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The palaeogeography of Northwest Europe during the last 20,000 years

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Abstract

Since the last glacial period, large vertical changes in the height of sea level relative to the land surface have led to considerable horizontal shifts in the position of coastlines around Northwest Europe. Indeed, for much of the last 20,000 years, extensive areas of the present-day shelf seabed were sub-aerially exposed due (primarily) to the glacial eustatic lowering of sea level. Accurate maps depicting these palaeogeographic changes are of great value to a wide spectrum of researchers including (*inter alia*) archaeologists, marine geomorphologists, climate scientists, biogeographers and palaeobotanists, although a lack of empirical sea level data has often hindered efforts to produce reliable palaeogeographic reconstructions. However, the processes which bring about change in relative sea level can be successfully simulated by computer models that describe the response of the solid Earth to the loading and unloading of glacial ice ('glacial rebound models'). In addition to simulating relative sea-levels, the output from these models can be combined with modern day bathymetric and topographic data to produce first-order palaeogeographic reconstructions. For this publication and associated map, numerical outputs from a recently published glacial rebound model are used to produce a series of palaeogeographic maps of Northwest Europe since the Last Glacial Termination. These maps, developed using GIS tools and presented here individually at a scale of 1:20,000,000, emphasize that for much of the period from 20,000 years ago to the present, large areas of the Northwest European shelf, now covered by sea, were dry land. However, they also suggest that whilst Britain maintained a 'land-bridge' connection with the continent until well into the Holocene interglacial (which began 11,700 years ago), any connection between Britain and Ireland would have been low-lying, probably ephemeral and unlikely to have existed after circa 15,000 years ago.

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1. Introduction

Detailed palaeogeographic maps, which accurately depict millennial-scale changes in the former position of the coastline, are of great value to a number of researchers operating within a variety of different academic fields. For example, the past few years have witnessed an increasing appreciation of the archaeological significance of the Continental Shelves, their importance to furthering knowledge of early prehistoric settlement and the potential of these areas to both hold and preserve archaeological information that might be rare or absent within contemporary terrestrial contexts (Bailey et al., 2010). This is especially apparent on the seabed surrounding Britain and Ireland (Figure 1) where a number of researchers and research groups have been focusing attention on the identification and mapping of submerged archaeological landscapes (e.g., Momber, 2000; Submerged Landscapes Archaeological Network, 2007; Gaffney et al., 2007; Dix et al., 2008). Yet to understand the potential distribution of submerged cultural landscapes, a firm understanding of past palaeogeographic changes is vital. In this region, the insularity of Ireland and the possible emergence of a land bridge during the Last Glacial Termination with Britain have also been of special interest (the Last Glacial Termination began in the Northern Hemisphere about 20,000 years ago and was essentially complete by 7000 years ago (Denton et al., 2010)). For some time discussion has been prevalent in Irish Quaternary literature regarding the potential location and timing of a land-bridge (e.g., Devoy, 1983; 1985; 1995; Sleeman et al., 1986; Davenport et al., 2008) with debates driven in part by the desire to understand the recolonisation of Ireland by plants and animals since the last glacial period (e.g., Mitchell, 1972; 1986). Others have required reliable reconstructions of palaeogeography to inform investigations into palaeo tidal regimes and past morphodynamic relationships at the seabed (e.g., Cooper et al., 2008; Scourse et al., 2009).

Changes in sea level relative to the land surface - 'relative sea-level' (RSL) - result from the interplay between vertical changes in both land and sea level. A detailed appreciation of spatial and temporal changes in RSL is clearly of critical importance to the successful mapping of palaeogeographies. Over the past ca. 40 years, a very large corpus of empirical sea level observations has been collected from across Britain and (albeit to a much lesser extent) Ireland, and these field data have enabled a series of local relative sea level histories to be reconstructed for the region (see Shennan et al. (2006) and Brooks and Edwards (2006) for details). However, despite this, our understanding of sea level change in this region over the past 20,000 years is far from complete and large spatial and temporal gaps in the empirical dataset remain. For example, the vast majority of sea level data from the region is of Holocene age (last 11,700 years) whilst the earliest (pre Holocene) records are strongly biased towards northern Britain. It is also the case that almost the entire body of dated field evidence for past changes in sea level is derived from shore based (mainly intertidal) sediments and very little accurate field data exists from the offshore continental shelf. Because of this, comparatively

