MID-HOLOCENE RELATIVE SEA-LEVEL CHANGES ALONG ATLANTIC PATAGONIA: NEW DATA FROM CAMARONES, CHUBUT, ARGENTINA

Journal:	*The Holocene*
Manuscript ID	HOL-16-0133.R2
Manuscript Type:	Paper
Date Submitted by the Author:	n/a

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Keywords:	relative sea level, Atlantic Patagonia, Holocene, coastal geomorphology, Camarones, biological indicators

Abstract:	This paper concerns the relative sea-level changes associated with the Atlantic Patagonian coast derived from sea-level index points whose elevation was determined by a DGPS. Bioencrustations from outcrops located near Camarones, Chubut and Argentina consist of autochthonous deposits characterized by Austromegabalanus psittacus MOLINA, 1782, encrusting acervulinid foraminifera, coralline red algae, and bryozoans. The association of the different organisms is interpreted as being associated with an intertidal environment and they have been used as index points to establish the relative sea-level position. The main conclusion was that the relative sea-level between c. 7000 and 5300 cal. yr BP was in the range of c. 4 - 2 m asl, with a mean value of c. 3.5 m asl. Our data seem to support the existence of different rates of relative sea-level fall in different sectors of Atlantic Patagonia during the Holocene, and highlight the importance of

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Abstract

This paper concerns the relative sea-level changes associated with the Atlantic Patagonian coast derived from sea-level index points whose elevation was determined by a DGPS. Bioencrustations from outcrops located near Camarones, Chubut and Argentina consist of autochthonous deposits characterized by *Austromegabalanus psittacus* MOLINA, 1782, encrusting acervulinid foraminifera, coralline red algae, and bryozoans. The association of the different organisms is interpreted as being associated with an intertidal environment and they have been used as index points to establish the relative sea-level position. The main conclusion was that the relative sea-level between *c.* 7000 and

5300 cal. yr BP was in the range of *c.* 4 - 2 m asl, with a mean value of *c.* 3.5 m asl. Our data seem to support the existence of different rates of relative sea-level fall in different sectors of Atlantic Patagonia during the Holocene, and highlight the importance of a more precise and accurate relative sea-level estimation by producing new data and revisiting the indicative meaning of most of the indicators so far used in the area.

Keywords

Relative sea-level, biological markers, Atlantic Patagonia, Holocene

Introduction

The impact of sea-level rise is one of the main concerns related to ongoing global warming, and our capacity to estimate the regional-to-local impact on the coast environment relies on the assumption that many local variables are known (e.g., eustatic sea-level component, tectonic uplift, subsidence, glacial isostatic adjustment; Alley et al., 2005; Blum and Roberts, 2009; Milne et al., 2009; PALSEA, 2009; Lambeck et al., 2014). In this framework, the reconstruction of the relative sea-level changes at regional scale during the Holocene is particularly relevant and the accuracy of its estimation is crucial for testing geophysical models (Milne and Mitrovica, 2008).

With its 2000 km of coast the Atlantic Patagonian passive margin represents a natural link for exploring the relative sea-level evolution between “near” and “far” field sites (Milne et al., 2005; Rostami et al., 2000). Therefore, this is a strategic area in which to focus paleo sea-level studies (Codignotto et al., 1992; Milne et al., 2005; Rutter et al.,1989, 1990; Rostami et al., 2000; Schellmann and Radke, 2000, 2003, 2010; Pedoja et al., 2011; Ribolini et al., 2011; Zanchetta et al., 2014; Isla and Angulo, 2015). However, a precise and accurate estimation of the relative sea-level (RSL) in this area has been complicated by several factors, namely: i) precise and accurate sea-level indicators such as notches, inner terrace margins, coral reefs, and algal encrustations have been rarely used or not found (Pedoja et al., 2011; Ribolini et al., 2011; Bini et al., 2013, 2014); ii) sea-level indicators have generally been measured by using a barometric altimeter or graduate bars equipped with spirit level, starting from the local high-tide level implying a wide vertical error up to ± 3 m (Zanchetta et al., 2012, 2014); iii) the coastal area is within the macrotidal regime (Isla and Bujalesky, 2008), and is characterised by high hydrodynamic regimes, so that most of the sea-level indicators are related to surf and storm extension rather than to mean sea-level. As a consequence, Schellmann and Radke (2010) and Zanchetta et al. (2014) reported a different altitudinal estimation for the Holocene RSL, using different indicators related to coastal sediments (i.e., beach ridges, littoral terraces). Some authors take a different approach in measuring reference sea level (e.g. top vs base of beach ridges; Pappalardo et al., 2015), complicating the use of reported data (Codignotto et al., 1992; Rutter et al., 1989, 1990; Pedoja et al., 2011; Ribolini et al., 2011), while others report data related to high-tide level (Schellmann and Radke, 2010 and references therein, Zanchetta et al., 2012, 2014). The correlation between elevation values measured above high tide and values measured above mean sea-level is not so straightforward and regional correlations are complicated. Although the data from this vast region would be of paramount importance, recent geophysical modelling of sea-level change along the South American coast has not accounted for the Patagonian data (Milne et al., 2005), presumably because of their very high level of uncertainty.

In this paper we report on a RSL reconstruction based on in situ fossil barnacles and foraminiferal-bryozoan concretions. These sea-level indicators have never been described along the Patagonian coast so far. Here, we describe the indicators found in the territory of Camarones (Chubut, Argentina, Fig.1), one of the nodal areas for the reconstruction of the relative sea-level oscillations along the Patagonian coast owing to its abundance of raised beaches with datable materials (Schellmann and Radke, 2010; Zanchetta et al., 2012; Pappalardo et al., 2015). Moreover, the elevation of the indicators was for the first time measured by a Differential Global Position System (DGPS), which provided reliable sea-level values at an accuracy never previously reached along the Patagonian coast. Finally, we standardized our data in terms of sea-level index and limiting points (e.g. Shennan et al., 2015; Vacchi et al., 2016; Rovere et al., 2016). This approach, totally new for the Patagonian coast, is mandatory for future regional and extra-regional correlations.

