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Sea-level history during the Last Interglacial complex on San Nicolas Island, California: implications for glacial isostatic adjustment processes, paleozoogeography and tectonics

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A R T I C L E I N F O

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A B S T R A C T

San Nicolas Island, California has one of the best records of fossiliferous Quaternary marine terraces in North America, with at least fourteen terraces rising to an elevation of ~270 m above present-day sea level. In our studies of the lowest terraces, we identified platforms at 38–36 m (terrace 2a), 33–28 m (terrace 2b), and 13–8 m (terrace 1). Uranium-series dating of solitary corals from these terraces yields three clusters of ages: ~120 ka on terrace 2a (marine isotope stage [MIS] 5.5), ~120 and ~100 ka on terrace 2b (MIS 5.5 and 5.3), and ~80 ka (MIS 5.1) on terrace 1. We conclude that corals on terrace 2b that date to ~120 ka were reworked from a formerly broader terrace 2a during the ~100 ka sea stand. Fossil faunas differ on the three terraces. Isolated fragments of terrace 2a have a fauna similar to that of modern waters surrounding San Nicolas Island. A mix of extralimital southern and extralimital northern species is found on terrace 2b, and extralimital northern species are on terrace 1. On terrace 2b, with its mixed faunas, extralimital southern species, indicating warmer than present waters, are interpreted to be from the ~120 ka high sea stand, reworked from terrace 2a. The extralimital northern species on terrace 2b, indicating cooler than present waters, are interpreted to be from the ~100 ka sea stand. The abundant extralimital northern species on terrace 1 indicate cooler than present waters at ~80 ka.

Using the highest elevations of the ~120 ka platform of terrace 2a, and assuming a paleo-sea level of +6 m based on previous studies, San Nicolas Island has experienced late Quaternary uplift rates of ~0.25–0.27 m/ka. These uplift rates, along with shoreline angle elevations and ages of terrace 2b (~100 ka) and terrace 1 (~80 ka) yield relative (local) paleo-sea level elevations of +2 to +6 m for the ~100 ka sea stand and −11 to −12 m for the ~80 ka sea stand. These estimates are significantly higher than those reported for the ~100 ka and ~80 ka sea stands on New Guinea and Barbados. Numerical models of the glacial isostatic adjustment (GIA) process presented here demonstrate that these differences in the high stands are expected, given the variable geographic distances between the sites and the former Laurentide and Cordilleran ice sheets. Moreover, the numerical results show that the absolute and differential elevations of the observed high stands provide a potentially important constraint on ice volumes during this time interval and on Earth structure.

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1. Introduction

Generation of a eustatic sea level curve that tracks glacial–interglacial cycles has been a goal of Quaternary stratigraphers and paleoclimatologists for decades. Emergent marine terraces have long been studied as a means of reconstructing sea level history, whether they are erosional, wave-cut platforms on high-energy coasts, or constructional, coral reef tracts on tropical coasts. Early studies were conducted on both tectonically stable coasts (e.g., Veeh, 1966) and uplifting coasts (Broecker et al., 1968; Veeh and Chappell, 1970) in the tropics, capitalizing on the unique suitability of coral, among marine invertebrates, for uranium-series dating. Study of emergent coral reefs on tectonically stable coasts gives information only on sea levels that were higher than present.

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For sea levels lower than present, tectonically active coasts, where uplift is in progress, can yield past sea level estimates for times when global ice volume was higher than present. In the present study, we address two issues related to Quaternary sea level history on the California coast.

One unresolved issue is the magnitude of sea level rise during relatively high sea stands that post-date the peak of the Last Interglacial complex at ~120 ka. The first studies on the uplifting coast of Barbados (Broecker et al., 1968; Matthews, 1973) showed that the ~80 ka sea stand was −13 to −18 m below present and the ~100 ka sea stand was −10 to −18 m below present, indicating global ice volumes significantly higher than those of today. Elevations and ages of uplifted reefs on other tropical islands in general support the early Barbados studies (Veeh and Chappell, 1970; Bloom et al., 1974; Chappell, 1974; Chappell and Veeh, 1978; Dodge et al., 1983). Later studies on Barbados (Potter et al., 2004; Schellmann et al., 2004; Thompson and Goldstein, 2005) indicate that sea level could have been as much as −18 to −20 m during the ~80 ka sea stand and perhaps −13 to −25 m during the ~100 ka sea stand. Moreover, some of these later studies indicate that there were multiple sea stands during MIS 5.1 (~80 ka) and MIS 5.3 (~100 ka).

Studies on other coastlines have yielded paleo-sea level estimates that differ significantly from those on Barbados. For example, Harmon et al. (1983), working on tectonically stable Bermuda, report coral-bearing marine deposits *above* modern sea level that date to ~100 ka and ~80 ka. Subsequent, higher-precision dating of emergent marine deposits on Bermuda by Muhs et al. (2002a) confirms the presence of marine deposits above present sea level at ~80 ka. On the tectonically stable Atlantic Coastal Plain of the eastern United States, Wehmiller et al. (2004) report marine deposits dating to ~80 ka a few meters above present sea level over a coastal distance of more than 700 km, from Virginia to Georgia. On the Japanese islands of Hateruma-shima and Kikai-jima, Ota and Omura (1992) report ages and elevations of marine terraces that indicate sea levels near present at ~80 ka and ~100 ka on Hateruma-shima or well above present at these times on Kikai-jima. Radtke et al. (1996) point out, however, that reworking of corals, at least on Hateruma-shima, makes paleo-sea level estimates from this island uncertain.

