The Island of Ireland: Drowning the Myth of an Irish Land-bridge?

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Abstract

At the Last Glacial Maximum (LGM) c. 26 000 calendar years ago, global sea levels were around 120 m lower than present due to the storage of water on land in the form of large, high-latitude ice sheets. This lowering of sea level exposed portions of the modern seafloor surrounding north-west Europe, forming 'land-bridges that joined Britain and Ireland to the rest of the continent. Sometime later, these land-bridges were drowned by rising sea levels as the ice sheets melted in response to a warming climate. Precisely when these land connections were severed has been a subject of debate for several decades, driven in part by the desire to understand the postglacial recolonisation of Ireland by plants and animals.

The level of the sea relative to the land surface (relative sea-level) results from the interplay between vertical changes in both land and sea level. These processes can be 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, when combined with bathymetric and topographic data, be used to produce first-order palaeogeographic reconstructions. This paper uses palaeogeographic reconstructions of this kind to investigate the location and duration of possible land-bridges joining Ireland to Britain. These reconstructions are derived from a recently developed glacial rebound model for Ireland that incorporates an updated British-Irish Ice Sheet component and is trained by geological sea-level indicators from around the Irish coast. The resulting reconstructions suggest that Ireland was separated from Britain by c. 16 000 calendar years ago, at which time climate was still cold and local ice caps persisted in parts of the country. No support is found for the idea that a Holocene land-bridge was instrumental in the migration of temperate flora and fauna into Ireland.

Keywords: Land-bridge; Relative sea-level change; Glacial Rebound Modelling; Palaeogeography.

Contents

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1. Introduction

The subject of 'land-bridges' inevitably arises in most discussions concerned with the post-glacial colonisation of Ireland. The location, extent and duration of possible land connections between Ireland, Britain and mainland Europe has received considerable attention in the diverse literature dealing with colonisation (e.g. Devoy, 1985, 1986; Mitchell, 1986; Sleeman et al., 1986; Devoy, 1995; Wingfield, 1995; Lambeck, 1995, 1996; Mitchell & Ryan, 1997; Lambeck & Purcell, 2001; Cooper et al., 2002; Kelley et al., 2006). In a useful review, Devoy (1995) identifies eight areas providing data that will be critical in resolving the land-bridge question. This paper is concerned with five of these key areas (glacio-isostatic modelling; the behaviour and extent of the British-Irish Ice sheet; offshore mapping and seismic stratigraphy; palaeoenvironmental data from sediment cores; and sea-level data), and focuses on some of the developments that have occurred since the 1990s.

The existence of a land-bridge is ultimately determined by the level of the sea relative to the land surface (termed relative sea-level (RSL)). Reconstructing RSL change through time is complex, since it reflects the interplay between a large number of variables operating at scales from global to local. When considering the gross changes that have occurred around Ireland since the height of the last glaciation (around 24 000 calendar years ago), two variables are of key importance: the rise of ocean levels caused by climate warming and the melting of land-based ice; and the vertical adjustment of the Earth's surface due to the redistribution of this mass (i.e. unloading of formerly glaciated regions and loading of the ocean basins and their flooded margins). As a consequence, RSL is location specific, and histories of change will vary considerably across the region once covered by the British-Irish Ice sheet (BIIS).

Geophysical models capable of simulating the Earth's response to changing loads (glacio-hydro-isostatic adjustment) have become important tools in the study of sea-level change, and provide a framework within which local RSL reconstructions can be placed and interpreted (e.g., Walcott, 1972; Peltier, 1974; Farrell & Clark, 1976; Peltier & Andrews, 1976; Nakada & Lambeck, 1987; Mitrovica & Peltier, 1991; Johnston, 1993; Milne & Mitrovica, 1996; Milne et al., 1999; Peltier et al., 2002, Peltier, 2004). These 'glacial rebound models' (GRM) can be thought of as comprising three principal elements: an ice loading model (which defines the changing global distribution of grounded ice thickness), an Earth model (which simulates the deformation of the solid Earth to surface loading) and an algorithm to compute associated changes in sea level. This modelling approach has been extensively tested and shown great skill in reproducing reconstructed RSL changes since the last glacial maximum (LGM) at locations around the globe (e.g. Peltier, 2004; Bassett et al., 2005; Peltier & Fairbanks, 2006).

Despite this success at the global scale, significant misfits between RSL data and model simulations can arise at the local to regional scale, relating to uncertainties in the ice and Earth models employed. The British Isles have attracted considerable attention from modellers due to the presence of a local ice sheet, their proximity to the major Fennoscandian ice mass, and the existence of a high quality database of RSL reconstructions with which to test and refine the simulations (e.g. Lambeck, 1991; Lambeck, 1993a; Lambeck, 1993b; Lambeck, 1995; Lambeck, 1996; Peltier et al., 2002; Shennan et al., 2002; Shennan et al., 2000a; Shennan et al., 2000b; Shennan et al., 2006a). Many of these studies have tended not to consider Ireland directly due the fragmentary nature of the Irish RSL record, and the paucity of observational constraints on the Irish Ice Sheet. The work of Lambeck (1996) and Lambeck & Purcell (2001) are notable exceptions to this, although the validity of their models has attracted criticism (see McCabe, 1997; McCabe & Clark, 2003; McCabe & Dunlop, 2006).

