Simulated Late-glacial and Holocene relative sea-level and palaeotidal changes on the Isles of Scilly: a new approach for assessing changes in the areal extent of the inter-tidal zone

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Human palaeodietary analyses indicate that the Neolithic transition in NW Europe may have been characterised in coastal populations by a shift from a marine-based to a terrestrial diet. In order to test whether this shift was at least partly forced by a reduction in the size of the inter-tidal zone – from which human communities forage for marine resources – we reconstruct the areal extent of the inter-tidal zone on the Isles of Scilly over the last 13,000 years. This novel pilot analysis, which incorporates relative sea-level simulations based on glacial isostatic adjustment model output and palaeotidal simulations, demonstrates the significance of coastal topography/gradient in determining inter-tidal extent. The simulations for Scilly show only very modest changes in the extent of the inter-tidal zone across the Neolithic transition indicating minimal or no physical influence at this location for any palaeodietary change. Nevertheless, these model data contribute to an informed assessment of the changing palaeogeography of Scilly over the last 13,000 years that provides a basis for testing via field observations. Furthermore, the tidal amplitude data can be used to correct the indicative meaning of emerging sea-level index points from Scilly.

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Introduction, aims and objectives

One of the most striking attributes of the European Mesolithic-Neolithic transition (*c*. 6,000 cal BP) to emerge from recent research is the apparent abandonment of marine resources in favour of terrestrial food sources in coastal populations, i.e. the replacement of fish and shellfish in the human diet by meat and vegetables (Richards and Hedges, 1999; Schulting and Richards, 2001; Richards and Schulting, 2006). Stable isotopic analyses of human bone from some localities provide convincing evidence for this palaeodietary hypothesis. Though there have been significant critiques of the rigidity and rapidity of this postulated change, and an understandable focus on the economic, social, cultural and technological drivers underpinning this transition (Milner *et al*., 2004, 2006), there were significant changes taking place in the physical environment coincident with the Mesolithic-Neolithic transition that may have influenced the rate of palaeodietary change and its spatial heterogeneity. These include palaeoclimatic changes (Roberts, 1998) and, significantly for an hypothesis involving marine resources, changes in relative sea level (rsl).

It is now widely recognised that as rsl changed during the Holocene, largely as a function of the interplay of glacio-eustatic and glacio-isostatic controls (Lambeck, 1995; Bradley *et al*., 2011), the tides also changed (Thomas and Sündermann, 1999; Egbert *et al*., 2004; Uehara *et al*., 2006; Arbic *et al*., 2008; Griffiths and Peltier, 2008). The ability to simulate past changes in tides and tide-dependent parameters provides the potential to interrogate what significant changes, if any, have taken place in the coastal marine environment over time. Here we present the results of palaeotidal reconstructions for the Isles of Scilly (Figure 1) covering time-slices from the Devensian Late-glacial and Holocene in order to test the hypothesis that the extent of the inter-tidal zone – the zone from which prehistoric communities are able to access marine resources – changed in areal extent significantly between the Mesolithic and the Neolithic. It is not the intention of this contribution to test whether any such change had any significant impact on resource access or on the character of the Mesolithic-Neolithic transition on Scilly. Rather, we confine our analysis to a reconstruction of the changes in tidal amplitudes and to the extent of the inter-tidal zone on Scilly through the last 13,000 years, and offer this as a methodological demonstration that palaeotidal simulations have the potential to reveal previously intractable aspects of coastal palaeoenvironmental change that may have significant implications for archaeological and ecological interpretation. We select the Isles of Scilly for this investigation because:

1) Island settings are well-constrained geographically and provide closed topographic boundaries that facilitate simulation.
2) The Isles of Scilly have a rich archaeological heritage (Johns, 2006), including Mesolithic and Neolithic material, demonstrating human influence across the transition in question.
3) The general pattern of Holocene relative sea-level change is reasonably known from sea-level index points from the wider region (Heyworth and Kidson, 1982; Healy, 1995; Massey *et al*., 2008; Gehrels *et al*., 2011).
4) Archaeological and Holocene palaeoenvironmental investigation are ongoing, including the generation of new sea-level index points (The Lyonnesse Project, Cornwall and Isles of Scilly Maritime Archaeological Society, 2013).

