Locating the Centre of Holocene Glacio-isostatic Uplift in Scotland

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Introduction

The coastal landscapes of Scotland offer widespread evidence of glacio-isostatic uplift. The extensive morphological evidence for displaced marine levels over much of the mainland has long been recognised as providing an opportunity for the detailed study of the crustal response to glacial unloading. In early studies isobase patterns were drawn by eye and based on measurements of raised marine features. (e.g. Sissons 1967, 1976) In recent years, models have consisted of either statistically defined isobase patterns (Figure 1) (Smith *et al.*, 2000, 2006) or of isobase patterns defined by rheologically based glacial isostatic adjustment models (Figure 2) (Lambeck 1993, 1995). In all cases, a single centre of uplift has been identified, although the location of that centre varies according to the model and the time period involved.

This paper seeks to define the location of the centre of glacio-isostatic uplift in Scotland during the Holocene, using shoreline-based evidence. Previous statistical models have been based upon altitude measurements taken from the extensive raised estuarine sediments of the carselands , but have overlooked the widespread evidence of the narrow sand terraces, which widely occupy the more exposed coastlines of mainland Scotland. New data on these terraces from an area around the Clyde estuary-Ayrshire coast and the offshore island of Bute is combined with data from Scottish carselands to determine the centre of uplift more closely than has been identified hitherto.

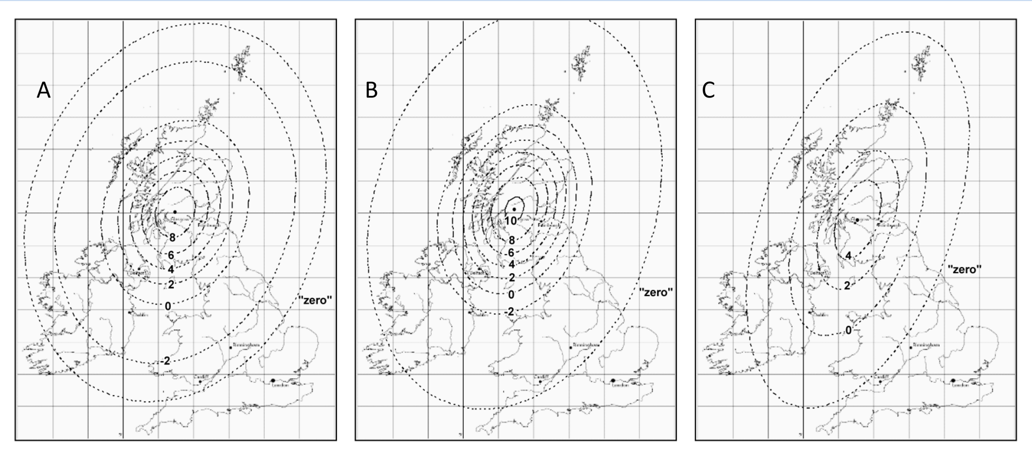

Figure 1. Isobase patternss derived from Gaussian trend surfaces for the A- Blairdrummond B- Main Postglacial C- Wigtown shorelines based on altitudes from raised marine estuarine terrace fragments (after Smith *et al.* 2006).

Figure 2. Isobase patterns derived from rheologically based glacial isostatic adjustment models (after Lambeck 1995)

The Data

The data analysed consist of altitude measurements taken at 50 metre intervals along the inner margin of raised marine terraces composed of sand and locally fine gravel along coastlines extending from the mouth of the Clyde through the Gareloch and Loch Long, to the Ayrshire coast as far south as Troon, and the island of Bute. This data are initially combined with altitude measurements taken along the carseland margin in the Forth lowland and subsequently with carselands in other areas of Scotland

It is recognised that tidal levels around Scotland vary and as a consequence all the altitudes have been corrected in relation to local Mean High Water Spring Tides (MHWS – Table 1). The altitudes of each terrace fragment were therefore reduced by the local MHWS value to ensure that tidal variations were removed. Whilst it is recognised that tidal variations may have been different in the past (e.g. Shennan *et al*. 2000) such changes are less pronounced than modern tidal variations.

