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ABSTRACT

Patagonia Argentina is a key area for the study of sea level changes in the Southern hemisphere, but the availability of reliable sea level markers in this area is still problematic. In fact the storm deposits (beach ridge) commonly used here to reconstruct past sea level oscillations introduce a wide error. Along the Puerto Deseado coast (Santa Cruz), morphometric analyses of 11 features were carried out using traditional measurement tools and a digital software-based method (tested on one selected feature) with the aim to investigate the possibility of their use as sea-level markers. By undertaking accurate topographic profiles we identified the relationship between notches and current sea level. In detail, we identified two clusters of notch retreat point elevations, with a very low internal variability. The lower was located a little below the mean high-tide level (mHT) and the upper located at least about 0.5 m above the Maximum high-tide level (MHT). Field observations of tidal levels and notches position suggest that the lower notches are active and the upper are inactive. This study on the abrasive notches attests their quality as sea level markers and opens up the use of fossil abrasive notches as palaeo sea-level markers

because the error linked to these features is substantially smaller than that introduced by beach ridges commonly used in the study area.

Key words: notch, rocky coast, sea level marker, Patagonia, Argentina.

INTRODUCTION

Patagonia offers a unique opportunity in the South Hemisphere to study the palaeoevironmental evolution of an area that lies between the mid and the low latitudes from the tropics to the margins of Antarctica. As a passive margin this area is tectonically relatively stable and is particularly suitable for the study of the eustatic sea-level oscillations over the Late Pleistocene and Holocene (Milne et al. 2005; Milne and Mitrovica 2008).The Patagonian coast is mainly characterized by a meso-macrotidal regime (Isla and Bujalesky, 2008) that in itself makes the study of palaeo sea-level difficult. Moreover, in Patagonia most of the studies on this topic are based on coastal deposits such as beach ridges (Codignotto et al., 1992; Rostami et al., 2000; Schellmann and Radtke, 2000; 2003; 2010; Pedoja et al., 2011; Ribolini et al., 2011; Isola et al., 2012; Zanchetta et al., 2012; Pappalardo et al. 2014). These deposits depending on the storm energy, wave exposure and tide range, usually lead to an overestimation of the mean sea-level value (e.g. Schellmann and Radtke, 2010). The best available deposits used to reconstruct palaeo sea-level in the Patagonian coast are river mouth terraces, formed by the interfingering of fluvial and littoral sediments at the outlet of rivers into the ocean. Their elevation, in fact, could be directly related to the high tide level (Schellmann and Radke, 2010), but their contribution to the study of past sea level is limited because they are very limited in occurrence. Coastal deposits and their significance as sea level markers have been largely studied along the Patagonian coast, while rocky coast have been nearly ignored, in spite of the presence of rock outcrops in coastal areas and the occurrence of notches.

These markers have been used in Puerto Deseado area by Pedoja et al. (2011) to state Pleistocene sea levels; they assumed for these features a direct connection with mean sea level. When used in order to assess Holocene palaeo sea levels in meso-macrotidal areas, though, the degree of accuracy required implies that their occurrence at a specific elevation within the tidal-range should be stated exactly.

In addition, abrasive notches in meso and macrotidal areas are poorly studied around the world probably because the tidal regime and the genetic typology of notches make difficult to understand their significance as sea level markers. In fact, notch shape and its relationship with sea-level is strictly linked to the predominant genetic process. Tidal notches formed in carbonatic rocks, by bioerosion and carbonate dissolution, are widely used and considered one of the best mean sea level indicators (i.e. Pirazzoli, 1986; Rust and Kershaw 2000; Kershaw and Guo, 2001; Lambeck et al. 2004; Kelletat, 2005; Evelpidou et al., 2012; Moses, 2013). Even if a debate on their genesis is still open (Moses, 2013), in microtidal area such as the Mediterranean sea, the elevation of the retreat point (i.e. the apex or the maximum curvature point of the notch profile) is considered to correspond to the palaeo mean sea-level with an accuracy that in the best cases reaches ±0.1 m (Ferranti et al., 2006). On the contrary, notches developed in non carbonatic rock by a predominantly abrasive process are generally considered unreliable as sea level marker. Commonly the relation between this type of notch and sea level is considered changing according to the availability of abrasive sediments and wave energy (Pirazzoli, 1986, Kelletat 2005). Nevertheless a morphometric study by Trenhaile et al. (1998) in the Canadian Coast attests that the retreat point of abrasive notches in macro tidal area is located a little below the mean high tide level. Dickinson (2000) in the Pacific Islands observed that the retreat point is located close to the high tide level, while Irion et al. (2012) related the floor of the notches to the spring high tide in the Brazilian Coast. This work describes abrasive notches, carved in volcanic massive rocks and their relation with current sea level in the meso-macrotidal environment of Puerto Deseado area. The study explores also the possibility to extrapolate this correlation to relict notches, and assesses their utility for measuring past sea levels. To understand the relationship between sea level and abrasive notches would improve their use as sea level marker, and contribute to the reconstruction of sea-level variations in the recent past in a key area for the study of climate change.

THE STUDY AREA

During the field surveys in 2010 and 2011, notches were found in different parts of the San Jorge Gulf (44° - 47° S Santa Cruz-Chubut Provinces), particularly in the Bahía Bustamante, Camarones and Deseado areas. Due to the availability of astronomical data we chose to concentrate our work in the southern portion of the gulf, in the Puerto Deseado area (Fig. 1).

