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# Terminal Antarctic melting inferred from a far-field coastal site

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ABSTRACT

The contribution of the Antarctic ice sheet (AIS) to deglacial sea-level rise is poorly constrained. This shortfall gives rise to concerns because incorrect AIS estimates impact significantly on our ability to predict sea-level change in the course of global warming. Given the scarcity of geological data and the complexity of the Antarctic response to glacio-isostatic adjustment processes, there is a need for accurate data to constrain the timing of the ice-sheet retreat. Here, we provide such data on the Holocene Antarctic melting through an isolated geographic site on the northern hemisphere, which we show is sensitive to the Antarctic signal. Using both our site, and other mid-latitudinal relative sea-level sites, our model provides a consensus estimate that the AIS released water corresponding to 5 m equivalent sea level at 8 ka and ceased melting at 6 ka. This is different to most AIS models, which release an equal amount of water at 11 ka or after 6 ka. Our findings change model assumptions about the terminal AIS melting and show that future Holocene sea-level research should focus on broad shelves and large coast embayments in the mid latitudes.

## 1. Introduction

An improved picture is today available for the modern Antarctic ice sheet (AIS) based on satellite altimetry, interferometry and gravimetry data (e.g., Shepherd et al., 2012), and for the past AIS based on glacial–geological evidence (Bentley et al., 2010) and improved ice models simulating ice-flow dynamics and ice loading (Whitehouse et al., 2012). The new picture suggests relatively small ice thickness and total mass change since the Last Glacial Maximum, possibly due to a previously unknown self-limiting behaviour of the ice sheet (A.S. Hein et al., 2011; C.J. Hein et al., 2011) and a difficult to model sensitivity of grounding ice to shelf bathymetry (Philippon et al., 2006). As a consequence, the AIS should contribute only a small amount of equivalent sea level (ESL) to the deglacial sea-level rise (Whitehouse et al., 2012; Ivins et al., 2013). However, ice-volume estimates derived from far-field sea-level records point to much more water stored in ice (Milne et al., 2002), and the estimate derived from the Barbados record seems to even underestimate the global ice volume (Austermann et al., 2013). Thus, the discrepancy between ESL contribution from the AIS and global ESL inferred from far-field records is today even larger, indicating that some northern or southern hemisphere ice is still unaccounted for. Equally inconclusive remains the timing of AIS retreat, whether it started due to significant sea-level forcing after around 12 ka (Huybrechts, 2002; Heroy and Anderson, 2007; Argus et al., 2014), significant ocean warming after 14 ka (Mackintosh et al., 2011) or the retreat was synchronous to the warming of the northern hemisphere (Weber et al., 2011) because part of the shelf ice was not grounded along deep marine troughs (Whitehouse et al., 2012).

On the orbital time scale the AIS seems to respond to ocean warming and local solar insolation (WAIS, 2013). But on the sub-orbital, Holocene, time scale direct evidence for glacier retreat is sparse. Most glacio-isostatic adjustment (GIA) models force the Antarctic to melt until the late Holocene (Huybrechts, 2002; Peltier, 2004; Ivins and James, 2005; Philippon et al., 2006; Mackintosh et al., 2011; Briggs and Tarasov, 2012; Whitehouse et al., 2012; Ivins et al., 2013; Argus et al., 2014), and some (Huybrechts, 2002; Peltier, 2004; Ivins and James, 2005; Mackintosh et al., 2011; Ivins et al., 2013), allow for a significant amount of ice to melt during the mid to late Holocene (Table S1). This water should flow away from the former ice margins due to the self-attraction of surface mass load and should create a geographically variable relative sea-level (RSL) signal in the far-field due to ocean loading and associated continental emergence. If the final Antarctic ESL was small, it is likely to be similar in amount to the sea-level changes

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caused by crustal rebound and ocean loading and therefore hard to model and to observe. If it was significant, an enhanced RSL amplitude (i.e. above the eustatic level) and associated RSL highstand should be observed in some far-field areas. To find the evidence for the terminal AIS melting history, high-spatial data-resolution of the near-field is required that is currently hard to achieve; or, alternatively, some special conditions on the far-field coast allow to fingerprint the AIS meltwater. Here we describe RSL data collected at a far-field coastal site situated on the southern shore of the Mediterranean Sea (Fig. 1; Fig. 2). We show its sensitivity to the Antarctic signal, which allows us to infer the terminal melting history of the AIS.

## 2. The Holocene relative sea-level highstand and Antarctic melting hypotheses

The Holocene RSL highstand was reported from numerous coastal sites (e.g., Jedoui et al., 1998; Dullo and Montaggioni, 1998; Yim and Huang, 2002; Milne et al., 2005; Angulo et al., 2006; Kench et al., 2009; A.S. Hein et al., 2011; C.J. Hein et al., 2011; Martínez and Rioja, 2013). Given large error bars and discrepancies in terms of age and elevation of the highstand (cf., Angulo et al., 2006), little effort was made to include GIA modelling, also because the underlying physics of this RSL change is, in general, well-understood (e.g., Mitrovica and Milne, 2002). However, with increasing precision of the RSL data the highstand becomes interesting because the GIA mechanisms are dependent on the timing of meltwater release and because a RSL site at a given location allows to fingerprint the meltwater release. Knowing the exact timing of the sea-level stand is therefore important and if a highstand developed after the dominant Laurentide ice sheet ceased melting, a fingerprint from another, the Antarctic ice sheet, can be inferred.

