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Earthquakes and coastal archaeology: Assessing shoreline shifts on the southernmost Pacific coast (Chonos Archipelago 43°50′–46°50′ S, Chile, South America)

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ABSTRACT

Subduction, isostatic rebound, and changes in global sea levels, combined with the last glaciation, have shaped the geography of the channels of Western Patagonia. Current archaeological research in this area includes some ten sites that allow us to characterize the occupation of this territory by marine hunter-gatherers. The studied archaeological sites also inform about the various geomorphological changes that the coastline has undergone. Archives dating back six thousand years ago and archaeological contexts yield new insights about the location, distribution, and position of the shoreline and its changes over time. We present a set of data, including new sites and AMS radiocarbon determinations, which supports the hypothesis that landforms have risen or subsided, and provide the bases for a working model in which archaeological ages can inform the chronology of changes in the region's coastal morphology. This paper suggest that human occupations between 6200 and 4400 cal BP recorded on high terraces of the Guiatecas Archipelago indicate higher local sea-levels, while the sites immediately on the waterfront are 2000 years younger. On the other hand, sites younger than 3300 cal BP on the modern coastline of the Chonos archipelago undergo permanent shaping, mainly due to local tectonics affecting vertical movement. Considering previously published and new data provided in this paper, we suggest preliminary uplift rates between 0.57 and 5.42 m/ka for the Guaitecas Archipelago, 0.31–1.48 m/ka for the northern sector of the Chonos Archipelago, and 0.85 m/ka in the central sector.

1. Introduction

On a global scale, post-glacial coastline changes are mainly associated with eustatic changes in sea levels that have been extensively documented (Siddall et al., 2003). Important studies also discuss the consequences that this process has produced in reshaping the coast, and its effects on communities dwelling in littoral environments (e.g. Fairbanks, 1989; Isla, 1989; Long, 2001; Murray-Wallace, 2007; Nakada and Lambeck, 1988). From the viewpoint of archaeology in the Americas, these changes hide and destroy material evidence accounting for how early human populations related with coastal environments since the terminal Pleistocene (e.g. Bailey and Parkington, 1988; Clark et al., 2014; Dillehay et al., 2008; Fedje and Christensen, 1999; Gusick and Faught, 2011; Punke and Davis, 2006; Reeder-Myers et al., 2015; Richardson, 1981; Sandweiss, 2008). Likewise, various studies have used evidence from archaeological records to infer the occurrence of associated catastrophic events (e.g. tsunamis or big storms) capable of shaping coastal geomorphology (Nichol et al., 2003; Carson, 2004; McFadgen and Goff, 2007). Consequently, a detailed study of coastal adaptations should be initiated with a thorough understanding of the processes involved in sea level change and the geoforms (i.e. marine terraces) produced by such processes, thereby providing the basis for assessing the incidence of local and regional factors involved. The Pacific coast of South America provides a unique context for evaluating human dispersal processes because it was the last continental coastal setting to be settled. Its lower latitudes were settled at 13,000 calibrated years

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before present (cal BP) as suggested coastal resource exploitation (Sandweiss et al., 1998; Dillehay et al., 2012; Méndez, 2013), and there is even older evidence at 14,600 cal BP in Monte Verde at 40° S as indicated by algae transport (Dillehay et al., 2008). While archaeological data has been used in studying coastal geomorphological change in areas along eastern Patagonia (e.g. Favier-Dubois and Kokot, 2011) and the Pacific of South America (e.g. May et al., 2015), the southernmost fringe of the Pacific littoral remains understudied and presents particular challenges, coastal remodeling being one of the most significant approaches.

In the Western Patagonian Channels of southernmost South America, specifically the area of the Magellan Strait and the Otway and Skyring Sounds, geo-archaeological studies reveal interesting associations between changes in the coastline throughout the post-glacial and the location of archaeological sites across an elevation gradient (McCulloch and Morello, 2009; San Román, 2013). In particular, these studies demonstrate a positive correlation between the elevation of archaeological sites and the chronology associated with changes in regional sea level evinced by geomorphological studies (Milne et al., 2005). These studies corroborate the occurrence of a marine transgression during the Mid-Holocene, originally determined only by numerical models (Clark et al., 1978). It may therefore be proposed that in areas where there are no comprehensive studies on coastal geomorphology and evolution, archaeological information might be used for an initial approach in order to estimate changes in sea levels; although acknowledging some of the problems this approach entails, such as the lack of direct association between the age of the site and the age of the landform.

The Chonos Archipelago (43°50′ - 46°50′ S), located in the northern part of the Western Patagonian channels (Fig. 1), constitutes a unique region where three tectonic plates converge, resulting in earthquake subduction (Lomnitz, 1970; Melnick et al., 2008; Ramos, 2005). This coincides with high levels of volcanic activity (Naranjo and Stern, 2004) and frequent large tsunamis (Abe, 1979). Moreover, during the Last Glacial Maximum (LGM) this area was covered by large glaciers whose advances and retreats shaped landscapes through various processes including isostatic rebound (Aniya, 1999; Haberle and Bennett, 2004; Heusser, 2002; Glasser and Ghiglione, 2009; Reed et al., 1988). All the above factors, combined with global changes in sea levels, produce singular challenges for discovering archaeological sites (Reyes et al., 2015, 2016) because it is significantly difficult to model and interpret old coastal shorelines. The conditions described for this area are different from those of other coastal zones in Patagonia, for example the Magellan Strait. The spatial distribution of the archaeological sites in the Chonos Archipelago is largely determined by an abrupt change in landscape at 41°S. The tectonic subsidence of the central area, glacial incision and the emergence of a series of inner seas and channels constitute elements not only conditioned human occupation of this region, but also influenced the survival of evidence of such occupation and the ability of archaeologists to detect it.

In previous works we have documented the characteristics of the available archaeological and bio-anthropological record (Reyes et al., 2011, 2013), as well as the chronology of occupation of the Chonos Archipelago by marine hunter-gatherers (Reyes et al., 2015). We have also highlighted the importance of addressing study of the cultural record of this zone in the context of human occupation of the southernmost part of South America (Orquera et al., 2011; Piana et al., 2012; San Román et al., 2016) and the importance of the archaeological record to inform geomorphological changes in the area (Reyes et al., 2016). The objective of the present work is to discuss how the archaeological record can be used to trace changes in the coastline during the post-glacial in an area where few data exist. This article summarizes the characteristics of the preservation of cultural deposits in the Chonos Archipelago, their location in relation to ancient and modern coastlines,

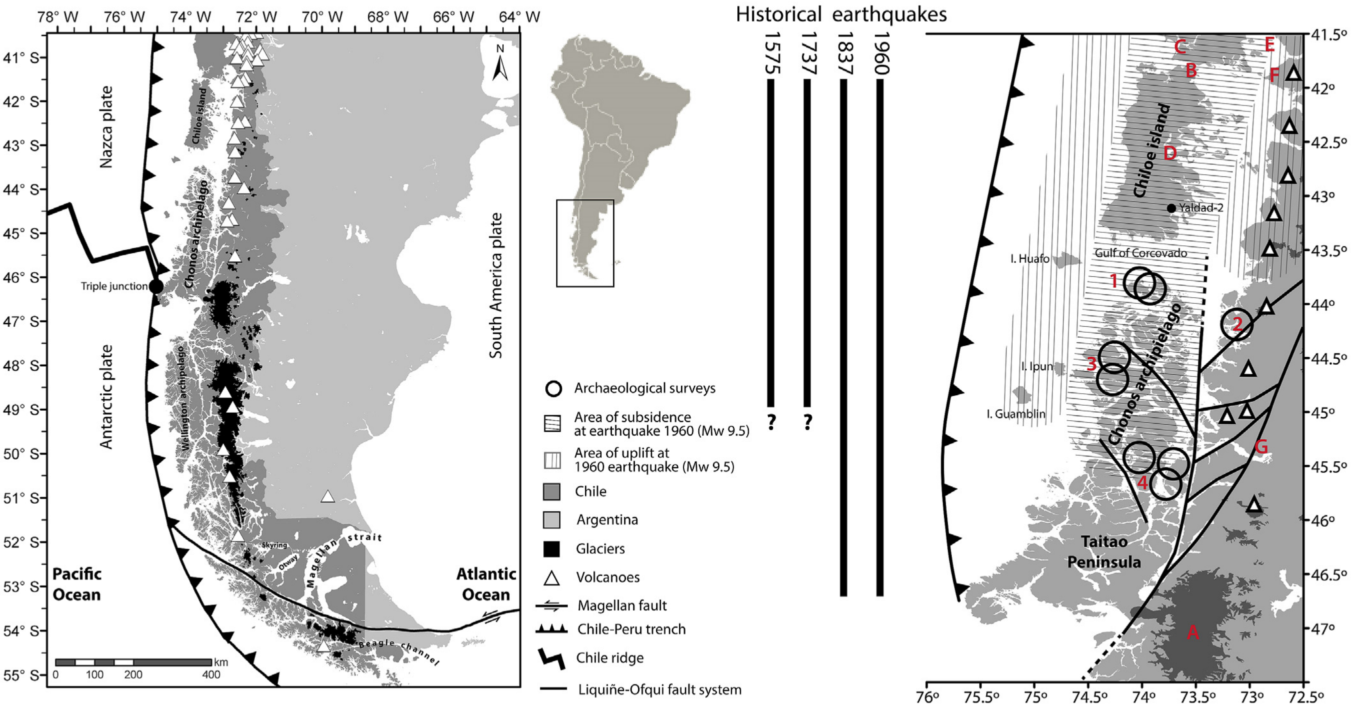

Fig. 1. General map of southernmost South America indicating the main geographical and tectonic features of the area and the main sites discussed in the text; (1) Guaitecas Archipelago, (2) Gala Sound (continental border), (3) central-west Chonos area, (4) central-south Chonos area, (A) Northern Icefield, (B) Chacao Channel, (C) Maullín, (D) Nercón, (E) Reloncaví Sound, (F) Hualaihué, (G) Aisén Fjord.

and the chronology associated with the ingression of marine sediments preserved between deposits of human origin (i.e. shell middens).