The study area

The study area is located in the southern part of the Bahía Camarones, Chubut (Argentina), a *c*. 40 km wide gulf extending from *c*. 44°54′ S to 44°34′ S (Fig. 1). Structurally, the area is located on the southern edge of the so-called "North Patagonia Massif" (Ferruglio, 1950). Mostly Jurassic volcanic rocks formed the pre-Quaternary succession (Marifill Formation, Lema et al., 2001). Inland morphology is characterised by flat surfaces covered by Late Neogene-Early Quaternary fluvial gravelly deposits ("*rodados Patagonicos*" in Martinez and Coronato, 2008), while the landscape is dominated by Quaternary littoral and continental deposits raised at various elevations close to the coast (Lema et al., 2001; Pappalardo et al., 2015).

Like most of coastal Patagonia, the area is dominated by high-energy, macro-tidal and stormy conditions (Isla and Bujaleski, 2008), resulting in a coastal morphology dominated by cliffs, shore platforms and coarse-clastic beach ridges ("swash built ridges" *sensu* Tanner, 1995).

In Camarones the predictions of the astronomic tide elevations are calculated in relation to the harbour of Puerto Santa Elena (Fig. 1) according to the data released by the Servicio de Hidrografia Naval (http://www.hidro.gov.ar). For the area of Camarones the maximum tidal range is *c*. 5 m, while the mean is *c*. 3.5 m (Fig. 2).

Most of the studies on Holocene coastal evolution are concentrated in the southern part of the Bahía Camarones area, and provide a robust chronological constraint for coastal aggradation during the Holocene (Codignotto et al., 1992; Schellmann 1998; Schellmann and Radtke 2000, 2003, 2010). Two evolutionary phases have been distinguished: 1) the first phase, the maximum Holocene ingression (*c*. 6.8-6.5 ky BP), is characterized by the formation of littoral and estuarine deposits (Schellmann and Radke, 2010) found at the sea embayment along local creeks (locally named *"cañadon"*); 2) the successive phase, still active, is marked by discontinuous coastal aggradation, with the formation of prominent higher gravelly beach ridges parallel to the present-day coast (Fig. 3).

Methodology

For stratigraphic and geomorphological investigations we followed the same approach already used in previous studies conducted in the area (Ribolini et al., 2011, Isola et al., 2011). A preliminary remote sensing analysis was performed by using LANDSAT7 images (acquisition dates, 1999-2001), and Quick Bird images (acquisition date, 2004) supported by the digital elevation model SRTM (www.jpl.nasa.gov/srtm). After this preliminary phase, field surveys were carried out in February 2009, 2010, and 2011 (Zanchetta et al., 2012; Pappalardo et al., 2015). In the first phase, the elevation data were obtained by using graduate bars equipped with spirit level, starting the measurements from the nearest IGN point (Instituto Geográfico Nacional), with a precision in the order of ±0.3 m (Zanchetta et al., 2014). A field survey conducted in January 2016 was dedicated to the DGPS measurement of sea-level indicators. The data were acquired by the WGS84 Geographic Coordinate System (maximum error in elevation of acquired points was 10 cm) and post-processed and referred to the current global geoid model EGM2008 (Pavlis et al. 2012) (4 cm planimetric error and 9 cm elevation error). Elevation measurements indicated as "asl" in this paper are referred to the vertical datum EGM2008. These data integrate and basically confirm those previously obtained by graduated bar measurement. For the study area Schellmann and Radke (2010) reported the altitudinal measurement of different sea-level indicators, by using a barometric altimeter (reported precision ±1 m) daily calibrated with the tide level. In order to compare our data with those reported by Schellmann and Radke (2010) we used the DGPS to re-measure some of the sections described by Schellmann and Radke (2010).

In situ barnacles and encrusting foraminiferal deposits were collected in the field and measured with DGPS (Figs. 1 and 3), alongside additional samples with articulated valves of *Mytilus edulis* from littoral deposits. The samples for radiocarbon dating were cleaned in an ultrasonic bath with the addition of oxygen peroxide and then gently etched with diluted HCl to remove any recent carbonate encrustation. Radiocarbon measurement was carried out at the CIRCE laboratory of Caserta, Italy (Terrasi et al., 2007, 2008) and calibrated by using the Marine13 curve (Reimer et al., 2015). However, the reservoir effect values for the Southern Atlantic Ocean and, in particular, Patagonia, are not well constrained (Schellmann and Radtke, 2010). Specific studies suggest that for different localities of the Patagonian coast between *c*. 42°S and 50°S the reservoir effect can vary between 180 and 530 years (Cordero et al., 2003; Butzin et al., 2005, Schellmann and Radtke, 2010).

Collected species, radiocarbon dates and sampling site elevation are reported in Table 1. The state of preservation of barnacles and encrustations, prior to dating were assessed by stereomicroscope analysis of thin sections and was investigated by X- Ray power Diffraction (XRD).

Results

The study area is located along a small river to the south of the Camarones village (Fig. 1). A succession of Holocene-Pleistocene gravelly beach ridges forms the coastal strandplain, up to a distance of more than 500 m inland from the present coastline. This arched beach ridge system is incised by a river valley where alluvial, marsh and coastal sediments were deposited (Figs. 3 and 4a). Along the river valley, bedrock crops out forming steep cliffs in some places and relict shore platforms locally. Three rocky outcrops, composed by welded ignimbrites of Marifil Formation, yielded barnacles (*Austromegabalanus psittacus* Molina, 1782) and foraminiferal encrustations (mostly *Acervulina inhaerens* Schulthe, 1854) in life position (Figs. 3, 4b, 4c, 4d, 5 and 6). The first outcrop (Figs. 3 and 4b) is formed by a vertical cliff exposed for *c*. 3-4 m and a flat top surface, located at *c.* 5 m asl, representing the remnant of a shore platform. Barnacles and foraminiferal encrustations are located on the cliff where barnacles are discontinuously spread for less than 1 m (between 3.4 m asl and 3.8 m asl) and encrustations for *c.* 1.5 m (between 3.3 m asl and 4.8 m asl; Figs. 4b and 5). The second outcrop (Figs. 3, 4c, and 5) is formed similarly by a vertical cliff with an on-top shore platform covered by gravelly deposits. On the vertical cliff barnacles span between 3.1 m and 3.9 m asl and incrustations from 3.3 m and 4.6 m asl. The third sampled inland site is represented by boulders at the toe of a rocky cliff (Figs. 3, 4d and 5). Barnacles and incrustations, spanning in elevation between 3.2 and 4.2 m asl, developed on the blocks and at the base of the cliff.