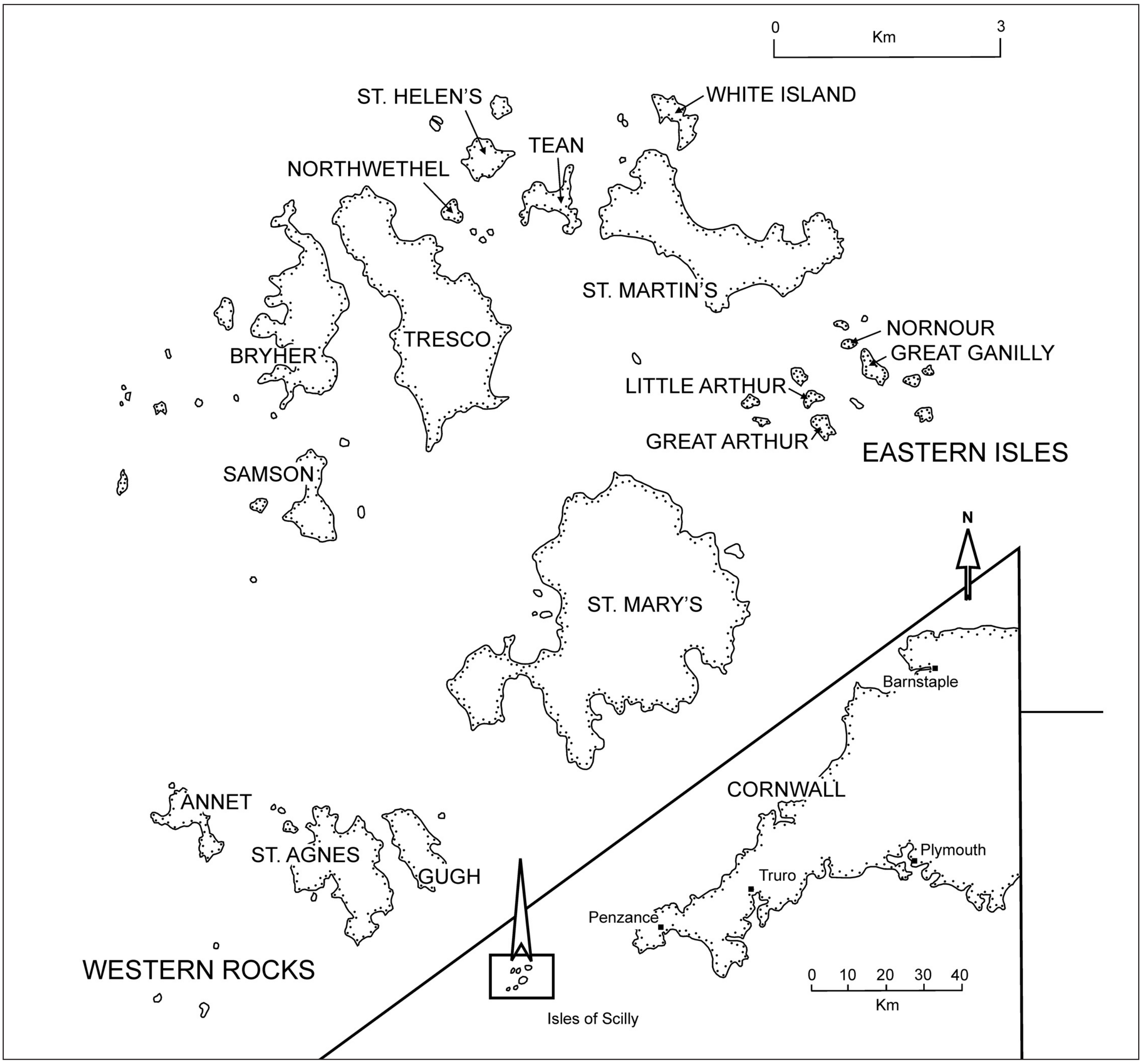


Figure 1. *The Isles of Scilly: location map.*

A secondary aim of this contribution is therefore to generate palaeotidal data that can be used to correct these new sea-level index points for changes in tidal amplitude. This is important because the indicative meaning of most sea-level index points represents Mean High Water Spring Tide Level so requiring a correction for past tidal range (amplitude x2) in order to reduce to Mean Sea Level. Present-day tidal range is often assumed but this can be erroneous (cf. Neill *et al.*, 2010; Scourse, 2013).

