Post-Glacial Relative Sea-Level Observations from Ireland and Their Role in Glacial Rebound Modelling

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ABSTRACT

The British Isles have been the focus of a number of recent modelling studies owing to the existence of a high quality sea-level data set for this region and the suitability of these data for constraining shallow Earth viscosity structure, local to regional ice sheet histories and the magnitude/timing of global melt water signals. Until recently, the paucity of both glaciological and relative sea-level (RSL) data from Ireland has meant that the majority of these glacial isostatic adjustment (GIA) modelling studies of the British Isles region have tended to concentrate on reconstructing ice cover over Britain. However, the recent development of a sea-level database for Ireland along with emergence of new glaciological data on the spatial extent, thickness and deglacial chronology of the Irish Ice Sheet means it is now possible to revisit this region of the British Isles. Here, we employ these new data to constrain the evolution of the Irish Ice Sheet. We find that in order to reconcile differences between model predictions and RSL evidence, a thick, spatially extensive ice sheet of c. 600-700m over much of north and central Ireland is required at the LGM with very rapid deglaciation after 21 000 cal. BP.

1. INTRODUCTION

Recently, a number of researchers have modelled observations of glacio-isostatic adjustment (GIA) from the British Isles (e.g. Lambeck, 1991; Lambeck, 1993a; Lambeck, 1993b; Lambeck, 1995; Lambeck *et al*., 1996; Peltier *et al*., 2002; Shennan *et al*., 2002; Shennan *et al*., 2000c; Shennan *et al*., 2000d; Shennan *et al*., 2006a). These efforts have been facilitated by the availability of long time-series records of relative sea-level (RSL) change in Britain which, through the process of geophysical modelling, can be used to gather information regarding former ice extent, thickness and melting history, as well as viscosity structure within the mantle. However, in the past, the fragmentary nature of the Irish RSL record, allied with a paucity of observational constraints on the Irish Ice Sheet, has deterred researchers from using these data to constrain either the ice history or sub-surface viscosity structure for this region. Notable exceptions to this are the works by Lambeck (1996) and Lambeck & Purcell (2001), which utilize existing records of RSL to constrain the vertical limits of the Irish Ice Sheet.

Since these publications, there have been a number of pertinent developments that mean it is now timely to re-evaluate the contribution Irish observational data can make to modelling GIA in the British Isles. Firstly, the body of available Irish sea-level data has grown since the work of Lambeck and co-workers. This is augmented by new, high resolution RSL records dating back to c. 16 000 BP, from sites immediately adjacent to Ireland (Shennan *et al*., 2006b), which provide a powerful and unique constraint on model reconstructions of the Irish Ice Sheet.

Secondly, Brooks & Edwards (2006) have developed a sea-level database for Ireland in which observations of RSL have been screened and classified according to established protocol for the analysis of sea-level data (e.g. Kidson & Heyworth, 1979; Heyworth & Kidson, 1982; Shennan, 1982; 1986; Shennan, 1989; Shennan & Horton, 2002). This objective classification permits users of the database to readily identify the reliability of the available RSL information, and helps to discriminate potentially erroneous data. A similar database for the UK (Shennan & Horton, 2002), has been integral to previous GIA modelling studies from Britain (e.g. Lambeck, 1995; Shennan *et al*., 2002; Shennan *et al*., 2006a).

Thirdly, new data on the spatial extent (e.g. O'Cofaigh & Evans, 2001; Hiemstra *et al*., 2006; Sejrup *et al*., 2005) and thickness (e.g. Rae *et al*., 2004; Bowen *et al*., 2002) of the Irish Ice Sheet since the Last Glacial Maximum (LGM) are now available. Furthermore, a number of Accelerator Mass Spectrometry (AMS) radiocarbon dates derived from marine muds have, for the first time, delivered chronological control on the post-LGM deglacial phase (e.g. McCabe & Haynes, 1996; McCabe & Clark, 1998, 2003; McCabe *et al*., 2005). In addition, field evidence now indicates that ice from the British Isles coalesced with Fennoscandian ice during the late Devensian (e.g. Sejrup *et al*., 1994, 2005; Svendsen *et al*., 2004; Carr *et al*., 2006), producing a more laterally extensive ice sheet than envisaged by Lambeck (1996).

Finally, Shennan *et al*. (2006a) have recently developed a revised GIA model for the British Isles (hereafter referred to as BIM-1), which satisfies key glaciological, seismic and sea-level constraints from both near- and far-field localities. This new model incorporates a more realistic assessment of ice sheet mass (and associated crustal loading) than previous studies by accounting for the effects of topography/bathymetry on ice thickness (Milne *et al*., 2006). Importantly, whilst this model has an Irish Ice Sheet component, it is not calibrated using any of the Irish RSL data. Consequently, the new dataset of Irish RSL reconstructions can provide a powerful, independent test of its earth and ice components.

In this paper, we evaluate the RSL predictions of BIM-1 against the independent Irish dataset. We demonstrate that significant misfits exist between observations and predictions for certain portions of the Irish coastline, indicating limitations in one or more components of BIM-1. We investigate the source of these limitations by examining the effects of modifying the Irish Ice Sheet and earth parameters of this model. In light of these results, we produce a revised model of the Irish Ice Sheet that satisfies both RSL and glaciological field constraints. Our results also indicate that minor modifications of the earth model are required to reconcile RSL predictions with observations from Ireland and the west coast of Britain.

2. MODELLING RELATIVE SEA-LEVEL CHANGE

The use of geophysical models to simulate RSL change associated with the growth and ablation of mid-to-high latitude ice sheets is well established (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). In essence, models of GIA consist of three key elements: an ice loading model (to define the global distribution of grounded ice thickness over time), an earth model (to simulate deformation of the solid earth to surface loading) and an algorithm to compute associated changes in sea level (which, as well as being a key observable, is also an important component of the GIA loading model).

Some authors have expressed concern about the ability of geophysical models to accurately reproduce patterns of RSL change (e.g. McCabe *et al*., 2005). It has been argued that models of this type are over-reliant on Holocene sea-level observations to constrain predictions of RSL change during the earlier deglacial phase (e.g. McCabe, 1997), whilst others have suggested that such models are unable to capture detailed variations in RSL change during the Holocene period (e.g. Smith, 2005). However, such criticisms are often based upon controvertible indicators of former sea-level which as yet cannot provide unequivocal data with which to test these suggestions.

This study tests and modifies the BIM-1 GIA model employed in Shennan *et al*. (2006a), the key components of which are outlined below.

2.1 Earth Model

The earth model employed in this investigation is a spherical, self-gravitating, compressible, Maxwell visco-elastic body. The elastic and density structure are taken from seismic constraints (Dziewonski & Anderson 1981) and are depth-parameterised with a resolution of between 10 and 25 km. The viscosity structure is more crudely parameterised into three layers which correspond to the lithosphere (in which the viscosity is set to a very high value of 1×10^{43} Pa s), the upper mantle (from the base of the lithosphere to the 670 km seismic discontinuity) and the lower mantle (from 670 km depth to the core-mantle boundary).

In this study, we employ the same viscosity parameters that have resolved discrepancies between far-field RSL data and model predictions (Bassett *et al*., 2005) and delivered a good fit to the observational evidence of post-glacial RSL change in Britain (Shennan *et al*., 2006a). These values are 1) a lithospheric thickness of 71km, 2) an upper mantle viscosity (v_{UM}) of 5 x 10^{20} Pa s, 3) a lower mantle viscosity (v_{LM}) of 4 x 10^{22} Pa s.

2.2 Sea-Level Model

To generate sea-level predictions based on an input earth and ice model, we solve the most recent, generalised, form of the sea-level equation (Mitrovica & Milne 2003; Kendall *et al*., 2005). By applying this most recent version of the theory, the influence of shoreline migration and sea-level changes in areas of ablating marine-based ice are accounted for. The theory we apply also takes into account the influence of GIA-induced perturbations in earth rotation on sea-level change (e.g. Milne & Mitrovica 1996). All predictions were generated using a spherical harmonic truncation of degree and order 256.

2.3 Ice Model

The ice model we adopt is comprised of a relatively low resolution global model with a higher resolution model for the BIIS. The global component of the ice model is the same as that used by Shennan *et al*. (2006a) and follows the analyses of Bassett *et al*. (2005) which gives a close fit with far-field observations of RSL dating from the time of the LGM to c. 9000 BP. The Holocene component of this model remains to be calibrated and so in the following analyses we adopt the findings of Nakada & Lambeck (1989) who suggest a late Holocene eustatic melt water contribution of c. 2m between 6000 and 2000 BP.

In order to accurately model GIA observations from Ireland and adjacent regions, a high-resolution spatial and temporal description of the local to regional ice load leading up to and following the LGM is required (Lambeck, 1993a). The space-time evolution of the Irish component of BIM-1 is illustrated in Figure 1. 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 c.33 000 BP and leading to coalescence of the British and Fennoscandian ice sheets. This configuration is interrupted by marked ice sheet retreat at 26

000 and 25 000 BP before rapid expansion of the BIIS around the time of the LGM. Deglaciation begins at 21 000 BP, with the removal of ice from both Ireland and the UK largely complete by 15 000 BP (e.g. Ballantyne, 1997).

3. RECONSTRUCTING RELATIVE SEA-LEVEL CHANGE

Over thirty years of international research, coordinated under the auspices of a series of International Geoscience Programme (IGCP) projects, has produced a well-defined methodology for developing records of relative sea-level change from sedimentary coasts (Edwards, 2005). Central to this is the use of sea level index points which fix the past altitude of sea level in time and space (Tooley, 1978; Preuss, 1979; Van de Plassche, 1986). Detailed consideration of sea level index points and their associated error terms are given in a series of publications (e.g. Kidson & Heyworth, 1979; Heyworth & Kidson, 1982; Shennan, 1982; 1986; Horton *et al*., 2000). In brief, for a sample to be established as a sea level index point, it must possess information regarding its location (latitude and longitude), its altitude (relative to a levelling datum), its age (commonly inferred from radiocarbon dating), and its vertical relationship to a contemporaneous tide level (termed the indicative meaning).