Local climate is characterized by a mean annual precipitation around 200 mm and an average annual air temperature of 8.2°C (Servicio Meteorologico Nacional-Argentina, http://www.smn.gov.ar). The coastal area experiences a meso-macrotidal regime (>4 mIsla and Bujalesky, 2008), with a tide range usually fluctuating between 2.5 and 5.5 metres (http://www.hidro.gov.ar/Oceanografia/Tmareas/Form_Tmareas.asp). The lunar and solar cycles produce a mixed tidal type yielding unequal low and high tides (Fig. 2).

The analysed notches are located along a W-E oriented coastline (Fig. 1), impacted by prevailing winds blowing from the West, less frequent are winds blowing from the Southwest and the North (www.windfinder.com).

The study area is located in the Deseado massif geological province, characterized by the outcrop of middle-upper Jurassic volcanic and volcanoclastic rocks of the Chon-Aike Formation of Bahía Laura Group (Guido et al., 2004; Sruoga et al. 2004). These rocks are mainly calc-alkaline and peraluminous rhyolites, with some dacitic members (Pankhurst and Rapela, 1995; Pankhurst et al., 1998), displaying a prevalent massive aspect (pyroclastic density currents deposits). The principal minerals are quartz, K-feldspar, plagioclase and biotite; accessories are magnetite, ilmenite, apatite and zircon with associated monazite (Sruoga et al. 2004).

The volcanic and volcanoclastic substratum dominates the area of Puerto Deseado settlement and part of the Rio Deseado river mouth. It is shaped in the form of rocky marine terraces sparsely covered by Quaternary marine and subaerial deposits (Ribolini et al. 2014; Zanchetta et al. 2014). A rocky promontory (Punta Foca-Punta Cavedish), with an indentation of a gravelly pocket beach, separates the Puerto Deseado area from the northern coast (Fig. 1). On the northern coast there are littoral deposits of Quaternary age that seaward cover a modern intertidal-lower supratidal shore platform (Feruglio, 1950; Codignotto et al., 1988; Zanchetta et al. 2014).

METHOD

Notches present in this area show a wide variability of dimensions and shapes (Fig. 3). The studied notches are located parallel to the current coastline at different elevations above HT level. The observed notches do not show evidence of structural control in their formation. In fact, they are carved in massive lithified pyroclastic units and there is no evidence of layering, discontinuity, fractures and structural weakness directions coinciding with the position of notches. The azimuthal distribution of the few detectable fractures in the surrounding area shows a maximum peak around N315E (Fig. 4), while the coastline directions shows a very narrow peak at N70E. Consequently no structural control in the development of notches could be supposed.

The morphometry of these notches is described according to the parameters suggested by Pirazzoli (1986, Fig. 5) total height (H), distance of retreat point from cliff face (D), height of retreat point from the floor (H_f) and measured using a graduated bar.

Taking into account that these parameters may vary inside a single feature depending on how they are measured a more accurate analyses was undertaken in one selected notch. This selected notch was surveyed using a software-based technology that allows the user to generate three-dimensional data from a surface using a series of overlapping images taken by a consumer-grade digital camera. In this case, 30 images have been processed by the open-source SfM software package Bundler (Snavely et al., 2006; 2007), obtaining a sparse 3D coloured point cloud with internally-consistent 3D geometry (Fig. 6). A detailed description of this method can be found in Favalli et al., (2011). The 3D point cloud has been processed using the free MeshLab software (http://meshlab.sourceforge.net/), which allows the editing process of the points. The post-processing phase was done in a GIS environment selecting the points belonging to the water surface filling the pool in front of the notch, then rotating the whole point cloud so that the selected pool points lay on a horizontal plane. Multiview 3D reconstructions have root mean square (RMS) errors that are usually less than 1% of the average linear dimensions. In our case the RMS error is under 5 cm (e.g. Cecchi et al,. 2003; Favalli et al., 2011). After that 13 profiles, spaced at 30 cm intervals, were derived (Fig.7). The H, D, H_f parameters and the range of elevation of the retreat points above the horizontal plane have been calculated for each profile.

The elevation above sea level was measured by means of graduated stacks equipped with a spirit level (three-meter rod). Through a centimetre-graduated bar, we constructed a topographic profile between the sea level and the retreat point of each notch, and we corrected the elevation data accordingly to the tide level at the time and date of measurement derived from astronomic tide tables, calculated for the 2011/01/28 in Puerto

Deseado. Through this method we reconstructed the topography of the shore platform in front of the notches, the elevation of morphological markers of high tide and the elevation of cliff at centimetric resolution.

The appearance of surface (polished, smooth etc.) and the lateral continuity of the notches were qualitatively described to better understand their genesis. We also analysed the relationship of the notches with other geomorphological and biological sea-level markers occurring in the same area as the high-tide morphological step in the beach, the upper limit of the ecological zone of barnacles, mussels and green-seaweed.

RESULTS

The shapes and morphometric characteristics of 11 notches directly measured in the field are reported in Figure 8. In particular, the height (H) ranges between 90 cm and 260 cm, and the distance (D) ranges between 21 and 1020 cm. All studied notches display an asymmetric shape with a gently sloping floor rising up to the retreat point that is quite low as shown by the small values of the elevation difference between retreat point and the floor (H_f).

