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**Article:**

Garrett, Ed, Melnick, Daniel, Dura, Tina et al. (2020) Holocene relative sea-level change along the tectonically active Chilean coast. *Quaternary Science Reviews*. 106281. ISSN: 0277-3791

<https://doi.org/10.1016/j.quascirev.2020.106281>

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1 **Holocene relative sea-level change along the tectonically active Chilean coast**

2

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17 **Abstract**

18

19 We present a comprehensive relative sea-level (RSL) database for north, central, and south-central  
20 Chile (18.5°S – 43.6°S) using a consistent, systematic, and internationally comparable approach.  
21 Despite its latitudinal extent, this coastline has received little rigorous or systematic attention and  
22 details of its RSL history remain largely unexplored. To address this knowledge gap, we re-evaluate  
23 the geological context and age of previously published sea-level indicators, providing 78 index points  
24 and 84 marine or terrestrial limiting points spanning from 11 ka to the present day. Many data  
25 points were originally collected for research in other fields and have not previously been examined  
26 for the information they provide on sea-level change. Additionally, we describe new sea-level data  
27 from four sites located between the Gulf of Arauco and Valdivia. By compiling RSL histories for 11  
28 different regions, we summarise current knowledge of Chilean RSL. These histories indicate mid  
29 Holocene sea levels above present in all regions, but at highly contrasting elevations from ~30 m to  
30 < 5 m. We compare the spatiotemporal distribution of sea-level data points with a suite of glacial  
31 isostatic adjustment models and place first-order constraints on the influence of tectonic processes  
32 over  $10^3$  to  $10^4$  year timescales. While seven regions indicate uplift rates  $< 1 \text{ m ka}^{-1}$ , the remaining  
33 regions may experience substantially higher rates. In addition to enabling discussion of the factors  
34 driving sea-level change, our compilation provides a resource to assist attempts to understand the  
35 distribution of archaeological, palaeoclimatic, and palaeoseismic evidence in the coastal zone and  
36 highlights directions for future sea-level research in Chile.

37

38 **Keywords:** Holocene; Sea-level changes; South America; Data analysis; Sea-level database; Glacial  
39 isostatic adjustment; Tectonics

## 40 **1. Introduction**

41

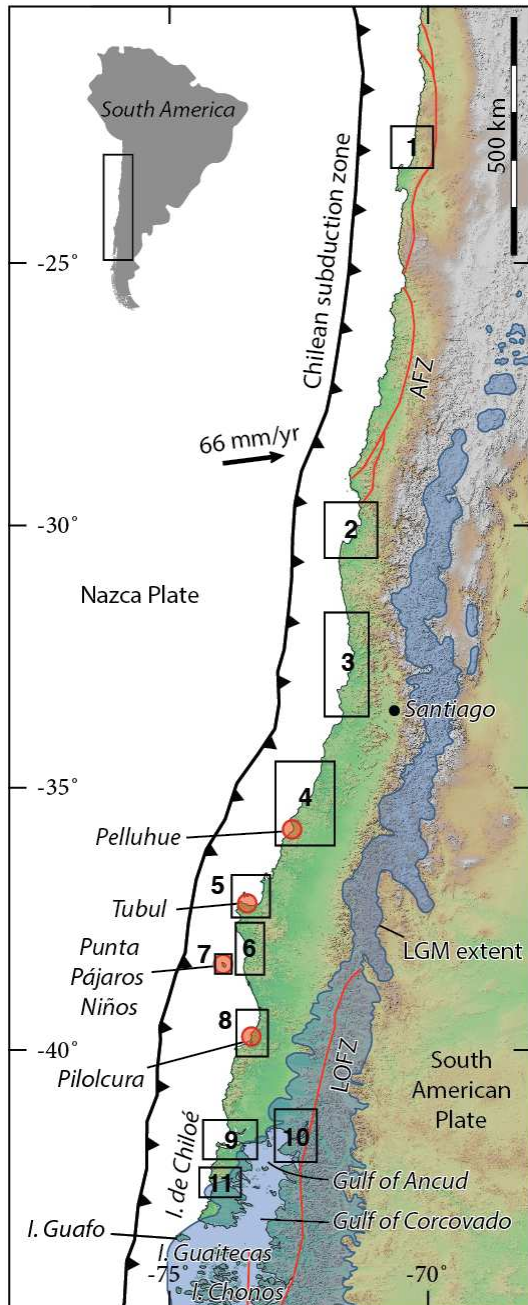
42 Eustatic, isostatic, tectonic, and local factors drive changes in Holocene relative sea level (RSL)  
43 (Farrell and Clark, 1976; Pirazzoli, 1991). Compilations of regional databases of Holocene index  
44 points, which constrain the age and elevation of past sea level, advance our understanding of the  
45 mechanisms and relative contributions of these driving factors in time and space. They highlight  
46 regional differences, provide constraints on glacial isostatic adjustment models and serve as a  
47 baseline for assessing future sea-level changes (Shennan et al., 2012, 2018; Engelhart et al., 2015;  
48 Khan et al., 2015; Vacchi et al., 2016). Despite extending through more than 37° of latitude, the  
49 Chilean coastline has not previously received rigorous or systematic attention, and details of its RSL  
50 history remain poorly understood. While previous coastal zone investigations have focussed on  
51 archaeology (e.g. Pino and Navarro, 2005; May et al., 2015), palaeoseismology (e.g. Cisternas et al.,  
52 2005; 2017; Dura et al., 2015; 2017; Garrett et al., 2015), tectonics (e.g. Stefer et al., 2010; Melnick  
53 et al., 2019), and palaeoclimate (e.g. Villa-Martínez and Villagrán, 1997; Frugone-Álvarez et al.,  
54 2017), only a limited number of studies have specifically addressed Holocene sea-level evolution  
55 (e.g. Leonard and Wehmiller, 1991; Atwater et al., 1992; Nelson and Manley, 1992). The limited  
56 scope of previous Holocene sea-level data compilations (Isla, 1989; Isla et al., 2012) and the  
57 potential to increase the temporal and spatial resolution of RSL histories in Chile using data from  
58 other fields of study necessitates a reappraisal of RSL data from this region.

59

60 For the first time, this paper compiles a comprehensive sea-level database for north, central, and  
61 south-central Chile (18.5°S – 43.6°S; Fig. 1) using a consistent, systematic, and internationally  
62 comparable approach (Hijma et al., 2015; Khan et al., 2019). Our database incorporates a range of  
63 different types of sea-level indicators, including tidal marsh sediments, beach ridges, marine  
64 deposits and freshwater sediments, dated using radiocarbon and luminescence approaches. We re-  
65 evaluate the geological context and age of previously published sea-level data, providing 78 index

66 points (reconstructions of the elevation of RSL at a specific time and location) and 84 limiting points  
67 (which place minimum or maximum constraints on the elevation of RSL) that span the period from  
68 11000 years ago to the present day. We also present a new index point and three new limiting  
69 points from four sites between 35.8°S and 43.6°S. By compiling and comparing the RSL history for 11  
70 different regions, we seek to summarise current knowledge of Chilean RSL, highlight directions for  
71 future sea-level research, and provide a resource to assist research into archaeological,  
72 palaeoclimatic, and palaeoseismic records in the coastal zone.

73



74

75 Figure 1: Location of the sea-level data points assessed in this study, grouped into regions (black  
 76 boxes). Red circles indicate new sites reported here for the first time. AFZ: Atacama fault zone, LOFZ:  
 77 Liquiñe-Ofqui fault zone, LGM: Last Glacial Maximum extent of the Patagonian ice sheet (blue  
 78 shading, following Ehlers et al., 2011).

79

80 **2. Study area**

81

82 We restrict our review of published sea-level data to the coastline between Arica (18.5°S) and Isla  
83 Guafo (43.6°S), a straight-line distance of almost 3000 km (Fig. 1). This coastline possesses a  
84 consistent tectonic setting, characterised by subduction of the Nazca Plate beneath South America.  
85 Despite the continuity in tectonic setting between Isla Guafo and the triple junction, close to the  
86 Taitao Peninsula (46.5°S), we do not discuss sites in this region due to the complex tidal regimes  
87 associated with the fjord setting. Due to its remote nature, few published Holocene sea-level records  
88 currently exist between Isla Guafo and the Taitao Peninsula; however, we note that Reyes et al.  
89 (2018) discuss coastal archaeological sites from the Guaitecas (43.9°S) and Chonos (45.3°S)  
90 archipelagos and provide minimum ages for the marine terraces on which these sites are located.  
91 While increased tidal ranges also influence sites bordering the gulfs of Ancud and Corcovado on the  
92 western side of Isla de Chiloé (Fig. 1), we include the small number of data points available from this  
93 area due to their proximity to sites facing the open ocean. Sea-level data are available from the  
94 southernmost regions of Chile (e.g. Porter et al., 1984; Rabassa et al., 1986; Gordillo et al., 1992;  
95 McCulloch and Davies, 2001; Bentley and McCulloch, 2005); however, the unique glacial history of  
96 this region, the different tectonic setting, and the importance of local postglacial faulting mean they  
97 deserve a separate analysis and lie beyond the scope of this paper.

98

## 99 2.1 Tectonic setting

100

101 In contrast to the largely stable locations on which the majority of previous sea-level databases  
102 focus, Chilean RSL change is influenced by significant tectonic activity associated with the subduction  
103 of the Nazca Plate. Plate convergence induces both folding and faulting within the overriding South  
104 American Plate and deformation associated with megathrust earthquakes on the subduction  
105 interface (Barrientos, 2007). Since the start of the 20<sup>th</sup> century, at least eight Chilean earthquakes  
106 have exceeded magnitude ( $M_w$ ) 8, including the largest event since the inception of modern seismic  
107 recording, the 1960 CE  $M_w$  9.5 Valdivia earthquake and the 2010 CE  $M_w$  8.8 Maule earthquake.

108 Decimetre- to metre-scale coseismic land-surface deformation accompanies these great  
109 earthquakes, resulting in abrupt relative sea-level changes over hundreds to thousands of kilometres  
110 of coastline (Plafker and Savage, 1970; Farías et al., 2010; Dura et al., 2017). Major interplate  
111 earthquakes (magnitude 7 – 8), occurring along the margin at a rate of ~50 per century, may also  
112 result in decimetre-scale land-surface deformation along tens of kilometres of coastline (Xu, 2017;  
113 Garrett et al., 2019). The sea-level history of tectonically active regions reflects these vertical  
114 coseismic changes and also the slower postseismic and interseismic deformation associated with  
115 strain accumulation between earthquakes.

116

117 In addition to deformation associated with slip on the subduction interface, concurrent splay faulting  
118 within the upper plate may contribute to abrupt local decimetre- to metre-scale changes in relative  
119 sea level (Melnick et al., 2012; Jara-Muñoz et al., 2017). Upper plate faults may also rupture quasi-  
120 independently of the megathrust. Two major fault systems lie parallel to the convergent margin (Fig.  
121 1): the Atacama fault zone of the northern coastal cordillera and the Liquiñe-Ofqui fault zone, a  
122 dextral intra-arc transform fault of the main cordillera of south-central and southern Chile  
123 (Cembrano *et al.*, 1996; Rosenau et al., 2006; Rehak *et al.*, 2008). Instrumentally recorded  
124 earthquakes associated with these structures have not exceeded  $M_w$  6.2 or produced evident  
125 coseismic coastal deformation (Barrientos, 2007; Lange et al., 2008).

126

## 127 2.2 Glacial history

128

129 At the maximum extent of the last glacial period, the Patagonian ice sheet extended along the Andes  
130 from ~38°S to ~56°S (Caldenius, 1932; Denton et al., 1999; Hulton et al., 2002; Glasser et al., 2008).  
131 The distribution of moraines and outwash plains suggests a piedmont lobe extended from the  
132 mainland and overran the southern half of Isla de Chiloé (Fig. 1), while northern Isla de Chiloé and  
133 the coastline of the mainland to the north remained ice free (Heusser and Flint, 1977; García, 2012).

134 In the south, the Patagonian ice sheet covered the Chilean mainland and outlying islands, with a  
135 modelled volume equivalent to 1.2 m of global sea level (Hulton et al., 2002). Patagonian piedmont  
136 glaciers rapidly retreated after 17500 – 17150 a BP (Denton et al., 1999; McCulloch et al., 2000), with  
137 the ice sheet losing over 80 % of its Last Glacial Maximum volume within 2000 years (Hulton et al.,  
138 2002). Relative warmth characterised the period from 13500 to 4000 a BP (Heusser and Streeter,  
139 1980; Rabassa and Clapperton, 1990), before late Holocene cooling and increases in precipitation  
140 resulted in Neoglacial icefield expansion (Glasser et al., 2004; Bertrand et al., 2012). Three or four  
141 periods of glacier advance ensued, including during the Little Ice Age (Mercer, 1970; Aniya, 1996;  
142 Araneda et al., 2007). Subsequent retreat has reduced the combined contemporary extent of the  
143 North and South Patagonian icefields (47°S – 51°S) and the smaller, discontinuous icefields of the  
144 Cordillera Darwin (54°S – 55°S) to 17,000 km<sup>2</sup> (Rignot et al., 2003). The contribution of the two larger  
145 icefields to global sea-level rise has averaged  $0.0052 \pm 0.0008$  mm yr<sup>-1</sup> since 1870 (Glasser et al.,  
146 2011). This figure has increased to  $0.067 \pm 0.004$  mm yr<sup>-1</sup> between 2000 and 2012 (Willis et al.,  
147 2012).

