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# HIGHER THAN PRESENT GLOBAL MEAN SEA LEVEL RECORDED BY AN EARLY PLIOCENE INTERTIDAL UNIT IN PATAGONIA (ARGENTINA).

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## ABSTRACT

Reconstructions of global mean sea level from earlier warm periods in Earth's history can help constrain future projections of sea level rise. Here we report on the sedimentology and age of a geological unit in central Patagonia, Argentina, that we dated to the Early Pliocene (4.69-5.23 Ma,  $2\sigma$ ) with strontium isotope stratigraphy. The unit was interpreted as representative of an intertidal environment, and its elevation was measured with differential GPS at ca. 36 m above present-day sea level. Considering modern tidal ranges, it was possible to constrain paleo relative sea level within  $\pm 2.7\text{m}$  ( $1\sigma$ ). We use glacial isostatic adjustment models and estimates of vertical land movement to calculate that, when the Camarones intertidal sequence was deposited, global mean sea level was  $28.4 \pm 11.7\text{m}$  ( $1\sigma$ ) above present. This estimate matches those derived from analogous Early Pliocene sea level proxies in the Mediterranean Sea and South Africa. Evidence from these three locations indicates that Early Pliocene sea level may have exceeded 20m above its present level. Such high global mean sea level values imply an ice-free Greenland, a significant melting of West Antarctica, and a contribution of marine-based sectors of East Antarctica to global mean sea level.

**Keywords** Early Pliocene · Sea level · Stratigraphy

## 1 INTRODUCTION

2 The survey, interpretation and dating of paleo relative sea level  
3 (RSL) indicators (such as fossil coral reefs or relic beach de-  
4 posits<sup>1</sup>) is paramount to constraining the maximum elevation  
5 reached by global mean sea level during periods of the Earth's  
6 history warmer than the pre-industrial. The elevation of paleo  
7 RSL indicators is the only direct proxy available to estimate  
8 global mean sea level in Earth's past. Once measured, observed  
9 paleo RSL indicators must be corrected for processes causing  
10 "Departures from Eustasy"<sup>2</sup> (such as tectonics, mantle dynamic  
11 topography, DT, and glacial isostatic adjustment, GIA<sup>3;4</sup>) to  
12 obtain paleo global mean sea level (GMSL) estimates. These  
13 are in turn important to informing models of ice sheet melting  
14 under future warmer climates<sup>5</sup>.

15 A recent global database<sup>6</sup> shows that about 5000 RSL indica-  
16 tors were preserved since the Last Glacial Maximum (30 ka).  
17 Well-preserved and dated RSL indicators are relatively rare for  
18 older time periods: another compilation of Pleistocene RSL in-  
19 dicators<sup>7</sup> reports more than 1000 Last Interglacial (MIS 5e, 125  
20 ka) and only around 20 MIS 11 (400 ka) RSL indicators. Only a  
21 handful of sites exist that document sea level highstands beyond  
22 one million years ago<sup>2;8;9;10;11</sup>. In general, robust RSL indica-  
23 tors predating 400 ka are rare to find because they are poorly  
24 preserved and are most often difficult to date with precision.  
25 Additionally, relating them to GMSL is difficult since they are

likely affected by significant post-depositional movements. This  
limits our ability to gauge the sensitivity of ice caps to warmer  
climate conditions, such as those that characterized Earth in the  
Pliocene.

Some of the oldest, precisely dated and measured RSL indicators  
were recently reported on the island of Mallorca (Balearic Is-  
lands, Spain), in a coastal cave called "Coves d'Artá". Here, six  
phreatic overgrowths on speleothems mark the paleo water/air  
interface within the cave<sup>9</sup>, and are therefore closely related to  
paleo RSL. The highest and oldest of these formations was mea-  
sured at  $31.8 \pm 0.25\text{m}$  above mean sea level, and yielded a U-Pb  
age of  $4.29 \pm 0.39\text{Ma}$  ( $2\sigma$ )<sup>9</sup>. Taking into account GIA and  
possible long-term deformation due to tectonics or dynamic to-  
pography, it was estimated that global mean sea level at the time  
of deposition of this RSL indicator was 25.1m above present,  
bounded by uncertainties represented by 16<sup>th</sup>-84<sup>th</sup> percentiles  
of 10.6-28.3m<sup>9</sup>. For the same time period, a second study<sup>10</sup>  
reported a site in the Republic of South Africa (Northern Cape  
Province, site Cliff Point-ZCP Section2). Here, oyster shells liv-  
ing in a paleo subtidal to intertidal environment constrain paleo  
RSL at  $35.1 \pm 2.2\text{m}$  ( $1\sigma$ ). The oysters were dated to 4.28-4.87  
Ma ( $2\sigma$  range) with strontium isotope stratigraphy (SIS). While  
paleo global mean sea level estimates were not calculated at  
this site, based on the Mallorca benchmark the authors argue

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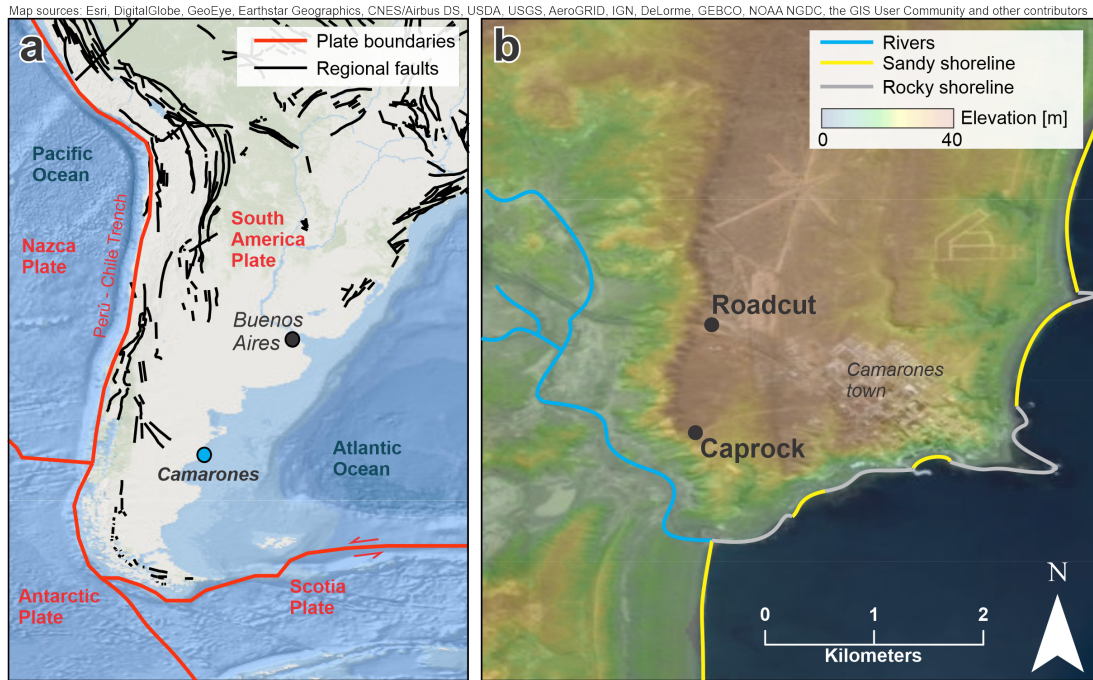


Figure 1: General and specific location of the study area. **a)** Location of the study area and main geological structures in the Southern part of South America. **b)** Topography of the Camarones town area, with location of the two outcrops (*Roadcut* and *Caprock*) presented in this study. Map sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, DeLorme, GEBCO, NOAA NGDC, SRTM, the GIS User Community and other contributors. Elevation data in B are from the Shuttle Radar Topography Mission<sup>12</sup>.

50 that this location was affected by relatively minor vertical land  
51 movements (possibly uplift) since 5 Ma.

52 While indirect paleo sea level estimates spanning the last 5.3 Ma  
53 are available from oxygen isotopes<sup>13;14;15</sup>, the two studies cited  
54 above are arguably the only ones reporting relatively precise and  
55 well-dated direct sea-level observations for the Early Pliocene,  
56 that is regarded as a past analogue for future warmer climate<sup>16</sup>.  
57 At this time, CO<sub>2</sub> was between pre-industrial and modern levels,  
58 with possibly higher peaks to 450 ppm<sup>17;16</sup>. During Early  
59 Pliocene interglacials, average global temperatures were 2-3°C  
60 higher than pre-industrial values<sup>18;16</sup>. Pliocene climate was  
61 modulated by a ca. 40 kyr periodicity in glacial/interglacial  
62 cycles with highstands and lowstands that were characterized by  
63 sea-level oscillations as high as 13 ± 5m<sup>19</sup>. Ice models suggest  
64 that, during the warmest Pliocene interglacials, Greenland was  
65 ice-free<sup>20</sup>. Similarly, they suggest that the West Antarctic Ice  
66 sheet was likely subject to periodic collapses<sup>21</sup>, and might have  
67 contributed as much as 7m<sup>22</sup> to GMSL. Ice models and field-  
68 based evidence<sup>23</sup> suggest that also the East Antarctic Ice Sheet  
69 might have been smaller than today, contributing another 3m<sup>22</sup>  
70 to 13-16m<sup>24</sup> to GMSL.

71 In this study, we report a foreshore (intertidal) sequence located  
72 in the town of Camarones, along the coast of central Patagonia,  
73 Argentina (Figure 1). Combining field data, SIS ages, GIA and  
74 DT models we conclude that this deposit formed 4.69-5.23Ma  
75 ago (2σ range) when sea level was 28.4 ± 11.7 (1σ) higher than  
76 today. This estimate is broadly consistent with those derived  
77 from the Republic of South Africa and Spain. Together,  
78 these three studies present a coherent picture of global mean sea

level during the Early Pliocene, that likely exceeded 20m above  
modern sea level.

### STUDY AREA: CAMARONES, CENTRAL PATAGONIA, ARGENTINA

The Patagonia geographic region includes territories belonging to the states of Argentina and Chile. Geologically, Patagonia represents the southernmost tip of the South American plate (Figure 1a). Along the Pacific coasts of Patagonia, the Nazca and the Antarctic plates are subducting below the Andes. Towards the south, the Scotia plate moves eastward and outlines Tierra del Fuego, at South America's southern tip<sup>25</sup>. To the East, the Patagonian Atlantic coast is a passive margin, tectonically characterized as an extensional stress field and bordered by a wide continental shelf. The central and eastern parts of this landmass are represented by the Andean foreland, formed by a Palaeozoic-Mesozoic metamorphic basement overlapped by Tertiary continental and marine sedimentary rocks, dating back to the Paleocene. These are covered by Eocene–Oligocene pyroclastic rocks and Middle Miocene fluvial sediments. Marine sedimentary rocks corresponding to Tertiary transgressions are located east of the Andean foreland<sup>26</sup>. In the Middle Miocene, the Chile Triple Junction migrated northward, leading to the opening of an asthenospheric window below southern Patagonia<sup>27</sup>. This caused a switch from subsidence to uplift, and the Patagonia region underwent a moderate but continuous uplift.<sup>28</sup>

Along the coastlines of Central Patagonia, several levels of paleo shorelines above modern sea level were noted by Charles Darwin

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Figure 2: The *Roadcut* outcrop at Camarones. The inset shows a detail of Unit **Cp**, a shelly-rich layer interpreted as representative of a foreshore (intertidal) environment dating to the Early Pliocene. Each unit is described in details in the Supplementary Note 2, including descriptions of the *Caprock* outcrop.

106 in his Beagle voyage<sup>29</sup>, and were the subject of more than 150  
 107 years of research (See Supplementary Note 1 and Supplementary  
 108 Table 1). Studies of Pleistocene coastal sequences in Central  
 109 Patagonia include outcrops of Holocene<sup>30;31</sup>, Pleistocene<sup>32;33;34</sup>  
 110 and Pliocene-to-Miocene<sup>35;36</sup> age. Among the latter, Del Río et  
 111 al. (2013)<sup>36</sup> dated Early Pliocene mollusks from marine deposits  
 112 few hundreds of kilometers south of the study area described in  
 113 this study.

114 The town of Camarones lies at the northern tip of the San Jorge  
 115 Gulf, approximately 1300 km south of Buenos Aires. Within a  
 116 few kilometers of Camarones, several paleo-sea level indicators  
 117 have been preserved, from the Holocene<sup>37</sup> to the Pleistocene<sup>32</sup>.  
 118 Already in the late 1940s, the Italian geologist Feruglio<sup>38</sup> iden-  
 119 tified an elevated marine terrace along a roadcut carved on the  
 120 main road leading into the town of Camarones that he tenta-  
 121 tively attributed to the Pliocene. He called this terrace, the  
 122 Camarones High Terrace (originally, in Spanish, *Teraza Alta de*  
 123 *Camarones*<sup>38</sup>). A recent study<sup>32</sup> confirmed the elevation of the  
 124 Camarones High Terrace at ca. 40m above sea level, at the lower  
 125 bound of the "beach barriers and terrace deposits between 40  
 126 and 110m elevation" reported by the 1:250.000 geological chart  
 127 of Camarones<sup>39</sup>.

