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Coastal paleogeography of the California–Oregon–Washington and Bering Sea continental shelves during the latest Pleistocene and Holocene: implications for the archaeological record



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ABSTRACT

Sea-level rise during the last deglaciation and through the Holocene was influenced by deformational, gravitational, and rotational effects (henceforth glacial isostatic adjustment, GIA) that led to regional departures from eustasy. Deglacial sea-level rise was particularly variable spatially in areas adjacent to the Cordilleran and Laurentide Ice Sheets. Such regional variability in sea level due to GIA is important to identify when investigating potential coastal migration pathways used by early Americans. An improved understanding of regional sea-level rise may also be used for predictive modeling of potential archaeological sites that are now submerged. Here we compute relative sea-level change across the California–Oregon–Washington and Bering Sea continental shelves since the Last Glacial Maximum using an ice-age sea-level theory that accurately incorporates time-varying shoreline geometry. The corresponding non-uniform sea-level rise across these continental shelves reveals significant departures from eustasy, which has important implications for improved understanding of potential coastal migration routes and predictive modeling of the location of now-submerged archaeological sites.

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1. Introduction

Following the Last Glacial Maximum (~26–19 ka) (ka: kiloyear. All years reported herein are in calendar years) (Clark et al., 2009), ice-sheet retreat caused globally averaged sea level to rise by ~130 m (Austermann et al., 2013; Yokoyama et al., 2000), with present sea level reached ~5 ka (Woodroffe et al., 2012). During this period of lower sea level, large expanses of continental shelves were exposed, providing coastal migration routes and occupation sites that have since become submerged as global sea level rose to its present height. Reconstructing the paleogeography of these now-submerged landscapes is thus important for inferring the most likely routes taken by early coastal migrations, as well as for predicting the locations of subsequent occupation sites.

These issues have recently become of wide interest along the west coast of the Americas, where new evidence for pre-Clovis cultures and early maritime activity has focused attention on the

importance of coastal paleogeography, particularly with regard to the peopling of the Americas (Graf et al., 2013). For much of the 20th century, the prevailing paradigm, referred to as the “Clovis First” model, posited that the initial colonization of the Americas south of the Laurentide and Cordilleran ice sheets was by migration from Beringia through an ice-free corridor that developed between the two ice sheets during the last deglaciation. The model was first developed because the locations of the first Clovis sites were south of the ice-sheet corridor, suggesting an initial entry point. The paradigm was subsequently supported by the evidence that the age for the opening of the ice-free corridor (Catto, 1996) roughly coincided with the earliest age of Clovis artifacts (Haynes, 2002), with the attendant implication that prior closure of the corridor would have prevented earlier migrations. The model implied that upon arriving to the interior of the continent south of the ice sheets, these early peoples slowly migrated towards coastal regions, where they adapted to the local environment (Erlandson et al., 2008).

Despite the prevailing view of the Clovis First model, several questions were raised as to whether humans would be able to survive the harsh environmental conditions and biologically unproductive landscape of the ice-free corridor (Fladmark, 1979; Mandryk, 1993; Meltzer, 2004). Largely for these reasons,

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Fladmark (1979), building on an earlier suggestion by Heusser (1960), proposed an alternative migration route along the western coast of North America, pointing out that a “chain of refugia” along the coast would have been more environmentally suitable for occupation, given the available marine resources and the possibility that the early people had simple watercraft for navigating the route.

A number of developments in the last ten years have further challenged the Clovis First model to the extent that some have now suggested that it is all but defunct (Adovasio and Pedler, 2013; Erlandson, 2013). The demise of the model has been largely driven by mitochondrial DNA (Fagundes et al., 2008; Perego et al., 2009) and archeological (Dillehay et al., 2008; Gilbert et al., 2008; Goebel et al., 2008; Jenkins et al., 2012; Waters et al., 2011a; Waters and Stafford, 2007; Waters et al., 2011b) studies which provide compelling evidence for pre-Clovis occupation of the Americas by 14–15 ka.

Based on current understanding, this earlier age for the arrival of First Americans south of the ice sheets likely preceded the opening of the ice-free corridor by several hundred to a thousand years (Dyke, 2004), although dating of post-glacial eolian sediments with optically stimulated luminescence suggests the possibility that the corridor was open early enough for a migration route by pre-Clovis peoples (Munyikwa et al., 2011). If the ice-free corridor route is no longer viable, however, then by default a coastal route is required, with a route along the west coast of North America now considered the most likely (Erlandson, 2013). Several lines of evidence have bolstered arguments for this route, including additional arguments for the wealth of resources that the route offered (Erlandson et al., 2007), the older ages of human settlement and maritime activity along the Pacific Coast (Erlandson and Braje, 2011; Erlandson et al., 2008, 2011), and the identification of areas along the Alaskan and British Columbian coasts that were habitable one to three millennia before the opening of the ice-free corridor (Mandryk et al., 2001; Mann and Hamilton, 1995; Misarti et al., 2012).

Reconstructing the paleogeography that existed at the time of a coastal migration, as well as during subsequent times when people inhabited now-submerged shelf areas, requires knowing the sea-level history during the last 20,000 years. A common approach to reconstruct coastal paleogeography (Anderson et al., 2013, 2010; Davis et al., 2004; Kennett et al., 2008; Manley, 2002) is to uniformly lower sea level by the amount suggested from far-field (e.g., Barbados, Tahiti) sea-level records (Bard et al., 1996; Fairbanks, 1989) which are assumed to represent the global mean. This uniform, global mean sea-level change is commonly referred to as the “eustatic” change. However, adopting the eustatic change to reconstruct coastal paleogeography moves beyond this simple definition to an implicit assumption that glacial meltwater entered the oceans in a geographically uniform manner (i.e., the so-called bathtub model). Sea-level rise during the last deglaciation, however, was influenced by glacial isostatic adjustment (GIA) associated with the exchange of mass between ice sheets and oceans that, for the majority of the ocean basins, led to significant regional departures from eustasy (Milne and Mitrovica, 2008).

Deglacial sea-level rise across the California–Oregon–Washington and Bering Sea continental shelves would have been particularly variable spatially as a consequence of their relative proximity to the Cordilleran and Laurentide Ice Sheets. In this article, we use a state-of-the-art numerical model of post-glacial sea-level change (Kendall et al., 2005) to predict relative sea-level (RSL) change in the region of the Channel Islands, California, and across the Oregon–Washington and Bering Sea continental shelves. We compare these predictions to sea-level changes that would be associated with a globally uniform “eustatic” rise.

2. Sea-level modeling

The ice-age sea-level calculations were performed using an algorithm (Kendall et al., 2005; Mitrovica and Milne, 2003) that requires, as input, models for both the global geometry of ice sheets over the last glacial cycle and the Earth's viscoelastic structure (see below). The algorithm yields a gravitationally self-consistent ocean redistribution and it accounts for the viscoelastic deformation of the solid Earth in response to the (ice plus water) loading, as well as associated perturbations to the Earth's gravitational field and rotational state (Mitrovica et al., 2005). The sea-level theory accurately treats for the migration of shorelines due to local sea-level variations and changes in the perimeter of grounded, marine-based ice sheets (Milne et al., 2002), and an iterative procedure adopted within the algorithm guarantees that the predicted present-day topography matches the observed topography (Kendall et al., 2005). Sediment redistribution, including both erosion and deposition, are not included in the modeling.

All our GIA calculations are based on a pseudo-spectral solver truncated at spherical harmonic degree 256, which provides a surface spatial resolution of GIA effects to a level of approximately 100 km (Kendall et al., 2005). In results presented below, these computed changes in global sea level are superimposed onto a high-resolution regional grid of modern topography to track changes in shoreline position as a function of time. Since GIA-induced changes in sea level have relatively smooth spatial geometries, adopting a higher truncation in the pseudo-spectral solver would not significantly alter the predicted evolution of shoreline positions. In the calculations presented below, we used the 3-arcsecond U.S. Coastal Relief Model (<http://www.ngdc.noaa.gov/mgg/coastal/crm.html>) for CA-OR-WA and the 1-arcminute ETOPO01 topography grid for Beringia (CRM coverage is not available for this region) (Amante and Eakins, 2009).

We adopt a spherically symmetric, self-gravitating, linear (Maxwell) viscoelastic Earth model. The elastic and density structure of this model is prescribed from the seismic model PREM (Dziewonski and Anderson, 1981). In an earlier, preliminary study (Clark et al., 2014) of shoreline migration in the same region, we adopted the so-called VM2 radial profile of mantle viscosity, which is coupled to the ICE-5G ice history since the last interglacial (Peltier, 2004). The VM2 model (Peltier, 2004) is characterized by a relatively moderate, factor of 5, increase in viscosity from the base of a 90 km thick, high viscosity (effectively elastic) lithosphere to the core-mantle-boundary. In contrast, the simulations described below adopt a model of ice history developed at the Australian National University (Fleming and Lambeck, 2004) which is coupled to an Earth model with a lithospheric thickness of 96 km, an upper mantle viscosity of 0.5×10^{21} Pa s, and a lower mantle viscosity of 8×10^{21} Pa s. This Earth model (henceforth the LM model) is consistent with inferences from a number of studies based on globally distributed sea-level data sets (Mitrovica and Forte, 2004; Nakada and Lambeck, 1989). Our adoption of the LM model is also motivated by the study of Muhs et al. (2012), who examined the sea-level history over the last glacial cycle at San Nicolas Island, CA, one of the Channel Islands, with emphasis on sea-level oscillations through marine isotope stage (MIS) 5. They found that MIS5a and 5c highstands at San Nicolas Island, as well as previously published highstands at Barbados and the Florida Keys, were best fit by a GIA prediction based on a model similar to our LM model, but were not well fit by the model VM2.

