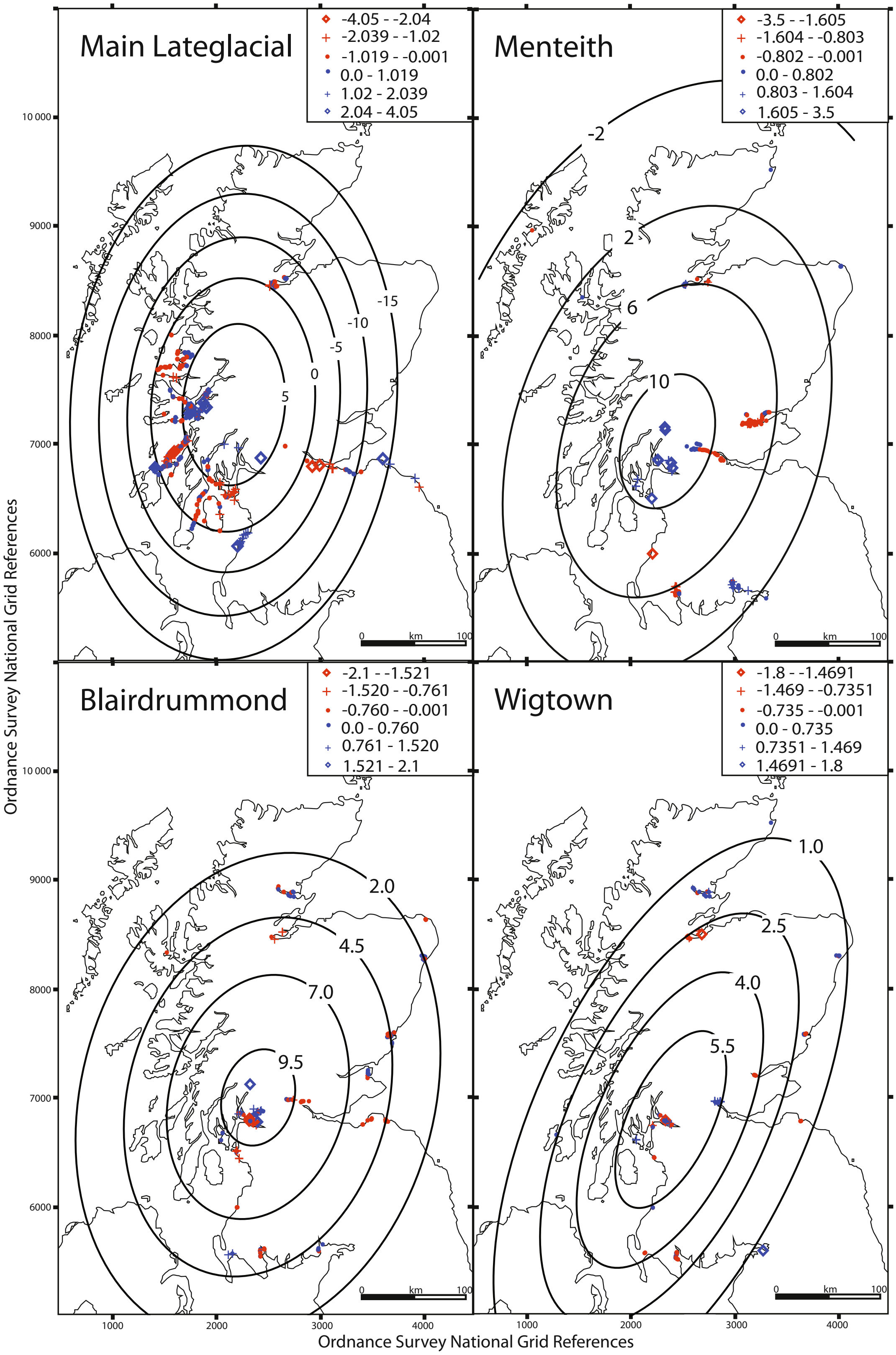

Fig. 5. Gaussian quadratic trend surface isobases of the pRSL (m) associated with a named shoreline and the associated residuals for each index point. Where the index points are very clustered some residuals are obscured.

Table 4. Summary statistics for the Gaussian quadratic isobase models of named Scottish shorelines.