The retreat point area is characterized by an abrupt decrease in roughness, with a rock surface notably smoother on touch than the notch roof and floor (Fig.3). Most notches show potholes located in the inner part of the floor, just below the retreat point, where abrasive materials were trapped against the foot of scarps. These potholes are characterized by elliptic shape with main axis coincident with notch length ranging from 0.4 m to 5 m, minor axis ranging from 0.1 to 0.6 m, and about 0.3 m deep. (Fig.3). Potholes are generally colonized by mussels (*Brachidontes purpuratus*), barnacles (*Balanus* sp.), and green algae. Marine water usually remains inside the potholes even during low tide (Fig.3).

Contrasting colours belts evidence the vertical biological zonation on the rock, in accordance with Stephenson and Stephenson (1972). This zonation is typical of sheltered areas (Stiros and Pirazzoli, 2008) and results from changes in the biological community structure. Specifically, from base to top of the zonation, the upper boundary of green algae marks the mean low tide at very low tide conditions, followed by a black band of mussels, white barnacles and black lichens. The continuous barnacle band upper limits marks the minimum high tide level in sheltered zone (Little et al. 2009; Stiros and Pirazzoli, 2008).The retreat points of notches 3, 4, 5, 7 and 8 (Fig.8) are located just above the band characterized by mussels and barnacles where abrasion prevents colonization of rock surface by organisms. Lichens are visible up to 1 m above the retreat point. On the contrary, the other notches do not show biological colonization.

A rocky shore platform is present in front of most of the notches, patchily covered by mixed sediment including sand and eterometric pebbles (from centimetre to decimetre in maximum diameter) of different lithologies. They are repeatedly moved by wave action as to excavate a great number of smoothly circular potholes on the rocky platform, attesting the potency of wave abrasion (Trenhaile 2004). The basal part of notches 6, 10 and 11 (Fig.8) is partially buried by coarse deposits. The deposit burying notch 6 consists on top of a few centimetres of a pebble lag with no evidence of soil development, covering ca 10 cm of dark, charcoal- and ash-rich sandy deposit containing abundant shell material and flints. This deposit is certainly an archaeological layer, covering the undisturbed beach ridge deposits below.

To better constrain the parameters variability within the same feature, a 3D digital model of notch 1 was derived using the multiview reconstruction (Favalli et al., 2011). Then 13 strips were generated (Fig. 7b) and the morphometric parameters calculated for each strip are listed in Table 1. Most of the calculated values have a large variability, in fact, H varies between about 180 and 300 cm, while D varies between about 80 and 320 cm. The

207 platform angle in front of the notch varies between about 3° to 7° (the higher values are
208 related to the seaward slope of the pothole located in the notch floor). The variability of the
209 retreat point elevations referenced to a horizontal plane is instead very low, ca. 30 cm.
210 Six topographic profiles (Fig.9) were undertaken in order to investigate the relationship
211 between notch elevation, sea level morphological indicators (fair weather berm, seaweed
212 beach wrack from the previous high tide) and high-tide elevation derived from astronomic
213 tide tables. All profiles show a good correlation between the elevation of the observed high
214 tide evidence and the corresponding value derived from tide table. The retreat points
215 elevation ranges between -30 cm and +170 cm with respect to the high tide. Based on
216 these elevations, notches could be split in two different groups: the first including notches
217 3, 4, 5, 7, 8 and 10 located close to high tide (HT) level, the second including notches 1, 2
218 ,6, 9 and 11 located about 1.5 m above HT. Direct observations during the days of the field
219 work confirm that water rises up to the first group during HT.
220
221 DISCUSSION
222
223 There is a large variability in the morphometric parameters calculated among the studied
224 notches (Fig.8) and also in those referred to a single feature (e.g. notch 1) (Fig. 7a, b).
225 Nevertheless, morphometric analysis of notch 1 shows that the retreat point elevation has
226 a very low variability (Fig.7b). This make us confident in using the value of retract point
227 elevation for sea level estimation.
228 The topographic profiles carried out to calculate the elevation of retreat points with respect
229 to HT of the 2011-01-28 provided two groups of elevation values, the first approximately
230 coincident with the high tide level, the second ranging about 1.50 m above it (Fig. 9). The
231 variability of retreat point elevation shows two clusters with a very low internal variability (±
232 0.3 m for the lower and ± 0.2 m for the upper notches, Fig. 10). When compared with the

tide curves derived from the local tide tables (Fig. 11), the elevation of lower group of notches is consistent with the monthly mean value of high tide (mHT), calculated on the tide table values recorded during the 15 months considered (Fig. 11). The elevation of upper notches is located at least ~0.5 m above the curve of the highest astronomical tide (MHT), consequently they can be reached by waves only during storms. Furthermore, at the base of notch 6 (upper notches group) we found a shellmidden deposit radiocarbon dated at 0-236 cal. yr B.P. (Table 2) (*Mytilus edulis*), and at the base of the sediment covering notch 11 (upper notches group) we dated an individual of *Nacella deaurata* yielding a radiocarbon age 476-521 cal yr B.P. (Zanchetta et al., 2014). The preservation of these deposits suggests that, even if occasionally reached by waves, the rates of erosion are so low that it cannot remove an unconsolidated deposit. These observations, along with the tidal values, allow us to consider the lower notches group as active forms and the upper ones as inactive. The presence/absence of organisms related to sea level in the lower/higher notches group supports this hypothesis. The limited elevation range of retreat point inside each group enable us to consider abrasive notches as a good morphological sea-level marker in this bay. Moreover the retreat point elevation of current notches in comparison with the high-tide level variation suggests that they mark the medium level of high tide. These results support the suitability of abrasive notches as palaeo sea-level markers in this area.