In results described below we will also consider the sensitivity of some of our predictions to the presence of lateral variations in Earth structure, including mantle viscosity and lithospheric thickness. We also incorporate tectonic plate boundaries as zones of particularly low viscosity. These calculations are based on a finite

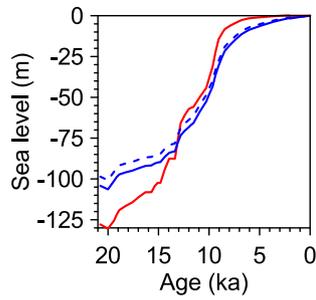


Fig. 1. Predicted relative sea level (RSL) curves (blue) for two sites within the Channel Islands region compared to the eustatic curve for the ANU deglaciation history (red). The RSL curves are computed for sites: 34°N 120°W (solid blue line) and 33.5°N 118°W (dashed blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

volume numerical model of ice age adjustments (Latychev et al., 2005).

3. Channel Islands, California

Maritime peoples occupied California's Channel Islands by at least ~13 ka, with the implication that they used seaworthy boats to travel to the islands from the mainland (Erlandson et al., 2005, 1996, 2011; Rick et al., 2001, 2005). Kennett et al. (2008) adopted a eustatic history inferred from far-field sea-level records (Bard et al., 1996; Fairbanks, 1989) to reconstruct the islands' changing paleogeographies and distance to the main coastline associated with postglacial sea-level rise, with attendant implications for changes in local marine resources. Reeder-Myers et al. (submitted for publication) are also considering GIA-induced changes in shoreline position in the vicinity of Channel Islands with a focus on ecological changes and human history.

We first show examples of two RSL curves from sites within the Channel Islands region, and compare these to the eustatic curve for the ANU ice history adopted in the numerical simulation (Fig. 1). The RSL curves show a marked departure from an assumption of eustasy. Near the end of the LGM at ~21 ka, RSL was ~25–30 m higher than would have been predicted by assuming eustatic sea level. For periods following ~13 ka, the sign of the discrepancy changes and the predicted RSL is as much as ~15 m lower than eustatic curve. Note that the multi-meter-scale differences between the predicted and eustatic curves continue up to the present, which has implications for predicting sites in present-day estuarine regions that would have remained exposed for much longer than otherwise predicted from the eustatic assumption.

The Channel Islands cover a large enough area that the predicted GIA contribution varies non-negligibly across the area. As an example, at the LGM, the predicted RSL at Santa Rosa Island (120°W, 34°N) is ~5 m lower than the prediction at the present Los Angeles coastline (118°W, 33.5°N) (Fig. 1). This difference reflects spatial gradients in the predicted RSL that are highlighted in Fig. 2, which shows regional maps of RSL from 20 ka to 6 ka predicted using the gravitationally self-consistent sea-level theory. The predicted RSL on these maps is more negative toward the southwest (i.e., sites toward the southwest would have experienced greater post-LGM sea-level rise), reflecting the combined effects of crustal subsidence within the peripheral bulge of the Laurentide-Cordilleran Ice Sheets and migration of water away from these ice sheets as they lost mass and thus exerted less of a gravitational pull on the oceans (Milne and Mitrovica, 2008). The predicted gradient is largest during the LGM and diminishes with time (Figs. 1 and 2).

Fig. 3 shows the modeled paleogeography for the Channel Islands at 20 ka and from 15 ka to 10 ka computed using either an assumption of a eustatic sea-level change (Fig. 3a) or the gravitationally self-consistent ice-age sea-level theory (Fig. 3b). Fig. 3c shows the difference in the predicted shoreline location for each of

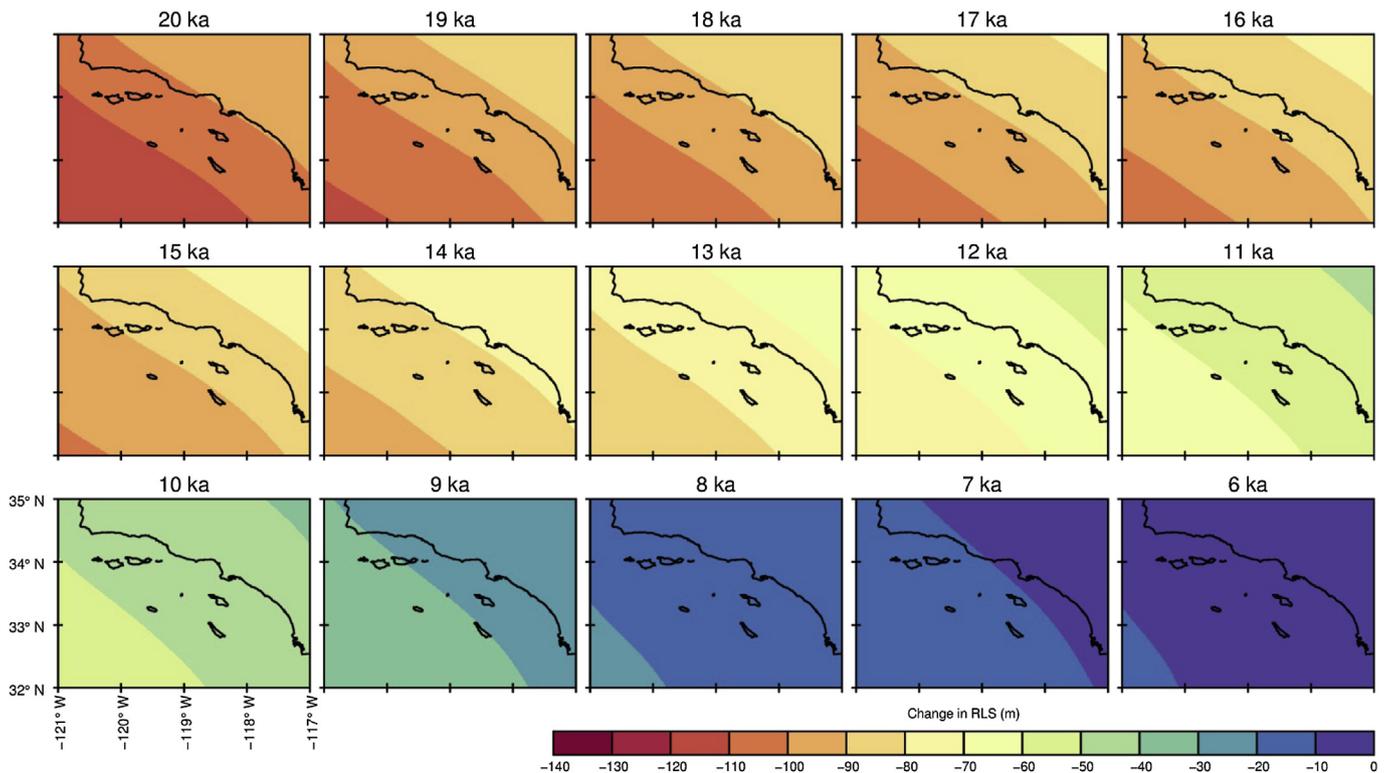


Fig. 2. Regional maps of relative sea level (RSL) from 20 ka to 6 ka predicted using the gravitationally self-consistent sea-level theory and the ANU/LM model of GIA (see text).