Tides change as a function of rsl because ocean basin and coastline shape, and palaeotopography (bathymetry) determine the resonance characteristics of the basin. The Severn Estuary/Bristol Channel system currently experiences megatidal amplitudes (tidal range >10 m) because the length of the embayment/estuary is close to resonance with the tide as it propagates across the shelf. At times of lower rsl, however, the coastline and palaeobathymetry were different from present and so the resonance characteristics of the basin were also different; the Bristol Channel now experiences tidal amplitudes higher than at any point in the recent geological past (Uehara *et al.*, 2006). However, the areal extent of the inter-tidal zone is a function not only of tidal amplitude, but also of seabed gradient (Figure 2; Scourse, 2013). For instance, surfaces available for colonisation by marine inter-tidal organisms on

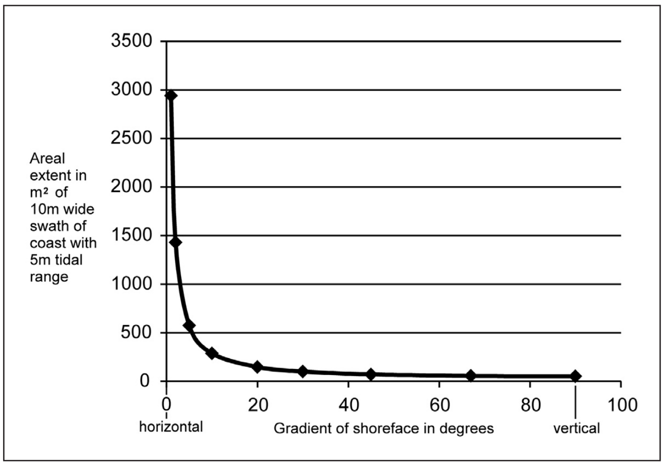


Figure 2. *Changes in areal extent of the inter-tidal zone in m² as a function of coastal gradient; this figure is based on a tidal range of 5 m for a swath of coast 10 m wide. The data demonstrate that the relationship between coastal gradient and tidal range is a negative exponential.*

vertical cliffs are equal to the tidal range experienced at that location multiplied by the lateral extent of the vertical cliff; this increases as a negative exponential as the cliff/bed gradient decreases to infinity across horizontal surfaces. Small changes in tidal amplitude across shallow shelving coasts therefore result in a disproportionately large change in the areal extent of the inter-tidal compared with the same amplitude change across a cliffed or more steeply sloping bed. Thus the gradient and form of the bed exerts a crucial control not only on the character of the tide but also on the area that can be colonised by inter-tidal organisms. Inter-tidal foraging by Mesolithic communities would have thus been significantly facilitated by gently shelving coastlines with large tidal amplitudes.

Methods

The tidal amplitude data for Scilly we use in this study were produced by the Uehara *et al.* (2006) palaeotidal simulations for the NW European continental shelf since the Last Glacial Maximum (LGM; last 22,000 years). Palaeotidal amplitudes were generated by applying palaeotopographies for every 1,000 yr from 13 cal ka BP to the present day to a two-dimensional finite-difference version of the Princeton Ocean Model (Blumberg and Mellor, 1987), also known as the Kyushu University Tidal Model (KUTM; Uehara *et al.*, 2006). Model resolution is 1/12 degree; full specifications are given in Uehara *et al.* (2006). The KUTM simulations accommodate vertical changes in overall crustal elevation – for the Scilly massif as part of the wider NW European continental shelf – as a function of glacio-isostatic deflection by integrating changes in palaeotopography generated by glacio-isostatic (un)loading using glacio-isostatic adjustment (GIA) model simulations as input variables. We use palaeotopographies for each timestep by combining the modern shelf bathymetry with changes in rsl generated by GIA model output based on Lambeck (1995; revised in Uehara *et al.*, 2006) as described in Scourse *et al.* (2009). The bathymetry of the present-day NW European shelf area was prepared by compiling datasets from several sources including the UK Proudman Oceanographic Laboratory (POL), British Geological Survey (BGS) and the US National Geophysical Data Center (NGDC).