Relative sea-level data from Ireland have recently been screened, classified and compiled into a database by Brooks & Edwards (2006) (see Appendix 1 for contributors). All index points have location information (latitude / longitude in decimal degrees) that is accurate to within 1 km. At present, lengthy suites of index points from single sites in Ireland are rare. Instead, SLIs are grouped into 21 distinct geographical regions to permit more meaningful comparison between RSL observations and predictions (see Table 1 and Figure 2). Most of the sea-level data have age information provided by radiocarbon dating, calibrated using CALIB 5.0.1 (Stuiver *et al*., 2005). Some of these dates are also corroborated via pollen chonostratigraphic data. The altitude of all index points is defined relative to OD (Belfast), a mean sea-level datum.

The RSL database classifies samples primarily on the quality of their indicative meaning. All ‘Primary’ SLIs have a quantified vertical relationship to a former tide level, associated with clearly defined error terms. In situations where the indicative meaning of a sample is less well quantified, data have been grouped into a ‘Secondary’ tier of index points. Where a dated sample has no discernable relationship with sea-level, or has formed outside of the tidal frame, samples are categorized as 'limiting dates', and provide a maximum (or minimum) limit for sea level at a given time. 'Primary' limiting dates include dated samples which are associated with a known environment (e.g. freshwater peat), whilst 'Secondary' limiting dates are derived from material whose source environment is unclear or contested. A number of AMS radiocarbon dates taken from foraminifera contained within 'glaciomarine muds' are included in this latter category.

Both types of data are useful for testing RSL predictions produced by GIA models, since sea-level curves should pass through SLIs and remain within the constraints imposed by limiting dates. Post-depositional compaction of the sediment column, either under its own weight or as a consequence of subsequent loading by water or an overlying sediment burden may lower the reconstructed altitude of former RSL. This will be greatest where index points are established from thick intercalated sedimentary sequences and consequently, when comparing predictions with observations from such sequences, best fit RSL predictions should lay towards the top of the SLI scatter (e.g. Shennan *et al*., 2002, 2006a).

4. TESTING THE BIM-1 GIA MODEL FOR THE BRITISH ISLES

The BIM-1 GIA model is used to produce estimated RSL curves for a series of locations around the Irish coast and adjacent areas in western Britain. These curves are plotted in Figure 3 alongside the geologically-based RSL reconstructions. The model predictions along Ireland's east coast (Dublin (1) and S. Wexford (2)), south coast (E. Cork (4)) and west coast (Connemara (11)), are in reasonable agreement with the observational dataset. This indicates that, away from the former centre of loading by the Irish ice sheet, BIM-1 is effective in reproducing the dominant patterns of change. Further to the north and west, however, significant discrepancies begin to emerge between the model predictions and the empirical RSL data.

The first of these misfits is the tendency for BIM-1 to underestimate the maximum height of late Devensian RSL along the north Ulster coastline, as indicated by abundant raised shoreline evidence in this region. Limitations associated with dating and quantifying the indicative meaning of raised shorelines, coupled with the lack of primary index points for this time period, prevents a precise quantification of this discrepancy. Nevertheless, these shorelines provide strong evidence of higher sea-levels, both to the west and south of Antrim, than indicated by the model (Stephens and Synge, 1965; Synge and Stephens, 1966; Synge, 1977a, b; Mitchell, 1977). For example, in Derry (17), a late Glacial RSL of up to +25 m (compared to a modelled estimate of c. +13m) is suggested by Stephens & Synge (1965), whilst in North Down (19), Stephens & McCabe (1977) find evidence of raised shorelines at heights of +30 m (compared to a modelled estimate of just over +10m).

The second misfit concerns the presence of a Holocene high-stand (commonly around 6000 BP), where ongoing crustal rebound starts to outpace dwindling sea level rise. The model delivers predictions of Holocene RSL higher than present as far south and west as Sligo (13), as indicated by the 0 m isobase in figure 4. In west Donegal (14), BIM-1 predicts RSL of approximately +2 m at 6000 BP. Whilst there are very few locations in Ireland where the magnitude of the Holocene highstand can be tightly constrained (Brooks & Edwards, 2006), the work of Shaw (1985), Shaw & Carter (1994), Gehrels (2004) and Harmon (2006) in Donegal has enabled the spatial signature of the 0 m Holocene isobase to be reasonably well defined. The index point data provided by the authors above shows that RSL occupied a position around -2m at c.5000 BP in west Donegal (14) and suggests that the 0 m threshold lies somewhere along the north Donegal coastline (i.e. further to the north and east than suggested by BIM-1). On the Isle of Man (24), similar discrepancies exist with the Holocene RSL data. Here, the model predicts values in excess of +5 m whereas the data constrain sea level to have been no more that 2 m above present during this period.

5. EXAMINING THE POSSIBLE CAUSES OF POOR MODEL PERFORMANCE

The RSL data from Ireland demonstrate that BIM-1 performs poorly in areas that have experienced the greatest loading from the Irish ice sheet, but that it can predict RSL change with reasonable accuracy in those areas that have experienced thinner, or shorter-duration ice cover. In light of this, we perform a series of analyses to examine the Irish Ice Sheet component of BIM-1 and its influence on the pattern and magnitude of predicted RSL change.

5.1 The role of the Irish Ice Sheet

In order to predict the timing and magnitude of glacial rebound, it is necessary to know the size (thickness and lateral extent) of the ice sheet. In addition, it is important to understand when, how fast and by how much this size has changed through time. This choice of input parameters inevitably means that there is a degree of model solution non-uniqueness due to the trade-off between variables, and this is a recognised limitation inherent in GIA modelling studies (e.g. Mitrovica & Peltier, 1995). However, both the observational RSL data and glaciological field evidence (below) provide a stringent set of independent conditions that must be met, and any adjustment to the nominal BIM-1 ice sheet model are made in light of these constraints.

Ireland (along with Britain) is thought to have been ice free during the Derryvree cold phase, in agreement with a radiocarbon date of c.34 000 BP derived from organic silts in northwest Ireland (Colhoun *et al*., 1972). This warm episode was abruptly terminated by rapid ice sheet growth and expansion which lasted until c.27 000 BP. Before the onset of the LGM in this region at 24 000 BP, a brief retreat phase of the BIIS ensued between 26 000 and 25 000 BP in agreement with the inferences of Serjup *et al*. (1994).

During the LGM, a laterally extensive ice sheet is believed to have existed over much of Ireland and out onto the adjacent shelf region (e.g. Evans *et al*., 1980; Warren, 1992; McCabe, 1995; Clark and Meehan, 2001; Serjup *et al*., 2005). To the south, ice is now considered to have extended beyond the traditional South of Ireland End Moraine (SIEM) limit (O'Cofaigh & Evans, 2001; Evans & O'Cofaigh, 2003; Hegarty, 2004; Ballantyne *et al*., 2006). Recent evidence also indicates ice extending out into the Celtic Sea south of the Isles of Scilly (Scourse *et al*., 1990; Scourse, 1991; Hiemstra *et al*., 2006). In terms of ice thickness, there is a relative paucity of constraints provided by trimline data within Ireland when compared to the UK (e.g. Ballantyne *et al*., 1998a, b; McCarroll & Ballantyne, 2000). In the south west of Ireland (Macgillycuddy's Reeks), Rae *et al*. (2004) use trimline evidence to infer an ice sheet thickness of c.370m whilst in the east (Wicklow Mountains), Ballantyne *et al*. (2006) employ similar evidence to suggest that only peaks above c.725m remained ice free at the LGM. Elsewhere, the evidence is more equivocal: In the north of Ireland, ice is believed to have reached a thickness of at least 750m (after terrain correction) (e.g. Clark & Meehan, 2001; McCabe, 1997) although thicknesses are suggested to be somewhat less further south since the highest peaks of the Knockmealdown mountains (Lewis, 1976), Galtee mountains (McCabe, 1985) and Connemara mountains (Coudé, 1977) are proposed to have been nunataks at the LGM.

In BIM- 1, the onset of deglaciation begins after 21 000 BP with (rapid) ice retreat taking place up until 19 000 BP. By this time, the Irish Midlands are suggested to have been ice free, and the ice margin in the Irish Sea occupied a position to the north of the Isle of Man. Interrupting this ice retreat from the LGM was a large-scale ice re-advance which affected much of the country (e.g. McCabe et al. 1998; McCabe & Clark, 2003; McCabe *et al*., 2005). This 'Killard Point' or 'Heinrich 1' event involved ice re-advance as far south as the Shannon estuary and the north of the Isle of Man in the Irish Sea Basin (Thomas *et al*., 2004). This event was brief however, and ice retreat followed shortly after, with the region becoming ice free by 15 000 BP (e.g. McCabe *et al*., 2005). During the Younger-Dryas event (c.13 000 BP) ice was confined to mountain cirque glaciation (Murray-Gray & Coxon, 1991; Coxon, 1997) and was on a significantly smaller scale than its equivalent in the Scottish Highlands (e.g. Thorp, 1986).

The underestimation of maximal late Devensian RSL by BIM-1 indicates the need for greater crustal depression at this time. This requires either an earlier, or larger LGM ice build up, and/or a more persistent ice sheet during deglaciation (e.g. slower melting). In contrast, the overestimation of the Holocene high-stand around 6000 BP indicates that the model predicts too much glacial rebound by this time. This requires a reduction in LGM ice volume and/or persistence accompanied by more rapid melting during the deglacial phase. The latter therefore places clear constraints on the modifications acceptable to produce the required late Devensian RSLs.