1.1. Regional context and environment

The southernmost part of the South American Pacific coast is dominated by a complex network of channels, fjords and thousands of islands known as the Western Archipelago or Patagonian Channels (Bird, 1988; Emperaire, 1963). From the Reloncaví Sound in the north to Cape Horn in the south (41°30′–55°60′S), a distance of 1600 km, more than 19,000 km of discontinuous shorelines enclose a land area >240,000 km^2 (Glasser and Ghiglione, 2009) (Fig. 1). In the northern part of the Patagonian Channels, the Chonos Archipelago forms a group of over 150 islands inserted in a maze of channels and fjords with narrow, abrupt shores. It is located between the southern end of the Chiloé Archipelago (Gulf of Corcovado 43°50′S) and the Taitao Peninsula (46°50′S). It covers an area >54,000 km^2, spanning 360 km from north to south and 150 km wide.

The age of this archipelago and the mechanism by which it was generated are unclear. However the evidence suggests that the submergence of the Central Valley (a subaerial landscape feature further north) and the consequent formation of a series of islands, channels and fjords, occurred during Pleistocene as a result of glacial shaping and tectonic subsidence (Borgel, 1970; Glasser et al., 2004; Heusser, 2003; McCulloch et al., 2000).

The region's climate is controlled by the seasonal variability of the westerly winds that bring abundant precipitation (>3000 mm per year) to the coastal areas rainfall diminish further east, due to the rain-shadow effect of the Andes (Garreaud et al., 2009). Temperatures are strongly influenced by the sea, and coastal areas present higher mean annual temperatures (10 °C) and greater variation over the year than higher or inland areas. This climate is classified as temperate with oceanic influence (Di Castri and Hajek, 1976). In the Andean range where the highest elevations in the region are found (>1000 masl), there is a reduction in mean annual temperatures, resulting in the persistence of icecaps, remnants of the last glacial period. The largest of these are the Northern (4200 km^2) and Southern (13,000 km^2) Patagonian Ice Fields (Warren and Sugden, 1993).

The regional vegetation is controlled by precipitation and temperature gradients that change with latitude and altitude (Gajardo, 1994; Luebert and Pliscoff, 2006; Oberdorfer, 1960; Schmithüsen, 1956). Thus in coastal areas, temperate rainforest with conifers predominates up to 45°S, whereas between 45° and 56°S the vegetation is dominated by temperate coastal peatland (Luebert and Pliscoff, 2006). Fauna in the channels is represented by a diversity of marine mammals, as well as many species of mollusks, crustaceans, echinoderms, fishes and a wide diversity of birds (Aguayo et al., 2006; Navarro and Pequeño, 1979; Osorio and Reid, 2004; Vuilleumier, 1985; Zamorano et al., 2010).

1.2. Factors affecting the coastal landscape in the Chonos Archipelago

Changes in the coastline during the post-glacial, result from a series of processes and factors that operate and interact on various spatial scales (i.e. global, regional and local). These are related not only with the changes in sea level associated with variations in the global volume of ice but also with regional glacial hydro-isostatic adjustments and local/regional tectonics (Milne and Shennan, 2007; Murray-Wallace, 2007; Nelson, 2007; Shennan, 2007). Thus coastline changes reflect changes in the relative sea level (RSL) that result from the real variation in sea level (associated with vertical movements of the ocean's surface due to the expansion/contraction of the polar and continental ice-caps over thousands of years) (Chappell et al., 1996) and apparent changes that are the inverse of the vertical changes in land surface levels along the coasts (Fig. 2) (Nelson, 2007). Variations in sea level in areas affected by glacio-isostatic or neo-tectonic rebound are expressed as relative changes since the real rates of rising sea levels (i.e. eustatic) and tectonic uplift are dissimilar. Specifically, the abrupt rise in sea levels during the deglaciation of the early Holocene was considerably greater than the tectonic uplift, producing rise in relative sea level (i.e. transgression). Subsequently, when the eustatic increase in the sea level slowed (i.e. Late Holocene), compensation occurred due to the tectonic uplift resulting in a fall in sea level (i.e. regression). These changes may be abrupt or gradual depending on regional/local tectonic behavior, as is the case on the west coast of South America. Furthermore, catastrophic events like earthquakes associated with subduction zones can cause major changes in coastlines through subsidence or uplift due to deformation of the earth's crust during the rupture associated with a seismic event (Nelson, 2007). Finally, phenomena such as tsunamis and big storms may also be responsible for modifying coastlines through erosion or by incorporating new sedimentary material (Morton et al., 2007).

In the Chonos Archipelago, coastline changes are associated not only with changes in sea level, but also with vertical deformation caused by isostatic glacial rebound and the subduction of the South American plate (Atwater et al., 1992; Barazangi and Isacks, 1976; Barrientos et al., 1992; Hervé and Ota, 1993; Thomson, 2002; Lara et al., 2008). This process is complemented by local subsidence and uplift related to major earthquakes, which may be linked with tsunamis (Cisternas et al., 2005). In particular, this archipelago is

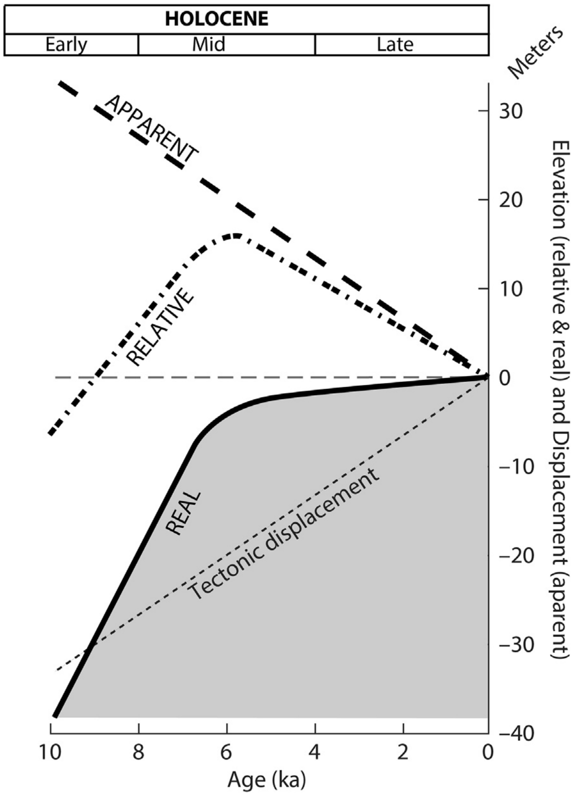

Fig. 2. Mechanisms involved in coastline changes associated with variations in sea level in areas affected by glacio-isostatic or neo-tectonic rebound (modified from Nelson, 2007).

located near an active subduction zone known as the Chilean Triple Junction where three tectonic plates (the Nazca, South American and Antarctic) converge (Thomson, 2002). This is associated with at a macro regional level with the Liquiñe-Ofqui fault system which extends for more than 1000 km from an area close to the Triple Junction (48°S) in the south to the area of the town of Liquiñe in the Andean range (38°S) (Thomson, 2002). This fault system also appears to be largely responsible for the morphology of the fjords and channels of the region (Cembrano et al., 1996; Glasser and Ghiglione, 2009).

The Liquiñe-Ofqui fault system determines the location of important centers of volcanic activity in the region (Stern, 2004), called the Southern Part of the Southern Volcanic Zone (SSVZ, 42°–46°S). The area contains thirteen volcanoes that experienced repeated eruptions during the Holocene (Naranjo and Stern, 2004). This fault system is also associated with significant seismic activity, leading to periodic earthquakes (Lange et al., 2008). One of the most recent events led to collapses caused by a tsunami on the northern shore of the Aysén Fjord (Naranjo et al., 2009).

Nevertheless, the most common cause of tsunamis in the region is the vertical deformation associated with ruptures (earthquakes) produced by the accumulation of stress between the ocean (i.e. Nazca) and continental (i.e. South American) plates during subduction (Fig. 2). This phenomenon has caused major earthquakes and tsunamis along the coast. For example, the largest contemporary subduction event recorded on a global scale (the 1960 earthquake in Chile between 37° and 48°S, Mw 9.5) caused a rise of more than 5.7 m on Guafo, Guamblin and Ipún Islands, and a subsidence of 1–2 m in the interior of the Chonos Archipelago. This event generated a fracture 1000 km long from north to south (37°–48°S) and 200 km wide, and surface displacement of between 20 and 40 m in some areas. Associated with this event occurred one of the most destructive tsunamis recorded, which affected much of the archipelago and the whole Pacific Basin (Abe, 1979; SHOA, 2000; Cisternas et al., 2005; Lagos and Cisternas, 2008). This earthquake led to important vertical changes in the earth's crust, including subsidence of much of the archipelago while neighboring areas experienced uplift (Plafker and Savage, 1970).

