**Title of manuscript:** Late Holocene ice mass changes recorded in a relative sea-level record from Joinville Island, Antarctica

Julie Zurbuchen[1] and Alexander R. Simms[1]

[1]*Department of Earth Science, University of California, Santa Barbara, jmzurbuchen@ucsb.edu*

## ABSTRACT

Recent ice-mass loss driven by warming along the Antarctic Peninsula (AP) has resulted in rapid changes in uplift rates across the region. Are such events only a function of recent warming? If not, does the Earth response to such events last long enough to be preserved in Holocene records of relative sea levels (RSL), and thus have a bearing on global-scale glacial isostatic (GIA) models (e.g. ICE-5G)? Answering such questions in Antarctica is hindered by the scarcity of RSL reconstructions within the region. Here, a new RSL reconstruction for Antarctica is presented based on beach ridges from Joinville Island on the AP. We find that RSL fell 4.9 ± 0.58 m over the last 3100 years, and the island experienced a significant increase in the rate of RSL fall from 1540 ± 125 cal yr BP to 1320 ± 125 cal yr BP. This increase in the rate of RSL fall is likely due to the viscoelastic response of the solid Earth to terrestrial ice mass loss from the AP, similar to the Earth response experienced after ice mass loss following acceleration of glaciers behind the collapsed Larsen B ice shelf in 2002. Additionally, slower rates of beach-ridge progradation from 695 ± 190 cal yr BP to 235 ± 175 cal yr BP potentially reflect erosion of beach ridges from a RSL rise induced by a local glacial advance. The rapid response of the Earth to minor ice-mass changes recorded in the RSL record further supports recent assertions of a more responsive Earth to glacial unloading and at time scales relevant for GIA of Holocene and Pleistocene sea levels. Thus, current continental and global GIA models may not accurately capture the ice mass changes of the Antarctic ice sheets at decadal and centennial time scales.

## INTRODUCTION

In 2002, the Larsen B ice shelf on the eastern Antarctic Peninsula (AP) collapsed, initiating accelerated ice flow and glacial thinning in the glaciers it once buttressed (Rignot et al., 2004; Scambos et al., 2004). The subsequent terrestrial ice-mass loss from the glaciers that once fed the ice shelf resulted in a pronounced increase in uplift rates recorded in GPS data across the AP (Thomas et al., 2011). The amount of uplift exceeded that which could be explained by elastic deformation of the solid Earth alone and must have included a viscoelastic response (Nield et al., 2014). Most current continental-scale glacial isostatic adjustment (GIA) models (Lambeck et al., 1998; Peltier et al., 2015) for the behavior of the Earth in response to late Pleistocene through late Holocene ice-sheet changes fail to reflect rapid decadal to centennial Earth responses to ice-mass loss. This shortcoming is in part a reflection of the relatively limited resolution of the relative sea-level (RSL) data available within Antarctica. While geologic evidence shows that many smaller ice shelves and glaciers around the AP have exhibited re-advances and retreats throughout the Holocene (Brachfeld et al., 2003; Hall, 2009; Hjort et al., 1997; Pudsey and Evans, 2001; Pudsey et al., 2006), the resolution of the few RSL curves in Antarctica prevents a full understanding of the solid-Earth response to such events.

In the AP, coastal marshes, microatolls, and other geological formations containing biological proxies often used for the generation of high-precision RSL curves are absent. In their absence, most RSL reconstructions within Antarctica have turned to using radiocarbon dating of organic material preserved within morphologic features, such as beach ridges or isolation basins (Bentley et al., 2005; Fretwell et al., 2010; Hall, 2010; Hjort et al., 1997; Hodgson et al., 2013; Roberts et al., 2009; Roberts et al., 2011; Simkins et al., 2013; Simms et al., 2018; Watcham et al., 2011). Isolation basins capture the age and elevation of RSL as the basin transitions from salt to fresh water or vice versa. However, finding an adequate number of basins at varying elevations is difficult and has failed to produce any late Holocene RSL reconstructions with more than half a dozen sea-level index points. Beach ridges, whose elevations and formation ages have been used to estimate RSL changes, provide their own set of challenges. Often the little organic material preserved within paleo-beach ridges, such as bones, shells, or seaweed, was reworked and may not reflect the age of beach formation. As a result, the age obtained often provides only limiting data. Additionally, beach ridge elevation is a function of not only mean sea level, but also wave energy, storm energy, tidal range, grain size and shape, and sediment availability (Lindhorst and Schutter, 2014; Scheffers et al., 2012).