148

### 149 **3. Database methodology**

150

151 Through a series of International Geological Correlation Programme and International Geoscience  
152 Programme (IGCP) projects (numbers 61, 200, 274, 367, 437, 495, 588 and 639), the sea-level  
153 community has derived and implemented standardised and globally applicable approaches to sea-  
154 level reconstruction. Integral to this endeavour, sea-level databases synthesise data from different  
155 studies to reconstruct regional relative sea-level histories (Bloom, 1977; Pirazzoli, 1991; Shennan et  
156 al., 2002; Khan et al., 2019). Databases contain sea-level index points, reconstructions of the  
157 elevation of RSL at a specific time and location, and limiting points, which place minimum or  
158 maximum constraints on the elevation of RSL (marine and terrestrial limiting points respectively).  
159 Our database compiles sea-level indicators from the literature, interpreting data from a wide range

160 of sources as either index or limiting points. For each data point, we quantify sources of vertical and  
161 temporal uncertainty following the approach set out by Hijma et al. (2015).

162

163 We subdivide our database into 11 regions based primarily on the proximity and clustering of sites.  
164 We assign sites to regions minimising the distances between sites within a region and maximising  
165 the distances between regions. The mean distance between a site and the centroid of its respective  
166 region is 22 km, with the centroids of adjacent regions generally separated by > 100 km. Despite the  
167 shorter distance between sites on Isla Mocha (region 7) and the adjacent mainland (region 6), we  
168 separate these regions based on their different tectonic histories (Nelson and Manley, 1992).  
169 Further subdivision to a finer spatial scale is currently unwarranted due to the low total number of  
170 sites and data points.

171

### 172 3.1 Data sources

173

174 Few studies have explicitly focussed on the history of RSL change in Chile; consequently, our data are  
175 principally derived from coastal investigations with different foci. In central and south-central Chile,  
176 we reanalyse sea-level indicators resulting from investigations into the occurrence of Holocene  
177 subduction zone earthquakes and tsunamis (e.g. Atwater et al., 1992; Cisternas et al., 2005; Nelson  
178 et al., 2009; Ely et al., 2014; Dura et al., 2015; Garrett et al., 2015; Hong et al., 2017). We also obtain  
179 sea-level data from datasets previously used to constrain tectonic uplift rates (Stefer et al., 2010;  
180 Melnick et al., 2019), identify human occupation of the coastal zone (Pino and Navarro, 2005), and  
181 reconstruct palaeoclimatic change (Villa-Martínez and Villagrán, 1997; Frugone-Álvarez et al., 2017).  
182 In northern and north-central Chile, we incorporate sea-level data from studies that have sought to  
183 constrain the age and elevation of mid-Holocene RSL (e.g. Ota and Paskoff, 1993; May et al., 2013;  
184 Hart et al., 2017). Similar RSL-focussed investigations in central and south-central Chile are less  
185 numerous (e.g. Nelson and Manley, 1992; Isla et al., 2012). Previous compilations included just three

186 (Isla, 1989) and ~30 (Isla et al., 2012) sea-level data points from our regions of interest. The use of a  
 187 wider range of data sources provides a substantially expanded compilation and, for the first time,  
 188 our compilation incorporates comprehensive data quality control and error assessment.

189

### 190 3.2 Indicative meaning

191

192 To serve as an index point, a sea-level indicator must have a defined relationship with tidal levels, or  
 193 *indicative meaning* (van de Plassche, 1986; Shennan, 2015). The indicative meaning consists of the  
 194 *reference water level*, the elevation at which the indicator occurs with respect to contemporaneous  
 195 tidal levels, and the *indicative range*, the span of elevations at which the indicator might be found.  
 196 We define indicative ranges for seven different types of index points and define reference water  
 197 levels as the mid-points of the indicative ranges (Table 1). We obtain tidal datums for each location,  
 198 modelling mean lower low water (MLLW), mean low water (MLW), mean tide level (MTL), mean high  
 199 water (MHW), mean higher high water (MHHW), and highest astronomical tide (HAT) using the  
 200 TPX08-ATLAS global model of ocean tides (Egbert and Erofeeva, 2010). We scale the modelled tidal  
 201 amplitude for each location following analysis of the differences between the tidal model and data  
 202 from 21 permanent tide gauge stations (supplementary information S1).

203

204 Table 1: Definition of the indicative meaning of the different sea-level indicators assessed in this  
 205 study. The reference water level is defined as the midpoint of the indicative range. HAT: Highest  
 206 Astronomical Tide, MHHW: Mean Higher High Water; MHW: Mean High Water, MTL: Mean Tide  
 207 Level, MLLW: Mean Lower Low Water.

Sample type	Evidence	Reference water level	Indicative range
<i>Index points</i>			
High tidal marsh environment	Organic sediments. High marsh plant macrofossils. Diatom or foraminiferal assemblages dominated by high marsh taxa.	$(MHW+HAT)/2$	MHW – HAT
Low tidal marsh/upper tidal flat environment	Organic or clastic sediments. Low marsh plant macrofossils. Diatom or foraminiferal assemblages dominated by low marsh/upper tidal flat taxa.	$(MTL+MHW)/2$	MTL – MHW

Undifferentiated tidal marsh environment	Organic sediments. Microfossil and macrofossil assemblages dominated by tidal marsh taxa that do not meet the requirements to be classified as strictly low or high tidal marsh.	$(MTL+HAT)/2$	$MTL - HAT$
Specified tidal marsh environment	Estimate of RWL and IR from quantitative approach e.g. microfossil transfer function.	Uniquely defined	Uniquely defined
Undifferentiated intertidal environment	Clastic sediments. Microfossils a mix of marine, brackish and freshwater species. May be supported by geomorphic setting.	$(MLLW+HAT)/2$	$MLLW - HAT$
Beach ridges	Sand- or gravel-rich shore-parallel ridges with a gently dipping or horizontal landward surface and a more steeply dipping seaward face.	$HAT+1.5\text{ m}$	$HAT - HAT+3\text{m}$
Undifferentiated beach environment	Sand- or gravel-rich sediments, may contain shells or shell fragments. Includes beachface, berm and beach ridge environments.	$(MLLW - HAT+3\text{m})/2$	$MLLW - HAT+3\text{m}$
<b>Limiting points</b>			
Marine sediments	Clastic sediments containing marine diatom or foraminiferal assemblages or in-situ marine shells.	MTL	Below MTL
	Clastic sediments without (or without reported) identifiable macrofossils or microfossils.	MHHW	Below MHHW
	Coquina containing transported intertidal or subtidal molluscs but lacking morphology indicative of supratidal beach ridge deposition.	HAT	Below HAT
	Undifferentiated clastic sediments where neither beach ridge nor subtidal deposition can be discounted	$HAT+3\text{m}$	Below $HAT+3\text{m}$
Terrestrial sediments	Organic soil or peat with freshwater microfossil assemblages or in-situ freshwater plant macrofossils (e.g. tree stumps).	HAT	Above HAT
	Organic soil or peat without (or without reported) identifiable intertidal macrofossils or microfossils.	MTL	Above MTL
	Organic or clastic sediments with sedimentary structures, faunal or floral assemblages, or geochemical composition typical of lacustrine sedimentation.	HAT	Above HAT
	Clastic sediments exhibiting sedimentary structures typical of aeolian dunes.	HAT	Above HAT
	Clastic sediments exhibiting sedimentary structures typical of colluvial wedges.	HAT	Above HAT

208

209 Tidal marsh environments provide the majority of our index points. We separate these into low  
210 marsh, high marsh, undifferentiated marsh, and specified marsh environments based on macro- and  
211 microfossil evidence (Atwater et al., 1992; Nelson et al., 2009; Garrett et al., 2015). Specified tidal  
212 marsh refers to samples with indicative meanings provided in the original study by the statistical  
213 comparison of modern and fossil microfossil assemblages, usually diatoms, using transfer functions  
214 (e.g. Garrett et al., 2015). The second largest group of index points come from beach ridges and  
215 undifferentiated beach environments. The relationship between the elevation of a beach ridge crest

216 and coeval sea level is complex, with elevation reflecting wave run-up and other sediment transport  
217 mechanisms (Orford et al., 1991; Otvos, 2000; Tamura, 2012). Tamura (2012) recommends that  
218 sandy beach ridges are not used as sea-level indicators as the uncertainties involved are frequently  
219 too large in comparison with reconstructed sea-level changes since the mid Holocene. As we are not  
220 seeking to identify small-scale sea-level changes, we choose to incorporate sandy beach ridges and  
221 account for uncertainties using appropriately cautious indicative ranges. Furthermore, the presence  
222 of low elevation modern ridges and the occurrence of multiple fossil ridges at low elevations  
223 indicates Chilean beach ridges form within a few metres of contemporaneous sea level (Nelson and  
224 Manley, 1992; Bookhagen et al., 2006). On the Atlantic coast of Patagonia, Schellmann and Radtke  
225 (2010) suggest that beach ridge crests lie between 2 and 3 m above the highest tide level on exposed  
226 shorelines and down to 1 m or less above the highest tides in wave-protected areas. In this work, we  
227 conservatively consider beach ridge crests to lie between HAT and 3 m above HAT (Table 1). Where  
228 sediments are described by the original authors as “beach deposits” or similar, we extend the  
229 indicative range described above for beach ridges to include the intertidal zone (i.e. between MLLW  
230 and HAT + 3m). A similar approach was recently used by Vacchi et al. (2018) in eastern Canada.

231

232 Terrestrial and marine limiting points each have a reference water level, but as their precise  
233 relationship with contemporaneous sea level is unknown, their indicative ranges are simply open-  
234 ended windows above or below the reference water level (Table 1). Marine limiting points include  
235 clastic sediments containing in situ marine macro- or microfossils, coquinas (deposits largely  
236 consisting of reworked shells), and clastic sediments without (or without reported) fossils. Terrestrial  
237 limiting points include freshwater marshes, lake sediments, and aeolian dunes. We use above MTL  
238 as a conservative indicative range, unless unequivocal evidence (e.g. in situ tree roots) warrants the  
239 use of HAT as the reference water level (Table 1).

240

241 3.3 Quantifying vertical uncertainties

242

243 We account for errors in the vertical position of each sea-level indicator, considering uncertainties in  
244 the sample depth and the absolute elevation of the top of the core, pit or exposure. Where these  
245 uncertainties are not explicitly stated by the original authors, we estimate appropriate values  
246 following Hijma et al. (2015). Where elevations are related to “mean sea level” (including datums of  
247 uncertain meaning such as “sea level”, “modern sea level”) or other tidal levels, and lack further  
248 details of how they were derived, we define the corresponding tidal uncertainty as  $\pm 0.5$  m, in  
249 keeping with the magnitude of uncertainties proposed by Hijma et al. (2015) for elevations derived  
250 from vegetation zones, digital elevation models, or using water depth measurements. Where sample  
251 elevations are relative to tidal levels measured using a portable tide gauge, with measurements over  
252 hours or days, we estimate the corresponding uncertainty as  $\pm 0.07$  m following Wesson et al.  
253 (2014). In the absence of local conversions from a reference geoid to mean sea level, where  
254 elevations are given with respect to the EGM96 geoid, we do not account for differences between  
255 this model and MSL. We do, however, include a vertical error of  $\pm 0.20$  m to reflect the uncertainty  
256 of this conversion (or lack thereof), reflecting the magnitude of the offsets identified for the Gulf of  
257 Arauco by González-Acuña (2012). We note that the future application of geoid undulation models  
258 may change the elevation of a small number of index and limiting points.

259

260 To account for disparities between the tidal model—which does not incorporate atmospheric  
261 effects—and actual tides, we include a further vertical uncertainty associated with modelling each  
262 reference water level based on a comparison of model predictions and data from 21 permanent tide  
263 gauges (supplementary information S1). This uncertainty is calculated as a percentage of the  
264 modelled reference water level and is site and sample-type specific, ranging from  $<0.01$  m to 0.27 m.

265

266 3.4 Accounting for tectonics, compaction and tidal range changes

267

268 For sites within the rupture zone of the 2010 Maule earthquake, where elevations were determined  
269 before 2010, we adjust for coseismic deformation using estimates of uplift or subsidence, with  
270 corresponding errors, from published field data (Farías et al., 2010; Melnick et al., 2012). Due to a  
271 lack of data, we do not adjust for postseismic deformation following the 2010 earthquake. Similarly,  
272 for sites outside the 2010 rupture area, we do not account for changes in RSL caused by interseismic  
273 deformation or other processes occurring between the timing of data collection and the present  
274 day. We do not correct for millennial-scale tectonic motions before presenting regional sea-level  
275 histories; rather, we choose to discuss reconstructed relative sea-level changes with respect to  
276 driving factors including tectonics.

