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The Mid-Pliocene sea-level conundrum: Glacial isostasy, eustasy and dynamic topography

A. Rovere[a,*], M.E. Raymo[a], J.X. Mitrovica[b], P.J. Hearty[c], M.J. O'Leary[d], J.D. Inglis[e]

[a] Lamont Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, NY 10964, USA
[b] Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138, USA
[c] Department of Environmental Studies, University of North Carolina at Wilmington, Wilmington, NC 28403, USA
[d] Department of Environment and Agriculture, Curtin University, Bentley, Western Australia 6102, Australia
[e] Department of Geological Sciences, University of North Carolina at Chapel Hill, Chapel Hill, NC 27516, United States

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ABSTRACT

Determining eustatic sea level during the Mid-Pliocene warm period (∼3.3 to 2.9 Ma) has been a central but elusive goal in the study of past warm climates. Estimates of eustatic sea level based on geologic data span a broad range; variation that we now recognize is due in part to geographically varying post-depositional displacement caused by glacial isostatic adjustment and dynamic topography. In this study, we combine field observations and glacial isostatic adjustment modeling to estimate the dynamic topography signal in three areas that are important to paleo-sea level studies of the Mid-Pliocene warm period (South Africa, West Australia and southeastern United States). We show that dynamic topography played a significant role in the post-depositional displacement of Pliocene, and even younger Pleistocene, shorelines. In this regard, we provide a robust paleo-sea level elevation data set, corrected for glacial isostatic adjustment, that can be used to evaluate predictions from mantle flow models of dynamic topography.

1. Introduction

The Mid-Pliocene warm period (MPWP), historically defined as the interval between ∼3.3 and 2.9 Ma, is widely considered to be an example of a past climate state in equilibrium with ∼400 ppmv atmospheric CO_2 levels (Pagani et al., 2009, compare to ∼400 ppmv value as of May 2013; see Fig. S1, Supplementary Materials, for a synopsis). For this reason, this interval of time is an attractive target for climate model validation studies that compare model predictions with climate proxy reconstructions. However, for one key climate variable, polar ice volume in the Pliocene relative to today, little consensus exists in the literature. An accurate estimate of peak eustatic sea level (ESL) at this time would provide insight into both the stability of Greenland and Antarctic ice sheets in a slightly warmer climate and help resolve discrepancies between ice sheet model predictions and data (e.g., Pollard and DeConto, 2009). (In this paper we define ESL change as the geographically uniform change in sea level that would be equal to the volume of meltwater flux into or out of the ocean.) Despite the general agreement on other climatic variables (such as sea-surface temperature), sea-level estimates for the MPWP vary widely, in part because signals associated with glacial isostatic adjustment (GIA) and dynamic topography (that is, topography supported by convectively-induced viscous stresses in the mantle and associated buoyancy variations in the lithosphere, henceforth "DT") have only recently been taken into account (Raymo et al., 2011; Rowley et al., 2013).

Along several passive margins, Mid- to late-Pliocene shallow water deposits are sometimes found tens of kilometers inland from the present-day shoreline, often at the base of distinctive scarps (Dowsett and Cronin, 1990; James et al., 2006). These scarps were carved, by the relentless erosive action of the sea over the course of dozens of orbitally-paced SL highstands that occurred between the late Miocene and late Pliocene (e.g., Lisiecki and Raymo, 2005). Further, the benthic oxygen isotope record (Lisiecki and Raymo, 2005) suggests that these highstands all peaked approximately the same eustatic value (see Fig. S1, Supplementary Materials, for details). As the ocean eroded steadily inland carving the paleo-sea cliffs, broad coastal terraces also evolved – these coastal plains are now observed to be mantled with younger Pliocene and Pleistocene sediments. At the break in slope, also called the toe, or 'inner margin,' of the scarp, shallow marine deposits date to the late Pliocene, a time correlative with the onset of global cooling associated with the intensification of northern hemisphere glaciation.

* Corresponding author. Tel.: +1 347 416 1164.
E-mail address: rovere@ldeo.columbia.edu (A. Rovere).