## 128 RESULTS: THE PLIOCENE SEA LEVEL RECORD AT 129 CAMARONES AND GMSL ESTIMATES

130 Radiometric ages, precise GPS elevations and stratigraphic de-  
 131 scriptions of cross-sections surveyed along the Camarones High  
 132 Terrace are the subject of this paper. Along this terrace, we  
 133 surveyed and dated samples from two sites, separated by less  
 134 than one kilometer. One is the *Roadcut*, already recognized  
 135 and described by Feruglio<sup>38</sup>. We did not find reports of the

second site (that we here call *Caprock*, Figure 1b) in the exist-  
 ing literature, although it is possible that it was included in the  
 geological description of the High Terrace by previous authors.  
 At both sites, we recognized a geological facies representative  
 of sedimentation in a foreshore environment (i.e. in the inter-  
 tidal zone) that marks paleo RSL with high accuracy. All data  
 described hereafter and in Supplementary Note 2 is available in  
 spreadsheet form from Rovere et al. (2020)<sup>40</sup>

**Paleo RSL.** In general, *Roadcut* and *Caprock* represent sedi-  
 mentation during a transgressive event on top of a raised shore  
 platform (Supplementary Figure 1-2). Among the units iden-  
 tified within the *Roadcut* (Figure 2), one (Unit **Cp**, see inset  
 in Figure 2) is composed of well-cemented fine conglomerates  
 with rounded pebbles and shells. In particular, the uppermost  
 part of this unit contains a dense faunal assemblage in the form  
 of a shellbed, where we recognized 15 different species of bi-  
 valves and 11 species of gastropods (Supplementary Table 2).  
 The bivalve shells are mostly intact and sometimes with paired  
 valves (articulated), but not in living position. This unit was  
 interpreted as representative of a foreshore environment, i.e. the  
 intertidal zone. The same unit has been identified at the *Caprock*  
 section, at roughly the same elevation. The elevation of Unit  
**Cp** was measured at two points at both *Roadcut* and *Caprock*  
 (Table 1). From these measurements, we calculate that Unit  
**Cp** has an **average elevation of  $36.2 \pm 0.9\text{m}$  ( $1\sigma$ )** above the  
 GEOIDEAR16 geoid<sup>41</sup>, which is the best approximation for  
 present sea level in Argentina. Using modern tidal values<sup>37</sup>,  
 and assuming no post-depositional movement, we calculate that  
 the two outcrops in the area of Camarones are indicative of a  
**paleo RSL at  $36.2 \pm 2.7\text{m}$  ( $1\sigma$ )** above present (see Methods for  
 details).



167 **Age.** Three oyster shells from *Roadcut* and *Caprock* were  
 168 analyzed by strontium isotope stratigraphy (SIS) relative dating  
 169 techniques. Using sequential leaching to target the least altered  
 170 inner carbonate of each shell, we obtained multiple SIS ages on  
 171 three different shells (one from *Caprock* and two from *Roadcut*;  
 172 see Sandstrom et al., 2020<sup>11</sup> for a detailed description of the  
 173 adopted methodology). The shells yielded an age range of **4.69–**  
 174 **5.23Ma** ( $n=6$ ,  $2\sigma$   $S_{EM}$ ).

175 **Glacial Isostatic Adjustment.** The Early Pliocene intertidal  
 176 units surveyed at Camarones were subject to processes that  
 177 caused their past and current elevation to depart from GMSL.  
 178 These include glacial isostatic adjustment (GIA) and other verti-  
 179 cal land motions (VLMs). We calculate GIA using 36 different  
 180 Earth models. For this site, we calculate a GIA correction of  
 181  $-14.6 \pm 3.2\text{m}$  ( $1\sigma$ ) (see Methods for details). This value is  
 182 subtracted from the observed paleo RSL and the uncertainty  
 183 propagated. This correction is a combination of effects associ-  
 184 ated with i) the ongoing response to the last deglaciation, and ii)  
 185 Antarctic ice sheet oscillations during the early Pliocene<sup>2</sup>. The  
 186 former contribution is  $-9.5 \pm 3\text{m}$  ( $1\sigma$ ), which means that the  
 187 Argentinian coast today experiences sea level fall due to a combi-  
 188 nation of effects associated with postglacial rebound due to the  
 189 melting of the glacial Patagonian ice sheet as well as continental  
 190 levering, ocean syphoning, and rotational effects. Once fully  
 191 relaxed, sea level at Camarones will therefore be lower (and a  
 192 paleo sea level indicator higher) by approximately 9.5m than  
 193 it is today. The additional contribution of  $\sim -5\text{m}$  is associated  
 194 with the adjustment to 40kyr oscillations in the Antarctic ice  
 195 sheet. The result is that, at Camarones, **GIA-corrected paleo**  
 196 **RSL is  $50.8 \pm 4.2\text{m}$**  ( $1\sigma$ ).

197 **Vertical Land Motions.** The GIA-corrected RSL elevation re-  
 198 ported above needs to be further corrected for VLMs, that can be  
 199 either due to crustal tectonics, mantle dynamic topography<sup>42;43</sup>  
 200 or deformation associated with sediment loading/unloading<sup>44;45</sup>.  
 201 As briefly outlined in the previous sections, Camarones is lo-  
 202 cated on a passive margin, likely subject to limited tectonic  
 203 influence. Dynamic topography models suggest that, since MIS  
 204 5e (125 ka), the area of Camarones was subject to uplift, with  
 205 rates increasing towards the South<sup>3</sup>. This is in line with obser-  
 206 vations of much higher Pliocene shorelines (70–170m above sea  
 207 level<sup>36</sup>) at locations 300–500 kilometers south of Camarones  
 208 (Supplementary Note 1). A long-term slight uplift trend is also  
 209 predicted by the models of Flament et al. (2015)<sup>46</sup> and Müller  
 210 et al. (2018)<sup>47</sup>. Predictions in these DT models average to  
 211  $4.5 \pm 2.2\text{m/Ma}$  (Table 3). Accounting for the age of the deposit  
 212 (including  $1\sigma$  uncertainties), this leads to a downward correc-  
 213 tion of our global mean sea level inference by  $22.4 \pm 11.0\text{m}$   
 214 ( $1\sigma$ ). As is apparent from the variation of estimates for the dy-  
 215 namic topography rate, this correction remains quite uncertain  
 216 and the true value can possibly be even outside of this range  
 217 given that it is difficult to fully explore model uncertainties (see  
 218 Discussion section).

219 **Global Mean Sea Level.** Using the value of VLM reported  
 220 above and propagating the uncertainties related to RSL, GIA  
 221 and VLM, we calculate that, at the time of deposition of the  
 222 *Caprock* and *Roadcut* outcrops, **GMSL was  $28.4 \pm 11.7\text{m}$**  ( $1\sigma$ )  
 223 . We remark that there are large unknowns associated with this  
 224 value. First, as described above, dynamic topography remains a

process that has high uncertainties that are generally not fully  
 quantified. Second, it is possible that, as it is the case for the US  
 Atlantic Coastal Plain<sup>44</sup>, flexural response to sediment loading  
 or tectonic deformation (that are not considered here) could also  
 contribute to further vertical land motions in this area.

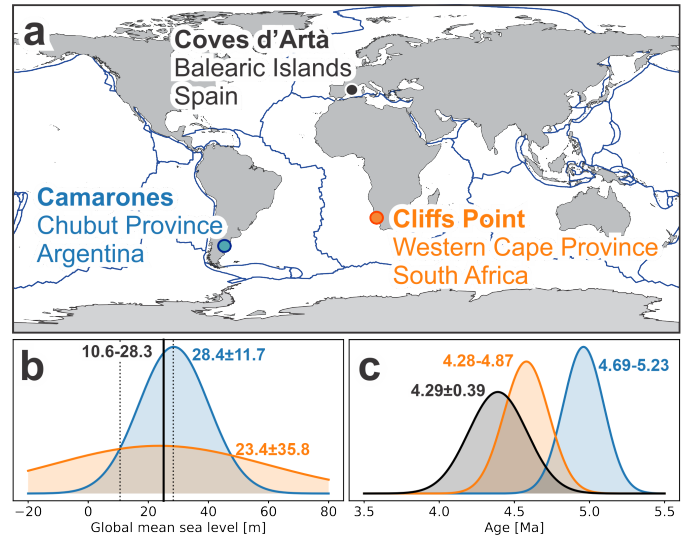


Figure 3: Comparison among Early Pliocene sea level stratigraphic reconstructions. **a)** Location of Early Pliocene RSL indicators discussed in the text. Plate boundaries are shown in dark blue for reference<sup>48</sup>. **b)** Global Mean Sea Level (GMSL) estimates for: i) Coves d'Artà (Balearic Islands, Spain), solid black line represents the most likely value (25.1m), dotted black lines the 16<sup>th</sup> and 84<sup>th</sup> percentiles<sup>9</sup>; ii) Camarones, Argentina (blue gaussian); iii) Cliffs Point, South Africa (orange gaussian, calculated from data in Hearty et al. (2020)<sup>10</sup>, corrected with the same GIA and subset of applicable DT models used for Camarones. **c)** Age estimates for Coves d'Artà (black), Camarones (blue) and Cliffs Point (orange).

## DISCUSSION: EARLY PLIOCENE GLOBAL MEAN SEA LEVEL

Our results show that the intertidal units at Camarones are of Early Pliocene age (4.69–5.23Ma,  $2\sigma$   $S_{EM}$ ). The sedimentological and stratigraphic characteristics of the deposits analysed in this study lead to the conclusion that they formed during a sea level highstand, when GMSL was  $28.4 \pm 11.7\text{m}$  ( $1\sigma$ ) higher than present. We note that there are still large uncertainties on this GMSL estimate, which derive mostly from vertical land motion corrections, stemming from the variability of published dynamic topography predictions<sup>46;47</sup>. Exploring and reducing these uncertainties requires improved mapping of the mantle structure beneath Patagonia from seismic tomography, a better understanding of how wave speeds map into density variations, and improved constraints on the rheology of the subsurface. Recent advances tackle these shortcomings and promise to reduce uncertainties in the estimate of vertical land motion<sup>57;58</sup>. Another strategy to investigate vertical land motions at Camarones would be to use the Pleistocene shorelines at the same site to extract a long-term uplift rate for the area. We argue that such approach would lead to similarly large error bars due to uncer-

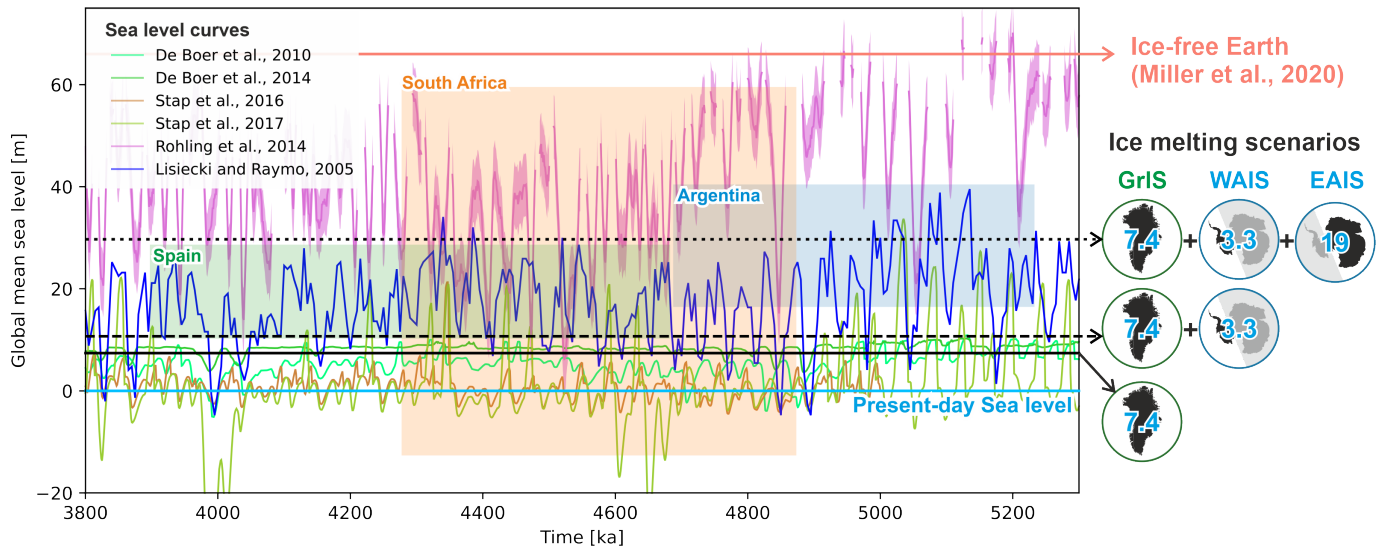


Figure 4: Comparison between sea-level data discussed in this study and global mean sea level derived from ice models<sup>49;50;51;52</sup> and indirect sea level proxies<sup>13;53</sup>. The blue curve shows the GMSL prediction that is used in the GIA model and based on scaling the benthic oxygen isotope record by Lisiecki and Raymo (2005)<sup>53</sup> following the steps described in the methods. Age ranges for observations are  $2\sigma$ , while elevation ranges are  $1\sigma$  for Argentina and South Africa, and 16<sup>th</sup>-84<sup>th</sup> percentiles for Spain. Horizontal black lines and graphics on the right side of the graph show total sea level equivalent for ice-free Greenland (GrIS, solid line<sup>54</sup>), melting of West Antarctic Ice Sheet (WAIS, dashed line<sup>55</sup>) and marine sectors of the East Antarctic Ice Sheet (EAIS, dotted line<sup>56</sup>). The upper red line shows GMSL in an ice-free Earth, estimated to 66m by Miller et al. (2020)<sup>15</sup>.