277

278 The majority of Chilean index and limiting points come from intercalated rather than basal settings  
279 and may be influenced by compaction. Intense seismic shaking could potentially exacerbate this  
280 phenomenon. Sediment compaction after deposition lowers intercalated sedimentary sea-level  
281 indicators, but does not influence basal data points (Horton and Shennan, 2009; Brain et al., 2012).  
282 Noting a lack of work on compaction in South American marshes and the scarcity of information on  
283 the depth to consolidated strata for many sea-level indicators in the database, we do not attempt to  
284 apply a correction for this factor.

285

286 Due to the predominantly linear and open configuration of the Chilean coast, we anticipate that  
287 latitudinal variations in tidal range are likely to have been consistent over the Holocene. Sites  
288 fringing the semi-enclosed gulfs on the eastern side of Isla de Chiloé are more likely to have  
289 experienced changes in tidal range; however, with the small number of data points from this region  
290 and without further information available on palaeotidal ranges, we do not consider this process in  
291 the current compilation.

292

293 3.5 Chronological control

294

295 Radiocarbon and luminescence approaches provide ages for each of the sea-level indicators. Where  
296 publications use radiocarbon dating, we recalibrate all ages using OxCal v.4.2 (Bronk Ramsey, 2009)  
297 and the latest calibration curves: ShCal13 (Hogg et al., 2013), Marine13 (Reimer et al., 2013), and  
298 Bomb13: southern hemisphere zone (Hua et al., 2013). An offset from the global marine reservoir  
299 ( $\Delta R$ ) must be applied where radiocarbon dates relate to marine samples; however, the Chilean  
300 coastline is poorly represented in the global marine reservoir database (<http://calib.org/marine/>).  
301 Two samples from Valparaíso (33°S) provide contrasting offsets of  $61 \pm 50$  years (Ingram and  
302 Southon, 1996) and  $313 \pm 76$  years (Taylor and Berger, 1967). To reflect this uncertainty, we use the  
303 weighted average of these samples,  $137 \pm 164$  years, as the offset for all locations south of 28.5°S.  
304 Towards the northern limit of the region discussed here, Taylor and Berger (1967) report an offset of  
305  $175 \pm 34$  years from Antofagasta (24°S). Ortlieb et al. (2011) report temporally variable  $\Delta R$  values  
306 from between 14°S and 24°S. We employ their mid to late Holocene mean value of  $226 \pm 98$  years as  
307 the offset for the single site included in our database that lies north of 28.5°S.

308

### 309 3.6 Data visualisation

310

311 On figures summarising the age and elevation of sea-level data points, we plot sea-level index points  
312 as rectangles, with the height proportional to the vertical uncertainty in RSL and the width  
313 proportional to the  $2\sigma$  age range. Following Hijma et al. (2015), we plot terrestrial limiting dates as  
314 green T-shaped symbols and marine limiting dates as blue  $\perp$ -shaped symbols. An arrowhead at the  
315 end of the vertical line points towards RSL lying below (for T-shaped terrestrial limiting points) or  
316 above (for  $\perp$ -shaped marine limiting points) the horizontal line, which sits at the extreme limit of the  
317 uncertainty range. The length of the vertical line reflects the total vertical uncertainty. We note that  
318 some studies have inverted the use of these symbols (Vacchi et al., 2016; Khan et al., 2017; García-

319 Artola et al., 2018), although not the colours, and care must consequently be taken to ensure that  
320 the intended meaning is fully understood.

321

### 322 3.7 Modelling glacial isostatic adjustment and tectonic uplift

323

324 To investigate the processes driving RSL change, we compare sea-level data with glacial isostatic  
325 adjustment (GIA) models. A GIA model requires two inputs: information about past global ice sheet  
326 change (the ‘ice model’) and information about the rheological properties of the solid Earth (the  
327 ‘Earth model’). For the purposes of this study, we assume Earth structure varies only radially,  
328 enabling us to define a series of ‘one-dimensional’ Earth models that differ in terms of the values  
329 assumed for lithospheric thickness and upper/lower mantle viscosity. For each of the 11 regions, we  
330 predict RSL at the centre of each region at 1 ka intervals using two ice models, ICE-5G (Peltier, 2004)  
331 and ICE-6G (Peltier et al., 2015). Each ice model is combined with 12 one-dimensional Earth models  
332 that encompass a realistic range of rheologies for the subduction zone. We use lithospheric  
333 thicknesses of 71, 96 and 120 km and upper mantle viscosities of  $5 \times 10^{19}$  Pa s,  $8 \times 10^{19}$  Pa s,  $1 \times 10^{20}$   
334 Pa s, and  $2 \times 10^{20}$  Pa s, with a lower mantle viscosity of  $10^{22}$  Pa s. Our upper mantle viscosities are  
335 lower than those typically used in passive margin settings (e.g. Shennan et al., 2018; Vacchi et al.,  
336 2016) and in previous studies of coastal palaeoseismic evidence (Dura et al., 2016). As such, they  
337 more closely reflect rheologies inferred at seismic-cycle timescales in Chile (Khazaradze et al., 2002;  
338 Lorenzo-Martin et al., 2006; Li et al., 2018) and other subduction zones (e.g. Wiseman et al., 2015;  
339 Freed et al., 2017). Studies of crustal rebound following recent ice loss from the Patagonian Icefields  
340 similarly suggest low upper mantle viscosities (Lange et al., 2014; Richter et al., 2016).

341

342 To assess the possible role and rates of millennial-scale tectonic uplift, we apply a range of linear  
343 corrections to the RSL data to improve the fit with the GIA model predictions in each region. To  
344 allow for shorter-term variability resulting from centennial-scale earthquake deformation cycles, we

345 include a  $\pm 1$  m envelope around the model predictions. The magnitude of this envelope provides a  
346 conservative assessment of centennial cycles, reflecting the upper bound of vertical deformation  
347 recorded at coastal sites during 20<sup>th</sup> and 21<sup>st</sup> century great earthquakes (Plafker and Savage, 1970;  
348 Fariás et al., 2010; Klein et al., 2017). We accept all corrections that result in index points (including  
349 error terms) overlapping the suite of model predictions, terrestrial limiting points sitting within or  
350 above the predictions, and marine limiting points lying within or below the predictions.

351

#### 352 **4. New sea-level data**

353

354 In addition to compiling and standardising sea-level data from the literature (section 5), we present  
355 four new sea-level data points from hitherto unstudied sites.

356

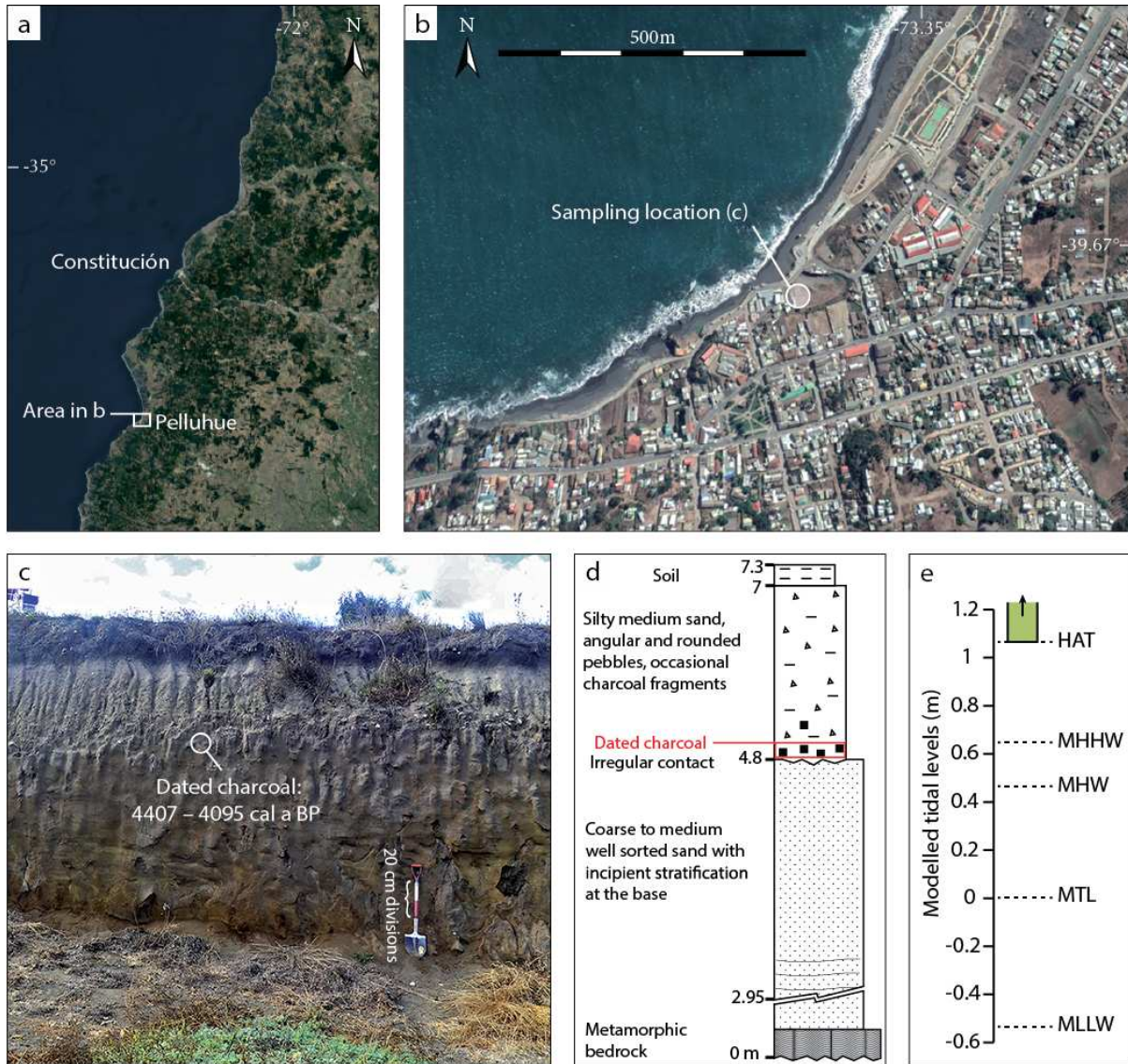
##### 357 4.1 Pelluhue, Maule region

358

359 At Pelluhue (35.8133°S 72.5762°W), an outcrop at the landward edge of the contemporary beach  
360 exposes an abrasion platform carved into metamorphic bedrock. Black volcanic sand and a colluvial  
361 wedge overlie the platform (Fig. 2). The medium to coarse volcanic sand is similar in composition  
362 and grain size to the contemporary beach sand but lacks datable organic material. The colluvium  
363 consists of angular pebbles, rounded cobbles and charcoal fragments that we interpret as having  
364 accumulated above the reach of tides. We radiocarbon dated three charcoal fragments from a layer  
365 at the base of the colluvium at an elevation of  $4.87 \pm 0.15$  m MSL. The resulting dates constrain the  
366 timing of the deposition of the colluvium; the median calibrated ages lie within 100 years of each  
367 other (Table 2). The youngest calibrated age range, 4407 – 4095 cal a BP, provides the age for a  
368 terrestrial limiting point. We derive the maximum elevation of RSL by taking the reference water  
369 level (HAT = 1.08 m) away from the sample elevation and adding the sum of the positive vertical  
370 uncertainties (comprising uncertainties related to the absolute elevation, the depth within the

371 section, and the indicative meaning: 0.19 m). The terrestrial limiting point therefore indicates RSL  
 372 was below 3.98 m.

373



374

375 Figure 2: Derivation of the new terrestrial limiting point from Pelluhue. a) Location of Pelluhue and  
 376 b) sampling location. c) Photograph and d) stratigraphic log of the dated section. e) Graphical  
 377 representation of the terrestrial limiting point's indicative meaning (open-ended green box; above  
 378 highest astronomical tide) relative to tidal levels at the site modelled using the TPX08-ATLAS tidal  
 379 model (Egbert and Erofeeva, 2010). Basemaps in a) and b) are from Bing Maps.

380

381 Table 2: Radiocarbon data associated with the new sea-level data points from Pelluhue, Tubul, Punta  
 382 Pájaros Niños, and Pilolcura. Reported ages are conventional  $^{14}\text{C}$  ages in years before 1950 CE,  
 383 corrected for isotopic fractionation using  $\delta^{13}\text{C}$  (NR =  $\delta^{13}\text{C}$  not reported). Ages calibrated with OxCal  
 384 4.2 (Bronk Ramsey, 2009) and the SHCal13 calibration curve (Hogg et al., 2013), except for the  
 385 calibrated range marked \*, which are calibrated using the Marine13 calibration curve (Reimer et al.,  
 386 2013) and  $\Delta R = 137 \pm 164$  years, as discussed in section 3.5.