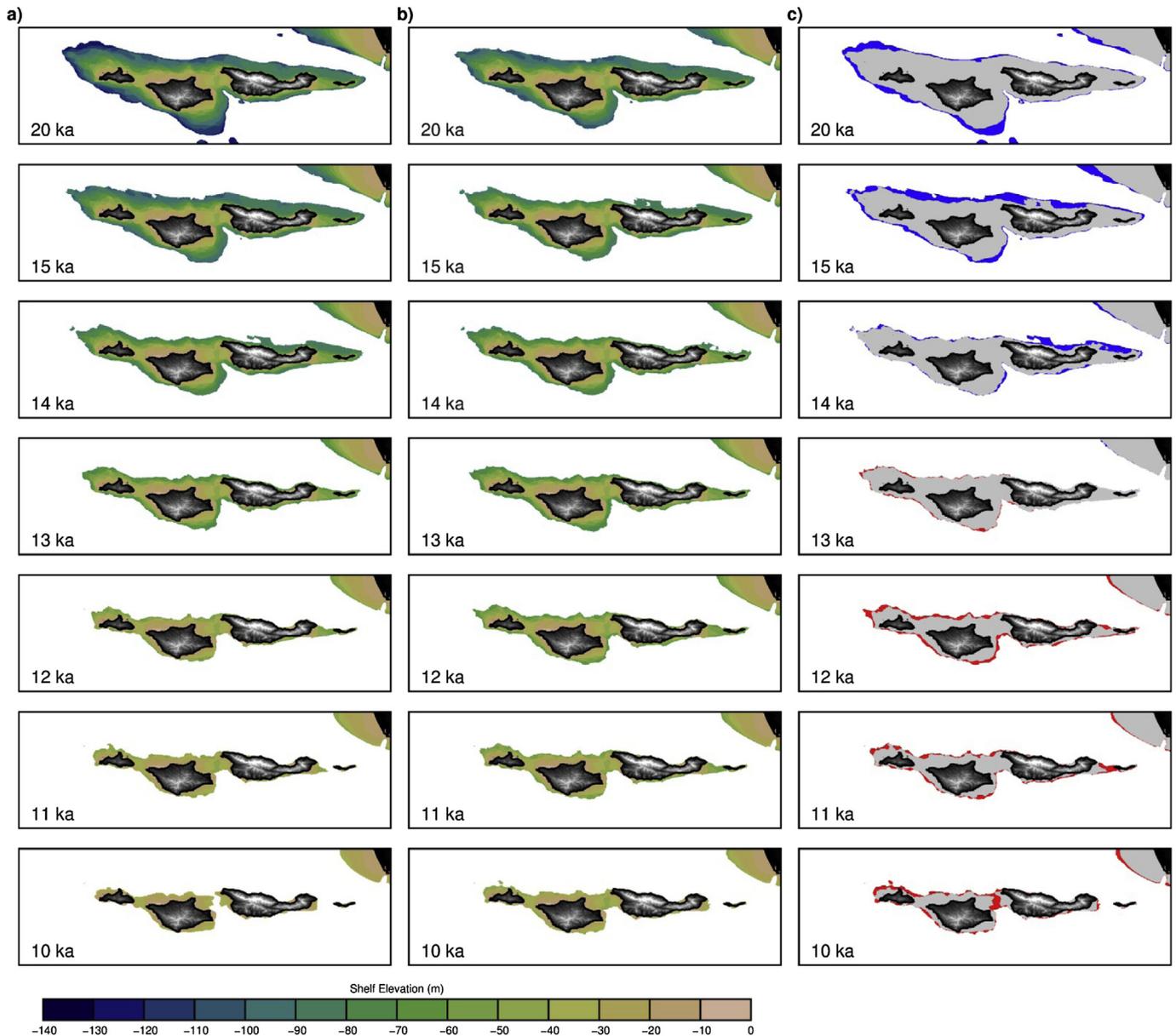


Fig. 3. The paleogeography for the Channel Islands region, CA, at 20 ka and from 15 to 10 ka (at 1-kyr intervals) computed: (a) with an assumption of a eustatic history; and (b) when accounting for the relative sea level (RSL) history shown in Fig. 2. (c) The difference in area of exposed shelf for the Channel Islands region computed using the eustatic history (frame a) and gravitationally self-consistent RSL history (frame b). The areas shown in blue represent zones exposed in the eustatic predictions but not in the GIA calculation, whereas areas in red are zones exposed in the latter but not the former. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

these snapshots. The predicted paleoshoreline position based on a eustatic sea level assumption can be in error by several km at, for example, 12 ka, corresponding to the time of early occupation of the islands (Erlandson et al., 1996, 2005; Rick et al., 2001, 2005). We conclude that the sea-level history near the Channel Islands is significantly impacted due to GIA even though the region is ~1500 km from the nearest North American ice sheets.

4. Oregon–Washington continental shelf

Most of the recorded archaeological sites along coastal regions of Oregon and Washington are younger than 5000 years ago (Lyman, 1991), with only two older sites identified: the Indian Sands site on the southern Oregon coast (Davis et al., 2004; Erlandson et al., 2008) and the Manis site in northern

Washington (Waters et al., 2011b). Some have argued that the lack of older sites suggests late occupation of the region (Lyman, 1991; Ross, 1990), but it more likely reflects coastal erosion or submergence of offshore sites associated with post-glacial sea-level rise amplified by periodic subsidence earthquakes and tsunamis (Erlandson et al., 2008).

The relation between local, site-specific RSL change for the continental shelf off of southern Oregon (42.5°N) and the eustatic sea level curve is similar to that described above for the Channel Islands, with differences of up to ~20 m and RSL reaching present-day levels ~6000 years later than predicted under the eustatic assumption (Fig. 4). As one moves north to the shelf off central Oregon (44.5°N), however, RSL is below eustatic throughout the full interval, with differences of as much as ~50 m at ~12 ka (Fig. 4). Further north on the shelf off southern Washington (46.5°N), the

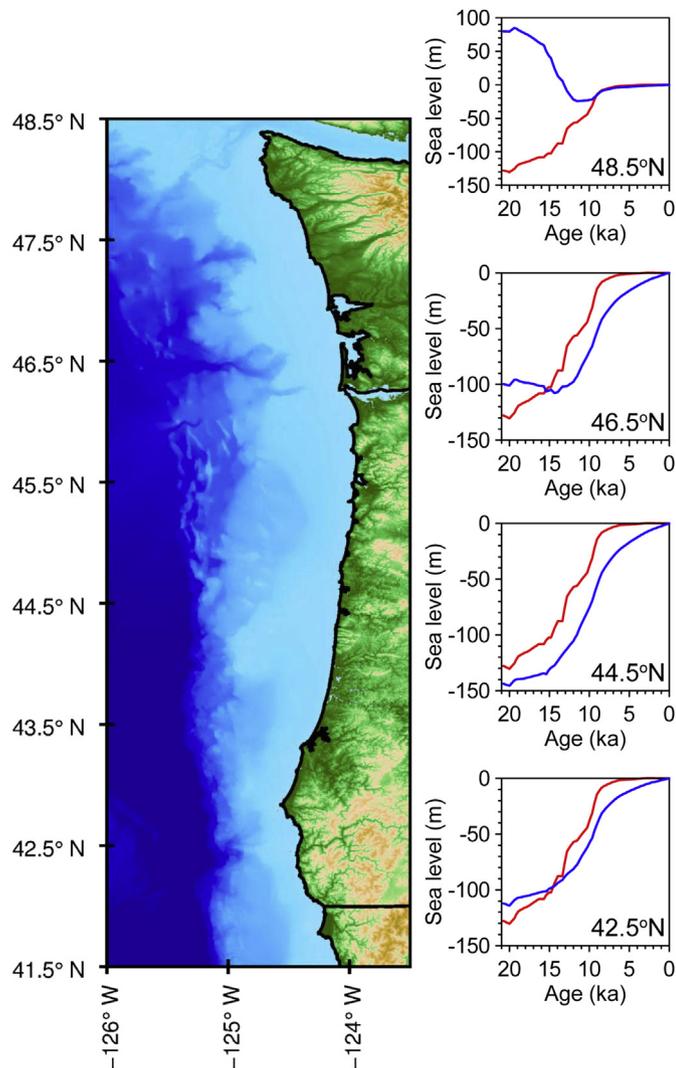


Fig. 4. Examples of relative sea level curves (blue) for four sites along the Oregon–Washington coast compared to the eustatic curve associated with the ANU deglaciation history (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

relation between RSL and eustatic sea level is again like that on the shelf off southern Oregon, with RSL initially above eustatic until ~15 ka, when the sign of the discrepancy changes and the predicted RSL is as much as ~40 m lower than eustatic. Closer to the margin of the Cordilleran Ice Sheet in northern Washington, this relation then changes significantly as the large isostatic and gravitational effects of the nearby ice sheet begin to dominate the signal. For example, at a site at 48.5°N, RSL was 50–80 m above present level from 20 to 15 ka (Fig. 4), suggesting that sea-level rise associated with the addition of meltwater was offset by sea-level fall due to isostatic uplift (or rebound) of the crust and the gravitationally-driven migration of water away from the melting ice sheet. From 15 to 12 ka, the latter mechanisms continue to dominate the meltwater addition component and sea level is predicted to fall ~75 m. After 12 ka, the eustatic signal associated with meltwater addition dominates, and sea level rose toward its present value. Over this time interval, the hinge point separating regions of post-glacial uplift from sites experiencing peripheral bulge subsidence migrated in this particular simulation, and therefore bulge subsidence also contributes to the predicted sea-level rise. Finally, further north in coastal areas of Canada that were formerly covered

by the ice sheet, a monotonic fall in RSL over the last 20,000 years is associated with the combined effects of crustal uplift and the gravitationally-driven migration of water away from the melting ice sheet.

Fig. 5a and b shows the paleogeography for the Oregon–Washington continental shelf from 20 ka to 6 ka computed either assuming eustatic sea level change or accounting for ice-age adjustments, respectively. Given the bathymetry of this region, there are some notable differences between these two paleogeographic reconstructions. As an illustration, we focus on two sites at two times that have implications for predictive modeling of offshore sites (Fig. 6).

The first case is for the central Oregon shelf at 14 ka. An assumption of eustatic sea level change predicts a series of small islands at this time as most of the shelf was submerged (Fig. 6a). In contrast, the prediction based on the computed RSL history shows that much of the shelf in this area remained emergent, with an extensive coastline (Fig. 6b). The second case is for the area close to and just north of where the Columbia River enters the Pacific. An assumption of eustasy predicts that much of the estuarine regions along this part of the coast were submerged at 6 ka (Fig. 6c), whereas the prediction using the RSL calculation suggests that the shoreline remained seaward of the present coast. These estuaries are predicted to have remained emergent at this time, and likely would not have served as coastal occupation sites (Fig. 6d).

Fig. 5c shows regional maps of the predicted RSL from 20 ka to 6 ka using the gravitationally self-consistent sea-level theory. As with the Channel Islands, these maps show that relative sea-level fall was not spatially uniform, but in comparison to Fig. 2, there are now much stronger gradients in RSL associated with GIA due to the greater proximity to the Cordilleran Ice Sheet. In particular, there is a strong SSW–NNE gradient in RSL on the northern Washington shelf, especially from 20 to 15 ka. As illustrated by Fig. 4, RSL in this northern region over this time interval was 50–80 m above present at the LGM, indicating that any sites from that time period would be exposed today along the coast.

