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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: kiloannum. 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. Costal 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