Shoreline	No. of values	Centre, OS National Grid, km from origin ±8 km	Major axis orientation ±5°	Minimum residual (m)	Maximum residual (m)	Mean absolute residual (m)	Range of 95% of residuals (m)	Standard error	R^2 coefficient of determination (%)	Zero value (m pRSL)
Main Lateglacial	413	Easting 217.4 Northing 735.0	5.26° east of north	−2.67	4.05	0.678	±2.06	0.84	95.34	−24.21
Menteith	194	Easting 235.3 Northing 702.9	19.21° east of north	−1.75	3.490	0.56	±1.60	0.70	96.57	−3.46
Blairdrummond	256	Easting 239.4 Northing 701.3	15.56° east of north	−1.94	2.03	0.47	±1.52	0.60	96.90	−1.29
Wigtown	134	Easting 237.6 Northing 679.0	24.97° east of north	−1.77	1.62	0.44	±1.47	0.51	92.83	−0.25

from Table 4 and is illustrated in Figs 4 and 6, the latter illustrating cross-sections across the modelled surfaces.

Comparison with GIA models

Recent terrain-corrected GIA models from Bradley *et al*. (2011) and Kuchar *et al*. (2012), illustrated by Bradley (in Smith *et al*. 2019) (Fig. 7) disclose patterns for mainland Scotland from ~10 000 to ~2000 a BP. These patterns take the form of an elongate dome orientated NNE–SSW (Bradley *et al*. (2011) or NE–SW (Kuchar *et al*. (2012). The Bradley model places the zone of greatest uplift in the Rannoch Moor area, whilst the Kuchar model identifies the head of the Tay estuary as the zone of greatest uplift. In both models, the zone of greatest uplift is unchanged throughout the last 10 000 years. The isobase models determined in this paper can be compared with the Bradley *et al*. (2011) and Kuchar *et al*. (2012) models in spatial terms only, since the Bradley and Kuchar models are referenced to a specific time period (e.g. not diachronous) and are not constrained by the need to fit a symmetrical mathematical model.

The Kuchar *et al*. (2012) model is considerably different to the shoreline height distribution, both as given in the present paper and in previous publications (e.g. Smith *et al*. 2012), whereas the Bradley *et al*. (2011) model bears relatively close correspondence to the shoreline height distribution described in this paper. This model places the area of maximum uplift south of Rannoch Moor. In Fig. 8, the areas of maximum uplift according to Bradley and Kuchar are compared with the shoreline-based isobase maps. Here, the area of maximum uplift shown by Bradley *et al*. (2011) lies S of the Main Lateglacial Shoreline centre, but N of the centres for the Holocene shorelines. In comparing the shoreline-based models with the Bradley *et al*. (2011) and Kuchar *et al*. (2012) models it should be noted that the shoreline-based models do not take account of any variability in regional sea surface levels. However, the main difference between the models is in the pattern of uplift displayed by the GIA models in comparison to the symmetrical zone produced by Gaussian trend surface analysis. The analysis of residuals indicated the gradient of the Main Lateglacial Shoreline in the present study was shallower towards the east and southwest than illustrated by the Gaussian models and thus supports an asymmetrical pattern of displacement. It is, however, noteworthy that the area of maximum uplift is modelled as unchanging in the GIA models, but is shown to have moved over time according to the shoreline-based models.

The recent Bradley *et al*. (2023) model depicts present-day rates of RSL change, showing a broadly NNE–SSW elongate dome, but extended towards the SSW and with an area of maximum uplift between the head of Loch Lomond and the upper Forth valley.

Table 5. Number of residual outliers and regions where all residuals are either positive or negative for each shoreline.

Shoreline	No. of outliers	Notable outliers	Region dominated by +ve residuals (actual values higher than model)	Region dominated by −ve residuals (actual values lower than model)
Main Lateglacial	11	Western Forth, Eastern Forth, Connal, NE Islay, Loch Lomond, Ayr	Eastern Forth, Connal, Eastern Mull, NE Islay, Ayr	Western Forth, Ardnamurchan, Bute, Inner Clyde
Menteith	9	Inner Clyde, Loch Lomond	Western Forth valley, Beauly Firth, Loch Lomond, Inner Clyde, Eastern Solway	Eastern Forth valley, Inner Moray Firth
Blairdrummond	6	Inner Clyde	Southern Loch Lomond, Luce Bay	Outer Forth estuary, Inner Moray Firth
Wigtown	3		Forth	Dunbar, Tay, Beauly Firth, Luce Bay