As a final point we emphasize that the RSL predictions in Figs. 4–6 are based on a single viscoelastic Earth model (LM) and ice history. The discrepancies between these predictions and eustatic sea level will be a function of the adopted Earth model and ice history, but predictions based on all plausible Earth models will show comparable levels of discrepancy.

5. Bering Sea continental shelf

During the LGM sea-level lowstand, nearly 2×10^6 km² of shallow continental shelf underlying the Bering and Chukchi Seas was exposed, creating the contiguous land mass referred to as Beringia that extended from eastern Siberia east to the Mackenzie River. The significance of this land bridge as a migration route between Asia and North America for animals and early people has long been recognized (Hopkins, 1967, 1973), and constraining when it became submerged is important to understanding when such land migrations ended. The timing is also important for assessing the influence of the opening of a water connection between the Pacific and Arctic Oceans on regional climate and ocean circulation (Hu et al., 2010).

Recognizing that the concept of eustatic sea level change should not be applied to reconstruct Beringian paleogeography, McManus and Creager (1984) constrained regional paleo water depths using marine faunal estimates and concluded that the initial submergence of the land bridge occurred ~17,500 years ago. In contrast, Elias et al. (1996) dated terrestrial plant remains from cores taken

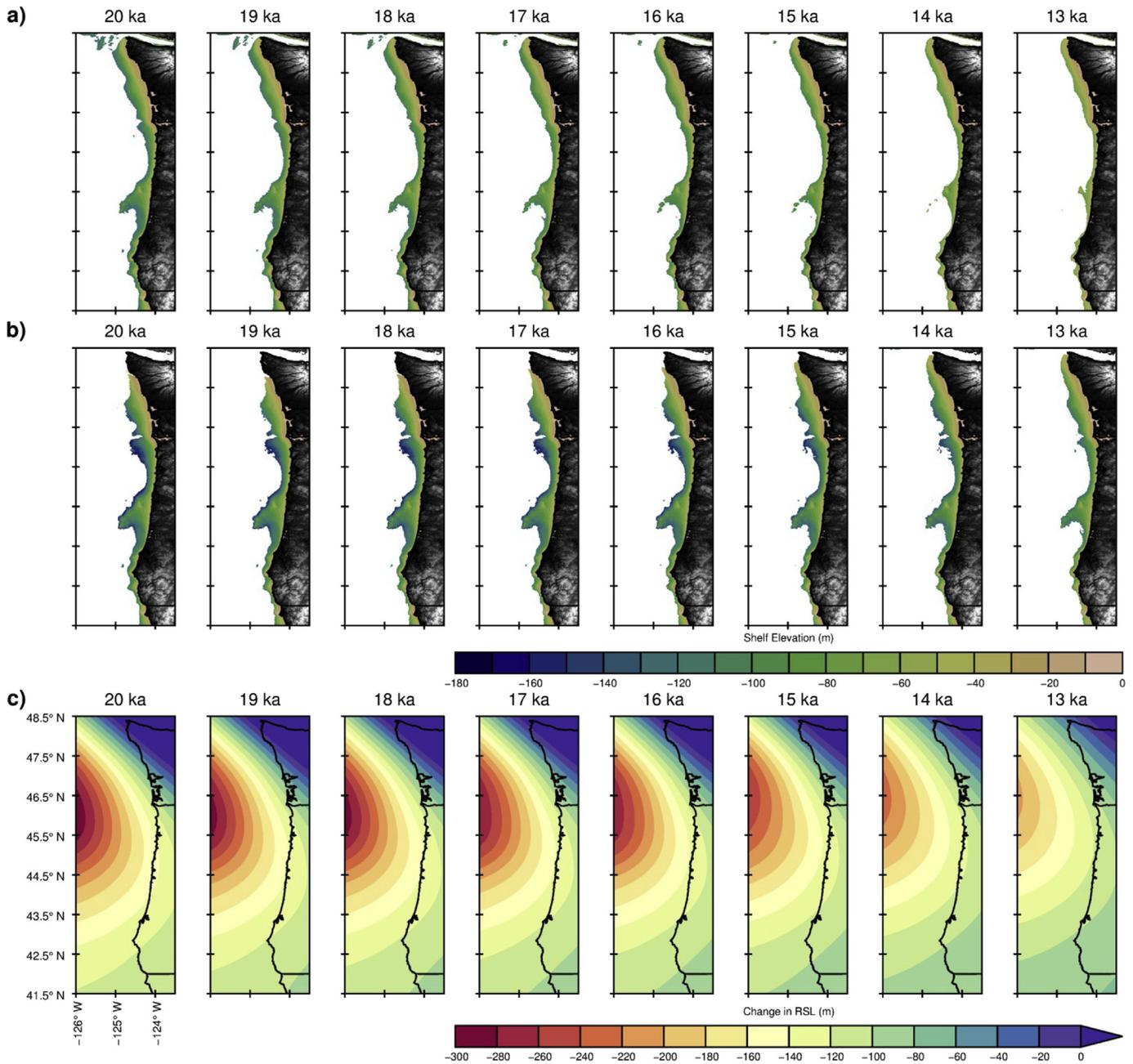


Fig. 5. The paleogeography and relative sea level (RSL) history for the Oregon–Washington continental shelves from 20 ka to 6 ka. (a) The paleogeography predicted using an assumption of a eustatic sea-level change. (b) The paleogeography predicted by accounting for the RSL history in Fig. 5c. (c) Regional maps of RSL predicted using the gravitationally self-consistent sea-level theory and the ANU/LM GIA model.

on the Chukchi and Bering Sea shelves that suggested that the submergence did not occur until ~13,000 years ago, and argued that the older ages from [McManus and Creager \(1984\)](#) likely were contaminated by old carbon.

[Fig. 7](#) shows our sea level predictions at each of the three sites where [Elias et al. \(1996\)](#) obtained constraints on RSL. Each frame includes the eustatic curve for the ANU ice history (red line) and GIA predictions based on the ANU/LM ice and Earth model pairing (blue line). Clearly, an accurate prediction of the space and time dependence of the inundation of Beringia requires that one account for ice-age adjustments on sea level. Moreover, RSL predictions based on the ANU/LM GIA model in [Fig. 7](#) are consistent with the RSL constraints provided by the limiting ages on terrestrial organics

from [Elias et al. \(1996\)](#), insofar as the presence of the organics suggests that they were not submerged until sometime after they lived.

[Fig. 8a](#) shows the paleogeography of the Bering Sea continental shelf from 15 ka to 6 ka under the assumption of a eustatic sea-level history (note that there are no substantial differences in the paleogeography of this region between 20 ka and 15 ka). [Fig. 8b](#) shows the paleogeography for the Bering Sea continental shelf from 15 ka to 6 ka computed using the RSL history in [Fig. 8c](#). There are some notable differences between the two reconstructions. In particular, we note three examples that have implications for predictive modeling of offshore sites as well as for the use of the Bering land bridge for migration. First, both

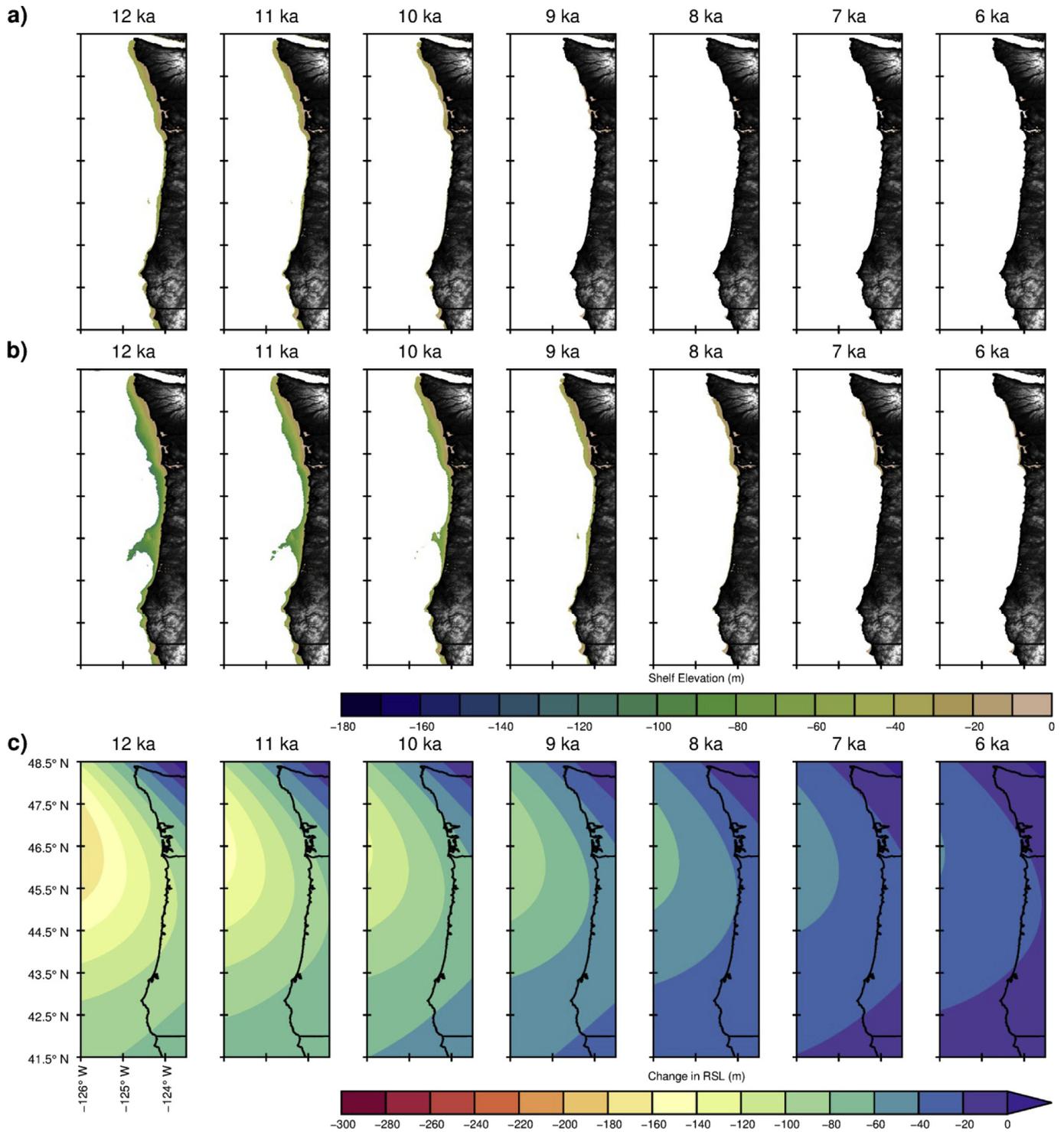


Fig. 5. (continued).