Considering the regional glacial history, evidence indicates that during the Last Glacial Maximum (~25,000–16,000 cal BP) lobes of ice descended from the Andes and covered extensive areas of territory located south-east of Chiloé Grande Island, the Chonos Archipelago and the Taitao Peninsula (Bennett et al., 2000; Denton et al., 1999; Haberle and Bennett, 2004; McCulloch et al., 2000; Villagrán, 1988). The potential interactions between glacial history and coastline evolution in the region can be established if we consider the possible isostatic rebound in response to the retreat of the ice in the post-glacial (Montgomery et al., 2001). Studies indicate uplift rates >10 mm/yr in the areas currently covered by the Patagonian Ice Fields and rates <10 mm/yr in adjacent areas (Dietrich et al., 2010; Hervé and Ota, 1993; Ivins and James, 2004; Lara et al., 2008).

Currently, the information on which to base understanding of coastline evolution in the Chonos Archipelago is fragmentary. Studies document the presence of deposits of marine origin located above the existing coastlines, which have been interpreted as evidence of a fall in sea level or the result of tectonic uplift (Atwater et al., 1992; Bartsch-Winkler and Schmoll, 1993; Hervé and Ota, 1993; Vargas et al., 2013). As a consequence of the above, building a comprehensive view of landscape transformation and its effects on the archaeological record is a major challenge of interdisciplinary research aiming to understand Holocene human trends and their interaction with the environment. In sum, tectonic activity, isostatic rebound and sea level changes exert control over the location of shorelines, thus affecting archaeological site formation by the time people conducted activities at specific locales, site preservation (e.g. erosion) and site discovery (e.g. sedimentation rates, vegetation cover).

1.3. Archaeological context

Before the European colonization of South America, the Chonos Archipelago was occupied by marine hunter-gatherer groups known historically as Chono. They lived along the coasts and travelled among the islands by canoe (Bird, 1988; Byron, 1901; Cooper, 1946; Emperaire, 1963; Simpson, 1875). As suggested by etnohistorical and archaeological information all through the archipelago, all the settlements documented to date are associated with the coastline and no one has yet been recorded inland on the islands. Although the thick vegetation and steep topography are barriers to visibility and movement, the preferential selection on marine resources and the use of canoes in the past are among the determining factors for the location of archaeological sites in this zone (Reyes et al., 2015). Currently we have obtained 54 radiocarbon dates of human bone remains from old archaeological collections (N = 10), human bone remains obtained during surveys and from the excavations of caves and shell middens (N = 10), and samples obtained from the archaeological deposits of the open-air sites and shell middens (N = 22) (Reyes et al., 2013, 2015). Some sites have yielded sequences including 5 dates. Although the first occupations occurred around 6000 cal BP, the majority of radiocarbon dates are concentrated in the last 2000 years (Méndez and Reyes, 2015).

Currently, a number of archaeological sites that cannot be dated have also been recorded with respect to their characteristics and position (N = 20, shell middens, fishing pens (also referred as fishing weirs), lithic material in the intertidal zone, and bone deposits). All this information has allowed a general interpretative panorama of human occupation and distribution in the archipelago and the characteristics of the sites selected along the coastline. It has allowed us to suggest a preliminary description of the lithic technology associated with these sites, which was specialized for hunting marine fauna (e.g. sea lions) and for wood-working (choppers and axes) probably for manufacturing houses and canoes. The faunal remains at the sites present a great variety of mollusks, fish and, to a lesser degree, remains of small marine mammals and seabirds. The levels of $\delta^{13}C$ and $\delta^{15}N$ isotopes in human bones are consistent with the consumption of mainly coastal marine resources, as expected with the intense gathering of the mussels which make up the shell middens (Reyes et al., 2015).

2. Material and methods

Fieldwork over the last five years has added up to a 1100 km linear coastal survey in the Chonos Archipelago (Fig. 1). Considering the data cited above, much of the search for sites followed geomorphological criteria, i.e. looking for and identifying landscape features (e.g. marine terraces located above the current coastline) that would provide information on past coastline changes related with fluctuations in the sea level or with local tectonics (Lomnitz, 1970; Plafker and Savage, 1970).

In order to detect cultural deposits where dense vegetation allowed little or no visibility, borehole tests were conducted systematically on both elevated (e.g. old terraces) and low landforms (e.g. deltas) with relation to the current shore level. This procedure enabled us to extract sediment cores up to 8 m deep thereby detecting buried archaeological deposits. Middens and paleosols were cored in order to provide and identify datable organic samples (e.g. shell, charred material, soils) and archaeological material in its stratigraphic position. Cores allowed defining potential locations for test pits.

In other locations, where the existence of anthropogenic deposits was already known (i.e. site GUA-010 previously excavated by Porter, 1993), recovery methods included the excavation of a 12 m^2 plan in order to determine the human activities carried on there. All of the sediments were sieved with 4 mm mesh. We used ^{14}C (radiocarbon) AMS dates to establish the chronology of human occupations and to understand site formation processes.

It is noteworthy that in this work we have considered only the radiocarbon dates from the bases of the anthropogenic deposits in order to obtain minimum or *terminus post quem* dates for the generation of the geoforms where the archaeological sites are located (Table 1). To provide the most accurate chronology, most dates were performed on organic terrestrial material (i.e. charcoal), so as to limit the reservoir effect of marine material (i.e. shells); which were only used in the absence of other datable sources. The ages used here provide a temporal background for specific landforms (i.e. terraces) which were already emerged and availability for campsites (San Román, 2013), but they should not be regarded as a definitive chronological marker for the formation of the landform. It is only through the regional assessment of several dated sites crossed with the local observation of subduction or uplift that one can suggest rates of vertical displacement. This sample of dates also enables us to assess how site selection has varied along time by comparing the sites location with the present coastline.

All the radiocarbon dates discussed here were calibrated into years before present (cal BP) with Calib 7.0.2 (Stuiver et al., 2013) applying the ShCal13 curve (Hogg et al., 2013) for terrestrial samples and the mixed Marine 13/ShCal13 curve for shell samples (Reimer et al., 2013).

Finally, in order to compare data provided in this paper with uplift rates from previous work in the region, we estimated uplift rates by considering basal ages and their elevation in our studied sites. These data were integrated by interpolating uplift rates using the Natural Neighbor algorithm using the Surfer program vers. 13 (Kowalczyk et al., 2010).

3. Results

Seventeen archaeological sites distributed in distinctive geomorphological settings were studied and dated. They provide base radiocarbon ages between 6200 cal BP to modern (Table 1). The archaeological implications underlying the age and distribution of the sites throughout the region, and for the colonization of the fjord area, have been discussed in detail elsewhere (Méndez and Reyes, 2015; Reyes et al., 2015, 2016). Here we will focus on the geomorphological implications for chronology in order to understand coastline evolution during the post-glacial. We distinguish at least three different geomorphological scenarios in the areas studied. The first consists of marine terraces located above the present coastline; these indicate changes produced by tectonic activity and/or changing sea levels. The second is related to the erosion of archaeological shell middens that were emergent at some time but are now submerged beneath the water surface, indicating that subsidence or sea level change has occurred since they were formed. The last case is the intrusion of sand deposits in archaeological sites. This reflects the entry of water and the formation of new sediments bracketed between periods of human occupation.

3.1. Ancient marine terraces and recent subsidence in Las Guaitecas

Given the fact that the earliest evidence for human occupation in the northern Chonos Archipelago is that on the Gran Guaitecas Island, efforts have focused on understanding the temporal and spatial dimensions of the archaeological sites there and their potential as a source for understanding tectonic activity. The main source of information has been gathered at archaeological middens located on marine terraces. Lithic scatters have been recognized as they were washed by daily tidal movements. The majority of artefacts in these assemblages are bifacial points, choppers and chopping tools, large debitage and net-weights (Reyes et al., 2016). Targeting such areas, where sea erosion has been favored by land subsidence, has proved ideal for recognizing archaeological sites (Porter, 1993; Reyes et al., 2007, 2011) in this otherwise densely vegetated environment.

The main information on ancient marine terraces comes from the Guaitecas Archipelago, which lies between the Gulf of Corcovado to the north and the Chonos Archipelago to the south (Fig. 3). The geology of this archipelago consists of a metamorphic basement that predominates in the west (i.e. Gran Guaiteca Island) and

Table 1

AMS radiocarbon dates from archaeological sites discussed in the text. SM: shell midden.