In this analysis we take the bathymetry in and around Scilly as fixed, based on the Admiralty Hydrographic Chart (Crown Copyright, 2001). We do not accommodate any changes in bed level as a function of erosion or sedimentation. For most of the area under consideration, particularly the outer margins of the Scilly massif, the seabed is coincident with rockhead and is not covered by significant sediment cover. This rockhead consists of biotite granite of Late Carboniferous and Early Permian age (Bristow, 1996) and the bathymetry of the Scilly massif is strongly controlled by the margins of the granite pluton. The granite is very resistant to marine erosion, certainly over the timescale under consideration here, and no major changes in granite bed level are likely to have occurred. However, the granite in the inner parts of the archipelago (e.g. St Mary's Pool, St Martin's Flats) is covered by mobile sands overlying Holocene sediments. These Holocene sequences are now yielding new sea-level index points (The Lyonnesse Project, Cornwall and Isles of Scilly Maritime Archaeological Society, 2013). We provide no feedback in this analysis between bed stress generated by the palaeotidal simulations and changes in bed level in this sedimentary province, and assume that the bed level in the Hydrographic Chart has remained constant over time. We do not consider this to be a major consideration since these sediments are thin and any changes in bed level as a function of sedimentation/erosion likely had little impact on tidal dynamics.

Uehara *et al.* (2006) demonstrated that the shelf tides are very sensitive to changes in the ocean tide since the LGM and that simulations based on time-dependent ocean tide input, rather than a fixed boundary based on the modern ocean tide, are supported by geological observational constraints (Scourse *et al.*, 2002). We therefore use simulations based on an ocean tide boundary forced from the output from a global tidal model (Uehara *et al.*, 2006) prescribed using the ICE-5G global GIA model output (Peltier, 2004).

Results and discussion

The Lambeck GIA simulation of rsl since the Late-glacial for Scilly is characterized by a eustatically-dominated gradual rise from -70 m O.D. at 13 cal ka BP to -9.5 m O.D. at 6 cal ka BP followed by a more gradual rise to the present (Figure 3a). No mid-Holocene highstand is predicted. The most rapid rates of rsl rise occurred between 11 and 7 cal ka BP with a mean rate of ~1 cm yr^{-1}. Relative sea level is now at its highest for any period since the Late-glacial and is likely at its highest since the highstand of the Last Interglacial when it may have exceeded current mean sea level by several metres as evidenced by the interglacial raised beaches of the Watermill Sands and Gravel (Marine Isotope Stage 5e; 125 ka BP; Scourse, 1991). Palaeotidal amplitudes (designated as full astronomic tide, FAT) were at their lowest in the Late-glacial at 13 cal ka BP (Figure 3b), coincident with the first inundation of the Scilly massif, with tidal range of around 3 m; current FAT range is twice this (6 m). Tidal ranges then increased rapidly as rsl increased, reaching 6m+ by 12 cal ka BP, and then remained high until 6 cal ka BP. Maximum tidal range occurred at 10 cal ka BP (~6.5 m). After 6 cal ka BP, coincident with the attaining of near-modern rsl, tidal range relaxed a little back to current values of ~6 m.

These changes in rsl and tidal amplitude, when combined with the present bathymetry, define the evolving extent of the intertidal zone (Figures 4 and 5). The Late-glacial and early Holocene (12-9 cal ka BP) palaeogeography of Scilly was characterized by a single massif/island that coincides with the outline of the granite pluton. The 13 cal ka BP reconstruction indicates peninsular connection with the wider continental shelf, and probable land connection to mainland Cornwall, but full insularity was attained by 12 cal ka BP. Between 13 and 11 cal ka the total extent of the inter-tidal zone was high; the largest extent of the inter-tidal of the entire period investigated is predicted for the earliest time-step, at 13 cal ka BP (27 km^2; Figure 5). This relates to the low rsl intersecting the lower gradients towards the base of the batholith, so even though tidal amplitudes were small at this time the low gradient results in an extensive inter-tidal zone (Figure 2). Tidal amplitudes then increased rapidly, but the extent of the inter-tidal zone