387

Sample name	Laboratory code	Sample elevation (mMSL)	Dated material	$\delta^{13}\text{C}$	$^{14}\text{C}$ years BP $\pm 1\sigma$	Calibrated age (years BP, $2\sigma$ )
<b>Pelluhue</b>						
PEL001	Poz-50368	$4.87 \pm 0.15$	Charcoal fragment	-23.8	$3925 \pm 35$	4420 – 4158
PEL002	Poz-50369	$4.87 \pm 0.15$	Charcoal fragment	-25.5	$3890 \pm 35$	4412 – 4150
PEL003	Poz-50370	$4.87 \pm 0.15$	Charcoal fragment	-25.0	$3870 \pm 35$	4407 – 4095
<b>Tubul</b>						
TUB001	Beta-276181	$2.72 \pm 0.13$	<i>Petricola rugosa</i> shell	-0.5	$4780 \pm 40$	5302 – 4421*
<b>Punta Pájaros Niños, Isla Mocha</b>						
PPN001	KIA 36874	$21.9 \pm 0.20$	<i>Leukoma thaca</i> shell	-1.1	$3625 \pm 30$	3790 – 2934*
<b>Pilolcura</b>						
PIL001	D-AMS 032803	$2.47 \pm 0.07$	Charcoal fragment	NR	$1161 \pm 36$	1089 – 932

388

389 4.2 Tubul, Arauco region

390

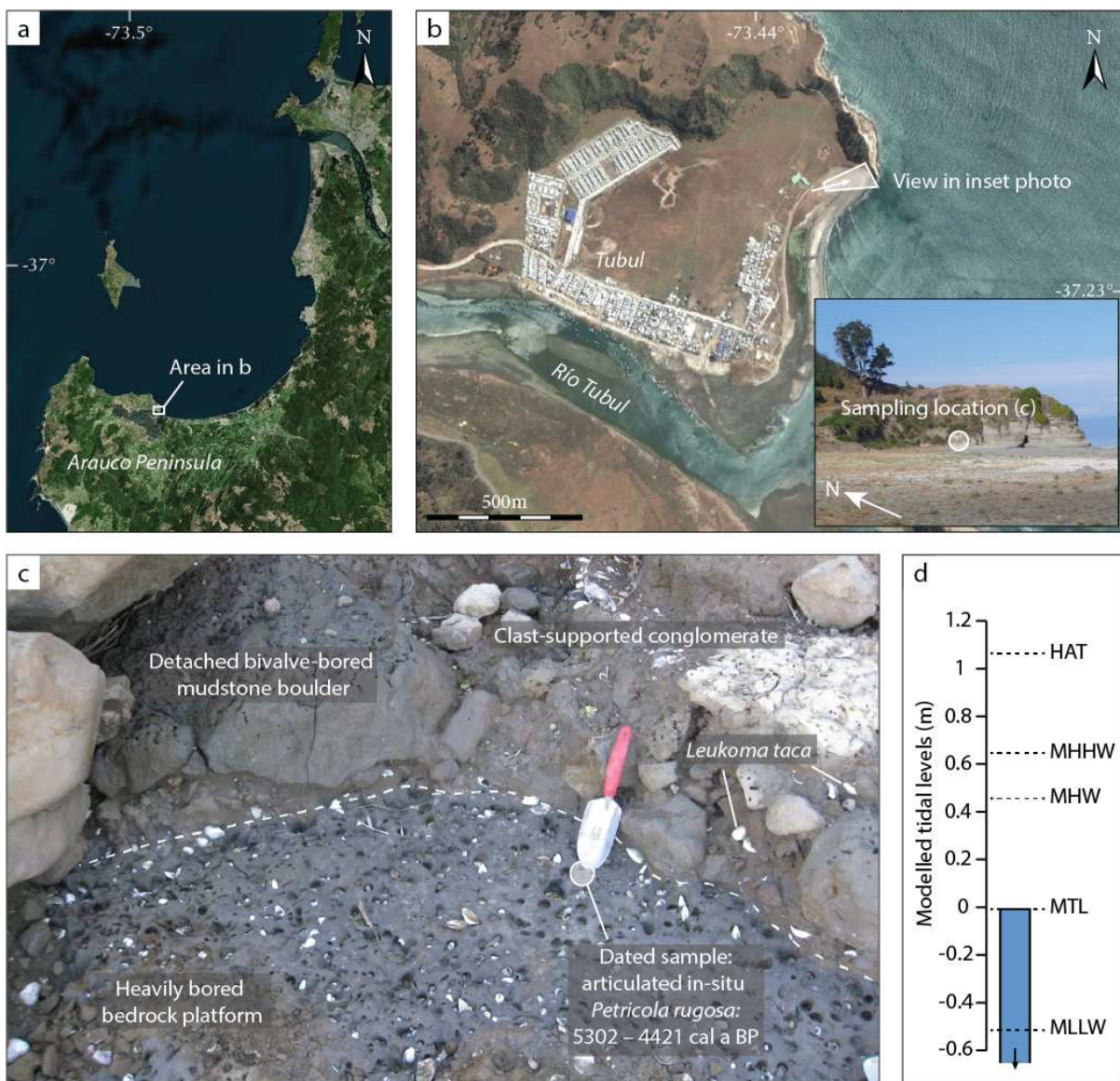
391 One kilometre north of the mouth of the Río Tubul ( $37.2265^{\circ}\text{S}$   $73.4357^{\circ}\text{W}$ ), a partially exhumed  
 392 wave-cut bedrock platform, cut into siltstone from the Plio-Pleistocene Tubul Formation, lies above  
 393 present sea level (Fig. 3). The surface of the platform is heavily pitted by the subtidal to low  
 394 intertidal rock-boring bivalves *Petricola rugosa*, *Petricola dactylus* and *Pholas chiloensis*. A poorly  
 395 consolidated clast-supported conglomerate containing subrounded bivalve-bored mudstone and  
 396 sandstone cobbles and boulders, gravel, articulated and fragmented subtidal clams (*Leukoma thaca*),  
 397 marine gastropods (*Turitella* sp.), charcoal fragments, and a sand-rich matrix locally overlies the  
 398 platform. We hypothesise that this conglomerate results from the debris from a landslide from the  
 399 adjacent cliffs that was subsequently reworked by waves. We base this assumption on our  
 400 observations of similar effects seen after the 2010 earthquake, which triggered a landslide above the

401 studied site. Since 2010, we have observed how storm waves have reworked the resulting landslide  
402 debris.

403

404 We dated an articulated *Petricola rugosa* shell found in life position inside its hole in the bedrock  
405 platform, which was preserved beneath the conglomerate (Table 2). As living *P. rugosa* individuals  
406 are found beneath MTL and generally in water depths of less than 10 m (Bernard, 1983), the  
407 resulting calibrated date, 5302 – 4421 cal a BP, provides the age of a marine limiting point.

408 Accounting for the sample elevation (2.69 m), the reference water level (MTL = -0.01 m), and the  
409 sum of the negative vertical uncertainties (0.13 m), the limiting point indicates RSL above 2.57 m.



410

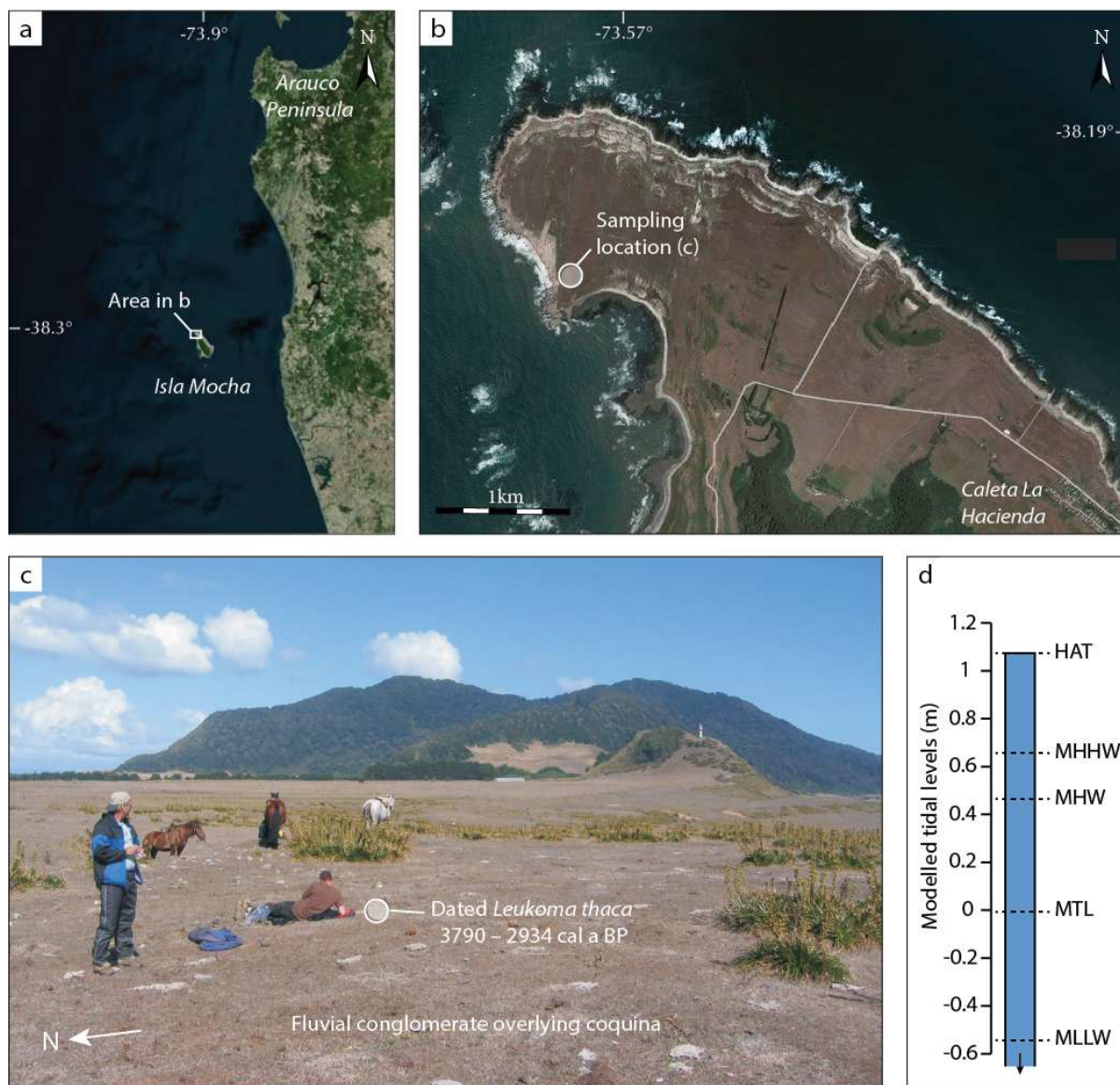
411 Figure 3: Derivation of the new marine limiting point from Tubul. a) Location of Tubul on the  
412 northern side of the Arauco Peninsula, b) sampling location on the headland east of Tubul, c)  
413 photograph of the bivalve-bored bedrock platform with the location of the dated *Petricola rugosa*, d)  
414 graphical representation of the marine limiting point's indicative meaning (open-ended blue box;  
415 below mean tide level) relative to tidal levels at the site modelled using the TPX08-ATLAS tidal  
416 model (Egbert and Erofeeva, 2010). Basemaps in a) and b) are from Bing Maps.

417

#### 418 4.3 Punta Pájaros Niños, Isla Mocha

419

420 Towards the northernmost point of Isla Mocha, at Punta Pájaros Niños (38.3250°S 73.9549°W), we  
421 encountered a coquina layer at an elevation of ~22 m (Fig. 4). The coquina contains bivalves  
422 (*Leukoma thaca*) and gastropods (*Tegula atra* or *Diloma nigerrimum*), with a poorly cemented sandy  
423 matrix. The high proportion of shell material and the presence of multiple marine species of differing  
424 environmental preference, including subtidal species from sandy substrates and intertidal species  
425 from rocky substrates, suggests reworking and deposition in a high-energy subtidal or possibly  
426 intertidal environment. The layer lacks any morphological evidence for supratidal deposition in the  
427 form of a beach ridge or shell midden, while the low gradient of the site substantially reduces the  
428 possibility of post-depositional reworking. The thin overlying conglomerate is of fluvial origin, with  
429 very well-rounded andesite clasts implying connectivity with the mainland or possibly reworking  
430 from higher elevations, although the latter hypothesis appears less likely given the site morphology.  
431 A whole, although not articulated, *Leukoma thaca* shell provides an age for the coquina of 3790 –  
432 2934 cal a BP (Table 2). As the water depth at which coquina deposits form is unknown in this  
433 setting, we conservatively treat the sample as a marine limiting point with an indicative range of  
434 below HAT. Taking away the reference water level (HAT = 1.09 m) and the sum of the negative  
435 vertical uncertainties (0.24 m) from the sample elevation (21.90 m) indicates RSL was above  
436 20.57 m.



