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

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Abstract

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

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

1. Introduction

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

For the first time, this paper compiles a comprehensive sea-level database for north, central, and south-central Chile (18.5°S – 43.6°S; Fig. 1) using a consistent, systematic, and internationally comparable approach (Hijma et al., 2015; Khan et al., 2019). Our database incorporates a range of different types of sea-level indicators, including tidal marsh sediments, beach ridges, marine deposits and freshwater sediments, dated using radiocarbon and luminescence approaches. We re-evaluate the geological context and age of previously published sea-level data, providing 78 index points (reconstructions of the elevation of RSL at a specific time and location) and 84 limiting points (which place minimum or maximum constraints on the elevation of RSL) that span the period from 11000 years ago to the present day. We also present a new index point and three new limiting points from four sites between 35.8°S and 43.6°S. By compiling and comparing the RSL history for 11 different regions, we seek to summarise current knowledge of Chilean RSL, highlight directions for future sea-level research, and provide a resource to assist research into archaeological, palaeoclimatic, and palaeoseismic records in the coastal zone.

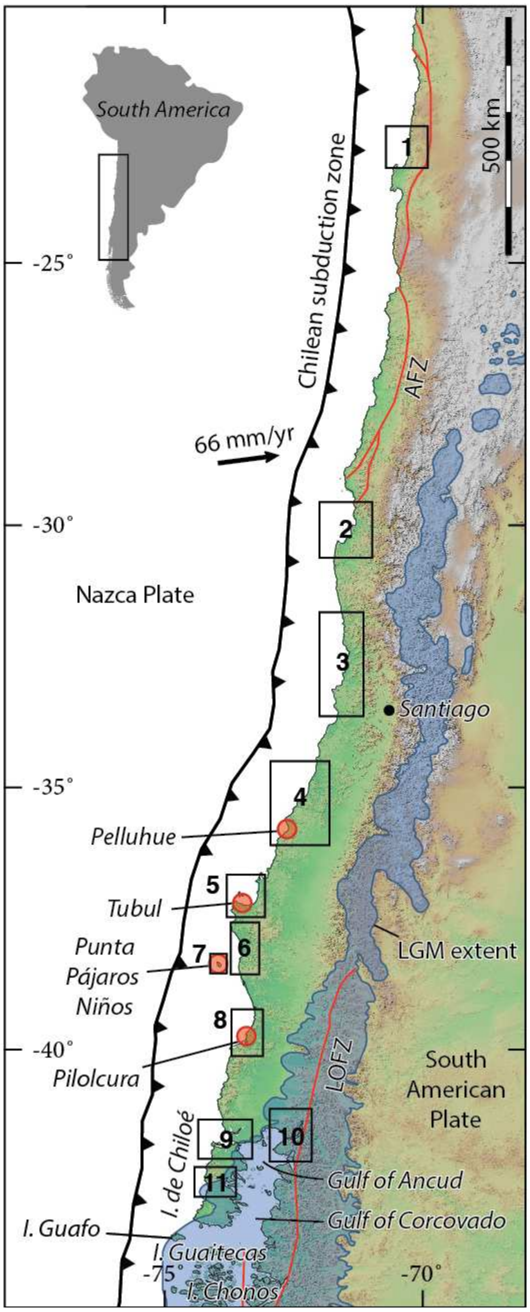

Figure 1: Location of the sea-level data points assessed in this study, grouped into regions (black boxes). Red circles indicate new sites reported here for the first time. AFZ: Atacama fault zone, LOFZ: Liquiñe-Ofqui fault zone, LGM: Last Glacial Maximum extent of the Patagonian ice sheet (blue shading,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

2. Study area

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

2.1 Tectonic setting

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

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

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

2.2 Glacial history

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

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

3. Database methodology

Through a series of International Geological Correlation Programme and International Geoscience Programme (IGCP) projects (numbers 61, 200, 274, 367, 437, 495, 588 and 639), the sea-level community has derived and implemented standardised and globally applicable approaches to sea-level reconstruction. Integral to this endeavour, sea-level databases synthesise data from different studies to reconstruct regional relative sea-level histories (Bloom, 1977; Pirazzoli, 1991; Shennan et al., 2002; Khan et al., 2019). Databases contain sea-level index points, reconstructions of the elevation of RSL at a specific time and location, and limiting points, which place minimum or maximum constraints on the elevation of RSL (marine and terrestrial limiting points respectively). Our database compiles sea-level indicators from the literature, interpreting data from a wide range of sources as either index or limiting points. For each data point, we quantify sources of vertical and temporal uncertainty following the approach set out by Hijma et al. (2015).

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

3.1 Data sources

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

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

3.2 Indicative meaning

To serve as an index point, a sea-level indicator must have a defined relationship with tidal levels, or *indicative meaning* (van de Plassche, 1986; Shennan, 2015). The indicative meaning consists of the *reference water level*, the elevation at which the indicator occurs with respect to contemporaneous tidal levels, and the *indicative range*, the span of elevations at which the indicator might be found. We define indicative ranges for seven different types of index points and define reference water levels as the mid-points of the indicative ranges (Table 1). We obtain tidal datums for each location, modelling mean lower low water (MLLW), mean low water (MLW), mean tide level (MTL), mean high water (MHW), mean higher high water (MHHW), and highest astronomical tide (HAT) using the TPXO8-ATLAS global model of ocean tides (Egbert and Erofeeva, 2010). We scale the modelled tidal amplitude for each location following analysis of the differences between the tidal model and data from 21 permanent tide gauge stations (supplementary information S1).