Possible causes of variations in the pattern of glacio-isostatic uplift

The Gaussian quadratic trend surface modelling process

The sensitivity analysis indicated that the centre and orientation of the modelled displacement dome for each shoreline were influenced by the modelling process. Changes to the zero value, the distribution of the data and alterations to the morphological correction values or possible palaeo-tidal variations had very limited impact on the orientation and centre of the dome. In contrast, reducing the clustering of points had a bigger impact on the centre of displacement, particularly on the Wigtown Shoreline, which moved 7.9 km. The model is particularly sensitive to systematic changes to the index points (e.g. values along the east coast being increased whilst those on the west coast are decreased), with the shallower domes showing the greater sensitivity. Such systematic variations would reflect significant errors in the data set caused by an unknown process. If such variations are present then the data only support a movement in the centre and orientation of the displacement dome between the Lateglacial and Holocene shorelines. If such variations are more limited then it is possible to identify a further movement south of the zone of greatest displacement during the Late Holocene.

Whilst statistically it would have been better to reduce the amount of clustering and auto-correlation associated with the data sets such a reduction would have limited the ability to identify shoreline dislocations and complex patterns of displacement.

Glacio-isostatic processes

Previous studies have identified spatial variations in the pattern of glacio-isostatic uplift in Scotland. Thus Haggart (1989) identified differential uplift patterns from RSL graphs, implying changes in the centre of maximum uplift. Previous shoreline studies have echoed such change: Gray (1983) suggested that an eastward shift of the centre of uplift in Scotland may have occurred between the Main Lateglacial Shoreline and the Menteith Shoreline and questioned the assumption that isostatic rebound proceeds by simple continuous tilting at a smoothly decelerating rate. Smith *et al.* (2006) suggested that the centre of uplift may have moved as successive Holocene shorelines were reached. Smith *et al.* (2012) showed an eastward movement of the centre of uplift between the Menteith and Blairdrummond shorelines, using Gaussian quadratic trend surface analysis, although this observation was subsumed in their subsequent common centre and axis models for Holocene shorelines.

One possible cause of changes in the uplift pattern may be in temporal and spatial differences in ice-loading. As the ice sheets in the Northern Hemisphere developed, ice, initially accumulating in mountainous areas, ultimately covered large lowland areas (Clark *et al.* 2021). Likewise, during ice wastage, the areas of maximum ice thickness reverted to the western centres of maximum precipitation rather than the central ice dome associated with the most extensive ice sheet. Hence the locus of maximum thickness and load moved over time. Ice-sheet growth and decay would therefore result in spatial changes in crustal load, as has been suggested from studies of changes in uplift determined from shoreline gradients associated with the Laurentide Ice Sheet (Andrews & Barnett 1972). In Scotland, comparisons between models of the thickness of the Late Devensian ice sheet (Fretwell *et al.* 2007) and the extent of the Loch Lomond Readvance disclose considerable differences in load distribution and thickness, but as yet no detailed comparisons between changes in the locus of maximum ice-load and their glacio-isostatic effects have been made.

Here, we use the results of the comprehensive BRITICE and BRITICE-CHRONO project (Clark *et al.* 2012, 2018, 2021), which provide more detailed evidence of ice thickness following the pioneering work of Fretwell *et al.* (2007). The BRITICE research shows that prior to the wastage of the Late Devensian ice sheet, the greatest ice-load was centred west of the main Scottish highland mass, with considerable thicknesses of ice located over the deep valleys and sea-lochs that are cut many hundreds of metres below the adjacent mountain surfaces (ignoring the water filled component, where roughly equivalent density ice would replace water, and vice versa; Clark *et al.* 2012: fig. 21). This