250 tainties related to GIA, Pleistocene global mean sea level and the  
 251 implicit assumption that uplift rates can be linearly extrapolated  
 252 over these time scales<sup>59</sup>.

253 Despite the uncertainties related to VLMs, there is overlap between  
 254 the calculated global mean sea levels for Camarones ( $28.4 \pm 11.7\text{m}$ ,  $1\sigma$ ) and Coves d'Artá (Spain<sup>9</sup>,  $25.1\text{m}$ , with 16<sup>th</sup>-  
 255 84<sup>th</sup> percentiles of 10.6-28.3m, Figure 3a,b). Correcting the  
 256 proxy record at Cliffs Point (South Africa<sup>10</sup>) with the same GIA  
 257 models used for Camarones (Table 2), results in a paleo RSL  
 258 of  $44.7 \pm 2.7\text{m}$  ( $1\sigma$ ) above present. The DT model predictions  
 259 by Müller et al. (2018)<sup>47</sup>, which were also used for Camarones,  
 260 indicate VLMs in the range of  $4.6 \pm 7.8\text{m/Ma}$  ( $1\sigma$ ). This results  
 261 in an average global mean sea level estimate that aligns with  
 262 those obtained from the other two sites, but bounded by very  
 263 large uncertainties ( $23.4 \pm 35.8\text{m}$ ,  $1\sigma$ ), Figure 3b). As already  
 264 underlined by Hearty et al. (2020)<sup>10</sup>, improving uplift estimates  
 265 for this region is paramount to enable the use of RSL data in  
 266 GMSL calculations.

268 The average global mean sea level calculated from the geological  
 269 facies reported in Argentina (this study), South Africa<sup>10</sup>  
 270 and Spain<sup>9</sup> is well above modern sea level. Compared to published  
 271 global mean sea level estimates that are based on ice sheet  
 272 models and indirect sea-level proxies (Figure 4), it is evident  
 273 that field evidence is most consistent with the highstands  
 274 obtained by scaling the Lisiecki and Raymo (2004)<sup>53</sup> benthic  
 275 oxygen isotope stack (see Methods for details). Our data is also  
 276 consistent with some peaks predicted by the one-dimensional  
 277 ice sheet model of Stap et al. (2017)<sup>52</sup>. Other ice sheet model  
 278 based estimates<sup>49;50;51</sup> significantly under predict the observed  
 279 Early Pliocene sea level records presented here. The almost-  
 280 continuous Gibraltar record<sup>13</sup>, derived from planktic  $\delta^{18}\text{O}$  cou-

281 pled with a hydraulic model, largely over predicts sea level  
 282 observed at both Argentina and Spain suggesting that, when the  
 283 Camarones outcrop was deposited, the Earth was substantially  
 284 ice-free. To align with this record, the three sites in this study  
 285 would have to be characterized by marked subsidence, instead  
 286 of uplift as indicated by almost all dynamic topography models  
 287 we considered. Early Pliocene observations from Argentina only  
 288 overlap with lowstands of the Gibraltar record, which would  
 289 have left regressive imprints. This is at odds with the sedi-  
 290 mentological characteristics of the *Roacut*, which represents a  
 291 transgressive system rather than a regressive one.

292 While GMSL estimates from South Africa<sup>10</sup> are affected by  
 293 large uncertainties, their average value together with the Arg-  
 294 entinian sea-level proxies presented in this study and those  
 295 obtained from Spain<sup>9</sup>, suggest that Early Pliocene GMSL might  
 296 have exceeded 20m above present-day levels. Reaching the average  
 297 GMSL calculated for Camarones (28.4m) would require an  
 298 ice-free Greenland (GrIS, 7.4m sea-level equivalent<sup>54</sup>), significant  
 299 melting of the West Antarctic Ice Sheet (WAIS, 3.3m sea-level  
 300 equivalent<sup>55</sup>) and the almost complete melting of marine  
 301 sectors of the East Antarctic Ice Sheet (EAIS, 19m sea-level  
 302 equivalent<sup>56</sup>). Reaching the lower end calculated for Camarones  
 303 (16.7m,  $1\sigma$  below the mean) would require complete melting  
 304 of the GrIS and WAIS, and melting of about 1/3 of the marine-  
 305 based sectors of the EAIS. This scenario would match almost  
 306 exactly a complete GrIS melting, and a contribution from Antarc-  
 307 tica in line with the one modelled by Golledge et al. (2007)<sup>60</sup>.  
 308 These authors calculated that the contribution of Antarctica to  
 309 GMSL during an Early Pliocene (4.23Ma) interglacial was 8.5m,  
 310 sourced primarily from WAIS and the Wilkes subglacial basin of  
 311 EAIS. Reaching the upper end calculated for Camarones (40.1m,

312  $1\sigma$  above the mean) would require significant contributions of  
 313 not only marine-based but also land-based sectors of the EAIS  
 314 in addition to melting of the GrIS and WAIS. We note that geo-  
 315 logical proxies suggest that a significant melting of land-based  
 316 portions of EAIS was unlikely over the past 8 million years<sup>61</sup>,  
 317 which makes this last scenario less likely.

## 318 CONCLUSIONS

319 The Early Pliocene world was characterized by global annual  
 320 mean temperatures of 2-3°C higher than pre-industrial, and CO<sub>2</sub>  
 321 levels between 280 and 450 ppm<sup>16</sup>. In face of these relatively  
 322 small differences in temperature and CO<sub>2</sub>, the Earth's climate  
 323 was substantially different than today<sup>17</sup>, and ice sheets were  
 324 significantly smaller. Until recently, field evidence to support  
 325 the answer to the question "How high was global mean sea level  
 326 in the Early Pliocene?" was elusive. In this study, we show that  
 327 independent paleo sea-level indicators of similar age on three  
 328 continents result in broadly similar GMSL estimates. While  
 329 affected by large uncertainties, stemming mostly from vertical  
 330 land motion estimates, they indicate that Early Pliocene sea  
 331 level may have exceeded 20m above present-day. This value can  
 332 be attained only with a complete melting of the Greenland ice  
 333 sheet and significant contributions of Antarctica (also including  
 334 marine-based sectors of East Antarctica).

335 The significance of the Early Pliocene and its potential role  
 336 as analog for present-day and near-future warming must be  
 337 taken into account as the world prepares to meet the "Paris  
 338 Agreement"<sup>62</sup> goals and limit global warming below the 1.5°C  
 339 threshold<sup>63</sup>.

## 340 METHODS

341 **Elevation measurements and paleo RSL estimates.** We  
 342 measured elevations with a differential GPS system (Trimble  
 343 ProXRT receiver and Trimble Tornado antenna) equipped to  
 344 receive OmniSTAR HP real-time corrections. As per technical  
 345 specifications by the service provider, these corrections allow to  
 346 measure, in optimal conditions, the elevation of a point with an  
 347 accuracy of 0.1-0.6 m ( $2\sigma$ ), depending on the survey conditions.  
 348 We remark that, while at the *Caprock* outcrop there is a free view  
 349 of the sky, at the *Roadcut* satellite reception is hindered by the  
 350 vertical cliff face. This could explain, in part, the discrepancy  
 351 in the two points collected at this outcrop at relatively short  
 352 distance from each other. Data were originally recorded  
 353 in geographic WGS84 coordinates and in height above the  
 354 ITRF2008 ellipsoid. For each GPS point, we calculated heights  
 355 above Mean Sea Level (orthometric height) subtracting from  
 356 the measured ITRF2008 ellipsoid height the GEOIDEAR16  
 357 geoid height<sup>41</sup>. These geoidal elevations are the best available  
 358 approximation of mean sea level in this area. GEOIDEAR16  
 359 was estimated to have an overall accuracy of 10 cm  
 360 (<https://www.ign.gob.ar/NuestrasActividades/Geodesia/Geoide-Ar16>). The location and elevations of Unit **Cp** at *Roadcut* and  
 362 *Caprock* are reported in Table 1.

363 From these elevations, we calculate that the average elevation  
 364 ( $\mu E$ ) is 36.2m. To calculate the elevation error ( $\sigma E$ ), we use the  
 365 following formula:

$$\sigma E = \sqrt{\frac{\sum_1^N (\sigma E_p^2 \cdot (p-1)) + p \cdot (\mu E - \mu E_p)}{N-1}} \quad (1)$$

366 Where N is the total number of filtered positions measured by  
 367 the GPS during the survey (439, sum of "Number of filtered  
 368 positions" in Table 1),  $\sigma E_p$  is the elevation error for each single  
 369 point,  $\mu E_p$  is the Height above geoid of each single point and  
 370  $\mu E$  is the average elevation (36.2m) (Table 1). On average, we  
 371 calculate that the elevation of Unit **Cp** is  $36.2 \pm 0.9\text{m}$  ( $1\sigma$ ).

372 The Unit **Cp** at the *Roadcut* and *Caprock* sites has been inter-  
 373 preted as forming in the foreshore zone, i.e., in the intertidal  
 374 zone. This means that its indicative meaning<sup>64</sup> spans from  
 375 Mean Lower Low Water (MLLW) to Mean Higher High Wa-  
 376 ter (MHHW). Based on predicted tidal data for the harbor of  
 377 Camarones, Bini et al. (2018)<sup>37</sup> report that the maximum tidal  
 378 range (MHHW to MLLW) in Camarones is 5m. We use this  
 379 value (5m) as the indicative range (IR) for a foreshore deposit in  
 380 our area, and the midpoint between MHHW and MLLW (0m)  
 381 as reference water level (RWL). Then, using the formulas de-  
 382 scribed in Rovere et al. (2016)<sup>1</sup>, we calculate paleo RSL and its  
 383 associated uncertainty as follows: 384

$$RSL = \mu E - RWL \quad (2)$$

$$\sigma RSL = \sqrt{\sigma E^2 + \left(\frac{IR}{2}\right)^2} \quad (3)$$

385 Using the equations above, we calculate that paleo RSL associ-  
 386 ated with Unit **Cp** is  $36.2 \pm 2.7\text{m}$ . We highlight that this value  
 387 does not take into account the possibility that, 5 Ma ago, tidal  
 388 ranges were different than present-day ones, due to different  
 389 shelf bathymetry under higher sea levels<sup>65</sup>.

390 To calculate global mean sea level (GMSL) and associated un-  
 391 certainties, we used the following formulas:

$$GMSL = RSL - \mu GIA - \mu VLM \quad (4)$$

391 Where  $\mu GIA$  is the average of the GIA models (Table 2) and  
 392  $\mu VLM$  is calculated as the product of mean dynamic topography  
 393 rate (Table 3) multiplied by the average age of the deposit.

$$\sigma GMSL = \sqrt{\sigma RSL^2 + \sigma GIA^2 + \sigma VLM^2} \quad (5)$$

394 Where  $\sigma GIA$  is the standard deviation of GIA models shown in  
 395 Table 2 and  $\sigma VLM$  is calculated as follows:

$$\sigma VLM = |VLM| \cdot \sqrt{\left(\frac{\sigma Age}{\mu Age}\right)^2 + \left(\frac{\sigma Rate}{\mu Rate}\right)^2} \quad (6)$$

396 Where  $\mu Age$  and  $\sigma Age$  are the average and  $1\sigma$  age of the deposit,  
 397 and  $\mu Rate$  and  $\sigma Rate$  are the average and  $1\sigma$  rates derived from  
 398 published dynamic topography models (Table 3).



Table 1: GPS position and elevation of Unit **Cp** measured at the *Roadcut* and *Caprock* sites. Lat/Lon are in WGS84 coordinates, Ellipsoid heights are referred to the ITRF08 ellipsoid, geoid heights to the GEOIDEAR16 geoid model.

Longitude (decimal degrees E)	Latitude (decimal degrees N)	Ellipsoid Height (m)	Height above geoid ( $\mu E_p$ ) (m)	Elevation error ( $\sigma E$ ) (m)	Number of filtered positions (p)
<b>Roadcut</b>					
-65.727604	-44.790083	49.67	36.8	0.06	27
-65.727619	-44.790069	47.68	34.8	0.28	134
<b>Caprock</b>					
-65.728221	-44.799297	49.40	36.5	0.17	249
-65.728221	-44.799298	49.64	36.8	0.12	29
Average			<b>36.2</b>		

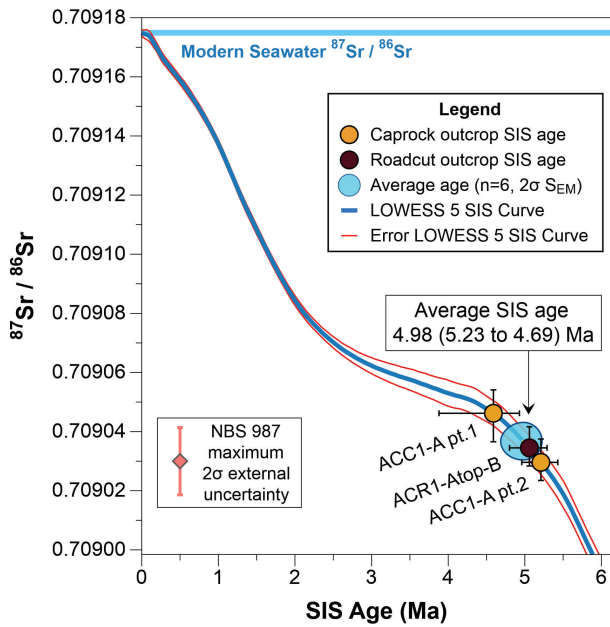


Figure 5: Sr isotope stratigraphy relative ages of oyster shells plotted on the SIS curve (LOWESS version 5)<sup>66</sup>. Orange points are from two separate portions of a shell from the *Caprock*, while maroon point is of a shell from unit **Cp** in the *Roadcut*. The average SIS age based on these samples is shown as a blue ellipse. Only inner leaches on the best-preserved specimens are shown. For the full dataset, see Supplementary Note 3 annexed to this paper. Modern seawater  $^{87}\text{Sr}/^{86}\text{Sr}$  values shown in light blue line. Maximum  $2\sigma$  external uncertainty for the Sr isotope external standard NBS 987 is shown as red point for comparison (see Methods for details).