In each sampled site barnacles (*A. psittacus*) occur as isolated or 2-3 jointed individuals (Fig. 6). Most of the encrustations consist of foraminifera identifiable as *Acervulina inhaerens* (Fig. 6d, e, f), which is the dominant component, while arborescent forms such as *Homotrema* and *Miniacina* are less frequent. All these encrusting foraminifera form repetitive or randomly-arranged inner superimposed growth stages. Superimposed growth stage bryozoans and rare coralline-red algal thalli occur within the *A. inhaerens*. The bryozoans are represented by encrusting cheilostomes (*Anascina*?), and the very low preservation does not allow their systematic identification. The corallines are almost micritized and/or recrystallized. A possible uniporate conceptacle was also identified. This reproductive character along with the vegetative characters (cell fusions, monomerous cell filaments) suggests a possible ascription to the Mastophoroideae subfamily (Fig. 6d, e, f).

The top surface of the first outcrops is carved in a previously modelled rocky terrace attributed by Schellmann and Radke (2010) to marine isotope stage 7 (MIS 7). A shell accumulation of *M. edulis* rests directly on the lateral margin of the lower shore platform, sealed by a few decimetre-thick slope deposits. No other deposits cover the shore platform. This shell accumulation, with a poor sandy matrix of some mm-size rounded-clasts, and some shells with valves still joined, is consistent with a storm deposit. One shell from the accumulation yielded a radiocarbon age of 5562±43 yr BP.

Concretion from the vertical cliff of this outcrop yielded a radiocarbon age of 4995±89 yr BP, whereas one barnacle yielded 5515±50 yr BP.

The top surface of the second rocky outcrop is covered by gravelly deposits, which did not yield suitable material for dating (i.e., only fragmented shells and not entire shells with articulated valves). However, these deposits are reasonably related to the formation of the Holocene erosional platform. In the vertical cliff of this second outcrop a barnacle yielded a radiocarbon age of 5132±67 yr BP. Here, the rocky cliff was crossed by some vertical fissures containing sediment and by some fossil remains, including *M. edulis* and barnacles (Fig. 6c). One sample with articulated valves of *M. edulis* collected from the infilling of the vertical fissures yielded a radiocarbon age of 5567±44 yr BP.

On the third site a sample of barnacles revealed a radiocarbon age of 5641±46 yr BP.

All the rocky cliffs are partially sealed by gravelly estuarine terraced deposits, namely valley-mouth terraces, according to Schellman and Radke (2010, Fig. 3). These deposits contain shells (principally *Prothotaca antiqua* and *M. edulis*) accumulated in lenses for which Schellman and Radke (2010) reported a radiocarbon age of 5560±38 yr BP. A new radiocarbon measurement was undertaken on an *M. edulis* from the same deposits, directly sealing the second cliff, yielding a consistent age of 5370±60 yr BP.

Discussion

Sea-level indicators in Atlantic Patagonia have yielded controversial results in the estimation of past RSL, and their accuracy and precision have been poorly defined, both for the precision of the measurement of the method applied (barometric altimeter, local maps, graduate bars) and for the unclear meaning of the indicators, e.g. storm, maximum high tide (Codignotto et al., 1992). Therefore, it is mandatory to transform sea-level indicators into index or limiting points to improve RSL estimations (Shennan et al., 2015). So far, the most precise and accurate indicators described for Atlantic Patagonia, which can be easily transformed into sea-level index points, are the erosive notches. Specifically, the retreat-point of notch defines the main high tide values (±0.3 m, Bini et al., 2014).

The Camarones association of barnacles, bryozoans and encrusting foraminifera can be generically interpreted as intertidal-subtidal indicator (e.g. Pirazzoli et al., 1985; Laborel and Laberel-Deguen, 1994; Baker et al., 2001; Ferranti et al., 2006; Rovere et al., 2015, 2016).

Specifically, the collected samples of barnacle correspond to the "acorn barnacle" *A. psittacus* (Fig. 6a), a species inhabiting mainly rocky substrates of the subtidal zone, where it forms dense aggregates between 5 and 7 m in water depth (López et al., 2010). However, the functional faculties of the barnacle could account for the high capacity of *A. psittacus* to also colonize habitats exposed to prolonged emersion periods like those characterizing intertidal settings (López et al., 2003). The barnacles generally live in groups forming dense hummocks, but in less favorable locations like the intertidal zones where they are less frequent and distant from each other. The relatively sparse association of barnacles in our sampling sites indicates the upper limit of the living range.

Present-day acervulinid foraminifera show a large bathymetric range from the intertidal zone down to 100 m in water depth (Perry and Hepburn, 2008; Bassi et al., 2012). Although acervulinids are more common in deeper water settings where interspecific competition for space may be reduced (Rasser and Piller, 1997), *Acervulina inharens* thrives in shallow water Bahamas shelf settings (< 30 m; Walker et al., 2011). *Homotrema* is reported from high-energy shallow-water settings (Gischler and Möder, 2009). So far, *Homotrema* has seemed to be an excellent indicator of high-energy water conditions for shallow near-shore and shelf/edge habitats, where water energy during tidal exchange is greater in tropical and subtropical environments (Walker et al., 2011) and, even in this case, it is consistent with the intertidal zone. Moreover, it is generally assumed that fossil barnacles and bio-encrustation in growth positions are easily eroded (Pirazzoli et al., 1985). Therefore, the survival of encrusted shell remains at higher-than-present levels suggests a sea-level fall sufficiently rapid for the shell to escape obliteration by wave erosion (Pirazzoli et al., 1985), a condition favoring the preservation of species that live in the upper limit of the high tide. In most cases, the age of the outer shells on a thick vertical encrustation will correspond to the terminal period of the former sea-level stand (Baker et al., 2001). Therefore, the Camarones barnacles, bryozoans and encrusting foraminifera association can be considered substantially intertidal and its definition of index point could be possible on the basis of tide oscillations (Shennan et al., 2015; Vacchi et al., 2016). By assuming that our association is strictly intertidal between *c.* 6100 cal yr BP and *c.* 5300 yr cal. BP RSL was around 3.7 and 3.9 m asl (Fig. 7).