438

439 Figure 4: Derivation of the new marine limiting point from Punta Pájaros Niños. a) Location of Isla  
 440 Mocha and b) the sampling location close to the northern tip of the island. c) Photograph of the  
 441 sampling site, d) graphical representation of the marine limiting point's indicative meaning (open-  
 442 ended blue box; below highest astronomical tide) relative to tidal levels at the site modelled using  
 443 the TPX08-ATLAS tidal model (Egbert and Erofeeva, 2010). Basemaps in a) and b) are from Bing  
 444 Maps.

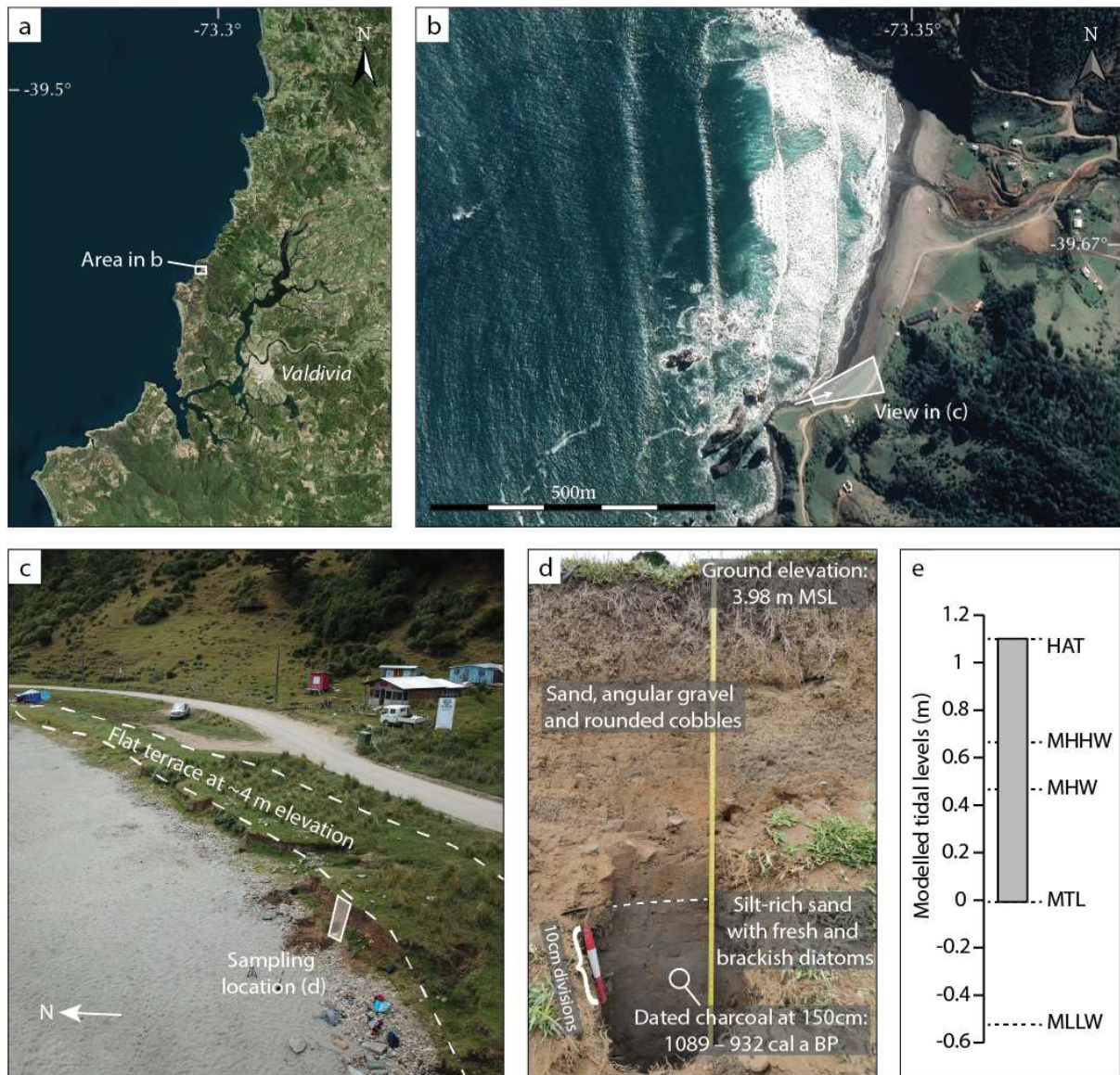
445

446 4.4 Pilolcura, Valdivia region

447

448 At Pilolcura (39.6723°S 73.3519°W), a ~1.8 m high section at the landward edge of the contemporary  
449 beach exposes a mid to dark grey silt-rich sand underlying ~1.2 m of colluvium (Fig. 5). The silt-rich  
450 sand contains a diatom assemblage dominated by freshwater or salt tolerant taxa (*Karayevia*  
451 *oblongella* and *Humidophila contenta*). The presence of infrequent brackish (e.g. *Luticola mutica*)  
452 and occasional marine species (e.g. *Petroneis marina*) suggests an environment with some tidal  
453 influence. The combination of a mixed-salinity diatom assemblage and fine-grained clastic sediments  
454 may indicate a tidally influenced lagoon behind a barrier or spit. Comparison of the fossil diatom  
455 assemblages with the contemporary distribution of intertidal diatoms in >250 samples from south-  
456 central Chile (Hocking et al., 2017) indicates a depositional elevation between MHHW and HAT  
457 (Supplementary Information S2). Nevertheless, the modern diatom database does not provide a  
458 close analogue for the Pilolcura assemblage, and we consequently assign a more conservative  
459 indicative range of between MTL and HAT (Fig. 5e). A fragment of charcoal at a depth of 1.50 m  
460 provides a calibrated radiocarbon age of 1089 – 932 cal a BP (Table 2). Taking the reference water  
461 level (midpoint between MTL and HAT: 0.55 m) away from the sample elevation (2.47 m), we infer  
462 sea level was at 1.92 m. The vertical uncertainty for this index point (0.57 m) is the sum of the  
463 uncertainties related to the absolute elevation, the depth within the exposure, and the indicative  
464 meaning.

465



466

467 Figure 5: Derivation of the new sea-level index point from Pilolcura. a) – c) Location of the sampling  
 468 site, d) photograph of the dated section, e) graphical representation of the index point's indicative  
 469 meaning (grey box; between mean tide level and highest astronomical tide) relative to tidal levels at  
 470 the site modelled using the TPXO8-ATLAS tidal model (Egbert and Erofeeva, 2010). Basemaps in a)  
 471 and b) are from Bing Maps.

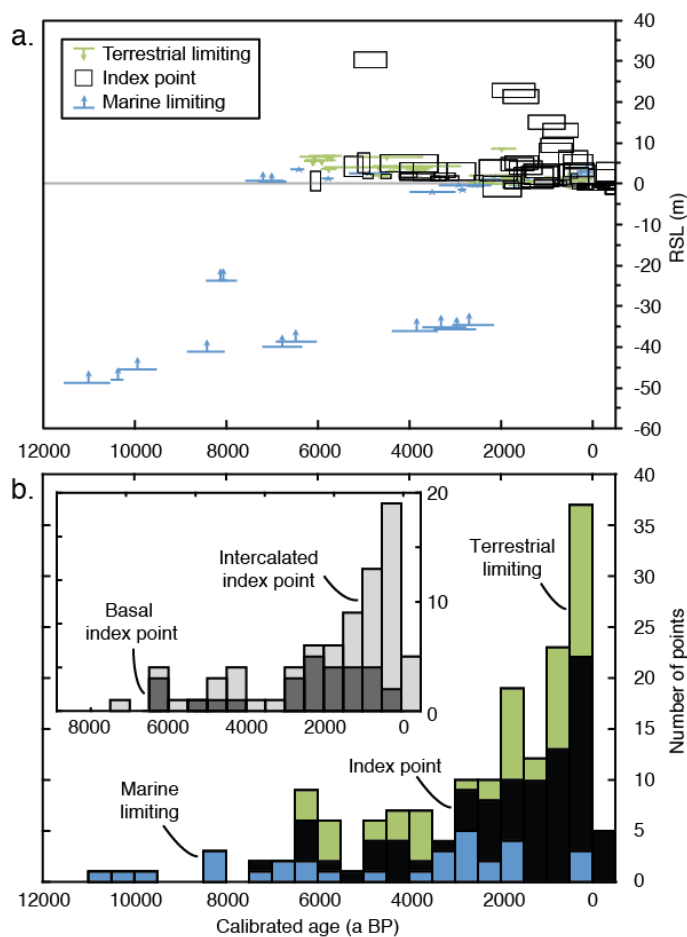
472

473 **5. The database and regional sea-level histories**

474

475 The Chilean Holocene RSL database (accessible via the data repository) consists of 166 accepted  
 476 points, of which 79 are index points, 56 are terrestrial limiting points, and 31 are marine limiting  
 477 points (Fig. 6). We reject a further 53 points for a range of reasons including uncertainties over  
 478 depositional environments, the possibility of reworking by storms, rivers, tsunamis, or human  
 479 activity, and chronological outliers identified by the original or subsequent authors. Of the accepted  
 480 points, 45 are from basal settings, including 28 index points, with the remaining 121 intercalated.  
 481 Almost 40 % of the accepted points have median ages postdating 1 ka BP, while only 10 points (6 %),  
 482 nine of which are marine limiting, are older than 6.5 ka BP (Fig. 6). In figure 7, we present sea-level  
 483 histories for the 11 regions shown in figure 1.

484



485

486 Figure 6: a. Plot of all accepted sea-level data points in the Chilean database. b. Stacked histogram of  
 487 the temporal distribution of accepted sea-level data points. Inset compares the distribution of basal  
 488 and intercalated sea-level index points.

489

490 5.1 Antofagasta (Fig. 7, region 1)

491

492 The coastline bordering the arid Atacama Desert, covering more than 10 degrees of latitude,  
493 currently provides a single Holocene marine limiting point. Leonard and Wehmiller (1991) report  
494 three uplifted marine terraces at Caleta Michilla, with only the lowermost having formed during the  
495 Holocene. Marine bivalves from this terrace, lying at an elevation of approximately 5.5 m above  
496 mean sea level, provide a median age of  $\sim 7.2$  ka BP. While the authors describe the dated sediments  
497 as marine, it is unclear whether the terrace is a raised beach deposited at or above HAT, or a marine  
498 deposit with a lower indicative range. Consequently, we consider this sample as a marine limiting  
499 point with a reference water level of HAT + 3 m. Our interpretation places RSL above  $\sim 0.5$  m at this  
500 time.

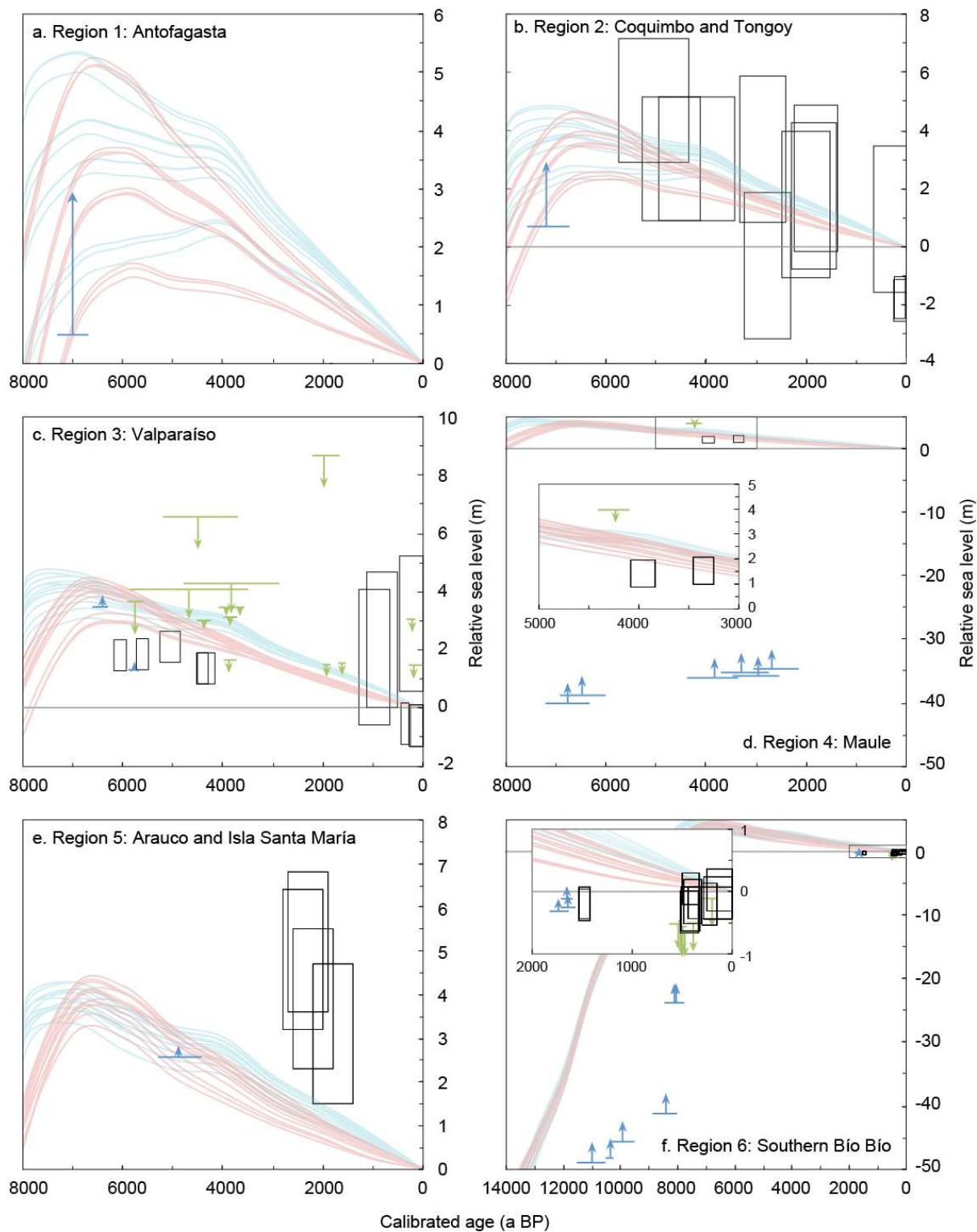
501

502 5.2 Coquimbo and Tongoy (Fig. 7, region 2)