Tidal station	MHWS	MLWS	MHWN	MLWN
Alloa	3.30	-2.2	1.9	n/a
Rosneath	1.78	1.08	-0.62	-1.59
Helensburgh	1.78	1.18	-0.62	-1.59
Port Glasgow	1.98	1.28	-0.62	-1.59
Greenock	1.78	1.18	-0.62	-1.59
Ardrossan	1.58	0.98	-0.52	-1.22
Rothesay Bay	1.98	1.38	-0.42	-1.12
Troon	1.58	0.98	-0.52	-1.22

Table 1: Tidal levels (in metres, OD) for the stations used in this work (Admiralty Tide Tables, 1995)

It is also recognised that the altitude of modern coastal landforms varies depending on the feature (e.g. mudflat, sandflat, saltmarsh, shingle ridge) and wave regime (exposure). Detailed measurements on modern coastal features (Table 2) indicate that sandflats occur at higher altitudes and demonstrate greater variation than modern mudflats. As a consequence altitudes of the raised marine terrace fragments have been corrected for landform variations and each terrace has been adjusted (raised) to MHWST based on the variation between modern features and the current tidal cycle.

Location	Maximum	Minimum	Mean (of all measurements)	No. of measurements
Forth estuary	-1.1	-1.76	-1.4	87
Ardgowan, Wemyss	-0.77	-1.28	-1.0	5
Ettrick Bay, Bute	-0.54	-1.72	-0.88	11
Ardrossan - Troon	-0.19	-0.78	-0.16	36
Summary, carselands	-1.1	-1.76	-1.4	87
Summary, sand terraces	-0.19	-1.72	-0.39	54

Table 2. Altitudes (in metres, local MHWS) taken at 50m intervals along the inner margin of present mudflats and inner margin of present sandflats

Data correlation

In all areas, four distinct terraces levels and four carseland surfaces can be identified. Generally, these lie in staircases, one above the next, so can easily be separated. However there are some locations where only two or three are visible, thus presenting problems of correlation. In the Forth carselands, correlation is possible through the continuity of the features, thus for example, a widespread surface may in places lie above or below more fragmentary features, and through radiocarbon dating of peat resting upon surfaces. In the Clyde estuary and surrounding areas, correlation is more problematic, but here again the continuity of the better preserved terraces enables correlation of more fragmentary ones. Cullingford and Smith (1980) developed a "staircase constraint", which has been used here to correlate uncertain terraces. However, only the upper three terraces/surfaces have been used in the analyses below, since the data for the lowest feature/s is only sporadically distributed.

Data analysis

In the initial analysis only the new data from the Clyde-Loch Lomond area were analysed. The fragments were correlated by using the staircase constraint and surfaces associated with the three shorelines of Smith et al. (2006), the Main Postglacial, Blairdummond and Wigtown shorelines were identified. Linear isobases derived from trend surface analysis were produced for each shoreline. The number of altitude measurements for each shoreline and the statistical significance of the surface are given in Table 3.