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

Sample type	**Evidence**	**Reference water level**	**Indicative range**
Index points			
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 m	HAT – HAT+3m
Undifferentiated beach environment	Sand- or gravel-rich sediments, may contain shells or shell fragments. Includes beachface, berm and beach ridge environments.	(MLLW – HAT+3m)/2	MLLW – HAT+3m
Limiting points			
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+3m	Below HAT+3m
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

Tidal marsh environments provide the majority of our index points. We separate these into low marsh, high marsh, undifferentiated marsh, and specified marsh environments based on macro- and microfossil evidence (Atwater et al., 1992; Nelson et al., 2009; Garrett et al., 2015). Specified tidal marsh refers to samples with indicative meanings provided in the original study by the statistical comparison of modern and fossil microfossil assemblages, usually diatoms, using transfer functions (e.g. Garrett et al., 2015). The second largest group of index points come from beach ridges and undifferentiated beach environments. The relationship between the elevation of a beach ridge crest and coeval sea level is complex, with elevation reflecting wave run-up and other sediment transport mechanisms (Orford et al., 1991; Otvos, 2000; Tamura, 2012). Tamura (2012) recommends that sandy beach ridges are not used as sea-level indicators as the uncertainties involved are frequently too large in comparison with reconstructed sea-level changes since the mid Holocene. As we are not seeking to identify small-scale sea-level changes, we choose to incorporate sandy beach ridges and account for uncertainties using appropriately cautious indicative ranges. Furthermore, the presence of low elevation modern ridges and the occurrence of multiple fossil ridges at low elevations indicates Chilean beach ridges form within a few metres of contemporaneous sea level (Nelson and Manley, 1992; Bookhagen et al., 2006). On the Atlantic coast of Patagonia, Schellmann and Radtke (2010) suggest that beach ridge crests lie between 2 and 3 m above the highest tide level on exposed shorelines and down to 1 m or less above the highest tides in wave-protected areas. In this work, we conservatively consider beach ridge crests to lie between HAT and 3 m above HAT (Table 1). Where sediments are described by the original authors as "beach deposits" or similar, we extend the indicative range described above for beach ridges to include the intertidal zone (i.e. between MLLW and HAT + 3m). A similar approach was recently used by Vacchi et al. (2018) in eastern Canada.

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

3.3 Quantifying vertical uncertainties

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

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

3.4 Accounting for tectonics, compaction and tidal range changes

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

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

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

3.5 Chronological control

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

3.6 Data visualisation

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

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

3.7 Modelling glacial isostatic adjustment and tectonic uplift

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

To assess the possible role and rates of millennial-scale tectonic uplift, we apply a range of linear corrections to the RSL data to improve the fit with the GIA model predictions in each region. To allow for shorter-term variability resulting from centennial-scale earthquake deformation cycles, we include a ± 1 m envelope around the model predictions. The magnitude of this envelope provides a conservative assessment of centennial cycles, reflecting the upper bound of vertical deformation recorded at coastal sites during 20th and 21st century great earthquakes (Plafker and Savage, 1970; Farías et al., 2010; Klein et al., 2017). We accept all corrections that result in index points (including error terms) overlapping the suite of model predictions, terrestrial limiting points sitting within or above the predictions, and marine limiting points lying within or below the predictions.

4. New sea-level data

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

4.1 Pelluhue, Maule region

At Pelluhue (35.8133°S 72.5762°W), an outcrop at the landward edge of the contemporary beach exposes an abrasion platform carved into metamorphic bedrock. Black volcanic sand and a colluvial wedge overlie the platform (Fig. 2). The medium to coarse volcanic sand is similar in composition and grain size to the contemporary beach sand but lacks datable organic material. The colluvium consists of angular pebbles, rounded cobbles and charcoal fragments that we interpret as having accumulated above the reach of tides. We radiocarbon dated three charcoal fragments from a layer at the base of the colluvium at an elevation of 4.87 ± 0.15 m MSL. The resulting dates constrain the timing of the deposition of the colluvium; the median calibrated ages lie within 100 years of each other (Table 2). The youngest calibrated age range, 4407 – 4095 cal a BP, provides the age for a terrestrial limiting point. We derive the maximum elevation of RSL by taking the reference water level (HAT = 1.08 m) away from the sample elevation and adding the sum of the positive vertical uncertainties (comprising uncertainties related to the absolute elevation, the depth within the section, and the indicative meaning: 0.19 m). The terrestrial limiting point therefore indicates RSL was below 3.98 m.