399 **Strontium Isotope Stratigraphy ages.** To attribute an age  
 400 to Unit **Cp**, we used the Strontium Isotope Stratigraphy (SIS)  
 401 curve published by McArthur et al. (2012)<sup>66</sup> (LOWESS version  
 402 5). Sr isotope ratios from carbonates are susceptible to post-  
 403 depositional alteration, therefore, any significant reworking of  
 404 Sr isotopes needs to be detected and discarded. Information on  
 405 shell preservation was determined using  $^{87}\text{Sr}/^{86}\text{Sr}$  measurements  
 406 on sequentially leached shell material (assuming smaller Sr iso-  
 407 tope variations between leaches implies better preservation<sup>67,68</sup>)  
 408 alongside standard screening techniques<sup>36,69</sup> and elemental anal-

409 ysis<sup>70,71</sup>). A preservation index between "1" (unaltered) and  
 410 "3" (highly altered) was established for each sample based on  
 411 these criteria (Supplementary Note 3, Supplementary Figures  
 412 3-7, Supplementary Table 3-4) with samples scoring above "2.0"  
 413 excluded from results. The same screening criteria have recently  
 414 been used by Hearty et al. (2020)<sup>10</sup> and are discussed in Sand-  
 415 strom et al. (2020)<sup>11</sup>. The latter also gives an overview of  
 416 the limits and implications of SIS analyses for Plio-Pleistocene  
 417 marine samples.

418 We selected Ostreidae species for SIS chronological constraints,  
 419 primarily because these shells precipitate original calcite min-  
 420 eral phases, making them more robust to diagenesis than arag-  
 421 onitic shells. Sample screening and chemical processing was  
 422 carried out at Lamont Doherty Earth Observatory (LDEO), and  
 423 all  $^{87}\text{Sr}/^{86}\text{Sr}$  measurements were made using Thermal Ion Mass  
 424 Spectrometry (TIMS) on an IsotopX Phoenix at SUNY Stony-  
 425 brook University (SBU) or a Finnigan Triton Plus at Lamont  
 426 Doherty Earth Observatory (LDEO).

427 We measured three oyster shells, one from the *Caprock* and two  
 428 from the *Roadcut* unit. The *Caprock* oyster (ACC1-A) was sam-  
 429 pled in three different locations, with inner leaches measured  
 430 on two of those splits, returning SIS ages of 4.59Ma (3.88 to  
 431 4.93Ma) and 5.21Ma (4.96 to 5.44Ma) (Figure 5). The third  
 432 sampling location was only measured for full dissolution, with  
 433 an average SIS age of 4.65Ma (4.42 to 4.83Ma), but provided  
 434 confidence in the shell Sr isotope heterogeneity and validated  
 435 analytical uncertainties. The preservation index score for the  
 436 caprock oyster(pt.1) was 1.92. The two shells measured from the  
 437 *Roadcut* (ACR1-Atop-B and ACR1-Ctop-C) had inner leach SIS  
 438 ages of 5.06Ma (4.80 to 5.28Ma), and 6.35Ma (6.19 to 6.53Ma),  
 439 respectively. Additional diagenesis screening techniques on  
 440 these shells included elemental analysis (Supplementary Note  
 441 3), and variation of  $^{87}\text{Sr}/^{86}\text{Sr}$  within the leach set of each sam-  
 442 ple. The results of sample variation compared to the inner leach  
 443  $^{87}\text{Sr}/^{86}\text{Sr}$  are shown in the Supplementary Note 3, with low Sr  
 444 isotope variation indicative of better preservation. Samples with  
 445 low variation tend to exhibit more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  values.  
 446 Sample ACR1-Atop-B had a preservation index of 1.56, while  
 447 ACR1-Ctop-C had a score of 2.33 (Supplementary Table 3).  
 448 Based on these screening criteria, we exclude sample ACR1-  
 449 Ctop-C, which appeared to have been altered by low  $^{87}\text{Sr}/^{86}\text{Sr}$   
 450 fluids (possibly of through leaching of surrounding volcanic  
 451 material from the Complejo Marifil<sup>39</sup>). The remaining inner  
 452 leaches that passed screening were averaged by filament to ob-

tain an age of  $4.98 \pm 0.245/-0.295$  Ma ( $n=6$ ,  $2\sigma$   $S_{EM}$ ). In the text, this age is reported as a  $2\sigma$  range, i.e., 4.69-5.23 Ma.

**Glacial Isostatic Adjustment.** To account for changes in vertical displacement and gravity field caused by GIA we use a gravitationally self-consistent sea level model, that accounts for the migration of shorelines and feedback of Earth’s rotation axis<sup>72</sup>. We compute both the contribution to GIA from the amount of residual deformation caused by the most recent Pleistocene glacial cycles and from ice age cycles during the Pliocene.

For the first contribution we use the results from Raymo et al. (2011)<sup>2</sup>, who calculated the residual deformation associated with the ice model ICE-5G<sup>73</sup>. This ice history is paired with a suite of 36 different earth models with varying lithospheric thickness (48km, 71km, and 96km), upper and lower mantle viscosities ( $3 \times 10^{20}$  and  $5 \times 10^{20}$  Pa s for the upper mantle, and  $3 \times 10^{21}$  -  $30 \times 10^{21}$  for the lower mantle) to calculate a mean and standard deviation in residual deformation (Figure 6).

For the second contribution we follow the approach described in Dumitru et al. (2019)<sup>9</sup> by estimating ice mass variability based on the benthic stack<sup>53</sup>. Following Miller et al. (2012)<sup>74</sup> we prescribe that 75% of the benthic  $\delta^{18}O$  variability is due to ice volume changes (the rest being due to temperature) and a further scaling of  $0.11\text{‰}/10\text{m}$  to convert  $\delta^{18}O_{seawater}$  into ice volume changes. These conversions are highly uncertain<sup>75:76</sup>, which highlights the need to obtain local sea level based ice volume estimates. Nonetheless, this scaling was used because it yielded comparable ice volume estimates to the results of Dumitru et al. (2019)<sup>9</sup>. To construct an ice history following this ice volume curve we only assume changes in Antarctic ice volume given evidence that continent wide expansion of northern hemisphere ice sheets did only start around 3.3 Ma<sup>77</sup>. However, we acknowledge that an earlier intermittent Greenland ice sheet might have existed<sup>78</sup>. We compute glacial isostatic adjustment using this ice history and the same suite of 36 different earth models described above. We extract local predictions of relative sea level for Argentina, Mallorca, and South Africa. To calculate global mean sea level changes we integrate the amount of water in the ocean basins as a function of time. We next calculate how this quantity has changed relative to the initial state and divide it by the oceanic area calculated at each time.

Note that this setup to calculate the GIA correction deviates slightly from the one described in Dumitru et al. (2019)<sup>9</sup> in three small ways, (1) we only consider one GMSL history for the Pliocene rather than a range of histories, (2) we only consider variability in southern hemisphere ice sheets and (3) we calculated GMSL as described above rather than as changes in grounded ice volume.

The GIA corrections from both processes are combined. In a last step we consider the age range for each sea level indicator and average the GIA correction during warm periods, which we define as times that had higher than average sea level over this time period<sup>9</sup>. The mean and standard deviation that is obtained is shown in Table 2. We also show the GIA correction calculated by Dumitru et al. (2019)<sup>9</sup> and note that the difference in mean GIA estimates stems mostly from our different definition of global mean sea level. For the analysis in the main text we use

the GIA correction described in Dumitru et al. (2019)<sup>9</sup> for the datapoint from Mallorca and not the one recalculated here.

Table 2: GIA correction for Pliocene sea level markers at the three locations discussed in the text. For comparison, we also report the results for Mallorca used in Dumitru et al.<sup>9</sup>.

Location	Longitude	Latitude	$\mu GIA$ (m)	$\sigma GIA$ (m)
Argentina	65.73° E	44.79° S	-14.6	3.2
South Africa	18.12° W	31.59° S	-9.6	1.6
Mallorca	3.45° W	39.66° N	2.9	2.2
Mallorca <sup>9</sup>	3.45° W	39.66° N	1.3	3.1

**Vertical Land Motions.** VLMs were extracted from published Dynamic Topography models<sup>46:47</sup>. The values extracted are reported in Table 3. Flament et al. (2015)<sup>46</sup> focus on the surface expression of subduction dynamics in South America. Their results are based on forward advection modeling with different tectonic surface boundary conditions. The different cases are based on different timings of slab flattening. Müller et al. (2018)<sup>47</sup> have a global focus and combine back advection (initialized with a seismic tomography model) and forward advection with tectonic surface boundary conditions. Their different models are based on different surface plate reconstructions and different viscosity profiles.

Table 3: Amount of Vertical Land Motion (VLM) at Camarones from two different studies. Predictions are given at the time step closest to the sea level indicator age, which is denoted as ‘Timing’. Rates are calculated based on this age and the predicted VLM and linearly interpolated to the age of the indicator.

Reference	Model	VLM (m)	Timing (Ma)	Rate (m/Ma)
Müller et al. (2018) <sup>47</sup>	M1	4.6	10	0.46
	M2	66.2	10	6.62
	M3	45.0	10	4.50
	M4	58.0	10	5.80
	M5	45.4	10	4.54
	M6	21.8	10	2.18
	M7	25.5	10	2.55
Flament et al. (2015) <sup>46</sup>	Case 1	35.7	5	7.14
	Case 2	37.6	5	7.52
	Case 3	22.9	5	4.58
	Case 4	18.6	5	3.73

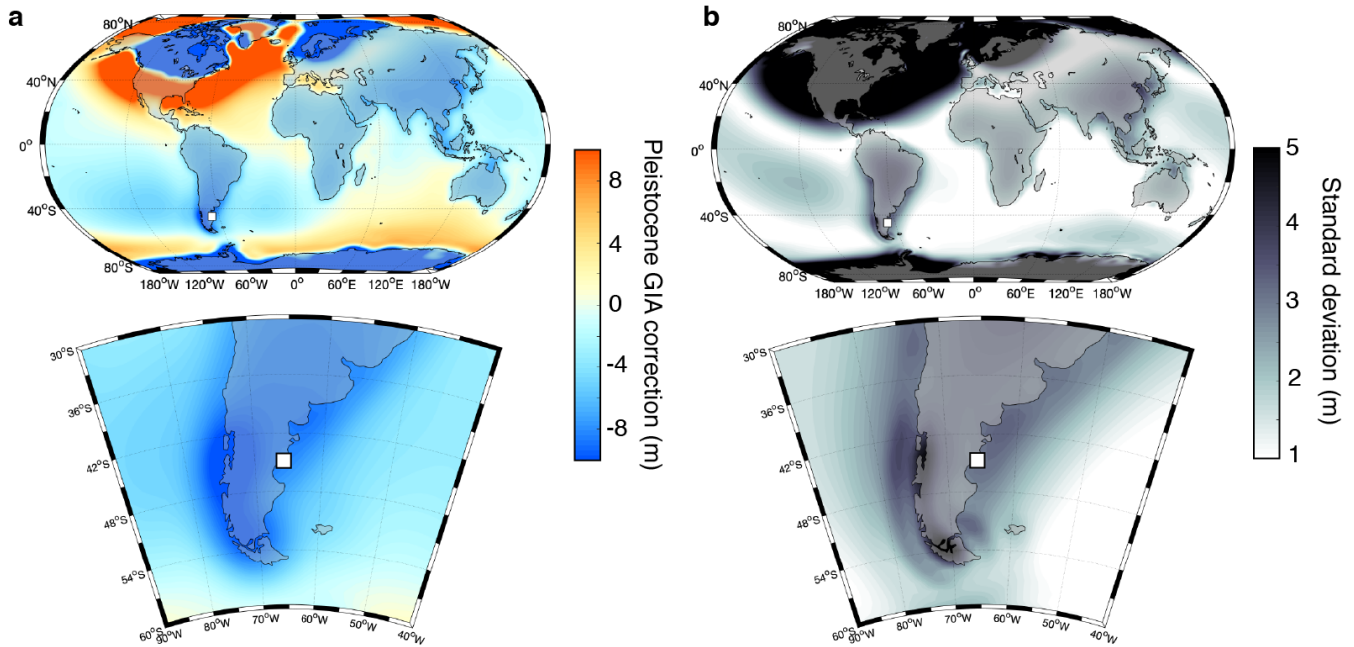


Figure 6: GIA contribution due to ongoing adjustment. The maps show the GIA contribution caused by the incomplete present-day adjustment to the late Pleistocene ice and ocean loading cycles. **a)** Model simulation using a viscosity structure of  $5 \times 10^{20}$  Pa s viscosity in the upper mantle,  $5 \times 10^{21}$  Pa s viscosity in the lower mantle, and an elastic lithospheric thickness of 96 km. **b)** Standard deviation of model predictions obtained using 36 different radial viscosity profiles, including varying the lithospheric thickness. The square in all insets marks the position of Camarones.