5.1.1 Sensitivity analysis

In order to demonstrate the effects of varying ice volume at the time of the LGM and during the deglacial phase, we begin by presenting two sets of sensitivity analyses conducted using BIM-1 but with differing modifications to the Irish Ice Sheet component. In the past, researchers working outside the GIA modelling community have sometimes expressed concern at the accuracy of GIA ice model components at the local scale and the impact these inaccuracies may have on predictions of RSL (e.g. McCabe, 1997; McCabe *et al*., 2005). For this reason, we first examine the influence of local-scale ice movements, such as the re-advance associated with the 'Killard Point' stadial included in the nominal ice model for BIM-1. We do this by considering the contrasting RSL changes that arise if Ireland were completely ice-free after 19 000 BP (Model A). We also consider a second model (Model B) in which the spatial extent of Irish ice to the west and north-west of Ireland at the time of the LGM is reduced, with (onshore) ice limits similar to those proposed by Stephens & Synge (1965), and Bowen *et al*. (2002).

The results of these two experiments are plotted in Figure 3 alongside the original RSL predictions of BIM-1. It is clear from this that in the south and southwest of Ireland (away from the centre of crustal loading), the effects of removing all ice from Ireland after 19 000 BP (Model A) are small. However, in the north of Ireland the changes are more pronounced. The greatest divergence from the nominal BIM-1 ice model occur at c. 15 000 BP with a reduction in RSL predictions of c.10-12m. During the Holocene there is also an appreciable difference between BIM-1 and Model A predictions, with the latter commonly reducing the amplitude of the Holocene highstand by c. 2-3m. The greatest difference between BIM-1 predictions and the RSL predictions from Model B (removal of west coast ice at the LGM) occurs, perhaps unsurprisingly, at sites located in NW Ireland. However, even in west Donegal (14), where the largest change in RSL is experienced, the effect of total offshore ice removal only contributes to c. 5 - 6m of RSL lowering at 20 000BP. At all sites, the influence on the Holocene GIA signature is not significant.

5:1:2 Improving the fit with empirical RSL evidence

The results of these sensitivity analyses clearly demonstrate the requirement for a very thin ice sheet during the deglacial phase, since significant reductions in the amplitude of the Holocene high stand (and the associated geographical location of the Holocene 0m isobase) cannot be generated by local-scale changes in LGM ice thickness alone (Model B). Whilst the results from Model A significantly improve the fit with Holocene RSL evidence, the position of the Holocene 0m isobase in Donegal is still too far to the west.

We perform a further set of analyses to examine the effects of changing the duration of ice loading, initiating deglaciation shortly after 22 000 BP (e.g. McCabe *et al*., 2005) as opposed to after 21 000 BP in BIM-1. In the first analysis (Model C), we adopt the same pre-LGM and LGM ice sheet as BIM- 1 and, in accordance with the earlier sensitivity analyses, adopt a very thin Irish Ice Sheet of approximately half the ice thickness of BIM-1 during the deglacial phase. The second analysis (Model D) is identical to Model C except that, at the time of the LGM, we invoke a more laterally extensive ice sheet of similar morphology to that proposed by Sejrup *et al*. (2005). In this model, offshore ice thicknesses approach c. 650m off NW Donegal with ice extending out to the continental shelf break. Ice thickness in the northern Irish Sea Basin are also increased to a similar thickness in order to reconcile glaciological evidence suggesting that Snaefell (621m) on the Isle of Man was transgressed by ice at the LGM (e.g. Bowen, 1973; Boulton *et al*., 1977).

Figure 5 shows a comparison between RSL predictions generated by the nominal ice model for BIM-1 and the revised ice models C and D. Once again, away from the centre of ice loading over the north of Ireland, the disparity between RSL predictions from the three models becomes insignificant. However, around the north of Ireland coastline the differences become more apparent. Predictions from Model C deliver a far better fit with the Holocene observational RSL data than BIM- 1 and the Holocene 0m isobase no longer lies to the west of Sligo. A brief comparison between Model C and Model A (all Irish ice removed from BIM -1 after 19 000 BP) reveals that after c. 15 000 BP, predictions from the two models are largely identical with differences in the Holocene of no more than a few decimetres.

The RSL predictions produced by Model D (laterally extensive, thicker LGM ice) show even greater agreement with RSL data. The geographical extent of the Holocene high stand in the north is restricted, whilst concomitantly increasing maximal late Devensian RSL predictions to heights above those delivered by Model C. However, even this increase is insufficient to satisfy the geomorphological RSL evidence and limiting data (minimum) provided by dated 'glaciomarine' muds from around the north and eastern Ulster coastline. Neither do predictions from Model D yield a particular good fit with the high resolution sea-level index point data from Islay (22) and Knapdale (23) in southeast Scotland. In fact, in the north of Ireland, maximal late Devensian RSL predictions derived from this ice model are no higher than those produced by BIM- 1 since the increase in RSL predictions induced by thicker ice is offset by the effects of rapid and earlier deglaciation.

5.1.3 A best-fit Irish Ice Model

The analyses conducted in section 5:1:2 demonstrate that whilst changes to the ice sheet in the deglacial phase have greatly improved the fit with the Holocene observational evidence, significant misfits remain between model predictions and geomorphological RSL evidence from the late Devensian. Specifically, the maximal predictions of late Devensian RSL are consistently below the geomorphological evidence of RSL for this time period. Because of this, it would appear that early deglaciation shortly after 22 000 BP is incompatible with the Irish RSL data. In light of these results, we develop a revised Irish Ice Sheet component for BIM-1 that is constrained by both glaciological and RSL data (Model E, Figure 6). This model uses the same pre LGM ice build up, and LGM duration (24 000 – 21 000 BP) as the nominal Irish Ice component of BIM-1. Our best fit model differs from BIM-1 by having thicker ice in the Irish Sea and to the northwest of Ireland at the LGM (similar to Model D). We also have thickened ice across the Wicklow Mountains, Irish Midlands and over Kerry, in accordance with the trimline data of Rae *et al*. (2004) and Ballantyne *et al*. (2006). During the deglacial phase (20 000 to 16 000 BP), we adopt an almost identical ice sheet to that described in Model C, including rapid onset of deglaciation at 21 000 BP (figures 6 and 7).

Despite significant differences between the Irish Ice Sheet component of the nominal BIM-1 model and our revised 'best fit' ice model (Model E), there are no discernible differences between the RSL predictions of the two models for the majority of sites along Ireland's east, south and west coasts (see figure 8). The only exception to this is in Dublin (1), where the significantly greater volume of ice in the Irish Sea Basin associated with Model E results in more crustal uplift and higher predicted Holocene RSLs. Similarly, for most sites along the western coast of Britain, there is good agreement between RSL predictions from the two models.

Model E also produces a greatly improved fit with RSL data from the north of Ireland. The problematic Holocene high stand from Sligo (13) no longer exists and is greatly lowered in west Donegal (14). At all sites along the Ulster coastline, RSL predictions from Model E now yield a far better fit with the limiting data (maximum) in both the Holocene and back into the late Devensian. This is achieved whilst also generating sufficient crustal depression to satisfy most of the raised shoreline data and a lot of the limiting data (minimum) from the AMS radiocarbon dated 'glaciomarine' muds.

Kelley *et al*. (2006) have recently uncovered new evidence for the depth of the Lateglacial sea level lowstand in Belfast Lough (region 19) based on a submerged 'beach' deposit at c. 30m below present sea level. AMS radiocarbon dates obtained from an 'inter-tidal' shell assemblage contained within the deposit return ages of c.13 400 BP although at this time, reconstructions of RSL associated with Model E are around -5m below present (Figure 8). The work of Kelley *et al*. (2006) suggests that model E underestimates the amount of isostatic rebound that has taken place since the onset of deglaciation although reference to figure 3 demonstrates that this discrepancy cannot be overcome through reducing ice thickness during the deglacial phase. It is worth noting however, that whilst the lithostratigraphic units described by Kelley and co workers appear consistent with the characteristics of beach material, the depositional setting cannot be established with certainty. Furthermore, it is hard to assess whether the dates obtained for this submerged shoreline were derived from *in situ* material and as such, this data cannot be regarded as robust evidence for the former position of sea level.

It is apparent that at both Islay (22) and Knapdale (23), the fit with the index point data is not as good as with BIM-1. This misfit is caused by our thin Irish Ice Sheet during the deglacial phase which has enabled increased crustal rebound to occur and a subsequent lowering of RSL. However, local scale adjustments in both Scottish ice thickness and more specifically the rate of ice retreat should provide a solution to these model misfits.

5.2 The Role of the Earth Model

The Earth model used in these analyses (and outlined in section 2:1) is parameterised into three layers which correspond to the lithosphere, the upper mantle and the lower mantle. When considering patterns of GIA in regions once occupied by small ice sheets such as the BIIS, changes in the depth/viscosity of the lithosphere and upper mantle are of greatest significance. Adjustments to the lower mantle would appear less important since even the rebound associated with the much larger Fennoscandian Ice Sheet is only weakly sensitive to this model parameter (Mitrovica and Peltier, 1991; Peltier, 1996).

Lithospheric thickness controls the magnitude of crustal depression in response to loading and any changes to this will either uniformly raise or lower predictions of RSL throughout the entire post glacial period. It follows that changes in the depth of the lithosphere will be unable to reconcile differences between predictions from BIM-1 and the RSL evidence since maximal predictions from BIM- 1 are generally too low in the late Devensian and too high in the Holocene. However, upper mantle viscosity is of more relevance here since this parameter controls the rate of crustal response to loading-unloading episodes (e.g. Lambeck, 1993a,b). Estimates for upper mantle viscosity have been consistent between various modelling studies from the British Isles with most workers preferring either a value of 4 x 10^{20} Pa ^{14}Cs (Lambeck, 1993a; Lambeck, 1993b; Lambeck, 1995; Lambeck *et al*., 1996; Shennan *et al*., 2000c) or 5 x 10^{20} Pa s (Peltier, 1998; Peltier, 2004; Peltier *et al*., 2002; Shennan *et al*., 2006a). Reducing the values of upper mantle viscosity will increase the response rate of the crust to loading and unloading episodes. The corollary of this will be a reduction in the rate of crustal deformation during the Holocene and consequently induce a lowering of RSL predictions during this period.