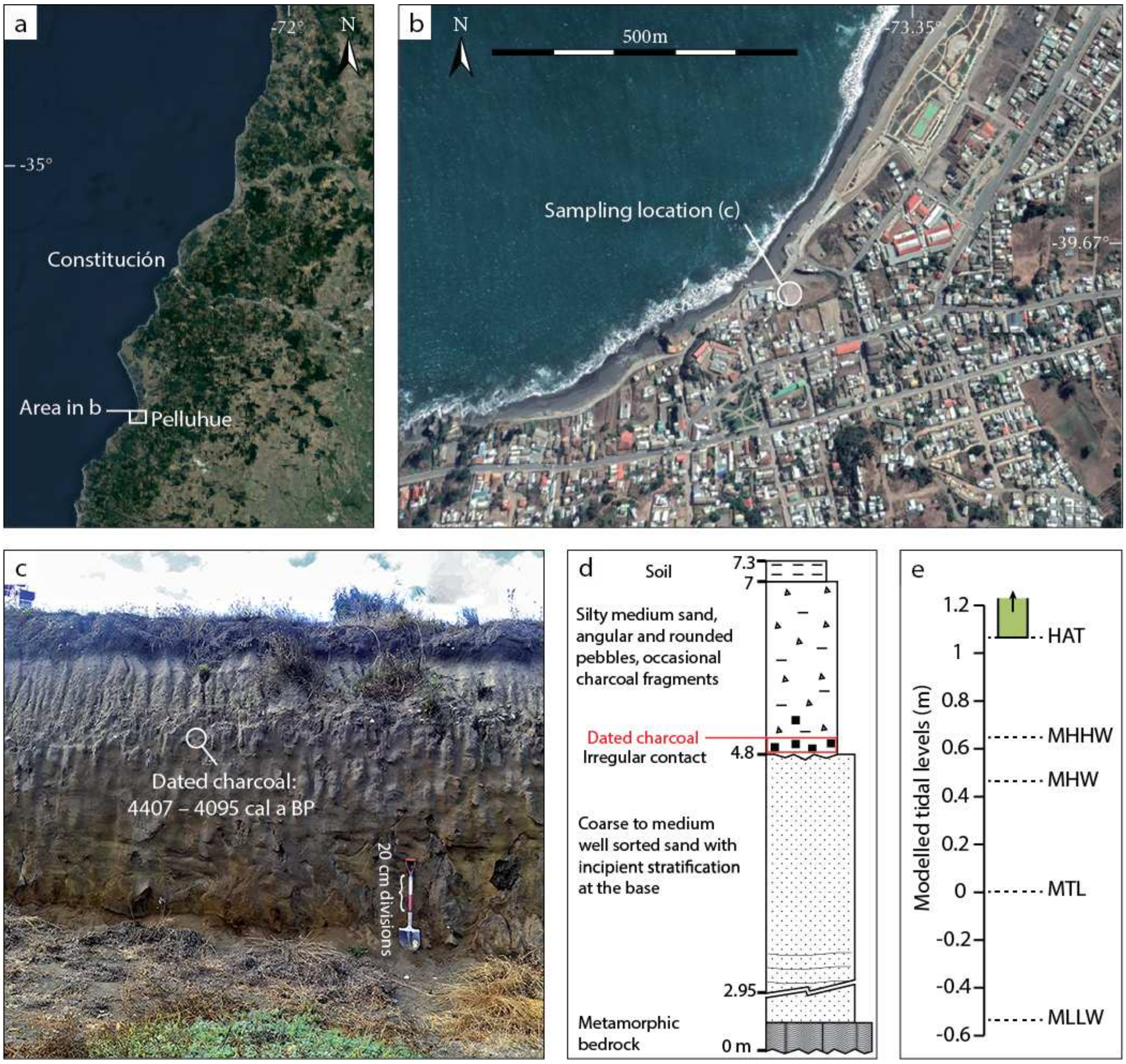

Figure 2: Derivation of the new terrestrial limiting point from Pelluhue. a) Location of Pelluhue and b) sampling location. c) Photograph and d) stratigraphic log of the dated section. e) Graphical representation of the terrestrial limiting point's indicative meaning (open-ended green box; above highest astronomical tide) relative to tidal levels at the site modelled using the TPXO8-ATLAS tidal model (Egbert and Erofeeva, 2010). Basemaps in a) and b) are from Bing Maps.

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

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

4.2 Tubul, Arauco region

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

We dated an articulated *Petricola rugosa* shell found in life position inside its hole in the bedrock platform, which was preserved beneath the conglomerate (Table 2). As living *P. rugosa* individuals are found beneath MTL and generally in water depths of less than 10 m (Bernard, 1983), the resulting calibrated date, 5302 – 4421 cal a BP, provides the age of a marine limiting point. Accounting for the sample elevation (2.69 m), the reference water level (MTL = -0.01 m), and the sum of the negative vertical uncertainties (0.13 m), the limiting point indicates RSL above 2.57 m.

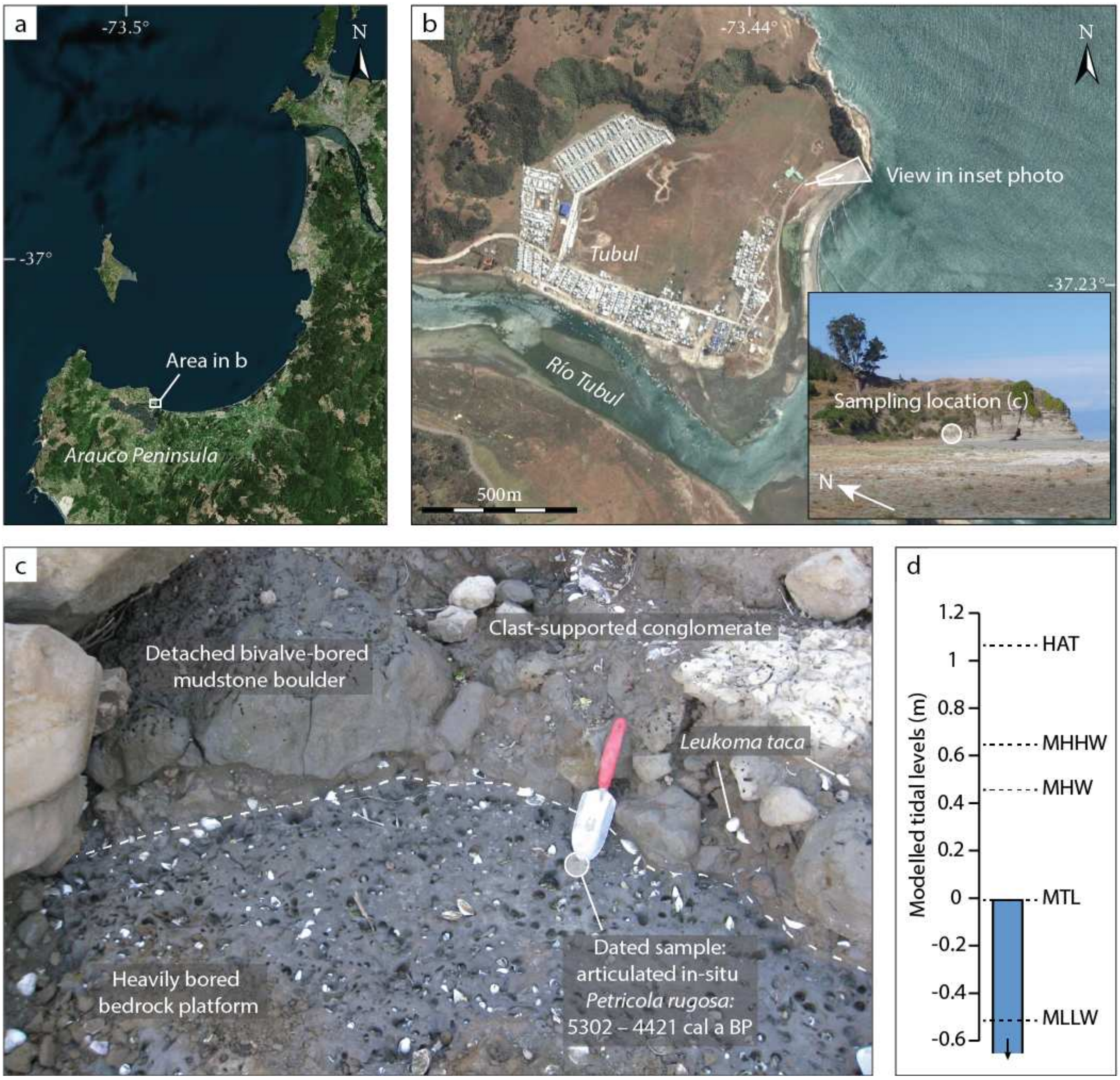

Figure 3: Derivation of the new marine limiting point from Tubul. a) Location of Tubul on the northern side of the Arauco Peninsula, b) sampling location on the headland east of Tubul, c) photograph of the bivalve-bored bedrock platform with the location of the dated *Petricola rugosa*, d) graphical representation of the marine limiting point's indicative meaning (open-ended blue box; below mean tide level) relative to tidal levels at the site modelled using the TPXO8-ATLAS tidal model (Egbert and Erofeeva, 2010). Basemaps in a) and b) are from Bing Maps.

