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Ice sheet retreat and glacio-isostatic adjustment in Lützow-Holm Bay, East Antarctica

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ABSTRACT

The East Antarctic Ice Sheet has relatively few field data to constrain its past volume and contribution to global sea-level change since the Last Glacial Maximum. We provide new data on deglaciation history and develop new relative sea-level (RSL) curves along an 80 km transect (from Skallen to Skarsvnes, Langhovde and the Ongul Islands) in Lützow Holm Bay, East Antarctica. The geological constraints were compared with output from two Glacial Isostatic Adjustment (GIA) models. The minimum radiocarbon age for regional deglaciation is c. 11,240 cal. yr BP on West Ongul Island with progressively younger deglaciation ages approaching the main regional ice outflow at Shirase Glacier. Marked regional differences in the magnitude and timing of RSL change were observed. More in particular, in Skarvsnes a minimum marine limit of 32.7 m was inferred, which is c. 12.7 m higher than previously published evidence, and at least 15 m higher than that reported in the other three ice-free areas. Current GIA model predictions slightly underestimate the rate of Late Holocene RSL fall at Skallen, Langhovde, and West Ongul, but provide a reasonable fit to the reconstructed minimum marine limit at these sites. GIA model predictions are unable to provide an explanation for the shape of the reconstructed RSL curve at Skarvsnes. We consider a range of possible explanations for the Skarvsnes RSL data and favour an interpretation where the anomalously high marine limit and rate of RSL fall is due to reactivation of a local fault.

1. Introduction

Estimates of the contribution of the continental ice-sheets to past and recent global sea-level change are still relatively imprecise (Bromwich and Nicolas, 2010; Clark and Tarasov, 2014). This is due to an incomplete understanding of changes in continental ice volume, including the maximum extent of glaciation, and the onset and rates of ice retreat. Some of this information can be inferred from radiocarbon dating of organic deposits that have accumulated after ice retreat, and from changes in relative sea-level (RSL) resulting from the glacio-isostatic response of the Earth's crust to ice mass changes. Accurate RSL reconstructions, together with GPS-derived uplift data, can track regional changes in glacial isostatic adjustment (GIA) (Thomas et al., 2011; Hodgson et al., 2016), a process that contaminates satellite gravity measurements of present-day ice sheet mass balance (e.g., Chen et al., 2009; Shepherd et al., 2012; Williams et al., 2014). In regions where measurements of GIA are sparse, or where modelled estimates are not compared with geological constraints, large errors can be introduced into the GIA correction and hence the mass balance calculations (Velicogna and Wahr, 2013). In Antarctica, the paucity of GIA constraints limits the accuracy of estimates of changes in the mass balance of the ice sheets derived from the Gravity Recovery and Climate Experiment (GRACE; Velicogna and Wahr, 2013; Clark and Tarasov, 2014) as well as predictions of future ice sheet

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contributions to global sea-level rise (e.g., Adhikari et al., 2014). Increasing the spatial resolution of geological data on ice sheet retreat and RSL reconstructions is therefore a recognized research priority (e.g., Watcham et al., 2011; Bentley et al., 2014).

Post Last Glacial Maximum (LGM) changes in RSL in previously glaciated regions principally reflect three processes: eustatic sea-level rise, regional GIA, and neotectonic events (Stewart et al., 2000; Bentley et al., 2005). The latter are generally assumed to be only important in tectonically active regions (e.g., Pacific coastline of North America (Plafker, 1972), the southern part of the Strait of Magellan and southernmost Tierra del Fuego (Bentley and McCulloch, 2005)), and can be the dominant forcing of regional variability in RSL changes. However, post-glacial unloading and rebound can also lead to the formation or re-activation of faults in continental shields and hence tectonic activity in otherwise stable areas (e.g., Lagerbäck, 1978; Risberg et al., 2005; Steffen et al., 2014). Therefore, if RSL changes are significantly influenced by neotectonic faulting, this needs to be taken into account when validating GIA models (Watcham et al., 2011).

Of all ice sheets, the Antarctic ice-sheets probably have the fewest RSL field data (Bentley et al., 2014; Mackintosh et al., 2014). This has resulted in a wide range of model-based estimates of Antarctic Ice Sheet contributions to global sea-level since the LGM, varying from 35 m (Nakada and Lambeck, 1988) to 13.6 m (Argus et al., 2014), 9 ± 1.5 m (Whitehouse et al., 2012a), and even 9 to 6 m (Gomez et al., 2013). Given (i) the potential of the EAIS to raise global sea-level by up to 50 m (Huybrechts, 2002), and (ii) some studies suggest that the melting of the EAIS might have contributed to the Eemian sea-level high stand, which was 6–9 m higher than today (Kopp et al., 2009; Pingree et al., 2011), identifying those areas of the EAIS that respond to Holocene and recent climate changes is critical (Mackintosh et al., 2014).