To examine the impact of changes in upper mantle viscosity, we perform a final set of sensitivity analyses on BIM-1 by producing RSL predictions generated with reduced upper mantle viscosity values of 3 x 10^{20} Pa s and 4 x 10^{20} Pa s. These are compared with the original RSL predictions from BIM-1 (v_{UM} 5 x 10^{20} Pa s) and the results presented in figure 9. In the south and west of Ireland, where the eustatic contribution to RSL change appears to dominate over the glacio-isostatic component, the reduction in upper mantle viscosity has negligible impact on the RSL predictions. However, toward the centre of loading in the north the impact of these changes becomes far more apparent. At all sites around the Ulster coastline, reduced upper mantle viscosity raises maximal predictions of RSL by, in the case of the v_{UM} 3 x 10^{20} Pa s model, in excess of 10m. Conversely, the magnitude (and geographical range) of the Holocene highstand is reduced: In west Donegal (14) it is lowered by c.2m by adopting the v_{UM} 4 x 10^{20} Pa s model, whilst the v_{UM} 3 x 10^{20} Pa s model has the effect of removing the highstand altogether. In fact, when adopting the low viscosity (v_{UM} 3 x 10^{20} Pa s) Earth model, the greatest magnitude of Holocene highstand in Ireland is no more than +2.5m.

Finally, we consider the effects of running our best fit model (Model E) with a lower upper mantle viscosity Earth model of 4 x 10^{22} Pa s. Reference to figures 10 and 11 shows that this combination of a thin Irish ice sheet during the deglacial phase coupled with a reduced upper mantle Earth model does yield a close fit with the empirical RSL data. The Holocene highstand is removed from west Donegal (14) and model predictions are now in good agreement with the index point data from this locality. In north Antrim (18) (where the isostatic component of the RSL signal is at its greatest) the Holocene highstand is c. +5m. This figure is significantly lower than the c. +8m highstand predicted by running BIM- 1 with an earth model of v_{UM} 5 x 10^{20} Pa s (as in the original Shennan *et al*., analyses). Elsewhere around the Ulster coastline, model predictions satisfy all the constraints placed by the primary limiting date evidence as well as a large number of the secondary limiting dates.

6 DISCUSSION

The analyses undertaken in section 5 outlines the extent to which model predictions of RSL respond to adjustments in both ice and Earth model input parameters. Significant improvements in the fit between BIM- 1 predictions and the Irish RSL data can be achieved through altering the Irish component of this regional ice model yet changes in the ice model alone have not completely reconciled discrepancies with observations of RSL. In particular, we are still left with a Holocene highstand in west Donegal which is unsubstantiated by field evidence. Interestingly, a similar problem relating to the position of the 0m Holocene isobase on the west coast of Britain has been encountered in recent modelling studies of the British data (Shennan *et al*., 2002; Shennan *et al*., 2006a) and, as in the case of this investigation, a solution could not be found through adjustments in the regional ice model. Model predictions of the geographical location of the 0m isobase can be marginally improved through increasing the eustatic melt water contribution since 7000 BP to a maximum of 3m (e.g. Lambeck, 2002). However, we are still left with predictions of a Holocene high stand in both west Donegal and north Wales which are at odds with available field evidence.

Both Milne *et al*. (2006) and Shennan *et al*. (2006a) have shown that predictions of RSL in the post glacial are sensitive to ice sheet evolution in the pre-LGM period. For this reason, changes in the ice sheet thickness were considered during the temporary retreat phase (25 000 – 26 000 BP). However, removing this retreat stage only imparted a very minor GIA signal after the LGM. Because no further changes can be made to the Irish ice model without contradicting the empirical glaciological evidence, it would appear that the Earth model employed in the Shennan *et al*. (2006a) analyses is untenable with the Irish RSL evidence.

Significant alterations to BIM- 1 RSL predictions can also be achieved through lowering the upper mantle viscosity of the Earth model. A greatly improved fit between BIM- 1 predictions and the Irish RSL dataset is achieved by adopting an upper mantle viscosity of 4×10^{20} Pa s which is a similar value to that used by Lambeck and co workers in their earlier analyses from the region. However, the problematic Holocene high stand remains in west Donegal. Whilst this may be removed by lowering the upper mantle viscosity still further to a value of 3×10^{20} Pa s, the overall fit with available RSL data from the north of Ireland becomes extremely poor: The greatest Holocene highstand around the Ulster coastline is no more than 2.5m and the RSL predictions become significantly at odds with the Holocene index point data from south Down (20) and south west Scotland. In order to reconcile the differences between the BIM-1 (v_{UM} 3×10^{20} Pa s) and the Holocene RSL data, a substantial increase in crustal loading would be required during a large part of the late Devensian. However, the resultant rise in RSL in the late Devensian time interval would almost certainly be at odds with available geomorphological evidence of RSL from Ireland. Similarly, it is hard to see how such a low viscosity upper mantle Earth model would be compatible with the long time-series records of RSL change from the west coast of Scotland, particularly since trimline evidence provides a strict upper bound for the maximum thickness of ice at the time of the LGM. Because of the above, such a low viscosity upper mantle is extremely unlikely to provide an acceptable solution.

The above demonstrates that a resolution for model misfits cannot be achieved through changes to one or the other of the ice/Earth model. Instead, it is evident that combined revisions to both the existing BIM- 1 ice model and the original Earth model are desirable in order to achieve a solution that satisfies the constraints provided by both the RSL and glaciological evidence from Ireland. Indeed, running our best fit ice model (Model E) with a slightly reduced upper mantle viscosity of 4 x 10^{20} Pa s would appear to provide a very good overall solution. Using this ice-Earth model combination satisfies nearly all the late Devensian RSL evidence from around the Ulster coastline and in Donegal, the predicted 0m isobase now occupies the same geographical location as that reconstructed through field evidence (figure 11). On the Isle of Man and in North Wales, the fit with the Holocene data is considerably improved. Importantly, the well constrained 0m Holocene isobase on the east coast of Britain is largely unaffected by the revision to the Earth model.

An important, additional test of this revised Earth-ice model solution is the quality of the fit to the long time-series RSL records from Scotland (see figure 10). On first inspection, it appears as though the new reduced viscosity model is incompatible with the index point data from both Islay and Knapdale. However, whilst BIM- 1 is constrained by glaciological evidence, it is also inferred on the basis of the Earth model employed in the Shennan *et al*. (2002) investigation. Significantly, the analyses of Shennan *et al*. (2006a) has shown that the 96km lithosphere used in the Shennan *et al*. (2002) paper is untenable with observational RSL data from Britain. This means that there now exists considerable scope to make local scale adjustments in the British Ice model, specifically in areas which are poorly constrained by trimline data. This will be addressed in a future paper that will consider GIA model fits to the entire UK and Irish RSL data as well as observations of present-day crustal motions derived from Global Positioning System (GPS) measurements.

7 Conclusion

Observations of post-glacial RSL around Ireland are limited in both time and space and are generally less complete than records found in Britain. However, we have shown that the newly compiled and quality assessed Irish RSL database (Brooks & Edwards, 2006) does provide an important data set with which to test GIA models for Ireland and the UK. Assuming that the influence of lateral earth structure beneath the British Isles produces a minor impact on predictions of RSL in this region, we conclude that the Irish Ice Sheet depicted in Shennan *et al*. (2006a) is wholly incompatible with observations of late Devensian and Holocene RSL in Ireland. Employing the same Earth model as Shennan *et al*., our 'best fit' ice model for Ireland comprises a thick, spatially extensive Irish ice sheet of around 700m over much of north and central Ireland at the LGM. Relatively thick ice out to the continental shelf off the west coast of Scotland and Ireland coupled with thick Irish Sea Ice is required to produce a sufficient fit with observational RSL data from the late Devensian.

We find that predictions of RSL are sensitive to the specific rate and timing of deglaciation prior to the LGM. The Irish RSL data strongly favour very rapid deglaciation after 21 000 BP: Early (pre 21 000 BP) deglaciation produces unacceptably low predictions of maximum late Devensian RSL in the north of Ireland and SW Scotland whilst gradual deglaciation between 20 000 to 16 000 BP deteriorates the fit with observations of Holocene RSL.

This study cannot offer unequivocal evidence for or against rejecting the South of Ireland End Moraine as the southerly limit of late Devensian Irish Ice. However, in order to fit the RSL data, a significant thickness of ice (c.500m) is needed over the Irish Midlands, which are only a short distance to the north of the South of Ireland End Moraine. If the moraine is taken as the true southern limit of LGM ice extent, it follows that the ice sheet would have had a very steep southern margin and this may be glaciologically implausible.

Significantly, all of the models considered in the analyses presented here deliver maximal predictions of late Devensian RSL along Ireland's west coast that are well below present msl. No evidence is found in support of the suggestion by McCabe (2005); McCabe *et al*. (1986; 2005); Thomas and Chiverrell (2006) of higher than present late Devensian RSL along this stretch of coastline.

Only a limited fit with available records of RSL can be obtained by altering the Irish Ice Sheet component of BIM-1. Significant discrepancies with RSL data could not be resolved, particularly those in relation to the geographical position of the 0m Holocene isobase. However, it was possible to solve this problem by making a minor reduction to the value of upper mantle viscosity employed in the Earth model. Despite the significant changes in RSL predictions bought about through making this adjustment to the Earth model, our results still conclusively demonstrate that the Irish component of BIM-1 is not compatible with the RSL data. The primary conclusion from our ice modelling – the need for a thinner Irish Ice Sheet soon after the LGM and throughout the deglacial phase - remains a robust requirement of the RSL data regardless of the adopted viscosity model.