Given that their elevation is linked to the mean high tide level, they display a small error (±0.30 m) when compared with other sea level markers commonly used in the Patagonian coast, as beach ridge crests, that overestimate the mean sea level value. Moreover, because of their genesis, notches indicate a marine stillstand phase while the other marine deposits commonly used in this area form during regressive phases (Pirazzoli, 1986; 1996; Kershaw and Guo, 2001; Kelletat, 2005; Ramos and Tsutsumi, 2010). On the other hand, marine deposits are suitable for dating because of their fossil content, while notches are quite difficult to date. Therefore a combined use of marine deposit chronology and related elevation of coeval notch may offer a more confident reconstruction of the past sea level.

The study area is a pocket beach characterized by the presence of several well-defined beach ridge crests testifying different phases of coastal aggradation (Zanchetta et al., 2014). Because of their position and the associated deposits, the notches with elevation ca. 1.5 m above current mean high tide can be correlated with the lowermost inactive beach ridges visible on the shoreplain located at ca 3 m above high tide (Zanchetta et al., 2014). This indicates that in a such protected bay the height of the beach ridge crest exceeds of ca 1.5 m that of notches i.e. the mean High Tide level. This datum is confirmed by our field measurements on active beach ridge crests attesting their elevation at about 1.3 – 1.5 above high tide.

CONCLUSION

Along the meso-macro tidal coast of Patagonia (Puerto Deseado area), the retreat point of active abrasive notches approximates the medium level of high tide with a small variability (±0.3 m). The retreat point seems not only correlated to the high-tide level, as already observed by Dickinson (2001) in the Pacific Islands, and Irion et al. (2012) on the coast of Brazil, but more precisely it is located slightly below the medium value of high tide level, in perfect agreement with the study made by Trenhaile et al. (1998) on the New Brunswick coast (Canada). This coherence between our data and those obtained in different environmental conditions underlines the general significance of the results obtained in this part of the Patagonian coast, excluding the influence of local factors. This result opens to the possibility of using fossil abrasive notches as palaeo sea-level markers, more effective than the markers frequently adopted in this coastal region (i.e. beach ridge crest, mouth/littoral terrace). Indeed, the lowermost inactive notches in this area is at 1.5 m ± 0.2

m above medium level of high tide, whereas the coeval beach ridge crest stands at 3 m above high tide.

An accurate determination of relative sea level through the selection of the appropriate markers such as notches is particularly useful to test geophysical models and to disentangle the glacio-eustatic, hydro-isostatic and neotectonic components in sea level change signal, a topic still debated in the Patagonian Coast.

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Captions

Fig. 1. The study area and the location of the11 abrasive notches analysed (red points).

Fig. 2. Tidal trends during the 15 months from 10/10 to 12/11 (http://www.hidro.gov.ar/Oceanografia/Tmareas/Form_Tmareas.asp). The lunar and solar cycles produces in this area a mixed tidal regime yielding unequal low tide and high tide (Max high tide; Max low tide; min high tide and min low tide). Elevation data are in reference to the reduction plane (theoretical plane located under the mean sea level in order to have only positive tidal values in the tables) located 3.20 m below the medium level.

Fig. 3 Examples of the observed notches

Fig. 4 Analysis of azimuth distribution of fractures (a) and coastal line (b) directions Notice how the predominant fracture direction is approximately at a right angle to the coastline.

Fig.5 Measured parameters: total height (H), distance of retreat point from cliff face (D), height of retreat point from the floor (H_f), according to Pirazzoli (1986)

Fig.6 a): Notch1 photography, b): 3D model displayed by MeshLab software, c): zoomed in area on the point cloud.

Fig.7 Variability of notches shape, shown through the 3D analysis modelling, a) 3D view of the point cloud, b) the 13 derived profiles.

Fig. 8. Morphometric characteristics of the 11 notches analyzed Rp = retreat point; H_f = elevation of retreat point above the floor; H = notch height; D= notch depth; hTE = elevation of retreat point above high tide. All data are reported in cm and are derived from field measurements.

Fig. 9. Topographic profiles in which notch position (black arrow) is compared with morphological evidence of high tide (black dashed arrow) and high tide elevation derived from tide tables, calculated for the 2011/01/28 in Puerto Deseado (black dashed line).

Fig. 10 Distribution of the retreat point elevations above high tide. In spite the low number of features they show two well separated clusters with a very low variability.