Australia, although tectonically stable like the U.S. Atlantic Coastal Plain and Bermuda, appears to have had a sea-level history in the period ~100–80 ka more akin to Barbados. In particular, while there are good records of the ~120 ka high sea stand along the Australian coastline, there is no evidence of sea levels above present at ~80 ka or ~100 ka based on extensive field surveys around the entire continent (Murray-Wallace and Belperio, 1991; Stirling et al., 1995, 1998; Murray-Wallace, 2002).

The geographic variability in the high sea stands may represent departures from eustasy due to the glacial isostatic adjustment (GIA) process, where GIA is the general term for perturbations in the Earth's gravitational, deformational and rotational state, associated with ice-ocean mass transfer during the Quaternary ice ages (Lambeck and Nakada, 1992; Potter and Lambeck, 2003; Milne and Mitrovica, 2008; Kopp et al., 2009; Tamisiea and Mitrovica, 2011). Indeed, Potter and Lambeck (2003) used a numerical model of GIA to explain divergent estimates of sea level at ~80 ka on the U.S. Atlantic Coastal Plain and Bermuda compared to those on Barbados. GIA provides a global-scale imprint on local sea-level histories. In the near field of the ancient ice complexes, the GIA-induced departure from eustasy is dominated by vertical crustal motions, while in the far-field it is largely governed by meltwater redistribution of smaller amplitude (we return to these issues below). In this regard, the Atlantic Coastal Plain and Bermuda are closer to the Laurentide ice sheet of North America during both of the two most recent major glacial periods (~160–140 ka [MIS 6] and ~25–12 ka [MIS 2]) than Barbados, New Guinea or Australia were to any major ice sheet.

It is important to validate and refine the idea that GIA processes produce different late Quaternary sea level records by examining other mid-latitude coastlines, particularly in the Northern Hemisphere. On the Pacific Coast of North America (Fig. 1), marine terraces form stair-step-like flights that resemble the uplifted reef terraces of Barbados and New Guinea. Unlike those islands, however, the terraces are not constructional reefs, but erosional landforms. Since the pioneering study of Alexander (1953), these flights of marine terraces have been interpreted to be the result of sea level fluctuations superimposed on steady tectonic uplift (Lajoie et al., 1991; Muhs et al., 1994, 2004). Although Pacific Coast marine terraces are erosional landforms that develop in the high-energy surf zone, after uplift they usually retain a veneer of marine sand and gravel, often including fossil marine invertebrates. Among these fossils, mollusks are by far the most common, but solitary corals are also found. Solitary corals contain U derived from seawater, like their hermatypic colonial counterparts (Muhs et al.,

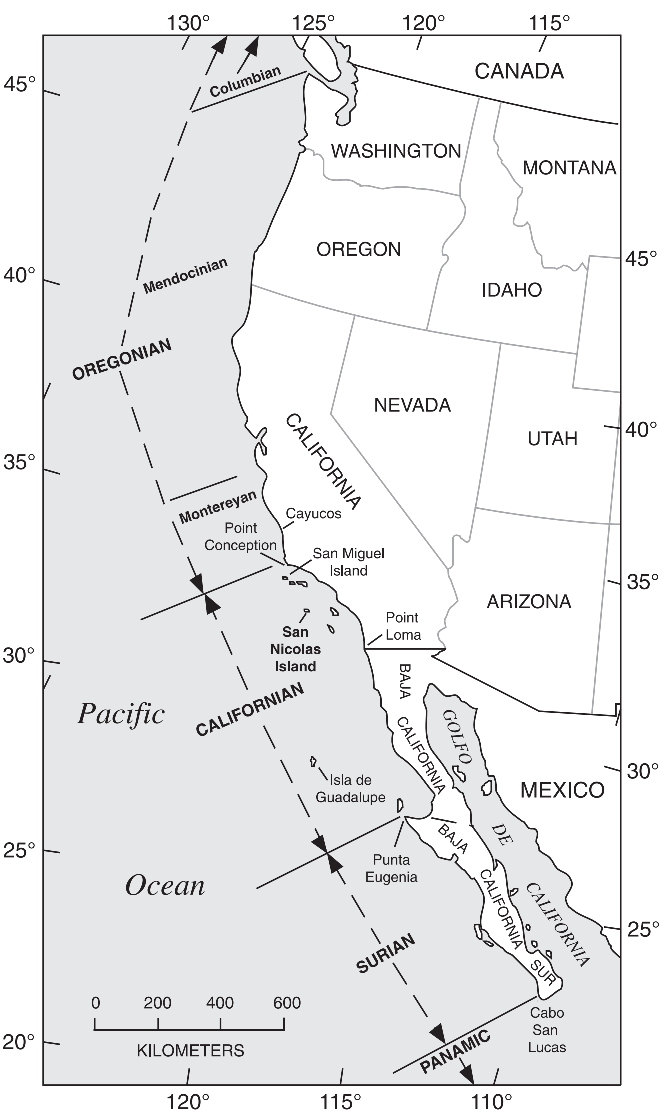

Fig. 1. Map of a portion of the Pacific Coast of North America, showing location of San Nicolas Island, marine invertebrate faunal zones (Valentine, 1966) and other localities referred to in the text.