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RECONSTRUCTING PAST SEA-LEVEL CHANGES FROM STORM-BUILT BEACH RIDGES

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ABSTRACT

Storm-built beach ridges, built by waves on sedimentary coasts, can be used as geomorphological indicators of past sea level. However, quantifying the relationship between the geomorphological elements of the ridge and the paleo sea level at the time of deposition is difficult, as a beach ridge is primarily correlated to wave energy and only secondarily to the position of sea level. In this work, we propose a methodology to quantify the upper and lower limits of a storm-built beach ridge based on remote sensing data. We use the tidal model FES2022, data from the Copernicus Marine Service and beach slope gathered from satellite imagery as inputs to different wave runup models, that are used to calculate the limits of the storm-built beach ridge. We test our approach on a particularly well-preserved Pleistocene storm-built beach ridge in Patagonia, Argentina. Our results show that the paleo relative sea level reconstructed using remote sensing data coincides (82.8% similarity) with that obtained from measured modern analog landforms at the same location.

Keywords Pleistocene sea level · Beach ridges · Patagonia, Argentina · Paleo sea level

1 INTRODUCTION

Beach ridges are shore-parallel elongated mounds, occurring as single features or in sets, backing the coastline (Taylor and Stone, 1996; Hesp, 2006; Otvos, 2020) and formed by coastal processes. Different types of beach ridges have been described, categorized based on morphological and sedimentological features (Otvos, 2020). They are considered as originally being deposited by swash during high or low wave-energy conditions, but some models account for their genesis as the product of aggradation of an offshore bar. Regardless the typology, all beach ridges are considered as progradational features.

Storm-built beach ridges on sedimentary coasts are created by the accumulation of sediments by waves above sea level (Tamura, 2012). The observation of beach ridges (that Charles Lyell defined "shingle beaches" in his "Principles of Geology", Lyell, 1837), and their use as proxies for the past position of relative sea level (RSL, that is local sea level uncorrected for vertical land motions), dates back at least to Charles Darwin who, on his voyage through South America, described several beach ridges with embedded shells and discussed their relationship with past positions of the shoreline (Darwin, 1846).

While coastal landforms (such as beach ridges) can be described with classic geologic methods, quantifying their relationship with a former sea level requires rigorous approaches, that have been employed since the mid-80s (Van de Plassche

2013, first edited in 1986, and Shennan, 1986). Recently, the "Handbook of sea-level research" by Shennan (2015) has collected the main methods that are currently used to study former sea-level changes, which have been since then successfully used to build global sea-level databases for different time periods (Khan et al., 2019; Rovere et al., 2023). One key concept is that a geomorphological feature can be considered a sea-level index point if three key properties are known: i) its position and elevation measured with the highest possible accuracy; ii) its age of formation; iii) its relationship with sea level at the time of its formation. This relationship is called the "indicative meaning" (Shennan, 1986).

The indicative meaning is composed by two numerical values. The indicative range (IR) represents the vertical elevation range occupied by a sea-level index point, relative to contemporary tidal datums. The reference water level (RWL) is the distance between the midpoint of the IR and the former tidal datum, and represents the elevational difference between the sea-level index point and the former sea-level (expressed as a former tidal datum, such as Mean Sea Level). The best way to quantify the indicative meaning of a sea-level index point is to measure a modern analog and apply the elevation offset (and associated uncertainty) between the modern sea-level and the modern feature to the paleo context (Shennan, 2015).

50 Several authors have used storm-built beach ridges as paleo sea-
 51 level index points. In particular, methods for extracting paleo
 52 sea-level information from the nearshore-shoreface inflection
 53 point on beach ridge systems surveyed with shallow surface
 54 geophysical techniques (e.g., ground-penetrating radar) have
 55 seen significant development (e.g. Brooke et al., 2019; Kumar
 56 et al., 2024). However, approaches for determining the indica-
 57 tive meaning of beach ridges in the absence of subsurface data
 58 remain underdeveloped.

59 Specifically, several studies have examined the surface eleva-
 60 tion (or the elevation of sedimentary or biological elements
 61 near the surface) of Pleistocene beach ridges along the Atlantic
 62 coasts of Argentina and Uruguay (e.g. Rostami et al., 2000;
 63 Schellmann and Radtke, 2000; Zanchetta et al., 2012; Martínez
 64 and Rojas, 2013; Pappalardo et al., 2015; Rovere et al., 2020).
 65 However, in comparison with other regions, these features are
 66 rarely described in the literature, complicating efforts to com-
 67 pile sea-level data (Gowan et al., 2021).

68 In this study, we present a method to determine the indica-
 69 tive meaning of a storm-built beach ridge using remote sensing
 70 data. Building on recent research and established definitions
 71 (Lorscheid and Rovere, 2019; Rubio-Sandoval et al., 2024),
 72 the method integrates modern wave and tidal data with wave
 73 runup models and beach slope extraction from satellite imagery.
 74 We apply this approach to a benchmark site in central Patago-
 75 nia, Argentina (south of the town of Caleta Olivia, Santa Cruz
 76 Province), where both the modern analog and the stratigraphy
 77 of the fossil beach ridge are well-defined and have been con-
 78 strained through field surveys.

79 2 BENCHMARK SITE

80 The site we use to benchmark our methodology ($46^{\circ}33'29.0''$
 81 S, $67^{\circ}25'59.9''$ W, hereafter called "*benchmark site*") is located
 82 within a quarry site locally named "*Cantera Delgado*", ~15 km
 83 south of the town of Caleta Olivia, in the central part of the San
 84 Jorge Gulf, ~1500 km south of Buenos Aires (Figure 1). In gen-
 85 eral, this area is located on a passive margin and is embedded
 86 within the South America Plate. Caleta Olivia is located along
 87 the central-southern coast of the Gulf of San Jorge, an intracra-
 88 tonic, extensional basin formed since the Mid- Jurassic between
 89 the two North Patagonian and Deseado Massifs (Ramos and
 90 Ghiglione, 2008).

91 In this area, several authors reported Holocene and Pleistocene
 92 beach ridges, that reach elevations of 10-20 meters above mod-
 93 ern sea level (e.g., Codignotto, 1983; Codignotto et al., 1992;
 94 Schellmann, 1998; Rostami et al., 2000; Aguirre, 2003; Schell-
 95 mann and Radtke, 2003; Ribolini et al., 2014; Richiano et al.,
 96 2021). Although the amount of literature on this site and the
 97 surrounding area is remarkable, so far there is no agreement
 98 on the interpretation of the beach ridges extensively occur-
 99 ring in this area as paleo-sea-level indicators. In fact, there
 100 is no correlation between their height and age, and in many
 101 cases the same height corresponds to different ages (e.g. Pleis-
 102 tocene/Holocene).

103 2.1 Survey methods

104 We used differential Global Navigation Satellite systems
 105 (GNSS) to measure the position and elevation of the modern

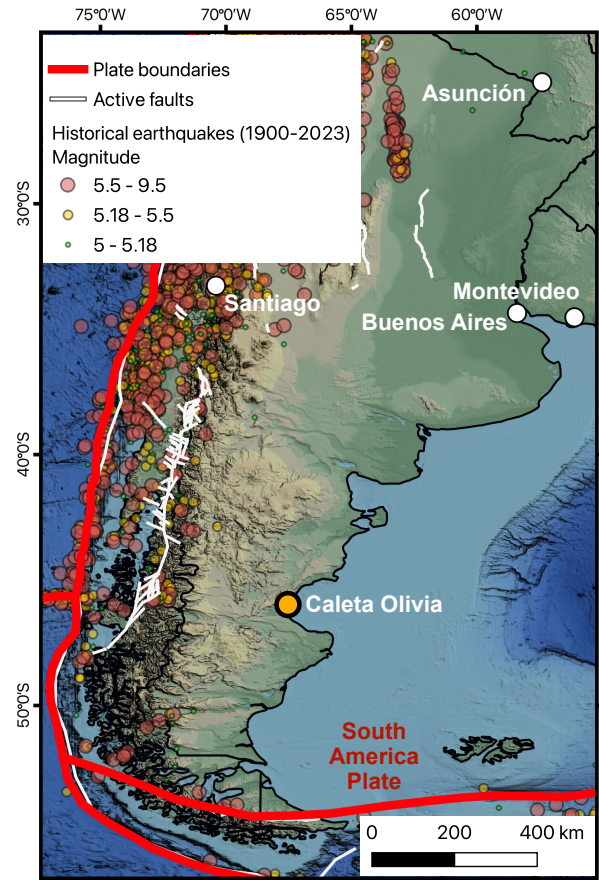


Figure 1: **Study area.** Location of the town of Caleta Olivia (the benchmark site is 15 km south of the town) within the Southern part of South America. Credits: Base map from Ryan et al. (2009). Active faults from Styron (2019) and plate boundaries derived from Bird (2003), as modified by Hugo Ahlenius and Nordpil on GitHub (<https://github.com/fraxen/tectonicplates>). Historical earthquakes from the US Geological Survey (2017).

106 beach profile (Figure 2 B) and the fossil beach ridge (Figure 2
 107 C). We employed a single-band EMLID RS+ GNSS composed
 108 of a base and a rover unit communicating via radio. The base
 109 station was located in full view of the sky and was left static
 110 collecting data for ~2h and 42 minutes. The data collected from
 111 the base station were processed using the Precise Point Posi-
 112 tioning service of the Natural Resources of Canada (NRCAN-
 113 PPP). This allowed gathering a corrected base position, which
 114 was then used to correct each rover point using the scripts avail-
 115 able in Rovere (2021).

