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Andean coastal uplift and active tectonics in southern Peru: 
$^{10}\text{Be}$ surface exposure dating of differentially uplifted marine terrace sequences (San Juan de Marcona, $\sim 15.4^\circ$S)

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Abstract

Along the San Juan de Marcona Bay of southern Peru, two spectacular sequences of preserved marine terraces record net Quaternary uplift. Previous geomorphic analysis of these paleo-shorelines has revealed evidence of upper plate deformation and regional uplift. However, in the
absence of a robust absolute dating method, these studies contain substantial uncertainties concerning the numerical dating of these marine markers and thus the corresponding calculated surface uplift rates. However, field mapping, surveying the neotectonic features and ¹⁰Be dating of abraded surfaces contained within two sequences of marine terraces along this margin should allow for the robust calculation of Pleistocene uplift rates.

The San Juan de Marcona Bay lies on the southern flank of the subducting and south-migrating aseismic Nazca Ridge where the maximum rates of coastal uplift are expected. In this locality, we measure high uplift rates ranging from 0.4 m/ka to 0.9 m/ka during the Pleistocene. Margin-parallel normal faults displace several marine terraces and influence the development of bays, thereby contributing to the configuration of paleo- and present-day coastlines. The faults have relatively low slip rates, <0.1 m/ka over 400 ka, and have been inactive for the last 80 ka. The presence and activity of these normal faults can be directly linked to subduction zone processes, with the release and accommodation of short-term coseismic compression during megathrust subduction-zone events. In contrast, the regional permanent uplift is probably controlled by post-seismic and/or interseismic strain accumulation over longer time-scales due to inelastic behavior of the upper plate. Since at least the latest Pliocene, the San Juan de Marcona area has experienced long-term regional tectonic uplift that has increased since about 800 ka due to the southward migration of the subducting Nazca Ridge. Based on migration velocity and geometry of the ridge, the influence of the Nazca Ridge on the uplift of the forearc should account for ~0.4 m/ka within 145 km south of the ridge axis. Hence, most of the post-400 ka mean uplift rate of the San Juan de Marcona area could be explained by the Nazca Ridge subduction.
Keywords

marine terrace; 10-Beryllium; CRN dating; uplift rate; slip rate; Peru; Nazca Ridge

1. Introduction

Marine terraces are important markers for quantifying coastal uplift along active margins over ~1 Ma; individual marine terraces are eroded during sea-level highstands and then preserved by subsequent coastal uplift (e.g., Chappell, 1974; Bloom, 1974; Pillans, 1983; Bull, 1985; Lajoie, 1986; Ota, 1986; Merrits and Bull, 1989; Lajoie et al., 1991; Pirazzoli et al., 1991, 1993; Zazo, 1999). In forearc basins, sequences of marine terraces preserve cumulative records of eustatic fluctuations and tectonic histories of coastal forearcs (Radtke, 1987; Muhs et al., 1990; Goy et al., 1992; Leonard and Wehmiller, 1992; Hsu, 1992; Macharé and Ortlieb, 1992; Ota et al., 1995; Ortlieb et al., 1996a; Cantalamessa and DiCelma, 2004; Marquardt et al., 2004; Pedoja et al., 2006a, 2006b; Saillard et al., 2009). As the present day sea-level is one of the highest levels recorded for Quaternary time span, every emerged marine terrace is preserved by coastal uplift. These marine markers are reference surfaces that record a spatial and temporal history of past sea-level highstands. When the terraces are of Quaternary age, as is the case in this study, these marine markers allow a calibration of coastal uplift rates based on their current elevation above modern sea level.

Thanks to a hyper-arid climate and very low erosion rates (<0.5 m/Ma; Alpers and Brimhall, 1988; Kober et al., 2007; Hall et al., 2008), marine terraces along the Pacific rim of South America have been remarkably well preserved. These climatic conditions make geomorphic markers such as these a perfect candidate for the application of cosmogenic
radionuclide (CRN) dating method. Indeed, *in-situ* produced CRNs, here we used $^{10}\text{Be}$, have been demonstrated to be a robust tool for the dating of marine terraces (Perg et al., 2001; Kim and Sutherland, 2004; Quezada et al., 2007; Alvarez-Marrón et al., 2008; Saillard et al., 2009). A number of previous authors have studied the marine terrace sequences of the San Juan de Marcona Bay ($15.4^\circ$S) using various chronological methods including amino-acid racemization, Electron Spin Resonance and U-series dating of shells (Fig. 1; Broggi, 1946; Rüegg, 1956, 1962; Hsu, 1988a, 1988b, 1992; Hsu et al., 1989; Ortlieb and Macharé, 1990; Macharé and Ortlieb, 1992). However, due to the small number of shells in the deposits accurate age determinations were insufficient to propose robust conclusions concerning vertical rock-uplift rates, as discussed in Goy et al. (1992).

The objective of this study is to quantify the timing of Andean forearc deformation and to evaluate how uplift and fault activity interact along the active margin where the Nazca Ridge is currently subducting. Here, we present a geomorphic analysis, including new tectonic mapping and new absolute dating of marine terraces in the San Juan de Marcona Bay. We use these measurements to quantify geodynamic processes (by calculating uplift and slip rates) in this region of the Andean forearc active over the last ~0.5 Ma. We compare the CRN ages of marine terraces to marine isotopic stages (MIS) using the eustatic curve of Siddall et al. (2006 and references therein). To assign ages to each terrace we correlated marine terraces to sea-level highstands (odd MIS) based on their measured exposure age and the ages determined by Siddall et al. (2006). Combined with the measured marine terrace elevations from kinematic GPS profiles, we use the tentative age assignments to calculate surface uplift rates. Uncertainties associated with uplift rates are due to uncertainties on tentative age assignments, marine terrace elevations and elevations reached by past sea-level highstands. We also calculate fault slip rates.
between the two differentially uplifted sequences of marine terraces. In this case, elevations of
the eustatic fluctuations are not needed as we study two marine terraces corresponding to the
same sea-level highstand. Uncertainties associated with faults slip rates are thus due only to
uncertainties on marine terrace ages and measured offsets.