More recently, Brooks et al. (2008) have produced revised RSL simulations for Ireland. The development of this new model, which is described in more detail below, builds on several important advances that have taken place since the investigations of Lambeck and co-workers, and addresses some of the criticisms associated with these earlier studies. There are now more primary RSL data from Ireland and these, coupled with the development of an Irish sea-level database (Brooks & Edwards, 2006), permit a more objective test for Irish RSL simulations. There have also been important advances in the understanding of late Devensian RSL change in areas immediately adjacent to Ireland (Shennan et al., 2006b). The provision of RSL data covering the last 16 000 years addresses the criticism that GRM models are only trained by Holocene data and may therefore be unreliable in simulating older RSL change (e.g. McCabe, 1997). Improvements have also been made in constraining the size and timing of changes in the Irish Ice Sheet and its relationship to British and Fennoscandian ice (e.g. O'Cofaigh & Evans, 2001; Hiemstra et al., 2006; Sejrup et al., 2005; Rae et al., 2004; Bowen et al., 2002; McCabe & Haynes, 1996; McCabe & Clark, 1998, 2003; McCabe et al., 2005; Sejrup et al., 1994, 2005; Svendsen et al., 2004; Carr et al., 2006). In addition to incorporating these updated data into its ice model, the revised GRM for Ireland incorporates a more realistic assessment of ice sheet mass (and associated crustal loading) than previous studies by accounting for the effects of topography and bathymetry on ice thickness (Milne et al., 2006).

This paper briefly summarises the RSL simulations produced by the new GRM for Ireland presented in Brooks et al. (2008). It then applies this model to produce palaeogeographic maps and assesses the resulting evidence for any land-bridge linking Ireland with Britain during the last 20 000 years.

2. Modelling Relative Sea-Level Change in Ireland

2.1 A New Glacial Rebound Model for Ireland

The development of the GRM for Ireland used in this paper is described in Brooks (2007) and Brooks et al. (2008), and is reviewed here in brief. It is an evolution of the GRM presented by Shennan et al. (2006a) who successfully model post-glacial RSL

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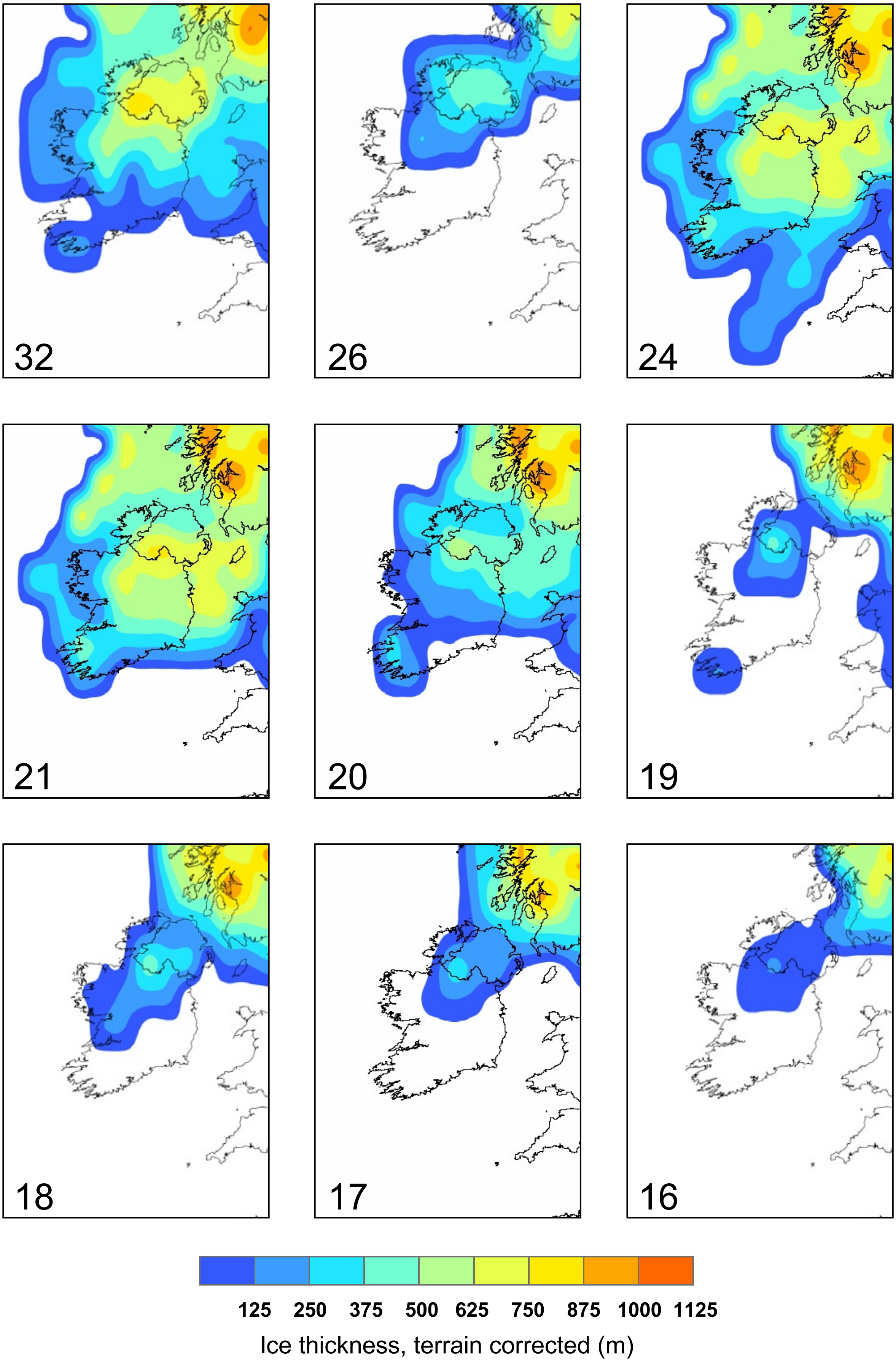

Figure 1 The space-time evolution of the Irish Ice Sheet employed in the new glacial rebound model for Ireland (Brooks et al., 2008). Small scale re-advances and minor differences in ice extent have negligible impact on the relative sea-level simulations.

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change in Britain. It employs an Earth model that approximates the response of a spherical, self-gravitating, compressible, Maxwell visco-elastic body. The elastic and density structure are taken from seismic constraints (Dziewonski & Anderson 1981), whilst the viscosity structure is parameterised into three layers corresponding to: the lithosphere (71 km thick); the upper mantle (from the base of the lithosphere to the 670 km seismic discontinuity; viscosity 4 x 1020 Pa s); and the lower mantle (from 670 km depth to the core-mantle boundary; viscosity 4 x 1022 Pa s).