	Site	UTM South	UTM East	Lab. #	Depth(cm)	Altitude (masl)	^{14}C yr BP	±	δ ^{13}C ‰	Dated material	2σ calibrated range (cal BP)
Chiloé Island	Yaldad-2	5227786	603400	Beta 182461		4	5950	80	–	Shell	6203–6551
Guaitecas archipelago	GUA-010	5144061	585106	BETA - 355644	60	5	5370	30	−24.6	Charcoal	5951–6208
	GUA-010 (SM)	5144032	585068	BETA - 355645	80	1	2170	30	1.5	Shell	1681–1858
	GG 2	5143946	585379	D-AMS 006073	50	6	3958	24	−22.8	Charcoal	4240–4421
	GG2 (SM)	5143918	585337	D-AMS 006069	100	2	1963	25	−6.1	Shell	1415–1598
	GG 3	5143741	586524	D-AMS 006070	160	1	1929	28	−0.6	Shell	1384–1554
	Isla Solitaria	5143038	587080	D-AMS 006072	35	3	607	22	−23.2	Charcoal	530–629
	GG 4	5147865	578546	D-AMS 006071	230	1	2259	26	−5.3	Shell	1785–1949
	Isla Marta	5148152	578391	D-AMS 006068	175	2	2074	30	3.3	Shell	1542–1741
Continental border	Piedra Azul	5404150	683000	BETA 144851		7	5580	40	−26.1	Charcoal	6327–6407
	Seno Gala 1	5110073	651414	BETA 230493	56	−1	1430	40	−25.5	Charcoal	1182–1359
Central west Chonos archipelago	ILEV1	5074749	563067	UGAMS 21284	100	0	120	25	−25	Charcoal	-3–253
	IIZA1	5075705	564794	UGAMS 21286ch	38	−0.6	110	25	−25	Charcoal	-3–252
	IIZA2	5071729	553665	UGAMS 21285ch	65	−0.3	70	25	−25.5	Charcoal	-4–242
	IBEN 2(2-1)	5048630	553783	UGAMS 21287ch	50*	1.62	2200	25	−26.8	Charcoal	2004–2304
	IBEN2(2-2)	5048630	553783	UGAMS 21288	88	2	2400	25	−25.8	Charcoal	2317–2465
Central south Chonos archipelago	Las Conchillas	4941988	594084	UGAMS 7755ch	780	−1	3110	25	−25.5	Charcoal	3165–3362
	Canal Cuche 1	4975801	584066	UGAMS 7749ch	360	2	1960	25	−25.4	Charcoal	1738–1925
	Canal Darwin 2	4964648	586787	UGAMS 7750	500	1	3360	25	−0.2	Shell	3141–3323
	Nahuelquín 1	4964230	602007	UGAMS 04950	300	2	1820	25	−1.2	Shell	1286–1432

a complex of volcanic breaches and intrusive rocks that appear in the islands in the east of the archipelago (Hervé et al., 1976). During successive field seasons in this sector, eight archaeological sites were identified on different marine geoforms, principally in the central and western parts of Gran Guaiteca Island.

The central sector of Gran Guaiteca Island contains the sites GUA-010, GUA-010 shell midden (GUA-010 SM), Gran Guaiteca 2 (GG-2), Gran Guaiteca 2 Conchal (GG-2 SM), Gran Guaiteca 3 (GG-3) and Isla Solitaria (Fig. 3A). The area is characterized by the presence of broad marine abrasion platforms containing unconsolidated deposits of glacial and marine origin accompanied by outcrops of the metamorphic basement which predominates in the area (Hervé et al., 1976). On top of this platform, at a variable distance from the present coastline, are two terraces of marine origin on which the anthropogenic deposits are found (Fig. 3B).

Only four sites were located on terraces between 3 and 6 m of elevation. They contain exclusively lithic material and particles of carbonized organic material. The systematic absence of bone material can be attributed to the acidity of the soil (Ph between 2.9 and 4.5). Shell middens located closer to the waterfront, with more calcium carbonate content (pH between 5 and 6.5), contain larger quantities of preserved bone remains of both fauna and humans. In these deposits, highly degraded shell remains produce matrices formed by rather homogeneous, dissolved stratigraphic sequences, with few evident features. They are also characterized by the absence of artefacts and other elements.

The main information gathered on ancient marine terraces comes from site GUA 010. The site is located at the edge of a terrace 5.5 masl, 90 m from the current coastline and extending towards the waterfront. An excavation was conducted on this high terrace in

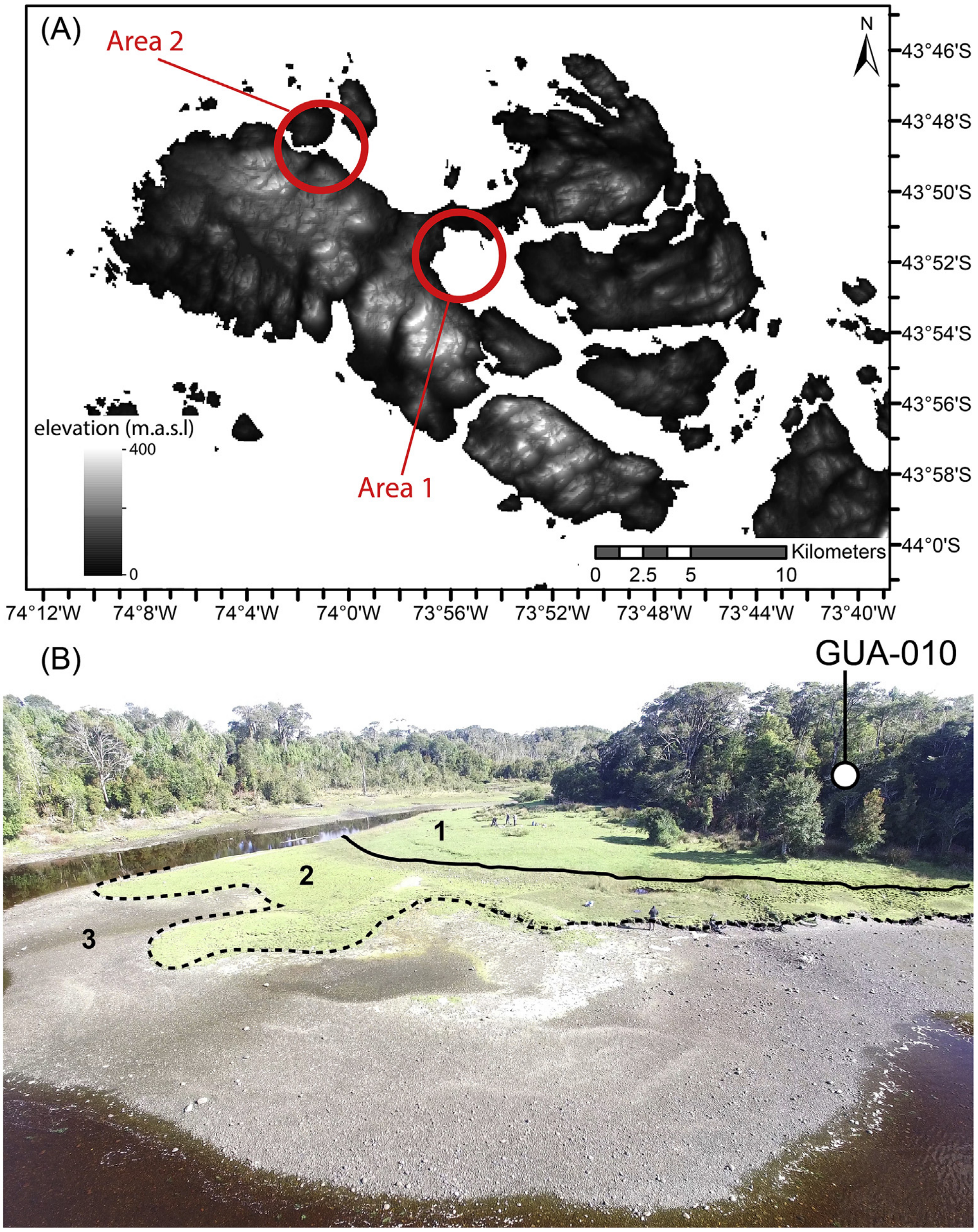

Fig. 3. (A). Digital elevation model (STMT 30 arcsec) of the Guaitecas Archipelago, indicating the sites discussed in the text; (1) Isla Marta 1, (2) Isla Marta 2, (3) GG4, (4) GUA010 (terrace and shell midden) and GG2 (terrace and shell midden); (B) Gran Guiateca island shore Photograph taken by a drone of the (1) lower marine terrace and GUA-010 shell midden site (2) shore platform and supratidal flat and (3) shore platform and intertidal flat where lithic materials were recovered.

order to assess the archaeological record of the activities of Mid-Holocene marine hunter-gatherers as suggested by earlier excavations conducted at the location. The deposit is buried under 20 cm of organic topsoil (Fig. 4). Below this topsoil, dark grey organic silt deposits yielded lithic artefacts extending no more than 20 cm. The sediments in the matrix suggest that the camp was located close to sea level judging by macroscopic comparisons with the types and variations (e.g. texture, clasts size, proportion and roundness, vegetation cover, natural mollusk occurrence) of sediments currently recorded along a 200 m transect on the immediate coastline which showed at least ten distinctive sediment ensembles. The proportion and types of clasts within an organic rich dark silt matrix recorded near a stream outlet indicates an analog of the original position that the site had during the formation of the terrace.

The excavations conducted on the higher terrace of GUA-010 exposed a surface where a low frequency of lithic debris and bifacial fragments in an early stage of manufacture were deposited in at least two segregated occupational events, as suggested by two statistically different ^{14}C dates (95% confidence level). The excavated assemblage is primarily composed of heavily weathered lithics and charcoal specks. Our preliminary interpretation is to attribute this weathering to the pH of the soil. The lack of other expected material such as bone remains may be also explained by soil acidity.

Part of the lithic assemblage at GUA-010 was recovered from the intertidal zone. It shows great similarity to the assemblage previously collected at the site by Porter (1993) on the same beach, consisting mainly of large bifacial points, choppers and chopping tools. The intertidal tool assemblage shows mainly local rocks procured in the immediate vicinity of the site as suggested by preliminary assessments of available raw materials on beaches in central Gran Guaiteca Island. This material shows strong signs of facial and edge erosion due the effect of constant tidal movement.