Two complementary approaches are traditionally used to develop RSL curves in Antarctica. The first one relies on radiocarbon dating of marine fossils in raised beaches as direct evidence of former sea-level changes (e.g., Berkman et al., 1998; Miura et al., 1998). The shortcoming of this approach however, is that the organisms producing the shells used for dating occur at different depths in the marine environment (Shennan et al., 2015). Dating fossils in raised beaches therefore typically provides minimum constraints on the height of former sea-levels (Shennan et al., 2015). The second approach is based on isolation lakes, which are natural depressions in the bedrock that have been inundated by and subsequently isolated from the sea as a result of RSL fall (Verleyen et al., 2004). The isolation event is identified by studying markers of marine and lacustrine phases, such as diatoms, fossil pigments and sedimentological changes (Watcham et al., 2011). The RSL curves are then derived from studying the timing of marine-lacustrine transitions in isolation basins situated at different altitudes (Zwartz et al., 1998). The advantage of isolation basins is that the height of their sills can be measured with precision and that this height therefore provides a better vertical constraint compared with that of fossils in raised beaches (Takano et al., 2012). Moreover, because in isolation lakes the organic matter in the lacustrine sediments that are deposited in equilibrium with atmospheric CO_2 can be dated, problems associated with the marine radiocarbon reservoir effect can be circumvented (Hodgson et al., 2001; Verleyen et al., 2005). One drawback of the isolation basin approach is that during storm over wash events marine diatoms can be transported into the lake, which can complicate to discriminate between lacustrine and marine sediments (Verleyen et al., 2004). A second shortcoming is that in saline and brackish lakes in Antarctica, the diatom communities are similar to those in the Southern Ocean (Verleyen et al., 2003), making it difficult to exactly identify the transition from marine to lacustrine sediments based on diatoms alone. However, despite the shortcomings of both approaches, they have been successfully applied to develop RSL curves in parts of the Antarctic Peninsula (Bentley et al., 2005; Hall, 2010; Roberts et al., 2011; Watcham et al., 2011) and a few ice-free regions along the East Antarctic coastline, such as the Vestfold Hills (Zwartz et al., 1998), Windmill Islands (Goodwin and Zweck, 2000), Rauer Islands (Berg et al., 2010; Hodgson et al., 2016), and Larsemann Hills (Verleyen et al., 2005).

Here, we present new RSL constraints for islands and peninsulas in the Lützow-Holm Bay region (Dronning Maud Land, East Antarctica, Fig. 1) based on two coastal lakes from Skarvsnes and five lakes from West Ongul Island situated at different elevations, as well as new raised beach data from Skarvsnes. We combined our data with recently published records from an isolation basin on Skallen and one on Skarvsnes (Takano et al., 2012), as well as with radiocarbon dates of fossils incorporated into raised beaches on Skallen, Skarvsnes, Langhovde and West Ongul Island (Miura et al., 1998, Fig. 1). These geological constraints were subsequently compared with regional predictions of RSL evolution and high stand from two recently-developed GIA models, namely the ICE-6G_C model (Argus et al., 2014) and the W12 model (Whitehouse et al., 2012a), in order to assess the potential offset between modelling results and the near-field data.

2. Site description

Lützow-Holm Bay is part of Antarctic Drainage System 7 based on ICESat data (Fig. 1) and is the discharge point of one of the larger East Antarctic glacier systems (Zwally et al., 2012), the Shirase Glacier, as well as of a number of smaller glaciers (Miura et al., 1998). The bay includes several ice-free peninsulas and islands composed of gneisses, metabasites, and granites, together with thin beds of marble and quartzite (Tatsumi and Kizaki, 1969). Different fault systems have been mapped, including one on Skarvsnes and one between West and East Ongul Island (Ishikawa et al., 1976, Fig. 1), but there are no records of neotectonic activity.

West Ongul Island is the largest ice-free island in the region. It is separated from the Antarctic continent by a c. 600 m deep glacial trough (Mackintosh et al., 2014) in front of the Langhovde and Hazuki Glaciers (Miura et al., 1998), and from East Ongul Island by the 40 m wide Naka-no-seto Strait. ^{14}C dates of *in situ* fossils in raised beaches on the Ongul Islands fall into two age classes; pre-LGM and Holocene. It has therefore been suggested that this part of the region was ice-free during the LGM and Marine Isotope Stage (MIS) 3 (Nakada et al., 2000), or even MIS 6–7 (Takada et al., 2003). The maximum Holocene marine limit for the region was estimated to be 17 m (10,590 ± 160 ^{14}C yr BP; Miura et al., 1998).

Langhovde is one of the two main peninsulas in the region. It is situated to the south west of the Langhovde Glacier and to the north east of the Honnør Glacier (Fig. 1). Marine fossils in the raised beaches are either of Late Pleistocene (or older) or Holocene age. The pre-Holocene ages are however only found on the northern part, which has led to the suggestion that this part was ice- free during the LGM, whereas the southern part was probably ice-covered (see Mackintosh et al., 2014 for a review). The maximum Holocene marine limit has been estimated at 17 m (6810 ± 60 ^{14}C yr BP; Miura et al., 1998).

Skarvsnes is the second of the two largest peninsulas and is situated south of Langhovde in between glacial troughs in front of the Honnør and Telen Glaciers (Miura et al., 1998). All but one of the ^{14}C-dated fossils derived from raised marine deposits on this peninsula are of Holocene age (Miura et al., 1998), suggesting that the region was ice-covered during the LGM. This is confirmed by a recent cosmogenic isotope dating campaign, which revealed that Skarvsnes emerged from at least 350 m of ice cover between 10 and