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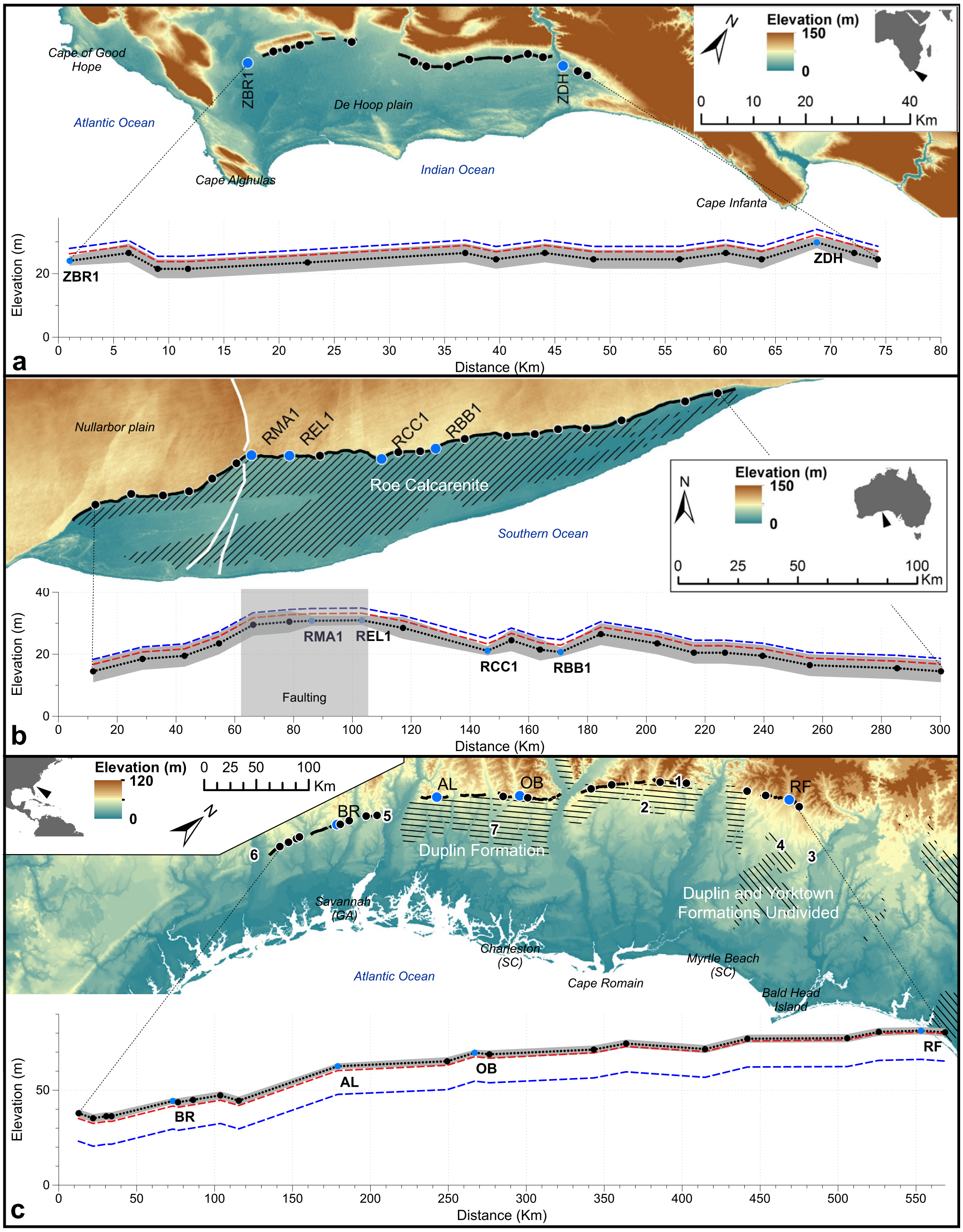

Fig. 1. Geographic location and elevation plots of MPWP shorelines at (a) De Hoop, South Africa, (b) Roe Plain, Australia and (c) the southeast US coast. Small black dots represent the position of paleo SL obtained from inner margins of broad terrace surfaces measured on DEMs. Labeled blue dots represent paleo SL position obtained from RSL markers measured in the field (refer to Table 1 and Supplementary Material). The black dotted line connects all the paleo SLs obtained in one area. The gray band represents the standard deviation of paleo SL points. The blue and red dashed lines represent the position of the paleo SL after GIA correction based on the LM (blue) and VM2 (red) viscosity models. In frame (b) the white lines on the map represent the main faults identified on the Nullabor and Roe Plains (Clark et al., 2012). In frame (c) the numbers 1–4 represent locations where the Duplin Formation has been sampled (corresponding to sites 1–4 of Dowsett and Cronin, 1990) while numbers 5–7 are locations of the Raysor Formation identified by Huddlestun (1988). Sr isotopic ratios yielded ages of 2.88–3.57 Ma for site 3 (McGregor et al., 2011), and of 2.3–2.8 Ma for site 4 (Graybill et al., 2009). Dashed areas in (b) and (c) represent the mapped extension of the Roe Calcarenite (James et al., 2006) as well as the Duplin Formation (SC) and Duplin–Yorktown Formation (Dicken et al., 2007). All distances in lower plots are calculated as linear distance from the beginning of the lines representing the scarp on the map. The projection used for the three maps is geographic coordinate system, WGS 84. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

We interpret the slope break as indicative of the former level of the sea just prior to the long-term global cooling trend that began at ∼2.9 Ma (see Supplementary Materials for details).

Using digital elevation models (DEMs) and field surveys, we measured the elevation of the slope break of three such scarps, as well as associated SL markers, across hundreds of kilometers in the southern Republic of South Africa, southern Western Australia, and southeastern United States (Fig. 1a, b, c and Table 1). Then, as described herein, we accounted for depositional effects due to GIA using a large set of numerical modeling results.

We then combine GIA-corrected scarp elevations with different eustatic sea-level scenarios to calculate a set of field-based DT predictions for each area, and compare these with previously published DT models. Our ultimate aim is to provide a robust dataset (attached as Supplementary Material) against which future DT model predictions in these three areas can be tested.