For the studied area, Schellmann and Radke (2010) reported several radiocarbon measurements for different sea-level indicators, which can complete and improve the interpretation of the data discussed in this paper. In our study, we selected only the valley-mouth terrace sea-level indicators, which are less affected by storm deposition, compared to beach-ridges, thus reducing the errors in elevation estimation (Schellmann and Radke, 2010; Tamura, 2012; Zanchetta et al., 2014). According to the observations of modern analogs by Schellmann and Radke (2010), valley-mouth terraces are estuarine deposits that contain lateral/vertical interfingering of mollusc-bearing littoral sediments and fluvial deposits forming at the mouth of small local rivers. The top of the valley-mouth terraces correlates directly to the former elevation of the high-tide level representing a suitable indicator to be used as index point. As can be inferred from Fig. 7, RSL from mouth-terraces is consistent within the indicative meaning of barnacles and encrustations supporting our interpretation. Indeed, at least three of our biological indicators, chronologically overlapping the data from valley mouth-terraces, lie within 1 m of the top of the mouth-terraces. Significantly, the presence of the storm deposit dated *c.* 5950 cal. yr BP, located directly on the erosive shore platform on top of the first cliff, represents an upper RSL limiting point (Fig. 7), constraining fairly well the values of fossil barnacles and mouth-terrace. The storm deposit can also be considered a *termine ante quem* for the formation of the rock platform on top of the first outcrop.

Considering the elevation of the index points obtained from mouth-terraces in the area together with the biological indicators discussed in this paper, this evidence collectively (Fig. 7) agrees on indicating the RSL to be from *c.* 2 to c. 4 m asl between *c.* 5300 and 7000 cal. yr BP.

In Fig. 7, the altimetric and chronological data of the valley-mouth terraces show a highstand between *c*. 7000 and 6600 cal. yr BP at *c*. 4 m asl, followed by a progressive fall to *c*. 2-2.5 m between 6200 and 5300 cal. yr BP. The radiocarbon age of the storm deposit above the shore platform may indicate that this shore platform was related to the higher sea stand at *c*. 7000 cal. yr BP, and was no longer significantly active during the progressive fall after ca. 6200 cal. yr BP, only occasionally reached by storms. However, the RLS variation recorded by the valley mouth terraces is not shown by barnacles and encrustation, thus suggesting that most of this variation falls within the range of error of the two index points.

Following Shennon and Horton (2002) the total vertical error (including vertical distribution of encrustation and barnacles, fig. 5; measurement errors and indicative meaning) for the biological sea-level indicators is *c.* 3.8 m. According to Schellman and Radke (2010), a minimum vertical error for valley mouth-terraces can be calculated at *c.* 2 m. However, a precise estimation of error should be associated with an accurate review of modern analogues on the valley mouth-terraces and of other findings from fixed biological indicators.

Overall, the mean RSL between *c.* 7000 and 5300 cal. yr BP, which can be obtained considering all the index points, is 3.4±0.6 m asl.

Initial glacio-hydro-isostatic models of the Patagonian coast suggested that the shoreline could be characterized by currently raised beaches, which started to form as soon as ice-sheet melting ceased (Clark et al., 1978). A more recent model (Milne and Mitrovica, 2008) predicted that relative sea-levels might have exceeded present by *c.* 5 m at 6000 cal. yr BP. Field evidence indicates that the highstand is somewhat *c.* 1.5 m lower than model prediction. These ranges of measurement can agree with the model considering all the vertical errors associated with the index points discussed.

A comparison of the different sectors of the Atlantic Patagonian coast is complicated by many factors. Codignotto et al. (1992) found a significant rate of relative sea-level changes during the Holocene in relation to different tectonic sectors. They indicated a maximum highstand at *c*. 12 m asl for the period *c.* 4-8 kyr BP for the area of Camarones-Bustamante, at *c.* 2 m asl for the period *c.*

4-6 kyr BP in the area of Bahia Solano (Fig. 8). These data are affected by poor quality radiocarbon dating together with low altimetric accuracy. Moreover, most data are obtained by measuring the altitudinal crest of beach ridges, which are largely affected by storm conditions (Schellmann and Radke, 2010; Tamura, 2012; Zanchetta et al., 2014). On the contrary, Schellmann and Radke (2010) observed no appreciable differences along the Patagonia coast. However, by using different sea-level indicators the authors observed different values (reported above high tide –a.h.T) for the highstand, occurring between *c*. 6-7 cal. kyr BP, ranging from *c*. 9 to 5 m ahT. Bini et al. (2013, 2014), and Zanchetta et al. (2014) reported a relative sea-level at *c*. 8 m asl at *c*. 3500 cal. yr BP by accurate measurements of erosive notches in the Puerto Deseado area (Fig. 1). Owing to the difficulty in dating erosive notches, Zanchetta et al. (2014) suggested that these notches were formed during a previous Holocene highstand. In any case, the relative sea-level marked by well-preserved notches is higher than that observed in the Camarones area, indicating that a different relative sea-level may exist along the Patagonian coast during the same period (Fig. 8).

In this respect, Pedoja et al. (2011) suggested that the presence of the Nazca and the Antarctic plates subducting under South America and southern Patagonian respectively (Ramos and Ghiglione, 2008, and references therein) may have produced a long wavelength tectonic effect, onto which the glacio-hydro-isostatic signal is overprinted. This signal can vary according to the different sectors of the Atlantic Patagonian coast. More recently, Isla and Angulo (2015) in an accurate review of existing data from MIS5 terraces along Atlantic Patagonia have shown the importance of the effect of subduing plates in determining regional trends in the rate of uplift. The data discussed in our paper seem to support the possible existence of a different uplift rate over the Atlantic Patagonian coast. However, subtle differences can only be identified by appropriate markers and are probably difficult to identify by using the data so far available, which are affected by large measurement uncertainty and incomplete understanding of the indicator meaning.

Conclusion

We have presented the first accurate Middle Holocene RSL determination for a well-dated period of time by using different sea-level indicators, for the Atlantic Patagonian coast, with altitudinal measurement obtained using DGPS. Once dated, and their meaning and vertical error discussed, the indicators were transformed into index points. In this paper, using the available evidences, we suggest that the *in situ* association of sparse barnacles, bryozoans and encrusting foraminifera can have the indicative meaning of intertidal indicators, in the absence of modern analogs for the area. The mean RSL was estimated at c. 3.50 m asl, lower than the *c.* 5 m predicted by the global model, using estuarine deposits (i.e. mouth terraces) together with barnacles, bryozoans and encrusting foraminifera, for the period comprised between *c.* 5300 and 7000 cal. yr BP (Milne and Mitrovica, 2008).