4.3 Punta Pájaros Niños, Isla Mocha

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

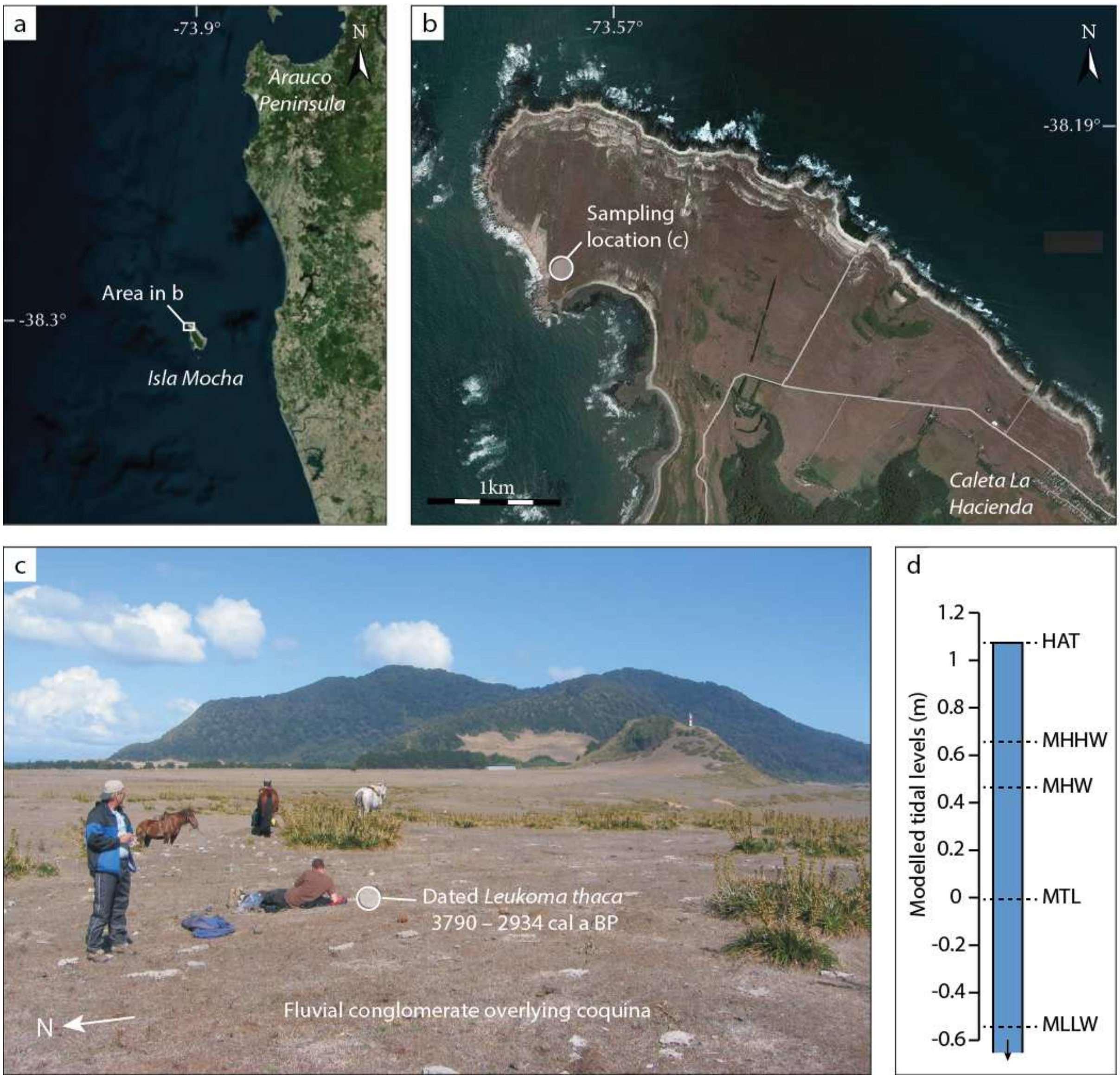

Figure 4: Derivation of the new marine limiting point from Punta Pájaros Niños. a) Location of Isla Mocha and b) the sampling location close to the northern tip of the island. c) Photograph of the sampling site, d) graphical representation of the marine limiting point's indicative meaning (open-ended blue box; below highest astronomical tide) relative to tidal levels at the site modelled using the TPXO8-ATLAS tidal model (Egbert and Erofeeva, 2010). Basemaps in a) and b) are from Bing Maps.