In this study, we present a new RSL reconstruction based on radiocarbon dated seaweed preserved within bedding of beach-ridge deposits from Joinville Island along the northeastern Antarctica Peninsula (Fig. 1). This new sea-level reconstruction is used to determine if similar periods of punctuated uplift, as occurred following the demise of the Larsen B Ice Shelf in 2002, occurred at other time periods during the Holocene.

## METHODS

GPS and ground-penetrating radar (GPR) surveys were conducted across 31 beach ridges on the eastern side of Tay Head, a small (~2.5 x 2 km) peninsula on the southern side of Joinville Island (Fig. 1). Beaches on Tay Head Peninsula were numbered from 1 to 31, lowest to highest (i.e. youngest to oldest). Elevation data were obtained using a UNAVCO Trimble Net R9 GNSS Receiver, a local Trimble Net R9 Receiver base station, and the O'Higgins permanent GPS station (www.sonel.org), located ~115 km away, upon failure of the local base station. Beach-ridge elevations were obtained from kinematic mode GPS surveys across the crest of each beach ridge (Fig. 1c; Supplementary Fig. S1), except for beach ridges 2 and 3, which each have 3 static elevation points due to the presence of wildlife. GPS data have horizontal and vertical precisions of < 0.25 m. Elevations were converted to mean sea level using 2 days of data from a locally deployed tide gauge matched to the tide gauge at Bahia Esperanza ~50 km away.

The incorporation of seaweed into the modern beaches was observed during the field campaign (Fig. 2). Thirty cm deep pits in the crest of the lower 18 beach ridges, except for beach ridge 14, revealed stratified gravels with mats of seaweed (Fig. 2) that often incorporated limpet shells. Both mats and limpets were radiocarbon dated (Supplementary Table S1). Thus, the *in situ* (cf. reworked) samples obtained on Joinville Island likely provide a better estimate of the timing of beach-ridge formation than minimum or maximum beach age constraints in many previous studies. Radiocarbon ages were first calibrated in CALIB v7.1 (Stuiver et al., 2018) using the MARINE13 calibration curve (Reimer et al., 2013) with a reservoir correction of 791 ± 121 years (Hall et al., 2010).

The Bacon age-depth modeling program (Blaauw and Christen, 2011) was used to estimate a progradation rate through time, using distance from the start of GPR LINE05 at the shoreline instead of the traditionally used depth. The RSL reconstruction was made using the mean elevation of beach ridges from GPS surveys and the median age for each beach ridge as derived from the Bacon age-model. To calculate the rate of RSL change (dRSL) through time, a Monte Carlo simulation was run using the equation

$$dRSL = \frac{(z_{i+1} - z_i)}{(t_{i+1} - t_i)}, (1)$$

where $z$ is the elevation of the beach ridge as chosen randomly from a Gaussian PDF determined from beach-ridge GPS surveys, and $t$ is the age of the beach ridge chosen from ages output from the Bacon age-model, which prohibits age reversals.

## RESULTS

Ground-penetrating radar (GPR) profiles collected perpendicular to the beach ridges display seaward-dipping reflections, at about 5-7°, typical of beach progradation (Lindhorst and Schutter, 2014) (Fig. 3). An erosional surface is imaged below the crest of beach ridges 1 and 2 and reflections within beach ridge 2 dip landward, onlapping the erosional surface (Fig. 3). Beaches 1-18 display no changes in grain characteristics within error, including sorting, rounding, or size (Fig. 4c).