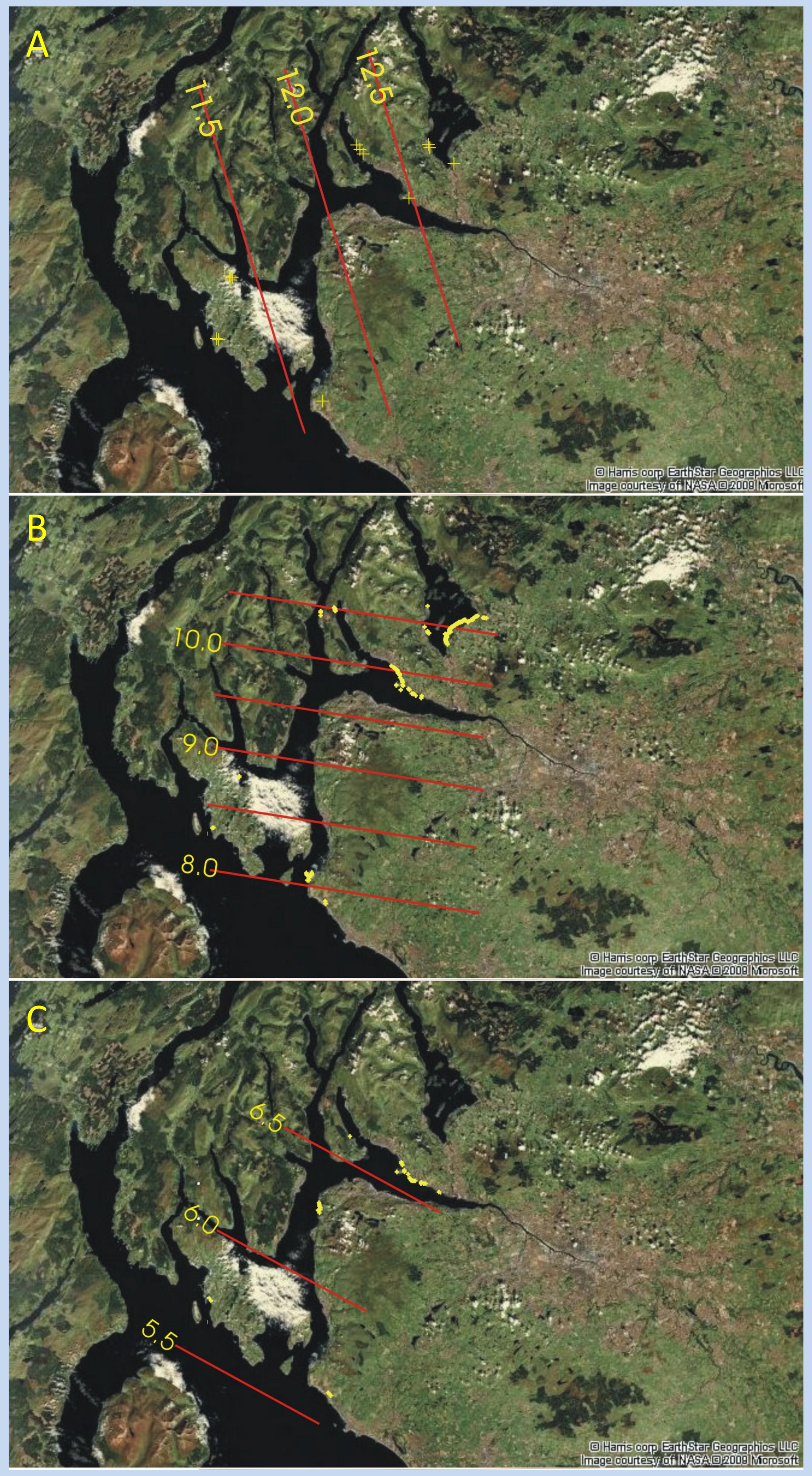

Figure 3: Linear isobases based on the Clyde-Loch Lomond shoreline data A – Main Postglacial B- Blairdrummond C- Wigtown

The three isobase maps indicate that the shorelines decline in altitude towards the south and west. The Main Postglacial Shoreline (Fig 3A) is based on relatively few data points and as a consequence is of limited value. Similarly the isobases associated with the Wigtown Shoreline display a low correlation and thus must be considered of limited value. In contrast the isobases associated with the Blairdrummond Shoreline are statistically significant and provide a good representation of the altitude variation of this feature.

Shoreline	No. of values (Clyde)	R^2 of linear trend surface
Main Postglacial	44	68.26%
Blairdrummond -	468	59.31%
Wigtown	162	23.40%

Table 3: Number of shoreline altitudes associated with each Clyde-Loch Lomond shoreline and the statistical significance of each linear trend surface.

The data for the Blairdrummond Shoreline for the Clyde-Loch Lomond region were then combined with shoreline data from the Forth (Fig. 4) to better define the centre of isostatic uplift. The second order (quadratic) trend surface associated with the combined data suggests that the centre of uplift lies north of Loch Lomond data set. It also suggests that the Blairdrummond shoreline gradient is steeper in the Forth than in the Clyde-Loch Lomond area.