503

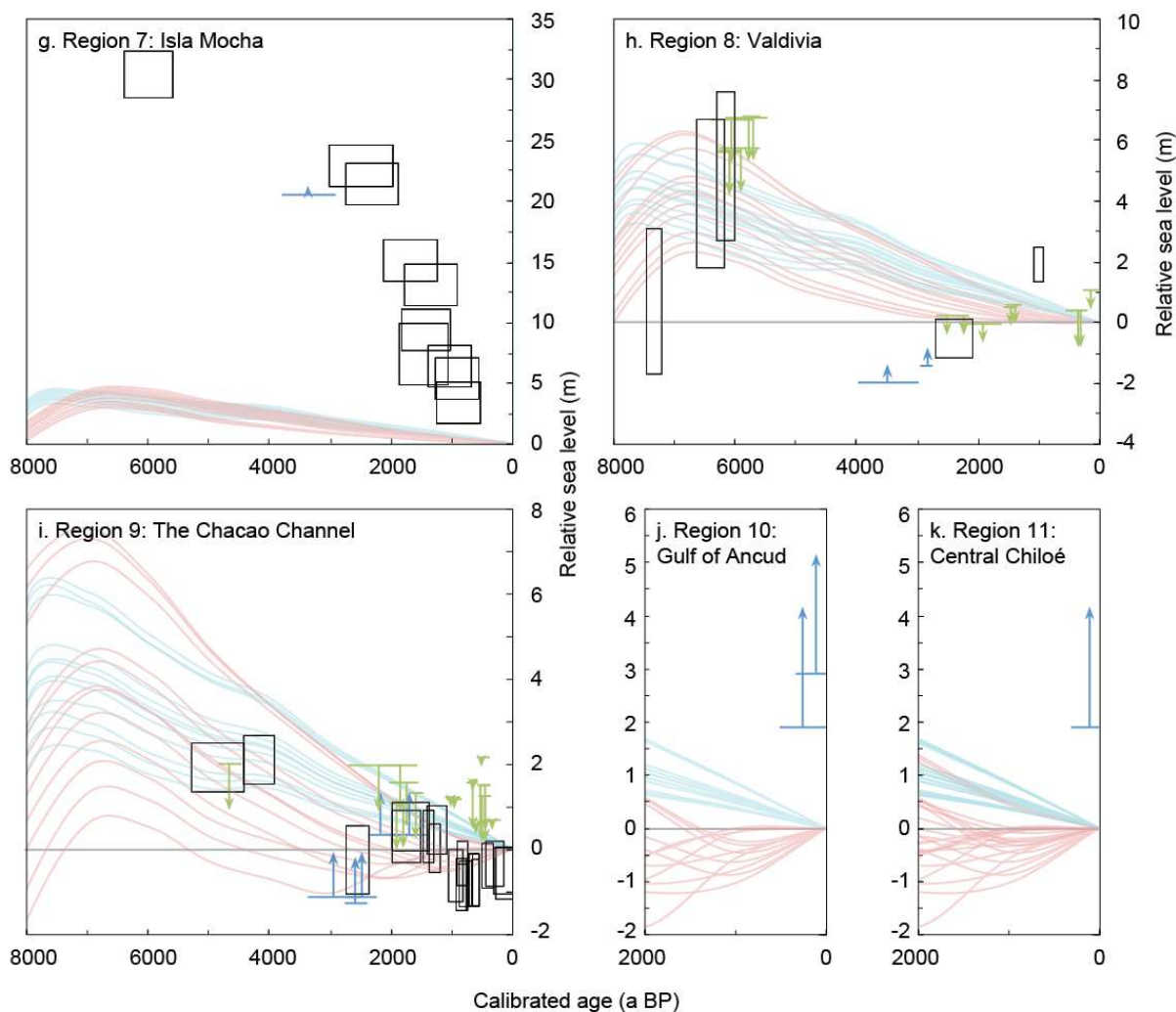
504 The RSL record of this semi-arid region consists of 11 index points and one marine limiting point  
505 from five sites. In contrast to the paucity in other regions, 9 of the 11 index points are from basal  
506 settings. The earliest sea-level data point, a  $\sim 7.2$  ka BP marine limiting point from Estero Tongoy (Ota  
507 and Paskoff, 1993), places sea level above  $\sim 0.7$  m. Index points from prograding sequences of beach  
508 ridges in the Bay of Coquimbo (Hart et al., 2017) and beach deposits at El Rincón and Punta Lengua  
509 de Vaca, both fringing Tongoy Bay (Ota and Paskoff, 1993), indicate falling sea level after  $\sim 5$  ka BP  
510 from a maximum of at least  $5.00 \pm 2.09$  m. Three index points from Puerto Aldea and El Rincón (Ota  
511 and Paskoff, 1993) indicate RSL was between 0 m and 5 m by 2 ka BP, with the large vertical  
512 uncertainty associated with the broad indicative range associated with index points from  
513 undifferentiated beach environments. Within the last 100 years, two index points from Quebrada de  
514 Teatinos, Bay of Coquimbo, place RSL around -1.8 m, with a vertical uncertainty of  $\sim 0.7$  m (May et

515 al., 2013). We do not incorporate further dated samples from Quebrada Los Chines (Ota and Paskoff,  
 516 1993), Quebrada de Teatinos, and Quebrada Pachingo (May et al., 2013) due to the potential for  
 517 reworking or chronological uncertainties identified by the original authors.  
 518



519

520 Figure 7: Regional plots comparing the age – elevation distribution of the sea-level data points with  
 521 glacial isostatic adjustment model predictions (following Peltier, 2004; Peltier et al., 2015). Sea-level  
 522 index points are black rectangles, terrestrial and marine limiting points are green T-shaped symbols  
 523 and blue ⊥-shaped symbols respectively. ICE\_5G predictions are light blue curves, ICE\_6G  
 524 predictions are pink curves; for both ice models, we vary the lithospheric thickness between 71 and  
 525 120 km and the upper mantle viscosity between  $5 \times 10^{19}$  Pa s and  $2 \times 10^{20}$  Pa s (see section 3.7). Note  
 526 different x-axis scaling for panel f and variable y-axis scaling between all panels.



527  
 528 Figure 7 (continued)

529  
 530 5.3 Valparaíso (Fig. 7, region 3)

531

532 Five sites in the Valparaíso region provide 11 index points, 2 marine limiting and 14 terrestrial  
533 limiting points. The earliest evidence comes from Algarrobo, where Encinas et al. (2006) report a  
534 silty sandstone containing well-preserved foraminifera, bivalves and gastropods, indicative of a  
535 shallow marine environment. This marine limiting point places RSL above ~3.5 m at ~6.4 ka BP. Tidal  
536 and freshwater marsh deposits at Quintero, originally investigated for their palaeotsunami record  
537 (Dura et al., 2015), provide mid Holocene index points and late Holocene terrestrial limiting points.  
538 These data indicate sea level was ~2 m at ~6 ka BP, below 1.65 m at ~3.9 ka BP, and below ~1.5 m  
539 during the last 2 ka. Terrestrial limiting points from alluvial deposits underlying the Longotoma dune  
540 field concur, indicating sea level below ~3.5 m at ~4 ka BP (May et al., 2015). Within the last  
541 millennium, index points from Los Vilos (May et al., 2013) indicate RSL above present, though with  
542 large vertical uncertainties, while index points from Pichicuy Bay (May et al., 2013) indicate RSL  
543 between -1.3 and 0.2 m.

544

#### 545 5.4 Maule (Fig. 7, region 4)

546

547 In addition to the new terrestrial limiting point from Pelluhue (section 4.1), the sea-level history of  
548 this region is further constrained by two index and six marine limiting points from two sites.  
549 Frugone-Álvarez et al. (2017) report 11 radiocarbon dates from cores taken from Lago Vichuquén.  
550 The lowermost six samples are from sediments interpreted by Frugone-Álvarez et al. (2017) as  
551 indicative of marine environments; consequently, the dates constrain the ages of marine limiting  
552 points. As the location and elevation of the sill between the lake basin and the sea at the time of  
553 deposition is uncertain (today it lies at 2.4 m above EGM2008), we conservatively assume that there  
554 was no sill. The accepted marine limiting points place RSL above -40 m at ~6.8 ka BP and above -  
555 35 m at ~2.7 ka BP. While the overlying sediments are interpreted as brackish and freshwater  
556 (Frugone-Álvarez et al., 2017), radiocarbon dates from these layers cannot be used to constrain sea  
557 level due to uncertainties over the isolation of the lake and the role of sediment supply and local

558 tectonics in building the sill. The terrestrial limiting point from Pelluhue places RSL below ~4 m at  
559 ~4.2 ka BP, while two index points from El Yolki indicate RSL between 0.85 and 2.1 m between 4 and  
560 3 ka BP (Hilleman, 2015; Melnick et al., 2019). We do not consider 13 other radiocarbon dates of  
561 ~4 ka BP from Melnick et al. (2019) due to their close proximity to the El Yolki Fault.

562

#### 563 5.5 The Arauco Peninsula and Isla Santa María (Fig. 7, region 5)

564

565 The RSL record consists of four basal index points from Isla Santa María and the new marine limiting  
566 point from Tubul. The eastern side of Isla Santa María features a sequence of 21 emerged Holocene  
567 beach ridges at elevations between 0.5 m and 8 m. Optically stimulated luminescence ages constrain  
568 the timing of the deposition of four of the ridges to the late Holocene, with the oldest dating to 2.1 –  
569 2.5 ka BP (Bookhagen et al., 2006). We use the elevation of these four ridges at the locations at  
570 which they were sampled for dating to define four index points, noting that the ridges are  
571 progressively tilted to the northwest at a rate estimated by Bookhagen et al. (2006) of  
572  $0.022 \pm 0.002$  °/ka. These index points place RSL between 3.11 m and 5.21 m, with vertical  
573 uncertainties of  $\pm 1.6$  m. As described in section 4.2, a marine limiting point from Tubul places sea  
574 level above 2.57 m at ~5 ka BP.

575

576 Although two shells have been dated on the coastal plains at Coronel and Carampangue (Isla et al.,  
577 2012), we are unable to derive index or limiting points. Because both dates relate to broken shells of  
578 unknown species, we cannot establish whether these shells are originally from subtidal, intertidal or  
579 supratidal environments and whether they are in-situ or have been subsequently transported.

580

#### 581 5.6 Southern Bío Bío (Fig. 7, region 6)

582

583 The RSL history of the Southern Bío Bío region is constrained by 10 index, 8 terrestrial limiting, and 9  
584 marine limiting points. We derive two marine limiting points from Lake Lanahue and four marine  
585 limiting points from Lake Llu Llu (Stefer et al., 2010). The dated samples, ranging from 8 to 11 ka  
586 BP, come from clastic sediments containing marine shells and foraminifera at elevations of between  
587 -22 m and -47 m. While the basins also contain subsequent lacustrine sedimentary infills, we cannot  
588 derive terrestrial limiting points from 17 further radiocarbon dates from these intervals due to the  
589 uncertain rate of tectonic uplift and coeval erosion of the sill that separates the contemporary lake  
590 from the Pacific. Organic silt and peat layers at Quidico (38.2°S) and Tirúa (38.3°S) provide 21 further  
591 sea-level data points, including 10 index points (Ely et al., 2014; Dura et al., 2017; Hong et al., 2017).  
592 The accepted ages are all within the last 1.9 ka and lie between -0.6 m and 0.4 m.