The geology of the western part of Gran Guaiteca Island (Fig. 3A) is similar to the area described above with a metamorphic basement consisting of nodular schists (Hervé et al., 1976). The geomorphology and chronology associated with the marine geoforms are also similar. In particular, there are two archaeological sites in this area, one either side of the Marta Channel which separates Gran Guaiteca Island (site GG-4) from Marta Island (Marta Island site). As can be seen in Fig. 5, an erosion scarp clearly divides the current coastline from a low terrace (1–2 m) on both coasts. The chronology associated with the anthropogenic deposits positioned on the two terraces provides at minimum ages of 1790–1950 cal BP (GG4) and 1540–1740 cal BP (Marta Island site) for the origin of these geoforms (Reyes et al., 2016). Furthermore, as in the central area, it may be observed that both terraces have been affected by tidal erosion, reflecting a recent subduction of the area during the 1960 earthquake between −0.9 and −1.7 m (Plafker and Savage, 1970).

3.2. *Evidence for recent subsidence/uplift events from archaeological sites in the Chonos Archipelago area*

The low elevation terraces and the associated sites in the Guaitecas Archipelago show evidence of tidal erosion. This suggests a rise in the sea level and/or a recent subsidence event. The same may be observed in other parts of the Chonos Archipelago. In this context, the archaeological sites in Izaza, Level and Benjamín Islands, as well as the site on the Gala Sound on the continental edge of the archipelago (Fig. 6), present a series of shell middens that have clearly suffered tidal erosion of their profiles. Indeed, the lowest occupation level of some of these sites, e.g. IZA-1 and IZA-2 (Izaza Island) and Posa Las Conchillas (Traiguén Island), is below the present high tide line.

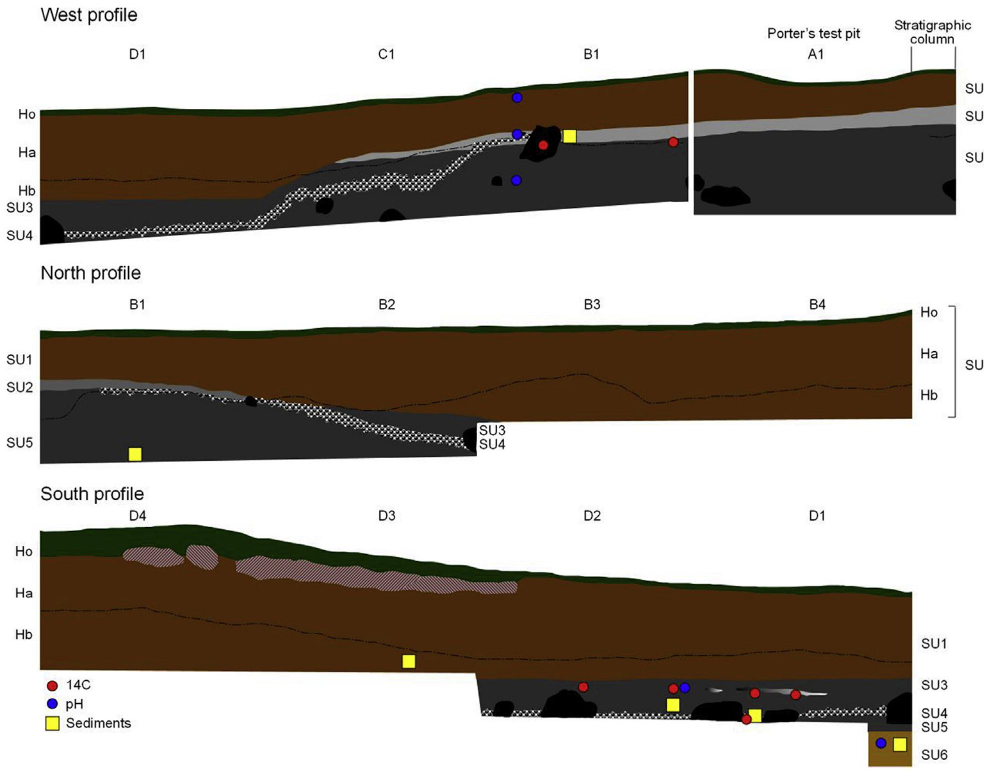

Fig. 4. Stratigraphic profiles of GUA-10 site showing stratigraphic units (SU) and soil horizons, SU1: light brown clay, SU2: gray sandy silt, SU3: organic black clay, SU4: black clay with granular gravel, SU5: black sandy clay, SU6: coarse sand.

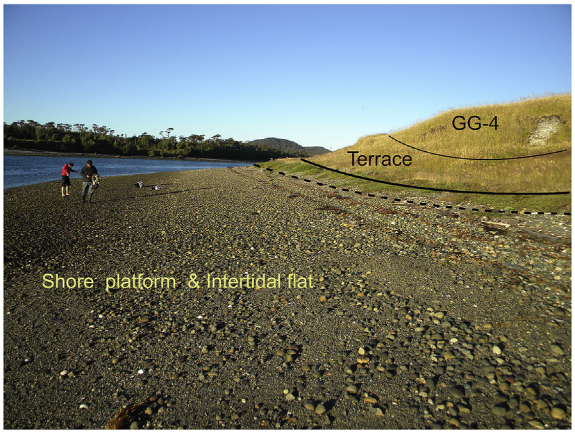

Fig. 5. Image of GG-4 site in Guaiteca Archipelago showing the terrace where the shell midden is located.

It should be noted however that although the geology of the area is similar to that of the Guaitecas Archipelago (i.e. metamorphic basement), it was not possible to identify terraces located above the coastline. There is no obvious, well-defined abrasion platform as in the Guaitecas Archipelago.

The sites dated with clear erosion features, like Seno Gala 1 on the continental edge of the Chonos Archipelago and Posa Las Conchillas in the south of Traiguén Island, are located further east in a different geological and tectonic configuration. In these areas we observe that the basement consists of granitic rocks, in contrast to the metamorphic basement which predominates further west. Furthermore sites to the east, lie close to important tectonic lines associated with the Liquiñe-Ofqui fault system (Fig. 1).

It is interesting to consider another type of evidence, with opposite results, from the Nahuelquín 2 and 3 archaeological sites in the south-west of Traiguén Island (Fig. 7). Here we have recorded emerged fishing pens (see Caldwell et al., 2012) located 1–2 m above the present high water line (Reyes et al., 2011, 2015). Fishing pens, used not only earlier, but also in historical times, consist of lines of rocks (or sticks and branches) placed in the intertidal zone for fish to remain trapped as the tide falls (Álvarez et al., 2008). For them to function, they must always be below the high water mark. However, these pens are located on the existing marine abrasion platform, and while there is no chronology for their abandonment, it can be seen that soil has started to develop inside the pens and vegetation grows on top and besides them. This should be regarded as evidence of a lowering in the sea level and/or tectonic uplift.

3.3. *Evidence for storm/tsunami events from archaeological sites in the Chonos Archipelago*

Finally, not all the evidence from archaeological sites in the study area is directly related with possible changes in sea level and/or vertical changes in the crust. In Benjamín Island 2 site (IBEN-2), we found that the archaeological shell midden was deposited on an old beach. One key stratigraphic feature of this site is the presence of a level of fine sands interbedded between shell midden deposits dated to 2000–2300 cal BP and to 2320–2470 cal BP (Fig. 8). This indicates a new beach was formed, after which the shell midden deposition was reactivated. We preliminarily discard the possibility that storms may have caused the incorporation of these sediments since the location is sheltered from the wind. The channel in which IBEN-2 is located lies 5 km from the inlet of a narrow 1,5 km wide channel, flanked in the front and in the back by two >700 masl mountain ranges, thus protected from prevailing winds. The short time span between the two dates from the shell deposits argue in favor of a relatively sudden phenomenon as responsible for the interbedding. This tsunami may have been provoked by an earthquake or by a landslide from the opposite coast, as was previously recorded 120 km to the southeast in the Aisén Fjord in 2007 (Lara et al., 2008; Vargas et al., 2013).

The incorporation of new sediments between periods of archaeological occupation has been found in different parts of the Guaitecas Archipelago, e.g. Marta Island-2 and Repollal Bajo 2. Unfortunately there are no dates from which to estimate when this sedimentation occurred. IBEN-2 is the first dated example of interbedding and allows us to set the base for future directed searching in order to assess whether this was a unique process or it occurred elsewhere in the region.

4. Discussion

Coastal exploration of the Chonos Archipelago signals how important is the incorporation of large, previously unknown areas into the discussion of marine adaptations in Patagonia. These have generally been limited to the Magellan Strait, the Beagle channel, and other archipelagos in southernmost Patagonia (Orquera et al., 2011; Piana et al., 2012; San Román et al., 2016). Despite the fact that its characteristics are theoretically appropriate for exploring maritime adaptations (islands can only be reached by open water navigation), the area of the Chonos Archipelago has not received much attention until recently. Among the main challenges for interdisciplinary research aiming at understanding past human occupations in the Chonos Archipelago are the effects of sea-level rise (Fairbanks, 1989), isostatic rebound (Reed et al., 1988) and local tectonics (Díaz-Naveas and Frutos, 2010).