Appendix 1
RSL Data Contributors

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Table Captions

Table 1: Source(s) of RSL data from Ireland and UK (west coast) sites

Figure captions

Figure 1: Time-space evolution of the Irish component of BIM- 1 (32 – 16ka cal. BP) (Adapted from Shennan *et al*., - 2006a)

Figure 2: Location map of the 30 RSL time-series records

Figure 3: RSL predictions generated by BIM- 1 (*solid line*); Model A (*long dashed line*) and Model B (*dotted line*)

Figure 4: BIM- 1 RSL isobase map at 6ka BP

Figure 5: RSL predictions generated by BIM- 1 (*solid line*); Model C (*long dashed line*) and Model D (*dotted line*)

Figure 6: Time-space evolution of our ‘best fit’ ice model (Model E) (32-16ka cal. BP)

Figure 7: Percentage volumetric change of Model E in the period 26-15ka BP

Figure 8: RSL predictions generated by BIM- 1 (*solid line*) and Model E (*long dashed line*)

Figure 9: RSL predictions generated by running BIM- 1 with v_{UM} 5 x 10^{20} Pa s (*solid line*), 4 x 10^{20} Pa s (*long dashed line*) and 3 x 10^{20} Pa s (*dotted line*)

Figure 10: RSL predictions generated by running BIM- 1 with v_{UM} 5 x 10^{20} Pa s (*solid line*) and Model E with v_{UM} 4 x 10^{20} Pa s (*long dashed line*)

Figure 11: Model E RSL isobase map at 6ka BP run with v_{UM} 4 x 10^{20} Pa s

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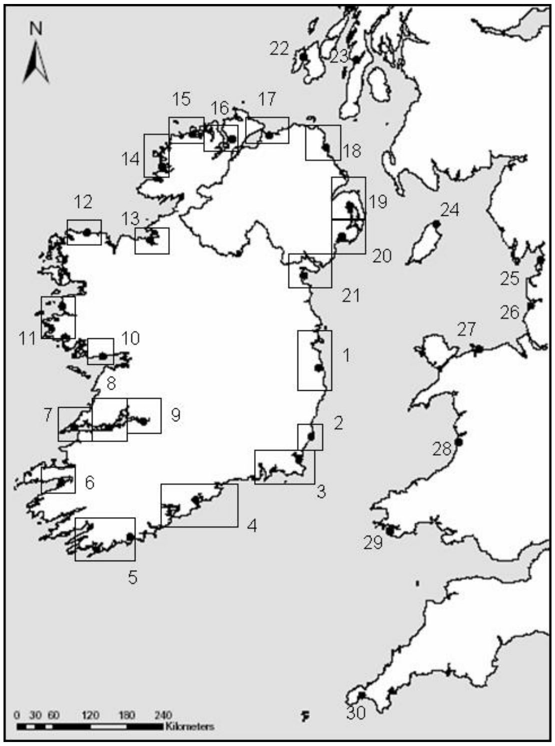
Table 1

Site	Name	Lat.	Long.	No. data	Reference(s)
01	Dublin	53.138	-6.123	0 (+ 7)	Mitchell (1976)
02	North Wexford	52.521	-6.232	1	Sinnott, (1999)
03	South Wexford	52.315	-6.412	11 (+ 5)	Mitchell (1977); Dresser, (1980); Carter & Orford, (1982); Orford & Carter (1982b); Maloney, (1985); Sinnott, (1999)
04	East Cork	51.949	-7.935	10 (+ 1)	Mitchell, (1976); Mitchell, (1977); Carter et al., (1989); Sinnott, (1999)
05	West Cork	51.607	-8.906	13 (+ 5)	Stillman, (1968); Buzer, (1980); Sinnott, (1999); Devoy et al., (2004)
06	Kerry	52.107	-9.916	1 (+ 10)	Carter et al., (1989)
07	South Clare	52.601	-9.721	0 (+ 5)	Pearson, (1979); Devoy et al., (1996); O’Sullivan, (2001)
08	Mid Shannon	52.601	-9.213	0 (+ 3)	O’Sullivan, (2001)
09	Inner Shannon	52.658	-8.705	0 (+ 9)	O’Sullivan, (2001)
10	Galway	53.238	-9.305	0 (+ 1)	Mitchell (1976)
11	Connemara	53.679	-9.900	0 (+ 10)	Jessen (1949); Devoy et al., (1996)
12	North Mayo	54.320	-9.540	0 (+ 8)	McCabe et al., (1986, 2005)
13	Sligo	54.258	-8.607	0 (+ 1)	Burenhuit, (1980)
14	West Donegal	54.885	-8.431	8 (+ 11)	Smith & Pilcher., (1973); Telford, (1978); Pearson, (1979); Carter, (1982); Gaulin et al., (1983); Shaw, (1985); Shaw and Carter, (1994); HOLSMEER, (2004); Harmon, (2006)
15	North Donegal	55.160	-7.979	3 (+ 6)	Shaw, (1985); Shaw and Carter, (1994)
16	Lough Swilly	55.119	-7.399	0 (+ 8)	Colhoun et al., (1973); Shaw and Carter, (1994); McCabe & Clark (2003)
17	Derry	55.15	-6.851	0 (+ 10)	Pearson, (1979); Battarbee et al., (1982); Carter & Wilson, (1990); Woodman, (unpub.*); Bazley et al., (unpub.*)
18	North Antrim	55.052	-6.014	0 (+ 8)	Mitchell & Stephens, (1974); Prior et al., (1981); Smith et al., (1974)
19	North Down	54.55	-5.658	0 (+ 15)	Stephens & Collins, (1960); Morrison & Stephens, (1961); Morrison & Stephens, (1965); Manning et al., (1970); Smith et al., (1974); Pearson & Pilcher, (1975); Harkness & Wilson, (1979); McCabe & Clark, (1998)
20	South Down	54.29	-5.774	2 (+ 10)	Hubbs, Bien & Suess, (1965); Dresser et al., (1973); Singh & Smith, (1973); Carter, (1982); McCabe & Clark, (1998)
21	Dundalk	53.947	-6.340	0 (+ 16)	Jessen, (1949); Mitchell, (1971); Penney, (1983); McCabe & Haynes, (1996); McCabe & Clark, (1998); McCabe et al., (2005) Clark et al., (submitted[+])
22	Islay	55.808	-6.343	8	Shennan et al., (submitted)
23	Knapdale	55.784	-5.561	9 (+ 7)	Shennan et al., (submitted)
24	Isle of Man	54.395	-4.388	12 (+ 2)	Tooley (1977); Roberts et al., (submitted)
25	Morecombe Bay	54.085	-2.958	21 (+ 3)	Tooley (1978a); Birks (1982); Zong & Tooley (1996)
26	Lancashire	53.685	-2.990	42	Tooley (1978a,c, 1985); Huddart (1992)
27	North Wales	53.300	-3.748	9	Tooley (1978a); Kidson & Heyworth (1982); Bedlington (1993)
28	Mid Males	52.473	-4.058	14 (+ 3)	Heyworth & Kidson (1982)
29	SW Wales	51.658	-5.066	1	Heyworth & Kidson (1982)
30	Cornwall	50.129	-5.482	7	Healy (1995)

* *cited in* Carter, (1982a); [+] *cited in* McCabe *et al.,* (2005)
(In the ‘No. data’ column, bracketed numbers refer to the number of non-primary index points)

Figure 1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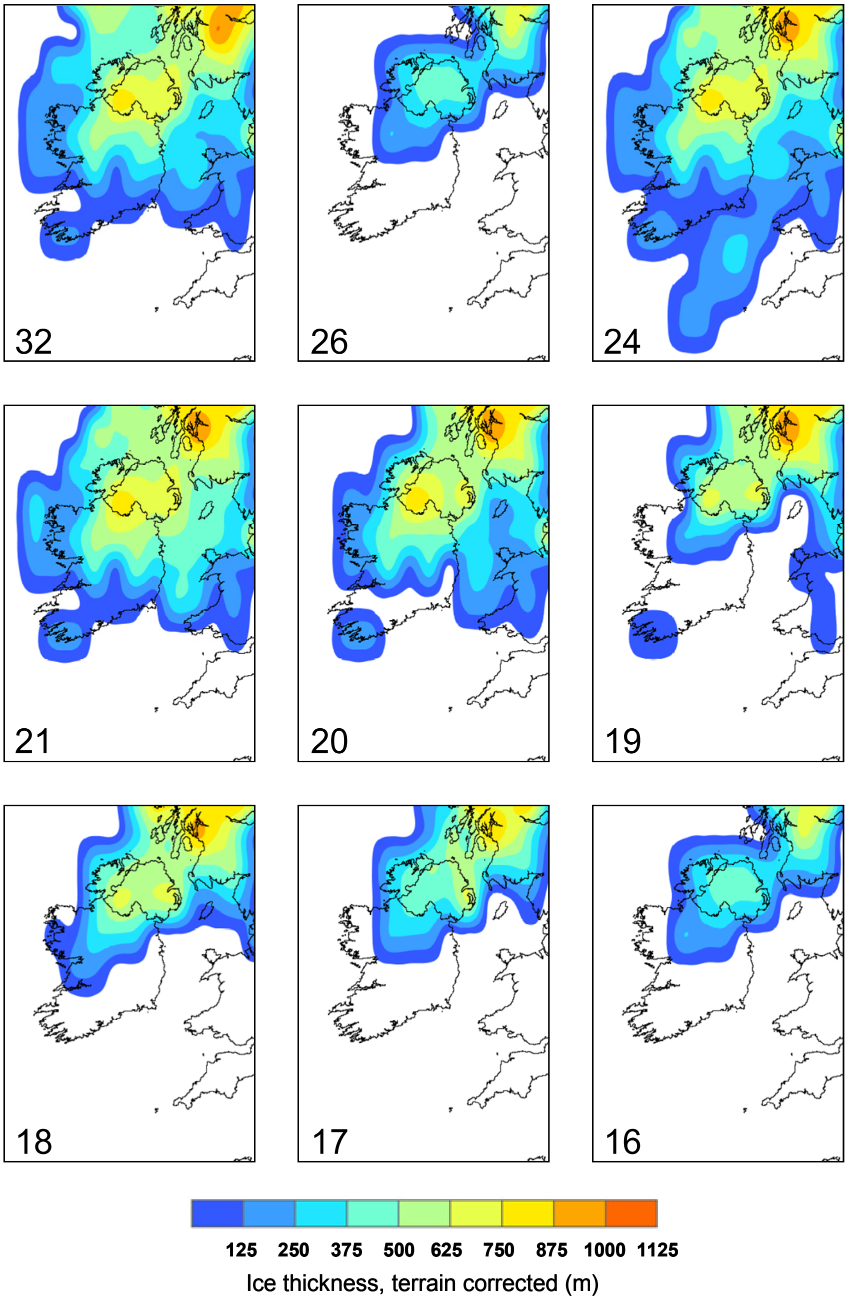
0 30 60 120 180 240
Kilometers