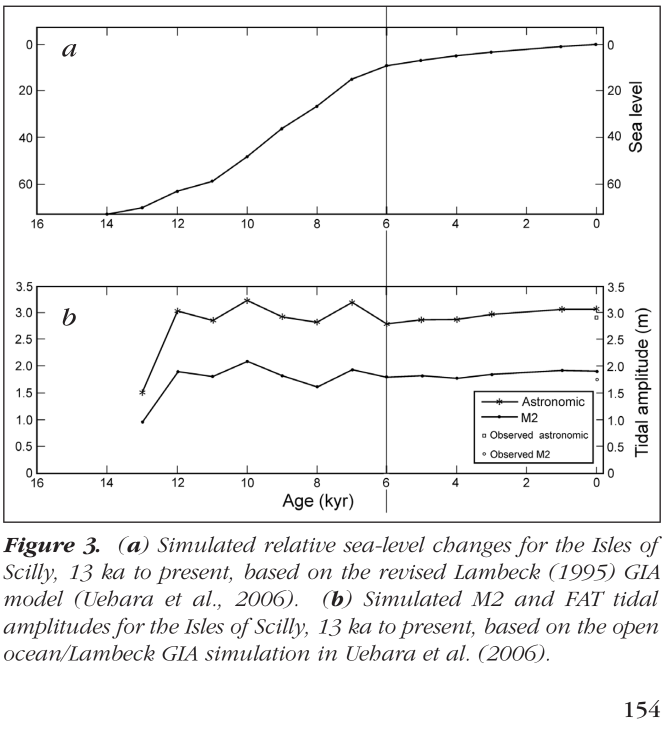
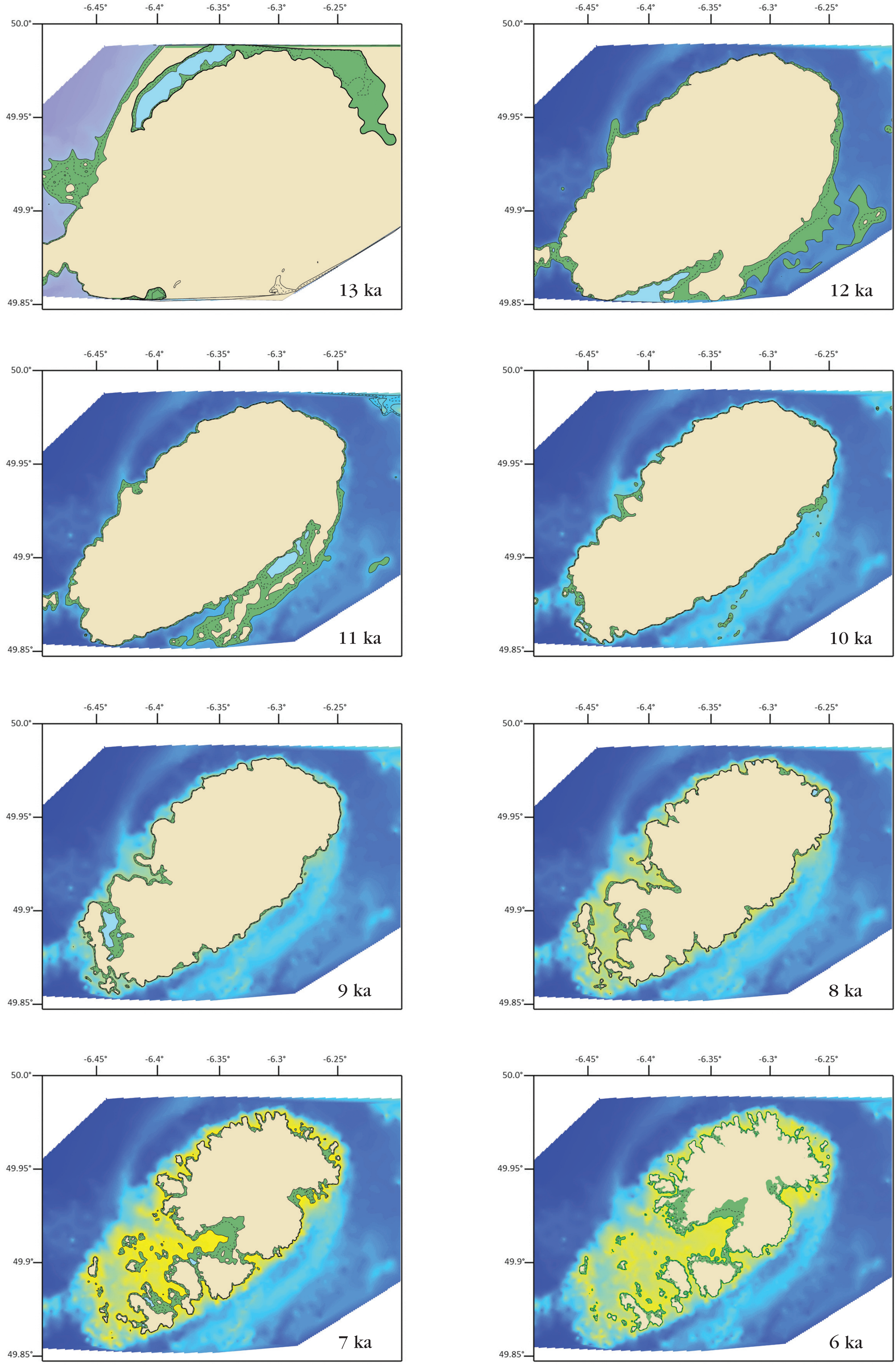