2. Geologic and tectonic setting

In southern Peru, Central Andes are related to the subduction of the Nazca Plate beneath
the South America Plate with a convergence velocity of 75 mm/yr and a convergence obliquity of
N77° (DeMets et al., 1990; Fig. 1). The forearc of southern Peru is characterized by the
subduction of the Nazca Ridge, an aseismic ridge that is more than 1000 km-long, 200 km-wide,
elevated 1500 m above the surrounding sea floor, and trends N42°. It has been suggested that
subduction of this buoyant topographic anomaly has led to the formation of a flat subduction
segment (Gutscher et al., 2000; Gutscher, 2002; Espurt et al., 2008). Subduction of the Nazca
Ridge beneath southern Peru began in the Miocene (11.2 Ma; Hampel, 2002) and has laterally
migrated south-east along the Peruvian coast from 11°S to 15°S (von Huene et al., 1996). The
recent collision zone is expressed by a narrowing of the shelf, a seaward shift of the coastline
(e.g., Paracas Peninsula at ~14°S) and many uplifted geomorphologic features reflecting
accelerated coastal uplift (von Huene and Suess, 1988; Hsu, 1992; Macharé and Ortlieb, 1992;
von Huene et al., 1996; Gutscher et al., 1999; Hampel, 2002; Clift et al., 2003; Wipf et al., 2008;
Regard et al., 2009). North of the subducting Nazca Ridge (around Lima, ~11°S), the coast is
currently subsiding (le Roux et al., 2000), possibly related to the transient response following the
passage of oceanic ridge subduction.

The San Juan de Marcona Bay is located above the south-eastern flank of the subducting
segment of the Nazca Ridge at ~15.4°S. The coastal uplift recorded at this location is the maximum measured along the entire Peruvian coast and is directly related to the subduction of the ridge (Macharé and Ortlieb, 1992; Hampel, 2002; Fig. 1). Fauna of the highest marine terrace of the San Juan de Marcona area at +780 m have been assigned to the Plio-Pleistocene boundary, however, most of the San Juan de Marcona terraces that are developed on two hills in the bay are of Pleistocene age (Macharé, 1987; Macharé and Ortlieb, 1992). With up to 20 levels of staircased marine terraces preserved below 500 m, San Juan de Marcona is one of the most spectacular examples of marine terrace sequences in the world. At this locality, the bay is bound by two isolated hills that are separated from one another by about 8 km: the Cerro El Huevo (CEH, 492 m asl) and the Cerro Tres Hermanas (CTH, 380 m asl; Fig. 2). The two marine terrace sequences are developed on the flanks of these hills (Figs 2, 3). The Cerro El Huevo marine terrace sequence is developed on SW flank of the hill with 8 terraces spanning 200 m in elevation. The terrace sequence at Cerro Tres Hermanas is best developed on the NW flank and comprises 7 major terraces up to 175 m in elevation (Fig. 3). Extending laterally between the two hills, the +105 m (CEH) and +80 m (CTH) marine terraces are morphologically connected around the San Juan de Marcona Bay (Figs 2 and 3).

The complete morphology of each marine terrace is composed of a former sea cliff, a planar surface (wave-cut surface) and a shoreline angle (Fig. 4). The shoreline angle is the elevation of the major change in slope between the planar terrace surface and the former sea cliff of the next higher marine terrace. The spatial location of the shoreline angle marks the position of the former coastline and its elevation characterizes each marine terrace (Lajoie, 1986). The name given to each marine terrace here refers to the elevation of its shoreline angle measured with kinematic GPS (for example, shoreline angle elevation of ~ +150 m marine terrace is about 153 ±
4 m; Fig. 3 and Table 1). Geomorphologic and tectonic mapping were performed from field investigations and satellite images analysis. The marine terraces here are mainly wave-cut platforms directly eroded into the bedrock (mostly intrusive rocks) with very few overlying younger deposits except near the shoreline angle. In this particular region, marine terraces are mostly isolated from any continental deposits post-dating their formation. Only a thin layer of sand (< 10 cm) irregularly covers the abraded bedrock surface. Some of the marine terraces preserve rocky paleo-sea stacks reaching up to a few meters in height (Fig. 3). Considering that each marine terrace is related to one sea-level highstand, our data reflects uplift rates over time spans of ~100 kyr. Even shorter time spans (~20 kyr) are represented by terraces that formed during Marine Isotopic Sub-Stage (MISS) highstands. This corresponds to the periodicity of marine terrace formation, abandonment during regression and preservation by coastal uplift. It is important to note that more rapid variations that may have occurred within this time step will not be preserved and represented on the morphological scale and thus are not considered.

Normal faults striking NW-SE partially dissect the San Juan de Marcona area (Fig. 2). On the northern edge of the site between the Cerro El Huevo and the Cerro Tres Hermanas, the SW-dipping Lomas Fault (LF) is the most extensive fault in the area. The lowest marine terrace levels are not displaced by this fault. Other minor faults are the NE-dipping El Huevo Fault (EHF), on the northern flank of the Cerro El Huevo, the NE-dipping San Juan Fault (SJF) that delimits the northern flank of the Cerro Tres Hermanas and the southern edge of the San Juan de Marcona Bay, and the NE-dipping Tres Hermanas Fault (THF) that cuts marine terraces of the Cerro Tres Hermanas (Fig. 2). The morphological signatures of the faults are different from those of former marine terrace sea cliffs as they are not exactly parallel to the modern shoreline and they offset several marine terraces (<~3 m of offset along any given terrace). Other minor normal faults also
cross-cut several marine terraces but with magnitude of displacement (≤0.2 m) in the study area. In this paper, we assume that any differential uplift between the two sequences of marine terraces results from displacement along the Lomas Fault rather than a broader tilting or warping of the terraces. Based on this assumption, we calculate the slip rates for the Lomas Fault. Nevertheless, one could note that the San Juan and Tres Hermanas Faults are antithetic to the Lomas Fault. As a result, slip rates calculated for the Lomas Fault between Cerro El Huevo and Cerro Tres Hermanas represent a minimum value. These normal faults do not accommodate much extension as they dip very steeply but the precise dips were not measurable in the field.

3. $^{10}$Be produced in-situ dating

3.1. Sampling strategy and methodology

$^{10}$Be produced in-situ records the duration of surface exposure to cosmic rays (cf. Gosse and Phillips, 2001) and can thus be used to provide a numerical exposure age of a surface. In the current study, this exposure age reflects the age of abandonment of a marine terrace by the sea.