116 Data were originally recorded in WGS84 coordinates, with
 117 height above the ITRF2008 ellipsoid. Orthometric heights
 118 (above mean sea level) were then calculated subtracting the
 119 GEOIDEAR16 geoid height from the measured ellipsoid
 120 height. It was estimated that the GEOIDEAR16 has an over-
 121 all vertical accuracy of 0.1 m (Piñón et al., 2018). It is worth
 122 noting that Pappalardo et al. (2019) surmised that in some areas
 123 of Patagonia, referring GNSS data to the GEOIDEAR16 geoid
 124 might be affected by large discrepancies if compared with the

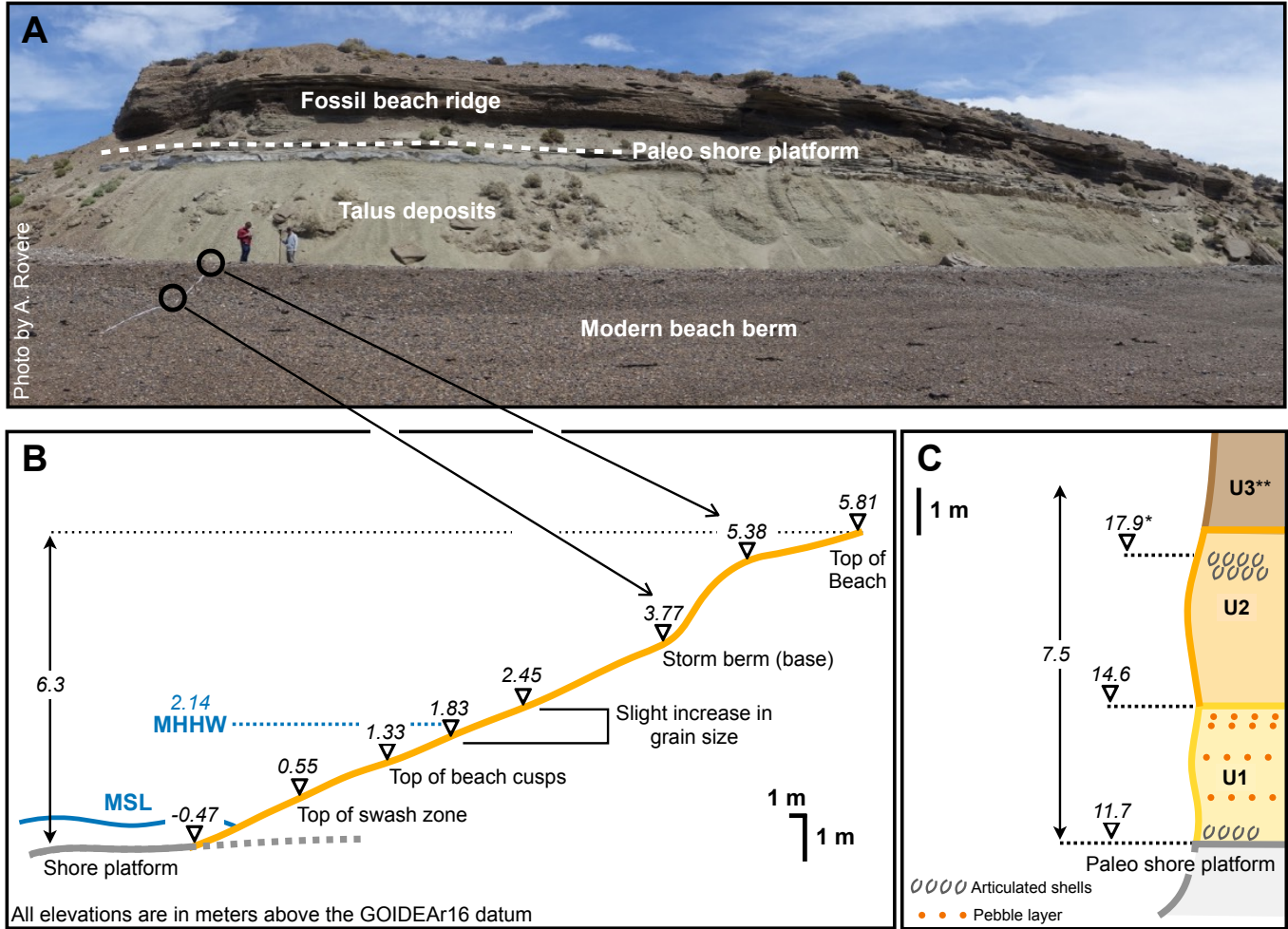


Figure 2: A) Composite photograph showing the modern beach berm (in the foreground) and the fossil beach ridge (in the background) at the benchmark site. B) GNSS profile of the modern beach with distinctive geomorphological elements. MSL = Mean Sea Level; MHHW = Mean Higher High Water. C) Stratigraphic section of the fossil (Pleistocene) beach ridge, divided into two units (U1 and U2). * indicates an elevation taken ~15 meters south of the section, as the point was not accessible on the vertical beach ridge face. ** Unit 3 was recognised at this section, but is more complete a few hundred meters from this section, and was described by Ribolini et al. (2014) starting at ~17m above sea level.

125 sea level datum obtained by tide gauge data. We remark that
 126 such discrepancy would not affect our results, as in the follow-
 127 ing sections we only compare elevation within this site, hence is
 128 it only relevant that the same elevation datum is used. However,
 129 we make available all the GNSS data collected in this work, that
 130 are originally referred to the ITRF2008 ellipsoid (see Supple-
 131 mentary Information for details).

132 The elevation error (σE) of each GNSS point surveyed in the
 133 field was calculated using the following formula:

$$\sigma E = \sqrt{GNSS_e^2 + Base_e^2 + Geoid_e^2} \quad (1)$$

134 Where $GNSS_e$ is the error given as output by the GNSS sys-
 135 tem, $Base_e$ (only for data collected with the Base-Rover EM-
 136 LID GNSS) is the elevation error of the base station, and $Geoid_e$
 137 is the error associated with the GEOIDEAR16 (0.1 m). Overall,

the 1σ elevation error associated to our measurements is 0.30
 m.

2.2 Modern beach

The modern beach at our benchmark site (Figure 2 A,B) lies
 upon a shore platform, carved into the sedimentary rocks of
 the Monte León formation (which a few kilometres north, in
 the Chubut Province, is called Chenque formation) (Upper
 Oligocene / Lower Miocene, Martínez et al., 2020). Abrasion
 and subordinately bioerosion are apparently the main processes
 shaping this platform (Supplementary Figure 1) The shore
 platform can be observed at low tide (Supplementary Figure 1 B,C),
 and the contact with the beach deposits was measured at -0.47
 m. The modern beach is characterised by beach cusps, at an ele-
 vation of 1.33 m. The grain size is between fine to very coarse
 gravels (4 to 64 mm diameter), with finer grain size close to
 the shore and a slight increase in grain size between the ele-

154 vation of 1.83 and 2.45 m, which correspond to Mean Higher
155 High Water (MHHW, 2.14 m). Above this level, a well-defined
156 storm berm is a prominent geomorphological feature between
157 3.77 and 5.38 m. The modern storm berm appears laterally con-
158 tinuous, and at this location covers a ca. 1.5 m high cliff carved
159 in an Holocene marine terrace which is clearly visible all along
160 the coast N and S of the benchmark site (Ribolini et al., 2014).
161 The beach deposits are covered by talus deposits created by
162 quarried materials at 5.81 m.

163 2.3 Pleistocene storm-built beach ridge

164 The talus deposits covering the upper part of the modern beach
165 have a resting angle of 30°- 40°(Figure 2 A), and are about 5m
166 high. At ~10 m above sea level, the Monte León formation out-
167 crops again. Here, it is cut by paleo marine abrasion, forming
168 a fossil shore platform overlain by two sedimentary units with
169 different characteristics. Unit 1 develops from 11.7 to 14.6 m
170 in elevation (Figure 2 C, Supplementary Figure 2 A). At the
171 base of this unit, very close to the contact with the shore plat-
172 form, there are mollusk shells of the species *Ameghinomya anti-*
173 *quua* (formerly *Protothaca antiqua*) articulated but not in living
174 position (Supplementary Figure 2 D). Unit 1 is composed by
175 fine sands, interbedded by decimetre-wide layers characterised
176 by coarser sediments (pebbles and gravels, Supplementary Fig-
177 ure 2 E). Towards the upper part of Unit 1, the coarser layers
178 become more frequent up to the transition with Unit 2 (Supple-
179 mentary Figure 2 C) and contain fragmented and disarticulated
180 whole valves of *Ameghinomya antiqua*, as well as articulated
181 valves. Unit 2 develops between 14.6 and ~18 m in elevation,
182 and is characterised by an alternation of pebbles and gravels
183 (Supplementary Figure 2 B) and by the presence, at its top, of
184 a layer with articulated shells of *Ameghinomya antiqua*, not in
185 living position.

186 A further unit (Unit 3), reaching up to 20.6 m, rests on top
187 of Unit 2. This is a complex continental unit, described by
188 Ribolini et al. (2014) a few hundred meters from the section
189 reported in this paper, still within "Cantera Delgado". Its bot-
190 tom part is represented by silty sand with scattered pebbles dis-
191 playing multiple pedogenetic carbonate crusts and incised by
192 periglacial features (sand wedges). An aeolian sand cover seals
193 the sequence. The formation of this continental unit was dated
194 by Ribolini et al. (2014) to a time span encompassing the Last
195 Glacial Maximum.