The ice model has the same global component as that used by Shennan et al. (2006a), since this gives a close fit with far-field observations of RSL dating from the time of the LGM to c. 9000 BP (see Bassett et al., 2005). However, the ice model incorporates a revised local ice component (Irish ice sheet), that is consistent with recent publications concerning the extent, thickness and timing of glaciation (e.g. O'Cofaigh & Evans, 2001; Bowen et al., 2002; Rae et al., 2004; Serjup et al., 2005; Hiemstra et al., 2006). The space-time evolution of the modelled Irish ice sheet component is illustrated in Figure 1. The Holocene eustatic component of the ice model is not well constrained by data, but this study uses a value of 2 m of eustatic rise between 6000 and 2000 BP in accordance with other simulations (e.g. Nakada & Lambeck, 1989; Shennan et al., 2006a).

Simulated RSLs are derived by solving the most recent, generalised, form of the sea-level equation (Mitrovica & Milne 2003; Kendall et al., 2005). This incorporates the influence of shoreline migration, and the influence of GIA-induced perturbations in Earth rotation (e.g. Milne & Mitrovica, 1996). All predictions are generated using a spherical harmonic truncation of degree and order 256. The model is run at time-stepped intervals of 1000 years and so does not show sub-millennial scale variability.

The model is developed in an iterative process by adjusting the initial input parameters to improve fit with reconstructed values of RSL derived from geological data (full details in Brooks, 2007; Brooks et al., 2008).

2.2 Simulated RSL Changes around the Irish Coast

Fifteen simulated RSL curves produced by the model are presented in Figure 2. These reveal the contrasting patterns of RSL change that have been experienced around the Irish coastline as a consequence of the balance between eustatic sea-level rise and glacio-isostatic rebound.

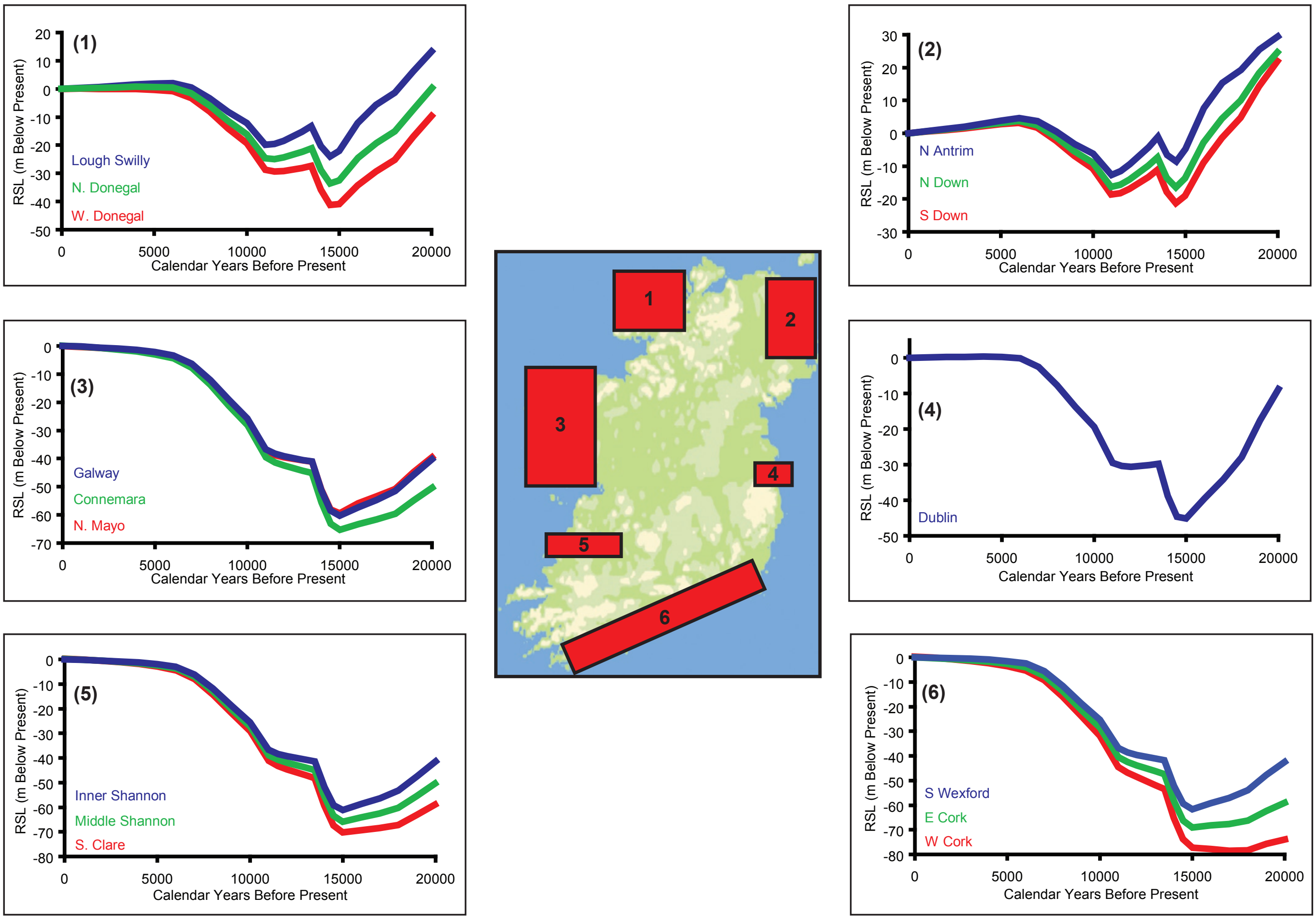

Figure 2 Simulated relative sea-level change produced by the new glacial rebound model for Ireland for selected areas around the Irish coast.