We sampled both exposed abraded bedrock and loose igneous clasts distributed on top of the bedrock terraces for cosmogenic analysis. Low-relief abraded and exposed bedrock terraces were sampled in two ways: 1) the top few centimeters of quartz-rich veins, exposed on the planar surface of the bedrock terrace, and 2) the top few centimeters of bedrock sea-stacks preserved on the terraces. While the samples taken from the planar bedrock surface are, at this time, free of sediment cover, we acknowledge that it is possible that these surfaces were covered intermittently with discontinuous sediments at times in the past. In this case, the $^{10}$Be concentration measured in these surfaces would be lowered due to surface burial. Also, as is the case with any of these
features, any surface erosion following abandonment from the sea would result in an apparently younger age. As the bedrock sea-stacks are cone-shaped and extend above the planar terrace surface, sediment deposits have not covered these features and therefore burial is not an issue. Where we have sampled sea-stacks of different heights from the same terrace, we consider two different models for plausible exposure history: 1) the highest sea-stack was the first bedrock exposed above sea-level and therefore records the highest $^{10}$Be concentration (oldest age) and the concentration will decrease with elevation to the planar surface (youngest age), or 2) differential erosion may have occurred where the highest sea-stack may have been subjected to the highest degree of erosion thus resulting in an apparently younger age (low $^{10}$Be concentration). In this second model $^{10}$Be concentrations would increase from the highest sea-stack (youngest age) to the planar surface (oldest age). In this scenario, samples from the planar surface of the marine terrace or from the smallest sea-stack are plausibly closer to the real age of abandonment.

Samples were also collected from quartz-rich igneous clasts set into the thin veneer of sediment deposited on the terrace. These samples may contain an inherited nuclide concentration from a pre-deposition transport history. Assuming that all of the deposits were delivered to the terrace surface shortly after the terrace was abandoned from the sea, multiple clast samples collected from a given terrace should have the age of the marine terrace in common but will have different inherited concentrations. In this case, the youngest sample reflects the sample with the least inheritance. Considering the sediment layer is very thin, it is not likely that clasts have been shielded by sediment burial.

We sampled three terrace surfaces on CEH and one surface on CTH. At each site, we collected and analyzed 3 samples within an area of ~6 m in diameter. We made sure to sample locations that were exceptionally planar without visible relief due to surface incision. Samples
were prepared at University of California Santa Cruz (UCSC) and measured at the Center for Accelerator Mass Spectrometry of the Lawrence Livermore National Laboratory (details in Table 1 and caption).

3.2. Results

As the Atacama Desert experiences extremely low erosion rates (Alpers and Brimhall, 1988; Hartley, 2003; Clarke, 2006; Kober et al., 2007; Hall et al., 2008), we present model ages calculated with zero erosion (Table 1). Where samples from a given terrace yield a tight cluster of ages, we calculate a mean age. From the Cerro El Huevo flank, we sampled the +150 m, +190 m and +220 m marine terraces (Fig. 3 and Table 1). For the +150 m and the +220 m marine terraces, we collected the top ~3-7 cm from angular quartz-rich igneous clasts (~10–40 cm in diameter) set into the thin veneer of sediment deposited on the terraces (mostly sand and colluvium). For the +190 m marine terrace, we collected samples from the top 3 cm of the abraded planar bedrock surface and from the top 4-5 cm of two different sized sea-stacks (1 and 2 m). Sampled clast ages from the +220 m terrace are tightly clustered at 442 ± 56 ka, 400 ± 49 ka, and 420 ± 49 ka, and yield an average age of 419 ± 30 ka (Table 1). Individual sample ages from the +150 m and +190 m terraces are not tightly clustered and thus present a more complicated scenario for determining the actual age of the surface. For the +190 m terrace, the two ages from the sea-stacks (high = 200 ± 26 ka, low = 255 ± 29 ka) are both much younger than the age of the one sample from the planar bedrock surface (318 ± 37 ka; Table 1). Possibly, the sea-stacks have been subjected to higher surface erosion resulting in apparently younger ages as discussed above (cf. 3.1) as ages decrease from the highest sea-stack to the planar surface. We propose that age of sample from the planar surface, the oldest age, is the most representative of the real age of the marine terrace, i.e.
~318 ka. The calculated ages for the three clasts sampled from the sediments on the +150 m terrace have a high degree of scatter: 228 ± 28 ka, 273 ± 32 ka, and 336 ± 40 ka. When $^{10}$Be exposure ages have a high degree of scatter, calculating an average age has little meaning for the actual age of the surface. As these samples are clasts unconformably deposited on the terrace bedrock, the large scatter is likely due to diverse inherited concentrations. Based on our model described above, we take the sample with the lowest nuclide concentration (lowest inheritance) as the age of the surface, i.e. ~228 ka.

At the Cerro Tres Hermanas, we sampled the +160 m marine terrace by collecting the top 4 cm of three quartz veins within the abraded bedrock (Fig. 3). The sample ages from this surface are tightly clustered at 354 ± 41 ka, 346 ± 40 ka, and 359 ± 42 ka, and yield an average age of 352 ± 24 ka. As the three samples are all from the abraded planar bedrock surface and likely have experienced similar surface erosion, we take the average age as the age of this surface to be ~352 ka.