Regional considerations indicating that the existence of different rates of relative sea-level falls in different sectors of Atlantic Patagonia, as reported in the past by Codignotto et al. (1992) and refuted by recent works (Schellmann and Radke, 2010), need to be reconsidered. In this framework, the existence of general tectonic components of uplift due to the subduction of the Nazca and the Antarctic plates (Pedoja et al., 2011; Isla and Angulo, 2015) needs to be better clarified. Indeed, it is necessary to identify the sectors characterized by different rates of uplift, by using a multi-indicator approach and by searching further sea-level indicators, different from those traditionally used in this area (Zanchetta et al., 2014). In this regard, it is fundamental to transform these indicators to sea-level index points and to clarify the indicative meaning also of the previous indicators studied for more correct regional correlations. This is particularly important for such a vast area, for which good quality data are still sparse. An improvement in the quality of the indicators is a priority for future research.

Acknowledgements

We thank J. Cause and the no-profit organization CADACE for the logistical support in the field campaign. This work was funded by the University of Pisa (Progetto Ateneo 2007, Leader G. Zanchetta, Progetto Ateneo 2014 Leader G. Zanchetta) and MIUR (PRIN2008, Leader G. Zanchetta). We are strongly indebted to two anonymous reviewers for their insightful criticism and encouraging suggestions that improved the manuscript.

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Figure 1 -Location map of the studied area. Green circles: sites mentioned along the text; orange circle: location of Puerto Santa Elena; red square: study area; red stars: location of sampled sites.

Figure 2 – Tide level derived from the current tide tables of Puerto Santa Elena. Elevation data are referred to the reduction plane (theoretical plane located under the mean sea level in order to have only positive tidal values in the tables). MLLW: Mean Lower Low Water; MLHW: Mean Lower High Water; MHLW: Mean Higher Low Water; MHHW: Mean Higher High Water; MHW: Mean High Water; MTL: Mean Tide Level.

Figure 3 - Simplified geomorphological map of the studied area: H=Holocene beach ridges subdivided into H1, H2, H3 from the oldest to the youngest Beach Ridge, according to the morphostratigraphic units identified by Schellmann and Radke 2010; P= Pleistocene beach ridge.

Figure 4 - Geological sections (see map in Fig.2 for location): 2a) geological section AA'2b) geological section BB'; 2c) geological section CC'.

Figure 5 - Elevation range of barnacles and incrustations in the three outcrops described. The data were measured by DGPS Trimble with a maximum error of 10 cm in elevation.

Figure 6 - Images of barnacles (*Austromegabalanuspsittacus*) (a); incrustation (b); storm deposit infilling fractures within bedrock (c). Thin-section microscope photographs of the studied bioencrustations. A-B, encrusting acervulind shells (ac) showing chamber arrangement (arrows) with successive layersin sub-axial sections; the chambers are open in lateral walls (arrows). C, encrusting coralline algal thallus (cor) showing the transversal section of a uniporate conceptacle (c) with a cylindrical porecanal (arrow). Scale bar represents 500 μm.

Figure 7 –Total plot of the Camarones area index points: fixed biological indicatorsfrom this work; valley mouth terrace indicators from Schellmann and Radke (2010). Limiting point from this work.

Figure 8 – Relative sea level data (RSL) along the Patagonian coast for the "high stand" by different authors: redline: data from Codignotto et al. (1992); dark line: data from Zanchetta et al. (2014), and from this work reported as a.s.l.; (for sites location see fig.1). The indicative meaning reported in the figure is discussed in the text, while the indicative meaning cannot be reported for Codignotto et al. 1992.

Table 1 - Radiocarbon ages obtained for this study wereperformed using IntCal13 and MARINE13 radiocarbon age calibration curves (Reimer et al. 2015). *Data from Schellmann and Radke (2010)

Lab. Code	Sample code	^{14}C yr BP	Cal yr BP (±2σ)	Material	Elevation (m asl)
DSH2744	Wpi-424-2	5641±46	5924-6168	*Australomegabalanus psittacus*	3.7
DSH3170	Wpi-436A	5515±50	5741-6015	*Australomegabalanus psittacus*	3.6
DSH2738	AO-164	5132±67	5313-5608	*Australomegabalanus psittacus*	3.9
DSH2742	Wpi-436b	4995±89	5106-5560	Encrustation	3.6
DSH2736	AO-154D	5567±44	5865-6099	*Mytilus edulis*	3.9
DSH2745	Wpi-436	5562±43	5861-6092	*Mytilus edulis*	5.2
DSH4023	AO-164	5370±60	5604-5878	*Mytilus edulis*	3.5
Hd-23504	Pa04/7*	5560±38	5866-6065	*Protothaca antiqua*	3.8

