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MIS 5e relative sea-level changes in the Mediterranean Sea: Contribution of isostatic disequilibrium

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ABSTRACT

Sea-level indicators dated to the Last Interglacial, or Marine Isotope Stage (MIS) 5e, have a twofold value. First, they can be used to constrain the melting of Greenland and Antarctic Ice Sheets in response to global warming scenarios. Second, they can be used to calculate the vertical crustal rates at active margins. For both applications, the contribution of glacio- and hydro-isostatic adjustment (GIA) to vertical displacement of sea-level indicators must be calculated. In this paper, we re-assess MIS 5e sea-level indicators at 11 Mediterranean sites that have been generally considered tectonically stable or affected by mild tectonics. These are found within a range of elevations of 2–10 m above modern mean sea level. Four sites are characterized by two separate sea-level stands, which suggest a two-step sea-level highstand during MIS 5e. Comparing field data with numerical modeling we show that (i) GIA is an important contributor to the spatial and temporal variability of the sea-level highstand during MIS 5e, (ii) the isostatic imbalance from the melting of the MIS 6 ice sheet can produce a >2.0 m sea-level highstand, and (iii) a two-step melting phase for the Greenland and Antarctic Ice Sheets reduces the differences between observations and predictions. Our results show that assumptions of tectonic stability on the basis of the MIS 5e records carry intrinsically large uncertainties, stemming either from uncertainties in field data and GIA models. The latter are propagated to either Holocene or Pleistocene sea-level reconstructions if tectonic rates are considered linear through time.

1. Introduction

Sea-level changes are primarily a reflection of water mass transfer between continents, where water is stored as ice during cold periods, and oceans, where meltwater is introduced during warmer periods. This process is known as glacial eustasy (Suess, 1906) and occurs in response to changes in atmosphere and ocean temperatures related to variations in atmospheric CO_2 concentrations and Milankovitch-driven insolation (Stocker et al., 2013). A fundamental aspect for the study of past climate change over glacial-interglacial time scales is the collection, analysis and interpretation of Relative Sea Level (RSL) indicators, that are fossil landforms, deposits or biological assemblages with a known relationship with a paleo sea level (Hibbert et al., 2016; Rovere et al., 2016a). Once vertical movements associated with Glacial Isostatic Adjustment (GIA) (Lambeck and Purcell, 2005), tectonics (Simms et al., 2016) or other post-depositional processes (Rovere et al.,

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2016b) are taken into account, paleo RSL indicators can be used to constrain ice-mass variations in response to changes in atmospheric and ocean temperatures during past interglacials (Dutton et al., 2015). In turn, estimates of paleo global mean sea level can be used to constrain processes regulating ice melting in paleo ice-sheet models, which eventually may be used to gauge the sensitivity of present-day polar ice sheets to future scenarios of global warming (e.g. Deconto and Pollard, 2016).

The most studied past interglacial is the Marine Isotopic Stage 5e (MIS 5e, 117–127 ka), which is the last period of the Earth's history when climate was warmer than today. Generally, MIS 5e sea-level studies are oriented towards two main goals. The first is to understand how to account for processes causing departures from eustasy (e.g., GIA, tectonics) in order to produce reliable estimates of past global mean sea levels. The second consists on the calculation of tectonic movements starting from the elevation of RSL indicators and assumptions on eustatic sea-level changes. This aspect is particularly relevant for the understanding of the long-term vertical movement of coastal areas, which is in turn important for the planning of coastal infrastructures in active geodynamic settings and need to be accounted for to correct future climate-related rates of RSL change (Antonioli et al., 2017).

Despite the common consideration in isolation, the two aims outlined above are mutually dependent and they are both tied to GIA predictions. In fact, to achieve the second goal, one must calculate the climate-related and GIA-modulated RSL elevations, which are the result of the first goal. The latter, however, stems from *a priori* information on long-term tectonic motions, which is the result of this second goal. Studies on MIS 5e RSL change in the Mediterranean Sea have often either adopted standard ESL values to calculate vertical tectonic rates at active sites or neglected the GIA overprint in the calculation of the ESL signal (Ferranti et al., 2006).

In this paper we focus on MIS 5e sea-level variations in the Mediterranean Sea. We investigate the GIA contributions to the spatiotemporal variability of RSL change during MIS 5e within the basin using GIA numerical simulations that incorporate the solid Earth and gravitational response to three glacial-interglacial cycles prior to MIS 5e and that evolve towards present. We also evaluate the GIA-modulated contribution of four scenarios for GrIS and AIS melting during MIS 5e. We compare our RSL predictions to observations from 11 sites that have been previously hypothesized as tectonically stable based on the low elevation of the MIS 5e shoreline.