4. Discussion

4.1. Marine terraces correlations to marine isotopic stages (MIS)

Comparing our $^{10}$Be ages to the sea-level variations on the eustatic curve of Siddall et al. (2006 and references therein), it appears that the +150 m terrace age of ~228 ka corresponds to the marine isotopic substage (MISS) 7e (232.5 ± 2.5 ka; Fig. 5, Table 2). The +190 m terrace dated to ~318 ka was likely last eroded during MISS 9c (321 ± 6 ka; Fig. 5) and the +220 m terrace age of ~400 ka corresponds to the MIS 11 (405 ± 10 ka; Table 2, Fig. 5). For the +160 m marine terrace dated to ~352 ka, the correlation is less straightforward. It could have last been
eroded during MIS 11 (405 ± 10 ka) or MISS 9c (321 ± 6 ka; Fig. 5). However, based on previous studies and lateral extents of all terraces, we assign the +160 m marine terrace to MISS 9c as discussed below. We combine our new age assignments of each marine terrace to a MIS with those in the literature in order to assign each undated marine terrace to a MIS. To do this, we made some assumptions: 1) a given MIS is necessarily recorded on both hills of the bay, the Cerro El Huevo and Tres Hermanas; 2) marine terraces are all assigned to sea-level highstands (Lajoie, 1986); and 3) only the highest sea-level highstands are recorded (i.e., 5a, 5c, 5e, 7c, 7e, 9a, 9c, 11) as marine terraces are large and well-developed in the landscape. In the Table 2, we report and compared our data to data existing in the literature where age assignments were made on the basis of amino-acid racemization studies (Hsu, 1988a, 1988b; Ortlieb and Macharé, 1990). Ortlieb and Macharé (1990) assigned the +105 m (CEH) and +80 m terrace (CTH) to MISS 5e, and the +160 m terrace (CTH) to MISS 9c. As the +105 m (CEH) and +80 m (CTH) marine terraces are laterally connected around the bay, we agree with Ortlieb and Macharé (1990) in assigning the +105 m (CEH) and +80 m (CTH) marine terraces to the MISS 5e (see discussion in Ortlieb and Macharé (1990, pp 100-101)). The two levels (+40 m and +70 m at CEH and +40 m and +55 m at CTH) lower than MISS 5e level, are therefore assigned to MISS 5a and 5c, respectively. Based on our assignment of the ~150 m and 130 m terraces to MISS 7e age, we assign the higher +170 m (CEH) and +145 m marine terraces (CTH) to MISS 9a. The +190 m (CEH) and thus the +160 m marine terraces (CTH) are likewise assigned to MISS 9c. Finally, the +220 m (CEH) and +177 m marine terraces (CTH) are assigned to MIS 11 (Table 2).

4.2. Coastal Uplift: Uplift rates of the San Juan de Marcona area

We calculate the mean uplift rate over a time interval ti–t0 (Δi0) between each marine
terrace (i) and present sea level (0), applying the following equation:

\[ \text{UpliftRate}_{\Delta t_0} = \frac{(ShA_i - E_i)}{\text{Age}_i} \]  

(1)

where \( ShA_i \) is the present-day elevation of the shoreline angle of the marine terrace (time \( t_i \)), \( E_i \) is the sea-level elevation at \( t_i \) compared to the present sea level, and \( \text{Age}_i \) is the MIS age of the marine terrace, based on age assignments discussed in the previous section.

We also calculate the incremental uplift rate over a time interval \( t_i - t_j (\Delta t_{ij}) \) between two successive marine terraces as described in Saillard et al. (2009). As the error bars are extremely large, we consider this calculation to be more of an exercise and the corresponding results should be considered a broad estimate:

\[ \text{UpliftRate}_{\Delta t_{ij}} = \frac{((ShA_i - E_i) - (ShA_j - E_j))}{(\text{Age}_i - \text{Age}_j)} \]  

(2)

where \( ShA_i \) is the present-day elevation of the shoreline angle of the older marine terrace (time \( t_i \)), \( E_i \) is the sea-level elevation at \( t_i \) compared to the present sea-level, \( ShA_j \) is the present-day elevation of the shoreline angle of the subsequent terrace (time \( t_j \)), \( E_j \) is the sea-level elevation at \( t_j \) compared to the present sea-level, \( \text{Age}_i \) is the age of the marine terrace, from MIS correlations (\( t_i \)) and \( \text{Age}_j \) is the age of the marine terrace, from MIS correlations (\( t_j \)). Our use of the age assignments to MIS is a direct product of the fact that the geomorphologic model of marine terrace formation considers that the marine terraces were formed during sea-level highstands (Lajoie, 1986).

The calculated uplift rates are reported in Table 3. Errors on uplift rates include the errors involved in the age and elevation of highstands and shoreline angle elevation of marine terraces (Table 3). Except for the youngest terrace of the Cerro El Huevo (+40 m, MISS 5a), cumulative uplift rates (equation 1) have progressively increased since ~400 ka, from ~0.55 ± 0.04 to 0.87 ±
0.07 m/ka and 0.44 ± 0.03 to 0.70 ± 0.08 m/ka for the CEH and CTH, respectively (Fig. 6; Table 3). If uplift rates have continued to increase since ~80 ka (MISS 5a), uplift rates may be considerably higher at present. The two sequences of marine terraces show the same trend of increasing uplift rates since ~400 ka although the magnitude of the uplift rates are slight different. This may be explained by the presence of the active Lomas Fault which separates the two sequences (Fig. 7).

4.3. Coastal tectonics: Slip rates along the Lomas Fault system

One of the aims of this project was to determine fault activity and calculate the slip rate along the major margin-parallel normal fault observed in the San Juan de Marcona coastal region (Lomas Fault, Figs 2, 6, 7). To do this, we used the MIS assigned ages and the elevation of marine terraces on both sides of the Lomas Fault. Slip rates are obtained along the fault considering differential uplift of the same marine terrace over a time interval since the MIS age assignment of the marine terrace. As the activity occurred sometime after the abandonment of the surface (MIS age assignment), this slip rate is a minimum rate:

\[
\text{SlipRate}_{ij} = \frac{(\text{ShA}_{CEH_{t_i}} - \text{ShA}_{CTH_{t_i}}) - (\text{ShA}_{CEH_{t_j}} - \text{ShA}_{CTH_{t_j}})}{(\text{Age}_{t_i} - \text{Age}_{t_j})}
\]

(3)

where \(\text{ShA}_{CEH_{t_i,j}}\) is the present-day elevation of the shoreline angle of the marine terrace (time \(t_i\) and \(t_j\)) on the Cerro El Huevo, \(\text{ShA}_{CTH_{t_i,j}}\) is the present-day elevation of the shoreline angle of the marine terrace (time \(t_i\) and \(t_j\)) on the Cerro Tres Hermanas, and \(\text{Age}_{t_i,j}\) is the MIS age assignment of the marine terrace \(t_i,j\).