Fig. 11. Relation between retreat point elevation and tide level derived from the current tide tables of Puerto Deseado. Elevation data are in reference to the reduction plane (theoretical plane located under the mean sea level in order to have only positive tidal values in the tables) located 3.20 m below the medium level.

strip	Ht (cm)	H_f(cm)	D (cm)
2	266.4	35.7	88.6
4	230.7	21.4	77.1
6	239.3	22.1	92.1
8	238.6	32.9	137.1
10	247.1	12.1	172.9
12	272.9	26.4	202.9
14	211.4	22.1	192.9
16	303.6	43.6	322.9
18	284.3	13.6	301.4
20	260.0	45.0	255.0
22	237.1	52.9	217.9
24	225.7	25.7	181.4
26	185.7	20.7	138.6
Field	260	50	350

Sample	Field code	^{14}C yr BP (±1σ)	^{14}C cal yr BP (±1σ)	Species or material
DSH1959	WP344	880±30	476-521	*Nacella (Patinigera) deaurata*
DSH2735	WPi 39	480±60	0-236	*Aulacomya atr*

Fig. 1. The study area and the location of the11 abrasive notches analysed (red points).
294x128mm (300 x 300 DPI)

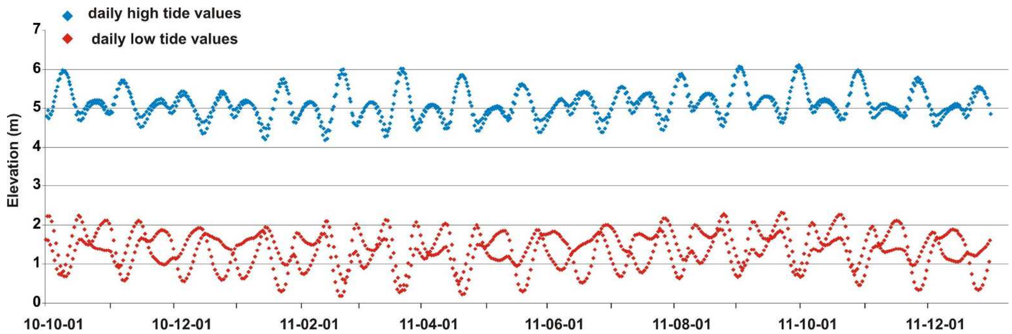


Fig. 2. Tidal trends during the 15 months from 10/10 to 12/11 (http://www.hidro.gov.ar/Oceanografia/Tmareas/Form_Tmareas.asp). The lunar and solar cycles produces in this area a mixed tidal regime yielding unequal low tide and high tide (Max high tide; Max low tide; min high tide and min low tide). Elevation data are in reference to the reduction plane (theoretical plane located under the mean sea level in order to have only positive tidal values in the tables) located 3.20 m below the medium level.
279x90mm (300 x 300 DPI)

Fig. 3 Examples of the observed notches
193x218mm (300 x 300 DPI)

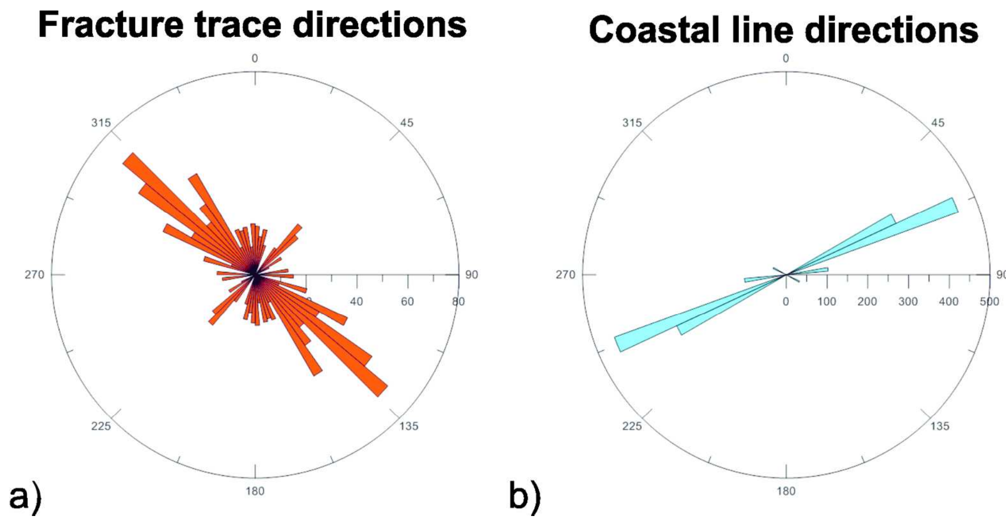


Fig. 4 Analysis of azimuth distribution of fractures (a) and coastal line (b) directions
Notice how the predominant fracture direction is approximately at a right angle to the coastline.

154x77mm (300 x 300 DPI)