196 The location of our benchmark site coincides with that reported
197 by Schellmann (1998) for samples Pa 124 to 126 (both *Amegh-*
198 *inomya antiqua* shells), that these authors collected between
199 16.5 and 18 meters above mean sea level (possibly within Unit
200 2 described here). Six replicates of these samples were dated
201 using Electron Spin Resonance, yielding ages ranging from
202 172±15 ka to 212±26 ka (hence consistent with Marine Iso-
203 topic Stage 7, Schellmann, 1998). Shells of the same species,
204 were sampled by Schellmann (1998) at two other sites (Pa 70
205 and Pa 71), located 5.5 to 6.5 kilometers south of our bench-
206 mark site from horizons at ~10 and ~15 meters above sea level
207 (Schellmann, 1998). These yielded ages consistent with Marine
208 Isotopic Stage (MIS) 5e (~125 ka). In the same general area,
209 at a site called "Bahía Langara" Rostami et al. (2000) obtained
210 U-series ages consistent with MIS 5e at 16-17 m and with MIS

7 at 14 m above sea level (no vertical datum reported, assumed
above mean sea level).

A definitive age attribution for this site lies beyond the scope
of this study. Nonetheless, the data confirm that the surveyed
beach ridge at the benchmark site is of Pleistocene age, likely
corresponding to either MIS 5e or MIS 7. Similarly, evaluat-
ing the causes behind the ridge's elevated position relative to
global mean sea level during these interglacials is outside the
study's focus. However, we note that the observed elevation
of the Pleistocene beach ridge in this region likely reflects the
combined effects of global mean sea level, glacial isostatic ad-
justment, and mantle dynamic topography, which during previ-
ous interglacials can cause departures from eustasy of several
meters Rubio-Sandoval et al., 2024.

3 PALEO RSL AT THE BENCHMARK SITE

3.1 Paleo RSL from modern analog

The paleo storm beach ridge exposure at the benchmark site is a
rare occurrence, at least within the Patagonian context (Blanco-
Chao et al., 2014). In fact, quarrying works in "Cantera Del-
gado" produced a clear-cut section across its face, exposing the
complete beach ridge sequence, from the paleo shore platform
up to the highest deposits. At most other locations only parts
of the beach ridge (usually the upper parts, showing articulated
shells as those in U2, Figure 2) are exposed. The advantage
of this peculiar exposure is that it is possible to better evalu-
ate the indicative meaning of the beach ridge, and give a ro-
bust quantification of RSL at this site. This is one of the few
places along the Atlantic coast of Patagonia where a shore plat-
form outcrops beneath the beach (Blanco-Chao et al., 2014),
providing the possibility to use it as a modern analog for paleo
sea-level reconstructions.

The geomorphological element of Patagonian beach ridges that
is often correlated to paleo sea level is a layer embedded within
coarse gravels or pebbles composing the ridge, characterised by
articulated shells of *Ameghinomya antiqua*. At the benchmark
site, this layer is embedded within Unit 2 at 17.9 m above mod-
ern sea level (Figure 2 C). While in the study area at the time of
survey we could not observe a modern analog shelly deposit on
the ridge, in the regional context similar accumulations of ar-
ticulated shells are observed between the ordinary berm (or the
swash zone of ordinary waves) and the storm berm (Figure 3).
In our modern beach profile, the top of the swash zone can be
approximated by the top of beach cusps (1.33 m) and the top of
the storm berm (5.38 m). Applying these two values of upper
and lower limits of the indicative range, we estimate that paleo
RSL at the time of formation of the beach ridge was 14.5 ± 2
m, 1σ .

The occurrence in the benchmark site of both the modern and
a paleo shore platform, the latter outcropping underneath the
Pleistocene storm-built beach ridge, provides a further possibil-
ity to calculate paleo RSL. This can be done accepting a num-
ber of approximations. In macrotidal and high-energy environ-
ments, similar shore platforms are often considered as intertidal
features (Sunamura, 1992).

We assume that the elevation at which the paleo shore platform
was measured (11.7 m, Figure 2 C) was originally located be-



Figure 3: Accumulation of articulated and disarticulated mollusk shells (white among the gray gravel sands) on the modern beach at Mazarredo, ~80 km south of the benchmark site.

267 tween mean sea level and Mean Lower Low Water (MLLW),
 268 corresponding to the shore platform outer edge. This could be
 269 an overestimation if the seaward portion of the former shore
 270 platform had been extensively eroded by the Holocene RSL
 271 transgression. The presence of the Holocene terrace under-
 272 neath the modern storm berm (reported in Ribolini et al., 2014),
 273 though, suggests that this was not the case. Consequently, the
 274 the upper and lower limits of the indicative range are assumed
 275 to be respectively Mean Sea Level (MSL) and MLLW. Their
 276 current position can be calculated assuming that the point mea-
 277 sured at -0.47 m broadly corresponds to the shore platform in-
 278 ner edge (Figure 2 B) and using 4.28 m as the tidal range. Paleo
 279 RSL at the time of the shore platform formation was 15.4 ± 1.1
 280 m, 1σ .

281 3.2 Paleo RSL from runup models - previous approaches

282 While the most reliable methodology to calculate paleo RSL
 283 from a storm beach ridge is the use of a modern analog as de-
 284 scribed in the previous section, this kind of information is not
 285 always available. For this reason, various approaches have been
 286 proposed in the literature using proxies for wave runup. These
 287 are summarised in the sections below. The new approach pro-
 288 posed in this work is presented in section 4.

289 Most of the data reviewed within in the World Atlas of Last
 290 Interglacial shorelines (Rovere et al., 2023), including a recent
 291 review of Argentinian beach ridges (Gowan et al., 2021), make
 292 use of IMCalc (Lorscheid and Rovere, 2019) to calculate the
 293 indicative meaning of coastal landforms, among which beach
 294 ridges. This tool that allows to give a first-order quantification
 295 of the indicative meaning based on wave and tidal data in ab-
 296 sence of data on modern analogs.

For storm beach ridges, IMCalc uses the formula of Stockdon
 et al. (2006) to calculate the wave runup exceeded by 2% of
 the waves (R_2) at high tide (MHHW) in fair weather and storm
 wave conditions, and equating them to the elevation of, respec-
 tively, the ordinary and storm berm on an ideal beach profile,
 with a general slope (β) of 0.08. The significant wave height
 and period are extracted from wave data from the CAWCR
 (Collaboration for Australian Weather and Climate Research)
 wave hindcast (Durrant et al., 2013), which is based on the
 NOAA WaveWatch III wave model (Tolman et al., 2009) and
 the NCEP CFSR surface winds and sea ice data (Saha et al.,
 2010). For fair weather conditions, IMCalc uses average wave
 height and period, while for storm conditions, it uses the up-
 per 2σ significant wave height and period. Using the IMCalc
 tool to calculate paleo RSL from the layer of articulated shells
 within Unit 2 (at 17.9 m), we obtain the a paleo RSL value of
 15.9 ± 0.7 m (1σ).

Rubio-Sandoval et al. (2024) suggests a more detailed approach
 than IMCalc, that employs wave data measured by satellite al-
 timetry and analysed with the RADWave software (Smith et al.,
 2020). This is a python package that provides access to altime-
 ter datasets using the Australian Ocean Data Network (AODN)
 database, that contains data spanning from 1985 to present, val-
 idated and calibrated by Ribal and Young (2019). Wave data
 for the period Jan 2000 - Jan 2023 (Supplementary Figure 3)
 were then employed in a runup model ensemble implemented
 in the *py-wave-runup* tool (Leaman et al., 2020), also account-
 ing for tides extracted from the FES2014 global tidal model
 (Lyard et al., 2021; Carrere et al., 2016). The beach slope was
 obtained with the CoastSat.Slope (Vos et al., 2020) tool. With
 this approach, we calculate that the upper limit of the indicative
 range for beach ridges at the benchmark site is 0.91 m, while
 the lower limit is 3.51 m (Supplementary Figure 3 B). Applying
 this range to the elevation of articulated shells of Unit 2 (17.9
 m), we calculate that paleo RSL is 15.7 ± 1.3 m (1σ).

4 NEW APPROACH TO CALCULATE THE INDICATIVE MEANING OF BEACH RIDGES

Here, we build on the concept idealised in IMCalc and on the
 approach of Rubio-Sandoval et al. (2024) described above to
 build a workflow that allows calculating the indicative meaning
 for a beach ridge using the best datasets and tools available. We
 validate the results with the paleo RSL obtained at the bench-
 mark site described above. The workflow is implemented in
 python and is divided in three steps, described below. Each
 step can be reproduced in other areas via the jupyter notebooks
 supporting this paper (Rovere, 2024a).

4.1 Tide and wave data

The first step of our methodology is to retrieve tidal and wave
 data from global datasets. Water level data over the period 01
 Jan 1980 to 30 Sept 2023 (~43 years) was calculated using the
 FES2022 global tidal model (Carrere et al., 2022) at a point
 slightly offshore of the benchmark site (Figure 4 A). Using
 these data as input to the "CO-OPS Tidal Analysis DatumCal-
 culator" (Licate et al., 2017) we calculate that MHHW is 2.14m
 and MLLW is - 2.14m (Figure 4 B).