Differential uplift of marine terraces ranges from about 20 to 46 m between 405 ± 10 ka (MIS 11) and 100 ± 5 ka (MISS 5c) and is null since 80 ka (MISS 5a; Figs 7, 8; Table 4). The last
fault activity can be deduced from the age of the youngest displaced marine terrace (100 ka) and
the age of the oldest terrace that is not displaced (80 ka). In this locality, last fault activity
probably occurred sometime between MISS 5c and 5a (Fig. 7), however this does not preclude
the fact that it may rupture again. In contrast to the dominance of margin-perpendicular normal
faults in southernmost Peru (Audin et al., 2008), margin-parallel normal faults are well developed
in the vicinity of Paracas and San Juan de Marcona in southern Peru, as well as along the Chilean
coast associated with the Bolivian Orocline (Ota et al., 1995; Hartley and Jolley, 1995; Delouis et
al., 1998; Heinze, 2003; Marquardt et al., 2004). On the Mejillones Peninsula of northern Chile,
rates of horizontal extension vary from 0.025 to 0.18 mm/a (Allmendinger and Gonzalez, 2009).
At both San Juan de Marcona and the Mejillones Peninsula it seems likely that these margin-
parallel faults are sometimes reactivated during major plate boundary thrust events (e.g., Audin et
al., 2008; Quezada et al., 2010). This type of fault activity is observed, in general, for the whole
Neogene time span and it constitutes a local response of the upper plate to stress released during
megathrust earthquakes in highly coupled subduction zones (Loveless et al., 2009).

Since the time of the oldest dated marine terrace (405 ka), the mean slip rate along the
Lomas Fault (46 m/405 kyr) is 0.11 ± 0.02 m/ka (Table 4). If we look at only the time interval
between 405 ± 10 ka (MIS 11) and 100 ± 5 ka (MISS 5c), the mean slip rate is 0.092 ± 0.003
m/ka; between 100 ± 5 ka (MISS 5c) and 80 ± 4 ka (MISS 5a), the mean slip rate is 0.85 ± 0.23
m/ka and it is null since 80 ka (MISS 5a; Table 4). As shown on Figure 8B, slip rates are
noticeably higher since 122 ± 7 ka (MISS 5e). We calculate a slip rate of ~0.21 ± 0.1 m/ka based
on the 122 ka age and the 26 m offset of this terrace (Table 4). In fact, this rate is twice the rate of
the long-term average slip rate. Further, if we consider that faulting stopped by 80 ka, the slip
rates between each highstand are even higher. As the MISS 5e and 5c terraces are differentially
uplifted by ~25 m (=26-1) and ~17 m (=18-1) respect to MISS 5a, respectively, the slip rate on
the Lomas Fault is $0.6 \pm 0.3$ m/ka between ~122 ka (MISS 5e) and 80 ka (MISS 5a). Between
~122 ka (MISS 5e) and ~100 ka (MISS 5c) the slip rate is $0.36 \pm 0.13$ m/ka and $0.85 \pm 0.23$ m/ka
between 100 ka (MISS 5c) and 80 ka (MISS 5a; Fig. 7 and Table 4).

4.4. Implications for coastal geodynamics of Peruvian margin

Based on marine terraces ages and elevations, we have shown that uplift rates have
increased progressively since ~405 ± 10 ka (MIS 11). These elevated rates may be related to the
increasing effect of the Nazca Ridge subduction (Figs 6, 7; Macharé and Ortlieb, 1992; Hampel,
2002). Previous studies report increasing uplift rates for the San Juan de Marcona Bay, especially
since the last 130 ka, based on marine terraces dating (Hsu, 1988a; Hsu et al., 1989; Ortlieb and
Macharé, 1990; Macharé and Ortlieb, 1992). These previous studies proposed mean uplift rates
of 0.40 m/ka since the Plio-Pleistocene boundary, 0.47 m/ka since 500 ka and 0.70 m/ka since the
last 130 ka. Macharé and Ortlieb (1992) have shown that the San Juan de Marcona area is located
above the southern flank of the Nazca Ridge and at the apex of the uplift induced by the
subduction of the Nazca Ridge. In order to separate the effect of the Nazca Ridge subduction
from the more general coastal forearc uplift, we compared uplift rates along the Andean margin.
Mean uplift rates calculated in the San Juan de Marcona area since ~400 ka are higher than those
calculated in most places along the Andean margin from northern Peru to southern Chile in
different tectonic settings (cf. Ortlieb and Macharé, 1990; Hsu, 1992; Macharé and Ortlieb, 1992;
Goy et al., 1992; Zazo et al., 1994; Ortlieb et al., 1995; Ortlieb et al., 1996a, 1996b, 1996c;
Pedoja, 2003; Marquardt et al., 2004; Cantalamessa and DiCelma, 2004; Pedoja et al., 2006a,
2006b; Quezada et al., 2007; Saillard, 2008; Melnick et al., 2009; Saillard et al., 2009; see Regard
et al., 2010 for a complete review).

Andean forearc uplift seems to be related to processes occurring along the megathrust subduction zone involving simultaneous compression at the base of and within the Andean wedge (trench to Coastal Cordillera area) and extension at the surface. No observations are reported on the co- and post-seismic deformation of the upper plate during earthquakes of 1942 or 1996 in Peru (Mw 8.1 and 7.7, respectively; Swenson and Beck, 1999). Perhaps these faults would only be activated after several seismic cycles in order to accommodate accumulated uplift (Briggs et al., 2006). Indeed, as for Sumatra subduction zones, marine terraces of San Juan de Marcona Bay and the greater Andean coastal area are broad and mostly flat, with little evidence of tilting and internal topographic discontinuities (i.e., secondary scarps; Fig. 8; Sieh et al., 1999). Long-term regional uplift along these coasts is responsible for the formation and preservation of marine markers. This suggests that a significant amount of the deformation leading to permanent uplift in San Juan de Marcona Bay occurs slowly and cumulatively during the interseismic period. The episodic brittle faulting in the upper plate in tandem with megathrust rupture on the interplate probably occurs, as discussed above, after multiple seismic cycles along the subduction zone (Rosenau et al., 2009). Given the pattern of the magnitudes of offset on multiple terraces (up to 40 m), offset along the fault seems to have been produced during several seismic events linked with subduction zone activity. Indeed, previous authors suggest that the coastal tectonics in the Central Andes reflect the interaction of upper plate crustal tectonics with the plate boundary seismic cycle (Audin et al., 2008). In the study area, an additional parameter is surely the high obliquity of the convergence vector (>30°). The detachment of forearc blocks from the overriding plate in cases of oblique convergence along subduction zones has been documented in other settings than the Andes (Fitch, 1972; Jarrard, 1986). McCaffrey (1996) suggested that about half
of all modern subduction zones should have mobile forearc blocks, among them the Peruvian part of the Central Andes. The extensional active structure of the San Juan de Marcona Bay could be related to the corresponding mobile block, however here we have only quantified the vertical component of the deformation.