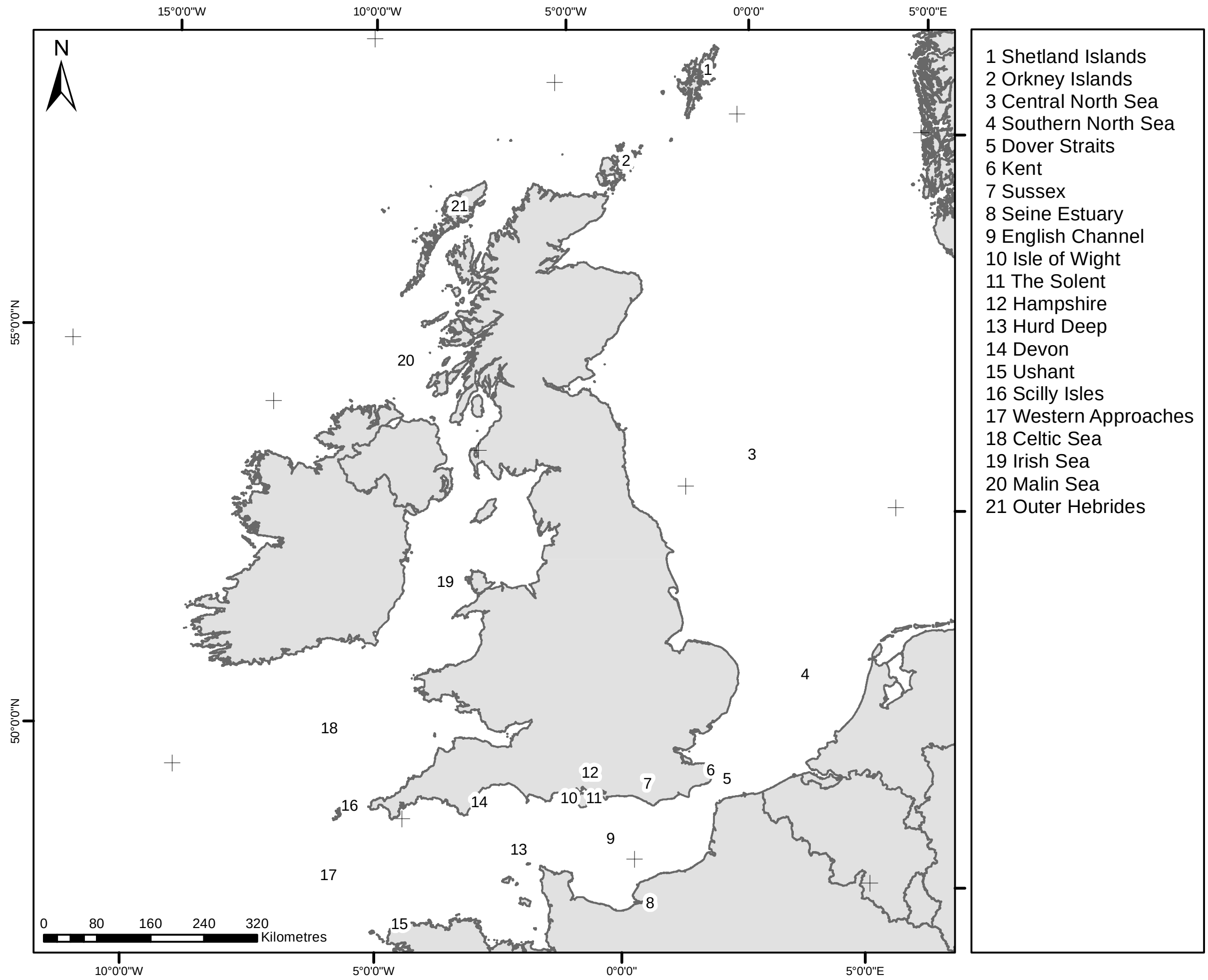

Figure 1. Locations referred to in the text.

little is known about the relative sea level histories of very large areas of the Northwest European continental shelf.

As a result of these large data gaps, it is not possible to develop a detailed picture of regional scale changes in palaeogeography solely from empirical records of sea level change. However, in the absence of field data, Glacial Isostatic Adjustment (GIA) models may be used to help address the gaps in the record, by providing simulations of past relative sea level change since the last glacial maximum (LGM). These mathematical models consist of three key elements: (1) an ice loading model (to define the global distribution of grounded ice thickness over time), (2) an Earth model (to simulate deformation of the solid Earth to surface loading), and (3) an algorithm to compute the redistribution of ocean mass (Bradley et al., 2009). In as far as is possible, the Earth model and ice model are constrained using a combination of seismic, geological and glaciological constraints. However, the available field evidence is not sufficient to permit a definitive representation of either GIA model element to be established. This is particularly the case with the ice model where gaps remain in our understanding of the spatial and temporal evolution of the former ice sheets at the local, regional and global scale. As such, the GIA Model simulations of RSL may also be compared with observational records of past sea-level to further refine both the Earth and particularly ice models, within the boundaries established by the available field evidence.