reconstructions show an elaborate archipelago to the south of the Bering land bridge that may have served as occupation sites, but with significant differences at the local scale that will be important to account for in predictive modeling. Second, the assumption of eustasy predicts that the Norton Sound (at bottom right on each frame) remained largely emergent until ~12 ka; in contrast, inundation of the Sound is predicted to have begun ~1000 years earlier at ~13 ka when GIA effects are incorporated into the reconstruction. Third, in the paleogeographic

reconstruction based on eustasy, inundation of the northern Bering land bridge in the Chukchi Sea region began at ~11 ka, whereas the RSL calculation predicts inundation ~10 ka, demonstrating that GIA effects had a significant impact on the evolution and ultimate disappearance of the land bridge. Lastly, Fig. 8c shows the predicted RSL history from 15 ka to 6 ka based on the ANU/LM GIA model. The regional predictions exhibit a spatial gradient of ~30 m from southwest to northeast at 15 ka and this gradient largely disappears by ~10 ka.

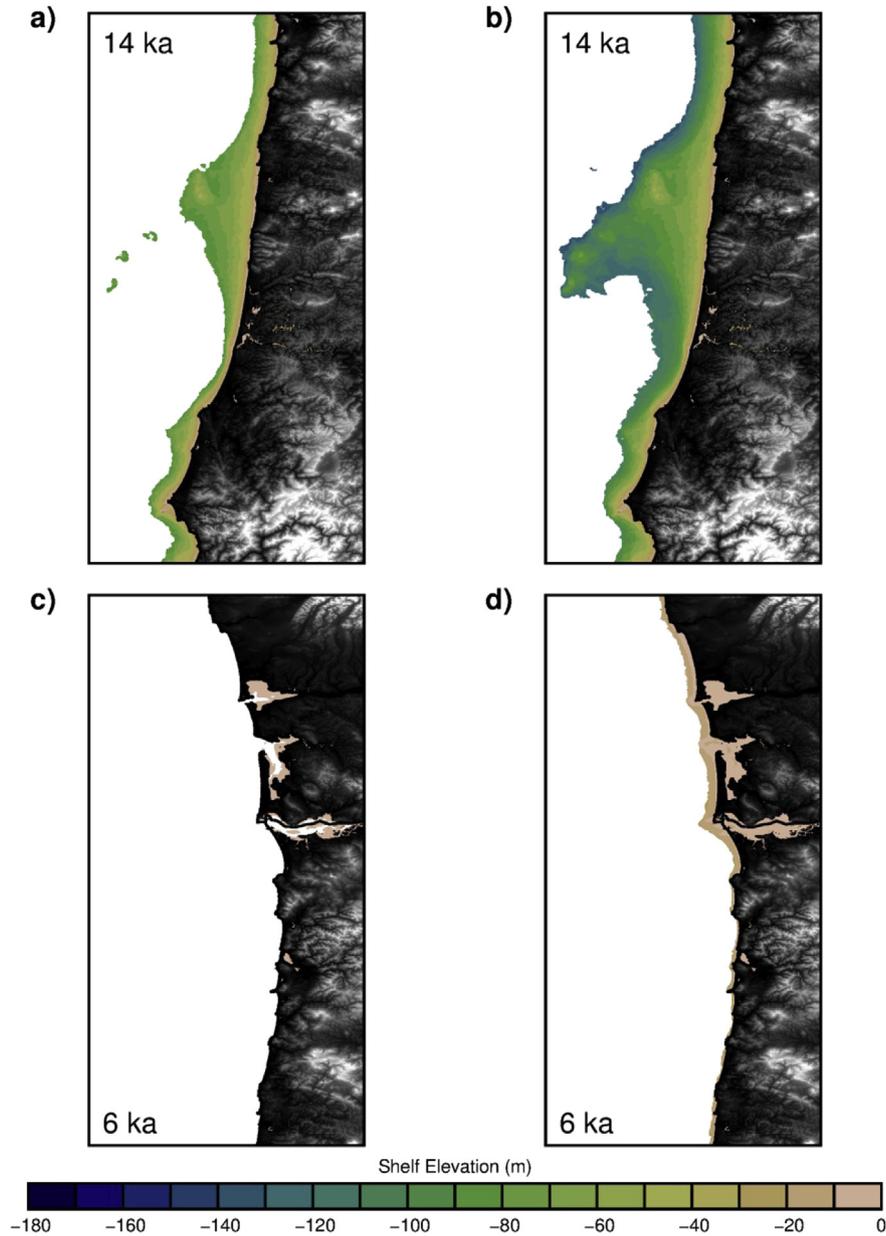


Fig. 6. Paleogeography of the central Oregon continental shelf at 14 ka predicted assuming either (a) a eustatic history, or (b) a gravitationally self-consistent RSL history based on the ANU/LM GIA model. (c, d) Analogous to frames (a, b) except for the continental shelf near the mouth of the Columbia River at 6 ka.

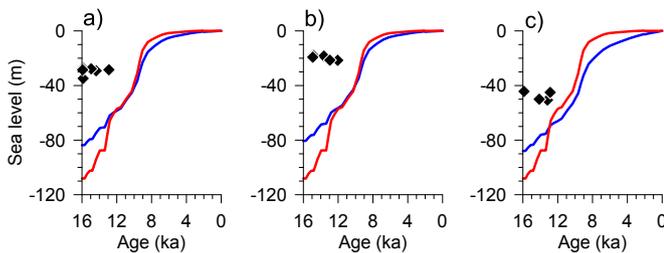


Fig. 7. Predictions of relative sea level change for three sites within the Beringian region based on the ANU/LM (blue line) GIA models (see text). Also shown is the eustatic curve associated with the ANU deglaciation history (red line). The diamonds on each frame represent RSL constraints (see text) recovered from marine cores (Elias et al., 1996). The three sites are located at: (a) 65.17°N, 167.5°W, (b) 64.08°N, 164.5°W, and (c) 71°N, 166°W. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Clark et al. (2014) considered predictions of GIA-induced Beringian sea level change using a different ice history/Earth model pairing; specifically, the VM2 radial profile of mantle viscosity, which is coupled to the ICE-5G ice history since the last interglacial (Peltier, 2004). The VM2 model is characterized by a 90-km thick elastic lithosphere and a moderate, factor of ~4–5 increase in viscosity from the upper mantle ($\sim 5 \times 10^{20}$ Pa s) to the lower mantle ($\sim 2 \times 10^{21}$ Pa s).

Fig. 9a shows the paleogeography of the Bering Sea continental shelf from 15 ka to 6 ka under the assumption of a eustatic sea-level history based on ICE5G. Fig. 9b shows the paleogeography for the Bering Sea continental shelf from 15 ka to 6 ka based on the RSL history predicted by adopting the ICE5G/VM2 GIA model (Fig. 9c). We focus on comparing the paleogeographies computed using the two GIA predictions (Fig. 8b compared to Fig. 9b). There are two notable differences that have relevance to the history of the Bering land bridge and possible coastal migration routes and occupation