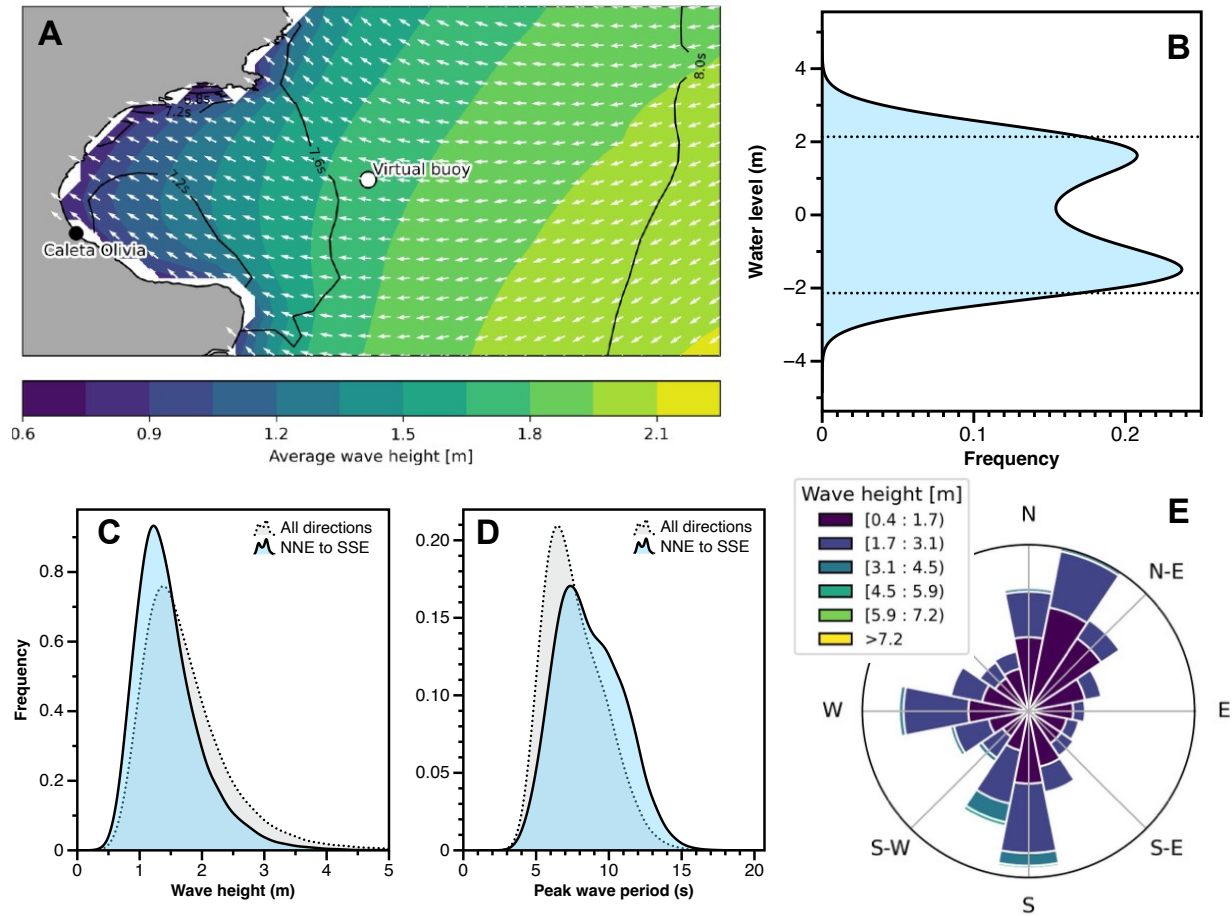


Figure 4: A) Average significant wave height (coloured contours), wave periods (black lines) and direction (white arrows) in the study area extracted from the Copernicus Marine Environment Monitoring Service (CMEMS) WAVEreanalysis (WAVERYs, Law-Chune et al., 2021), with indication of the point where wave data were extracted (virtual buoy). B) Smoothed histogram plot of tidal data extracted from the FES2022 model at Caleta Olivia (Carrere et al., 2022). The horizontal lines represent MHHW and MLLW calculated by the "CO-OPS Tidal Analysis Datum Calculator" (Licate et al., 2017). C) and D) Smoothed histogram plots of, respectively, significant wave height and period at the virtual buoy (location shown in panel A) for all directions (grey shade) and perpendicular to the coast (NNE to SSE, cyan shade). E) Wave rose for the virtual buoy (location shown in A).

Wave data is retrieved from the Copernicus Marine Environment Monitoring Service (CMEMS) WAVEreanalysis (WAVERYs, Law-Chune et al., 2021). WAVERYs oceanic currents from the GLORYS12 physical ocean reanalysis (Lellouche et al., 2018) and assimilates wave heights from altimetry missions and directional wave spectra from Sentinel 1 synthetic aperture radar from 2017 onwards. This dataset spans the last ~43 years (01 Jan 1980 to 30 Sept 2023), sampled slightly offshore our benchmark site (Figure 4 A). In our area of interest, the waves directed towards the coast (with direction NNE to SSE) have a median significant wave height of 1.4 m and median significant wave period of 8 s (Figure 4 C,D), with main direction of waves from NNE and South sectors (Figure 4 E).

4.2 Beach slope

Determining the beach slope (β) is a simple operation, that can be performed on any beach with basic topographic methods. At our benchmark site (Figure 2 B), it can be determined by dividing the difference between the base of the storm berm (3.77 m)

and the top of swash zone (0.55 m) by the distance between the two (30.5 m). With this operation, we can determine that β is 0.1.

If no modern analog data is available, calculating β becomes more difficult. It is possible to do it via satellite-derived shorelines with CoastSat.Slope (Vos et al., 2020), a tool implemented within the CoastSat software (Vos et al., 2019). Thanks to this software, we could download 350 satellite images from Landsat 5, 7, 8, 9 and Sentinel 2, spanning from January 1986 to October 2024. Over a coastal stretch of ~1 km around our study site, we identified 5 transects (Figure 5 A), where we evaluated the evolution of the shoreline over the period of available imagery. Using the tidal data calculated as described above, CoastSat.Slope (Vos et al., 2020) calculated the beach slope along each transect, including a median value and 5-95% confidence intervals. We then calculate the distribution of possible slopes with a function that selects randomly a transect and then samples a random value generated within the confidence interval with the median (Slope) acting as the peak likelihood using a triangular distribu-

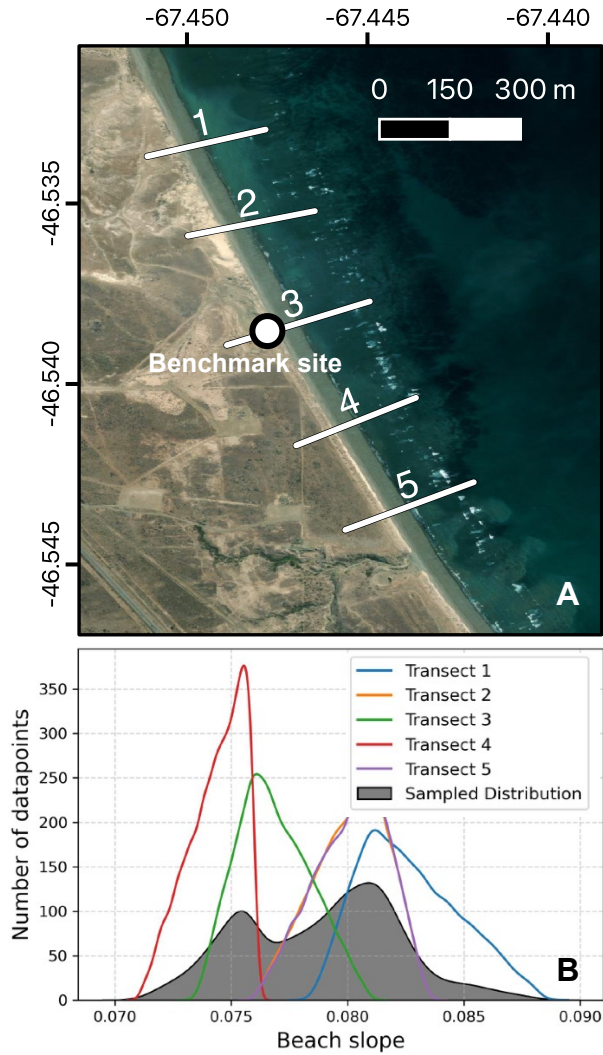


Figure 5: A) Satellite image of the study area, with transects 1-5 analysed in CoastSat to calculate the beach slope, and location of the benchmark site. Basemap sources: Esri, Maxar, Earthstar Geographics, and the GIS User Community. B) Slope calculated for each transect using satellite images and contemporaneous tidal levels (see Vos et al., 2020, for details on the methodology) and overall slope distribution calculated at the benchmark site.

389 tion (Figure 5 B). We calculate that the average β over the five
 390 transects is between 0.07 and 0.09 (grey distribution in Figure 5
 391 B), which is in good agreement with what we measured in the
 392 field (0.1).

393 It is also worth noting that the results of this processing show
 394 that this beach, at the net of seasonal variations, has been rather
 395 stable throughout the last ~38 years (Supplementary Figure 4).
 396 This is an important point, as it strengthens the assumption that
 397 the modern beach and the modern beach slope are representa-
 398 tive of a steady-state, hence they are more representative of
 399 long-term conditions of this beach.