593

#### 594 5.7 Isla Mocha (Fig. 7, region 7)

595

596 Ten index points, all of them from basal settings, and one marine limiting point constrain the sea-  
597 level history of Isla Mocha. The island, lying approximately 30 km off the coast of mainland Chile,  
598 features a kilometre-wide fringe of uplifted Holocene beach ridges (Nelson and Manley, 1992). Two  
599 studies provide radiocarbon ages from either shell fragments or intact shells from beach ridges at  
600 elevations up to 33 m (Kaizuka et al., 1973; Nelson and Manley, 1992). Following Nelson and Manley  
601 (1992), we exclude several of these ages due to the probability of reworking of older shell material.  
602 The 10 accepted index points, along with our new marine limiting point from the north of the island  
603 at Punta Pájaros Niños, place RSL around 30 m at ~6 ka BP, falling to ~23 m at ~2.5 ka BP and  
604 subsequently falling at a faster rate to below 5 m at ~0.9 ka BP.

605

#### 606 5.8 Valdivia (Fig. 7, region 8)

607

608 Five index, two marine limiting and 14 terrestrial limiting points provide the RSL record for the  
609 Valdivia region. The oldest index point, coming from shell-bearing sands indicative of a beach  
610 environment at Isla Mancera (Villalobos Silva, 2005), dates to ~7.3 ka BP and places RSL between -  
611 1.7 m and 3.1 m, with the large vertical uncertainty reflecting a broad indicative range. Index points  
612 from beach sediments and terrestrial limiting points from aeolian dunes at Chan Chan indicate RSL  
613 was between 1.8 m and 7.6 m at ~6 ka BP (Pino and Navarro, 2005). Between ~3.5 ka BP and  
614 present, index and marine limiting points from tidally influenced clastic sediments and terrestrial  
615 limiting points from freshwater soils in the Las Coloradas inlet and Isla Mancera place RSL between -  
616 2 m and 1 m (Villalobos Silva, 2005; Nelson et al., 2009). The new index point from Pilolcura places  
617 RSL at  $1.92 \pm 0.57$  m, ~1 ka BP.

618

#### 619 5.9 The Chacao Channel (Fig. 7, region 9)

620

621 The coast of northern Chiloé and the adjacent continental coast around the Río Maullín, collectively  
622 termed the Chacao Channel region, provide 26 index, five marine limiting and 19 terrestrial limiting  
623 points. These points stem from palaeoseismic studies of coastal lowlands and marshes (Atwater et  
624 al., 1992; Cisternas et al., 2005; 2017; Garrett et al., 2015). The earliest sea-level data come from  
625 Chocoi, where tidal marsh peat layers exposed in a sea cliff attest to RSL ~2 m above present  
626 between 5 and 4 ka BP (Atwater et al., 1992). A subsequent fall in RSL is recorded by tidal marsh  
627 deposits at Maullín (Cisternas et al., 2005), Dadi, and Puente Cariquilda (Atwater et al., 1992). Six  
628 index points from these locations place RSL between -1 m and 1 m during the period between 3 and  
629 1 ka BP. Terrestrial limiting points in this interval place sea level below 2 m, with marine limiting  
630 points indicating sea level above -1.5 m at ~3 ka BP and above 0.35 m at ~2 ka BP. Twelve index  
631 points from Chucalen (Garrett et al., 2015) and six from Maullín (Cisternas et al., 2005) indicate RSL  
632 was ~1 m below present at ~0.9 ka BP, with the subsequent rise to present overprinted by metre-  
633 scale coseismic subsidence events resulting from great subduction earthquakes (Garrett et al.,

634 2015). Terrestrial limiting points for the last 1 ka from Maullín (Cisternas et al., 2005) and Cocotué  
635 (Cisternas et al., 2017) indicate sea level below elevations varying between 2.3 m and 0.7 m.

636

637 5.10 Reloncaví Sound and Gulf of Ancud (Fig. 7, region 10)

638

639 Two marine limiting points constrain the RSL history of the semi-enclosed coastlines to the northeast  
640 of Chiloé. Both points come from Bahía Hualaihué, where intertidal or subtidal bivalves in living  
641 position indicate sea levels above 1.90 m and 2.90 m (Hervé and Ota, 1993). Both samples have  
642 median ages within the last 0.3 ka. We reject further dated shells from Bahía Hualaihué and sites at  
643 Ralún at the head of Fiordo Reloncaví and the Cholgo Canal (Hervé and Ota, 1993) due to the  
644 possibility of reworking by extreme waves or human activity.

645

646 5.11 Central Chiloé (Fig. 7, region 11)

647

648 Central Chiloé provides a single marine limiting point, with no further accepted sea-level data from  
649 southern Chiloé, Isla Guafo or the continental coastline or islands of the Gulf of Corcovado. At Cucao,  
650 on the western coast of Chiloé, Hervé and Ota (1993) report subtidal bivalves in living position  
651 indicating RSL above 1.89 m. Recalibration of the radiocarbon age provides a range of 325 cal a BP to  
652 present. We reject one dated shell from Nercón on the eastern coast of Chiloé (Hervé and Ota, 1993)  
653 due to the possibility of reworking.

654

## 655 **6. Discussion**

656

657 6.1 Glacial isostatic adjustment

658

659 The Chilean sea-level database includes 166 accepted sea-level data points. Nevertheless, as these  
660 are unevenly spread across 2200 km of coast (20 degrees of latitude), our current knowledge of past  
661 sea levels is spatially variable and, in some areas (regions 1, 4, 10, 11, and all remaining stretches of  
662 coastline that lack any data), highly limited. Nonetheless, the presence of several data-rich regions  
663 with well-constrained sea-level histories highlights a high degree of spatial variability in Holocene  
664 RSL change and provides an opportunity to make a preliminary investigation into the processes  
665 driving these changes. To this end, we compare the distribution of sea-level data with RSL  
666 predictions from a suite of GIA models (Fig. 7).

667

668 GIA model predictions display a high degree of variability along the Chilean coastline. The two  
669 northernmost regions are characterised by modelled mid Holocene highstands 1.5 – 5.5 m above  
670 present between 7 ka and 4 ka (Fig. 7a-b). The five central regions between Valparaíso and Isla  
671 Mocha share modelled highstands 3 – 6 m above present at 7 ka or 6 ka (Figs. 7c-g). The predictions  
672 for the four southernmost regions, around Valdivia and Isla de Chiloé, display maxima at elevations  
673 between 0.5 and 8 m above present at 8 ka or 7 ka, with a high degree of variability between  
674 different models (Figs. 7h-k). Unlike in regions 1 – 8, where all models predict RSL fall following the  
675 highstand, models that adopt low values for upper mantle viscosity, when combined with the ICE-6G  
676 ice model, predict RSL rise over the last 1 – 3 ka in regions 9 – 11 (Figs. 7i-k).

677

678 For the majority of Chilean regions, the database of sea-level data points and the GIA model  
679 predictions provide a coherent account of the pattern of Holocene RSL change. No additional factors  
680 are required to explain the age and elevation of data points in regions 1 and 4 (Fig. 7); however, this  
681 may reflect the paucity of data in these regions. In regions 2, 3, 6, 8, and 9, decimetre- to metre-  
682 scale vertical motions associated with centennial-scale earthquake cycle deformation would be  
683 sufficient to account for the small disparities between sea-level data and GIA model predictions. In  
684 the remaining regions—Arauco and Isla Santa María (region 5), Isla Mocha (region 7), the Gulf of

685 Ancud (region 10), and Central Chiloé (region 11)—index and marine limiting points consistently lie  
686 above the GIA predictions, suggesting the importance of other factors at these locations. In the  
687 following section, we explore the potential for millennial-scale secular tectonic uplift to account for  
688 these differences.

689

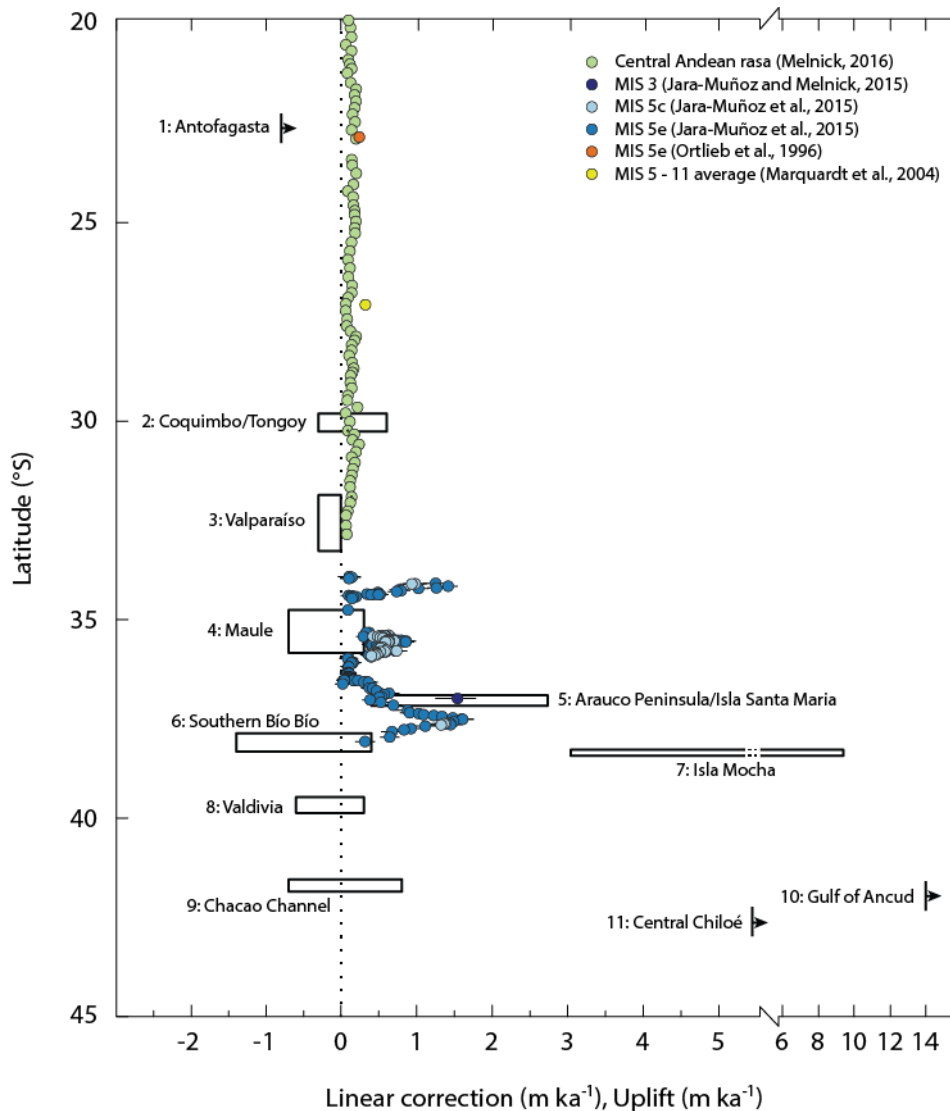
## 690 6.2 Regional tectonic uplift

691

692 Allowing for centennial-scale earthquake deformation cycles, we apply linear corrections to the RSL  
693 data to improve the fit with the GIA model predictions (see section 3.7 and Supplementary  
694 information S3). We summarise the range of acceptable linear corrections for each region in Figure 8  
695 and compare these with independently derived estimates of multi-millennial-scale tectonic uplift.  
696 We note that our linear corrections provide a first approximation of tectonic uplift rates, but also  
697 reflect the cumulative effects of other processes including sediment compaction and sediment  
698 isostasy, among other local processes. We make an initial exploration of the possible role of tectonic  
699 uplift and other processes in each region in the following paragraphs.

700

701 As previously stated, once centennial-scale deformation cycles are accounted for, no additional  
702 correction is required to explain data-model discrepancies in regions 1, 2, 3, 4, 6, 8, and 9. However,  
703 a range of positive and/or negative corrections may still provide acceptable fits with the model  
704 predictions. In regions 1 and 2, our accepted ranges of linear corrections ( $>-0.8 \text{ m ka}^{-1}$  and  $-0.3 -$   
705  $0.6 \text{ m ka}^{-1}$  respectively) overlap with Melnick's (2016) independent estimates based on a landscape  
706 evolution model for the central Andean *rasa* (Fig. 8). In region 3, as mid-Holocene index points lie  
707 below GIA model predictions, we invoke negative rates of  $-0.3$  to  $0 \text{ m ka}^{-1}$  (subsidence) (Fig. 8). The  
708 slight discrepancy between this and Melnick's (2016) tectonic uplift rate of  $0.06 \pm 0.02 \text{ m ka}^{-1}$  could  
709 indicate sediment compaction affects the intercalated index points from the organic-rich lowland at  
710 Quintero (Dura et al., 2015).