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The RSL curve for the Dublin area shows the typical signature of a quasi-stable location situated at the margins of a former ice sheet. The deglacial period post 20 000 years ago is characterised by RSL fall due to crustal rebound from unloading of glacial ice. There is a pronounced inflection in the curve between 15 000 and 14 000 years ago associated with a rapid addition of meltwater from wasting ice sheets (meltwater pulse 1a). This is followed by a couple of thousand years of RSL stability as the rate of rising sea level was matched by crustal rebound. By the start of the Holocene period (10 000 years ago), the rate of eustatic sea-level rise had outpaced the waning land surface response, causing RSL to increase. Relative sea-levels around Dublin have remained close to those of the present day for the last 6000 years.

The same general patterns of change are apparent from the RSL curves from southern Ireland (South Wexford, East and West Cork), the Shannon (South Clare, Middle and Inner Shannon), and western Ireland (Galway, Connemara and North Mayo). The main differences are that these areas have experienced rising RSL during the last 6000 years, with highest rates in the south west, located furthest from the former centres of major ice loading.

The RSL curves from the north west (West and North Donegal, Lough Swilly) and north east (North Antrim, North and South Down), show the greater influence of crustal rebound due to their location closer to the centres of ice loading. In the north west, RSL higher than present is simulated for the early deglacial period due to the large amount of crustal depression at this time. In the north east, RSL has been higher than present in both the deglacial phase and during the middle Holocene, with RSL falling during the last 6000 years.

3. Simulating the Late- and Post-Glacial Palaeogeography of Ireland

In order to investigate the possible existence of a land-bridge between Ireland and Britain, it is necessary to combine the simulated RSL information with topographic and bathymetric data which describe the shape of the Earth's surface. In effect, this approach considers the impact of raising or lowering sea level over a surface of fixed morphology, and has been used to produce similar palaeogeographic reconstructions for Britain and elsewhere (e.g. Lambeck, 1995; Shennan et al., 2000a; Lambeck & Chappell, 2001; Lambeck, 2004). The resulting first-order palaeogeographies do not account for processes such as erosion and deposition that may re-shape topography or bathymetry, and their accuracy will vary according to the local significance of these processes.

3.1 Method

Data concerning present day topography and bathymetry are obtained from the National Geophysics Data Centre. Bathymetric data are derived from Smith & Sandwell (1997) and comprise measurements from satellite altimetry in combination with ship-board echo-sounding. These data are defined on a two minute grid which equates to a resolution of approximately one data point every 12 km^2. Consequently, these reconstructions are indicative of more general, regional changes rather than detailed site-specific ones.

3.2 Results

Palaeogeographic maps of Ireland for the last 20 000 years are presented at 2000 year intervals in Figure 3, with the exception of the last 4000 years during which time change is minimal at the resolution of the current data. These show the broad-scale changes in land extent as a consequence of vertical movements in land and sea level. The proximity of a relatively steeply sloping shelf means that lateral migrations in coastline have been comparatively limited around many parts of Ireland, with areas apparently experiencing less than c. 30 km of shoreline change since the LGM. This is in marked contrast to similar studies of the North Sea and English Channel regions that indicate dramatic shifts in coastline and substantial submergence of land (Lambeck, 1995; Shennan et al., 2000a).

The palaeogeographies indicate that around 20 000 years ago, a low-lying isthmus extending from south-eastern Ireland to south-west Britain would have joined the two land masses together. At this time, much of Ireland was shrouded beneath an extensive ice cap that similarly 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, further increasing the connectivity. Between 20 000 and 16 000 years ago, the ice mass covering Ireland reduced in extent, but most likely remained connected to the neighbouring ice sheet in Scotland. During this interval, the model output suggests rising global sea levels would have outpaced any vertical movements in land level, resulting in the submergence of the low-lying land-bridge between south-east Ireland and south-west Britain. The palaeogeographies indicate the formation of an archipelago of small islands surrounded by shallow water (perhaps < 20 m deep). Between 15 000 and 14 000 years ago, a large pulse of meltwater (meltwater pulse 1a), equivalent to the wasting of almost three times the amount of ice currently stored in the Greenland Ice Sheet, resulted in a rapid increase in global sea levels. This meltwater signal is imprinted on the Irish RSL curves (see Fig. 2). By the time of this rapid rise in RSL the ice sheet connecting Ireland to Scotland had also wasted away, leaving Ireland completely isolated from Britain by water over 30 m in depth. By the opening of the Holocene (10 000 BP) water depths in excess of 50 m clearly separated Ireland from Britain and the rest of Europe.

4. Discussion

The palaeogeographies presented in Figure 3 are first order approximations of changing coastal configurations and are intended to provide broad indications of regional and millennial-scale changes. Importantly, they are driven by the model of RSL change, and therefore best approximate coastal changes