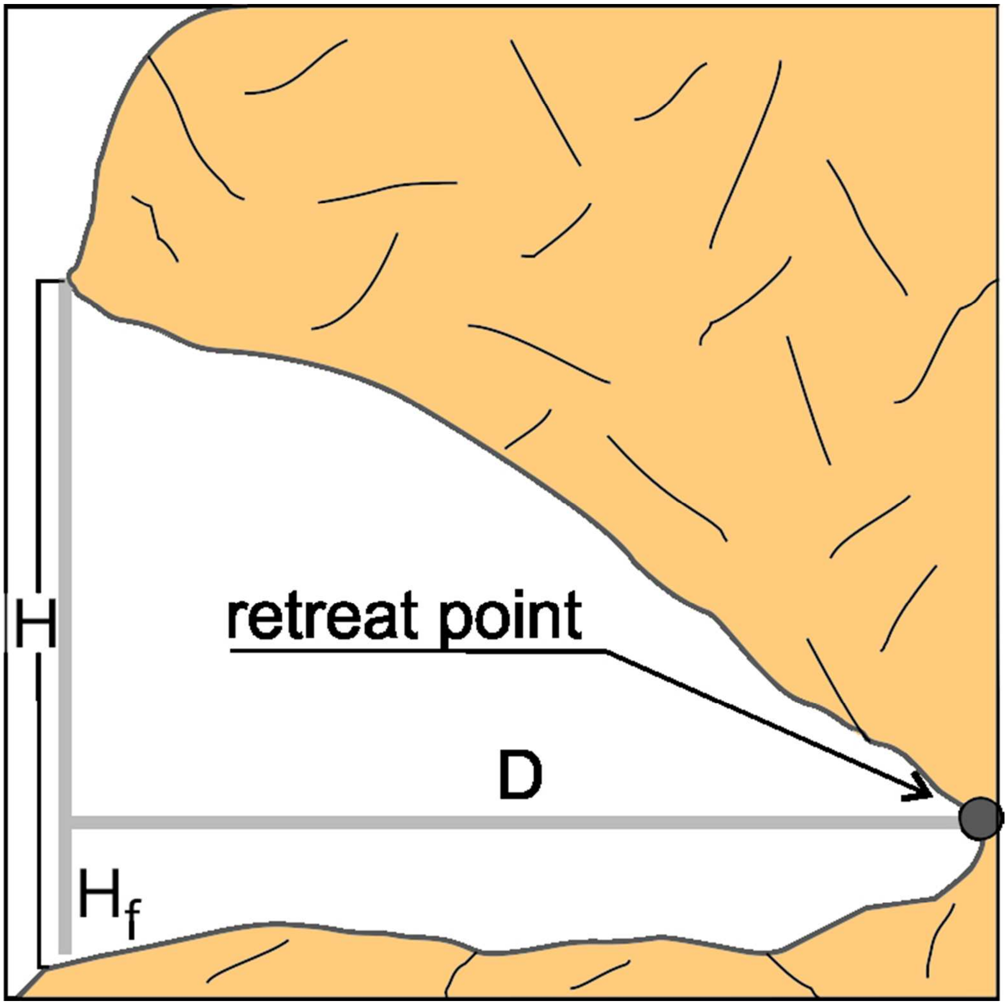


Fig.5 Measured parameters: total height (H), distance of retreat point from cliff face (D), height of retreat point from the floor (Hf), according to Pirazzoli (1986)
63x63mm (300 x 300 DPI)

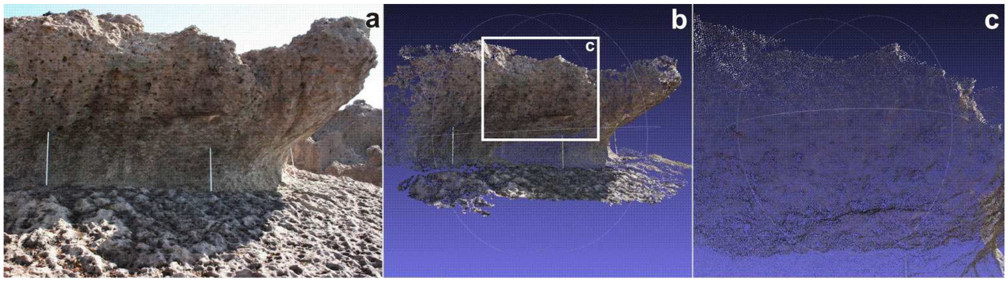


Fig.6 a): Notch1 photography, b): 3D model displayed by MeshLab software, c): zoomed in area on the point cloud.
202x55mm (300 x 300 DPI)

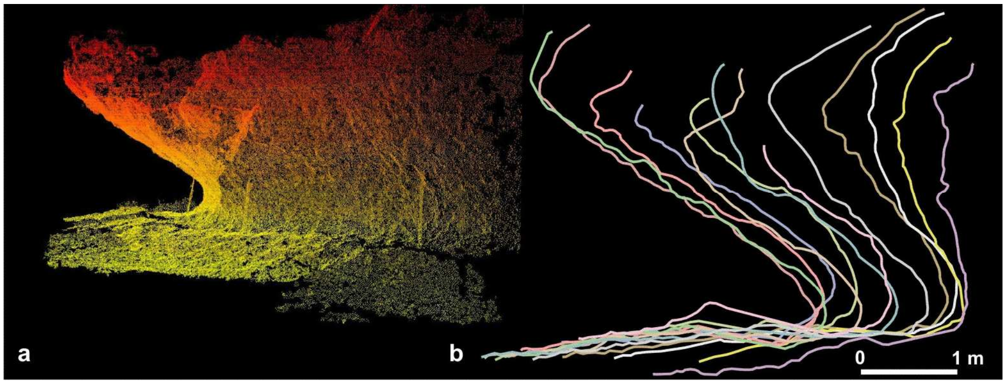


Fig.7 Variability of notches shape, shown through the 3D analysis modelling, a) 3D view of the point cloud, b) the 13 derived profiles.
204x77mm (300 x 300 DPI)