A number of publications detailing modelled observations of the GIA from the British Isles are available and several of these include model reconstructions of palaeogeography (e.g., Lambeck, 1996; Shennan et al., 2000; Peltier et al., 2002). However, the process of model development is an iterative one and continued advances in knowledge regarding (amongst other things) the extent, thickness, and deglacial history of the former British and Irish Ice Sheet (BIIS) as well as the Holocene glacio-eustatic term (Shennan et al., 2006; Brooks et al., 2008; Bradley et al., 2011), have permitted significant further improvements to be made. These new models also account for the underlying topography beneath the former ice sheet and thus offer a far more realistic assessment of the surface loading by ice. However, whilst RSL simulations from this new generation of models have previously been used to investigate palaeogeographic changes in the Irish Sea region (Edwards et al., 2008), no attempt has yet been made to deliver a series of reconstructions for the Northwest European region as a whole. In this investigation, we address this by combining model RSL simulations generated by the Bradley et al. (2011) GIA model with a modern day topographic/bathymetric grid covering Northwest Europe to deliver a series of palaeogeographic maps at various time intervals over the past 20,000 years.

Within this paper, all ages are expressed in calendar years before present unless otherwise stated.

2. Methods

The reconstruction of palaeogeography may be achieved through solving equation 1: (where the locus of $h(t) = 0$ determines the location of the shoreline at time t):

$$h(t) = h(t_0) - \Delta\zeta_{rsl}(t) + \delta h \tag{1}$$

where $h(t)$ equals altitude / depth of a point at time t, $h(t_0)$ represents contemporary altitude / depth and $\Delta\zeta_{rsl}$ is sea-level change since time t (δh is a correction for any erosion or sedimentation that may have occurred in the interval $t - t_0$ although in reality, this is almost impossible to define accurately) (Lambeck, 2004).

A digital surface elevation layer for present day Northwest Europe ($h(t_0)$ in equation 1) has been generated by combining separately gridded topography and bathymetric datasets. The principal topographic data source used for mapping was the Ordnance Survey 50 m digital elevation model (DEM), whilst digital bathymetric data made available by the United Kingdom Hydrographic Office (UKHO) was combined with the most recent (2008) General Bathymetric Chart of the Oceans (GEBCO) gridded dataset (http://www.gebco.net/) to provide a bathymetric map for the Northwest European shelf. The GEBCO dataset is a 30 arc-second grid of global elevations and is a continuous terrain model for ocean and land. The grid was generated by combining quality-controlled ship depth soundings with interpolation between sounding points guided by satellite-derived gravity data. Broadly, the UKHO dataset was selected for coastal waters around Britain where localised inaccuracies were clearly apparent in the GEBCO grid.

Values for $\Delta\zeta_{rsl}$ were derived from the GIA model presented in Bradley et al. (2011). This study brings together elements from a number of recent papers on the GIA in Great Britain and Ireland (Milne et al., 2006; Shennan et al., 2006; Brooks et al., 2008; Bradley et al., 2009), and the best-fitting model presented by Bradley and co-workers can be considered as the culmination of these previous efforts in terms of seeking a GIA model that is compatible with a variety of observations from Great Britain and Ireland. The space-time evolution of the BIIS presented in Bradley et al. (2011) is illustrated in the main accompanying map. Overall advance and retreat phases are based on the findings of Sejrup et al. (1994; 2005), with extensive ice accumulation signalling the end of the Alesund Interstadial at ca. 33,000 years BP and leading to coalescence of the BIIS and Fennoscandian ice sheet. This configuration is interrupted by marked ice sheet retreat approximately 25,000 years BP before rapid expansion of the BIIS around the time of the LGM. Deglaciation begins at 21,000 years BP, with the removal of ice from both Ireland and the UK largely complete by 15,000 years BP (e.g., Ballantyne, 1997).

The close match between the model simulations and observational evidence provides confidence in the validity of the GIA modelling presented in Bradley et al. (2011), although some authors highlight apparent misfits between field data and model simulations of RSL from the Late Glacial period (see McCabe (1997); Lambeck and Purcell (2001); Edwards et al. (2008); McCabe (2008)). However, in the absence of reliable empirical records of relative sea level stretching back to the LGM, GIA models represent the only realistic way of reconstructing RSL positions across formerly exposed Continental Shelves (Dix et al., 2008).