524 DATA AVAILABILITY

525 Spreadsheets containing GPS data, GMSL calculations, and  
 526 details on shell preservation and ages are available from  
 527 <https://doi.org/10.5281/zenodo.3929150><sup>40</sup> (CC-BY 4.0 license).  
 528 The GEOIDEAR16 geoid model was created by the Insti-  
 529 tuto Geográfico Nacional (Ministerio de Defensa, Argentina)  
 530 and it was retrieved from the International Service for  
 531 the Geoid <http://www.isgeoid.polimi.it/>. Plate boundaries  
 532 in Figure 1 and Figure 3 were downloaded from GitHub:  
 533 <https://github.com/fraxen/tectonicplates/> (ODC-By license), and  
 534 are derived from data by Peter Bird<sup>48</sup>, Hugo Ahlenius and  
 535 Nordpil. The background shoreline maps in Figure 3A and  
 536 Figure 6 were retrieved from NOAA-NCEI (Global Self-  
 537 consistent Hierarchical High-resolution Shoreline, GSHHS<sup>79</sup>).  
 538 Equation (1) was derived from a StackExchange discus-  
 539 sion ([https://stats.stackexchange.com/questions/25848/how-to-](https://stats.stackexchange.com/questions/25848/how-to-sum-a-standard-deviation)  
 540 [sum-a-standard-deviation](https://stats.stackexchange.com/questions/25848/how-to-sum-a-standard-deviation)). Samples described in this study  
 541 were registered in the System for Earth Sample Registration  
 542 <https://www.geosamples.org/>, and assigned an International Geo-  
 543 Sample number (IGSN). Dynamic topography model outputs  
 544 were obtained from the Gplates portal (<http://portal.gplates.org/>).

545 CODE AVAILABILITY

546 The python scripts used to produce panels b and c of  
 547 Figure 3 and the main panel of Figure 4 are available  
 548 from <https://doi.org/10.5281/zenodo.3689426><sup>80</sup> (MIT license).  
 549 The computer code used to do the sea-level (GIA) cal-

550 culation, written in MATLAB, is available on GitHub  
 551 (<https://github.com/jaustermann/SLcode>).

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## 575 AUTHOR CONTRIBUTIONS

576 AR, MP and SR wrote the MS and supplementary materials,  
 577 including figures. SR elaborated the stratigraphic description  
 578 of the *Roadcut* outcrop. MA provided expertise on the faunal  
 579 composition of the *Roadcut* and *Caprock* outcrops. MRS per-  
 580 formed SIS dating and contributed text on SIS methods and  
 581 results. JA produced GIA estimates, advised on DT and GMSL  
 582 calculations, and contributed to the writing of the paper. PJH  
 583 provided expertise on stratigraphic and geological interpretation  
 584 on the Camarones outcrops. All authors (except JA) participated  
 585 in different phases of the field expeditions to Camarones. IC  
 586 identified the *Caprock* site in the field. MER provided expertise  
 587 on the paleoclimatic implications of the study. All authors re-  
 588 visited the main text and Supplementary Information, and agree  
 589 with its contents.

## 590 COMPETING INTERESTS

591 The authors declare no competing interests

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# HIGHER THAN PRESENT GLOBAL MEAN SEA LEVEL RECORDED BY AN EARLY PLIOCENE INTERTIDAL UNIT IN PATAGONIA (ARGENTINA) - SUPPLEMENTARY INFORMATION -

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## 1 SUPPLEMENTARY NOTE 1: PALEO RELATIVE SEA LEVEL 2 INDICATORS IN PATAGONIA

marine/beach deposits were recognized from present-day coast-  
line inland. 39 40

**Holocene.** Holocene sea level indicators at Camarones mark  
the maximum sea level transgression and a sequence of regres-  
sive beach ridges. Bini et al. (2018)<sup>22</sup> reported precisely mea-  
sured Holocene RSL proxies dated with <sup>14</sup>C, indicating that,  
between ca. 5300 and 7000 cal. yr BP, RSL was 2 to 4 m above  
present sea level (elevations referred to the EGM2008 Geoid). 41 42 43 44 45 46

**Marine Isotopic Stage 5e.** The Last Interglacial is also pre-  
served in the form of relic beach ridges in the Camarones area.  
These were investigated and dated by different authors through-  
out the years<sup>9;12;10;23</sup> (Supplementary Table 1). A recent study  
by Pappalardo et al. (2015)<sup>9</sup> provides more precise measure-  
ments, interpretations and additional dating of the MIS 5e beach  
ridge complex at Camarones. According to these authors<sup>9</sup>, the  
beach ridges at Camarones indicate a MIS 5e paleo RSL at 7.5  
+2/-3.5m above present. 47 48 49 50 51 52 53 54 55

**Marine Isotopic Stage 11.** At one site south of Camarones  
town, articulated shells from (Sample Pa 35) was dated by Schell-  
mann and Radtke (2000)<sup>12</sup> as MIS 9 or older. U-series mollusk  
ages by Pappalardo et al. (2015)<sup>9</sup> confirm the attribution to  
MIS 11. We measured the deposits dated by these authors at  
16.7 ± 0.4m above present sea level. 56 57 58 59 60 61

## SUPPLEMENTARY NOTE 2: DETAILED DESCRIPTION OF *Roadcut* AND *Caprock* UNITS AT CAMARONES

The *Roadcut* section (Supplementary Figure 1) is characterized  
by the bedrock (*Formación Río Chico*) outcropping from the  
road level up to ca.12m above it. The topmost part of the bedrock  
is exposed for a maximum thickness of 1.2m in the western  
part of the outcrop and it is shaped as a flat, gently eastward  
(i.e. seaward) dipping platform. All the overlying units are  
separated from it by a sharp erosional unconformity. Less than  
1 km south of the *Roadcut*, another outcrop shows the same  
geological context. We refer to this as the *Caprock* outcrop 64 65 66 67 68 69 70 71 72

3 The study of paleo shorelines in Patagonia dates back to Charles  
4 Darwin, who was the first to provide an account of the coastal  
5 stratigraphy in the region<sup>1</sup>. Nearly a century later, the Italian ge-  
6 ologist Feruglio reported the first full account of marine terraces  
7 along the Patagonian coast (Chubut and Santa Cruz Provinces)<sup>2</sup>,  
8 that he grouped into six systems. The two uppermost systems  
9 were attributed to the to late Pliocene–early Pleistocene<sup>3</sup> based  
10 on biostratigraphic features and their high elevation (40-50 and  
11 80-95 m asl). Several studies detailed the stratigraphy, elevation  
12 and age of Holocene<sup>4;5</sup>, Pleistocene<sup>6;7;8;9;10;11;12</sup> and Pliocene-  
13 to-Miocene<sup>13;14</sup> marine and coastal deposits. The Tertiary ma-  
14 rine sediments were assigned to Miocene and Pliocene periods  
15 mostly on the basis of biostratigraphy. Several authors worked  
16 to characterize the Marine Miocene of Patagonia<sup>15;16;17</sup> and the  
17 Mio-Pliocene<sup>18</sup>. Concerning the Early Pliocene, a marine de-  
18 posit in Northern Patagonia (Rio Negro Province) yielded a  
19 fission track age of 4.41 Ma<sup>19</sup>, but this age was later considered  
20 inconsistent with biostratigraphic characteristics of the deposits  
21 and thus rejected<sup>20</sup>. Del Río et al. (2013)<sup>14</sup> dated samples of  
22 mollusks from marine deposits in Central and Southern Patag-  
23 onia, few hundreds kilometers south of our study area. The  
24 marine deposits of Cerro Laciár (300 km south of the area in-  
25 vestigated in this study, 170-185m above MSL) yielded ages of  
26 5.10 ± 0.21 Ma, and those of Cañadon Darwin (540 km south of  
27 the area investigated by this study, 65-75m above MSL) yielded  
28 ages of 5.15 ± 0.18 Ma. These two data points represent the  
29 first geochemically constrained evidence of a (Early) Pliocene  
30 transgression in the area.

31 In the coastal area around the Camarones town, the main lithos-  
32 tratigraphic units are a Jurassic volcanic complex (*Complejo*  
33 *Marifil*), and Upper Paleocene sedimentary rocks (*Formación*  
34 *Río Chico*)<sup>21</sup>. According to published geological maps<sup>21</sup>, the  
35 volcanic complex is composed by reddish rhyolites, leucorhyo-  
36 lites and ignimbrites, whereas the Río Chico formation is made  
37 of mudstones, sandstones and conglomerates, often volcanoclas-  
38 tic. Along the same coastal section, fossil beach ridges and

Supplementary Table 1: Ages of beach ridges associated to MIS 5e in the Camarones area.

Location	Author	Sample	Subsample	Age (ka)	Age uncertainty (ka)	Dating technique	
Camarones North IV	Schellmann (1998) <sup>23</sup>	Pa 30	D2412A	117	21	ESR	
			D2635	123	22	ESR	
			K2412B	139	8	ESR	
			D2550	92	9	ESR	
			D2549	99	12	ESR	
Camarones North I	Schellmann (1998) <sup>23</sup>	Pa 47c	D2665	115	9	ESR	
			D2547	117	13	ESR	
			D2546	133	15	ESR	
			D2545	137	18	ESR	
			D2548	144	19	ESR	
Camarones 12km South	Rostami et al., 2000 <sup>10</sup>	3	3-0/1	117	5	U-Series	
			3-0/2	115	9	U-Series	
			3-0/2	110	8	ESR	
			3-0/3	112	13	U-Series	
			3-0/3	114	9	ESR	
Various sites North and south of Camarones	Pappalardo et al., 2015 <sup>9</sup>	WP64A(3)	N/A	121	0.9	U-Series	
			WP65(1)	N/A	130	2.5	U-Series
			WP68(1)	N/A	131	1.1	U-Series
			WP70(B)	N/A	127	1.2	U-Series

(Supplementary Figure 2). This rests on a relative topographic high of the bedrock, which at this location is represented by the volcanic rocks pertaining to the *Complejo Marifil*, capped by a thin sedimentary unit, as thick as 1m maximum, identical to the upper part of the Cp Unit observed in the *Roadcut* section. Each overlying unit is described separately hereafter.

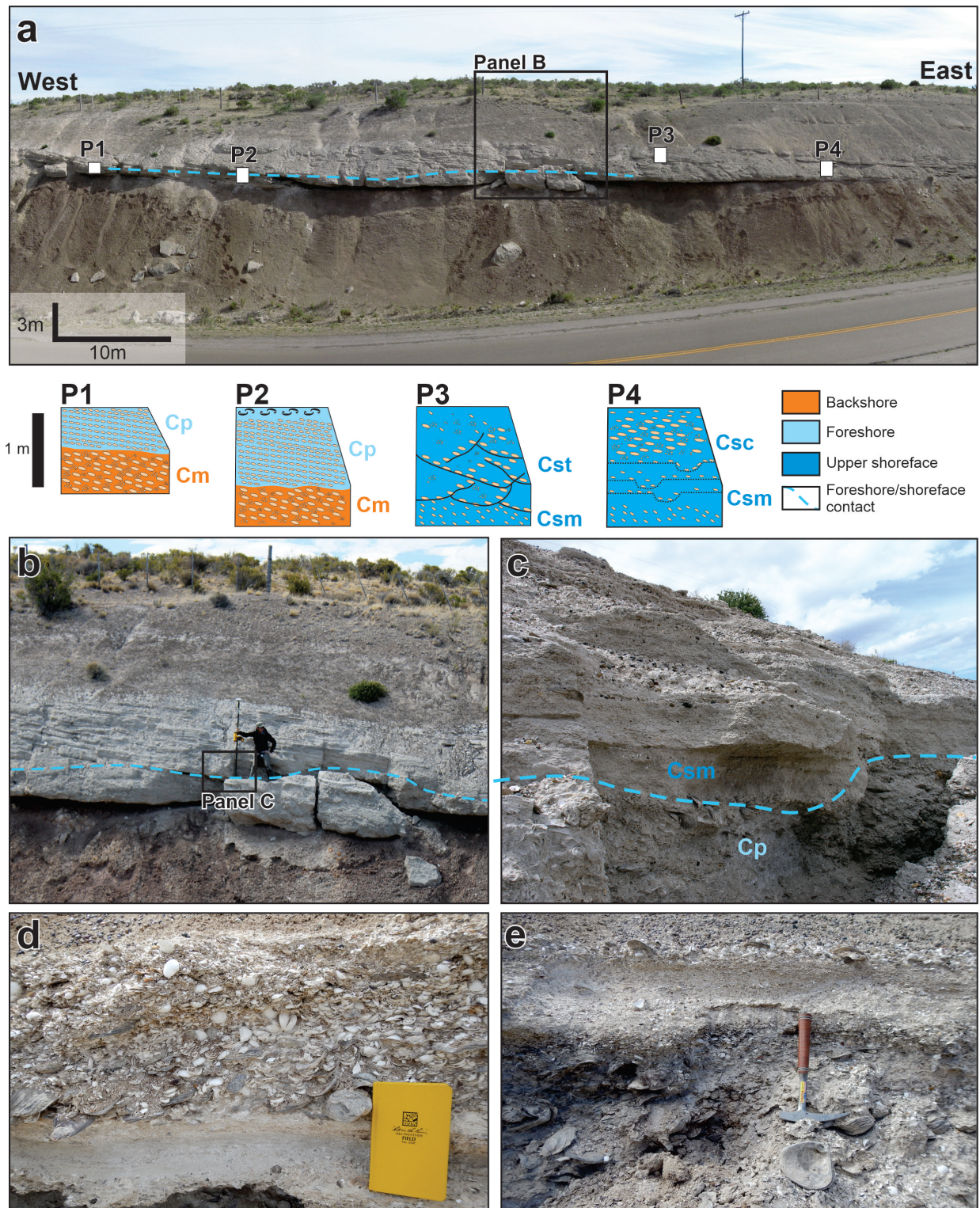
**Unit Cm.** In the western part of the section on top of the bedrock rests a basal unit (Cm). This is represented by a massive, clast-supported conglomerate with coarse rounded pebbles of different rock types. Pebbles have an imbricated, seaward dipping bedding. Faunal content is absent.