The current locus of the Nazca Ridge crest subduction is situated 110 km northwest of the study area. Due to the obliquity of the convergence vector (Hampel, 2002; Regard et al., 2009; Fig. 9), this zone migrates southeastward along the active plate boundary. The collision of the ridge causes additional local deformation of the upper plate and hundreds of meters of forearc uplift. Here we quantify the effect of the Nazca Ridge subduction on the coastal surface uplift rates by calculating the expected uplift rates based on the ridge and subduction zone geometry. First, we determined the migration velocity of the ridge crest. Considering a N42°-trending ridge axis, a N130°-trending subduction trench, and the convergence vector (i.e., 75 mm/a, in a N77° direction; Nuvel-1A, DeMets et al., 1990), we calculate a migration velocity of 43 mm/yr southeastward along the trench (Hampel, 2002). Next, we have extracted topographic cross-sections of the ridge (Fig. 9B). The first topographic expression of the ridge on the sea floor is detected at 320 km to the south-east of the ridge crest. This corresponds onshore to Atico (~16.2°S-73.6°W), the northernmost area where the ridge-related uplift has been observed (Regard et al. 2010; Fig. 9). At 145 km from the ridge crest, there is a change in the ridge slope angle splitting the zone into the two segments. In the northern segment between the ridge crest and 145 km to the southeast, the ridge slope angle is ~0.55°, and in the southern segment between 145 km and 320 km away from the ridge crest, the ridge slope angle is ~0.15° (Fig. 9). The location of San Juan de Marcona (110 km from the ridge axis) is located near to the position of the change in slope (145 km from the ridge axis; Fig. 9). Considering a migration velocity
parallel to the trench and a mean ridge slope angle, we can calculate the expected uplift, $U_e$, of the forearc above the Nazca Ridge with the following equation:

$$U_e = V_M \tan S$$

where $V_M$ is the migration velocity of the Nazca Ridge parallel to the trench and $S$ is the slope of the Nazca Ridge flank (Fig. 9). This equation does not take into account the flexure of the ridge when it subducts. Considering a migration velocity parallel to the trench of 43 mm/a and a mean ridge slope of $\sim0.55^\circ$, we determined an expected uplift rate of $\sim0.41$ m/ka for the northern segment of the ridge crest, which includes the San Juan de Marcona area. For the southern segment, between 145 km to 320 km away from the ridge axis, we determined an expected uplift rate of 0.11 m/ka. Hence, most of the calculated post-400 ka mean uplift rate the San Juan de Marcona area (0.55 m/ka for the CEH and 0.44 for the CTH) could be explained by the subduction and migration of the Nazca Ridge. We hypothesize that the difference between the calculated uplift rates from marine terraces and the expected uplift due to subduction and migration of the ridge could have the same origin as the regional uplift observed along the Central Andes forearc to the south of the study area (Regard et al., 2010). Considering the migration velocity of the Nazca Ridge along the trench (43 mm/a), the 35 km-distance between the San Juan de Marcona bay (110 km) and the onshore location of the changing slope of the Nazca Ridge (145 km), we infer that the uplift rate has increased due to ridge subduction since about 800 ka.

5. Conclusion

$^{10}$Be surface exposure dating of differentially uplifted marine terrace sequences in the San
Juan de Marcona Bay allows us to quantify the timing of forearc uplift in coastal Peru related to the subduction of the aseismic Nazca Ridge. This study has shown that variations in local uplift patterns and uplift rates that have progressively increased since at least the Middle Pleistocene, ranging from 0.44 m/ka to 0.87 m/ka. Slip rates along the Lomas margin-parallel normal fault between the two sequences of marine terraces are very slow, ~0.11 m/ka since 400 ka. If we consider that faulting stopped by 80 ka, differential uplift indicates a very slow rate of displacement of ~0.09 m/ka between 400 and 100 ka, a high rate of displacement of ~0.85 m/ka between 100 ka and 80 ka and no activity for the last 80 ky. Fault activity seems to be triggered by the release and accommodation of short-term coseismic compression, whereas the regional uplift is probably controlled by post-seismic and/or interseismic strain accumulation at a longer time scale. The San Juan de Marcona area has experienced long-term regional tectonic uplift, since at least the latest Pliocene. In this study, we suggest that coastal uplift rates have increased since about 800 ka in relation to the subduction and southward migration of the Nazca Ridge beneath the South America Plate. We calculate the expected coastal uplift rates of the coastal area within 145 km south of the Nazca Ridge axis to be ~0.4 m/ka and diminish to 0.1 m/ka between 145-320 km south of the axis. Hence, most of the post-400 ka mean uplift rate of the San Juan de Marcona area is explained by the Nazca Ridge subduction.

Acknowledgments

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References


CRONUS-Earth online cosmogenic-nuclide calculators. http://hess.ess.washington.edu/


Hsu, J.T., 1992. Quaternary uplift of the Peruvian coast related to the subduction of the Nazca Ridge: 13.5 to 15.6 degrees south latitude. Quaternary International 15–16, 87–97.


American Earth Sciences 22, 1–21.


Rüegg, W., 1956. Geologiezwischen Cañete-San Juan 13°00’ – 14°27’ Sud-Peru. Geol. Runsdsh. 45 (3), 775–856.