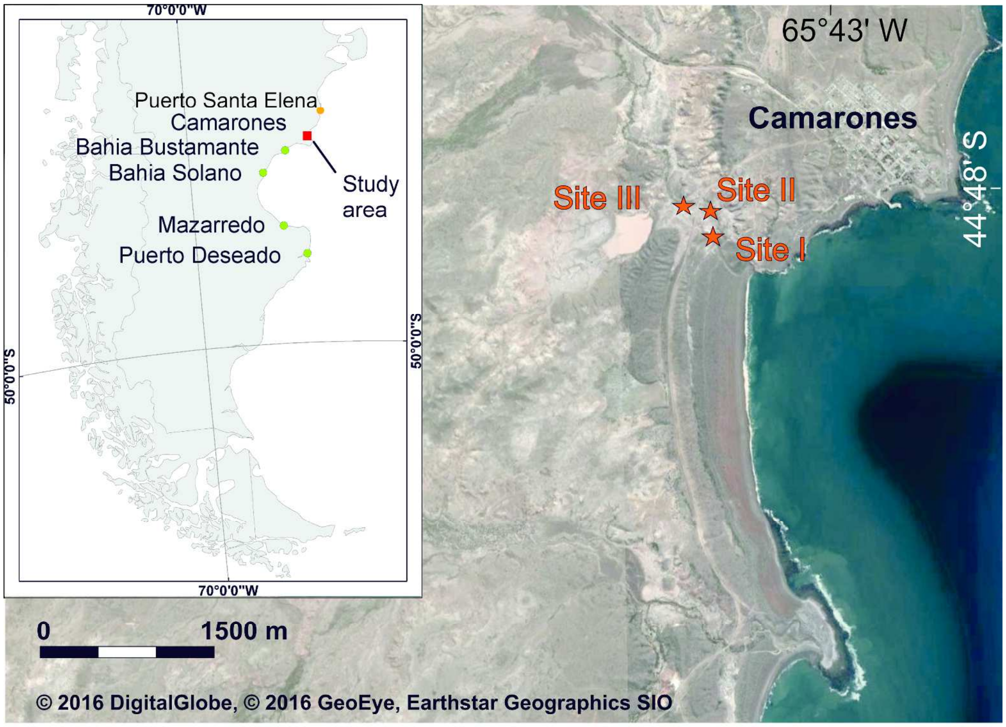
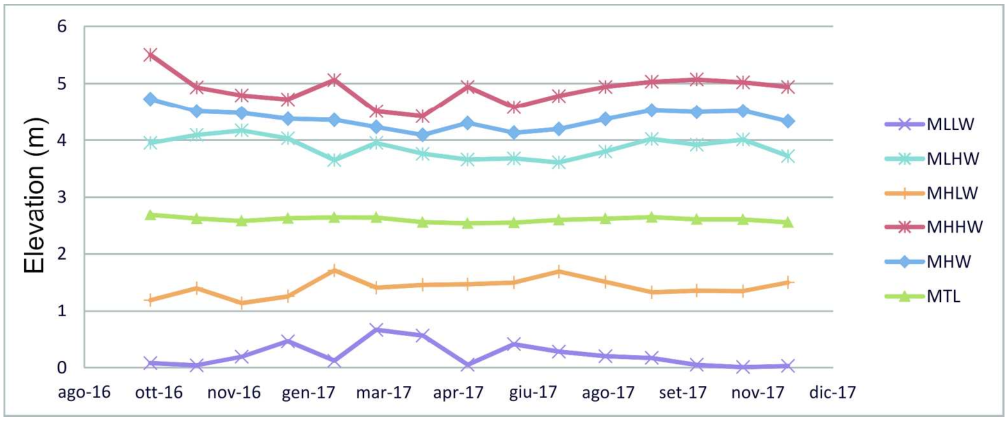


Figure 1 -Location map of the studied area. Green circles: sites mentioned along the text; orange circle: location of Puerto Santa Elena; red square: study area; red stars: location of sampled sites.

270x195mm (300 x 300 DPI)



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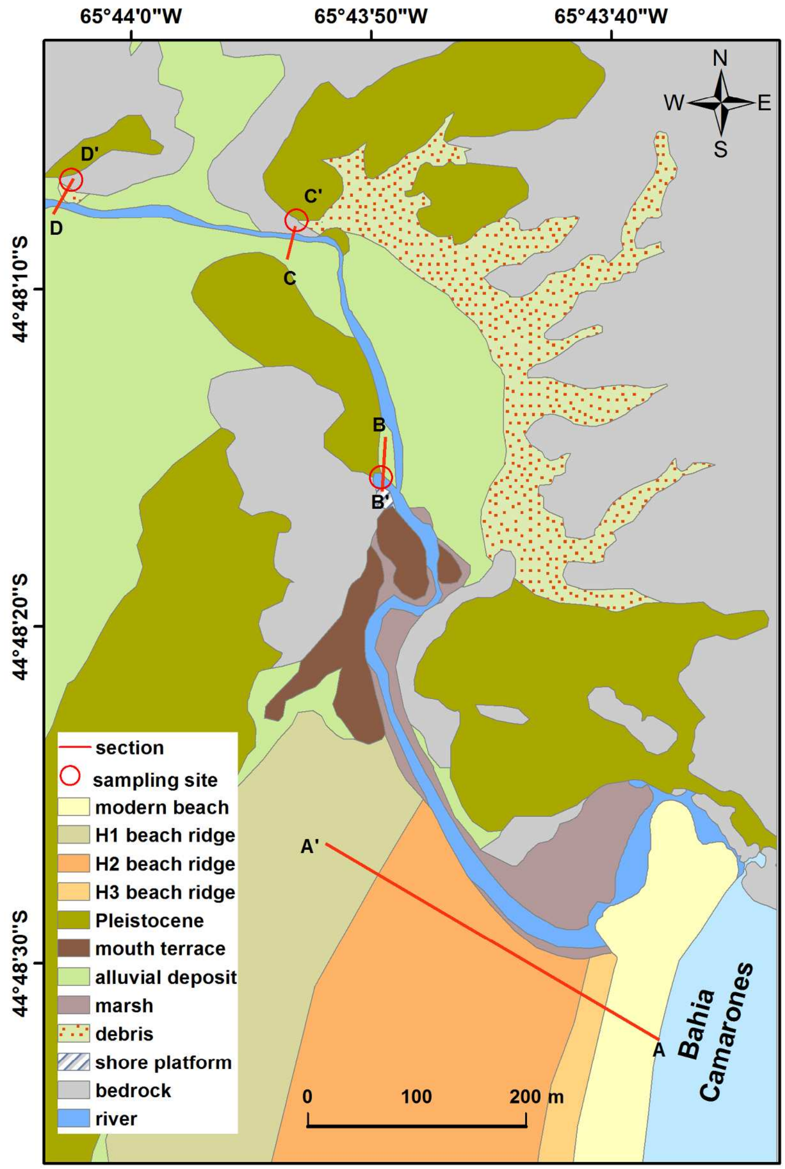
185x76mm (300 x 300 DPI)



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150x219mm (300 x 300 DPI)