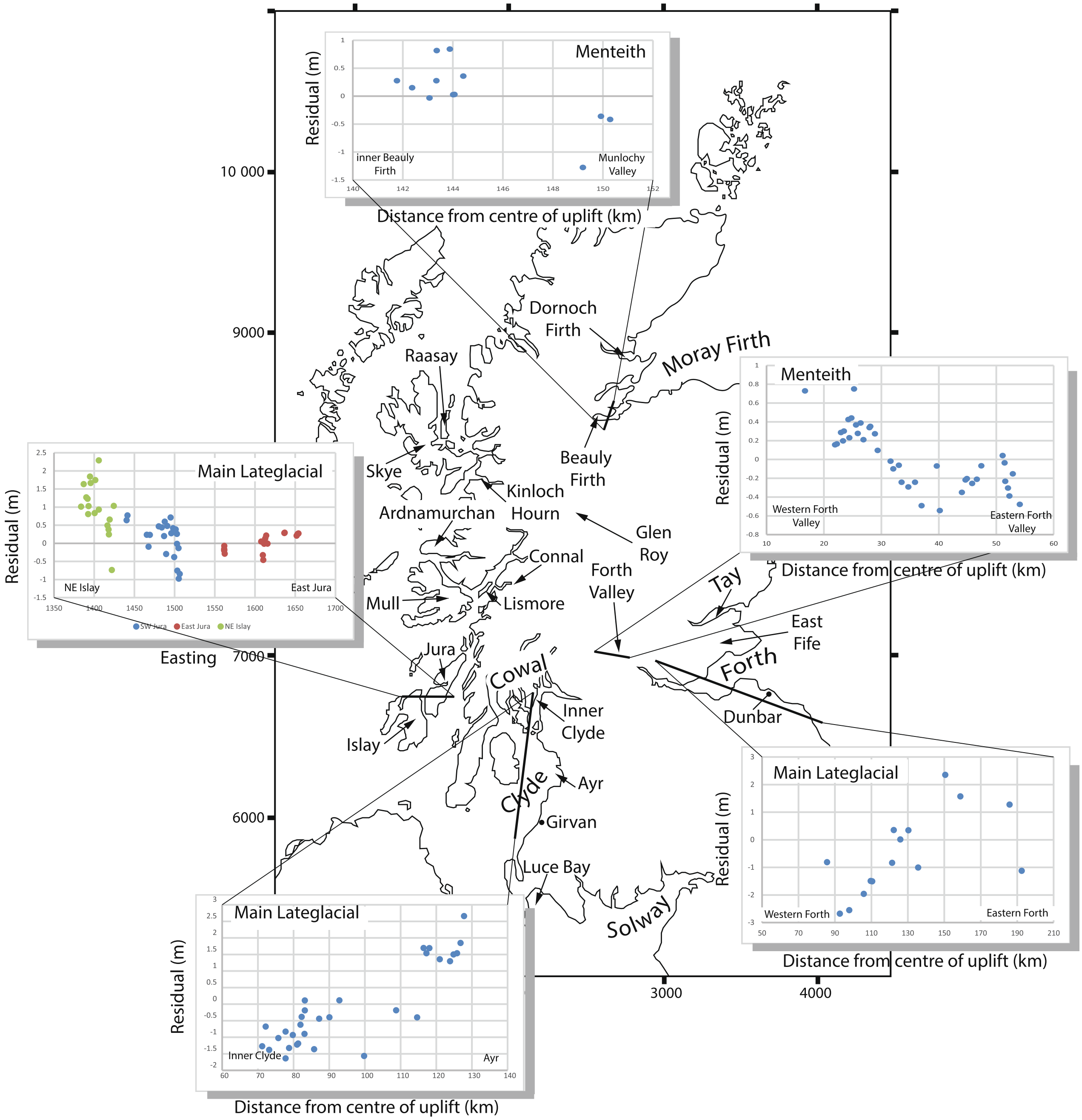

Fig. 6. Location of sites outlined in the residual analysis section and cross-sections along selected transects of residuals (m) associated with the Gaussian trend surface analysis of pRSL index points. Positive residuals indicate that the palaeo-RSL index point is higher than proposed by the Gaussian model. Negative residuals indicate the pRSL index point is lower than proposed by the Gaussian model.

could account for the location of the zone of maximum displacement for the Main Lateglacial Shoreline (Fig. 4), which is west of the central ice dome associated with the maximum of glaciation (Clark *et al.* 2021).

The Holocene shorelines developed after the Younger Dryas glaciation (Loch Lomond Readvance (LLR)), which followed a period with little or no ice cover (Bickerdike *et al.* 2018). The glacial load imposed on the landscape during this glacial event was also focused on western Highland Scotland, with a dominant load over the Rannoch Moor and the outlet valleys, especially the upper valley of Loch Lomond (Golledge *et al.* 2008: figs 11, 12). In these valleys up to 750 m of ice thickness existed above the lake level. With this scenario, it is possible that the southward movement of the Holocene centres of uplift is a function of the shifting ice