Figure 2


32
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875
1000
1125
Ice thickness, terrain corrected (m)

Figure 3

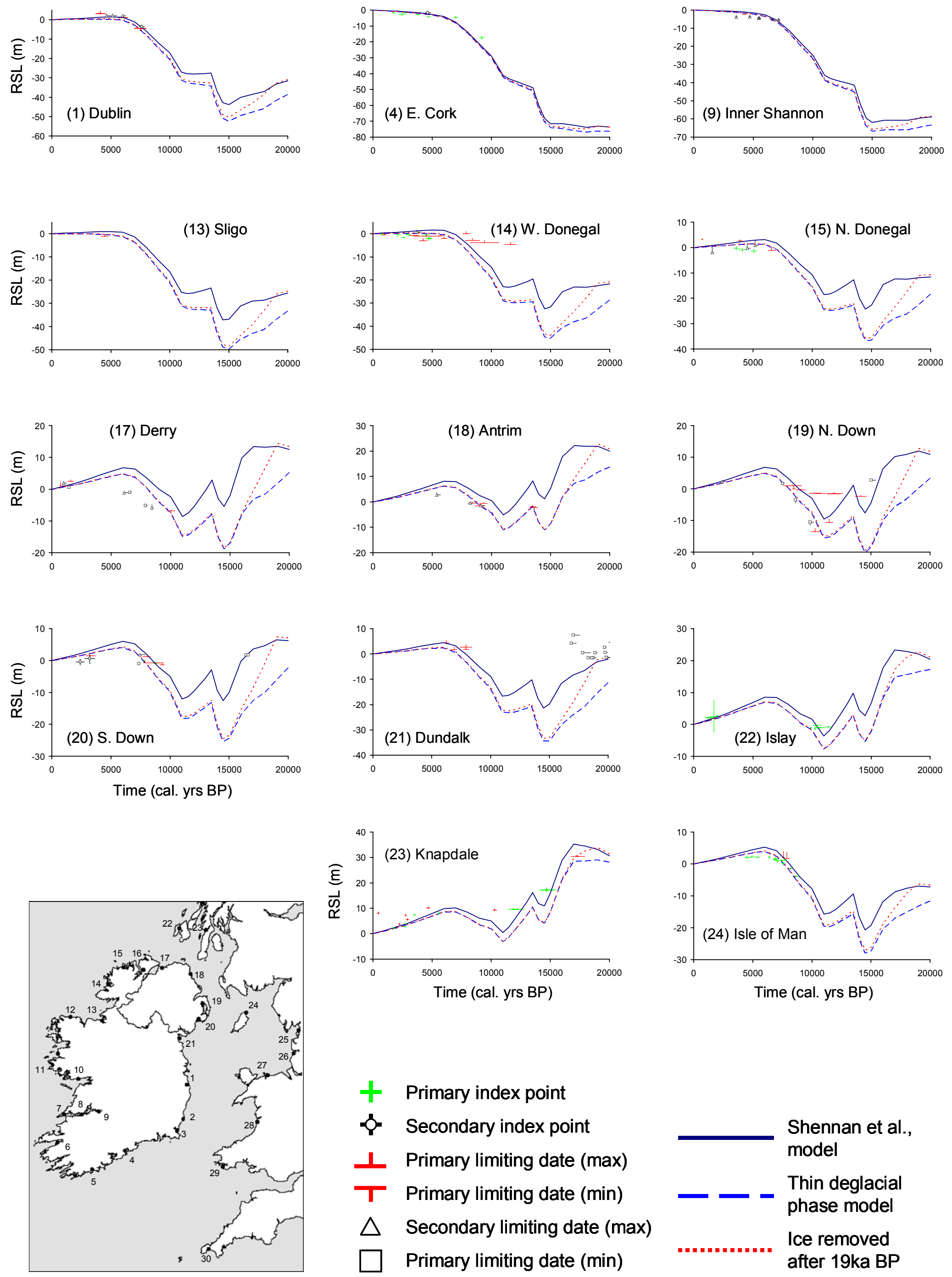
(1) Dublin
(4) E. Cork
(9) Inner Shannon
(13) Sligo
(14) W. Donegal
(15) N. Donegal
(17) Derry
(18) Antrim
(19) N. Down
(20) S. Down
(21) Dundalk
(22) Islay
(23) Knapdale
(24) Isle of Man
RSL (m)
Time (cal. yrs BP)
0
5000
10000
15000
20000
Primary index point
Secondary index point
Primary limiting date (max)
Primary limiting date (min)
Secondary limiting date (max)
Primary limiting date (min)
Shennan et al., model
Thin deglacial phase model
Ice removed after 19ka BP
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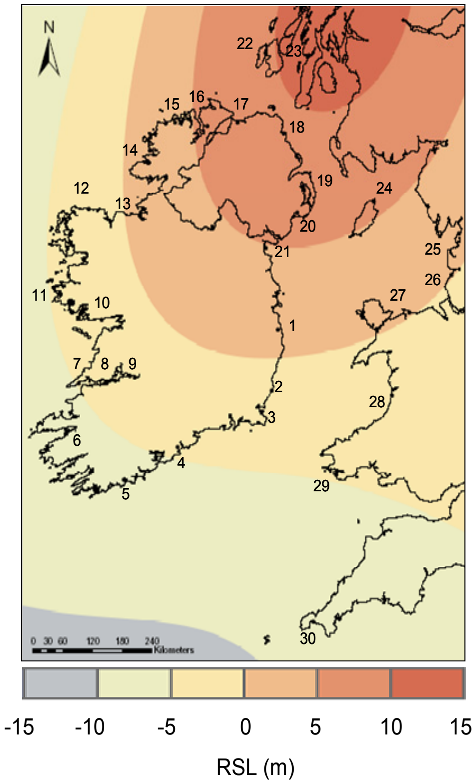
Figure 4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0 30 60 120 180 240
Kilometers
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-10
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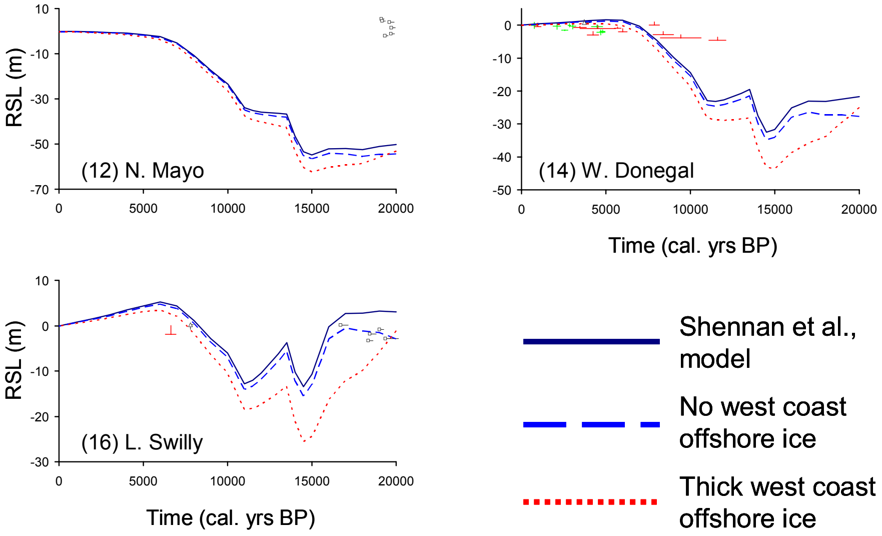
10
15
RSL (m)