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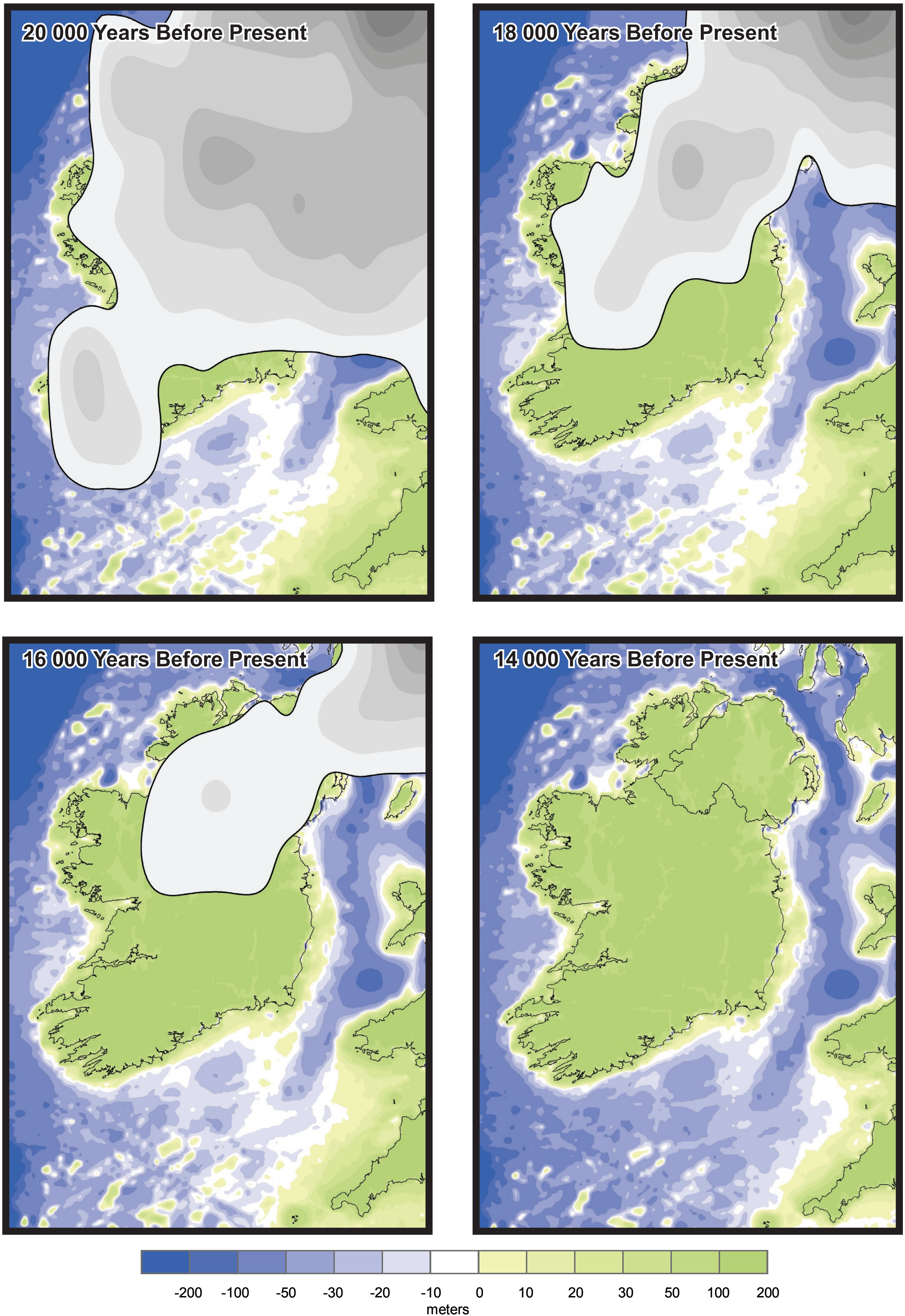

***Figure 3** First order palaeogeographic reconstructions for Ireland covering the last 20 000 years. These reconstructions are driven by the glacial rebound model and based upon modern topographic / bathymetric data. They simulate regional and millennial scale changes (see text for details).*

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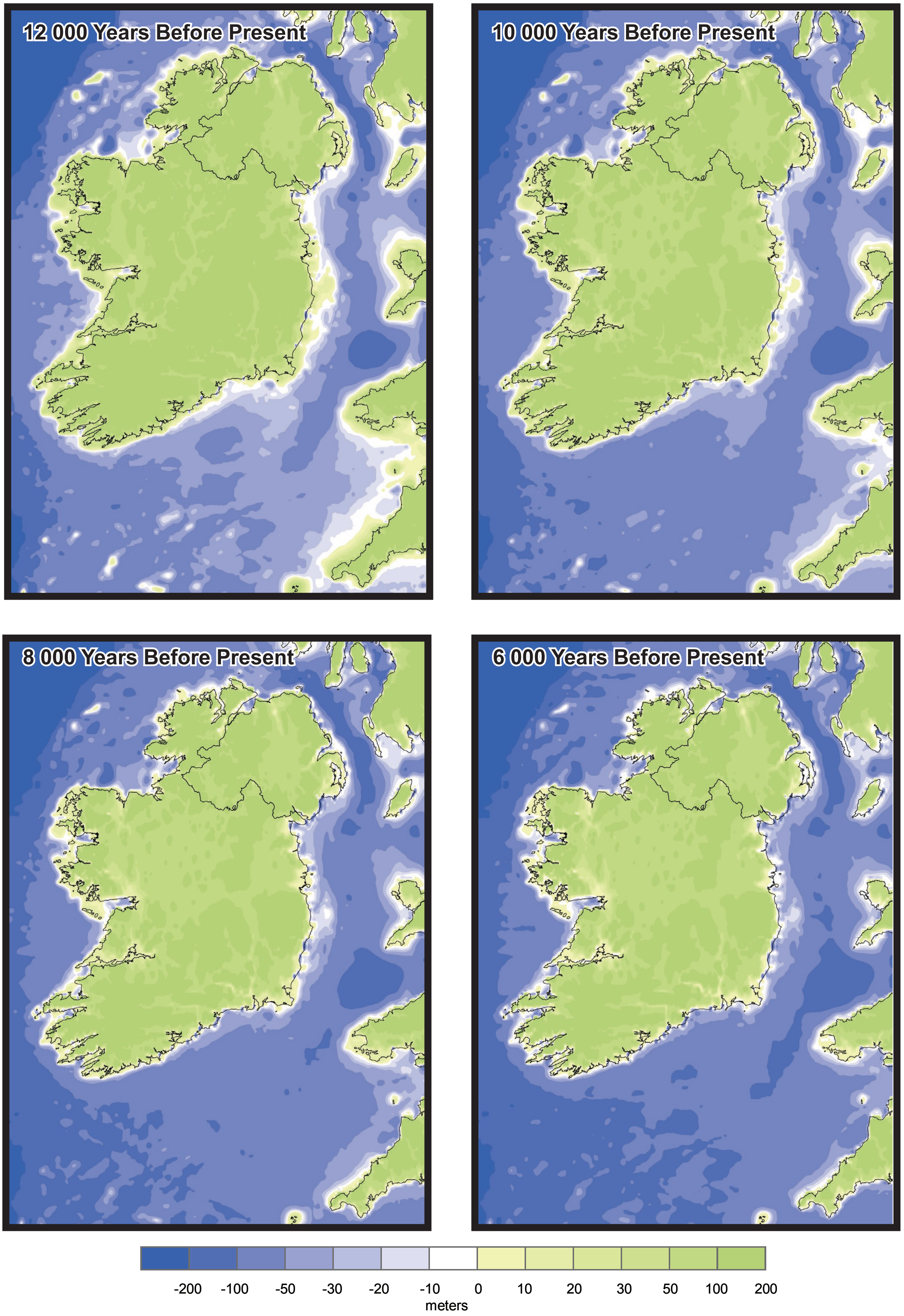