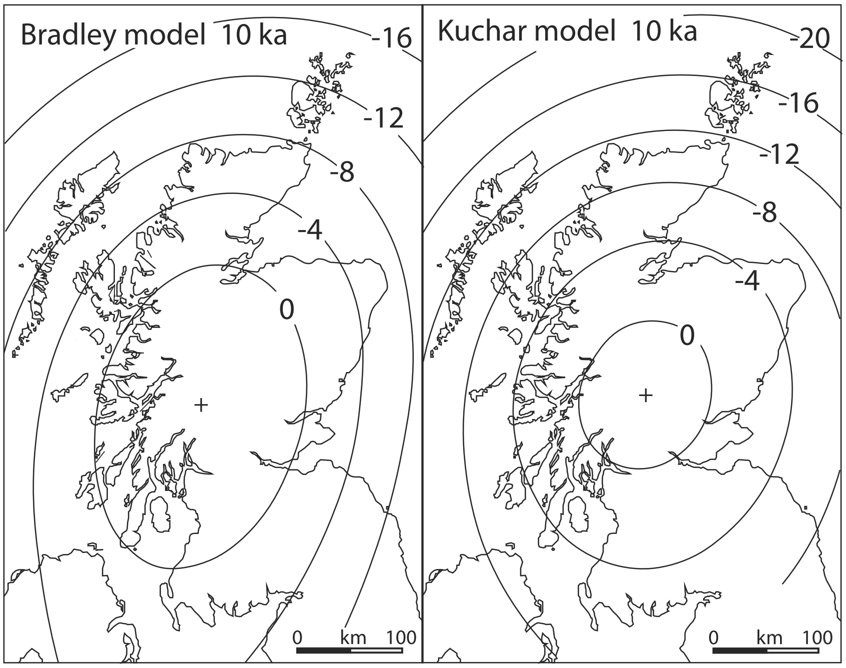

Fig. 7. Bradley *et al.* (2011) and Kuchar *et al.* (2012) GIA models for 10 ka BP modified from Smith *et al.* (2019): fig. 23.

thicknesses between the end of the Late Devensian ice sheet and the maximum ice cover during the LLR.

Hydro-isostatic loading

With a water load restricted to a ~60-m increase following ice wastage, this process is unlikely to have a major effect on the pattern of crustal rebound. However, it is worth noting that the amount of water load would vary, with the maximum values occurring in the deep sea-lochs and the western seas, with no direct effect over the land and less than 60 m over the shallow estuaries. In this case, the most acute water load, relative to the glacier displacement, would be around western coasts, and it is argued that this could be a factor in diverting the centre of the Wigtown Shoreline isobase towards the south and west (Fig. 4).

Neotectonics

It is generally agreed that an ice-load during glaciation imposes stress upon the asthenosphere and that during deglaciation the release of stress may result in the reactivation of pre-existing faults or even the development of new faults. However, the distribution of faults that were active during and following deglaciation depends upon the tectonic background of an area, the geomorphology, the ice-load and the fault geometry (Steffen *et al.* 2014), and faulting may reflect complex variations in conditions both spatially and temporally (Stewart *et al.* 2000). Research in this field has developed rapidly in recent years, with in particular the advent of LIDAR (Ojala *et al.* 2019) and the development of modelling approaches (Steffen *et al.* 2020). Recently, a GIS data inventory of confirmed and proposed glacially induced faults has been developed. In general terms, it appears likely from the studies reported that fault reactivation and development may be marked during and after deglaciation, and are likely to decrease thereafter, but that the distribution of faulting will reflect the many and diverse conditions mentioned above.

In Scotland, the more seismically active areas lie in the broad area of the former Younger Dryas ice cap (Musson 1996, 2007), and the largest recent fault dislocations have been reported from this area. Thus, on Raasay, Smith *et al.* (2009, 2021) measured dislocation at the Beinn na Leac Fault of at least 7.12 m during the Younger Dryas, while in Glen Roy, Chen (2012) and Palmer and Lowe (2017) measured up to 5.12 m displacement also during the Younger Dryas. Ballantyne *et al.* (2014) have maintained that the retreat of the last ice sheet was followed by a period of enhanced rock slope failure due to glacial unloading and uplift-driven seismicity. They infer that this activity decreased as the effect of the ice-load diminished.