Figure 5


(12) N. Mayo
(14) W. Donegal
(16) L. Swilly
RSL (m)
Time (cal. yrs BP)
10
-10
-30
-50
-70
0
-20
-40
0
5000
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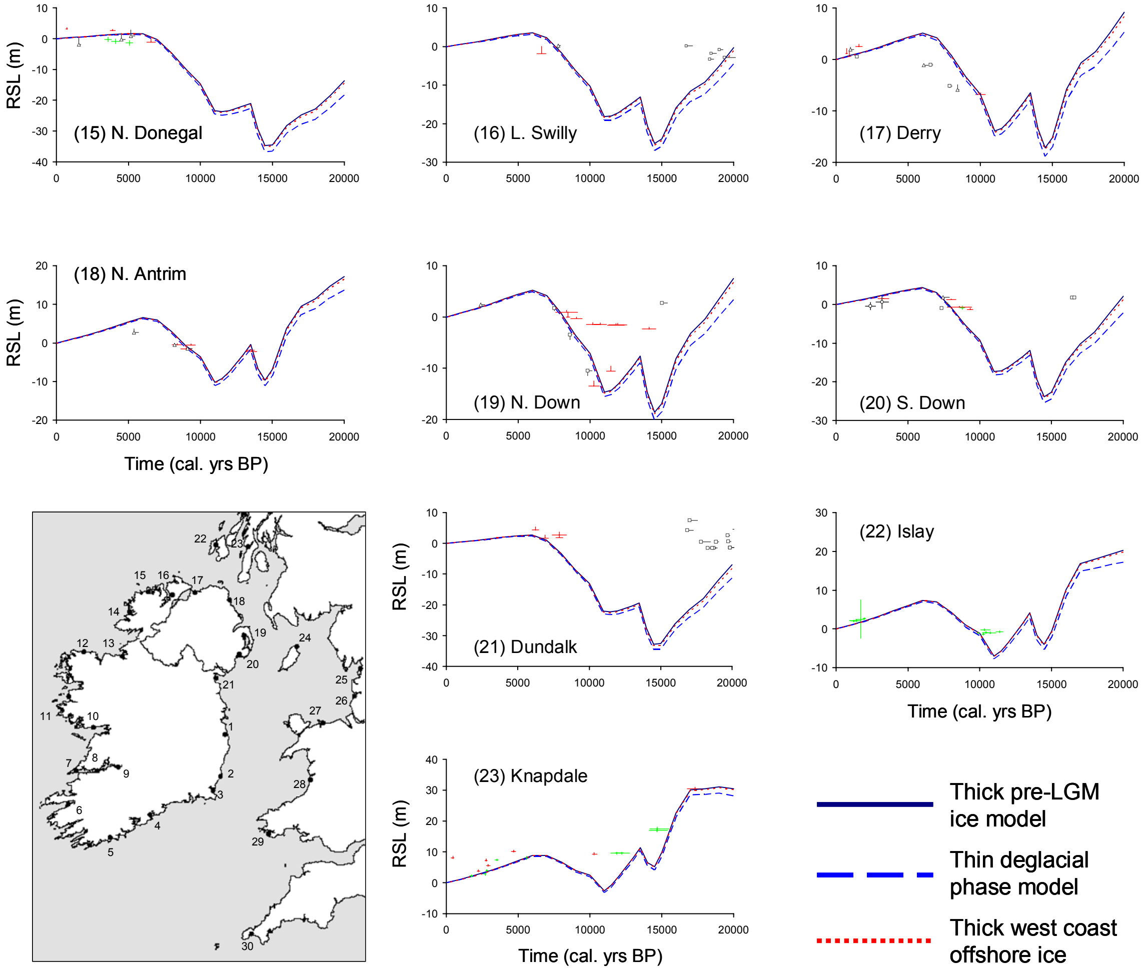
20000
Shennan et al., model
No west coast offshore ice
Thick west coast offshore ice

Figure 6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(16) L. Swilly
(17) Derry
(18) N. Antrim
(19) N. Down
(20) S. Down
(21) Dundalk
(22) Islay
(23) Knapdale
RSL (m)
Time (cal. yrs BP)
0
5000
10000
15000
20000
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30
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-10
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-30
-40
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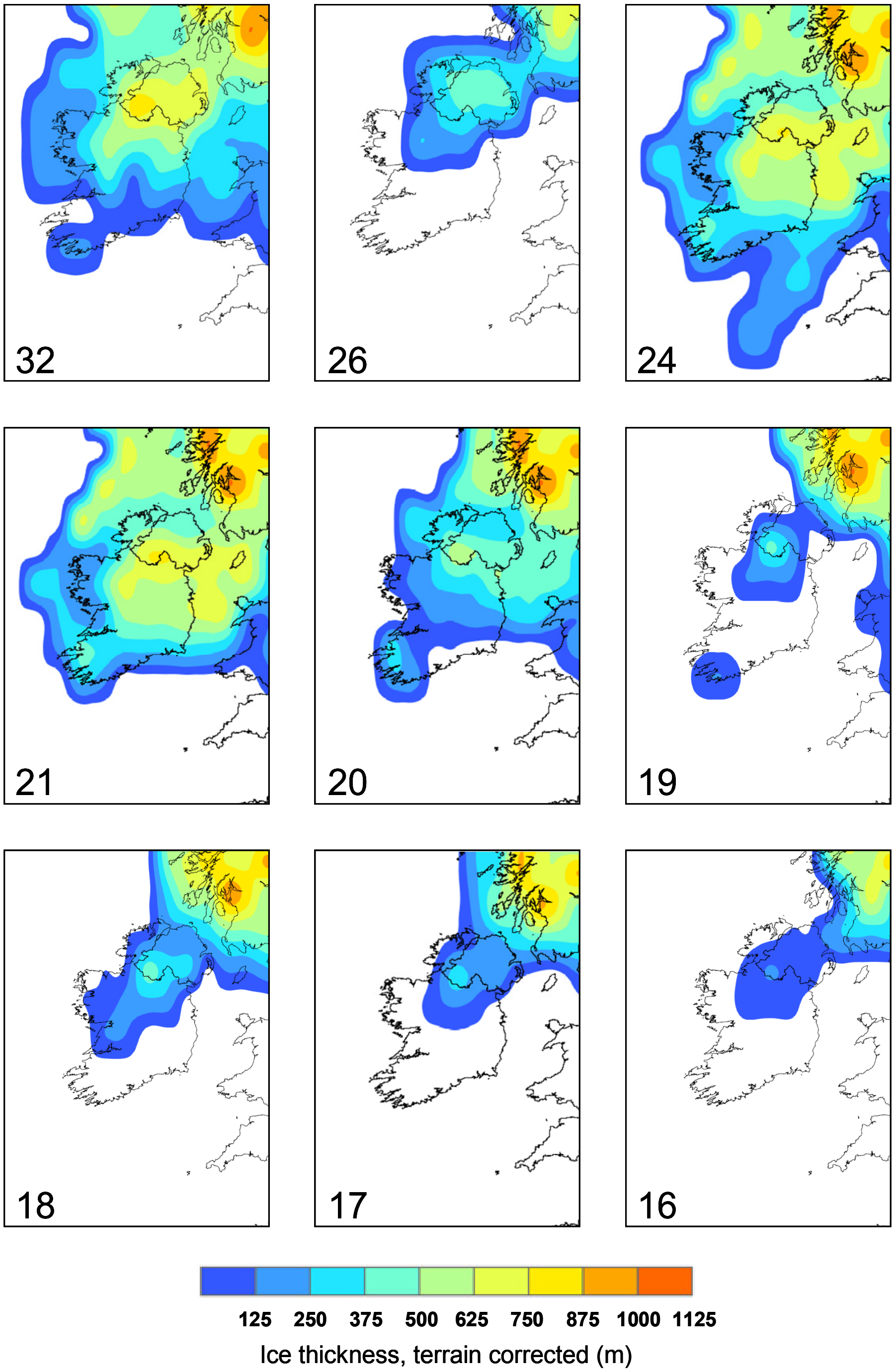
Thick pre-LGM ice model
Thin deglacial phase model
Thick west coast offshore ice

Figure 7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Ice thickness, terrain corrected (m)

Figure 8

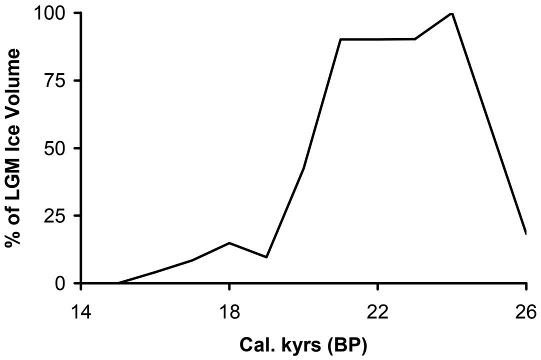
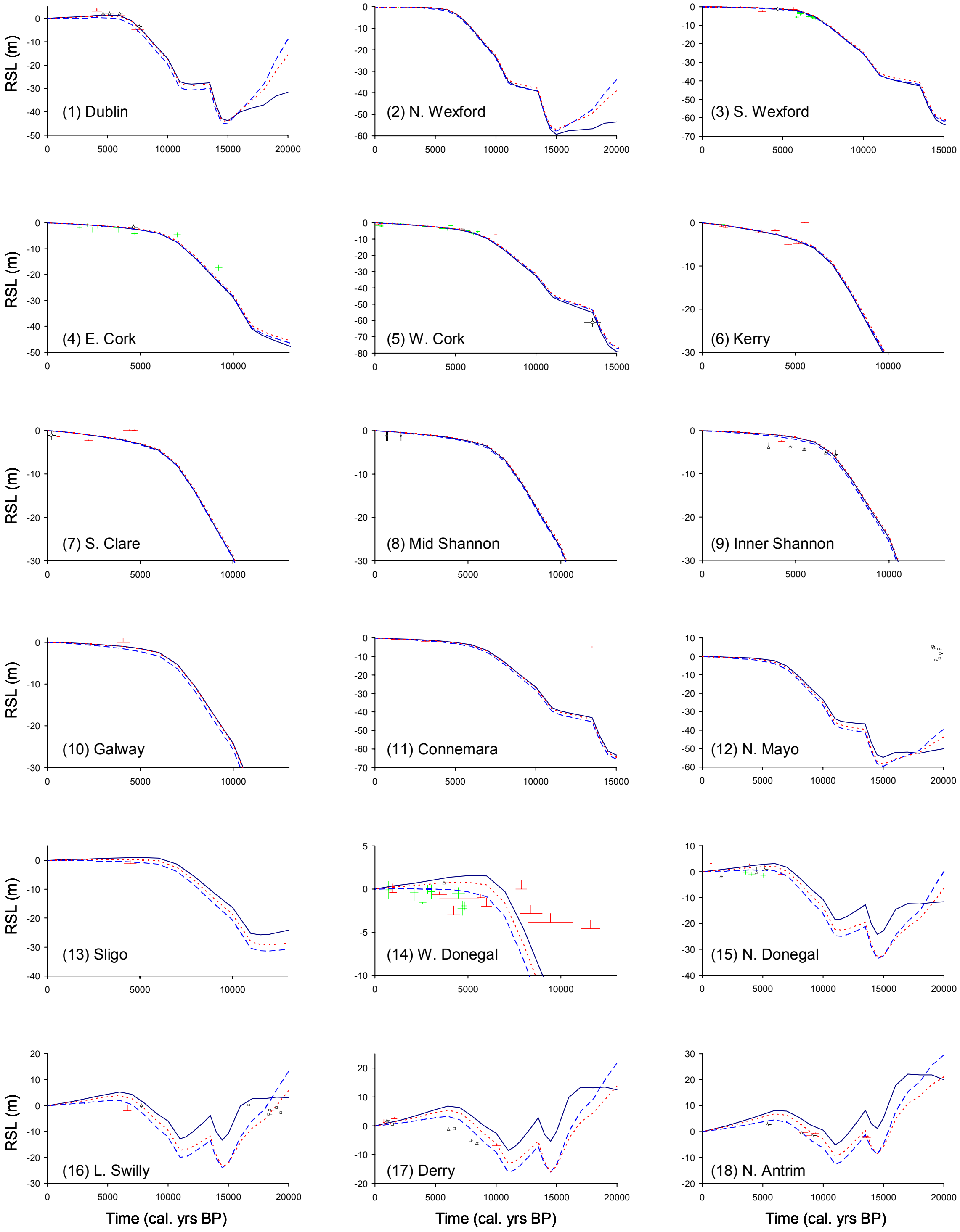