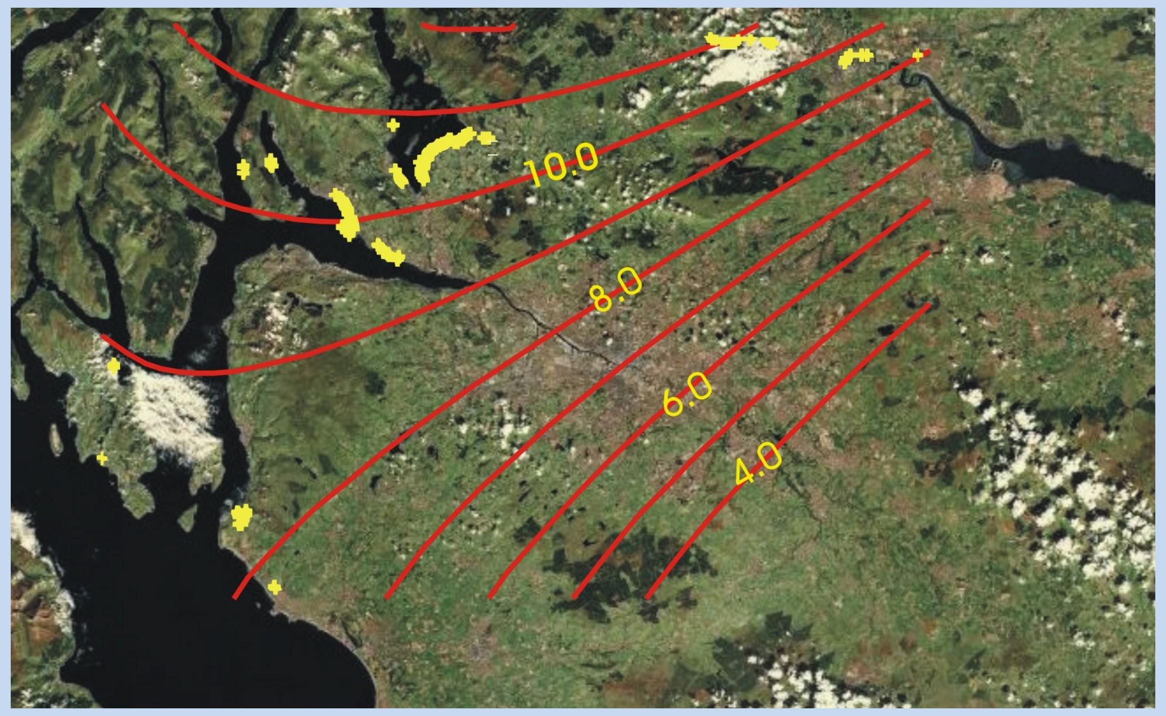

Figure 4: Quadratic trend surface for the Blairdrummond Shoreline based on Clyde-Loch Lomond – Forth shoreline data

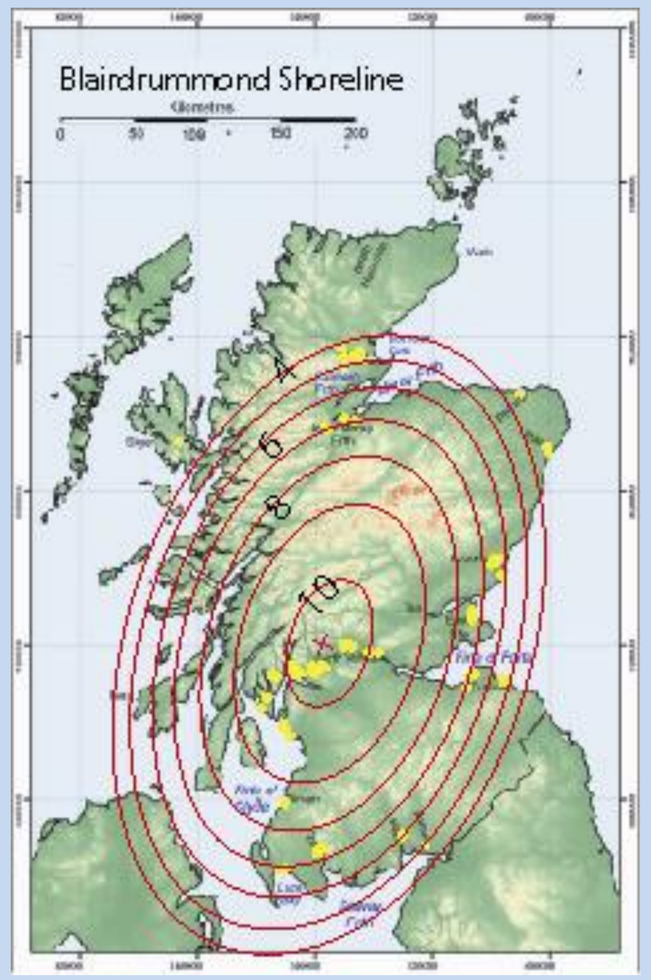

Figure 5: Quadratic trend surface for the Blairdrummond Shoreline based on raised sandflat and mudflat terraces from Scotland.

Smith (2005) and Smith *et al.* (2006) have indicated that the Blairdrummond Shoreline (5800-4500 cal yrs BP) is the best feature to use to determine uplift isobases for Scotland since it is associated with the largest number of shoreline fragments which also have the widest distribution. The Clyde-Loch Lomond data enhance the distribution of this shoreline and trend surface analysis was used to produce a second order (quadratic) isobase map (Fig. 5). The map suggests the centre of uplift lies near Aberfoyle at the head of the Forth valley, just east of Loch Lomond.