4.3 Wave runup

400 In the last step of our workflow, we use wave, tidal data, and
 401 the beach slope calculated above to simulate R_2 . There are sev-
 402 eral approaches and several empirical formulas that have been
 403 proposed to calculate R_2 on sandy beaches (see a recent review
 404 by Gomes da Silva et al., 2020). The most common among
 405 these were compiled in the *py-wave-runup* tool (Leaman et al.,
 406 2020). Using this tool, we run nine models that require as in-
 407 put significant wave height, period and beach slope (Holman,
 408 1986; Ruggiero et al., 2001; Stockdon et al., 2006; Nielsen,
 409 2009; Senechal et al., 2011; Vousdoukas et al., 2012; Atkin-
 410 son et al., 2017; Passarella et al., 2018; Power et al., 2019). For
 411 Power et al. (2019), which requires an estimate of the Hydraulic
 412 roughness length, we use the relationship suggested by Leaman
 413 et al. (2020) of $2.5 \times D_{50}$, where D_{50} (grain size) is set to 8mm.
 414 We run these models using as wave conditions those directed
 415 between NNE and SSE in the study area (Figure 4). We also
 416 consider only the waves hitting the coast when the tide is equal
 417 or above mean sea level, as we assume that waves hitting be-
 418 low MSL would produce ephemeral landforms, that are usually
 419 re-eroded within one or two tidal cycles.
 420

421 We test the results of these models against the height of the
 422 swash zone measured at the time of our survey (0.55 m, Supple-
 423 mentary Figure 6). The modelled runup (corrected by the tide
 424 at the time of survey) shows good agreement with the observed
 425 reach of waves during the survey. Also the other morphologi-
 426 cal elements we observed on the modern beach fall within the
 427 probability density distribution of the modelled runup (Figure 6
 428 A).

429 The modern runup is representative of the wave and tidal condi-
 430 tions over the period 1980-2024. Over an interglacial, it is pos-
 431 sible that the same storm measured in the modern happened
 432 at different stages of the tide. To account for this possibility,
 433 we create a synthetic dataset composed of one million differ-
 434 ent conditions of waves, tides and beach slope. The synthetic
 435 dataset is created by randomly sampling a pair of values for
 436 wave height and period, one tidal level above MSL and one
 437 value of beach slope (β) from the distribution shown in Fig-
 438 ure 5 B. We then use this dataset as input to the runup models
 439 described above, obtaining the probability distribution shown
 440 in Figure 6 B.

441 We use this distribution to derive the indicative meaning of the
 442 storm beach ridge in the area, assuming that it would form be-
 443 tween the 1st and 99th percentiles of the calculated wave runup.
 444 Under this assumption, the upper and lower limits of the indica-
 445 tive range would be, respectively, 4.5 m and 0.9 m (Figure 6 B).
 446 Using these values, we calculate that paleo RSL as indicated by
 447 the articulated shells layer at 17.9 m (Figure 2 C) is 15.2 ± 1.8
 448 m (1σ).

5 DISCUSSION

449 From the measurement of the modern analog, we reconstruct
 450 that paleo RSL at the benchmark site used in this work is 14.5
 451 ± 2 m. This is consistent with the interpretation of Unit 1,
 452 located below the articulated shells we used as index point,
 453 that was interpreted as forming in the lower intertidal / subti-
 454 dal zone (Schellmann, 1998). The paleo RSL calculated from
 455 the beach ridge at this site is also confirmed by that derived
 456

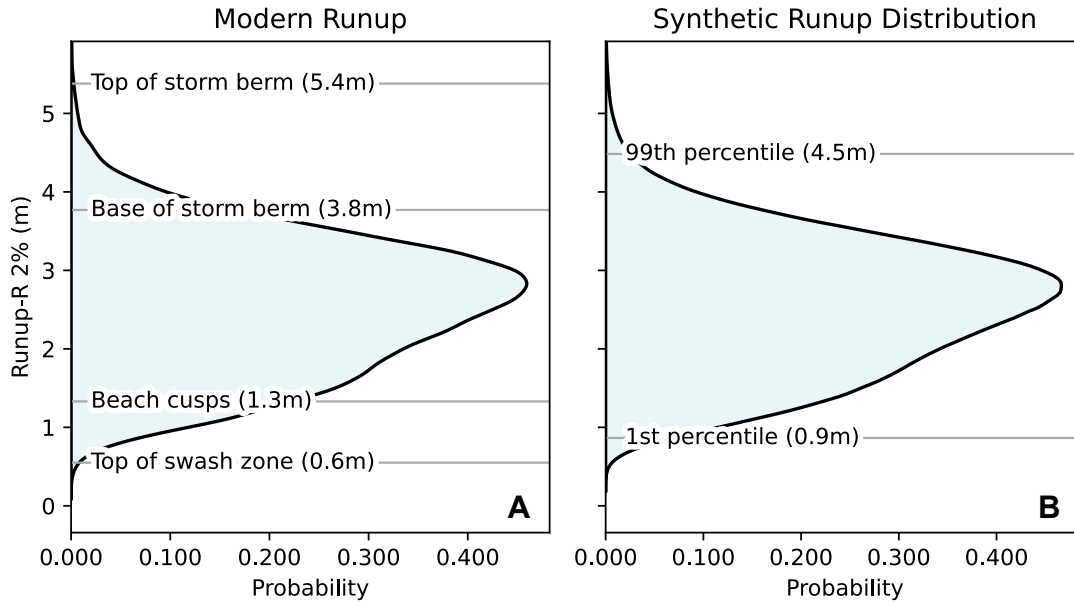


Figure 6: A) Probability density plots representing simulated 2% wave runup (R_2) at the benchmark site between 1980 and 2024, for waves with directions between NNE and SSE and reaching the coast in tidal conditions from MSL to high tide. Elements measured on the modern shoreline are plotted as grey lines with labels. A breakup of this histogram into the contribution of different runup models is shown in [Supplementary Figure 5](#). B) Probability density plot representing simulated 2% wave runup at the benchmark site for the synthetic dataset, calculated as described in the main text. The grey lines show the 1st and 99th percentiles of this distribution.

457 from the paleo shore platform, which sets paleo RSL at $15.4 \pm$
 458 1.1 m ([Figure 7](#)). There is a striking similarity between the paleo
 459 RSL reconstructed from the modern analog and that derived
 460 from the runup-based reconstructions of [Lorscheid and Rovere](#)
 461 (2019), [Rubio-Sandoval et al. \(2024\)](#) and the one used in this
 462 work ([Figure 7](#)).

463 To quantify the similarity between the paleo RSL distributions
 464 obtained with runup models and the one gathered from the
 465 modern analog, we use the Kolmogorov-Smirnov test. The
 466 test returns a statistic D which is the maximum difference between
 467 the empirical distribution functions of the two samples. D varies
 468 between 0 and 1, with a lower D value indicating more
 469 similarity. We calculate the similarity in percentage as
 470 $(1 - D) \times 100$. We calculate that the similarity between the paleo
 471 RSL calculated from the modern analog and that obtained from
 472 IMCalc is 49.7%. The same comparison with the method of
 473 [Rubio-Sandoval et al. \(2024\)](#) yields a similarity score of 67.8%
 474 and with the one from the workflow presented in this study,
 475 the similarity score improves to 82.8%. Compared to previous
 476 runup-based approaches, both IMCalc ([Lorscheid and Rovere,](#)
 477 2019) and [Rubio-Sandoval et al. \(2024\)](#) reconstruct correctly
 478 the paleo RSL at the benchmark site, but they underestimate
 479 error bars.

480 While the methodology we proposed in this work performs well
 481 at the benchmark site, there are some caveats and limitations
 482 that must be considered when applying this work to other sites,
 483 with different characteristics. We discuss them hereafter.

484 The runup models employed in this study were mostly developed
 485 for sandy beaches, with relatively uniform nearshore slope.
 486 The benchmark site deviates from this pattern, as it is

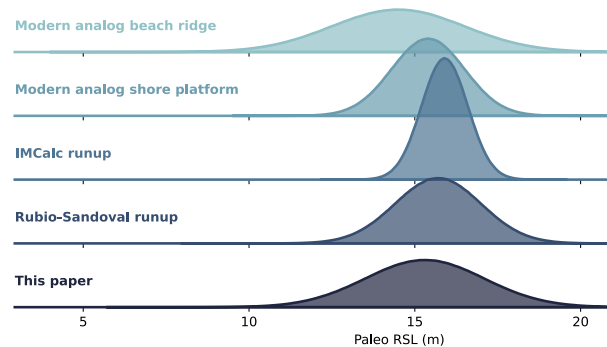


Figure 7: Comparison between paleo RSL calculated using indicative meaning estimated by the modern analog, IMCalc ([Lorscheid and Rovere, 2019](#)) and the methodology outlined in this work.

487 a gravel beach underlain by a shore platform. Despite this de-
 488 parture from the ideal case, our modelling chain performs well
 489 when runup values are compared to sedimentary structures on
 490 the beach ([Figure 6 A](#)) or with observed wave runup at the time of
 491 survey ([Supplementary Figure 6](#)). The little influence of the
 492 shore platform might be due to the fact that it outcrops only at
 493 low tide, allowing therefore waves to reach the shore and dissi-
 494 pate on the beach at high tide. The coarser grain size does not
 495 seem to affect much the runup values. In fact, the only runup
 496 model that takes into account grain size in the form of hydraulic
 497 roughness ([Power et al., 2019](#)) gives results that do not deviate
 498 significantly from the other models ([Supplementary Figure 5](#)).

499 As Power et al. (2019) highlight, "wave height, wavelength,
500 and beach slope are shown to be the three primary factors in-
501 fluencing wave runup, with grain size/bed roughness having a
502 smaller, but still significant influence on the runup".

503 We have not tested the method we propose here on beaches that
504 have been affected by significant erosion or that have been sub-
505 ject to significant vertical movement; either process may sig-
506 nificantly altered beach slope over time. To account for this
507 potential complication, we include in our workflow the anal-
508 ysis of shoreline variations through time (Supplementary Fig-
509 ure 4), where possible. This analysis may reveal any significant
510 changes to the modern beach slope that would result in an inac-
511 curate paleo runup model.