RSL on Tay Head Peninsula shows an overall fall of 4.9 ± 0.58 m from the oldest dated beach ridge at 3095 ± 195 cal yr BP (calibrated years before present; present defined as 1950) to the modern (Fig. 4a). A discrete fall in RSL of 1.32 ± 0.15 m is observed between beach ridges 7b and 8. A trough (Fig. 3) and potential RSL fall is observed between beach ridges 12 and 11b (Fig, 4a), and a ~460-year hiatus occurs between beach ridges 3 and 2. Progradation of the beach ridges was relatively constant through time at a rate of ~9 cm/yr, until a significant decrease ~695 cal yr BP to present.

An abrupt increase in the rate of RSL change occurs at 1540 ± 125 cal yr BP, increasing from -0.01 ± 3.95 mm/yr to 6.06 ± 4.72 mm/yr after the deposition of beach ridge 8 (Fig 4b). This increase is followed by a 500-year gradual decrease in rates of RSL fall, with another possible increase in the last 200 years (Fig. 4b).

## BEACH RIDGES AS RSL INDICATORS

A change in formation processes on beach ridges (e.g. waves, sea ice, etc.), could inhibit the use of their elevation as RSL indicators. However, a change in these processes would also change the grain size and shape, as well as stratigraphy recorded in the GPR of the beach ridges. Yet, none of these characteristics within the GPR or grains change, except for an erosional surface observed beneath beach ridges 1 and 2 (discussed below). Additionally, features typical of ice-push processes, such as melt pits or push ridges (Butler, 1999), are not observed within the lower 18 beach ridges. Furthermore, the lower beaches exhibit stratification, uncommon in ice-formed features. Together, this is taken to indicate that no significant changes in beach ridge formation mechanisms occurred over the last 3000 years.

Other mechanisms that could be responsible for sudden elevation changes include earthquakes or tidal changes. Although the continent of Antarctica is stable, the Antarctic Peninsula is known to be an area of active seismicity (Kaminuma, 1995). However, existing catalogs of seismicity across the AP suggest earthquakes are centered around the South Shetland Islands (Fig. 1a) and the South Scotia Ridge (farther to the northeast) – both tectonic arcs. Furthermore, estimates of tectonic uplift in the South Shetland Islands range from 0.4 to 0.48 mm/yr (Watcham et al., 2011), an order of magnitude less than the maximum rate of RSL change of 6.06 ± 4.72 mm/yr calculated for Joinville Island. Although no paleo-tide reconstructions are available for the Firth of Tay, the bathymetry of the fjord would not have changed greatly with 2-3 m of RSL change. Thus, following Fretwell et al. (2010), the changes in beach-ridge elevations from Joinville Island are considered to largely reflect changes in RSL.

## LINKS TO ICE MASS CHANGES

Coincident with the RSL falls at ~1540 cal yr BP and possibly ~2240 cal yr BP are two distinct diatomaceous ooze layers deposited beneath the former Larsen A ice shelf, dated from sediment cores to be 1400 ± 250 cal yr BP and ~2100 ± 250 cal yr BP (Brachfeld et al., 2003). The abundance of diatoms in these layers reflects higher surface water productivity, indicative of an ice free environment (Buffen et al., 2007). Additionally, low overall total organic carbon and elevated water content measured in the layers could indicate an increasing influence of meltwater (Brachfeld et al., 2003; Domack et al., 1993). Temperature anomaly records from an ice core at

James Ross Island (Fig. 1a), located south of Joinville Island, indicate increased warmth before these two time periods (Mulvaney et al., 2012), and smaller ice shelves are known to respond faster to climatic changes, enhanced by surface-crevasse propagation due to increased surface meltwater (Scambos et al., 2000). Southern Prince Gustav Channel, which had an ice shelf until it's collapse in 1995, is thought to have had episodes of growth and decay during the Holocene, although the scarcity of carbonate material within cores from the channel preclude accurate age dating of these episodes (Nývlt et al., 2014; Pudsey et al., 2006).