Both the model output and present day topography and bathymetry data were available as a series of xyz coordinates and surfaces were created from these point files. All of the interpolation was undertaken in ArcGIS 9.3 using 3D Analyst and Spatial Analyst extensions. A 2-step interpolation process was undertaken to provide consistent surfaces for comparison. Step 1 interpolated the points into a Triangular Irregular Network (TIN). A TIN surface joined the elevations of 3 adjacent points into a continuous triangular structure, applying a linear interpolation between the elevations of each set of 3 adjacent points. One of the advantages of this interpolation method was that it used a simple linear algorithm to derive unknown elevations and could not introduce data that was outside of the range of the input points. A TIN also preserved the precise elevation of each sample point in the final surface.

It was unsuitable to compare TIN surfaces directly as the data structure of each surface was dependent on the location and spacing of the input points. This problem was overcome in step 2 of the interpolation process which converted each TIN into a grid surface by calculating the average (mean) elevation of the TIN within each square grid cell. Each grid was created with the same cell size to enable direct comparisons to be made between the datasets. For the present study a cell size of 0.09 degrees was chosen to maintain a sufficient level of detail within the palaeogeographic maps. Figure 2 shows the gridded surface interpolated from the glacial rebound model simulations of RSL elevation at 20,000 years BP.

Within the palaeogeographic reconstructions, no attempt was made to correct for changes in bathymetry that may have occurred due to erosion or sedimentation over the past 20,000 years (δh in equation 1). This is largely because it remains almost impossible to account for such changes at anything other than the local scale. However, the approach adopted here is considered adequate for the task at hand which is aimed at identifying regional (as opposed to local) scale changes in palaeogeography.

Because the GIA model employed here is calibrated against RSL data, the lack of pre-LGM (i.e. before circa 26,000 years ago) data prevents its extension back into the pre-LGM period. Furthermore, the simulation of RSL change prior to the LGM is also hampered by uncertainties in the lateral extent and thickness of the BIIS (which will control local-regional-scale glacio-isostatic movements), as well as the volume of the large mid-high latitude ice sheets (which is the main factor in controlling global sea surface change). The estimations of RSL change from this time period may be evaluated accordingly.