512 Another important caveat is related to the hydrodynamic
513 boundary conditions we use in our workflow. Using modern
514 tide and wave data, the implicit key assumption is that the wave
515 intensity and tidal range were, in the area of interest, the same
516 at the time of formation of the beach ridge as they are today.
517 This might not be accurate.

518 Models of paleo tidal ranges during the Pleistocene are con-
519 strained to either discrete periods of time (Wilmes et al., 2023)
520 or restricted geographic areas (Lorscheid et al., 2017). Sub-
521 stantially more work on tidal range changes and on their im-
522 plication on the reconstruction of paleo RSL has been done for
523 the Holocene (Horton et al., 2013; Sulzbach et al., 2023; Hill
524 et al., 2011). A global model of tidal range changes for the
525 Pleistocene interglacials does not exist, but it would allow cor-
526 recting the runup calculations for different tides.

527 Also the intensity of waves in previous interglacials (more
528 specifically in the Last Interglacial) has been widely debated,
529 mostly on the basis of particular landforms (Rovere et al.,
530 2017a; Hearty and Tormey, 2018; Rovere et al., 2018b). Mod-
531 els on the intensity and direction of storms and tropical cy-
532 clones suggest that it cannot be assumed that wave characteris-
533 tics were the same between the present and the Last Interglacial
534 (Kaspar et al., 2007; Yan et al., 2021; Huan et al., 2023), but
535 models that quantify the change in significant wave height and
536 period at the local scale that would be needed to correct our
537 data are still missing.

538 Scussolini et al. (2023) provide global models of storm surges
539 for extreme storms in the Last Interglacial which, for the area
540 of interest, indicate that extreme storm surge would have been
541 higher by 6 cm with respect to present-day (Supplementary Fig-
542 ure 7). This would not change substantially the paleo RSL cal-
543 culated above. We note that, towards the Northern part of the
544 San Jorge gulf, this assumption might not be true, and the up-
545 per limit of storm-built beach ridges would have to be corrected
546 upwards by up to ~20 cm (Supplementary Figure 7).

547 6 CONCLUSIONS

548 Storm-built beach ridges are widely used, in particular along
549 the Atlantic coasts, to reconstruct Holocene and Pleistocene
550 sea-level changes. However, the modern analog of these land-
551 forms is less studied and is seldom reported in the literature.
552 Our results show that it is possible to exploit freely available
553 satellite-derived data and models that are commonly employed

to study modern coastal processes to obtain a reliable estimate
of the paleo RSL associated with beach ridges.

554
555
556 With our workflow, that is entirely based on remotely sensed
557 data, we calculate paleo RSL at the benchmark site with sim-
558 ilarity of 82.8% with respect to the paleo RSL calculated
559 from modern analog data, outperforming previous similar ap-
560 proaches. We surmise that the approach proposed in this work
561 may be used to better quantify the indicative meaning of fossil
562 storm beach ridges.

563 It is also worth noting that, from the wave, tidal and runup data
564 calculated by the workflow presented here, it may be possible
565 to calculate the indicative meaning of other depositional sea-
566 level index points, such as other types of beach deposit. As an
567 example, the general definition of beach deposits entails that
568 they form between the ordinary berm and the depth of closure
569 of ordinary waves (Rovere et al., 2016), which can be easily
570 quantified from wave data and runup models (Lorscheid and
571 Rovere, 2019), such as those used in our workflow for beach
572 ridges.

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580 ([https://data.marine.copernicus.eu/product/
581 GLOBAL_MULTIYEAR_WAV_001_032/description](https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_WAV_001_032/description)). The
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607 AUTHORS CONTRIBUTIONS

608 AR had the initial idea and wrote the paper with substantial in-
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 610 in the paper. SR, AM and PMR provided insights on local ge-
 611 ology, geomorphology and paleobiology. AR, MP, SR, DDR,
 612 KRS, PMR and EJG participated to different field campaigns at
 613 Caleta Olivia, that resulted in the data used for this paper. All
 614 authors revised the text, giving input according to their exper-
 615 tise, and agree with its contents.

616 SUPPLEMENTARY INFORMATION

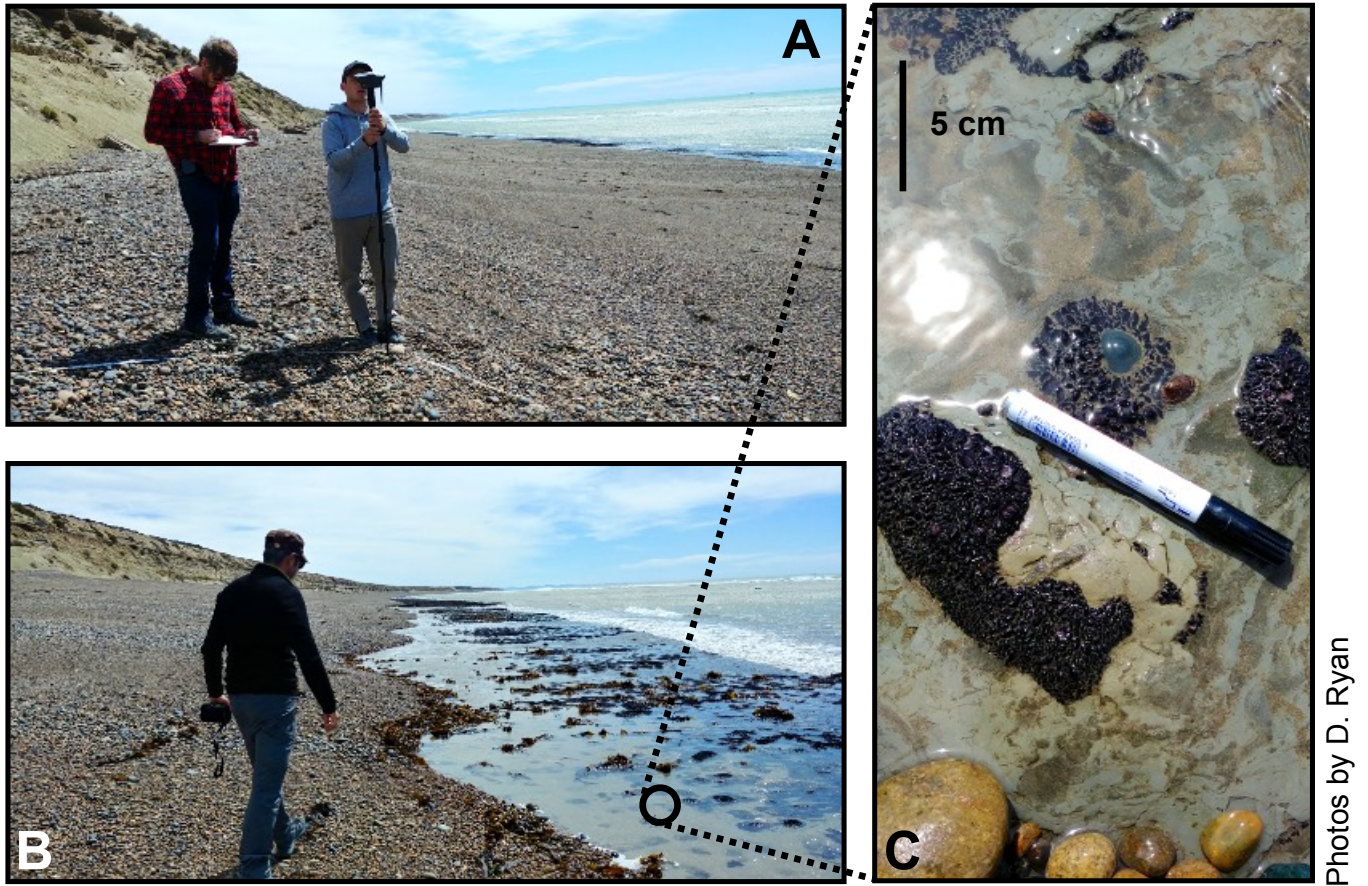
617 The Supplementary Information to this paper contains all the
 618 raw data described in this paper and the Jupyter notebooks to
 619 reproduce the results of this work and apply the same workflow
 620 in other areas. The pre-review version of the scripts is available
 621 as [Rovere \(2024b\)](#) and the final version is available as [Rovere](#)
 622 [\(2024a\)](#).