Following the 2002 break-up of Larsen B, the uplift rates recorded in GPS at Palmer Station increased from 0.08 ± 1.87 mm/yr to 8.75 ± 0.64 mm/yr (Thomas et al., 2011). The increased rate of RSL fall ~1540 cal yr BP observed at Joinville Island, ~100 km away from Prince Gustav Channel and ~200 km away from Larsen A, is similar in magnitude to the uplift rates observed at Palmer Station, ~100 km away from the former Larsen B ice shelf. Changes in the sea surface height, including gravitational attraction between the ice and water, for the AP are estimated to be ~0.2-0.3 mm/yr for the time period between 1500 cal yr BP and the present (Simms et al., 2018) indicating they alone cannot account for the high rate of RSL fall observed at Joinville Island. As ice shelves retreat, the glaciers that were once buttressed by them accelerate flow into marine waters, indicating that accelerated glacial mass loss following a potential collapse of the Larsen A or Prince Gustav Channel ice shelves may have been responsible for the increased rate of RSL fall. However, without more records of RSL from across the AP, the precise size or location of the ice mass loss resulting in the increase in the rate of RSL fall on Joinville Island cannot be determined.

The hiatus in beach ridge formation and slowdown in progradation rate after 695 ± 190 cal yr BP may suggest a reduction in sediment supply and/or erosion of the beach. The erosional surface imaged beneath beach ridges 1 and 2 precedes 235 ± 175 cal yr BP and postdates the deposition of beach ridge 3 at 695 ± 190 cal yr BP. Possible causes of the erosional surface include increased wave or storm activity, or a minor sea-level transgression. No changes in grain size or roundness were found between beach ridges 2 and 3, as would be expected if the erosion was the result of greater wave action or storm activity (Fig 3c). The hiatus in deposition and erosional surface correspond to cooler temperatures in the AP from 370 to 70 cal yr BP with minor glacial advances documented in West Antarctica (Consortium et al., 2013; Domack et al., 1995). Furthermore, temperature records from the nearby James Ross Island ice core show a cooling trend during this time interval (Mulvaney et al., 2012), causing an advance of local glaciers on the island (Davies et al., 2014). The erosional surface therefore may have formed as a result of RSL rise on Tay Head Peninsula driven by the GIA response to a local or regional glacial advance. Following the retreat of previously advancing glaciers, the land would once again rebound, causing an RSL fall, and the preservation of beach ridges 2 and 1.

Overall, the RSL reconstruction of Joinville Island follows an exponential fall in sea-level through time, also reflected in the closest RSL curve ~100 km away at Beak Island (Roberts et al., 2011). However, the limited resolution (3 RSL points) of the Beak Island data prevents comparison of decadal to centennial changes. The centennial timescale variability of RSL rates presented in our RSL reconstruction, suggests that even small episodes of growth and decay of ice sheets over time can induce a recordable solid Earth response. Such a response is only possible with lower upper mantle viscosities than currently assumed in most global-scale GIA models (e.g. ICE-5G; Simms et al., 2018). Thus not only are such low upper mantle viscosities necessary for explaining ongoing rapid changes recorded in GPS studies (e.g. Nield et al., 2014) but also at time scales relevant for the Holocene. As the resolution and number of RSL records increase, future GIA models should incorporate these smaller oscillations in ice sheets to investigate the impact on uplift rates through time and if they may be masking the behavior of the ice sheets during the early Holocene and Late Pleistocene.

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## FIGURE CAPTIONS

Figure 1. Location map of Joinville Island. a, Regional map of the Antarctic Peninsula. Joinville Island is located at the northeastern tip of the peninsula, red box indicates area shown in panel b. b, Tay Head Peninsula, on the southern edge of Joinville Island, sticks out into the Firth of Tay, red box indicates area shown in panel c. c, Selected beach ridges to show morphology, shown by dashed white lines, on Tay Head Peninsula, as well as radiocarbon collection sites in green circles, and GPR transect LINE05 in yellow.