**Unit Cp.** Eastward, a finer unit (Cp) overlaps the previous one and, towards the East, unconformably rests on the bedrock. Unit Cp is composed of well-cemented fine conglomerates with rounded pebbles, mostly unbroken shells and abundant sandy matrix, displaying a low-angle planar cross-stratification. The uppermost part of Cp contains a dense faunal assemblage in the form of a shellbed, with different shell types (Supplementary Table 2) mostly intact and sometimes with paired valves (articulated), but not in living position. Only the fragmentation of Pectinids is relevant, which is expected even with minimal transport as they have a fragile shell structure. The shells in Unit Cp are characterized by different stages of preservation, depending mostly on the shell type. Big oysters (*Crassostrea* sp.), up to 15 cm in size, are frequent, mostly oriented concordant with strata dip and strike. They underwent partial dissolution, especially of their outer part, which explains the high degree of cementation of this unit. The faunal assemblage of Unit Cp is analogous to that of the Pleistocene terraces towards the coast, with notable exceptions. The absence of *Tegula atra* (cold gastropod species), together with the occurrence of bivalves of warm/warm-temperate affinity (*C. patagonica*, *D. patagonica*, *F. vilardebona*, *M. cf. isabelleana*), is the main difference relative to the Pleistocene deposits. Cp has a maximum thickness of 1m in the western part of the outcrop (stratigraphic column B, Supplementary Figure 1b).

**Unit Cs.** East of this point, the Cp unit becomes progressively thinner, and is overlapped by a finer unit (Cs) of matrix-supported sandy conglomerates. The contact between Cp and Cs is planar and displays a lateral continuity up to the midpoint of the section, East of which Cs lays directly on the bedrock. The basal part of Cs is massive (Csm) with no sedimentary structures, whereas its uppermost part, separated from Csm by a gradational contact, displays trough cross-stratification (Cst) and, more eastward, longitudinal channels (Csc).

Overall, this section represents the product of sedimentation due to a transgressive event on top of a marine platform carved in the volcanic bedrock. The sequence is fining (and thus deepening) upward. The similarities of the basal unit (Cm) with modern storm berms in the area suggest that it was formed in a backshore environment. We interpret Unit Cp as the product of sedimentation in a foreshore environment. The bedding of marine shells within this unit testifies that they have been reworked within the surf zone where sediments from upper offshore and shoreface are floated towards the beachface and from there are driven back by rip currents, producing an isorientation of single shells parallel to the current direction. The topmost Units (Csm, Cst and Csc) can be interpreted as mainly developed in middle to upper shoreface. The sedimentary structures within these units can be interpreted as the product of longitudinal currents caused by coastal drift.





Supplementary Figure 1: **a**) General view of the *Roadcut* section. Below the photo, four stratigraphic profiles (P1-P4) detailing the relationships between the main sedimentary facies. **Cm**: Conglomerate, massive; **Cp**: Conglomerate with low angle planar cross-stratification; **Csm**: Sandy conglomerate, massive; **Cst**: Sandy conglomerate with trough cross-stratification; **Csc**: Sandy conglomerate with longitudinal channels. **b**) Location where the elevation of unit **Cp** has been measured (the points listed in the main paper are located near the person standing on the outcrop). **c**) Detail of the contact between **Cp** (foreshore) and **Csm** (upper foreshore). **d**) and **e**) Details of the bivalve-rich horizon sampled for Sr isotopes dating.



Supplementary Table 2: Faunal assemblage in the marine deposits outcropping at the *Roadcut* section at Camarones. Most of the species recognized by Feruglio<sup>3;2</sup> and assigned to the highest terrace system (that was tentatively dated to Pliocene) were detected in the Cp Unit of the *Roadcut* section (This work). Nomenclature of the taxa has been updated as some generic or specific names do not agree with those used by Feruglio. \* indicates species with warm/warm-temperate affinity.

BIVALVIA	Feruglio <sup>3;2</sup>	This work
<i>Aulacomya atra</i> (Molina, 1782)	X	X
<i>Aequipecten tehuelchus</i> (d'Orbigny, 1842)	X	
<i>Zygochlamys patagonica</i> (King, 1832)	X	X
<i>Pectinidae</i> indet.		X
<i>Ostrea equestris</i> Say, 1834		X
<i>Ostrea puelchana</i> d'Orbigny, 1842	X	
<i>Ostrea tehuelcha</i> Feruglio	X	X
<i>Ostrea cf. tehuelcha</i> Feruglio		X
<i>Ostrea sp.</i>		X
<i>Ostrea tehuelcha</i> d'Orbigny*		X
<i>Diplodonta patagonica</i> (d'Orbigny, 1842)*		X
<i>Felaniella vilardeboana</i> (d'Orbigny, 1846)*	X	
<i>Diplodonta sp.</i>	X	
<i>Abra sp.</i>		X
<i>Mactra cf. isabellena</i> d'Orbigny, 1846*	X	X
<i>Mactra cf. patagonica</i> d'Orbigny		X
<i>Eurhomalea exalbida</i> (Dilwyn, 1817)		X
<i>Ameghinomya antiqua</i> (King, 1832)		X
<i>Pitar rostratus</i> (Philippi, 1844)	X	X
<i>Corbula patagonica</i> d'Orbigny 1845	X	X
<b>GASTROPODA</b>		
<i>Epitonium georgettinum</i> (Kiener, 1838)	X	X
<i>Trophon varians</i> (d'Orbigny, 1841)	X	X
<i>Trophon geversianus</i> (Pallas, 1774)	X	X
<i>Trophon laciniatus</i> (Martin)	X	X
<i>Adelomelon ancilla</i> (Lightfoot, 1786)	X	X
<i>Adelomelon ferussaci</i> (Donovan, 1824)		
<i>Adelomelon sp.</i>		X
<i>Odontocymbiola magellanica</i> (Gmelin, 1791)	X	X
<i>Olivancillaria auricularia</i> (Lamarck, 1811)	X	X
<i>Olivancillaria cf. carcellesi</i> Klappenbach, 1965		
<i>Buccinanops deformis</i> (P.P. King, 1832)	X	X
<i>Buccinanops cochlidium</i> (Dilwyn, 1817)	X	
<i>Buccinanops sp.</i>	X	X
<i>Siphonaria lessonii</i> Blainville, 1827		
<i>Volutidae</i> indet.	X	X

134 SUPPLEMENTARY NOTE 3: SIS AGE DETAILS.

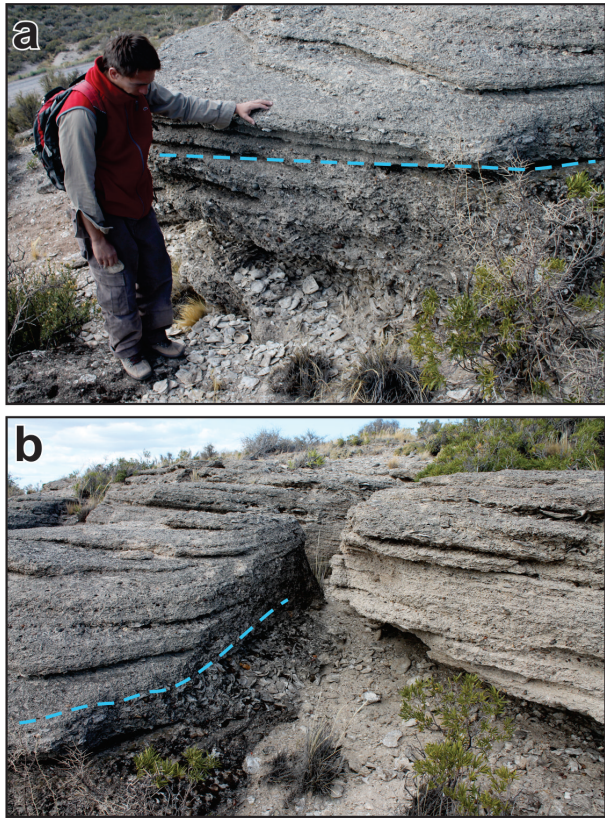
135 Details on samples and SIS analyses performed are shown here-  
 136 after, in Supplementary Figures 3 to 7. Full SIS age results are  
 137 reported in Supplementary Table 4.

138 Initial field selection criteria involved visual assessment based on  
 139 shell thickness, coloration, and diagnostic features of preservation  
 140 of original layers, and irregularities in structure<sup>14;24;25</sup> (Sup-  
 141 plementary Figure 4. In the laboratory, samples were slabbed,  
 142 polished and imaged using an optical microscope with CCD  
 143 camera for further inspection. and an ASPEX Express scanning  
 144 electron microscope (SEM). This preliminary screening method  
 145 helps identify locations of alteration that can be correlated with  
 146 the <sup>87</sup>Sr/<sup>86</sup>Sr leach variations and establishes the overall integrity  
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of preservation in each shell. A preservation scoring system was  
 established as outlined in Hearty et al. (2020)<sup>26</sup>, with optical  
 and SEM images assigned scores from "1" (no visible alteration)  
 to "3" (significant alteration observable) based on screening  
 criteria above (Supplementary Table 3).

Shells were micro sampled in the best-preserved regions, pri-  
 marily through physical micro-drilling using a handheld drill  
 and the subsequent powder was homogenized by hand (except  
 in the case ACC1-A pt.2, where the shell was carefully frag-  
 mented to sand-sized grains and the Sr split was picked under a  
 microscope). Minor and trace elements were measured for three  
 samples on a Thermo iCap Q quadrupole ICP-MS at LDEO.  
 Samples were prepared and analyzed following methods similar  
 to Yu et al<sup>27</sup>. Briefly, ca.250 µg of powder was diluted to 75 ppm

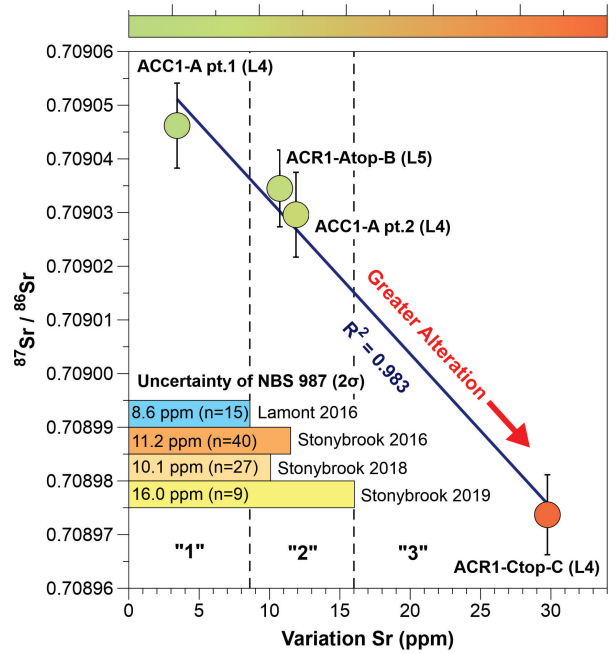
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Supplementary Figure 2: **a)** and **b)** Contact between the unit Cp (lower) and Cs (higher) at the Caprock site.

along with the full dissolution splits (Supplementary Table 4 and Supplementary Figure 5). Sr was isolated and dried down using typical separation techniques with Eichon exchange resin. Following separation, 1% of Sr was removed and measured on a mass spectrometer to determine concentration. A drop of 0.05 N Phosphoric acid was added and between 150-375 ng of Sr (for each measurement) was loaded onto degassed Rhenium filaments using tantalum chloride loader.

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Supplementary Figure 3: Variation of  $^{87}\text{Sr}/^{86}\text{Sr}$  within a leach set (as ppm) vs. the inner leach  $^{87}\text{Sr}/^{86}\text{Sr}$  of that shell. Sr leach variation scores are shown by dashed black line; these scores are based on the range of ppm error from seasonal long-term averages of the standard NBS 987. Green circles have low variation within leach sets (usually better preservation) and display younger SIS ages than shell ACC1-Ctop-C (red point) with high variation. This sample is excluded from the average shoreline SIS age based on high Sr variation and other screening criteria (Supplementary Table 3). Long-term uncertainty of standard NBS987 for each year/lab plotted on lower left as ppm variation.