Figure 3 (continued)

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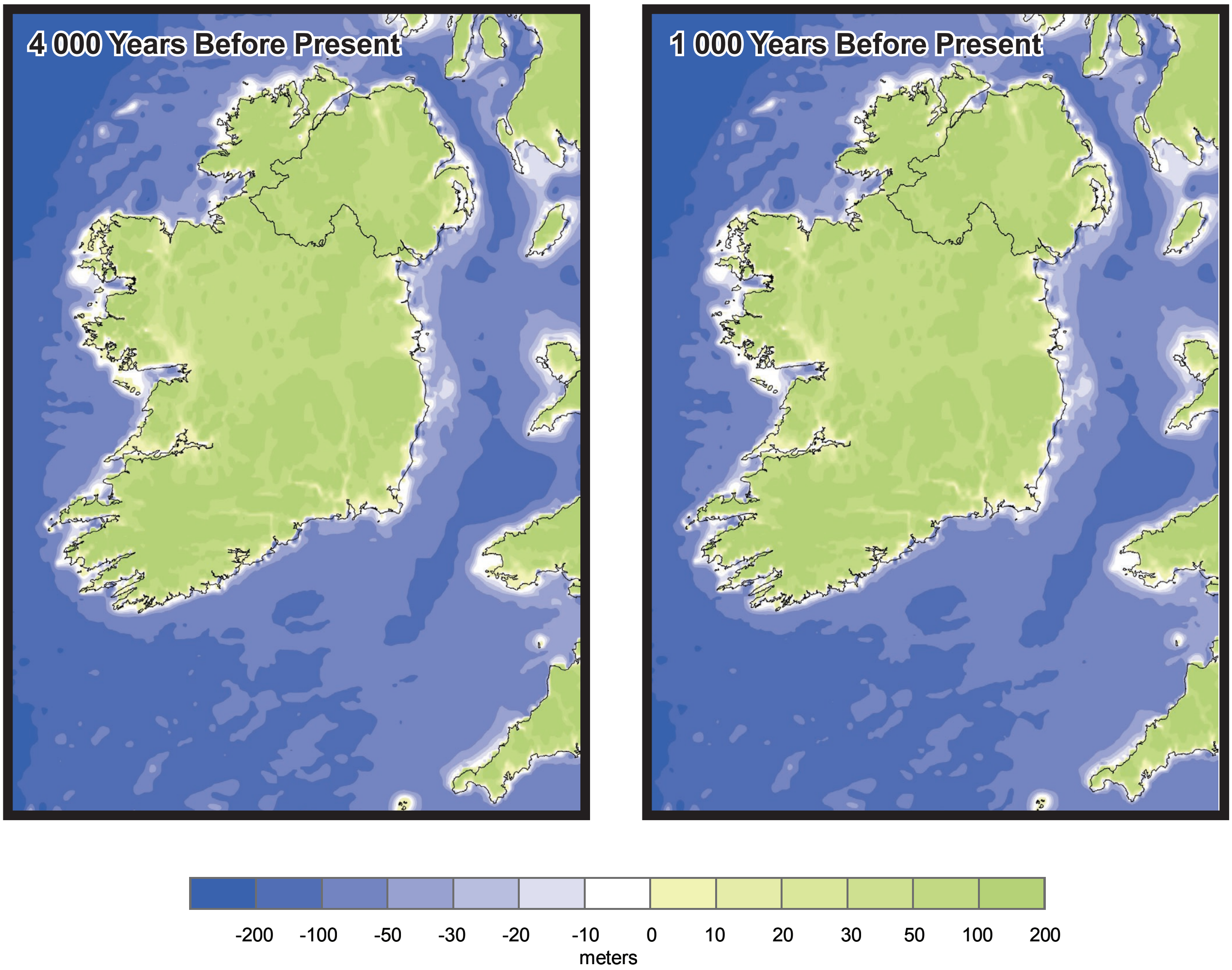

Figure 3 (continued)

where these predominantly reflect the influence of changing RSL. Where other processes have played significant roles in forming the coastline, such as sediment erosion and deposition, the simulated coastlines may diverge considerably from real conditions.

For example, the palaeogeographies are based on modern topography and bathymetry, and therefore inherently assume minimal morphological change over time. In areas with hard substrates, or where sediment erosion or deposition have been slight, this is reasonable. However, the model will not be able to reproduce phenomena such as the retreat of soft, cliffed shorelines, and will tend to underestimate the loss of land as a consequence of this process.

In general, the assumption that coastal change predominantly reflects RSL change becomes less robust as spatial scales are reduced. Consequently, this current generation of simulations should not be interpreted at the site-scale. Similarly, water depths / altitudes around the critical 0 m interface are deliberately presented in broad bins of 10 metres reflecting the uncertainties associated with morphological changes and the vertical precision of modelled RSL curves.

It should also be noted that data interpolation can introduce anomalies or errors, especially where high elevation land fringes the modern coast. These artefacts are evident at various locations around the coast where they appear as small, localised 'deep pools' or ponds. For example, this is clearly seen in the reconstruction of 4000 BP where a series of localised 'pools' are visible along the Cork, and Wexford coasts, as well as several locations around the north-east. Once again, the model output should be used to examine broad scale changes and not detailed, local geometries.