Figure 2. Seaweed on and in the beach ridges. a, Picture showing wrack line of seaweed on the modern beach at Tay Head Peninsula. b, Layer of in situ seaweed, outlined in dashed white lines, from a pit dug into beach ridge 10.

Figure 3. Beach ridge stratigraphy. a, 200 Mhz GPR LINE05 labeled by beach ridge. TTWT is two-way travel time, VE is vertical exaggeration, msl is mean sea level. b, Traces of GPR reflections, labeled by beach ridge age.

Figure 4. RSL reconstruction, temperature anomaly, and sediment changes on beach ridges through the Late Holocene. 2 red lines show ages of diatomaceous ooze layers from Brachfeld et al., 2003, with error in grey boxes. Hiatus in beach ridge formation shown by brown box. a, RSL reconstruction for the beach ridges on Joinville Island, errors are shown as 2$\sigma$. b, Rates of RSL change, positive is RSL fall, negative is RSL rise, pink link shows the median rate of RSL change and boxes show 95% confidence intervals. c, James Ross Island temperature reconstruction, blue line shows 10-year average, red line shows 100-year average (Mulvaney et

al., 2012). d, Grain characteristics showing error as 1σ. Roundness is plotted using the Powers scales, 5 is well-rounded, 1 is angular.

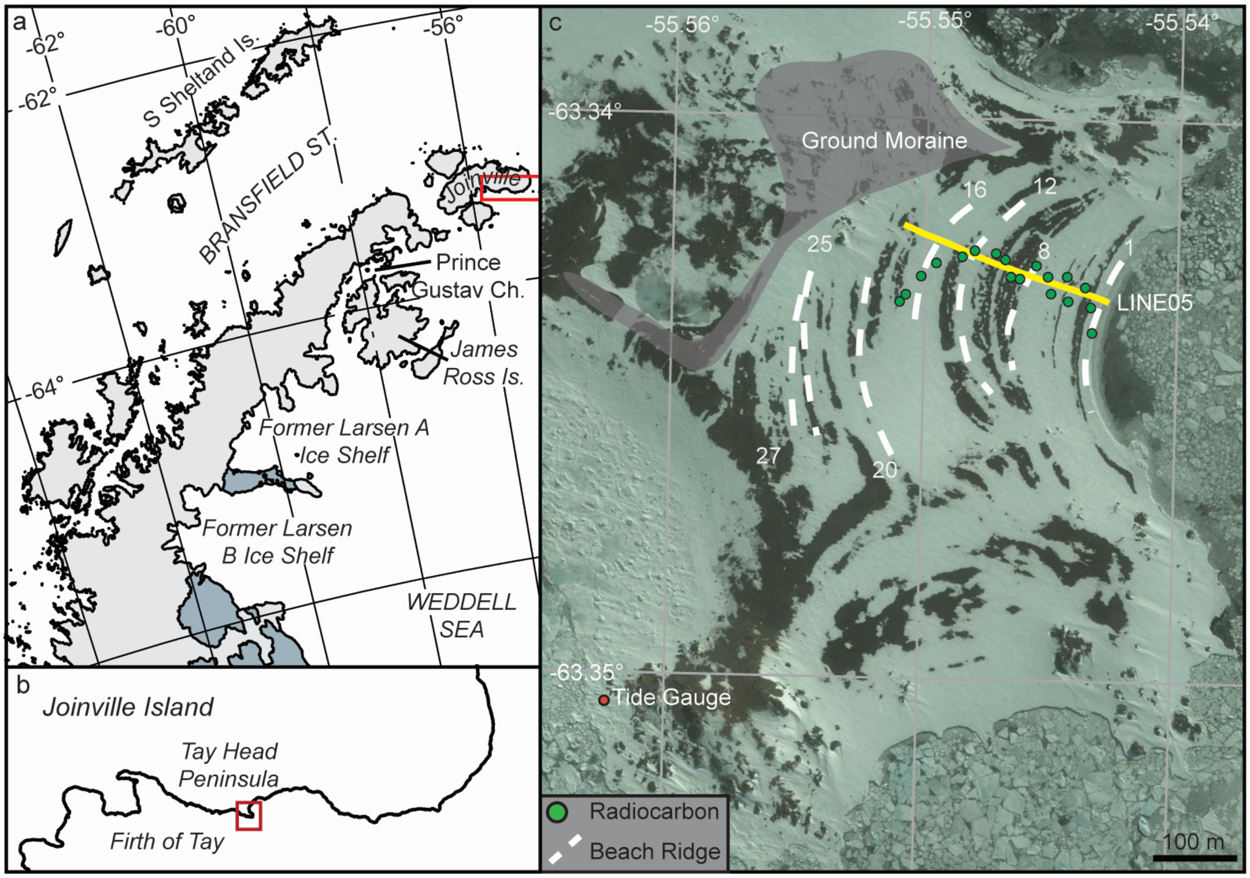


Figure 1.


Figure 2.

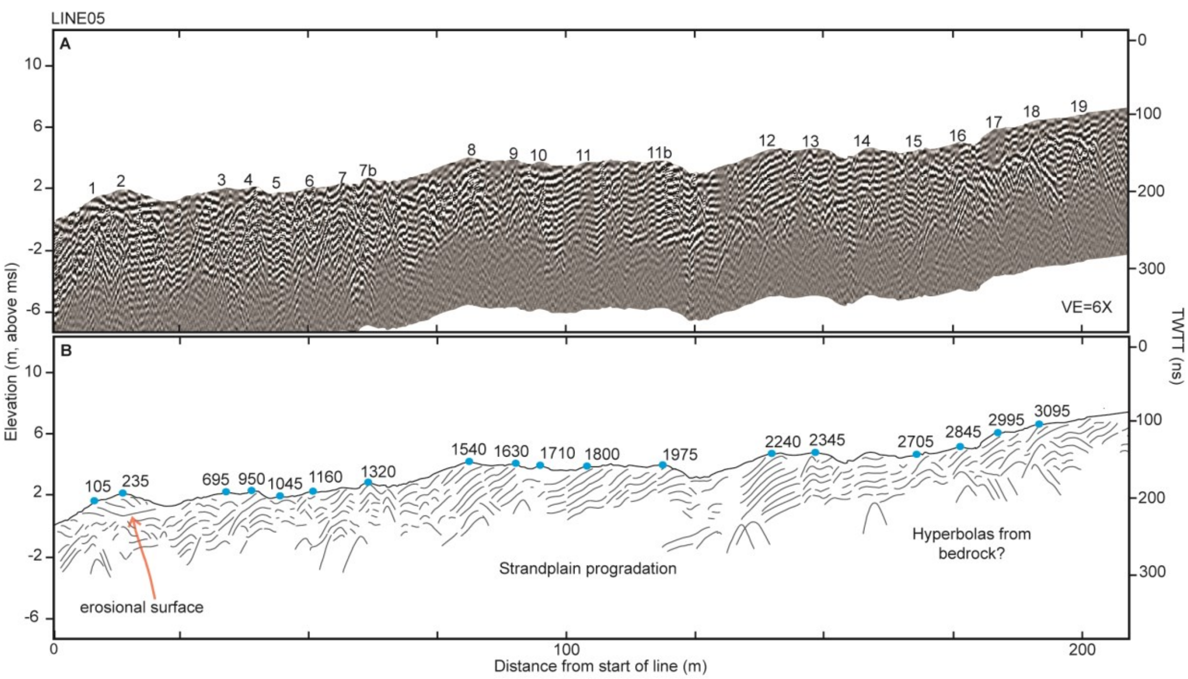


Figure 3.