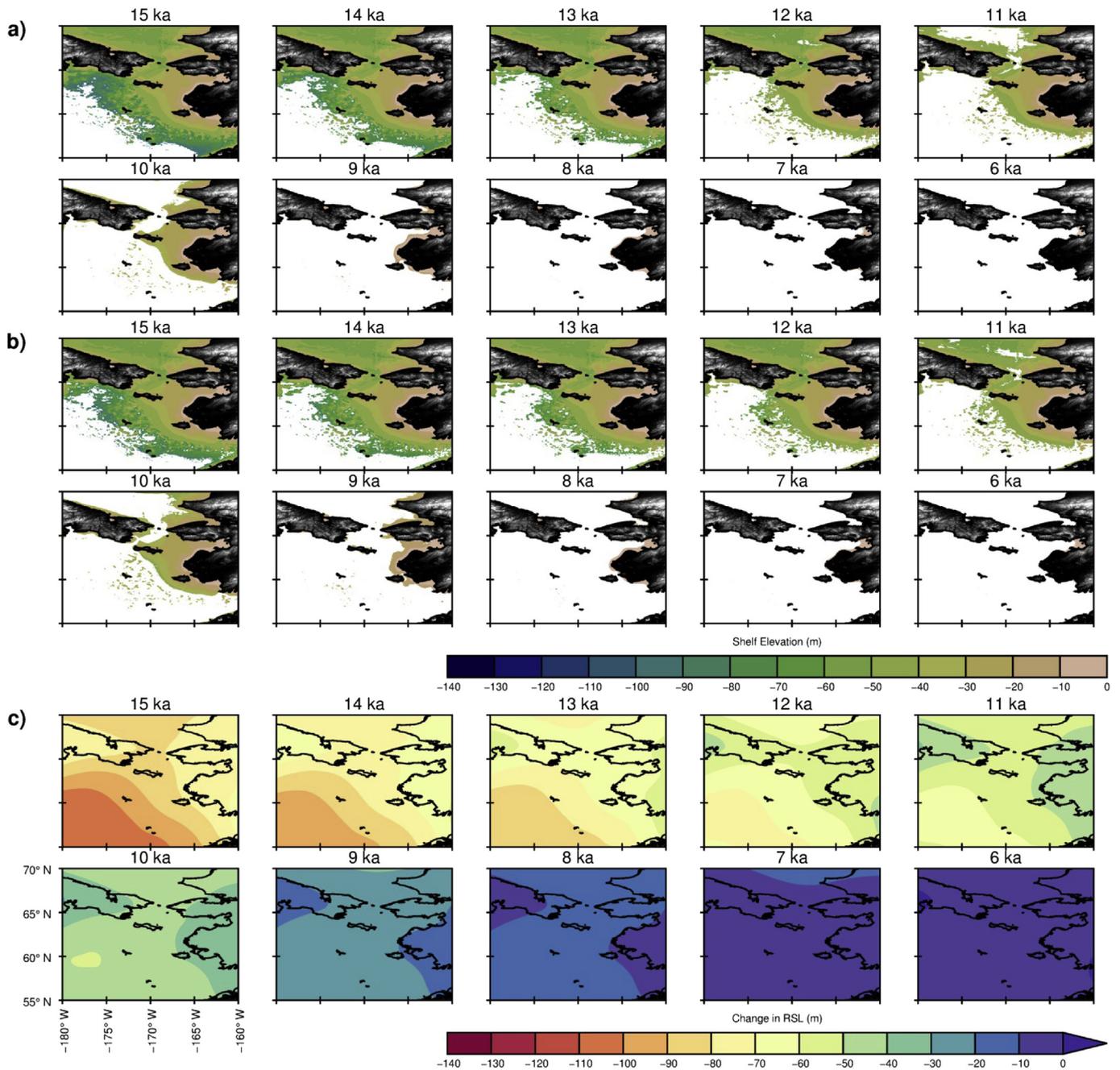


Fig. 8. Predicted paleogeography and relative sea level (RSL) history for the Beringian continental shelf from 15 ka to 6 ka. (a) Paleogeography computed using an assumption of a eustatic sea level change derived from the ANU deglaciation history (Fleming et al., 1998). (b) Paleogeography when accounting for the gravitationally self-consistent RSL changes in (c), where the latter was computed using the ANU/LM GIA model.

sites. First, the RSL prediction based on the ICE5G/VM2 GIA model shows that initial submergence of the Bering Straits occurred ~11 ka, or ~1000 years earlier than the prediction based on the ANU/LM GIA model. Second, the ICE5G/VM2 GIA model results predict that much of the Norton Sound remained submerged since the LGM, in contrast to the ANU/LM GIA model, which predicts that the inundation of the

6. A sensitivity analysis

The predictions described thus far were based on 1-D viscoelastic Earth models; specifically, model LM in Figs. 1–8 and VM2 in Fig. 9. However, the west coast of North America is characterized by an

active plate boundary and variations in both lithospheric thickness (Watts, 2001) and mantle structure (Ritsema et al., 2011). To consider the impact that this complexity might have on the predictions of sea-level change and shoreline migration, we ran a sea-level simulation on a finite volume numerical model of the GIA process that is capable of incorporating such features (Latychev et al., 2005). The 3-D Earth structure adopted in the simulation is described in detail in Austermann et al. (2013), although in the present case we incorporate lateral variations in viscosity throughout the mantle and superimpose these on the 1-D LM viscosity profile. The variations reach five orders of magnitude peak-to-peak.

Fig. 10 shows predictions of relative sea level change at the four sites along the Oregon–Washington coast considered in Fig. 4. The

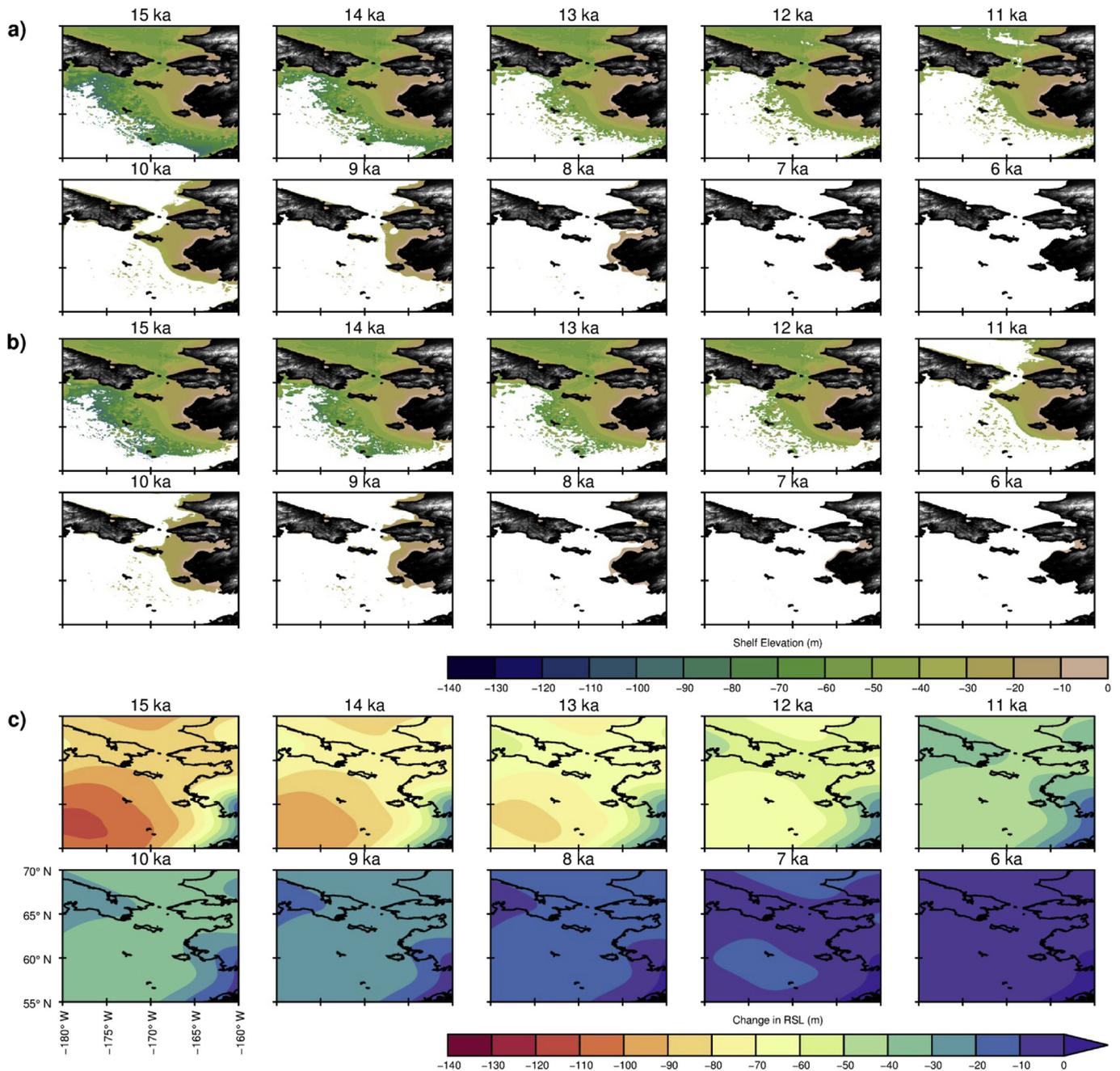


Fig. 9. Predicted paleogeography and relative sea level (RSL) history for the Beringian continental shelf from 15 ka to 6 ka. (a) Paleogeography computed using an assumption of a eustatic sea level change derived from the ICE5G deglaciation history (Peltier, 2004). (b) Paleogeography when accounting for the gravitationally self-consistent RSL changes in (c), where the latter was computed using the ICE5G/VM2 GIA model (Peltier, 2004).

blue lines are predictions based on the 1-D viscoelastic Earth model ANU (i.e., these results are reproduced from Fig. 4), while the red lines are computed using the 3-D viscoelastic Earth model. Both simulations adopt the ANU ice history. The perturbations to the predictions associated with lateral variations in structure are non-monotonic in time and in very general terms the 3-D predictions are shifted earlier by ~1 kyr relative to the 1-D simulation. (The result for the site at 46.5°N at times prior to 15 ka is a clear exception.) We conclude that in archaeological applications where predictions of shoreline evolution require a precision better than ~ 1 kyr, the sea-level simulations adopted in such analyses should incorporate the full complexity of Earth structure beneath western North America.