4.4 Pilolcura, Valdivia region

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

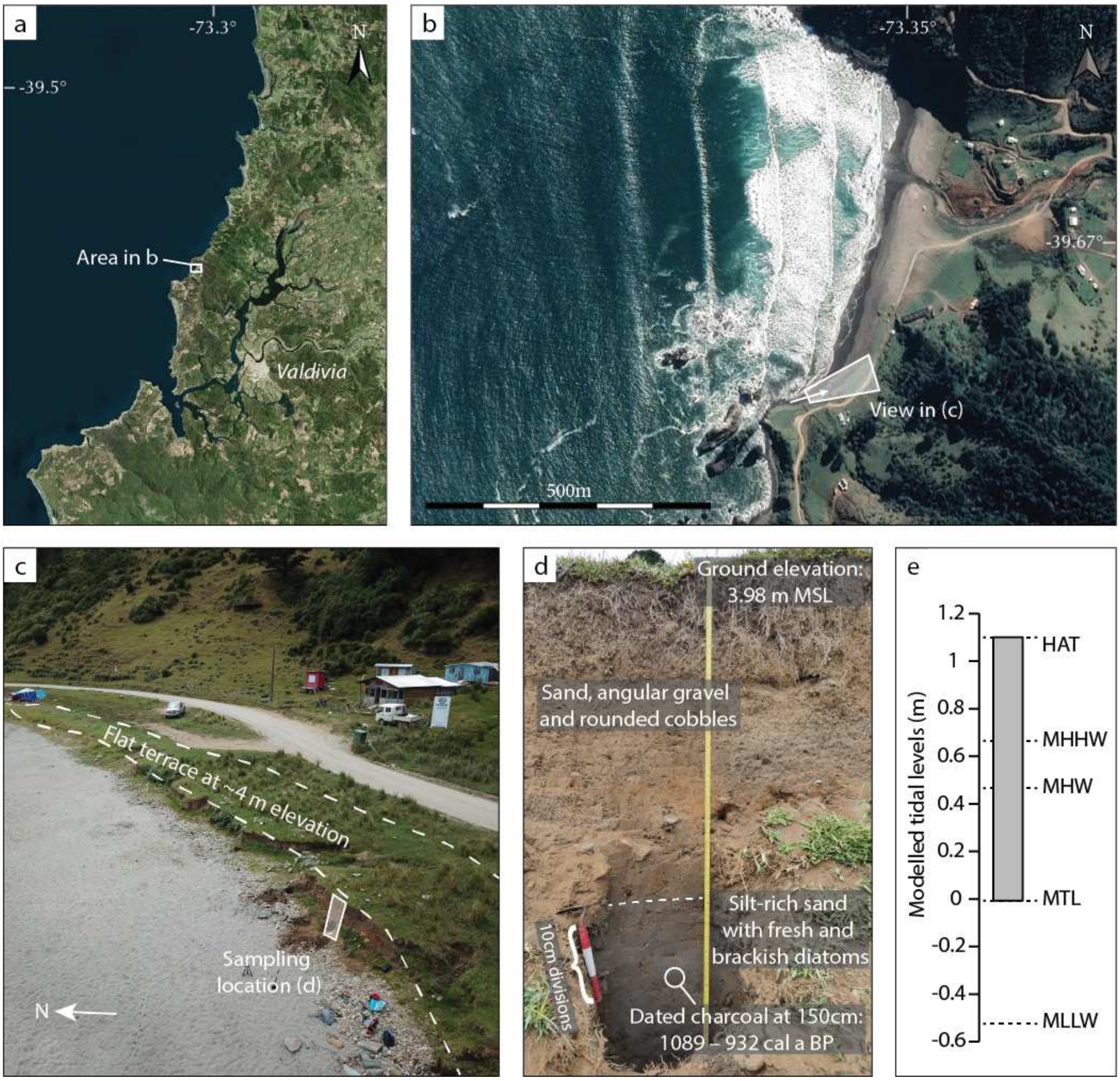

Figure 5: Derivation of the new sea-level index point from Pilolcura. a) – c) Location of the sampling site, d) photograph of the dated section, e) graphical representation of the index point's indicative meaning (grey box; between mean tide level and highest astronomical tide) relative to tidal levels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

5. The database and regional sea-level histories

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

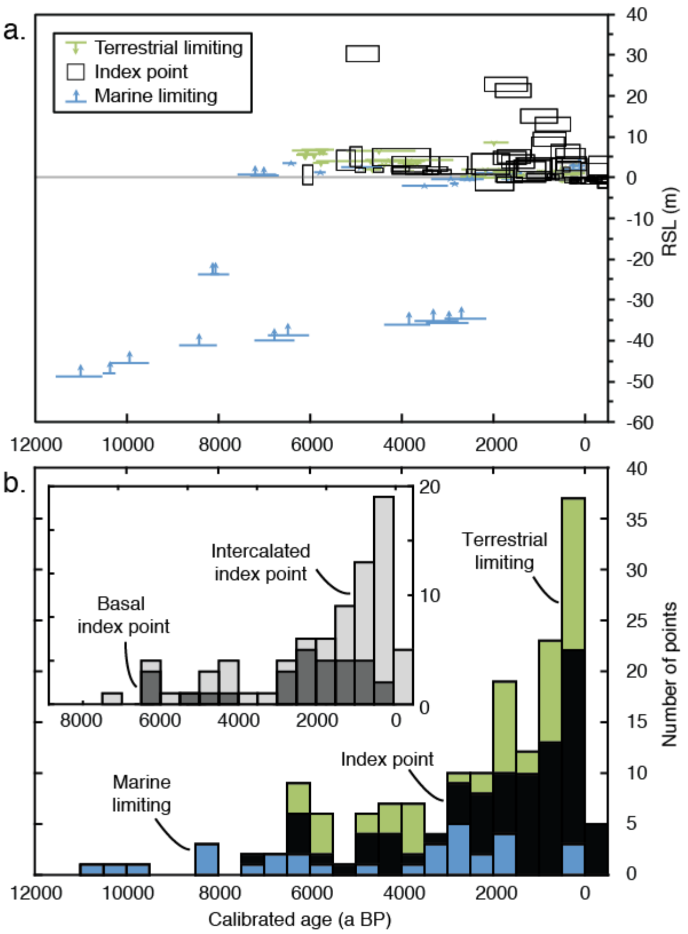

Figure 6: a. Plot of all accepted sea-level data points in the Chilean database. b. Stacked histogram of the temporal distribution of accepted sea-level data points. Inset compares the distribution of basal and intercalated sea-level index points.

5.1 Antofagasta (Fig. 7, region 1)

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

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

The RSL record of this semi-arid region consists of 11 index points and one marine limiting point from five sites. In contrast to the paucity in other regions, 9 of the 11 index points are from basal settings. The earliest sea-level data point, a ~7.2 ka BP marine limiting point from Estero Tongoy (Ota and Paskoff, 1993), places sea level above ~0.7 m. Index points from prograding sequences of beach ridges in the Bay of Coquimbo (Hart et al., 2017) and beach deposits at El Rincón and Punta Lengua de Vaca, both fringing Tongoy Bay (Ota and Paskoff, 1993), indicate falling sea level after ~5 ka BP from a maximum of at least 5.00 ± 2.09 m. Three index points from Puerto Aldea and El Rincón (Ota and Paskoff, 1993) indicate RSL was between 0 m and 5 m by 2 ka BP, with the large vertical uncertainty associated with the broad indicative range associated with index points from undifferentiated beach environments. Within the last 100 years, two index points from Quebrada de Teatinos, Bay of Coquimbo, place RSL around -1.8 m, with a vertical uncertainty of ~0.7 m (May et al., 2013). We do not incorporate further dated samples from Quebrada Los Chines (Ota and Paskoff, 1993), Quebrada de Teatinos, and Quebrada Pachingo (May et al., 2013) due to the potential for reworking or chronological uncertainties identified by the original authors.