We use field data and numerical GIA predictions at these sites to address the following questions:

1. How much of the observed MIS 5e RSL variability in the Mediterranean can be explained by GIA?
2. How significant are the uncertainties in GIA, as well as GrIS and AIS melting scenarios when using MIS 5e shorelines to calculate tectonic vertical motions?

2. Materials and methods

2.1. Paleo relative sea-level indicators

The Mediterranean Sea has been a central focus for studies on sea level changes for over two centuries (Benjamin et al., 2017). The basin is characterized by different tectonic regimes (Fig. 1, see Supplementary Text for a brief outline) and its relatively low tidal amplitudes and low wave energy helped to preserve RSL indicators almost ubiquitously (see Fig. 1 in Ferranti et al., 2006 for an overview and detailed reports in Anzidei et al., 2014; Ferranti et al., 2006; Galili et al., 2007; Mauz et al., 2012; Pedoja et al., 2014).

In the absence of MIS 5e reefs (Dutton and Lambeck, 2012; Hibbert et al., 2016), the main Mediterranean Pleistocene RSL indicators can be divided into three main categories: i) Depositional, consisting mostly of cemented beach or shallow marine deposits (Fig. 2a–c,e,f). ii) Biological, consisting of fossil remains of benthic organisms living attached to hard substrates (Rovere et al., 2015) or traces of bioeroding organisms (e.g. *L. lithophaga* boreholes, Fig. 2d). iii) Geomorphological: all landforms formed by the action of the sea over time. Typical geomorphological MIS 5e markers include fossil shore platforms or tidal notches (Fig. 2d, f, Antonioli et al., 2015). Often, dating of Mediterranean MIS 5e RSL indicators is challenging because the preservation of *in situ* corals for U-series measurements is rare.

To calculate the paleo RSL from the measured elevation of a RSL indicator, it is essential to decouple the actual measured elevation of the indicator and the interpretation of the paleo sea level that it

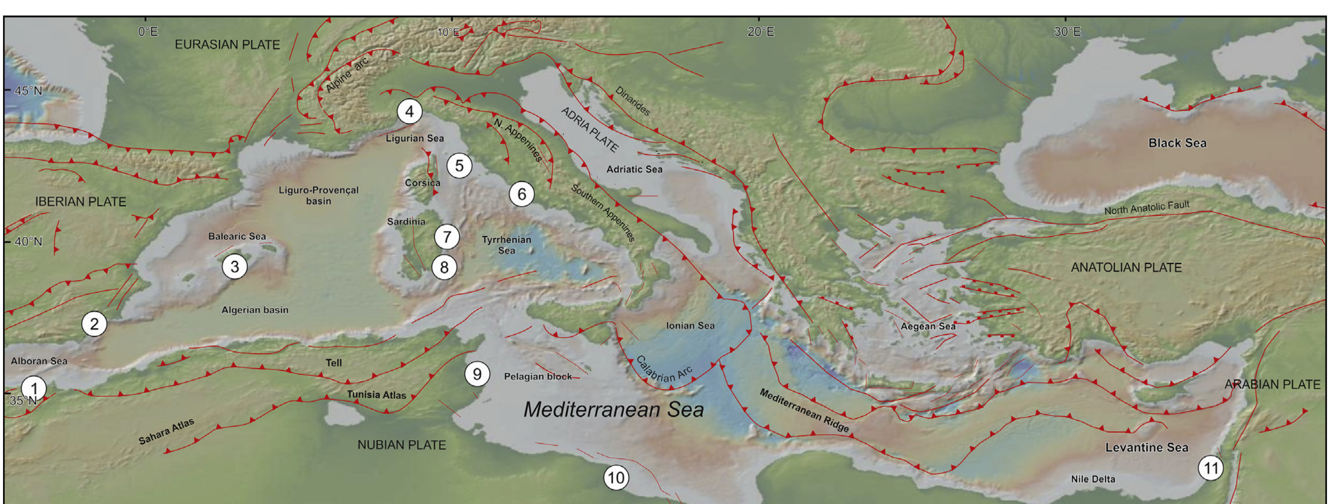

Fig. 1. Tectonics map of the Mediterranean Sea and geographical locations of the 11 RSL sites that considered in this study. Faults are modified after Faccenna et al. (2014). Site names: 1- Morocco-Al Hoceima; 2- Italy-Pianosa; 3- Spain-Cala Blava; 4- Italy-Bergeggi; 5- Italy-Pianosa; 6- Italy-Pisco Montano; 7- Italy-Cala Luna; 8- Italy-Cala Mosca; 9- Tunisia-Hergla-S; 10- Libia-W Libia; 11- Israel-Nahal Galim.