The first to describe the GIA mechanism triggered by a uniform thinning of the West Antarctic ice sheet (WAIS) were Clark and Lingle (1977). In this pioneering study an enhanced sea level was predicted for the mid-latitudinal North Atlantic and North Pacific and the southern Indian Ocean immediately after the thinning has occurred. The signal on the northern hemisphere should be a result of the deforming earth crust in the middle of the ocean due to water load with subsequent emergence of its respective continental margins (Clark and Lingle, 1977). Gomez et al. (2010) reproduced the model results of Clark and Lingle (1977) and advanced the modelling by considering rotational feedback, moving shorelines and the accommodation space created by the disappearance of the marine based WAIS. The spatial pattern of sea-level change resulting from the new algorithm is similar but the values of RSL enhancement are 10–15% higher affecting not only the ocean centres but also coastlines. However, the subsequent RSL fall could be a result of ocean water re-distribution (‘ocean syphoning’; Mitrovica and Peltier, 1991), a mechanism that affects mostly tropical coasts (Mitrovica and Milne, 2002). Evidence for RSL enhancement should therefore be sought in the far-field, but outside the tropics. We investigated the El Grine site (Fig. 1) on the tectonically stable coast of the Gulf of Gabès (34°N; East Mediterranean Sea) which shows a mid-Holocene RSL highstand of about 1.5 m (Jedoui et al., 1998; Morhange and Pirazzoli, 2005).

## 3. Material and methods

### *3.1. RSL observational data*

RSL observational data were generated through conventional field mapping, logging and elevation measurements using differential GPS. Tectonic stability was inferred through the positions of two shorelines on the shore of the Gulf of Gabès, one from the Last Interglacial (Bouaziz et al., 2003) and one from Roman time (Anzidei et al., 2011). Morphological evidence for present-day mean low and high tide and mean spring/neap shoreline and tide gauge data (Gabès, 33° 53′N, 10° 07′E) were taken into account assuming the geometry of this tectonically stable coast has not changed during the Holocene. The range of the astronomical tide was ignored due to the intertidal nature of the deposit and its significance for sea level (Hopley, 1986; Mauz et al., 2015). The midpoint of the deposit was used as the reference water level (tidal datum). To determine the indicative meaning impregnated and polished thin sections were analysed using petrographic microscope and cathodoluminescence (Technosyn 8200 Mk operating at 10 kV and 30–40 mA, unfocused electron beam under He atmosphere at 0.2 Torr vacuum pressure). With the first method composition, texture and matrix is identified; with the second diagenetic phases and stages of cementation can be described. Integration of resulting data allows inferring the depositional environment and hence, water depth. The error of the water depth estimate was obtained by combining in quadrature the independent error terms of levelling, tidal range and indicative meaning.

The age of the deposit was determined by calibrating and averaging published radiocarbon ages (Jedoui et al., 1998; Morhange and Pirazzoli, 2005; Anzidei et al., 2011). Age data with unknown radiocarbon data or unknown origin were excluded from the average. Optical (optically stimulated luminescence, OSL) dating of quartz was used for age estimation of those deposits that were not dated by previous studies (Table S1). Sample preparation followed standard procedures to extract sand-sized quartz grains from carbonate-rich sediment samples. A standard single-aliquot regenerative-dose protocol was employed for tests and for equivalent-dose estimation using 3 mm aliquots. Data obtained after applying standard rejection criteria were fitted using a linear or a one component exponential growth function. The optical ages were estimated using the carbonate model (Nathan and Mauz, 2008), which accounts for the post-depositional chemical alteration of the sediment caused by lithification and post-mortem Uranium uptake in mollusc shells. The dose rate over time is constructed as a series of values where the water content is reduced proportionately to the accumulation of carbonate in the sediment pores until it reaches a new constant level. The age of the sample is estimated as the length of time needed for the integrated dose rate to equal the equivalent dose. Uncertainties in dose rate and ages are estimated using a Monte-Carlo approach.

### *3.2. GIA modelling*

The GIA computations were based on the solution of the Sea Level Equation (SLE) using the SELEN code (Spada and Stocchi, 2007) which accounts for the time-dependent geoid variations and deformations of the solid Earth driven by the partial melting of late-Quaternary ice sheets. An improved version of the code incorporates the lateral migration of the shorelines in response to local sea-level changes and the feedback on sea level from the glaciation-induced perturbations in Earth rotation. The SLE was solved through 5 iterations to harmonic degree LMAX = 256, adopting the ICE-5G ice chronology model downloaded from www.atmosp.physics.utoronto.ca/~peltier/in October 2013. The post-LGM palaeo-topography was reconstructed by means of the method outlined in Peltier (2004), adopting ETOPO5 at present time. The Earth response to surface loads is evaluated using a spherically symmetric, self-gravitating, incompressible, Maxwell visco-elastic earth model. The elastic structure of the Earth is based on the seismic model PREM. The finely-layered VM2 viscosity profile associated with model ICE-5G, in which the lithospheric thickness is set to LT = 90 km, is volume-averaged across the