Figure 3. *(**a**) Simulated relative sea-level changes for the Isles of Scilly, 13 ka to present, based on the revised Lambeck (1995) GIA model (Uehara et al., 2006). (**b**) Simulated M2 and FAT tidal amplitudes for the Isles of Scilly, 13 ka to present, based on the open ocean/Lambeck GIA simulation in Uehara et al. (2006).*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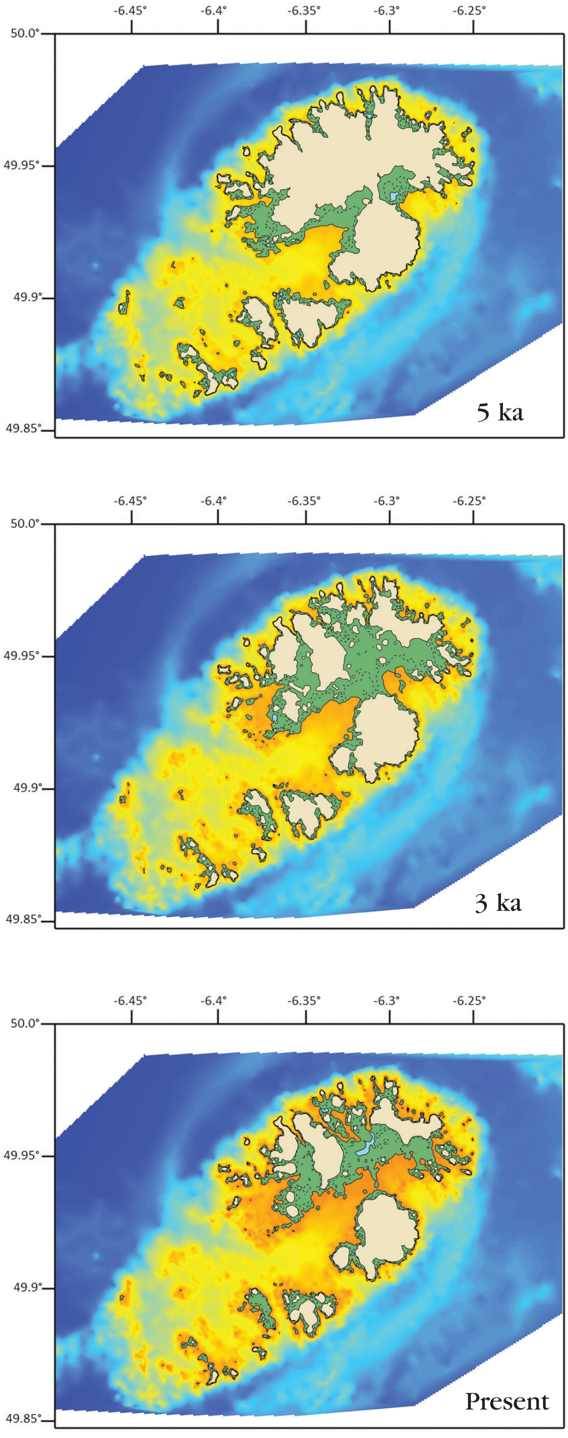

Figure 4. *The changing palaeogeography of the Isles of Scilly from 13 ka to present showing the extent of the inter-tidal zone (in green); land in brown and bathymetry from yellow (shallow) to blue (deep). Latitude in degrees shown on y axis and longitude in degrees on x axis.*