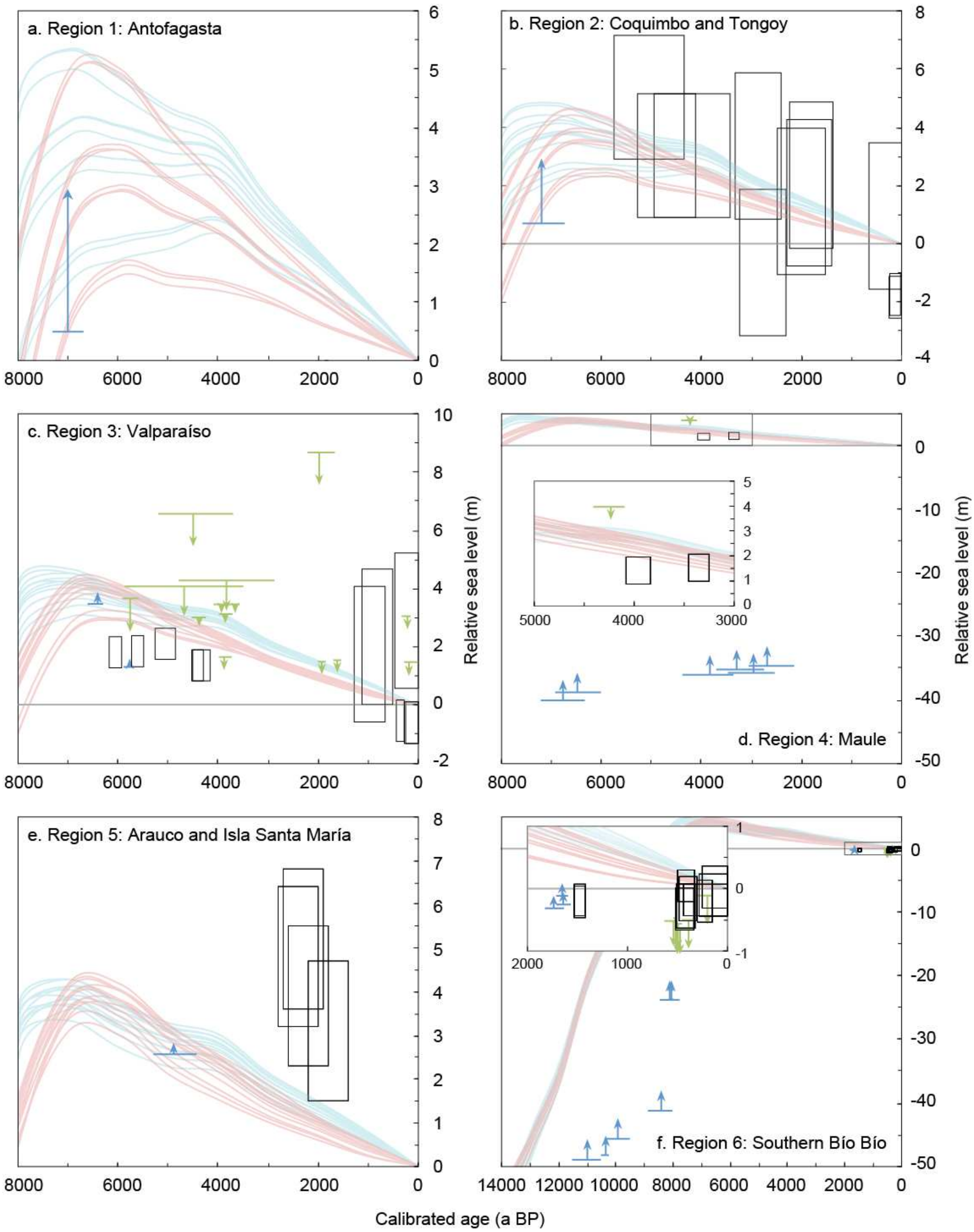

Figure 7: Regional plots comparing the age – elevation distribution of the sea-level data points with glacial isostatic adjustment model predictions (following Peltier, 2004; Peltier et al., 2015). Sea-level index points are black rectangles, terrestrial and marine limiting points are green T-shaped symbols and blue ⊥-shaped symbols respectively. ICE_5G predictions are light blue curves, ICE_6G predictions are pink curves; for both ice models, we vary the lithospheric thickness between 71 and 120 km and the upper mantle viscosity between 5 x 10^{19} Pa s and 2 x 10^{20} Pa s (see section 3.7). Note different x-axis scaling for panel f and variable y-axis scaling between all panels.