Saillard, M., 2008. Dynamique du soulèvement côtier Pléistocène des Andes centrales: Étude de l’évolution géomorphologique et datations (10Be) de séquences de terrasses marines (Sud Pérou-


**Figure captions**

Figure 1: A: Geodynamic setting of the Central Andes in southern Peru. The base map is produced using bathymetric data from the Geosat and ERS-1 spacecraft (Smith and Sandwell, 1997) and elevation data from NASA SRTM GTOPO30. Velocity is calculated from NUVEL-1A plate motion model of DeMets et al. (1990). B: The San Juan de Marcona Bay (black and white square, mapped in Fig. 2) is located in southern Peruvian forearc, above the south-eastern flank of the subducting Nazca Ridge (Macharé and Ortlieb, 1992). Bathymetric and topographic digital
elevation models have been drawn with GMT software.

Figure 2: Map of the San Juan de Marcona area. Red lines are normal faults striking NW-SE. Red squares show the downthrown block and red dashed line is the inferred extension of LF. LF – Lomas Fault. EHF – El Huevo Fault. THF – Tres Hermanas Fault. SJF – San Juan Fault. Blue frames indicate the two marine terraces sequences developed in the CEH and CTH flanks (see Fig. 3). Inset shows location of the study area (white square) in Peru.

Figure 3: Marine terraces sequences of the San Juan de Marcona area. A – Panorama of the Cerro El Huevo sequence. B - Panorama of the Cerro Tres Hermanas sequence. C-D – Cartography of marine terraces of the Cerro El Huevo sequence (C) and of the Cerro Tres Hermanas sequence (D) from Google Earth images (http://earth.google.fr). Copyright: Terrametrics images 2008, DigitalGlobe images 2008, Europa Technologies image 2007. Red lines are normal faults and red squares indicate the downthrown block. Black shaded areas are former sea cliffs of marine terraces. Black numbers indicate shoreline angle (cliff foot) elevations above mean sea-level. Shoreline angle elevation measurements were performed by kinematic GPS profiles. Black arrows associated to white numbers are names given to studied marine terraces. Blue stars are dated marine terraces with \(^{10}\)Be method. Stars 1, 2, 3 and 4 correspond to +150, +190, +220 m (CEH) and +160 m (CTH) marine terraces, respectively. Black framed numbers in D are shoreline angle elevations from Ortileb and Macharé (1990). The small asperities on the planar surface of marine terraces in A are sea-stack relicts.

Figure 4: The complete morphology of marine terrace. MT I: The oldest marine terrace; MT II: the youngest marine terrace.
Figure 5: Correlation of marine terrace ages to marine isotopic stages (MIS) from the eustatic curve of Siddall et al. (2006 and references therein). +150, +160, +190, +220 m are names of the dated marine terraces of the San Juan area and their respective age. Mean ages and associated errors of +220 m and +160 m marine terraces are weighted by inverse variance (1/σ²). Ages of +190 m and +150 m marine terraces come from one sample analyzed and associated errors are the sum of internal and external uncertainties (see Table 1 and text for further explanations).

Figure 6: Marine terrace shoreline angle elevation vs. last sea-level highstand ages for Cerro El Huevo (A) and Cerro Tres Hermanas (B). Left: solid black lines correspond to the uplift rates calculated for each marine terrace respect to present-day and represent the timing of the uplift of the Andean coastal forearc in the study area. Ages and magnitudes of sea-level highstands used in the calculation of uplift rates are based on Siddall et al. (2006) and references therein, Fleming et al. (1998) and Lambeck et al. (2002).

Figure 7: Uplift rates for the two sequences of marine terraces of the San Juan de Marcona area and slip rates calculated assuming that all differential uplift is a result of displacement along the Lomas Fault that separates the two sequences.

Figure 8: A – Lateral correlations of marine terraces assigned to the same MIS between the two sequences of the Cerro El Huevo and Tres Hermanas. Each color corresponds to a MIS or MISS indicated in black squares. Red framed numbers are names of marine terraces and black numbers are their respective shoreline angle elevation. Red lines are GPS profile of marine terrace sequences. Black dashed lines are the simplified GPS profile before erosion and cliff foot
depositional processes. B – Offsets of marine terraces along the Lomas Fault with their respective error bars vs. tentative age assignments of marine terraces (MIS). The regression curve gives a mean slip rate of about 0.1 m/ka since ~400 ka. C-D: GPS tracks on Cerro El Huevo (C) and Cerro Tres Hermanas (D) used in A from Google Earth images (http://earth.google.fr).


Figure 9: A - Bathymetry of the Pacific Ocean offshore of the study area (cf. Smith and Sandwell, 1997, extracted from GeoMapApp software, lightest tones for greatest depths). The Nazca Ridge and trench are trending N42° and N130°, respectively. Convergence velocity is 75 mm/yr in a N77° direction (Nuvel-1A, DeMets et al., 1990). Migration velocity of the Nazca Ridge is 43 mm/yr (Hampel, 2002). B - Topographic cross section across the ridge and parallel to the trench; it shows an average slope of ~0.55° for the first 145 km and then of ~0.15° up to 320 km from ridge summit. Note that the study area (San Juan de Marcona) is situated near the transition between the lower and higher slope. Farther than 320 km from the ridge (Atico), it can be considered there is no more ridge influence and the average slope is null. C – Geometric relations between the expected coastal uplift rate (Ue) due to ridge subduction, the migration velocity $V_M$ of the Nazca ridge along the trench and the mean slope of the southern flank of the Nazca Ridge (S).
Tables

Table 1: Zero erosion model $^{10}$Be surface exposure ages. All the samples are surface samples. The ages were calculated using CRONUS-Earth online cosmogenic-nuclide calculators and the production rate scaling factors from Stone (2000) and Lal (1991). The $^{10}$Be/$^{9}$Be ratio measurements were made at the Center for Accelerator Mass Spectrometry of the Lawrence Livermore National Laboratory and normalized to ICN $^{10}$Be standards prepared by K. Nishiizumi (07KNSTD3110) using a $^{10}$Be half-life of 1.5 Ma. Thus, data do not need to be renormalized before using the online calculator. The internal uncertainty (1 sigma) is only analytical error, the external uncertainty (1 sigma) includes errors associated with the calculated production rates. The reference production rate is the sea-level high-latitude $^{10}$Be production rate of $5.1 \pm 0.3$ $^{10}$Be atoms.g$^{-1}$.y$^{-1}$ (Stone, 2000). This production rate is scaled for latitude and altitude according to Lal (1991) and Stone (2000) and for shielding and sample thickness according to the CRONUS-Earth online cosmogenic-nuclide calculators. Average ages of +220 m and +160 m marine terraces correspond to the mean weighted by inverse variance (1/$\sigma^2$); associated errors are also weighted by inverse variance. Ages of +190 m and +150 m marine terraces come from one sample analyzed (black arrows) and associated errors are the sum of internal and external uncertainties (1 sigma). See text for explanations.