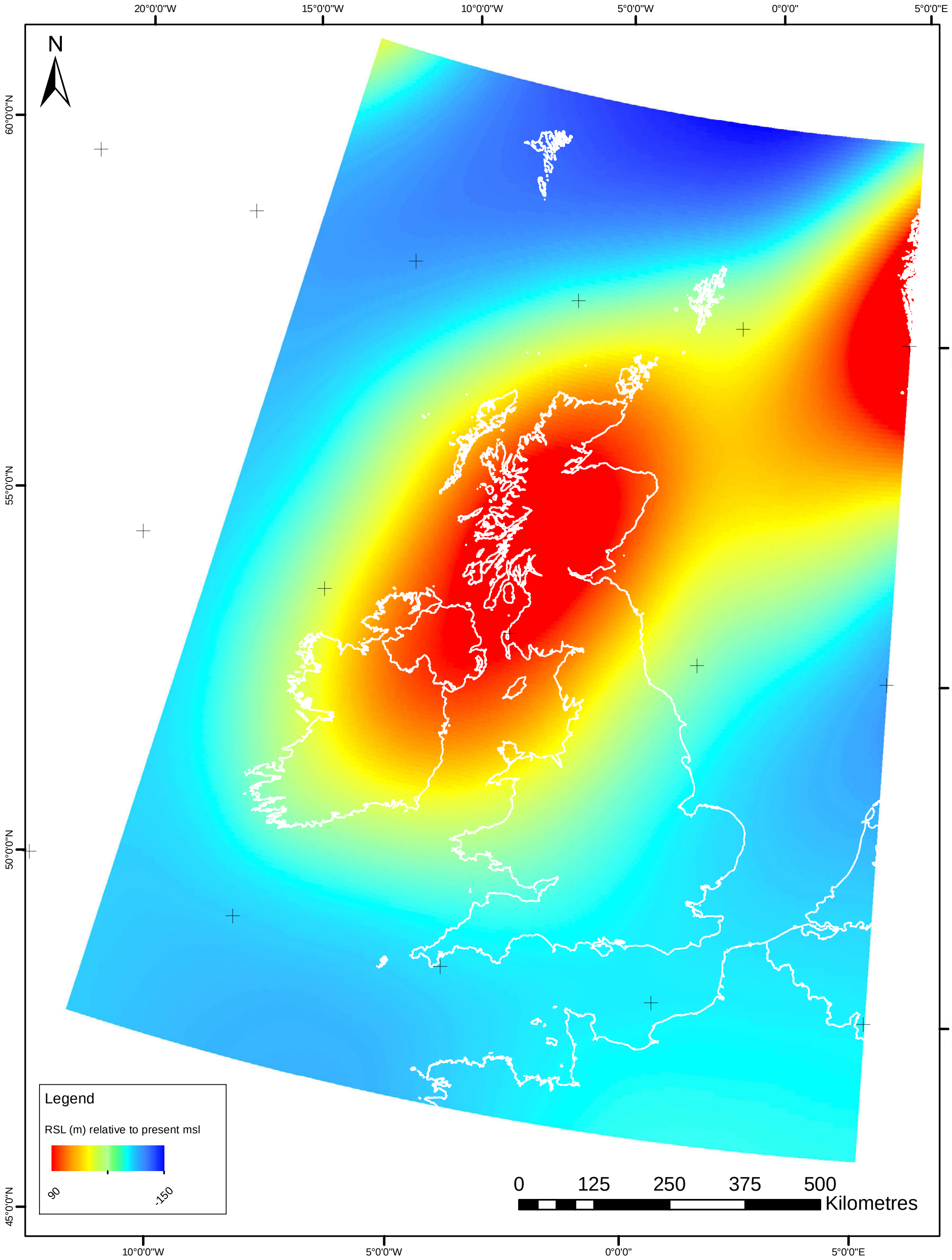

Figure 2. . Isobase plot interpolated from the glacial rebound model simulations of RSL elevation (in metres relative to present mean sea level) at 20,000 years BP.

3. Results

The palaeographic reconstructions based upon RSL simulations derived from the (Bradley et al., 2011) investigation depict the broad-scale changes in land extent as a consequence of vertical movements of land and sea level.

The accompanying palaeogeographic maps indicate that in the North Sea region, shorelines attained a maximum northerly extent of around $55 - 60°$N and retreat from this position was, in general, relatively slow. Indeed, by the start of the Holocene, most of the central and southern North Sea still occupied a subaerial setting. However, during this retreat phase, a very large embayment emerged off the northeast coast of England and an archipelago of small islands surrounded by shallow water are also present in this region.

Within the English Channel region, reconstructions suggest that at around 20,000 years BP, the coastline occupied a position to the west of the Scilly Isles, extending in a southeasterly direction towards Ushant. At first, retreat from this position was relatively slow although a large embayment is apparent at the western end of the English Channel region by around 16,000 years BP. However, the pace of shoreline retreat increased significantly after ca. 15,000 years BP and a large, narrow coastal inlet centred on the Hurd Deep had emerged by ca. 14,000 years BP. From here, tidal waters advanced up the Western Approaches, progressively flooding the former Fleuve Manche river system (e.g., Antoine et al., 2003). Breaching of the Dover Straits had occurred by ca. 8,000 years BP and examples of drowned coastal peats that date from this initial inundation are reported from the Devon, Hampshire, Sussex, and Kent coasts of England (Devoy, 1979; Jennings and Smyth, 1987; Waller and Kirby, 2002; Momber, 2000; Gupta et al., 2004; Massey et al., 2008) and from the Seine Estuary (Frouin et al., 2007) in France (see Long (2010) for further discussion). At this time, subaerially exposed shelves were present along much of the southern coast of Britain such that the Isle of Wight was linked to the mainland and the Solent was a fluvial valley.

The model suggests that between approximately 20,000–15,000 years BP, the Celtic Sea region was an archipelago of small islands which were surrounded by very shallow (<20 m) waters. At this time, much of Ireland was located beneath an extensive ice cap that joined Ireland to Britain across the Malin and Irish Seas. By analogy to comparable environments today, extensive sea ice cover would have flanked these ice sheets, and many of the small islands present in the Celtic Sea are likely to have become connected. Despite this, it does not appear that waters were sufficiently shallow to allow a land bridge to form between Britain and Ireland. This represents a departure from the findings of a number of previous studies which have envisaged the operation of a land bridge at various times during the last 20,000 years BP (e.g., Mitchell, 1976; 1986; Devoy, 1985; Preece et al., 1986; Wingfield, 1995; Lambeck, 1996; Peltier et al., 2002). However, given that the model is relatively poorly constrained in this region and the fact that bed level changes arising from erosion and deposition are not accounted for, it remains feasible that a low-lying land bridge may have existed at some point up until circa 15,000 years BP. Some (equivocal) evidence does in fact exist for the presence of a large freshwater lacustrine system (Glacial Lake Lllyn Boddedig) occupying the Celtic Deep Basin from deglaciation until well into the Late Glacial Interstadial (Furze, 2004). This freshwater body is evidenced by laminated basal muds containing sparse reworked marine floras and is suggested to have been inundated by marine incursion over a subaerially exposed (land bridge) by 13 500 years BP. For the reasons discussed above, these findings are broadly compatible with the model and it may well be the case that Glacial Lake Lllyn Boddedig became inundated by marine waters as a consequence of MWP1a (meltwater pulse). By the opening of the Holocene (11,700 years BP), water depths in excess of 50 m clearly separated Ireland from Britain and the rest of Europe.