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Ca (to negate matrix effects), and run alongside calibration standards covering the range of elements concentrations. The results were normalized to the in-house reference standards QC-Calcite and planktonic standard V03, the latter of which has long-term ( $n = 86$ )  $2\sigma$  errors of: Sr/Ca = 1.4%, Mg/Ca = 1.3%, U/Ca = 3.0%, Ba/Ca = 1.8%, Mn/Ca = 1.2%, Al/Ca = 15.8%, Fe/Ca = 2.1% and Na/Ca = 1.3%. A Holocene bivalve (*Tridacna gigas* standard JCT-1) was run alongside the samples for comparison. An elemental scoring system was established for Mg, Mn, and Fe (Supplementary Table 3), elements thought to be indicative of diagenesis<sup>28;29;26</sup>. Scores ranged from "1" (unaltered) to "3" (altered) based on comparison to a set of Holocene corals and bivalves (for a better overview of screening methods, see Sandstrom et al. (2020)<sup>30</sup>). Sample splits were taken for Sr isotope analysis (ca. 50 mg for leach fraction, and ca. 10 mg for full dissolution).

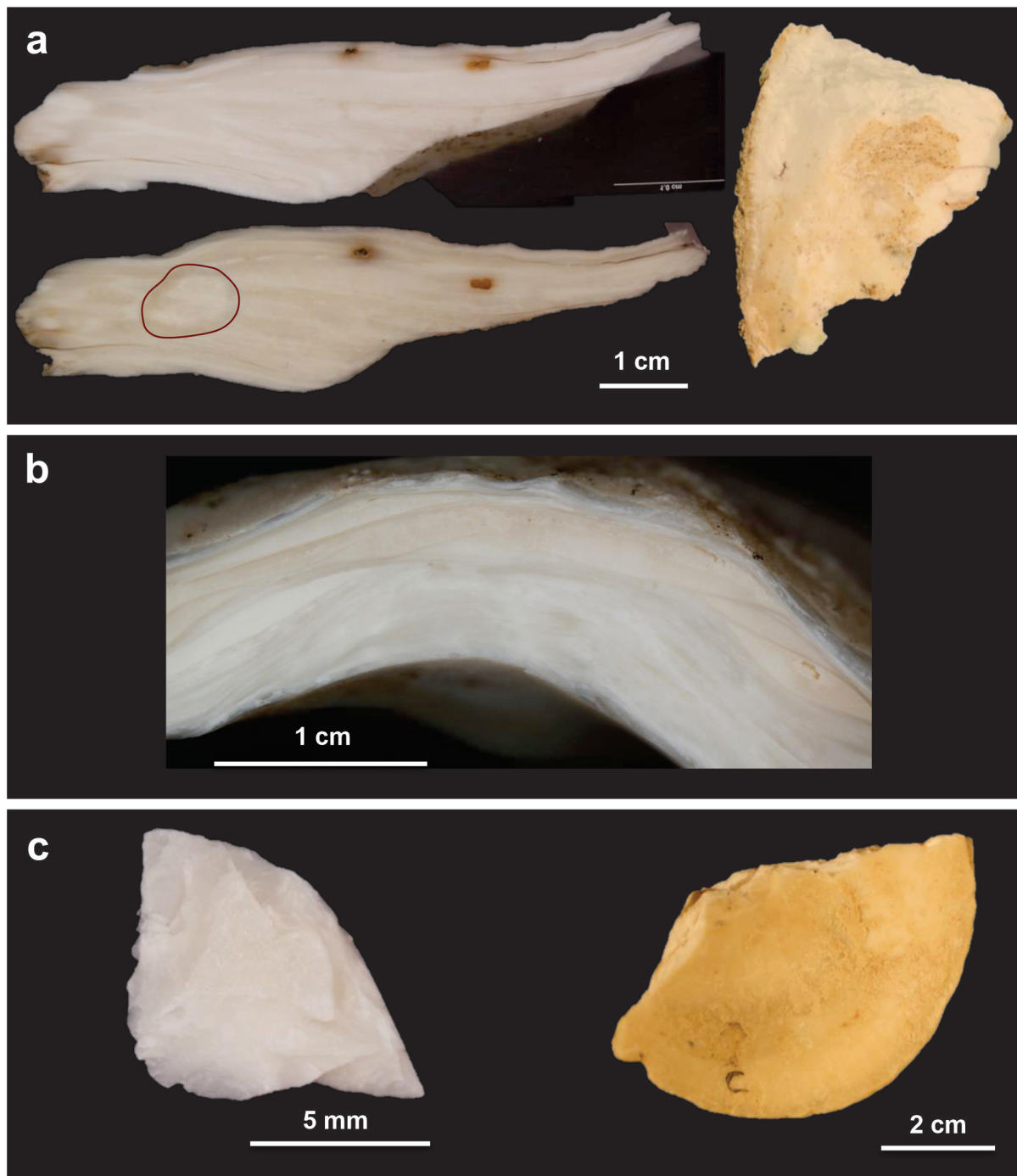
Leaching procedures are modified from Bailey et al<sup>31</sup> (see Hearty et al., 2020<sup>26</sup>), and involve weak (ca. 0.1M) Acetic acid leaches on the powdered/fragmented shell, designed to preferentially dissolve the more loosely bound secondary  $^{87}\text{Sr}/^{86}\text{Sr}$  material before attacking the primary Sr. Typically, four to five leaches were performed per sample, each dissolving ca. 8-12 mg of carbonate (representing 16-25% of the total sample by weight). An additional split (10mg) for each sample was also fully dissolved, as an indication of the average bulk  $^{87}\text{Sr}/^{86}\text{Sr}$ . Typically, this resulted in 1400-4200 ng of Sr per leach. Only the initial (L1) and inner leaches (defined here as the dissolved 50-80% portions of each sample [i.e. L4 and L5]) were measured,

$^{87}\text{Sr}/^{86}\text{Sr}$  ratios were measured on either an IsotopX Phoenix62 Thermal Ionization Mass Spectrometer (TIMS) at Stonybrook University, or a Finnigan Triton Plus TIMS at Lamont-Doherty Earth Observatory (LDEO). Measurements at Stonybrook were conducted in a very similar manner to Gothmann et al<sup>29</sup>, with a dynamic routine measuring masses 84, 85, 86, 87, and 88 over 160 cycles for each sample. Filaments were slowly ramped up to 2.8 - 3.2 A and a temperature of ca. 1400 degrees Celsius, to achieve a beam intensity between 3-5 V on mass 88. TIMS measurements at LDEO were carried out using a static routine for 200-400 cycles with similar parameters to Stonybrook. The Sr isotope external standard NBS SRM 987 long-term instrument accuracy at the two labs was computed every season and ranged between 8.6 - 16 ppm ( $2\sigma$ ) (Supplementary Figure 3). At Stonybrook: NBS 987 =  $0.710245 \pm 0.000008$  ( $2\sigma$ ; 2016,  $n = 40$ );  $0.709241 \pm 0.000007$  ( $2\sigma$ ; 2018,  $n = 27$ ), and

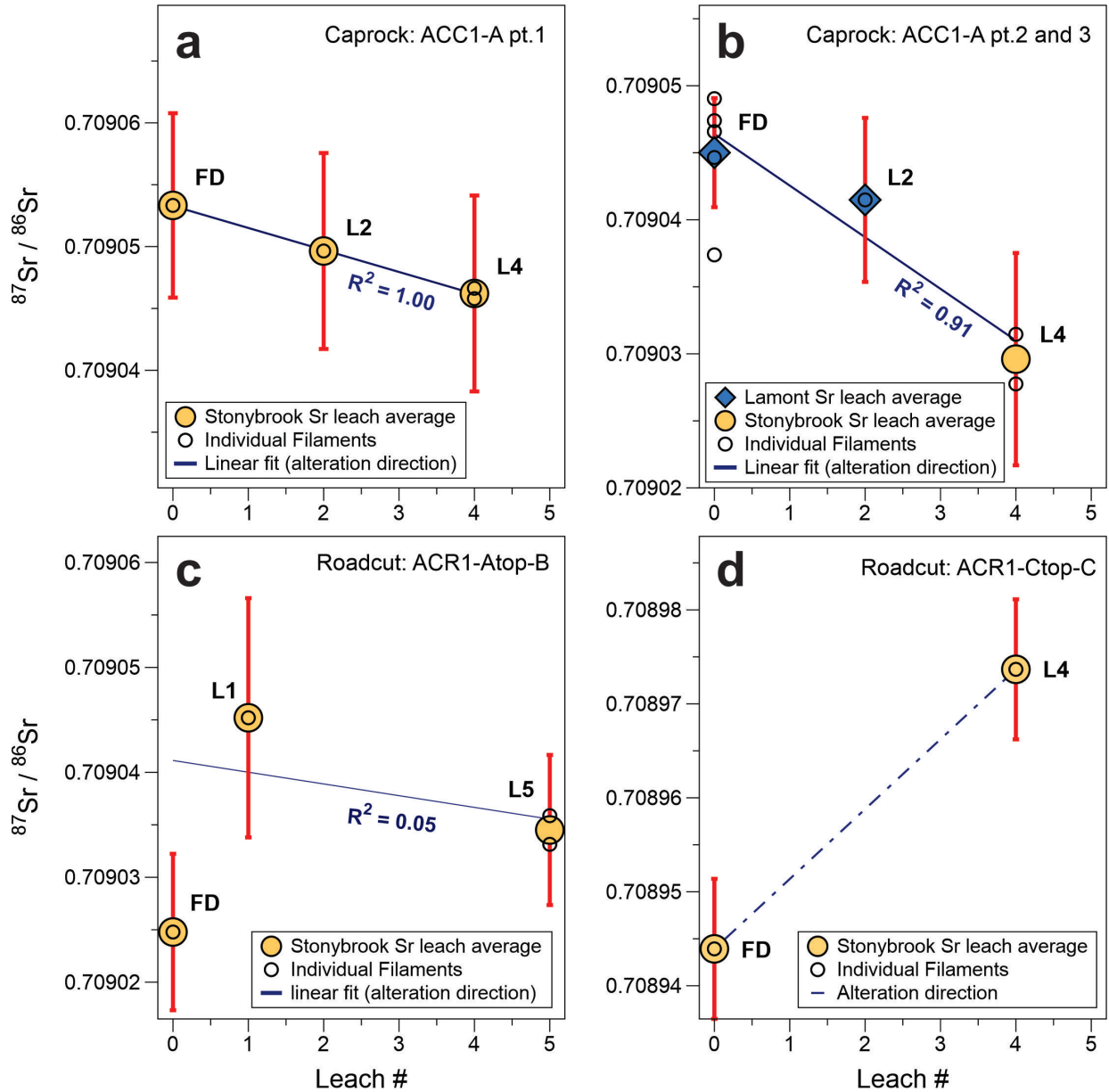
214  $0.710244 \pm 0.000011$  ( $2\sigma$ ; 2019, n =9) and at LDEO: NBS 987  
215  $= 0.710238 \pm 0.000006$  ( $2\sigma$ ; 2016, n = 15). Sr isotopes were all  
216 corrected for mass fractionation based on an  $^{86}\text{Sr}/^{88}\text{Sr}$  ratio of  
217 0.1194 and normalized to the accepted NBS 987 standard value  
218  $= 0.709248$ . Sr isotope stratigraphy ages were calculated using  
219 the LOWESS version 5 curve from McArthur et al.<sup>28</sup>.

220 Sr isotope variations were calculated as ppm within leach sets (as  
221 the total range of  $^{87}\text{Sr}/^{86}\text{Sr}$  values within a leach set, multiplied  
222 by a million to read as ppm) for each sample (Supplementary  
223 Table 3). A scoring system from "1" to "3" was established based  
224 on long-term uncertainties of NBS 987, where samples with Sr  
225 isotope variations  $< 8.6\text{ppm} = 1$ , between 8.6-16 ppm = 2, and  $>$   
226 16 ppm = 3 (see Supplementary Figure 3, Supplementary Table  
227 3 and Sandstrom et al., 2020<sup>30</sup>).

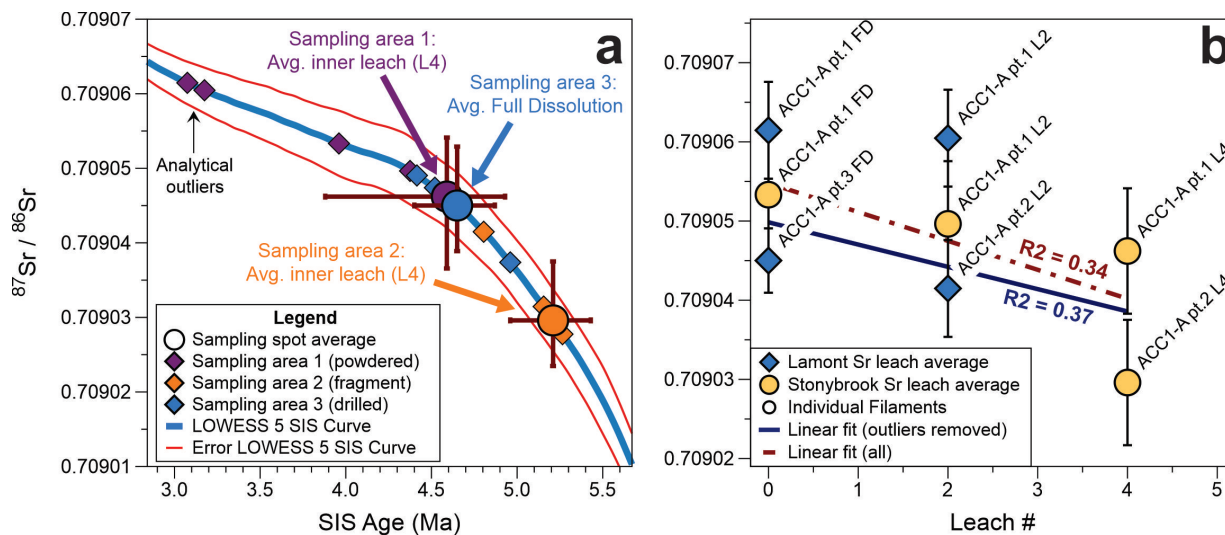




Supplementary Figure 4: Sample images. **a)** Oyster shell ACC1-A, showing slabbed x-section (top left), part 3 drill location (bottom left), and original shell fragment (right). **b)** Sample ACR1-Atop-B slabbed x-section. **c)** Shell ACR1-Ctop-C showing fragment used in Sr isotope dating (left) and partial shell collected from the field (right).