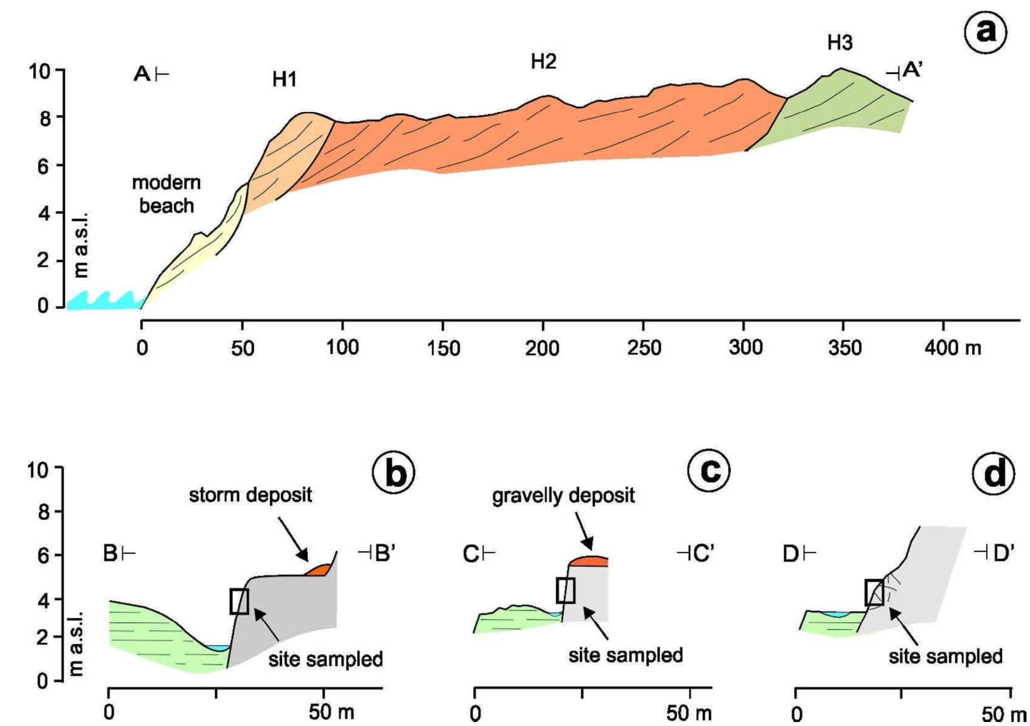

Figure 4 - Geological sections (see map in Fig. 3 for location): 2a) geological section AA'2b) geological section BB'; 2c) geological section CC'.

138x98mm (299 x 299 DPI)

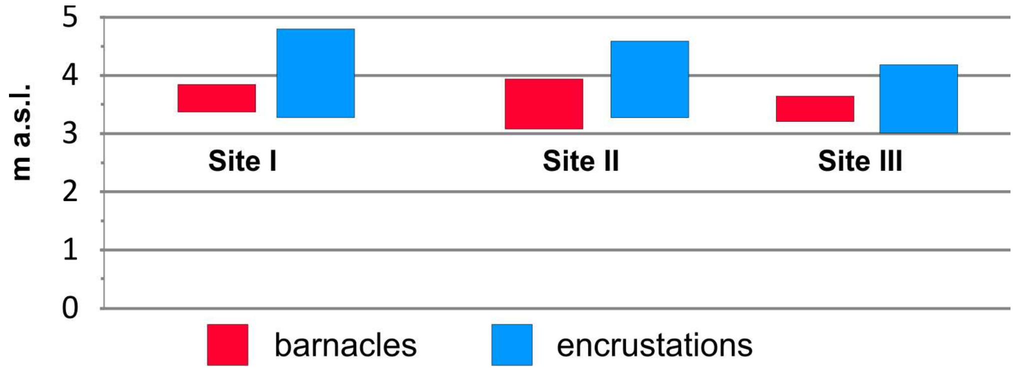

Figure 5 - Elevation range of barnacles and incrustations in the three outcrops described. The data were measured by DGPS Trimble with a maximum error of 10 cm in elevation.

170x61mm (300 x 300 DPI)

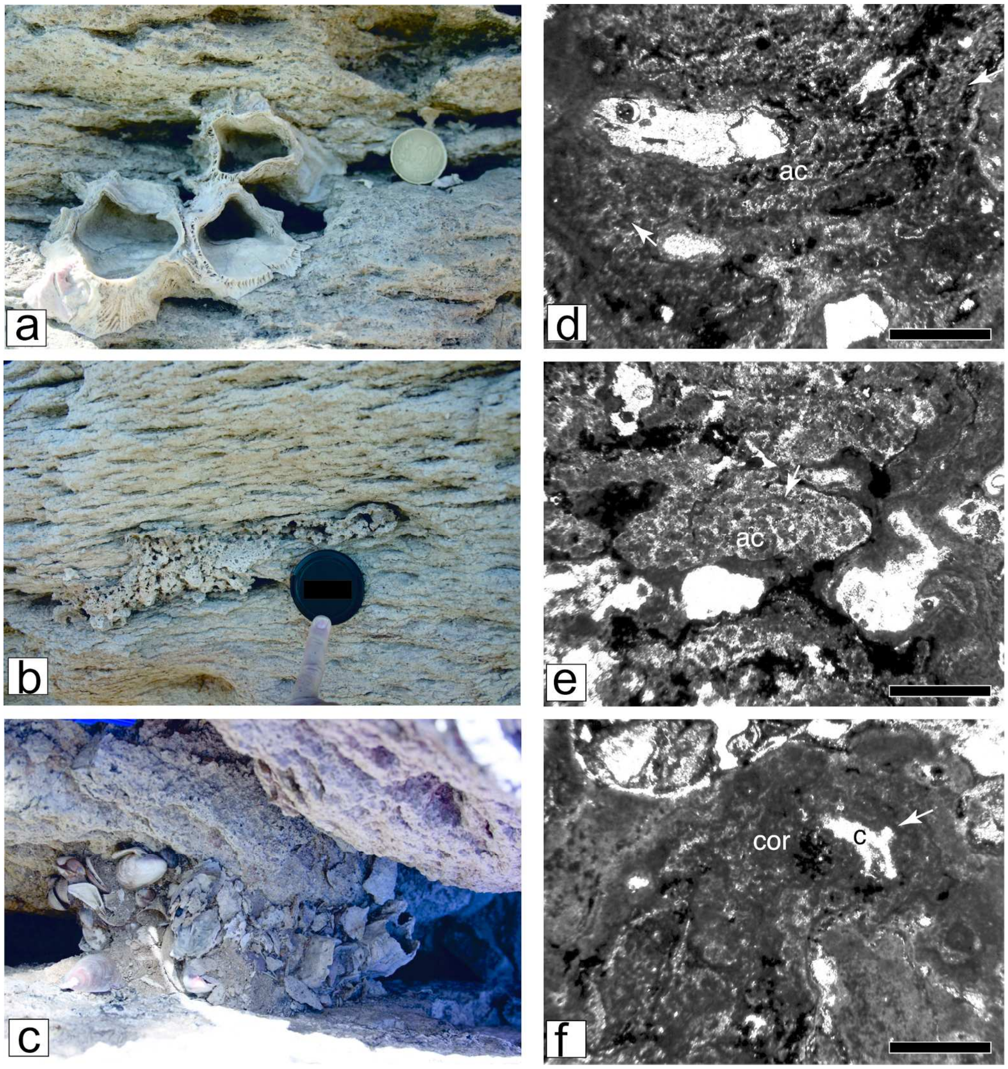

Figure 6 - Images of barnacles (Austromegabalanuspsittacus) (a); incrustation (b); storm deposit infilling fractures within bedrock (c). Thin-section microscope photographs of the studied bioencrustations. A-B, encrusting acervulind shells (ac) showing chamber arrangement (arrows) with successive layersin sub-axial sections; the chambers are open in lateral walls (arrows). C, encrusting coralline algal thallus (cor) showing the transversal section of a uniporate conceptacle (c) with a cylindrical porecanal (arrow). Scale bar represents 500 μm.