As stated in the introduction, the main objective of this work is to assess the potential of the archaeological record for understanding coastline evolution during the post-glacial in an area where few data exist. The information available comes mainly from digital models and punctual data which suggest important changes in the coastline in the study area (Clark et al., 1978; Milne et al., 2005; Hervé and Ota, 1993; Vargas et al., 2013). Nevertheless, there is as yet no clear picture of the chronology and direction of these changes, or their possible links with fluctuations in sea level and/or vertical movements of the crust. Our results are based on two premises. The first has to do with the relationship between the base ages of archaeological sites and their location on marine geoforms; in this case we consider these ages to be the minima for the formation of these geoforms. The second refers to the occupation dynamic of these coastal spaces by groups of marine hunter-gatherers and how it relates to coastline evolution. For this we consider that archaeological sites would be positioned on geoforms not far removed from the coast. Thus if there was a tendency for the coastline to change on a regional scale during the post-glacial, we would expect to find a correlation in time and space between the data presented here. The results do support these premises, in that they indicate a positive correlation between the occupation chronology, the elevation of the archaeological sites and their distance from the present coastline (Fig. 9).

The archaeological findings, suggest that the earliest occupations recorded in the Guaitecas Archipelago, dated between 6200 and 4400 cal BP, were all located on high terraces, while the shell middens recorded immediately on the waterfront of these sites are at least 2000 years younger (Reyes et al., 2016). This early occupation, comparable to the early Chiloé Archipelago sites located further north (Fig. 1) (Legoupil, 2005; Rivas et al., 1999; San Román et al., 2016), suggests that these higher terraces would have been available by the Mid-Holocene denoting a progressive marine regression during the Late Holocene. Results at the level of the

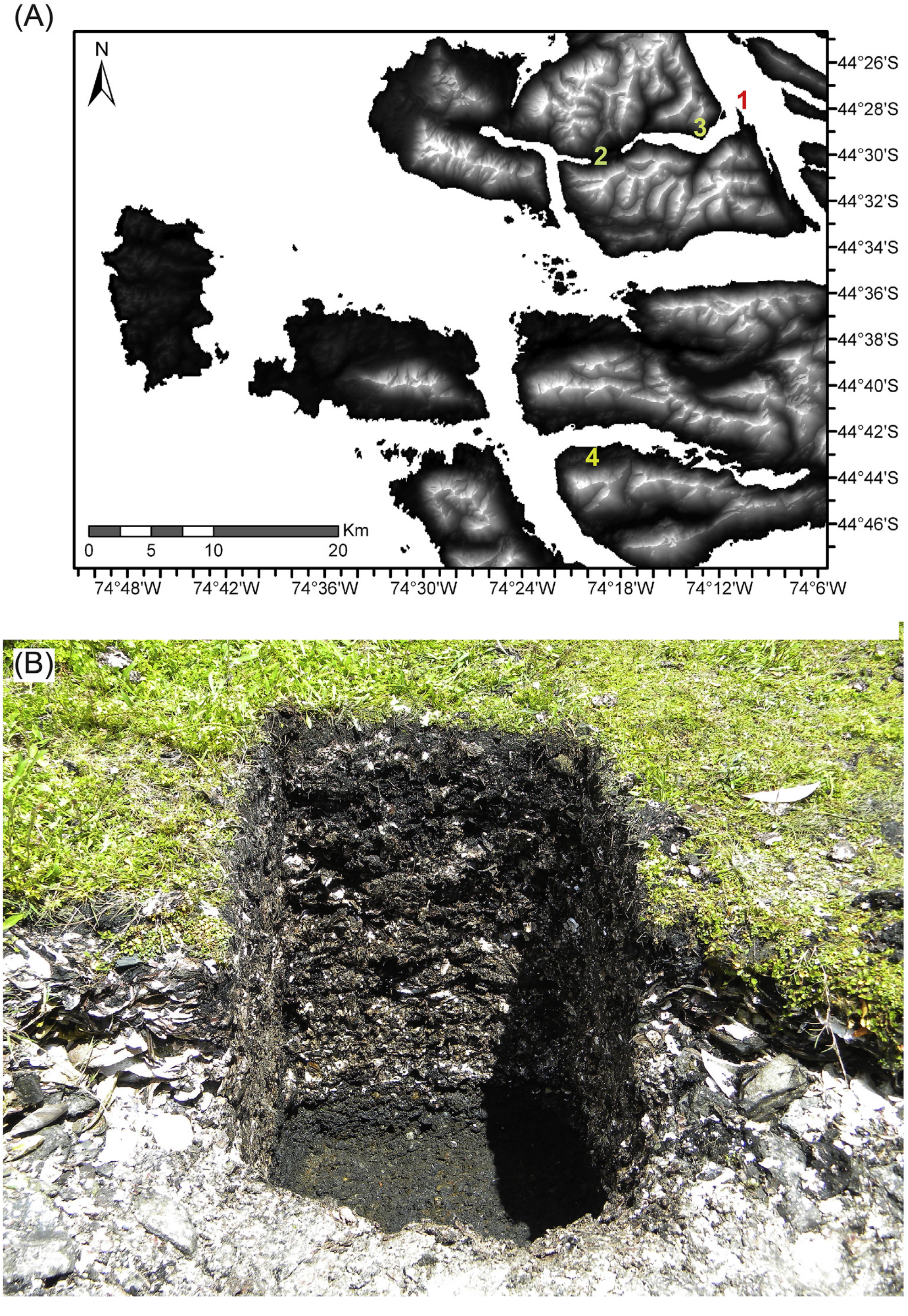

Fig. 6. (A) Digital elevation model (STMT 30 arcsec) of the central west Chonos archipelago showing the locations of (1) IZA-1, (2) IZA-2, (3) ILEV-1, and (4) IBEN-2 sites; (B) Test pit at the IZA-2 site showing the basal anthropogenic deposit at 30 cm currently below the high tide line (marked in the picture).

modern coastline in the southern part of the archipelago (44°S-45°S) indicate that the records of marine hunter-gatherers are younger than 3300 cal BP. Thus, the higher terraces dating from the Mid-Holocene may be considered a geoarchaeological mark in this territory, providing strong evidence for a relatively high sea level over a long period during the early to mid-Holocene as the model suggested (Clark et al., 1978; Milne et al., 2005).

Considering the results from the numerical estimates of eustatic change (Clark et al., 1978; Milne et al., 2005) it is possible to observe an abrupt increment in relative sea-level change before 7000 cal BP, which is in agreement with the early to mid-Holocene transgression. Particularly, Milne et al. (2005), shows how eustatic changes postdating 7000 cal BP are almost negligible. Thus, if we consider that all of our basal dates are located within the time frame of minor to negligible eustatic changes, it is possible to suggest that all sea level changes in the study area as interpreted by the genesis of observed landforms (i.e. marine terraces) will be a product of either tectonic or isostatic uplift. This argument has been used in previous studies in western Patagonia, which report uplift rates based on the elevation and minimum ages obtained for the