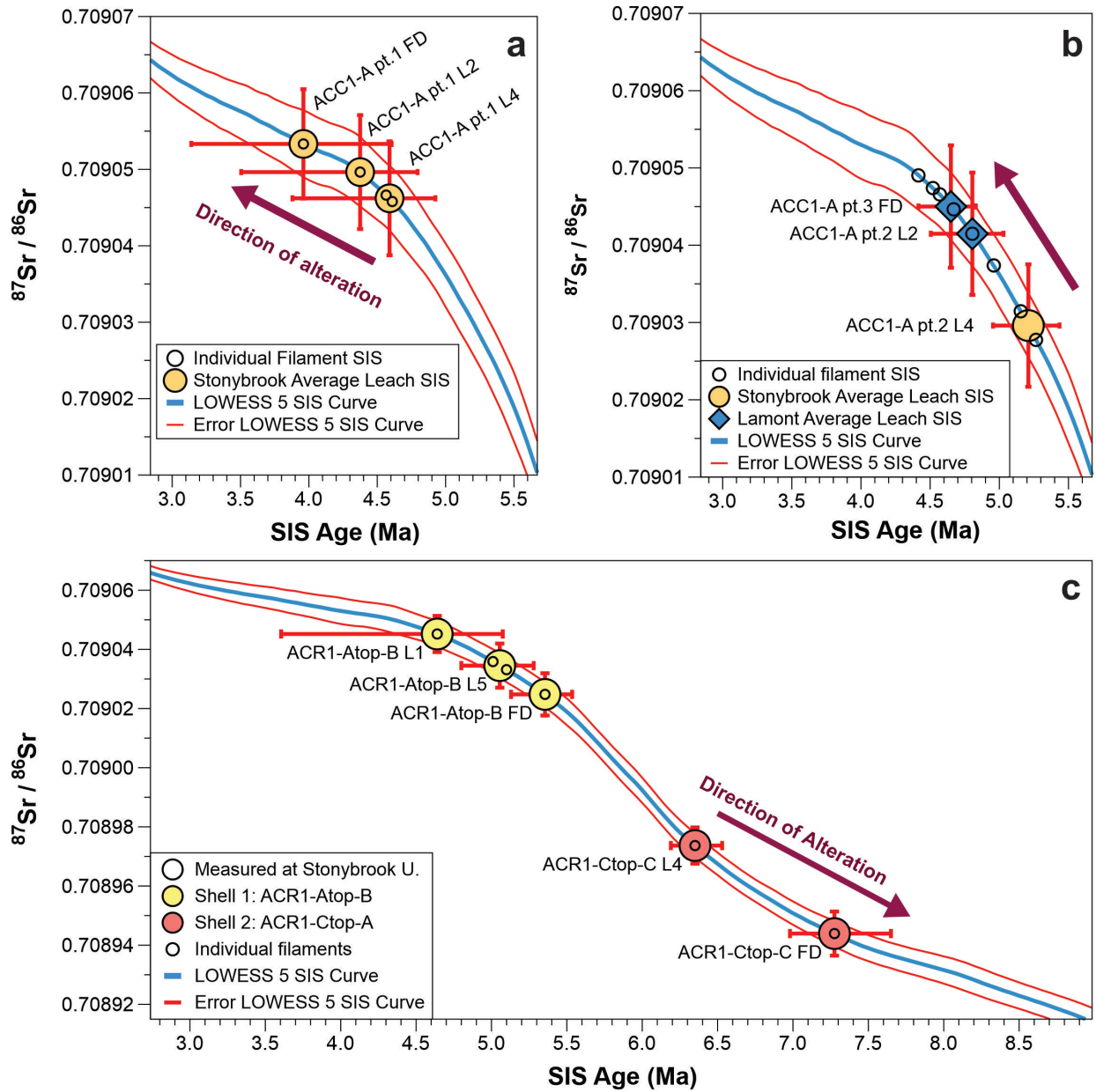


Supplementary Figure 5: Sr isotope leach set data for individual sample areas. Red error bars represent  $2\sigma$  external uncertainty of NBS987 (except for full dissolution ACC1-A pt.3 FD, which is  $2\sigma$  standard error of the mean). Linear regression lines (blue) indicate direction of alteration, with altering fluids causing the *Caprock* oyster (**a** and **b**) to appear slightly younger (more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$ ), and the *Roadcut* samples (**c** and **d**) to appear older (alteration fluid with low  $^{87}\text{Sr}/^{86}\text{Sr}$ ). **a** and **b**) Leach set data for sample ACC1-A parts 1 and 2 showing less radioactive  $^{87}\text{Sr}/^{86}\text{Sr}$  (increased SIS age) with better preservation (L4). **c**) The inner leach lies between the initial leach and full dissolution, overlapping both within uncertainty. The leach set suggests alteration fluids cause ages to appear younger, while the full dissolution indicates the opposite. However, based upon the excellent preservation index score, the inner leach (L5) most likely reflects the original Sr isotopic ratio. **d**) The trend of significantly increasing  $^{87}\text{Sr}/^{86}\text{Sr}$  of the inner leach compared to the full dissolution indicates post-depositional alteration in this sample.



Supplementary Figure 6: **a)** Oyster shell ACC1-A (*Caprock*) detailed Sr isotopes and SIS age assignments from three different sampling locations. **b)** Leach Sr values and different TIMS machines (yellow = stonybrook, blue = Lamont). Sample splits ACC-1A pt.1 FD and L2 measured at LDEO appear to be outliers for reasons unknown [possibly turret related? as this was the first turret run?]. Repeated measurements on these same splits at SBU yielded more reliable  $^{87}\text{Sr}/^{86}\text{Sr}$  values that more closely align with other measurements from different sections of this shell, both at SBU and LDEO. Linear regression was computed for all leach averages (red) and also excluding the two outliers (blue) with similar results. There is a slight trend toward less radiogenic values for the better preserved inner leach measurements.





Supplementary Figure 7: Same data as Supplementary Figure 5. Sr isotope leach set data for individual sample areas, plotted against Lowess5 SIS curve. Red error bars represent  $2\sigma$  external uncertainty of NBS987 (except for full dissolution ACC1-A pt.3 FD, which is  $2\sigma$  standard error of the mean). Purple arrows indicate direction of alteration, with altering fluids causing the *Caprock* oyster (panels a and b) to appear younger (more radioactive  $^{87}\text{Sr}/^{86}\text{Sr}$ ), and the *Roadcut* samples (panel c) to appear older (in the case of ACR1-Ctop-C), and possibly younger in the case of ACR1-Atop-A, but no distinct trend can be assigned.

Supplementary Table 3: Elemental and diagenetic screening results of oyster samples. BDL = below detection limit. n.a. = not measured. <sup>a</sup> Jct-1 is the Holocene Tridactna standard<sup>32</sup>. <sup>b</sup> Samples used in elemental score average. <sup>c</sup> Full dissolution used for variation calculation, as L1 was not measured. <sup>d</sup> Scoring criteria outlined in Sandstrom et al. (2020)<sup>30</sup>. <sup>e</sup> See Supp. methods and Hearty et al. (2020)<sup>26</sup>. <sup>f</sup> Leach variation scores: "1" = <8.6ppm; "2" = 8.6 to 16 ppm; "3" = >16 ppm. <sup>g</sup> Samples with preservation index scores  $\geq$  "2" are considered altered and excluded.

Sample code	ACC1-A pt.1	ACR1-Atop-B	ACR1-Ctop-C	Jct-1 <sup>a</sup>
SESAR IGSN ID	IEMRS006J	IEMRS006L	IEMRS006P	N/A
Description	Caprock - Oyster	Roadcut - Oyster	Roadcut - Oyster	Holocene Tridactna
Na/Ca (mmol/mol)	8.1	9.5	11.7	19.9
Mg/Ca (mmol/mol) <sup>b</sup>	2.9	3.3	4.9	1.2
Al/Ca ( $\mu$ mol/mol)	4.6	BDL	20.4	17.2
Mn/Ca ( $\mu$ mol/mol) <sup>b</sup>	78.8	16.2	1484.7	2.6
Fe/Ca ( $\mu$ mol/mol) <sup>b</sup>	1.7	BDL	144.5	BDL
Sr/Ca (mmol/mol)	0.58	0.85	1.50	1.84
Ba/Ca ( $\mu$ mol/mol)	2.2	2.2	5.9	1.6
U/Ca (nmol/mol)	89.2	107.5	155.2	33.3
number of splits	1	2	1	3
<sup>87</sup> Sr/ <sup>86</sup> Sr leach variation (ppm)	11.88	10.73	29.75 <sup>c</sup>	n.a.
Elemental score (1-3) <sup>d</sup>	1.67	1.67	2.33	1.00
SEM score (1-3) <sup>e</sup>	2	n.d.	2	n.a.
Optical score (1-3) <sup>e</sup>	2	1	2	1
<sup>87</sup> Sr/ <sup>87</sup> Sr variation score (1-3) <sup>f</sup>	2	2	3	n.a.
<b>Preservation Index Score<sup>g</sup> (average of all scores: 1-3)</b>	<b>1.92</b>	<b>1.56</b>	<b>2.33</b>	<b>1.00</b>

Supplementary Table 4:  $^{87}\text{Sr}/^{86}\text{Sr}$  results and Sr isotope stratigraphy ages for Caprock and Roadcut outcrops. <sup>a</sup> Inner leach Sr isotope values for sample; <sup>b</sup> Sample leaches excluded based on analytical or diagenetic criteria; <sup>c</sup> Sample excluded from shoreline age based on significant diagenesis (see Table S3); <sup>d</sup> Uncertainty based on  $2\sigma$ SEM; <sup>e</sup> Sample variation is calculated as the difference between the initial leach [or full dissolution] and last leach, multiplied by one million (ppm); <sup>f</sup> Average of inner leaches on samples that passed screening criteria: ACC1-A pts. 1 and 2, and ACR1-Atop-B; <sup>g</sup> Uncertainty based on combined analytical [ $2\sigma$ SEM] and SIS curve [LOWESS 5] errors.

Sample Name	TIMS Lab	Leach ID	Nb. filaments	$^{87}\text{Sr}/^{86}\text{Sr}$ (measured)	$^{87}\text{Sr}/^{86}\text{Sr}$ (normalized to NBS97)	$2\sigma$ external uncertainty	Mean SIS Age (Ma)	Maximum SIS Age (Ma)	Minimum SIS Age (Ma)	Uncorrected SIS Age (Ma)
<b>Average <math>^{87}\text{Sr}/^{86}\text{Sr}</math> by Leach</b>										
<b>Caprock</b>										
ACC1-A pt.1 FD	SBU	FD	1	0.7090465	0.7090533	0.0000075	3.960	4.605	3.140	4.58
ACC1-A pt.1 L2	SBU	L2	1	0.7090462	0.7090496	0.0000079	4.375	4.795	3.505	4.59
ACC1-A pt.1 L4 <sup>a</sup>	SBU	L4	2	0.7090427	0.7090462	0.0000079	4.590	4.925	3.880	4.76
ACC1-A pt.1 FD <sup>b</sup>	LDEO	FD	1	0.7090509	0.7090615	0.0000061	3.075	3.745	2.635	4.27
ACC1-A pt.1 L2 <sup>b</sup>	LDEO	L2	1	0.7090499	0.7090605	0.0000061	3.175	3.855	2.695	4.36
ACC1-A pt.2 L2	LDEO	L2	1	0.7090309	0.7090415	0.0000061	4.805	5.030	4.505	5.17
ACC1-A pt.2 L4 <sup>a</sup>	SBU	L4	2	0.7090261	0.7090296	0.0000079	5.210	5.435	4.955	5.32
ACC1-A pt.3 FD	LDEO	FD	5	0.7090345	0.7090344	0.0000041 <sup>d</sup>	4.650	4.415	4.830	5.055
<b>Roadcut</b>										
ACR1-Atop-B FD	SBU	FD	1	0.7090180	0.7090248	0.0000075	5.355	5.535	5.130	5.52
ACR1-Atop-B L1	SBU	L1	1	0.7090409	0.7090452	0.0000114	4.640	5.075	3.605	4.83
ACR1-Atop-B L5 <sup>a</sup>	SBU	L5	2	0.7090279	0.7090345	0.0000072	5.055	5.280	4.800	5.27
ACR1-Ctop-C FD	SBU	FD	1	0.7089371	0.7089439	0.0000075	7.275	7.650	6.980	7.62
ACR1-Ctop-C L4 <sup>a,c</sup>	SBU	L4	1	0.7089668	0.7089737	0.0000075	6.350	6.530	6.190	6.52
<b>Average Shoreline SIS Age</b>										
Average of screened inner leaches <sup>f</sup>	SBU	L4, L5	6	0.7090322	0.7090368	0.0000064 <sup>d</sup>	4.98	5.225 <sup>e</sup>	4.685 <sup>e</sup>	5.13



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