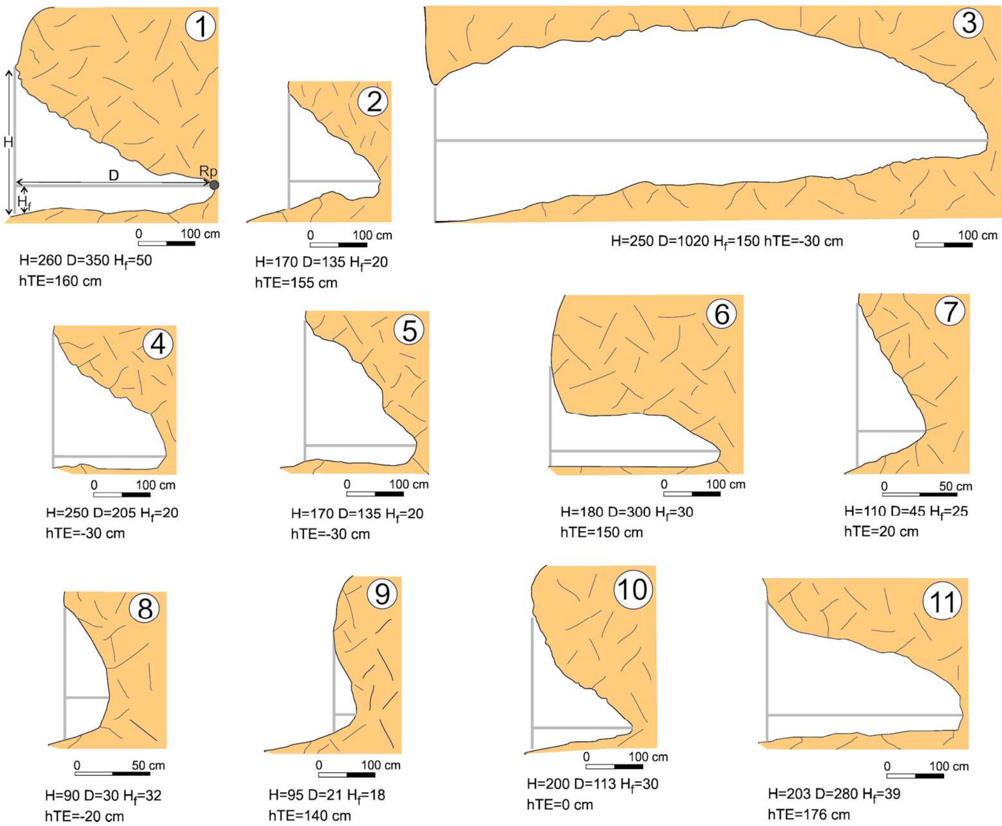
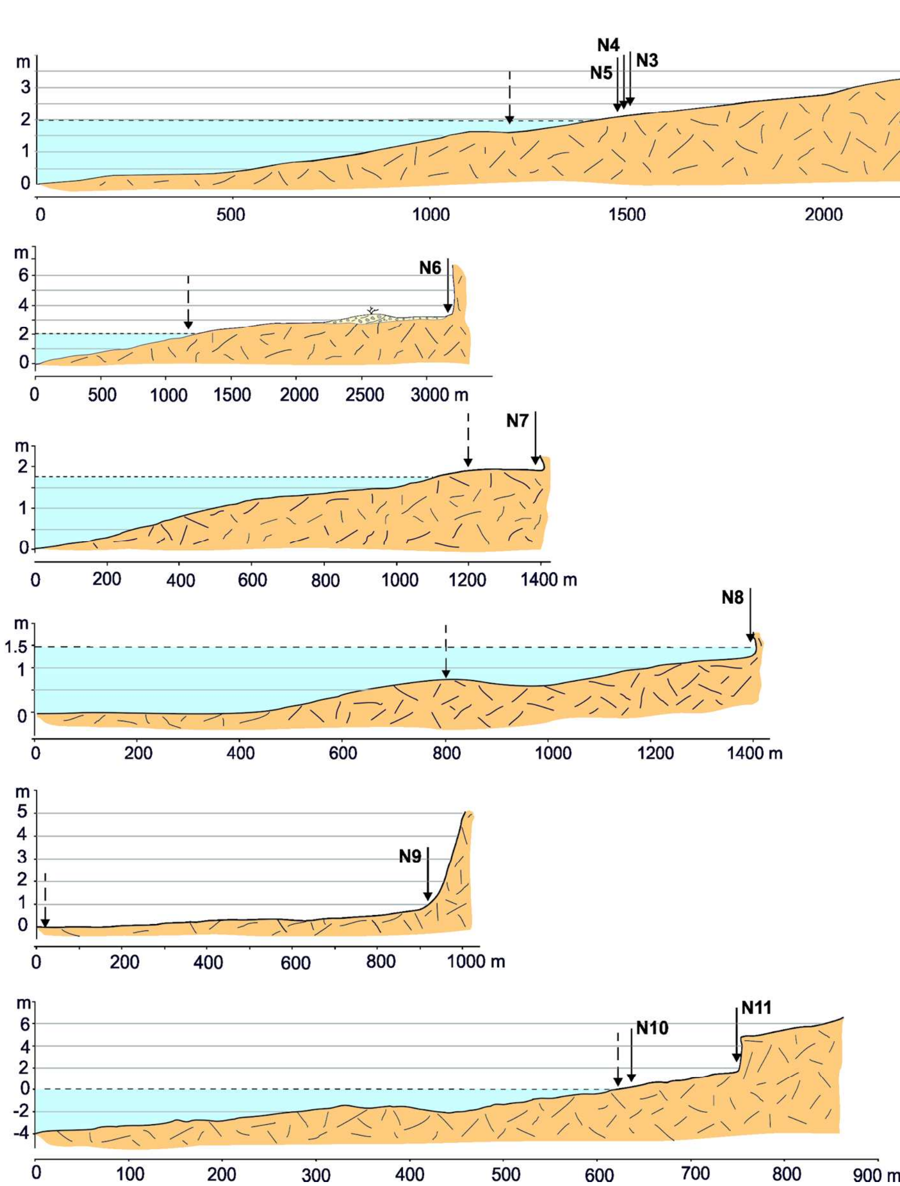
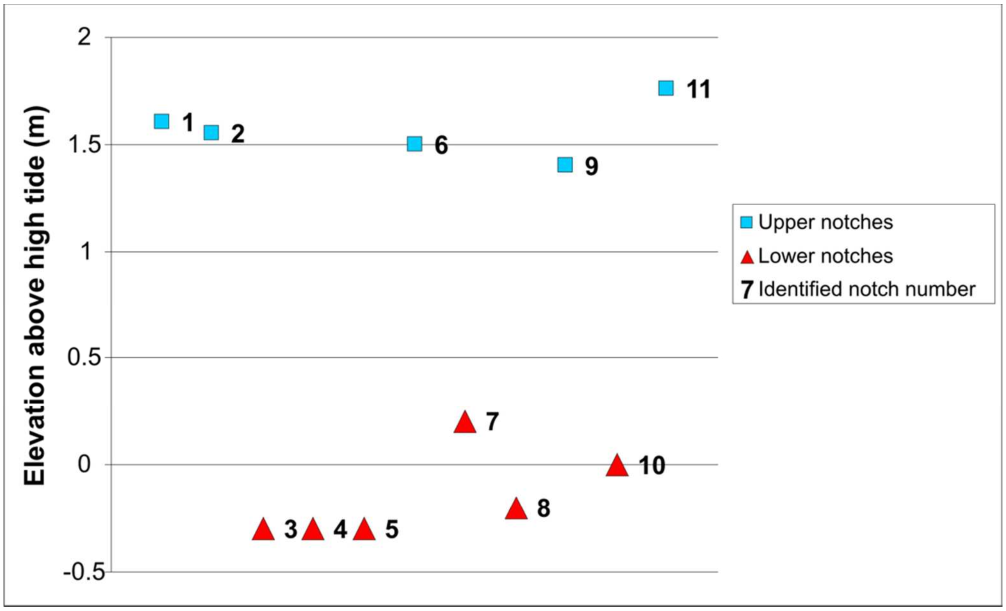