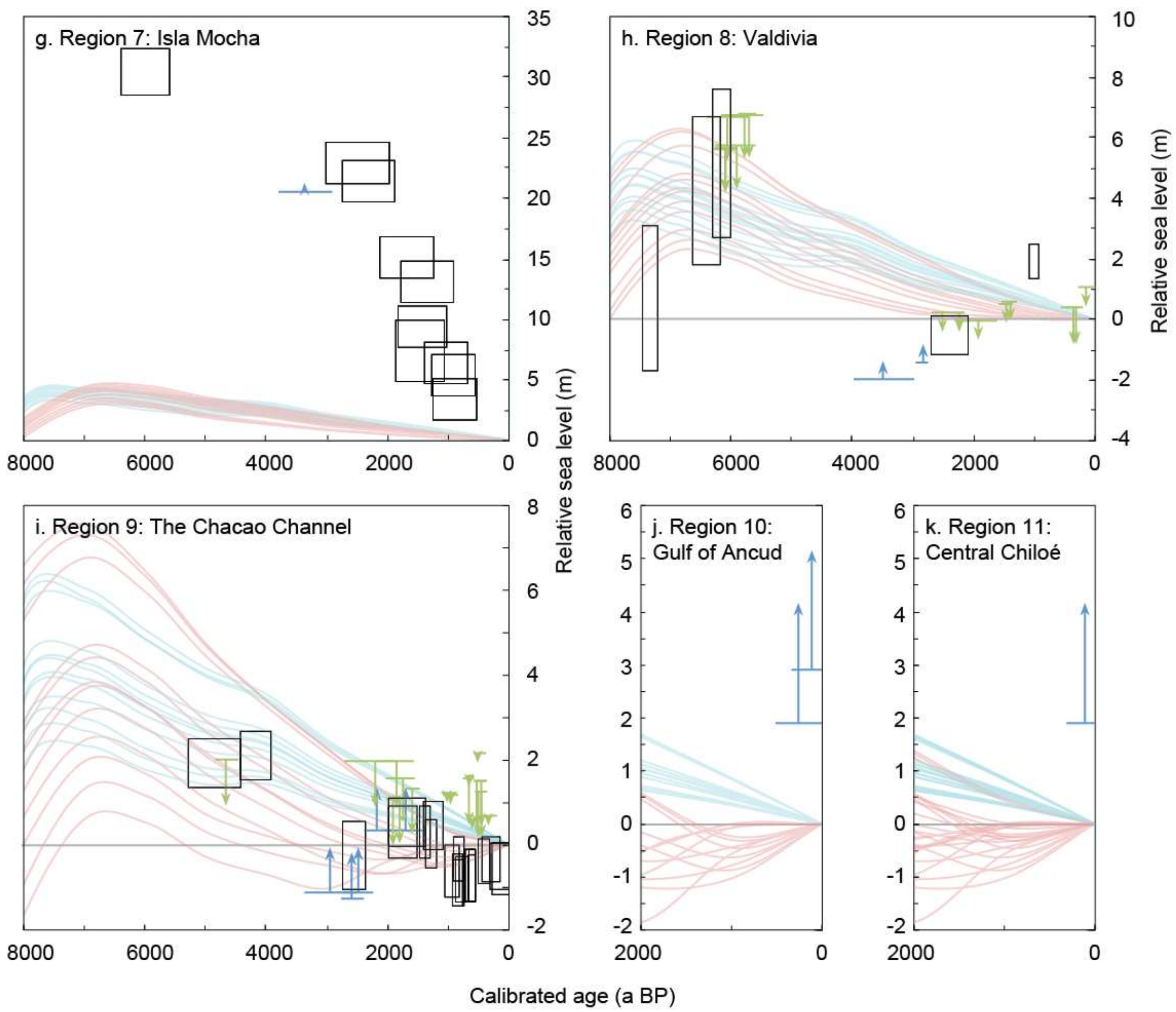

Figure 7 (continued)

5.3 Valparaíso (Fig. 7, region 3)

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

5.4 Maule (Fig. 7, region 4)

In addition to the new terrestrial limiting point from Pelluhue (section 4.1), the sea-level history of this region is further constrained by two index and six marine limiting points from two sites. Frugone-Álvarez et al. (2017) report 11 radiocarbon dates from cores taken from Lago Vichuquén. The lowermost six samples are from sediments interpreted by Frugone-Álvarez et al. (2017) as indicative of marine environments; consequently, the dates constrain the ages of marine limiting points. As the location and elevation of the sill between the lake basin and the sea at the time of deposition is uncertain (today it lies at 2.4 m above EGM2008), we conservatively assume that there was no sill. The accepted marine limiting points place RSL above -40 m at ~6.8 ka BP and above -35 m at ~2.7 ka BP. While the overlying sediments are interpreted as brackish and freshwater (Frugone-Álvarez et al., 2017), radiocarbon dates from these layers cannot be used to constrain sea level due to uncertainties over the isolation of the lake and the role of sediment supply and local tectonics in building the sill. The terrestrial limiting point from Pelluhue places RSL below ~4 m at ~4.2 ka BP, while two index points from El Yolki indicate RSL between 0.85 and 2.1 m between 4 and 3 ka BP (Hilleman, 2015; Melnick et al., 2019). We do not consider 13 other radiocarbon dates of ~4 ka BP from Melnick et al. (2019) due to their close proximity to the El Yolki Fault.

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

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

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

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

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

5.7 Isla Mocha (Fig. 7, region 7)

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

5.8 Valdivia (Fig. 7, region 8)

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

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

The coast of northern Chiloé and the adjacent continental coast around the Río Maullín, collectively termed the Chacao Channel region, provide 26 index, five marine limiting and 19 terrestrial limiting points. These points stem from palaeoseismic studies of coastal lowlands and marshes (Atwater et al., 1992; Cisternas et al., 2005; 2017; Garrett et al., 2015). The earliest sea-level data come from Chocoi, where tidal marsh peat layers exposed in a sea cliff attest to RSL ~2 m above present between 5 and 4 ka BP (Atwater et al., 1992). A subsequent fall in RSL is recorded by tidal marsh deposits at Maullín (Cisternas et al., 2005), Dadi, and Puente Cariquilda (Atwater et al., 1992). Six index points from these locations place RSL between -1 m and 1 m during the period between 3 and 1 ka BP. Terrestrial limiting points in this interval place sea level below 2 m, with marine limiting points indicating sea level above -1.5 m at ~3 ka BP and above 0.35 m at ~2 ka BP. Twelve index points from Chucalen (Garrett et al., 2015) and six from Maullín (Cisternas et al., 2005) indicate RSL was ~1 m below present at ~0.9 ka BP, with the subsequent rise to present overprinted by metre-scale coseismic subsidence events resulting from great subduction earthquakes (Garrett et al., 2015). Terrestrial limiting points for the last 1 ka from Maullín (Cisternas et al., 2005) and Cocotué (Cisternas et al., 2017) indicate sea level below elevations varying between 2.3 m and 0.7 m.