Given the widespread evidence for crustal uplift in Scotland during and following ice-sheet removal, it is unsurprising that the Main Lateglacial Shoreline exhibits dislocation, and on Mull evidence of fault dislocation, probably reactivation, has been summarized by Firth and Stewart (2000) and Firth in Smith

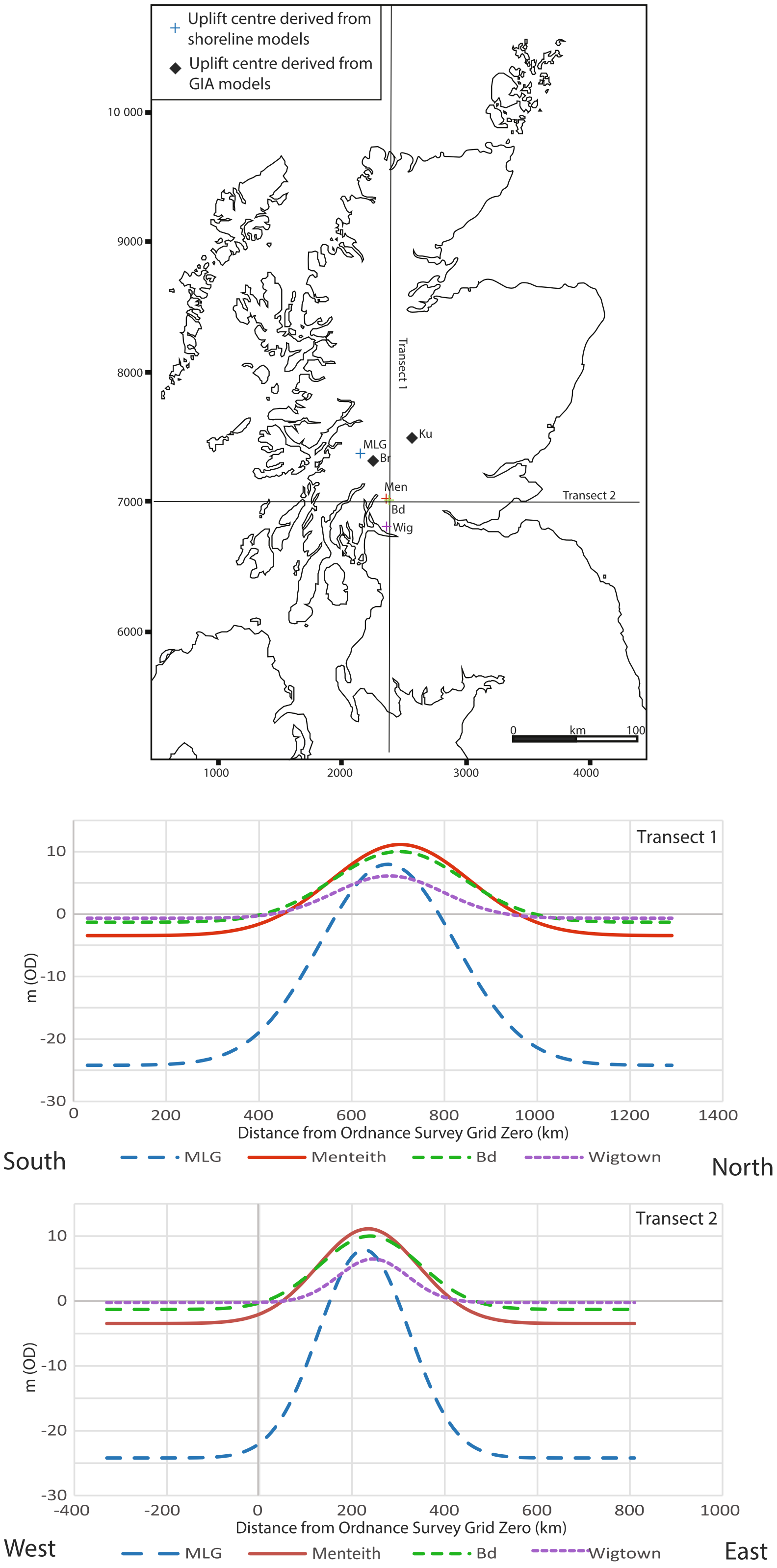

Fig. 8. Location of the centre of the displaced pRSL derived from Gaussian quadratic trend surface shoreline-based models (MLG = Main Lateglacial; Men = Menteith; Bd = Blairdrummond; Wig = Wigtown) and GIA models (Br = Bradley *et al.* 2011; Ku = Kuchar *et al.* 2012) and cross-sections of the pRSL through the Gaussian quadratic trend surface models.

et al. (2019). Such dislocation has been estimated at up to 2.7 m at Port Domain, Mull. In the Forth valley, Sissons (1972) identified dislocations of up to 1.5 m in Holocene faulting across the Abbey Craig or possibly Ochil faults.