Discussion

It is recognised that the quadratic isobase map (Fig. 5) is a simplification of the pattern of uplift particularly since the technique evens out known shoreline dislocations/irregularities (Firth & Stewart, 2000). The analysis has also produced a simple dome and it is recognised that a gaussian trend surface would be more appropriate if a broader area is considered. The simple trend surface however is an effective method to identify the statistical centre of uplift based on the data available.

It is noteworthy that the isobase map generated by incorporating sandflat data from the inner Clyde-Loch Lomond area is very similar to the map derived from raised estuarine flats alone (e.g. Fig. 1 A). It suggests that the quadratic map is representative of the uplift isobases and not just the product of the distribution of the data set.

The analysis has also indicated that shoreline altitudes derived from contrasting raised marine features (e.g. the inner marines of mudflats and sandflats) can be combined to identify national isobase patterns. Additional data from the Cowal Peninsula, Jura, Islay and the Firth of Lorn are available to further enhance the model. The improved distribution of data may also make it possible to produce more detailed isobase maps which model the actual altitude variations, including dislocations.

The centre and generalised patterns of uplift derived from the shoreline data are very similar to the current pattern of uplift reported by Bradley *et* al. (2009) from rheologically based glacio isostatic adjustment (GIA) models (Fig. 6 A). The zone of greatest uplift extends from the inner Clyde north-eastwards to Spean Valley with the centre near Crainlarich, just north of Loch Lomond. In contrast the model based on GPS monitoring sites alone (Fig. 6 B) suggests the area of maximum uplift is located at the head of the inner Clyde with a centre just east of Largs. Since all three shorelines from the Clyde – Loch Lomond area decline in altitude towards the south and west it suggests that the patterns derived on the GPS monitoring sites alone places the centre of uplift too far south.

The correspondence of uplift patterns between the updated GIA models and the shoreline data is encouraging and it suggests that the shoreline data may hold the key to produce the more detailed local/regional uplift maps required by coastal engineers.

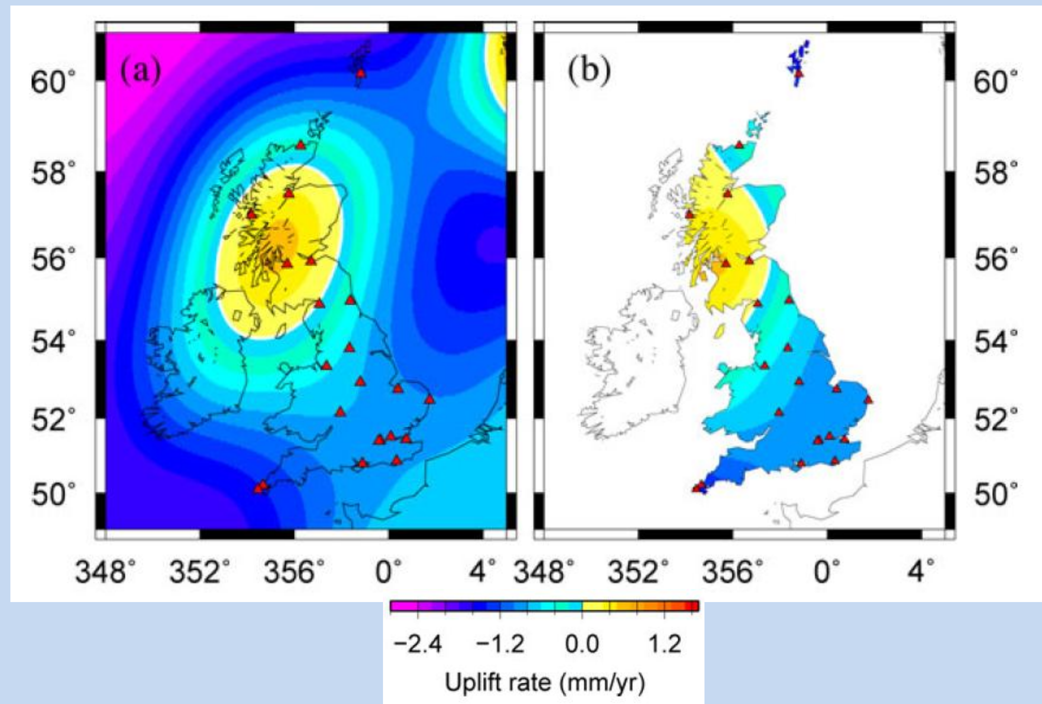

Figure 6: The current pattern of crustal uplift derived from A- rheologically based glacial isostatic adjustment (GIA)models; B- GIA models but uplift estimates restricted to GPS station sites.(Bradley *et al*. 2009).

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