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

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

5.11 Central Chiloé (Fig. 7, region 11)

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

6. Discussion

6.1 Glacial isostatic adjustment

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

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

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

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

6.2 Regional tectonic uplift

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

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

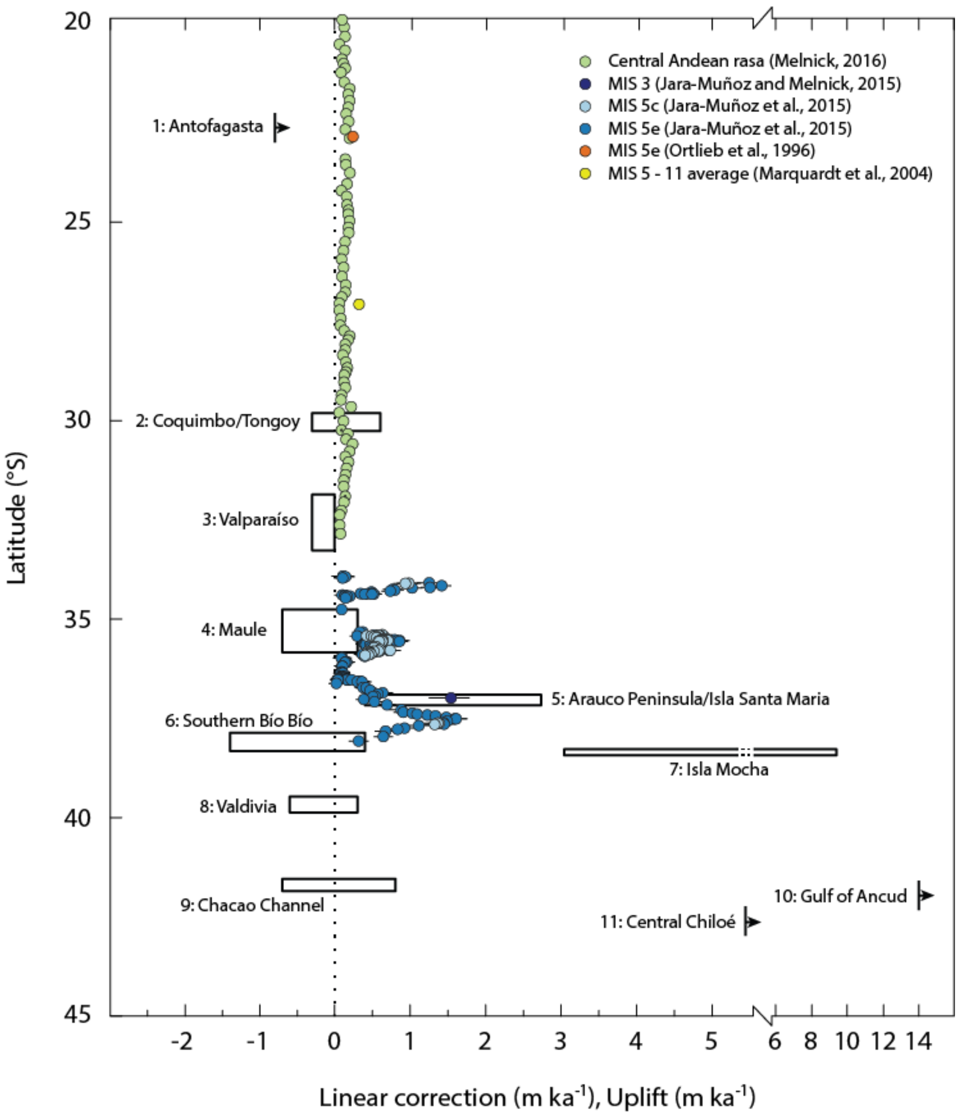

Figure 8: Comparison of best-fit linear correction rates (black rectangles) required to remove the misfit between sea-level data and a suite of glacial isostatic adjustment models with independently derived estimates of tectonic uplift (coloured circles). Sea-level data and GIA models for the 11 regions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

Accepted linear correction rates for region 4 range from -0.7 m ka^{-1} (subsidence) to 0.3 m ka^{-1} (uplift) (Fig. 8). Jara-Muñoz et al. (2015) suggest higher tectonic uplift rates in the region since the last interglacial, with rates of 0.4 to 0.8 m ka^{-1} associated with a long-wavelength upwarping zone and the activity of three major crustal normal faults that intersect the coastline and displace the marine isotope stage (MIS) 5 marine terraces. Correcting the sea-level data for such high tectonic uplift rates would lower index points below our model predictions. This could 1) potentially indicate a greater level of spatial variability in uplift rates associated with local crustal structures than previously identified, 2) suggest that late Holocene tectonic uplift rates have not been sustained over longer timescales, or 3) reflect spatial complexity in Earth rheology that is not accounted for by GIA models. Uplift rates inferred from last interglacial terraces do not account for local departures from the global eustatic sea level associated with GIA (Creveling et al., 2015), potentially also contributing to the disparity with the inferred Holocene rates.

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

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

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

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

Linear corrections of -0.6 m ka^{-1} (subsidence) to 0.3 m ka^{-1} (uplift) provide an acceptable fit between data and models in region 8, with a similar range of -0.7 m ka^{-1} (subsidence) to 0.8 m ka^{-1} (uplift) for region 9 (Fig. 8). Notably, in region 9, index points for the last 1000 years are below present sea level. This pattern, apparent from two sites separated by ~40 km, was previously recognised by Garrett et al. (2015) and tentatively attributed to incomplete interseismic uplift following coseismic subsidence during the 1960 earthquake. Interseismic uplift rates have been slowly increasing over the past few decades (Melnick et al. 2018), a trend that would raise the dated sediments back towards present sea level. In addition, effects at a local scale such as sediment compaction, or at a larger scale such as neoglacial forebulge collapse, might influence RSL in this region over the last millennium. While GIA model predictions generated using the ICE-6G ice model (Peltier et al., 2015) in combination with relatively weak upper mantle viscosities replicate a late Holocene sea-level rise, this signal may occur due to the low spatial resolution of the model and its inability to fully resolve water loading and shoreline changes in this landscape of deep marine gulfs and mountains. The cause of late Holocene sea-level rise in this region remains uncertain; nevertheless, its occurrence provides accommodation space and may explain the preservation of palaeoseismic evidence at sites in the region (Cisternas et al., 2005; 2017; Garrett et al., 2015).

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

6.3 Data paucity and areas for future focus

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

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

7. Conclusions

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

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

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

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

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Data availability

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

http://dx.doi.org/10.17632/9459bd6gpt

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