Finally, in the north and northwest of Britain, reconstructions suggest that the island groups comprising the Outer Hebrides, the Orkney Islands, and the Shetland Islands were joined to form larger individual land masses. In addition, a number of other, smaller islands appear to have been present in this region at various times during the Last Glacial Termination. However, the majority of these islands had been inundated by the start of the Holocene (11,700 years BP).

In summary, it is apparent that the largest changes in palaeogeography are generally observed in the North Sea and English Channel regions where extensive areas of the present day shelf were once dry land. Conversely, despite the occurrence of significant isostatic and eustatic change since the LGM, there has been surprisingly little lateral migration of the coastline around Ireland. Indeed, for the most part it would appear that the Irish coastline has not deviated by more than about 30 km from its contemporary location throughout the past 20,000 years (providing that erosion has not significantly altered the position of cliff-lines at a large scale). These regional variations can be explained by the contrasting bathymetries around the British Isles: the coastline around southern Britain is flanked by very shallow seas whereas around much of Ireland, it is characterized by a relatively steeply sloping shelf.

4. Map Accuracy

The palaeogeographic reconstructions provide broad indications of regional and millennial-scale changes in the position of the coastline of Northwest Europe. It is important to emphasize that these spatial and temporal changes are driven by modelled changes in RSL, and therefore best approximate coastal changes where these predominantly reflect the influence of changing RSL. In locations where other processes such as erosion and sediment deposition have been the driving force of change, the position of the reconstructed shoreline may differ considerably from reality. In general, confidence in the accuracy of the maps becomes less as the spatial extent of the geographical area under consideration is reduced. Because of this, the maps do not provide a reliable picture of site-scale changes. This is especially the case within estuarine and lowland environments which may contain considerable thicknesses of Holocene sediment and which have often experienced extensive land reclamation within historic times (e.g., Gallois, 1994; Haslett et al., 1998; Healy and Hickey, 2002; Brooks, 2007; Museum of London Archaeology (MLA), 2009). Furthermore, the GEBCO digital bathymetry layer has been used to derive palaeogeographies in (present day) offshore regions and around the Irish coastline. The GEBCO layer is defined on a much coarser grid than the UKHO bathymetric layer (which has been used to derive palaeogeographies for coastal area around Britain). Because of the coarse nature of the GEBCO grid, localised bathymetric 'irregularities' are apparent around the Irish coastline and these irregularities have been transferred over into the palaeogeographic reconstructions.

The validity of the palaeogeographic reconstructions are ultimately dependent on the accuracy of the simulated RSL curves used to generate them which, in turn, relates to the ability of the model in reproducing the actual RSL histories of the areas. As previously mentioned, there exists an uneven temporal and spatial distribution of high quality RSL data around Britain and Ireland, and in some areas this has complicated model testing. In particular, there is a lack of sea level index points from many parts of the Irish coast, and even fewer areas where these points are distributed throughout the Holocene (Brooks and Edwards, 2006). Confidence in the accuracy of the palaeogeographic reconstructions is therefore less in this region than for other areas of the British Isles.

5. Conclusions

The palaeogeographic maps indicate that large areas of land on the Northwest European continental shelf have been lost beneath the sea. The greatest spatial changes in the position of the coastline are observed in the North Sea and English Channel regions where substantial areas of the shelf seabed were subaerially exposed 20,000-15,000 years ago. These regions contrast with the coastal waters surrounding Ireland where the relative steepness of the shelf has meant only limited palaeogeographic changes have taken place throughout the past 20,000 years. Nevertheless the reconstructions suggest that a number of the shallow embayments in this region most likely contained considerable expanses of terrestrial and/or littoral environments. It is likely that areas such as these were foci for human activity and may still contain an important archaeological record dating back to at least the upper Palaeolithic. Accordingly, these palaeogeographic maps provide a useful (first order) guide to identifying areas such as these and may be used to inform future seabed surveying campaigns aimed at identifying submerged cultural landscapes. The maps presented here may also be of value to researchers interested in mapping the migration of plants and animals across Northwest Europe over the past 20,000 years. In particular, the results from this investigation suggest that contrary to several earlier studies, at no point during the Last Glacial Termination did a well developed land-bridge emerge to connect Britain and Ireland. This finding may then help inform debates surrounding the re-colonisation of Ireland, such as the mechanisms by which new plant taxa were introduced following the retreat of the last ice sheet.