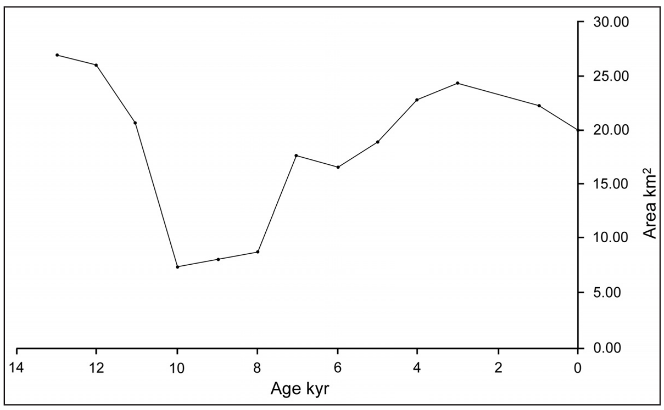

Figure 5. *Simulated changes in the extent of the inter-tidal zone on the Isles of Scilly, 13 ka to present, based on FAT tidal range simulations deriving from the Uehara et al. (2006) palaeotidal model.*

decreased very rapidly as rsl increased against the steepest walls of the batholith, reaching a minima of 7 km^2, the lowest inter-tidal extent of the entire period, at 10 cal ka BP. Some now submerged satellite islands are predicted on the southern and western side of the batholith at 12-11 cal ka BP, but these were inundated completely by 10 cal ka BP when only a single island was present apart from one or two small islets.

As rsl continued to rise rapidly, the upper levels of the batholith, with shallower gradients, were attained and the single island started its fragmentation into the current archipelago. The first of the modern islands to separate were the Western Rocks and St Agnes, by 7 cal ka BP. This process was accompanied by an increase in the extent of the inter-tidal zone, attaining 20 km^2 by 7 cal ka BP. By 6 cal ka BP the largest single island consisted of St Mary's connected by a rapidly narrowing isthmus to a connected agglomeration of the northern islands, but this neck was inundated by 4 cal ka BP; this marks the first separation of St Mary's, Bryher, Tresco and St Martin's. Nevertheless these major islands remain connected by the inter-tidal zone at extreme low tide to the present day. The extent of the inter-tidal zone continued to increase, reaching a maximum of 25 km^2 at 3 cal ka BP, but diminishing to 20 km^2 at present.

The areal extent of the inter-tidal zone on Scilly was therefore very high in the Late-glacial, rapidly diminishing to a minimum in the early Holocene, followed by an increase to a maxima at 7 cal ka BP, a small decrease across the Mesolithic-Neolithic transition and subsequently an increase until 3 cal ka BP with a slight reduction over the last three millennia (Figure 5).

This analysis indicates that there have been very significant changes in the extent of the inter-tidal zone available to human communities for marine foraging since the period of occupation. Even though at the time of the transition from the Mesolithic into the Neolithic there was an ongoing decrease in the size of the inter-tidal zone, this was a modest decrease at a time when the overall extent of the inter-tidal was quite high. It is therefore very unlikely that this change had any significant impact on the area available for marine foraging by communities across this major societal transition. It is emphasized that this interpretation only applies to the Isles of Scilly. Similar but independent analyses would have to be undertaken on other areas to ascertain any changes in the areal extent of the inter-tidal zone over the Neolithic transition; the key variables within each area are the gradient of the evolving inter-tidal zone and simulated changes in tidal amplitudes.

This method for reconstructing the areal extent of the inter-tidal zone is effectively an extension of palaeo-Ecological Niche Modelling (pENM; Scourse 2013) in that the inter-tidal is a definable ecosystem. However, most existing exercises in pENM, such as the reconstruction of kelp forest in Southern California by Graham *et al*. (2010), simply incorporate observations of coastal topography, rsl change and palaeoclimatic changes based on palaeoceanographic evidence. This is the first pENM exercise to explicitly integrate simulations of palaeotidal change.

Further refinement of such simulations would revolve around testing some of the major assumptions, including the integration of bed level change into the modelling and the nesting of a spatially more highly-resolved palaeotidal model for the area of interest within the shelf-wide model.

Conclusions

Palaeotidal simulations reconstructing the extent of the inter-tidal zone on Scilly provide data on the changing palaeogeography of the archipelago over the past 13,000 years, including an assessment of the timings of (pen)insularity. The data do not indicate any major decrease in the size of the inter-tidal zone across the Neolithic-Mesolithic transition and it is therefore very unlikely that this purely physical control on marine foraging had any significant impact on the transition from marine to terrestrial diet on Scilly. Nevertheless:

1) This analysis provides a new methodology for quantitative assessment of the change in the extent of the inter-tidal zone as a function of coastal topography, rsl and palaeotidal change that can be applied to any coastline.

2) The model data contribute to an informed assessment of the changing palaeogeography of Scilly over the last 13,000 years that provide a basis for testing via field observations.

3) The tidal amplitude data can be used to correct the indicative meaning of emerging sea-level index points from Scilly.

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