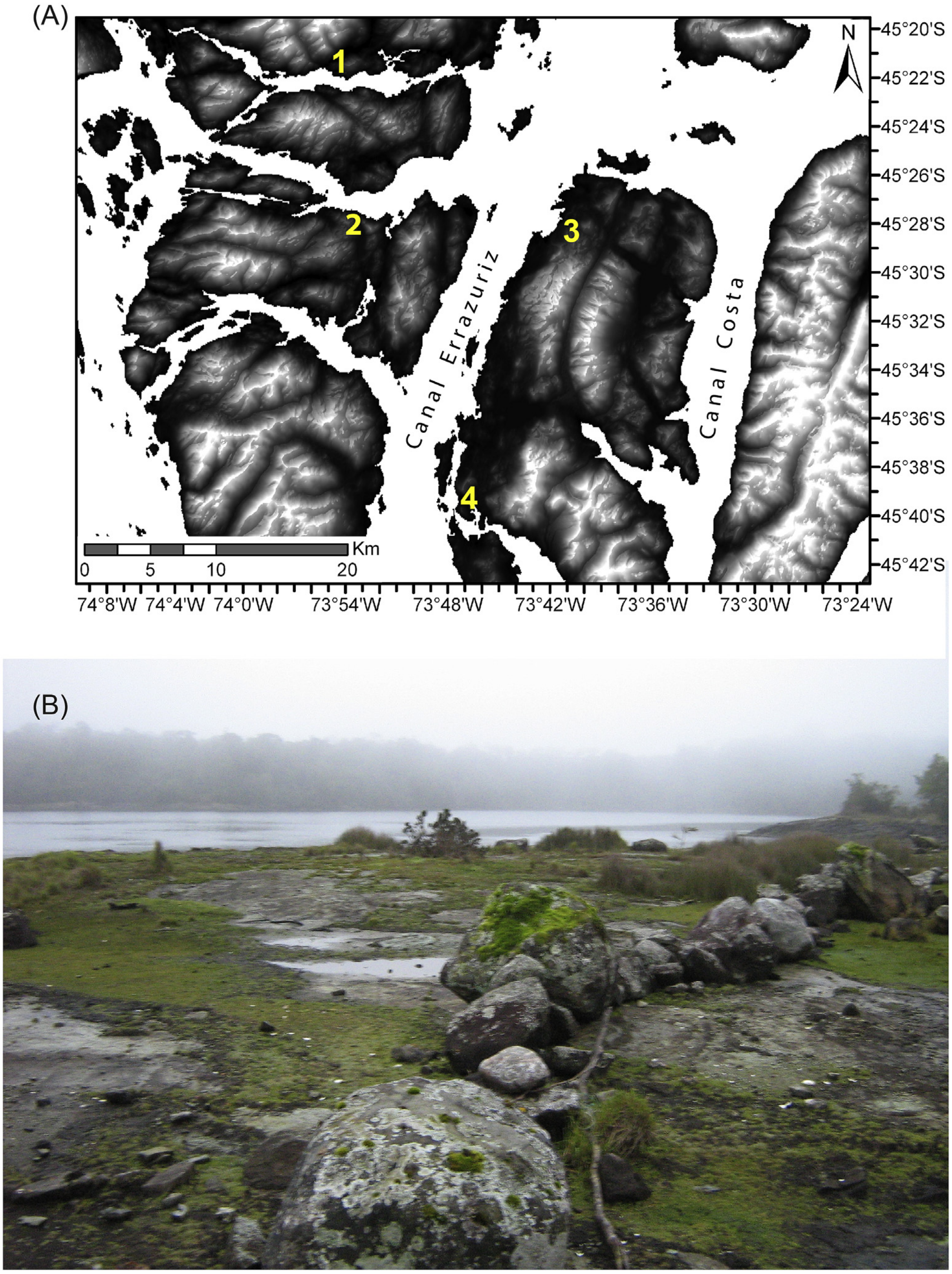

Fig. 7. (A) Digital elevation model (STMT 30 arcsec) of the central south Chonos archipelago showing the locations of the (1) Canal Cuche 1, (2) Canal Darwin 2, (3) Nahuelquín 2 and 3, and (4) Posa Las Conchillas sites; (B) emerged fishing pens at the Nahuelquín 2 site in the Traiguén Island.

transgressive event (Hervé and Ota, 1993; Vargas et al., 2013) (Table 2).

Fig. 10 shows an integrated version of uplift data constructed from geomorphologic and archaeological sources. For instance, geomorphological studies suggest that coastal areas of the Los Lagos Region (i.e. Maullín and the Chacao Channel) experienced tectonic uplift at a rate of 0.625–1.5 m/ka (thousands of years) during the Holocene (Atwater et al., 1992). Other studies indicate that in the area of Chiloé Grande Island, the uplift rate may have been higher with values between 7.1 m/ka on the west coast (Lago Cucao) and 3.1 m/ka on the east coast (Nercon) (Hervé and Ota, 1993). In continental Chiloé, data suggest uplift rates between 4 and 4.9 m/ka to the west of Hualaihué Bay and 10.3 m/ka inland of the bay. In the area of the Reloncaví Fjord (between Ralún and Cochamó) the tectonic uplift rate is estimated at 10.6 m/ka (Hervé and Ota, 1993). Studies in the Aysén Fjord area (Río Cuervo) report the presence of delta systems and terraces of marine origin located 8–10 m above current sea level dated to between 7.7 and 8.5 ka, suggesting tectonic uplift rates of 1.1–1.4 m/ka over the last 7000 years (Vargas et al., 2013).

Regarding isostatic change, studies indicate that despite the area was largely covered by ice during the LGM, and thereby susceptible to isostatic rebound, it is also true that this may have happened during the millennium following deglaciation and not after. This seems to be the case of isostatic adjustment and the visco-elastic structure of the lithosphere in the Chonos Archipelago. Studies

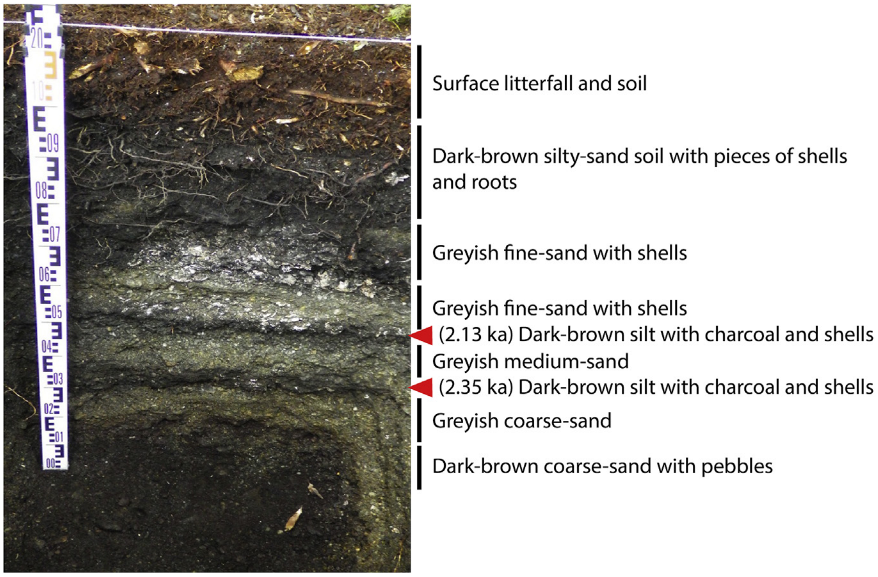

Fig. 8. Stratigraphic profile of the Isla Benjamín 2 site showing the dated anthropogenic deposits bracketing 10 cm of fine sands.

suggest that by the end of the glacial period the area of the Chonos Archipelago would have been about 25 m below its present level (Ivins and James, 1999), but the lithosphere reacted rapidly with the loss of ice-weight by isostatic rebound. These data are consistent with the GPS measurements obtained in different parts of Patagonia, showing that important loss in ice mass has triggered an abrupt isostatic rebound, for instance that recorded in the Southern Patagonian Ice Field, which corresponds to the fastest recorded uplifts (39 mm/yr) associated with isostatic glacial rebound (Dietrich et al., 2010).

Our data suggest uplift rates between 0.57 and 5.42 m/ka (mean = 1.49 m/ka) for the Guaitecas Archipelago, 0.31–1.48 m/ka (mean = 0.96 m/ka) for the central-west Chonos Archipelago and 0.85 m/ka in the central-south Chonos Archipelago. Although these suggested uplift rates must be regarded as preliminary, since they refer to distant minimum ages associated with the geoforms in each location, it is nevertheless evident that during the period covered by the archaeological sites studied (i.e. Mid to Late Holocene), eustatic changes in sea level were smaller (Fig. 10). Thus the trends observed in our data, and corroborated in the other studies, support the hypothesis of net uplift of the territory throughout the region during much of the post-glacial (Atwater et al., 1992; Vita-

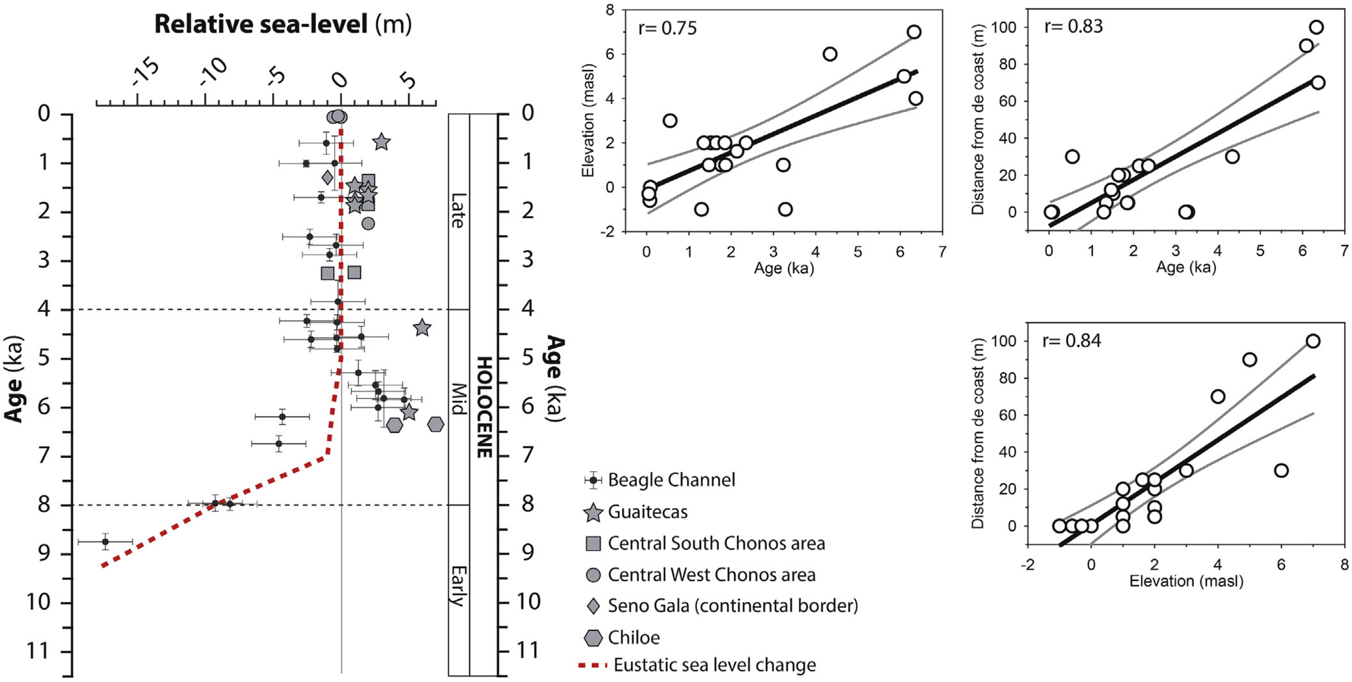

Fig. 9. (A) Comparison between relative changes in sea level from the Beagle Channel (Porter et al., 1984; Rabassa et al., 2000) and eustatic changes in sea level obtained by modelling the glacial isostatic adjustment (GIA) (Milne et al., 2005) versus the basal ages of the archaeological sites discussed in this study and associated with geoforms of marine origin; (B) Distribution graphs showing the correlation between ages, elevation, and distance from the coast.