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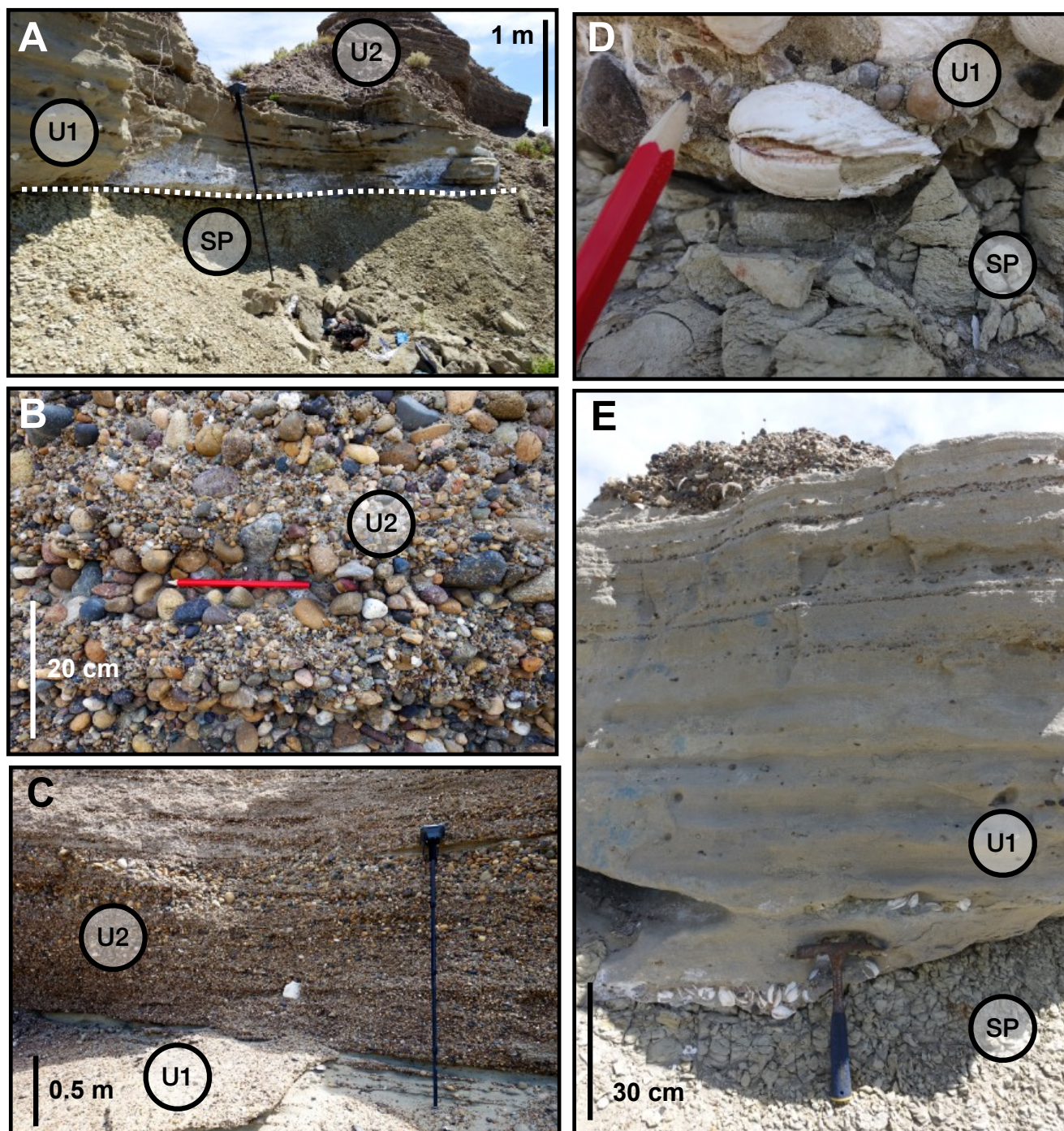
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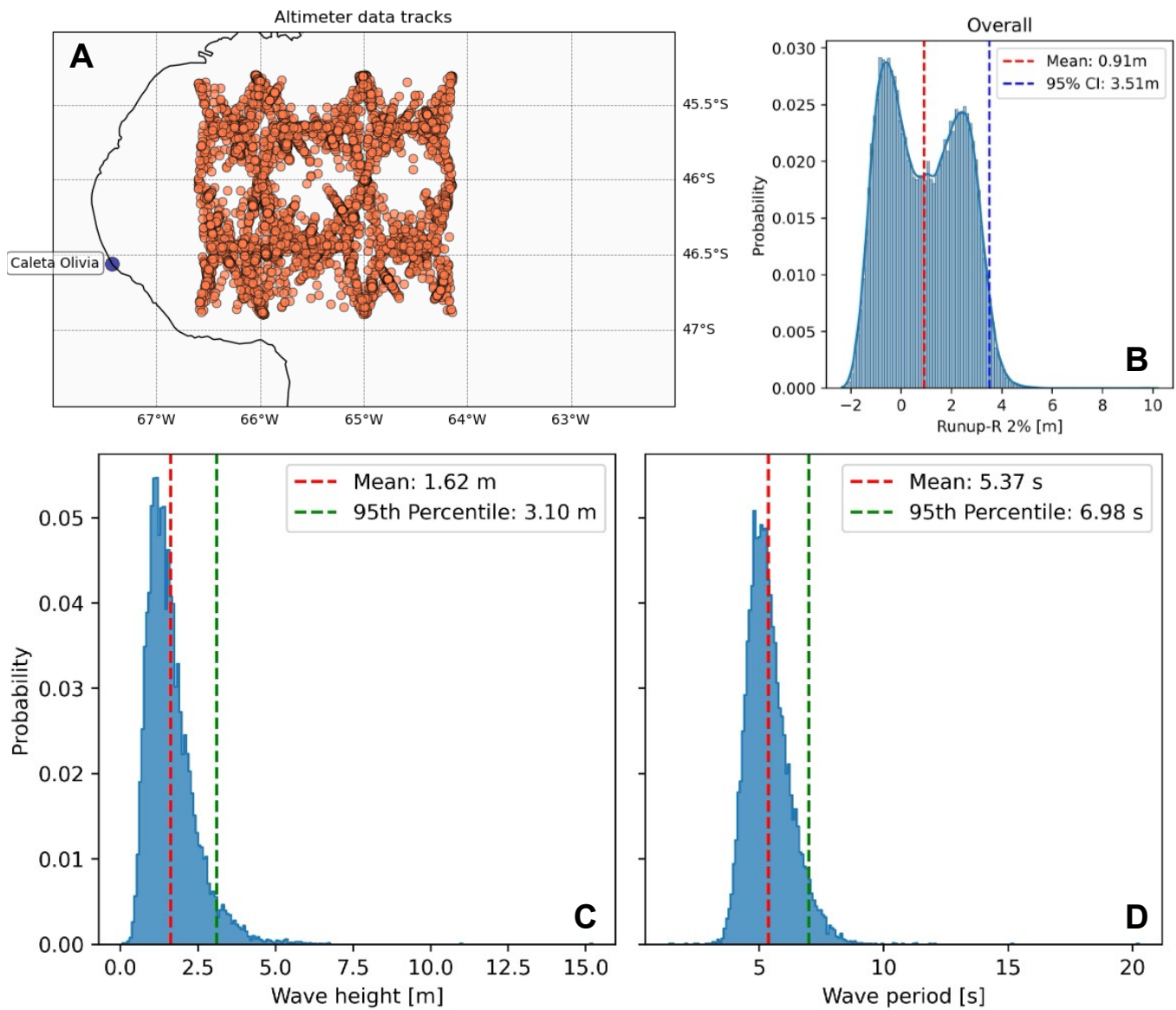
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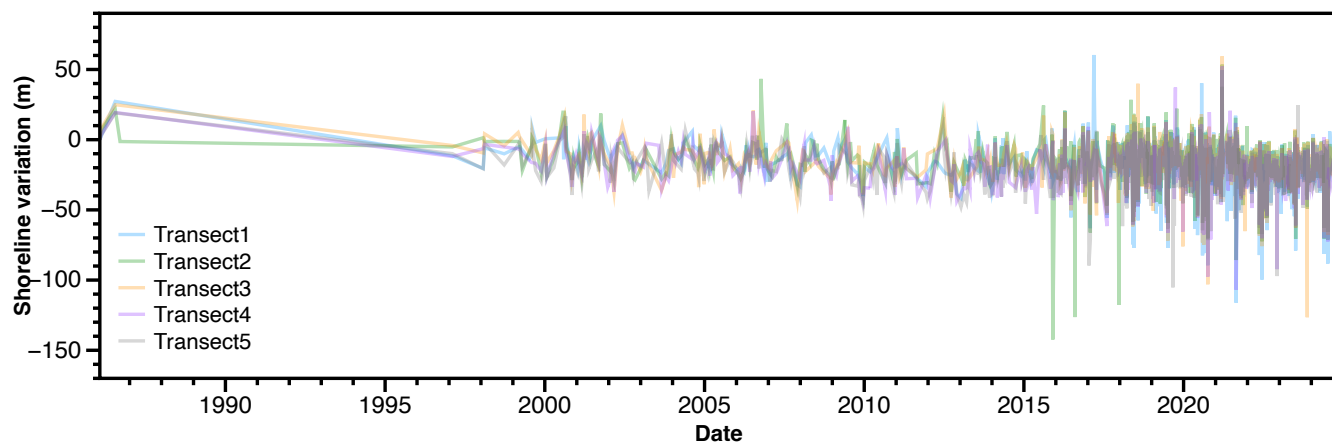
Supplementary Figure 1: Details of the modern beach at the benchmark site (Figure 2). A) view of the modern storm berm. B) lower part of the beach, with the exposed shore platform at low tide. C) detail of the shore platform, with encrusting organisms living on it.