Figure 9


RSL (m)
(1) Dublin
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0
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10000
15000
20000
(2) N. Wexford
0
-10
-20
-30
-40
-50
-60
(3) S. Wexford
0
-10
-20
-30
-40
-50
-60
-70
(4) E. Cork
(5) W. Cork
-80
(6) Kerry
(7) S. Clare
(8) Mid Shannon
(9) Inner Shannon
(10) Galway
(11) Connemara
(12) N. Mayo
10
(13) Sligo
(14) W. Donegal
5
-5
(15) N. Donegal
(16) L. Swilly
20
(17) Derry
(18) N. Antrim
30
Time (cal. yrs BP)

Figure 9… (cont)

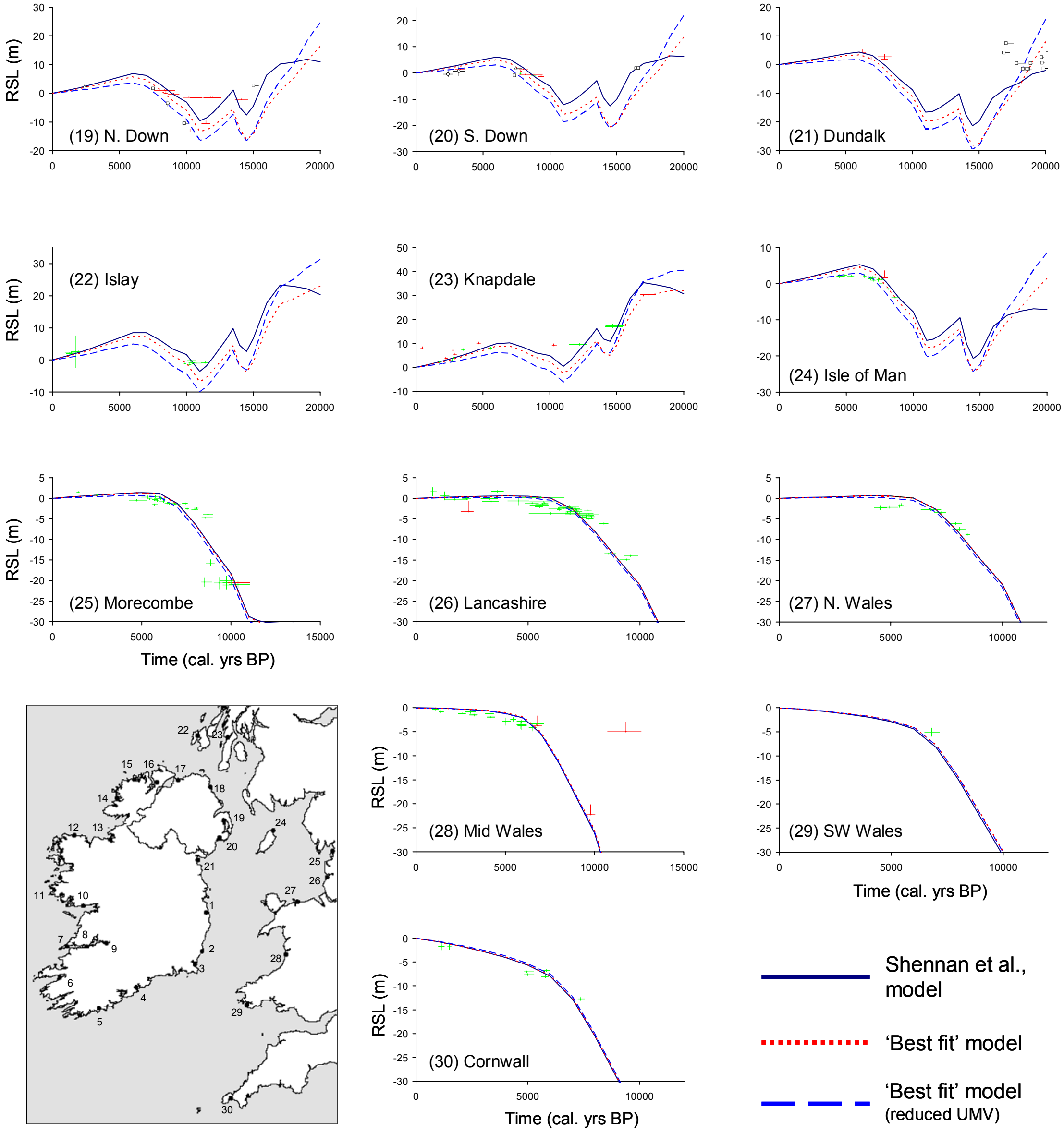
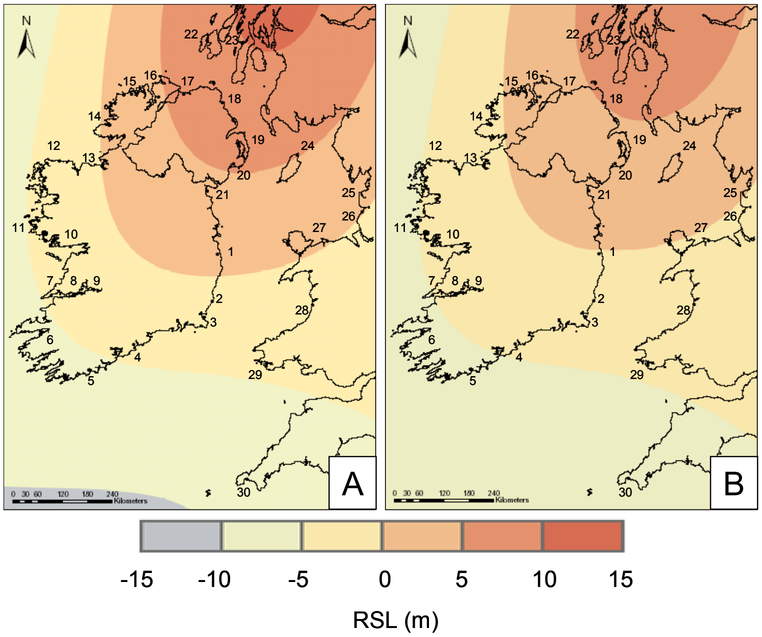


Figure 10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Kilometers
A
B
-15
-10
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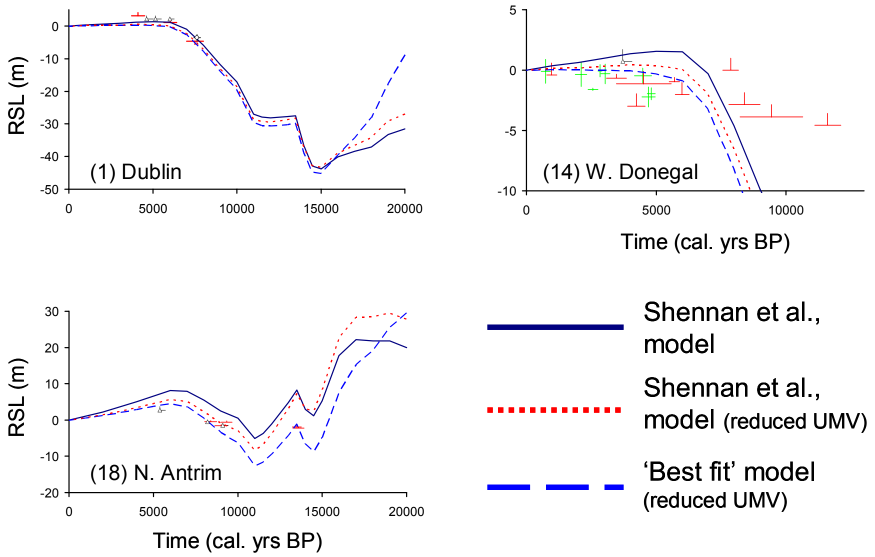
0
5
10
15
RSL (m)

Figure 11


RSL (m)
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-40
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10000
15000
20000
(1) Dublin
5
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-5
-10
0
5000
10000
(14) W. Donegal
Time (cal. yrs BP)
RSL (m)
30
20
10
0
-10
-20
0
5000
10000
15000
20000
(18) N. Antrim
Time (cal. yrs BP)
Shennan et al., model
Shennan et al., model (reduced UMV)
'Best fit' model (reduced UMV)

Appendix A: RSL database contributors

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