712

713 Figure 8: Comparison of best-fit linear correction rates (black rectangles) required to remove the  
 714 misfit between sea-level data and a suite of glacial isostatic adjustment models with independently  
 715 derived estimates of tectonic uplift (coloured circles). Sea-level data and GIA models for the 11  
 716 regions are shown in Figure 7 and the linear corrections are illustrated in Supplementary Information  
 717 S3.

718

719 Accepted linear correction rates for region 4 range from  $-0.7 \text{ m ka}^{-1}$  (subsidence) to  $0.3 \text{ m ka}^{-1}$  (uplift)  
 720 (Fig. 8). Jara-Muñoz et al. (2015) suggest higher tectonic uplift rates in the region since the last  
 721 interglacial, with rates of  $0.4$  to  $0.8 \text{ m ka}^{-1}$  associated with a long-wavelength upwarping zone and

722 the activity of three major crustal normal faults that intersect the coastline and displace the marine  
723 isotope stage (MIS) 5 marine terraces. Correcting the sea-level data for such high tectonic uplift rates  
724 would lower index points below our model predictions. This could 1) potentially indicate a greater  
725 level of spatial variability in uplift rates associated with local crustal structures than previously  
726 identified, 2) suggest that late Holocene tectonic uplift rates have not been sustained over longer  
727 timescales, or 3) reflect spatial complexity in Earth rheology that is not accounted for by GIA models.  
728 Uplift rates inferred from last interglacial terraces do not account for local departures from the  
729 global eustatic sea level associated with GIA (Creveling et al., 2015), potentially also contributing to  
730 the disparity with the inferred Holocene rates.

731

732 A linear correction of between  $0.4$  and  $2.7 \text{ m ka}^{-1}$  (uplift) could account for the elevated position of  
733 the four index points from Isla Santa María with respect to the GIA model predictions for region 5  
734 (Figs. 7e, 8). Jara-Muñoz and Melnick (2015) concur, inferring a tectonic uplift rate of  $1.5 \pm 0.3 \text{ m ka}^{-1}$   
735 from MIS 3 sediments on Isla Santa María. We note that continued debate over MIS 3 sea levels may  
736 lead to a reassessment of this rate (Pico et al., 2017; Dalton et al., 2019). Jara-Muñoz et al. (2015)  
737 indicate lower post-MIS 5e tectonic uplift rates for the Arauco Peninsula, including  $\sim 0.3 \text{ m ka}^{-1}$  at the  
738 latitude of our site at Tubul. Neither the MIS 5e nor the MIS 3 uplift rates account for local GIA-  
739 induced departures from global eustasy (Creveling et al., 2015).

740

741 Linear corrections of  $-1.4 \text{ m ka}^{-1}$  (subsidence) to  $0.4 \text{ m ka}^{-1}$  (uplift) provide the best fit for the late  
742 Holocene in region 6 (Fig. 8). Based on comparison of the early Holocene record from lakes Lanalhue  
743 and Lleu Lleu with “global” sea-level curves, Stefer et al. (2010) inferred tectonic uplift rates in the  
744 region of  $0.5 \text{ m ka}^{-1}$ . We update this analysis by comparing reassessed sea-level data from the two  
745 lakes with the suite of GIA model predictions for this particular location. As a result of isostatic  
746 rebound, the model predictions for this region lie substantially above farfield RSL curves, implying  
747 that the uplift rates derived in the original study were overestimated. While the Lanalhue and Lleu

748 Llew marine limiting points lie above the global curves (Stefer et al., 2010), they lie below the local  
749 model predictions (Fig. 7f and supplementary figure S3f). Consequently, no tectonic uplift is required  
750 to reconcile the observations of Stefer et al. (2010) with the model predictions, in contrast to the  
751 conclusions of the original study.

752

753 Sea-level index points from Isla Mocha lie above the suite of GIA model predictions for region 7 (Fig.  
754 7g). Linear corrections of between  $3 \text{ m ka}^{-1}$  and  $9.5 \text{ m ka}^{-1}$  reduce the misfit, with the highest uplift  
755 rates required to reconcile data from the last 3000 years (Fig. 8). No single rate can bring every index  
756 point within the suite of model predictions, potentially indicating an increase in uplift rates during  
757 the Holocene, as identified by Nelson and Manley (1992). The rapid localised tectonic uplift of Isla  
758 Mocha, contrasting with the adjacent southern Bío Bío region, may reflect aseismic and/or seismic  
759 slip on imbricate thrust faults within the South American Plate (von Heune et al., 1985; Nelson and  
760 Manley, 1992).

761

762 Linear corrections of  $-0.6 \text{ m ka}^{-1}$  (subsidence) to  $0.3 \text{ m ka}^{-1}$  (uplift) provide an acceptable fit between  
763 data and models in region 8, with a similar range of  $-0.7 \text{ m ka}^{-1}$  (subsidence) to  $0.8 \text{ m ka}^{-1}$  (uplift) for  
764 region 9 (Fig. 8). Notably, in region 9, index points for the last 1000 years are below present sea  
765 level. This pattern, apparent from two sites separated by  $\sim 40 \text{ km}$ , was previously recognised by  
766 Garrett et al. (2015) and tentatively attributed to incomplete interseismic uplift following coseismic  
767 subsidence during the 1960 earthquake. Interseismic uplift rates have been slowly increasing over  
768 the past few decades (Melnick et al. 2018), a trend that would raise the dated sediments back  
769 towards present sea level. In addition, effects at a local scale such as sediment compaction, or at a  
770 larger scale such as neoglacial forebulge collapse, might influence RSL in this region over the last  
771 millennium. While GIA model predictions generated using the ICE-6G ice model (Peltier et al., 2015)  
772 in combination with relatively weak upper mantle viscosities replicate a late Holocene sea-level rise,  
773 this signal may occur due to the low spatial resolution of the model and its inability to fully resolve

774 water loading and shoreline changes in this landscape of deep marine gulfs and mountains. The  
775 cause of late Holocene sea-level rise in this region remains uncertain; nevertheless, its occurrence  
776 provides accommodation space and may explain the preservation of palaeoseismic evidence at sites  
777 in the region (Cisternas et al., 2005; 2017; Garrett et al., 2015).

778

779 Hervé and Ota (1993) inferred extremely fast tectonic uplift rates of 5 to 10 m ka<sup>-1</sup> in regions 10 and  
780 11 during the late Holocene. While we have rejected four of the seven dates in these regions due to  
781 the possibility for reworking by extreme waves or human activity, the remaining three marine  
782 limiting points require linear correction rates of > 14 m ka<sup>-1</sup> (region 10) and > 5.5 m ka<sup>-1</sup> (region 11)  
783 to bring them in line with the model predictions (Fig. 8). While rapid uplift in region 10 may be  
784 associated with the Liquiñe-Ofqui fault zone, further data are required to corroborate and extend  
785 the record of RSL change in the continental region east of Isla de Chiloé.

786

### 787 6.3 Data paucity and areas for future focus

788

789 The Chilean sea-level database highlights the scarcity of sea-level data from northern Chile. Few  
790 studies have focussed on the relative sea-level history in this region, or on allied endeavours that  
791 may produce sea-level data points, such as coastal palaeoseismology. We attribute this lack to the  
792 rarity of coastal fine-grained sedimentary depocentres and the terrestrial organic fossils to date  
793 resulting from the region's aridity. To overcome this problem, future studies may consider rocky-  
794 shore geomorphic markers and beach or beach ridge deposits that can be dated using marine shells  
795 or through luminescence approaches. Such features have successfully provided sea-level data in  
796 central Chile (Nelson and Manley, 1992; Bookhagen et al., 2006; Hart et al., 2017) and are present  
797 along the coast of northern Chile. Future work should also focus on providing appropriate local  
798 estimates of the indicative meaning of such features through surveying analogous modern sea-level  
799 indicators and relating these to tidal datums.

800

801 While central and south-central Chile are more comprehensively represented in the database, the  
802 majority of sea-level data points are limited to the late Holocene and, particularly, the last 2 ka (Fig.  
803 6). Consequently, there are few data to constrain key features of RSL history of this region. The  
804 height and timing of the mid-Holocene highstand remains a major uncertainty, with proxy  
805 reconstructions and GIA modelling indicating elevations between 2 and 6 m at Valdivia and between  
806 0.5 and 7.5 m in the vicinity of the Chacao Channel.

807

## 808 7. Conclusions

809

810 The Chilean Holocene sea-level database presented in this paper provides a systematic, quality  
811 controlled, and internationally comparable database of sea-level data from the tectonically active  
812 coast of north, central and south-central Chile (18.5 – 43.6°S). We reinterpret indicative meanings  
813 (the relationship between a sea-level indicator and contemporaneous tidal levels), recalibrate ages,  
814 and fully assess all sources of error for sea-level indicators stemming from research into relative sea-  
815 level change, coastal palaeoseismology, palaeoclimatology, and archaeology. Much of the  
816 information on past sea levels provided by these sources has previously been overlooked. Our  
817 database summarises 166 accepted points, including 79 index points, 31 marine limiting points, and  
818 56 terrestrial limiting points. We reject a further 53 data points due to ambiguities over the  
819 interpretation of depositional environments, the possibility of reworking by storm, fluvial, tsunami,  
820 or human activity, along with chronological inconsistencies.

821

822 The database includes sea-level data from four new sites presented here for the first time: Pelluhue  
823 (south of Constitución), Tubul (northern Arauco Peninsula), Punta Pájaros Niños (northern Isla  
824 Mocha), and Pilolcura (north of Valdivia). These sites illustrate how a range of different data sources,  
825 including alluvial deposits, marine shells, and intertidal sediments can provide constraints on past

826 sea level. Collectively, the new sites provide two marine limiting points, one terrestrial limiting point  
827 and one index point.

828

829 Combining new and reassessed data, we use the database to describe relative sea-level histories for  
830 11 coastal regions of Chile, noting the spatial inhomogeneity of the data. These histories highlight  
831 substantial spatial differences in Holocene relative sea level: while the mid Holocene was  
832 characterised by sea level above present in all regions, elevations vary from <5 m to 30 m.  
833 Comparison of sea-level data with a suite of glacial isostatic adjustment models enables us to assess  
834 the processes driving RSL change and highlights regions where millennial-scale tectonic deformation  
835 may cause the data to significantly diverge from model predictions (particularly Isla Santa María, Isla  
836 Mocha, and regions close to the Liquiñe-Ofqui fault zone). Uplift rates likely exceed  $1 \text{ m ka}^{-1}$  in these  
837 regions and may be an order of magnitude greater over centennial timescales. We identify that no  
838 net uplift is required to reconcile data and model predictions in many areas, including the southern  
839 Bío Bío region, in contrast to the findings of an earlier study (Stefer et al., 2010).

840

841 We highlight northern Chile and the early to mid Holocene in all regions as particularly data poor.  
842 Future efforts to address these data gaps will continue to assist efforts to address questions over the  
843 driving mechanisms of sea-level variability (Khan et al., 2019). Furthermore, with the spatiotemporal  
844 distribution of coastal archaeological and palaeoseismic evidence closely related to relative sea-level  
845 change (Dickinson, 2011; Dura et al., 2016), the current Chilean sea-level database and future  
846 advances in constraining RSL histories along the Chilean coast will support future research in these  
847 and other fields.

848 **Acknowledgements**

849 EG undertook this work while in receipt of funding from the European Union/Durham University  
850 (COFUND under the DIFeREns 2 scheme). The authors acknowledge financial support from the  
851 Millennium Nucleus CYCLO “The Seismic Cycle Along Subduction Zones” funded by the Millennium  
852 Scientific Initiative (ICM) of the Chilean Government Grant Number NC160025. Additional support  
853 for MC and DM was provided by FONDECYT, project N° 1190258. TD was supported by National  
854 Science Foundation (NSF) awards EAR-1566253, EAR-1624795, and EAR-1624533. LE was supported  
855 by National Geographic Society Research Grant 8577-08 and NSF awards EAR-1036057, EAR-1145170,  
856 and EAR-1624542. JJM was supported by the Deutsche Forschungsgemeinschaft Grant JA 2860/1-1.  
857 The authors acknowledge PALSEA (a PAGES/INQUA working group) and HOLSEA (an INQUA project)  
858 for useful discussions at the 2019 meeting, Dublin, Ireland. We thank Nicole Khan and Matteo Vacchi  
859 for their constructive reviews. This is a contribution to International Geoscience Programme (IGCP)  
860 project 639. Any use of trade, firm, or product names is for descriptive purposes only and does not  
861 imply endorsement by the U.S. Government.

862

863 **Data availability**

864 The Chilean sea-level database is available via Mendeley Data:

865 <http://dx.doi.org/10.17632/9459bd6gpt>

866

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