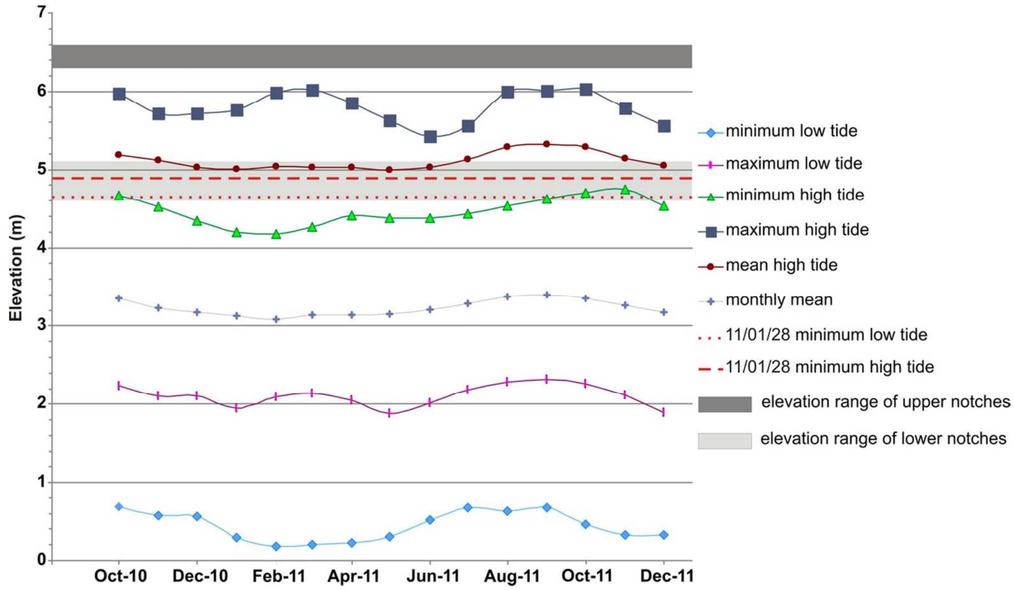
Fig. 8. Morphometric characteristics of the 11 notches analyzed Rp = retreat point; Hf = elevation of retreat point above the floor; H = notch height; D= notch depth; hTE = elevation of retreat point above high tide. All data are reported in cm and are derived from field measurements.
187x152mm (300 x 300 DPI)



Topographic profiles in which notch position (black arrow) is compared with morphological evidence of high tide (black dashed arrow) and high tide elevation derived from tide tables, calculated for the 2011/01/28 in Puerto Deseado (black dashed line).
160x188mm (300 x 300 DPI)



Distribution of the retreat point elevations above high tide. In spite the low number of features they show two well separated clusters with a very low variability.
102x61mm (300 x 300 DPI)



Relation between retreat point elevation and tide level derived from the current tide tables of Puerto Deseado. Elevation data are in reference to the reduction plane (theoretical plane located under the mean sea level in order to have only positive tidal values in the tables) located 3.20 m below the medium level.
117x67mm (300 x 300 DPI)