Table 2
Radiocarbon dates from geological sites discussed in the text; *relative sea-level based on data reported by the authors in the references cited; **value correspondent to the slope of a curve net uplift uncorrected for potential terrain displacement associated with earthquakes.

Site	UTM South	UTM East	Lab. #	Altitude* (masl)	^{14}C yr BP	±	Dated material	Median (cal BP)	Uplift rate** (m/ka)	Reference
Yel-35	5412937	727077	GaK-15008	30	3130	80	Shell	2919	10,28	Hervé and Ota 1993
Yel-36	5294039	600226	GaK-15009	6	1960	80	Shell	1515	3,96	Hervé and Ota 1993
Yel-37	5279422	573249	GaK-15010	3	420	80	Shell	418	7,18	Hervé and Ota 1993
Horn-16	5345213	691622	GaK-15004	3	750	80	Shell	385	7,79	Hervé and Ota 1993
Horn-17	5345213	691622	GaK-15005	10	2050	90	Shell	1624	6,16	Hervé and Ota 1993
Horn-45	5344489	695472	GaK-15007	4	430	80	Shell	427	9,37	Hervé and Ota 1993
Rio Cuervo	4975447	653164	BETA-243279	10	6950	60	Wood	7745	1,29	Vargas et al., 2013
Rio Cuervo	4975447	653164	BETA-243280	10	7650	70	Wood	8413	1,19	Vargas et al., 2013
Rio Cuervo	4975447	653164	BETA-243281	10	7790	60	Wood	8522	1,17	Vargas et al., 2013
Chocoi	5378550	605300	BETA-31517	2	4150	60	Branch	4639	0,43	Atwater et al., 1992
Puente Cariquilda	5387200	623650	GX-15732	1,5	2190	110	Twig	2144	0,70	Atwater et al., 1992
Rio Ballenar	5392130	619850	GX-15726	0,5	1408	76	Leaf	1274	0,39	Atwater et al., 1992
Huinay	5305695	712328	FO-1415 1B	3	8540	40	Wood	9504	0,32	Hervé et al., 2015

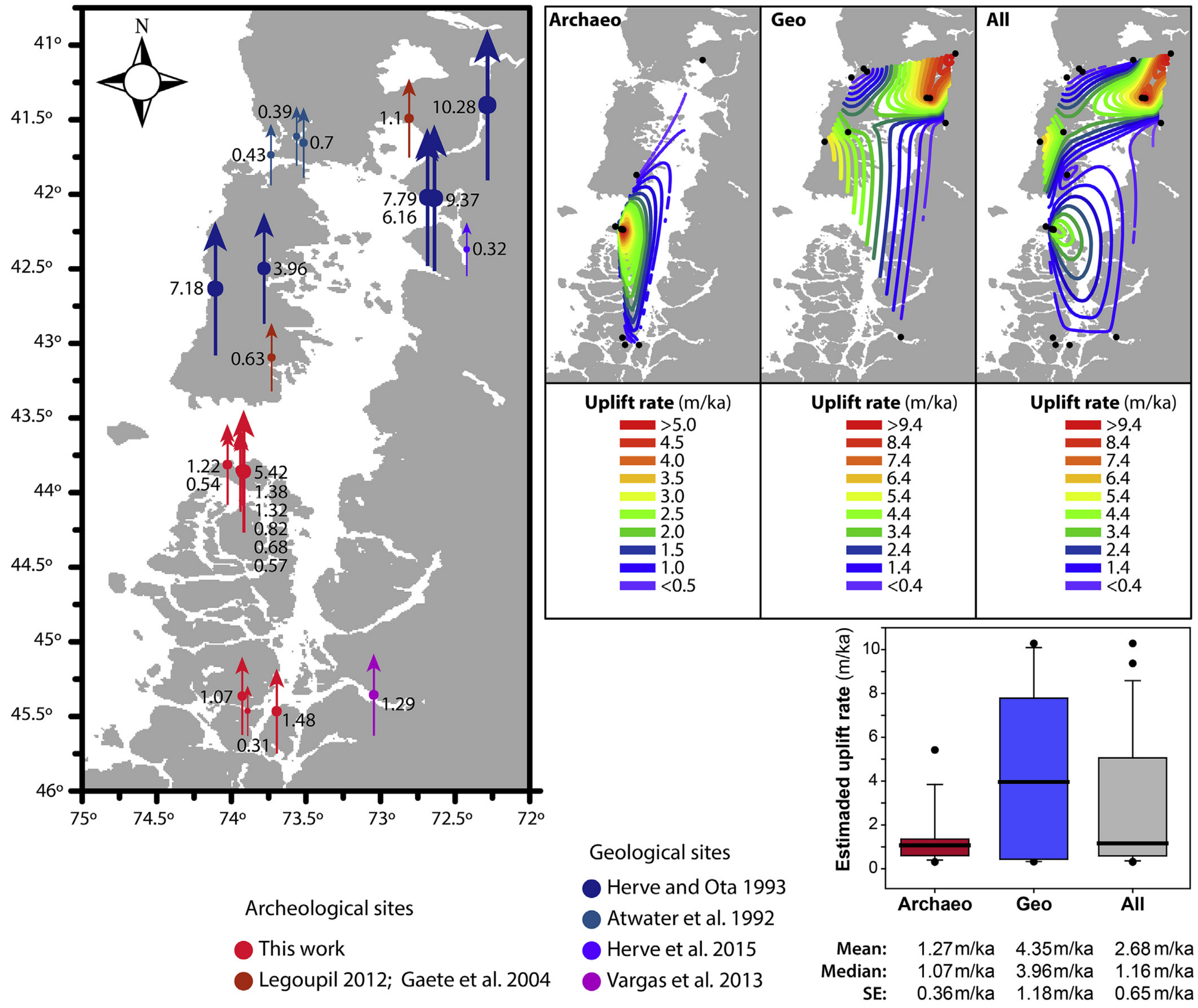

Fig. 10. (A) Regional uplift rates based on archaeological and geological sites from the study area (arrow sizes indicate proportional magnitudes of vertical movement); (B) Natural Neighbor interpolation of uplift rates based on archaeological, geological and combined data; (C). Boxplot graphs indicating uplift average values based on archaeological, geological and combined data (Gaete et al., 2004).

Finzi, 1996). The presence of sites affected by tidal erosion reflects the recent subsidence that has occurred in much of the Chonos Archipelago. The same appears to be indicated by the many tree trunks still standing in the intertidal and supratidal zones of the present coastal platform, showing the presence of ancient forests in area once above the ancient high water line. This evidence agrees with the historical data of the 1960 earthquake when subduction affected a large part of the archipelago (Plafker and Savage, 1970). As a result of this seismic event, several sites appear under the current tideline and subsequent tidal action has eroded human burials and stone tools in the intertidal zone (Reyes et al., 2007, 2011, 2013). This suggests that there may be significant numbers of archaeological sites in this area that are now under water or completely washed away by marine erosion. One major difficulty has been to establish the chronology of lithic material recovered from intertidal zones. The lack of formal diagnostic tool-types in the shell middens adjacent to these distributions has precluded the possibility of suggesting chronological links based on morphological criteria.

Uplifted structures resembling fishing pens indicate areas once available for intertidal economic activities that are no longer in use (Traiguén Island). The location of these structures to the east of the area of maximum subduction suggests that these sectors may be close to the axis of inflection between the subduction, and the uplift experienced during the 1960 earthquake. Furthermore it has been observed that areas close to the Liquiñe-Ofqui fault system tend to experience a greater uplift than the rest of the territory (Thomson, 2002; Adriasola and Stockhert, 2008; Lara et al., 2008). Other types of localities throughout the region therefore need to be studied in the near future. For example, offshore islands and mainland areas located outside the subduction axis may provide appropriate target areas for uncovering new Mid-Holocene assemblages. In summary, anthropogenic deposits may help to date changes in relative local sea levels given that violent sediment deposition may be interbedded in shell middens. If these deposits are elevated, dating them may prove valuable for reconstructing past transformations of the coastline.

5. Conclusion

Through this paper we have presented data from archaeological sites distributed in different coastal geoforms all through the northern part of the western Patagonian channels. These locations, their proximity to old and active shorelines, the basal chronology from the archaeological sites, an stratigraphic characterization and regional paleoenvironmental data, allows discussing their relation to changes in sea-level in global and local scales (isostatic rebound and tectonics). On the one hand, the earliest sites, between 6200 and 4400 cal BP, are located in high marine terraces far from current shorelines. On the other hand, sites postdating 3300 cal BP are located closer to the shoreline or in the intertidal zone, thus sunken and eroded. Using radiocarbon dates from basal units of these same sites and their elevation data we have suggested preliminary uplift rates between 0.57 and 5.42 m/ka for the Guaitecas Archipelago, 0.31–1.48 m/ka for the central west and 0.85 m/ka in the central south of the Chonos Archipelago. In a regional scope, these data along with that produced in other sites, suggest that tectonic uplift is the main mechanism contributing changes in coastal reshaping in the northern part of the western Patagonian channels. In this way, we acknowledge the potential of old anthropogenic deposits in coastal settings as paleoindicators for estimating past sea-levels, the impact of their change and the incidence of coastal reshaping for human settlement in a much broader scale.

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