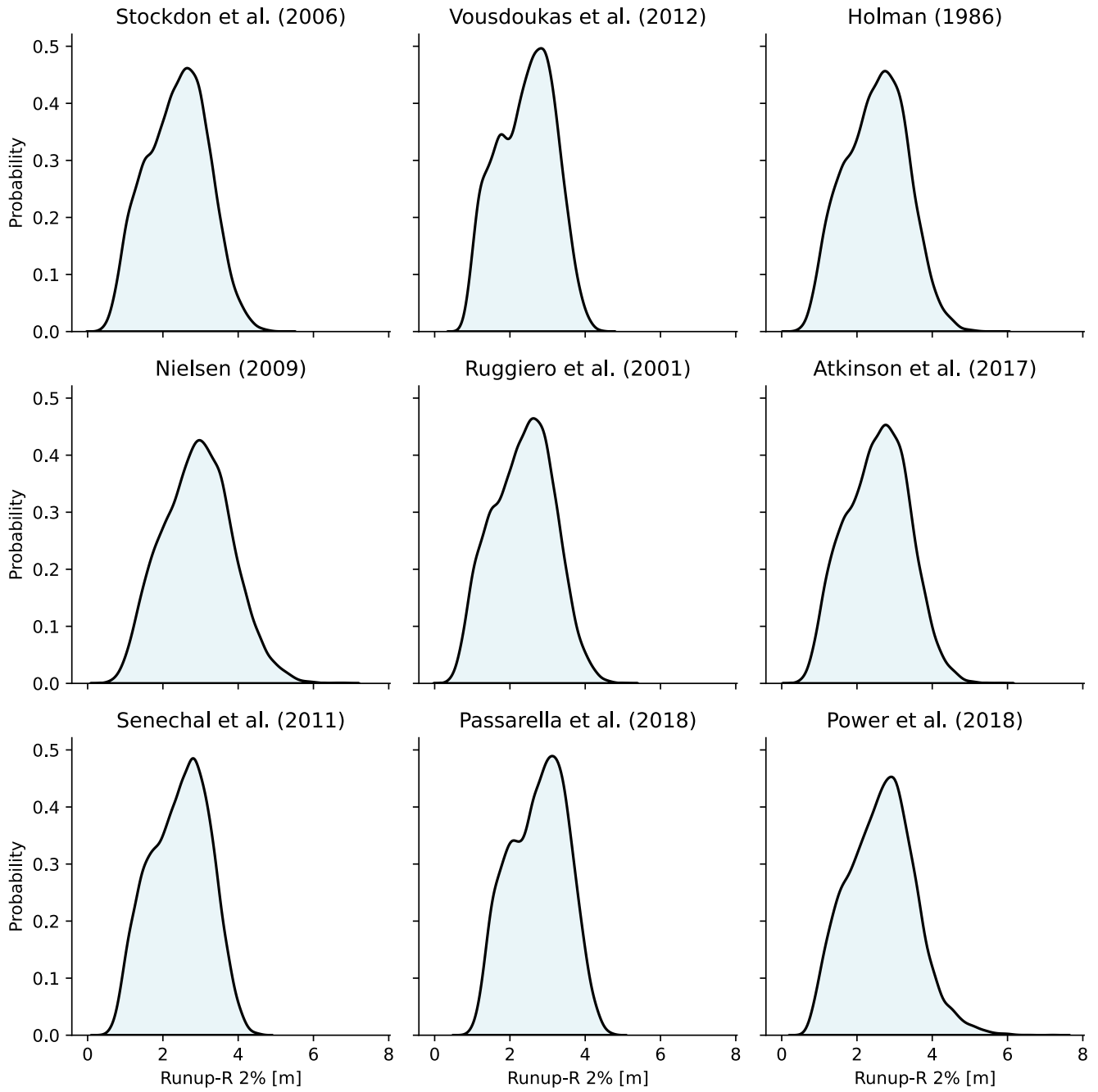
Supplementary Figure 2: Results of the runup calculations, divided by model employed, for waves perpendicular to the shore reaching the coast in tidal conditions above MSL.



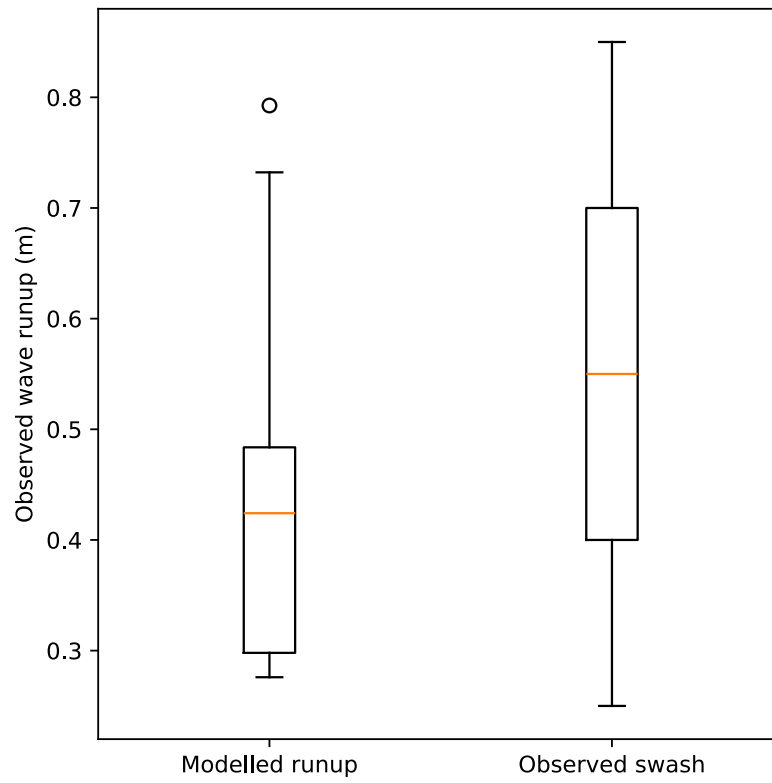
Supplementary Figure 3: A) satellite altimetry data tracks exported by the RADWave software. B) Wave runup calculated at Caleta Olivia with the approach of [Rubio-Sandoval et al. \(2024\)](#). C) and D) respectively wave height and period extracted from the satellite altimetry data.



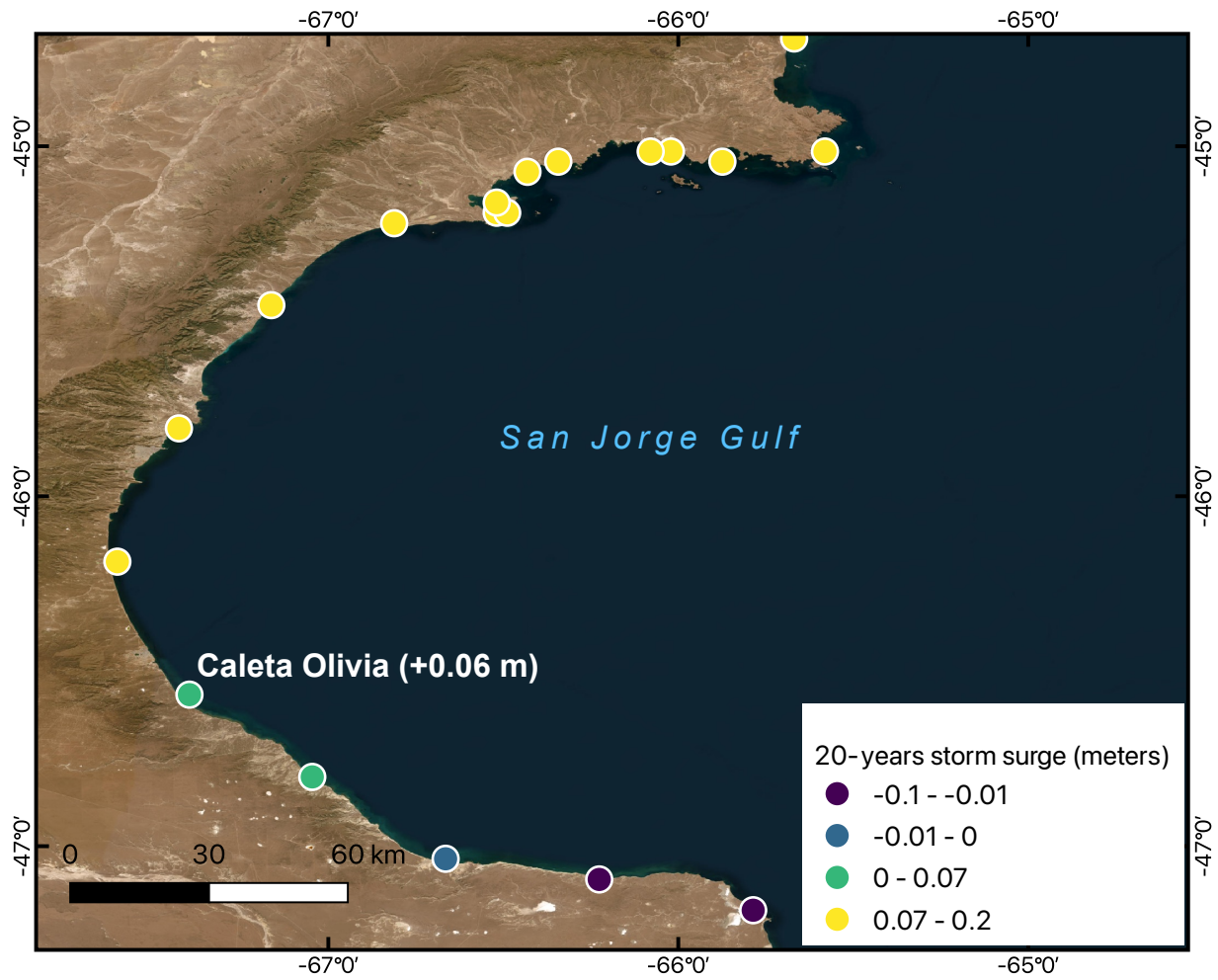
Supplementary Figure 4: Shoreline variations extracted with CoastSat (Vos et al., 2019) along the five transects using satellite imagery collected between 25 Jan 1986 and 30 Oct 2024.



Supplementary Figure 5: Results of the different runup models used in this work. Only the runup values above MSL are shown here.



Supplementary Figure 6: Comparison between modelled and observed swash height at the time of survey (11 Feb 2019, 15.55 PM).



Supplementary Figure 7: Annual anomalies (Last Interglacial minus Present Interglacial) in sea level extremes at the 20-year return period in the San Jorge Gulf (Scussolini et al., 2023). Background imagery from ESRI ArcGIS Pro (World Imagery), source: Earthstar Geographics (TerraColor NextGen)