7. Conclusions

The evidence for pre-Clovis occupation of the Americas as early as ~15–16 ka provides additional support for the Fladmark (1979) hypothesis that the first Americans migrated from Asia to lands south of the North American ice sheets by a route along the west coast of North America. Constraining possible migration pathways, as well as identifying potential early occupation sites that are now below sea level, requires an accurate retrodiction of sea-level change during the last deglaciation and through the Holocene. We have shown that departures from a uniform (eustatic) deglacial sea-level rise due to deformational, gravitational, and rotational effects driven by the exchange of mass between ice sheets and

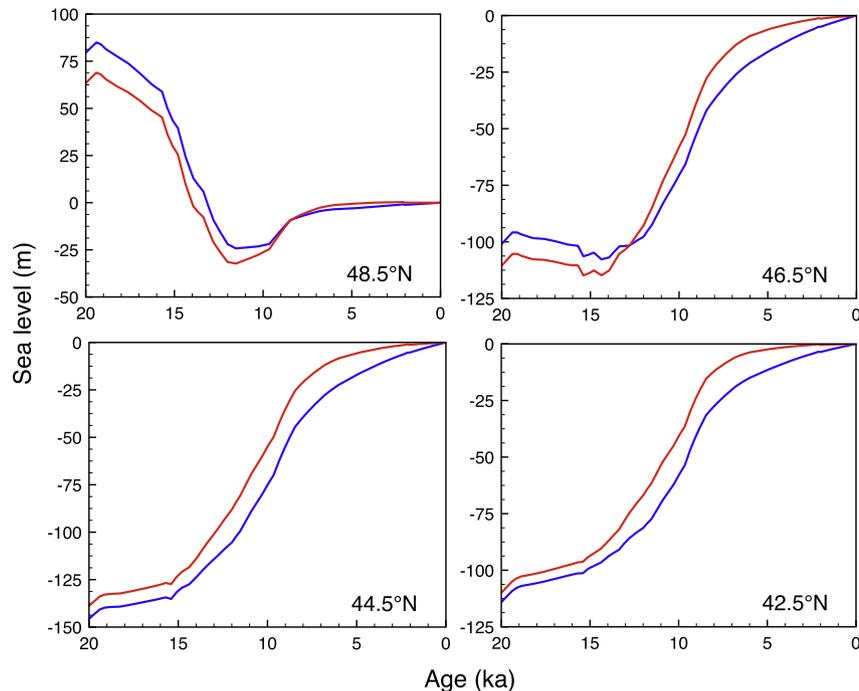


Fig. 10. Predicted relative sea level curves for four sites along the Oregon–Washington coast. The blue lines are predictions based on the 1-D viscoelastic Earth model LM and the ANU deglaciation history (these lines are reproduced from Fig. 4). The red lines are analogous to the blue lines except that the predictions are based on the 3-D viscoelastic Earth model described in the text. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

oceans during the last deglaciation (i.e., glacial isostatic adjustment) led to substantial impacts on the paleogeography across the California–Oregon–Washington and Bering Sea continental shelves. These departures must be accounted for in any paleogeographic reconstruction of these regions. Numerical predictions of post-glacial sea-level changes described herein were based on a specific pairing of ice history and Earth model. The paleogeographic reconstructions, however, will be sensitive to uncertainties in either input. In addition, our modeling did not include the impact on sea level of sediment redistribution, which may be significant in the vicinity of the Columbia, Eel and Klamath/Trinity river systems. Further work is required to address each of these issues before definitive predictions of the location of now-submerged archaeological sites are possible.

References

- Adovasio, J.M., Pedler, D.R., 2013. The ones that still won't go away: more biased thoughts on the pre-Clovis peopling of the New World. In: Graf, K.E., Ketron, C., Waters, M.R. (Eds.), *PaleoAmerican Odyssey*. Center for the Study of the First Americans, College Station, TX, pp. 511–520.
- Amante, C., Eakins, B.W., 2009. ETOPO1 1 Arc-minute Global Relief Model: Procedures, Data Sources and Analysis.
- Anderson, D.G., Bissett, T.G., Yerka, S.J., 2013. The late-Pleistocene human settlement of interior North America: the role of physiography and sea-level change. In: Graf, K.E., Ketron, C., Waters, M.R. (Eds.), *PaleoAmerican Odyssey*. Center for the Study of the First Americans, College Station, TX, pp. 183–206.
- Anderson, D.G., Yerka, S.J., Gillam, J.C., 2010. Employing high-resolution bathymetric data to infer possible migration routes of Pleistocene populations. *Curr. Res. Pleistocene* 27, 60–64.
- Austermann, J., Mitrova, J.X., Latychev, K., Milne, G.A., 2013. Barbados-based estimate of ice volume at Last Glacial Maximum affected by subducted plate. *Nat. Geosci.* 6, 553–557.
- Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G., Rougerie, F., 1996. Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature* 382, 241–244.
- Catto, N.R., 1996. Richardson mountains, Yukon-Northwest territories: the northern portal of the postulated 'ice-free corridor'. *Quat. Int.* 32, 3–19.
- Clark, J., Mitrova, J.X., Alder, J., 2014. Regional variability in latest Pleistocene and Holocene sea-level rise across the California–Oregon–Washington and Bering Sea continental shelves. In: Stanford, D.J., Stegner, A.T. (Eds.), *Pre-Clovis in the Americas: Washington, DC, International Science Conference Proceedings*, Smithsonian Institution, pp. 49–62.
- Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrova, J.X., Hostetler, S.W., McCabe, A.M., 2009. The last glacial maximum. *Science* 325, 710–714.
- Davis, L.G., Punke, M.L., Hall, R.L., Fillmore, M., Willis, S.C., 2004. A Late Pleistocene occupation on the southern coast of Oregon. *J. Field Archaeol.* 29, 7–16.
- Dillehay, T.D., Ramirez, C., Pino, M., Collins, M.B., Rossen, J., Pino-Navarro, J.D., 2008. Monte Verde: seaweed, food, medicine, and the peopling of South America. *Science* 320, 784–786.
- Dyke, A.S., 2004. An outline of North American deglaciation with emphasis on central and northern Canada. In: Ehlers, J., Gibbard, P.L. (Eds.), *Quaternary Glaciations: Extent and Chronology*, vol. 2b. Elsevier, Amsterdam, pp. 373–424.
- Dziewonski, A.M., Anderson, D.L., 1981. Preliminary reference Earth model. *Phys. Earth Planet. Inter.* 25, 297–356.
- Elias, S.A., Short, S.K., Nelson, C.H., Birks, H.H., 1996. Life and times of the Bering land bridge. *Nature* 382, 60–63.
- Erlandson, J.M., 2013. After Clovis-First collapsed: reimagining the peopling of the Americas. In: Graf, K.E., Ketron, C.V., Waters, M.R. (Eds.), *Center for the Study of the First Americans. PaleoAmerican Odyssey*, College Station, TX, pp. 127–132.
- Erlandson, J.M., Braje, T.J., 2011. From Asia to the Americas by boat? Paleogeography, paleoecology, and stemmed points of the northwest Pacific. *Quat. Int.* 239, 28–37.
- Erlandson, J.M., Braje, T.J., Rick, T.C., Peterson, J., 2005. Beads, bifaces, and boats: an early maritime adaptation on the South Coast of San Miguel Island, California. *Am. Anthropol.* 107, 677–683.
- Erlandson, J.M., Graham, M.H., Bourque, B.J., Corbett, D.C., Estes, J.A., Steneck, R.S., 2007. The Kelp highway hypothesis: marine ecology, the coastal migration theory, and the peopling of the Americas. *J. Isl. Coast. Archaeol.* 2, 161–174.
- Erlandson, J.M., Kennett, D.J., Ingram, B.L., Guthrie, D.A., Morris, D.P., Tveskov, M.A., West, G.J., Walker, P.L., 1996. An archaeological and paleontological chronology for Daisy Cave (CA-SMI-261), San Miguel Island, California. *Radiocarbon* 38, 355–373.
- Erlandson, J.M., Moss, M.L., Des Lauriers, M., 2008. Life on the edge: early maritime cultures of the Pacific Coast of North America. *Quat. Sci. Rev.* 27, 2232–2245.
- Erlandson, J.M., et al., 2011. Paleoindian seafaring, maritime technologies, and coastal foraging on California's Channel Islands. *Science* 331, 1181–1185.
- Fagundes, N.J.R., Kanitz, R., Eckert, R., Valls, A.C.S., Bogo, M.R., Salzano, F.M., Smith, D.G., Silva, W.A., Zago, M.A., Ribeiro-Dos-Santos, A.K., Santos, S.E.B., Petzl-Erler, M.L., Bonatto, S.L., 2008. Mitochondrial population genomics supports a single pre-Clovis origin with a coastal route for the peopling of the Americas. *Am. J. Hum. Genet.* 82, 583–592.
- Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342, 637–642.
- Flandmark, K.R., 1979. Routes: alternate migration corridors for Early Man in North America. *Am. Antiq.* 44, 55–69.

- Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth Planet. Sci. Lett.* 163, 327–342.
- Fleming, K., Lambeck, K., 2004. Constraints on the Greenland Ice Sheet since the Last Glacial Maximum from sea-level observations and glacial-rebound models. *Quat. Sci. Rev.* 23, 1053–1077.
- Gilbert, M.T.P., Jenkins, D.L., Gotherstrom, A., Naveran, N., Sanchez, J.J., Hofreiter, M., Thomsen, P.F., Binladen, J., Higham, T.F.G., Yohe, R.M., Parr, R., Cummings, L.S., Willerslev, E., 2008. DNA from pre-Clovis human coprolites in Oregon, North America. *Science* 320, 786–789.
- Goebel, T., Waters, M.R., O'Rourke, D.H., 2008. The Late Pleistocene dispersal of modern humans in the Americas. *Science* 319, 1497–1502.
- Graf, K.E., Ketron, C.V., Waters, M.R., 2013. *PaleoAmerican Odyssey*. Center for the Study of the First Americans, College Station, TX, p. 573.
- Haynes, G., 2002. *The Early Settlement of North America: the Clovis Era*. Cambridge University Press, Cambridge, UK, p. 340.
- Heusser, C.J., 1960. Late-Pleistocene Environments of North Pacific North America: an Elaboration of Late-glacial and Postglacial Climatic, Physiographic, and Biotic Changes. American Geographical Society, New York, NY, 308 p.
- Hopkins, D.M., 1967. *The Bering Land Bridge*. Stanford University Press, Palo Alto, p. 495.
- Hopkins, D.M., 1973. Sea level history in Beringia during the past 250,000 years. *Quat. Res.* 3, 520–540.
- Hu, A.X., Meehl, G.A., Otto-Bliesner, B.L., Waelbroeck, C., Han, W.Q., Loutre, M.F., Lambeck, K., Mitrovica, J.X., Rosenbloom, N., 2010. Influence of Bering Strait flow and North Atlantic circulation on glacial sea-level changes. *Nat. Geosci.* 3, 118–121.
- Jenkins, D.L., Davis, L.G., Stafford Jr., T.W., Campos, P.F., Hockett, B., Jones, G.T., Cummings, L.S., Yost, C., Connolly, T.J., Yohe II, R.M., Gibbons, S.C., Raghavan, M., Rasmussen, M., Pajjmans, J.L.A., Hofreiter, M., Kemp, B.M., Barta, J.L., Monroe, C., Gilbert, M.T.P., Willerslev, E., 2012. Clovis age western stemmed projectile points and human coprolites at the Paisley caves. *Science* 337, 223–228.
- Kendall, R.A., Mitrovica, J.X., Milne, G.A., 2005. On post-glacial sea level – II. Numerical formulation and comparative results on spherically symmetric models. *Geophys. J. Int.* 161, 679–706.
- Kennett, D.J., Kennett, J.P., West, G.J., Erlandson, J.M., Johnson, J.R., Hendy, I.L., Westg, A., Culleton, B.J., Jones, T.L., Stafford Jr., T.W., 2008. Wildfire and abrupt ecosystem disruption on California's Northern Channel Islands at the Allerød–Younger Dryas boundary (13.0–12.9 ka). *Quat. Sci. Rev.* 27, 2530–2545.
- Latychev, K., Mitrovica, J.X., Tromp, J., Tamisiea, M.E., Komatitsch, D., Christara, C., 2005. Glacial isostatic adjustment on 3-D earth models: a new finite-element formulation. *Geophys. J. Int.* 161, 421–444.
- Lyman, R.L., 1991. *Prehistory of the Oregon Coast: the Effects of Excavation Strategies and Assemblage Size on Archaeological Inquiry*. Academic Press, New York, 341 p.
- Mandryk, C.A.S., 1993. Hunter-gatherer social costs and the nonviability of sub-marginal environments. *J. Anthropol. Res.* 49, 39–71.
- Mandryk, C.A.S., Josenhans, H., Fedje, D.W., Mathewes, R.W., 2001. Late Quaternary paleoenvironments of Northwestern North America: implications for inland versus coastal migration routes. *Quat. Sci. Rev.* 20, 301–314.
- Manley, W.F., 2002. *Postglacial Flooding of the Bering Land Bridge: A Geospatial Animation*. Boulder.
- Mann, D.H., Hamilton, A.C., 1995. Late Pleistocene and Holocene paleoenvironments of the North Pacific coast. *Quat. Sci. Rev.* 14, 449–471.
- McManus, D.A., Creager, J.S., 1984. Sea-level data for parts of the Bering-Chukchi shelves of Beringia from 19,000 to 10,000 C-14 yr BP. *Quat. Res.* 21, 317–325.
- Meltzer, D.J., 2004. Peopling of North America. In: Gillespie, A., Porter, S.C., Atwater, B. (Eds.), *The Quaternary Period in the United States*. Elsevier, New York, pp. 539–563.
- Milne, G.A., Mitrovica, J.X., 2008. Searching for eustasy in deglacial sea-level histories. *Quat. Sci. Rev.* 27, 2292–2302.
- Milne, G.A., Mitrovica, J.X., Schrag, D.P., 2002. Estimating past continental ice volume from sea-level data. *Quat. Sci. Rev.* 21, 361–376.
- Misarti, N., Finney, B.P., Jordan, J.W., Maschner, H.D.G., Addison, J.A., Shapley, M.D., Krumhardt, A., Beget, J.E., 2012. Early retreat of the Alaska Peninsula Glacier Complex and the implications for coastal migrations of First Americans. *Quat. Sci. Rev.* 48, 1–6.
- Mitrovica, J.X., Forte, A.M., 2004. A new inference of mantle viscosity based upon joint inversion of convection and glacial isostatic adjustment data. *Earth Planet. Sci. Lett.* 225, 177–189.
- Mitrovica, J.X., Milne, G.A., 2003. On post-glacial sea level: I. General theory. *Geophys. J. Int.* 154, 253–267.
- Mitrovica, J.X., Wahr, J., Matsuyama, I., Paulson, A., 2005. The rotational stability of an ice-age earth. *Geophys. J. Int.* 161, 491–506.
- Muhs, D.R., Simmons, K.R., Schumann, R.R., Groves, L.T., Mitrovica, J.X., Laurel, D., 2012. Sea-level history during the Last Interglacial complex on San Nicolas Island, California: implications for glacial isostatic adjustment processes, paleo-zoogeography and tectonics. *Quat. Sci. Rev.* 37, 1–25.
- Munyakwa, K., Feathers, J.K., Rittenour, T.M., Shrimpton, H.K., 2011. Constraining the Late Wisconsinan retreat of the Laurentide ice sheet from western Canada using luminescence ages from postglacial aeolian dunes. *Quat. Geochronol.* 6, 407–422.
- Nakada, M., Lambeck, K., 1989. Late Pleistocene and Holocene sea-level change in the Australian region and mantle rheology. *Geophys. J. Int.* 96, 497–517.
- Peltier, W.R., 2004. Global glacial isostasy and the surface of the ice-age earth: the ice-5G (VM2) model and grace. *Annu. Rev. Earth Planet. Sci.* 32, 111–149.
- Perego, U.A., Achilli, A., Angerhofer, N., Accetturo, M., Pala, M., Olivieri, A., Kashani, B.H., Ritchie, K.H., Scozzari, R., Kong, Q.P., Myres, N.M., Salas, A., Semino, O., Bandelt, H.J., Woodward, S.R., Torroni, A., 2009. Distinctive Paleo-Indian migration routes from Beringia marked by two rare mtDNA Haplogroups. *Curr. Biol.* 19, 1–8.
- Reeder-Myers, L., Erlandson, J.M., Muhs, D.A., Rick, T.C., 2014. Paleogeography, paleoecology, and archaeology on California's Northern Channel Islands. *Quat. Res.* (submitted for publication).
- Rick, T.C., Erlandson, J.M., Vellanoweth, R.L., 2001. Paleocoastal marine fishing on the Pacific coast of the Americas: perspectives from Daisy Cave, California. *Am. Antiqu.* 66, 595–613.
- Rick, T.C., Erlandson, J.M., Vellanoweth, R.L., Braje, T.J., 2005. From Pleistocene mariners to complex hunter-gatherers: the archaeology of the California Channel Islands. *J. World Prehist.* 19, 169–228.
- Ross, R.E., 1990. Prehistory of the Oregon coast. In: Suttles, W. (Ed.), *Northwest Coast. Handbook of North American Indians*, vol. 7. Smithsonian Institution, Washington, DC, pp. 554–559.
- Ritsema, J., Deuss, A., van Heijst, H.J., Woodhouse, J.H., 2011. S40RTS: a degree-40 shear-velocity model of the mantle from new Rayleigh wave dispersion, teleseismic traveltimes and normal-mode splitting function measurements. *Geophys. J. Int.* 184, 1223–1236.
- Waters, M.R., Forman, S.L., Jennings, T.A., Nordt, L.C., Driese, S.G., Feinberg, J.M., Keene, J.L., Halligan, J., Lindquist, A., Pierson, J., Hallmark, C.T., Collins, M.B., Wiederhold, J.E., 2011a. The Buttermilk Creek Complex and the origins of Clovis at the Debra L. Friedkin site, Texas. *Science* 331, 1599–1603.
- Waters, M.R., Stafford, T.W., 2007. Redefining the age of Clovis: implications for the peopling of the Americas. *Science* 315, 1122–1126.
- Waters, M.R., Stafford, T.W., McDonald, H.G., Gustafson, C., Rasmussen, M., Cappellini, E., Olsen, J.V., Szklarczyk, D., Jensen, L.J., Gilbert, M.T.P., Willerslev, E., 2011b. Pre-Clovis Mastodon Hunting 13,800 Years Ago at the Manis Site, Washington. *Science* 334, 351–353.
- Watts, A.B., 2001. *Isostasy and Flexure of the Lithosphere*. Cambridge Univ. Press.
- Woodroffe, C.D., McGregor, H.V., Lambeck, K., Smithers, S.G., Fink, D., 2012. Mid-Pacific microatolls record sea-level stability over the past 5000 yr. *Geology* 40, 951–954.
- Yokoyama, Y., Lambeck, K., De Deckker, P., Johnston, P., Fifield, L.K., 2000. Timing of the Last Glacial Maximum from observed sea-level minima. *Nature* 406, 713–716.