Software

Both the glacial rebound model output and present day topography and bathymetry data were available as a series of xyz coordinates and surfaces were created from these point files using 3D Analyst and Spatial Analyst extensions within ESRI ArcGIS 9.3. As previously noted, several different sources were used for the topographic and bathymetric data and once individual surfaces were created, they were combined using the 'mosaic' tool within ArcGIS. The 'Raster calculator' function within ArcGIS was used to calculate the difference between the present day DEM and the surfaces derived from the glacial rebound model output, depicting spatial variations in RSL. The final map was created using ESRI ArcMap 9.3.

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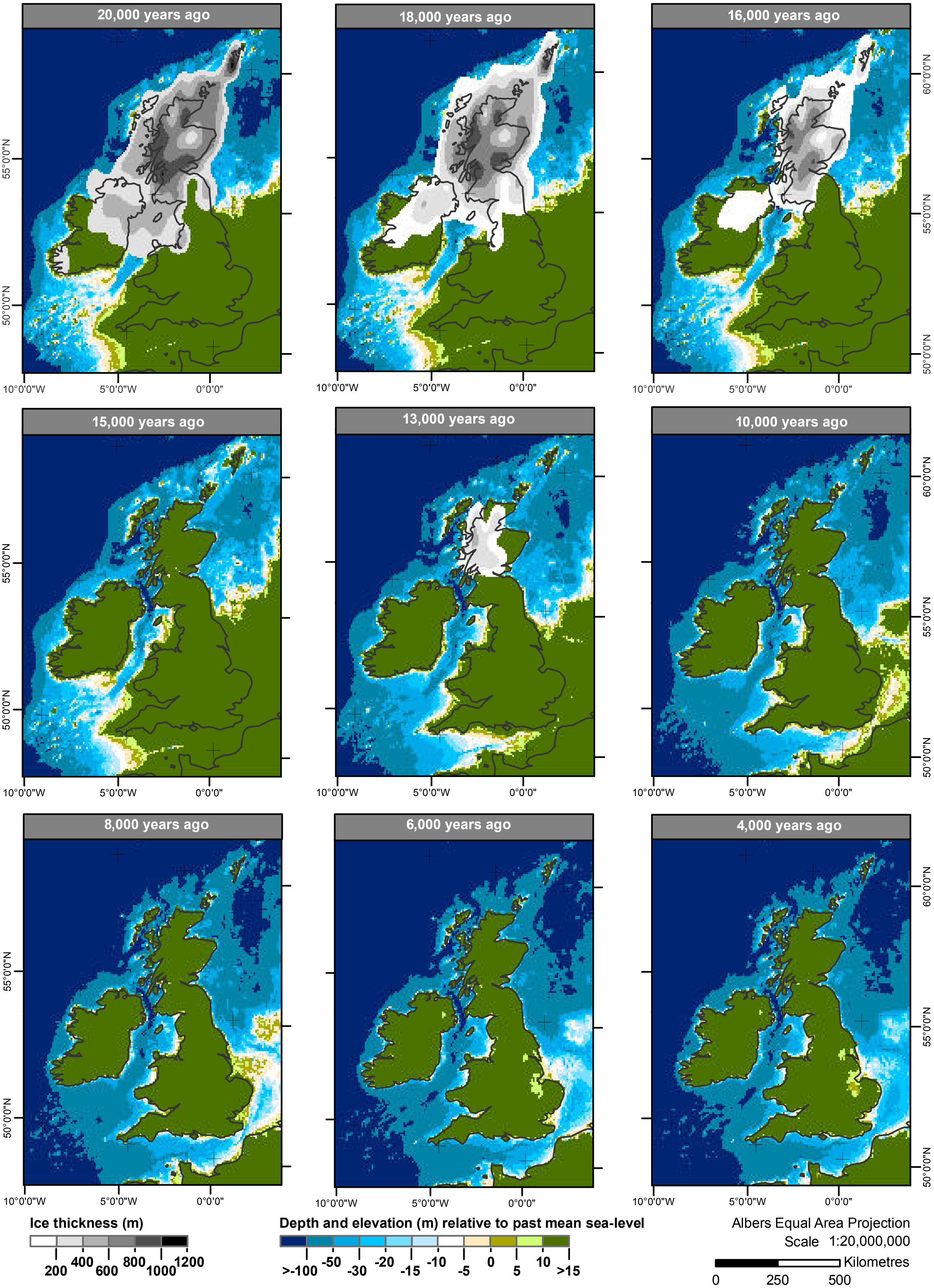
The palaeogeography of Northwest Europe during the last 20,000 years