In the Clyde area, evidence for neotectonic activity is however at present inconclusive. Of particular interest is the possible effect of movement along the Highland Boundary Fault, which runs across Loch Lomond and southwestward across the coast east of Helensburgh and the Isle of Bute. Opinions vary concerning the nature and extent of movement at the fault, for which seismicity is known around the town of Comrie, in Perthshire and Aberfoyle, in Stirlingshire. However, whilst Ottemöller and Thomas (2007) have mentioned postglacial isostatic rebound as a possible cause, implying some movement along shorelines, others have questioned the tectonic significance of the fault (Tanner 2008), and the survey undertaken in this work did not disclose any change in shoreline altitudes across the fault (see Helensburgh (Drumfork) – Helensburgh (Arden), Fig. 2). To the south of the Highland Boundary Fault, the Ochil Fault, where seismicity has also been recorded (Dollar 1950) also crosses raised shorelines at Cardross, east of Helensburgh, but there is no apparent evidence of dislocation revealed by shoreline elevations in the area where this fault crosses the Clyde estuary.

The effect of fault dislocation on patterns of glacio-isostatic uplift in Scotland is difficult to determine, both in the Clyde area and more widely, given that most studies appear to have concentrated on local effects. Sissons (1972) remarked that episodes of differential movement of shorelines at faults may have occurred episodically as glacio-isostatic tilting occurred. Indeed, Sissons (1972) observed that two shorelines, both dislocated by the same fault movement, might later have been uplifted at the same rate, as glacio-isostatic tilting continued. The observations of Sissons implied that an area of glacio-isostatic uplift may comprise areas of little or no differential movement that, taken together, form the uplifted surface regionally. Sissons concluded that raised shorelines in areas of glacial rebound may not have uniform or gradually changing gradients. If correct, these observations emphasize that variations in the pattern of uplift across the Scottish glacio-isostatic area may occur both spatially and temporally, perhaps affecting patterns of glacio-isostatic uplift.

Conclusions

The results of detailed field study of raised marine shoreline altitudes in the northern Clyde area and around Loch Lomond, in western central Scotland are described. Along with the results of similar work from elsewhere in Scotland, these data are analysed using Gaussian trend surface analysis in order to determine the patterns of shoreline displacement and uplift following Late Devensian ice wastage, renewed Younger Dryas glaciation and final ice wastage. The results relate to shorelines that extend through the Lateglacial and Holocene and show that:

- The southwestern Highlands and Loch Lomond are close to the centre of glacio-isostatic uplift of the British–Irish Ice Sheet (BIIS).
- The shoreline-based isobase models place the zone of maximum uplift for the Main Lateglacial Shoreline to the NNW of Loch Lomond, in close agreement with the GIA model of Bradley (in Smith *et al.* 2019).
- The shoreline-based isobase models for the Holocene-age Menteith, Blairdrummond and Wigtown shorelines indicate that the zone of maximum uplift for these shorelines is SSE of the Main Lateglacial displacement, and that these zones move progressively south over time.
- The factors responsible for these changes are discussed, in terms of glacio-isostasy, hydro-isostasy and neotectonics.
- The locus of ice thickness during the waning stage of the Late Devensian glaciation on the Scottish Highlands can provide an explanation for the location of the Main Lateglacial centre of deformation.
- Maximum thicknesses of ice on Rannoch Moor and the deep outlet valleys may be responsible for the diversion of the centre of deformation, southwards to the area of Loch Lomond.
- Water loading by the maximum effects of eustatic sea-level rise in the sea-lochs of western Scotland is tentatively suggested as a cause of the migration of the Late Holocene Wigtown Shoreline further south to the region of the Vale of Leven.
- Although there is substantial evidence for neotectonic activity in Scotland since the last deglaciation, there is no direct evidence for neotectonic activity in the inner Clyde and Loch Lomond regions. However, examination of the residual values from the trend surfaces generated by this research will point to areas worthy of further investigation.

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Supporting Information

Additional Supporting Information to this article is available at http://www.boreas.dk.

Table S1. Scottish shoreline fragment data.

Table S2. Gaussian Quadratic Trend Surface program.

Data S1. Sensitivity analysis of Gaussian trend surface models.