The validity of these palaeogeographies is also ultimately dependent on the accuracy of the simulated RSL curves used to generate them which, in turn, relates to the skill of the new GRM in reproducing the actual RSL histories of the areas. The uneven temporal and spatial distribution of high quality RSL data for Ireland (Brooks & Edwards, 2006) complicates 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 (see Brooks & Edwards, 2006 for distributions). Sea level index points possess information on sample location, altitude relative to a geodetic datum, age (commonly determined by radiocarbon dating) and indicative meaning (the vertical relationship between the sample and a contemporaneous tide level). This latter parameter is of critical importance in fixing the altitude of former RSL, and is commonly derived from combined lithostratigraphic and biostratigraphic analysis of former inter-tidal environments (see Edwards, 2007; Gehrels, 2007; Shennan, 2007).

The best published sea-level data come from the Cork and Wexford areas (Carter et al., 1989; Sinnott, 1999; Devoy et al., 2004), and Figure 4 shows the simulated RSL for these regions plotted against the reconstructed RSL derived from geological data. From these curves, it is clear that the model shows good skill in reproducing the pattern of reconstructed RSL change in these areas. Also evident is the patchy distribution of sea level index points (SLIPs). For example, whilst Cork has SLIPs covering most of the Holocene, there are no reliable sea-level data from Wexford for the last 5000 years. In addition, none of these areas currently have SLIPs from the period 20 000 - 10 000 years ago which will be important in testing the critical early phases of RSL change during which time the isolation of Ireland is proposed to have occurred. This situation is worse in other parts of Ireland where large stretches of coastline are devoid of SLIPs from any time period.

In areas with no SLIP data, past changes in RSL must be inferred from less precise field data such as 'raised beaches', wave-cut platforms or marine notches. These are associated with large and unquantified vertical errors (e.g. storm waves can deposit material tens of metres above mean sea level), and are extremely difficult to date due to the general absence of suitable material. This renders them of little use to the study of metre-scale RSL changes typical of the Holocene, but potentially of interest when considering late Glacial RSL changes of several tens of metres. Similarly, the dating of in-situ¬ material indicative of a marine or terrestrial environment, whilst incapable of pinpointing the position of former RSL, can provide upper or lower limits to the marine influence. Examples of these 'limiting dates' are freshwater peat deposits, or rooted trees which indicate that the upper limit of marine influence must have been below the altitude at which the samples were recovered. Figure 5 shows a comparison between these kinds of limiting data and simulated RSL for the N. Down area of north east Ireland where no SLIP data are currently available. The general bounds of the RSL are broadly delimited between c. 11 000 and 6000 BP by a series of terrestrial limiting dates (e.g. freshwater peat) and driftwood (interpreted as having been deposited in estuarine sediments) which bracket former RSL. The RSL simulations plot consistently below the terrestrial deposits, and appear to closely follow the inferred 'driftwood' limiting dates.

A discussion of RSL around Ireland would be incomplete without brief reference to the current controversy surrounding the existence of higher than present RSL during the late Devensian. An example of this can be seen in Figure 5 where a purportedly marine limiting date at 15 000 BP plots around 20 metres above the simulated RSL curve. This date comes from clay containing an assemblage characterised by foraminifera such as Elphidium excavatum. These are marine organisms which, if reliably dated and in-situ, would indicate the current generation of GRMs are significantly in error during the pre-Holocene period. This issue has tended to polarise opinion between those who feel that current models fail to capture the speed and magnitude of the crustal response to a dynamic ice sheet, and those who disagree with the interpretation of the field data ('glaciomarine muds'), arguing that they are not reliable sea-level indicators (see McCabe, 1997; Lambeck & Purcell, 2001; McCarroll, 2001; McCabe & Clark, 2003; Hiemstra et al., 2006; McCabe & Dunlop, 2006).