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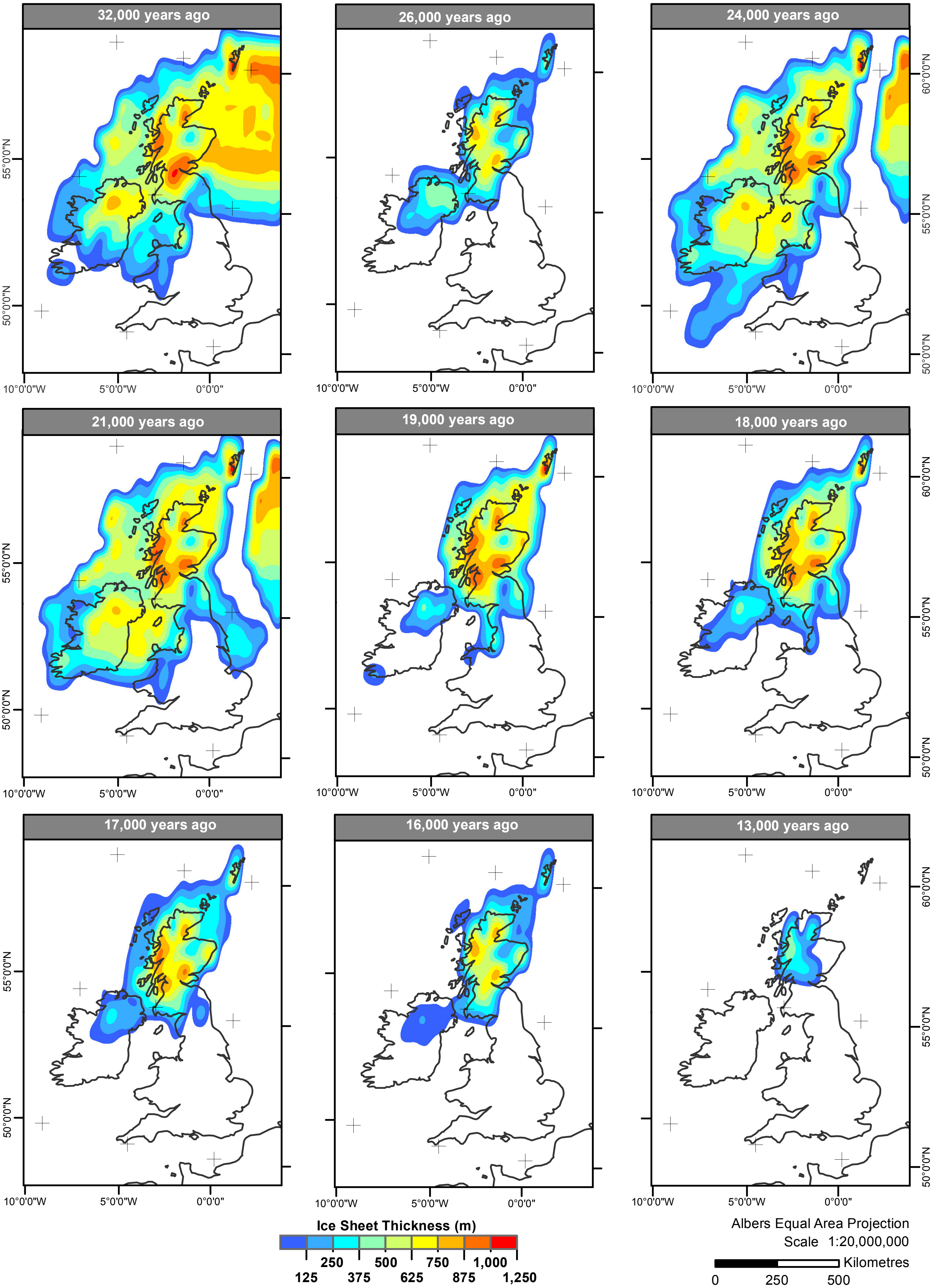
Reconstructions based on the glacial rebound modelling analyses presented in Bradley SL., Milne G., Shennan I., Edwards R. 2011. An improved glacial isostatic adjustment model for the British Isles. Journal of Quaternary Science 26 (5) 541-552. Modern day bathymetry from the United Kingdom Hydrographic Office (UKHO) and the 2008 General Bathymetric Chart of the Oceans (GEBCO).

Ice thickness maps of the British-Irish ice sheet



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