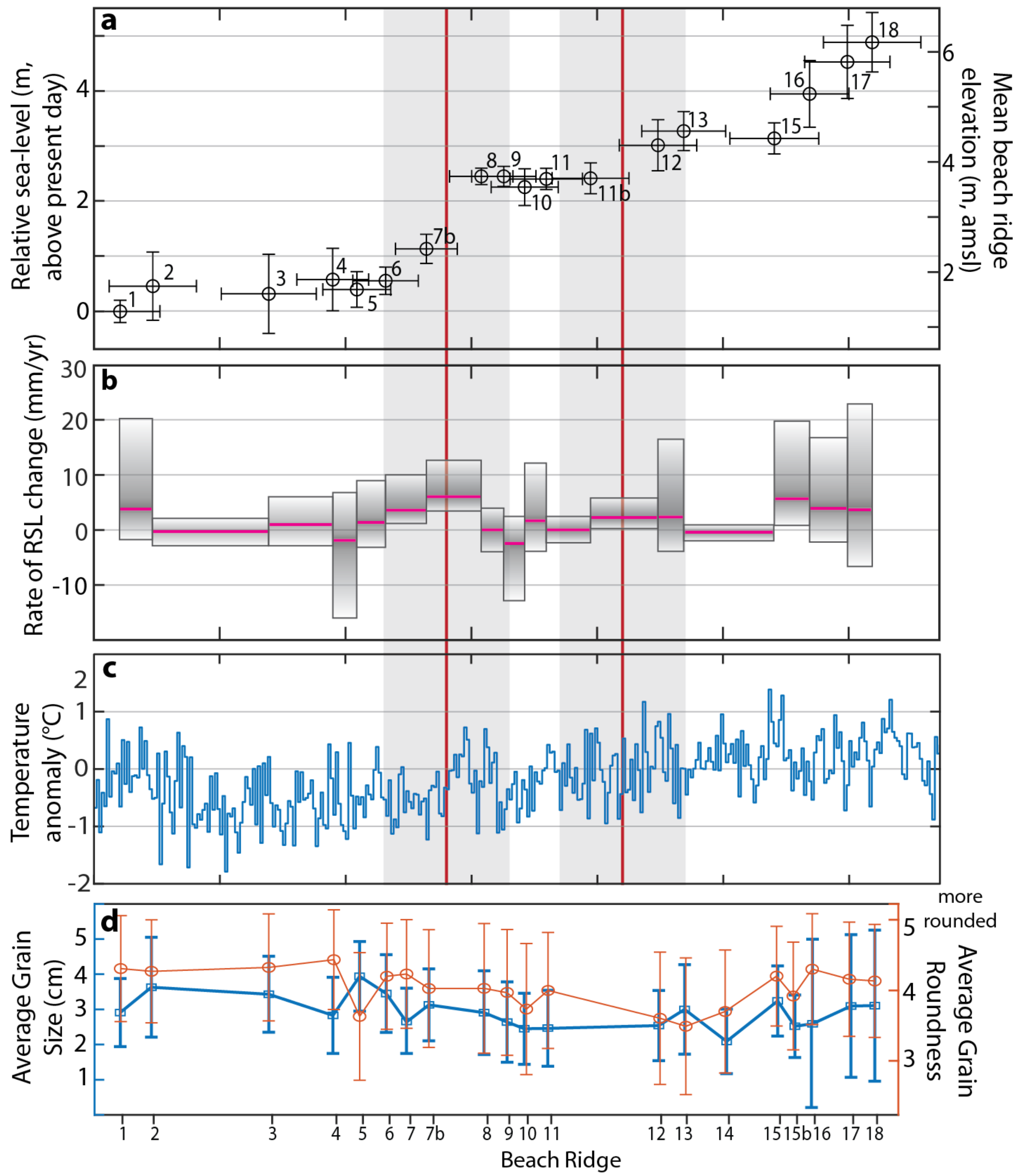
a
Relative sea-level (m, above present day)
Mean beach ridge elevation (m, amsl)
b
Rate of RSL change (mm/yr)
c
Temperature anomaly (°C)
d
Average Grain Size (cm)
Average Grain Roundness
more rounded
Beach Ridge

Figure 4.

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