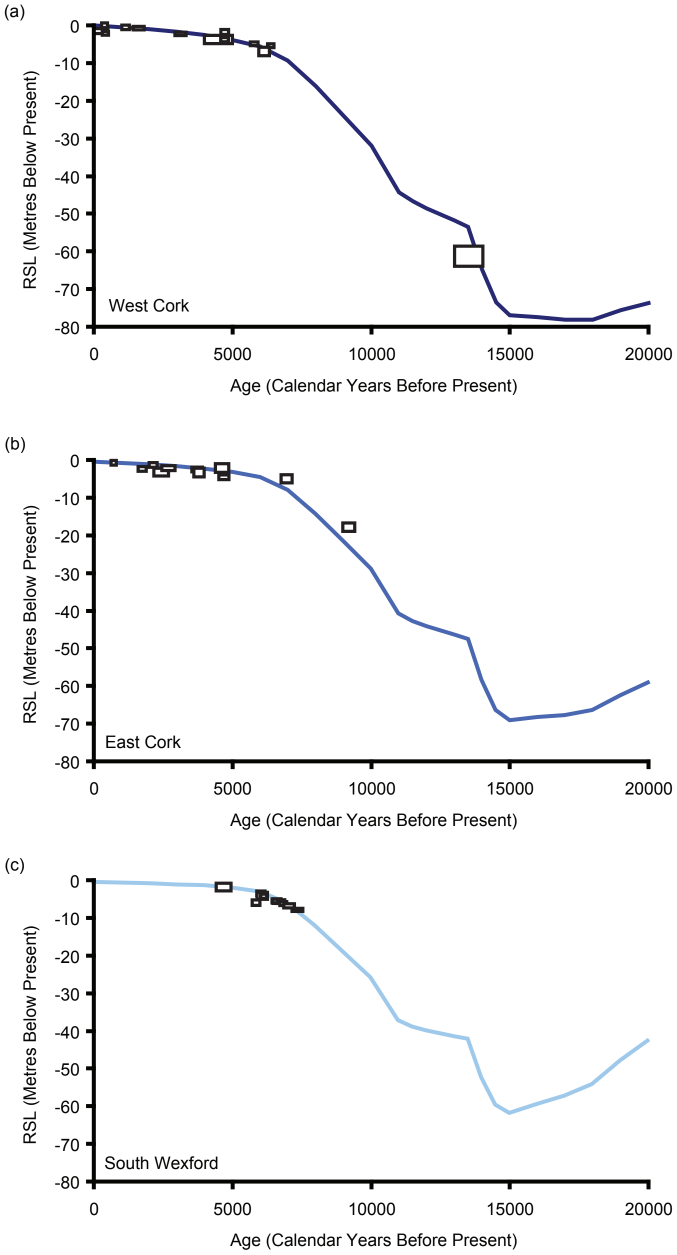

Figure 4 A comparison between simulated relative sea-levels and sea level index points (reconstructed relative sea-level) from southern Ireland. Boxes represent the age and altitude errors associated with each sea-level index point.

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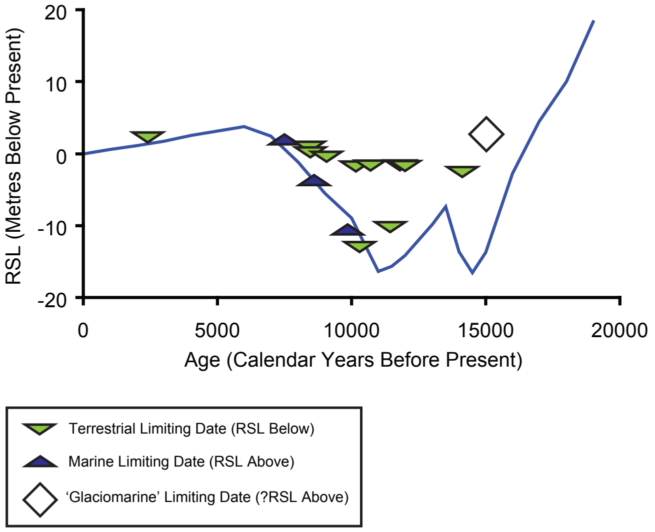

***Figure 5** A comparison between the simulated relative sea-level for North Down and the limiting dates for the same region. (See text for discussion).*

A detailed consideration of this debate in light of the new RSL simulations produced by the Brooks et al. (2008) model is beyond the scope of this paper and will be addressed elsewhere. In simple terms, greater depression of the Earth's surface under loading and / or a more rapid rise in eustatic sea level are required to generate high RSLs. The eustatic term is well-constrained by far-field data from coral reefs, and the current generation of models shows good skill in simulating the reconstructed patterns of late-glacial RSL changes in these areas. Importantly, there is only equivocal evidence in the far-field records for a proposed rapid rise in eustatic sea level around 19 000 BP, which forms an important component of the depositional model associated with some of the 'glaciomarine' sediments (see Peltier & Fairbanks, 2006). There is perhaps more scope for a solution in examining the nature of crustal rebound upon deglaciation. Recently, a critical new record from north-west Scotland has provided sea-level index points for the late-glacial period (Shennan et al., 200b). The close proximity of these data means that they will provide important constraints to any proposed changes in crustal response for the north east of Ireland.

5. Concluding Remarks

Devoy (1995) concluded that the existence of a land-bridge connecting Britain and Ireland was best regarded as a possibility rather than a probability, and suggested that geophysical modelling was a logical way to proceed in investigating this issue. The palaeogeographies and modelled RSL curves presented here are in accordance with this suggestion, and represent the current state of the art concerning Irish sea levels. On the basis of these simulations, it is now perhaps best to regard the absence of a land-bridge as a probability, at least when considering the Late Glacial and Holocene periods during which the migration of plants, animals and people have been traditionally associated. Corridors above sea level most likely existed prior to 16 000 BP, as both over ice and low-lying land routes, although Ireland still retained local ice at this time, and presumably any migrants using these pathways would be restricted to cold-tolerant taxa.

Whilst there is a tendency to simply refer to 'land-bridges', and focus attention on their role as connectors or conduits, it is important not to lose sight of the fact that these were real landscapes in the fullest sense of the word, associated with all the diversity and complexity of their more easily accessible counterparts currently located above sea level. The palaeogeographic maps indicate that substantial areas of land off the present day coastlines of eastern, southern and western Ireland have been lost beneath the sea. For example, around 8000 BP, the model suggests that the Aran islands, Clare Island, Inisturk, and Inisboffin, were joined to the mainland, and shallow embayments such as Clew Bay and Galway Bay most likely contained considerable expanses of terrestrial and/or littoral environments. It is likely that these areas were foci for human activity and may still contain an important archaeological record of the early occupants of Ireland. Investigating these environments through geophysical modelling, seismic surveying and underwater archaeology are some of the goals of the Submerged Landscapes Archaeological Network (SLAN), and will be foci of future research (see http://www.science.ulster.ac.uk/cma/slan/). In particular the integration of high-resolution bathymetric surveys, seismic profiling of sedimentary sequences and geophysical modelling will be able to test and improve the resolution and accuracy of the palaeogeographies presented here.

As part of these and other studies, new field data will be collected with which to test and further refine existing geophysical models and their simulations. There is a critical need to focus on the provision of high quality sea-level index points that have quantified, consistent and unambiguous vertical relationships to former RSL. In addition, limiting data that definitively indicate terrestrial or marine conditions, and are demonstrably in-situ, may also be useful in constraining RSL histories in areas where more precise data are lacking. The collection of offshore sediment cores is likely to be especially constructive in this regard, and model simulations can help to target critical locations for sampling. Future collaboration between field scientists and geophysical modellers will undoubtedly prove to be the most effective method of 'closing the gap' that currently exists in our understanding of RSL change and the island of Ireland.

Acknowledgements

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