182x193mm (300 x 300 DPI)

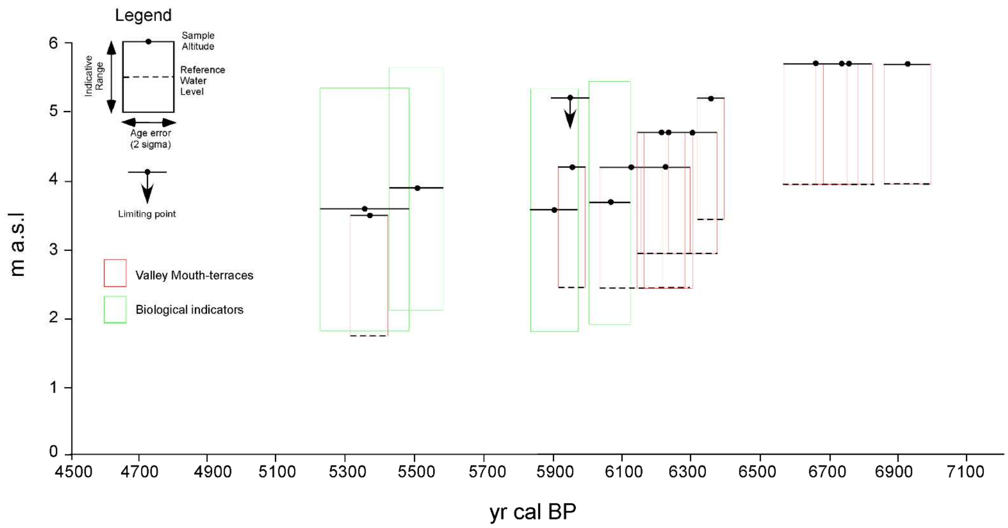

Figure 7 –Total plot of the Camarones area index points: fixed biological indicatorsfrom this work; valley mouth terrace indicators from Schellmann and Radke (2010). Limiting point from this work.

288x149mm (300 x 300 DPI)

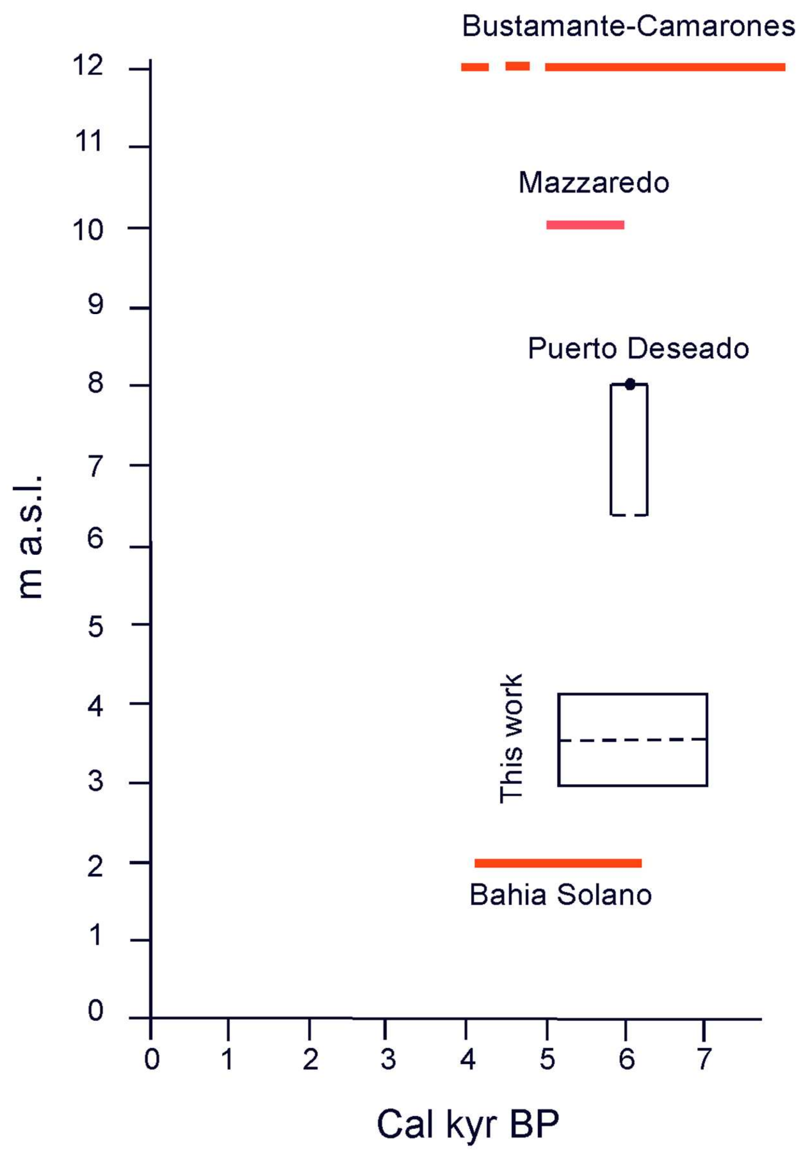

Figure 8 – Relative sea level data (RSL) along the Patagonian coast for the "high stand" by different authors: redline: data from Codignotto et al. (1992); dark line: data from Zanchetta et al. (2014), and from this work reported as a.s.l.; (for sites location see fig.1). The indicative meaning reported in the figure is discussed in the text, while the indicative meaning cannot be reported for Codignotto et al. 1992.

102x151mm (300 x 300 DPI)