<table>
<thead>
<tr>
<th>Sites</th>
<th>Marine terrace</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Elevation (m)</th>
<th>Sample thickness (cm)</th>
<th>Type of material</th>
<th>Atoms $^{10}$Be/g O2</th>
<th>Error in atoms $^{10}$Be/g O2</th>
<th>Thickness scaling factor</th>
<th>Shielding factor</th>
<th>Production ratios (atoms/gyr)</th>
<th>Internal uncertainty (yr)</th>
<th>External uncertainty (yr)</th>
<th>Exposure age (yr)</th>
<th>Internal + external uncertainty (yr)</th>
<th>Terro age (ka)</th>
<th>± Error (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerro El Huervo</td>
<td>+159 m</td>
<td>-15.31 to -15.31</td>
<td>-75.15 to -75.15</td>
<td>130 to 130</td>
<td>130 to 130</td>
<td>Clasla</td>
<td>781607.0</td>
<td>0.9510</td>
<td>0.9594</td>
<td>0.206</td>
<td>3.31</td>
<td>6186</td>
<td>5842</td>
<td>7246</td>
<td>21753</td>
<td>5511</td>
<td>33974</td>
</tr>
<tr>
<td>Cerro Tres Hermanos</td>
<td>+160 m</td>
<td>-15.37 to -15.37</td>
<td>-75.10 to -75.10</td>
<td>162 to 162</td>
<td>162 to 162</td>
<td>Quartz vein</td>
<td>119615.0</td>
<td>0.9707</td>
<td>0.9980</td>
<td>0.208</td>
<td>3.45</td>
<td>7668</td>
<td>5407</td>
<td>53562</td>
<td>41116</td>
<td>40123</td>
<td>41725</td>
</tr>
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</table>
Table 2: Marine terrace assignments to MIS using chronological data from literature and $^{10}$Be dating. These data are used to assign undated marine terrace levels of the study area to MIS. Grey and bold lines are marine terraces dated by $^{10}$Be method.

<table>
<thead>
<tr>
<th>Marine terraces</th>
<th>Hsu (1998 a, b)</th>
<th>Ortlieb and Macharé (1990)</th>
<th>This study</th>
<th>Ortlieb and Macharé (1990)</th>
<th>This study</th>
</tr>
</thead>
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<tr>
<td></td>
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<td>MIS age (ka)</td>
<td>MIS age (ka)</td>
<td>MIS age (ka)</td>
<td>MIS age (ka)</td>
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<td>3</td>
<td>60</td>
<td>5a</td>
<td>80</td>
<td>5a</td>
</tr>
<tr>
<td>+55 m</td>
<td>5a</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+70 m</td>
<td>5c</td>
<td>125</td>
<td>5c</td>
<td>100</td>
<td>5c</td>
</tr>
<tr>
<td>+105 m</td>
<td>7a</td>
<td>200</td>
<td>5e</td>
<td>122</td>
<td>5e</td>
</tr>
<tr>
<td>+150 m</td>
<td>9</td>
<td>300</td>
<td>7e</td>
<td>228 ± 28</td>
<td>7e</td>
</tr>
<tr>
<td>+170 m</td>
<td>11</td>
<td>400</td>
<td>9a</td>
<td>220</td>
<td>9a</td>
</tr>
<tr>
<td>+190 m</td>
<td>13</td>
<td>500</td>
<td>9c</td>
<td>330</td>
<td>9c</td>
</tr>
<tr>
<td>+220 m</td>
<td></td>
<td>419 ± 30</td>
<td>11</td>
<td>405</td>
<td>11</td>
</tr>
</tbody>
</table>

$^{10}$Be age (ka)
Table 3: Uplift rates of the San Juan de Marcona area since the Plio-Pleistocene boundary. Uplift rate 1 column: cumulative uplift rates calculated for each marine terrace, using shoreline angle elevation, tentative age assignment and the respective sea-level highstand elevation of the stage (Cf. Equation 1 and Figs 6 and 8). Uplift rate 2 column: incremental uplift rates calculated between two marine terraces, using shoreline angle elevation, tentative age assignment and the respective sea-level highstand elevation of the stage (Cf. Equation 2). Considering uplift rates calculated following equation (2), we note uplift rates are especially high since ~230 ka (MISS 7e), although error terms are large and make these incremental rates meaningless. Grey and bold lines are marine terraces dated by $^{10}$Be method. Uplift rates of previous studies are taken from Macharé and Ortlieb (1992) and references therein.

<table>
<thead>
<tr>
<th>Marine terraces</th>
<th>Shoreline angle elevation (m)</th>
<th>$^{10}$Be Age (ka)</th>
<th>MIS</th>
<th>MIS Age (ka)</th>
<th>Sea-level highstand elevation (m)</th>
<th>Uplift rate 1 (m/ka)</th>
<th>Uplift rate 2 (m/ka)</th>
</tr>
</thead>
<tbody>
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<td>Cerro El Huevo</td>
<td>+40 m 42 ± 1</td>
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<td>5a</td>
<td>80 ± 4</td>
<td>-15 ± 5</td>
<td>0.71 ± 0.08</td>
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<td>+70 m 72 ± 1</td>
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<td>1.50 ± 0.90</td>
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<tr>
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<td>+105 m 103 ± 5</td>
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<td>5e</td>
<td>122 ± 7</td>
<td>+3 ± 3</td>
<td>0.62 ± 0.08</td>
<td>0.59 ± 0.71</td>
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<tr>
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<td>+150 m 153 ± 4</td>
<td>228 ± 28</td>
<td>7e</td>
<td>232.5 ± 2.5</td>
<td>-10 ± 5</td>
<td>0.70 ± 0.04</td>
<td>0.57 ± 0.16</td>
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<td></td>
<td>+170 m 170 ± 2</td>
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<td>9a</td>
<td>285 ± 5</td>
<td>-15 ± 5</td>
<td>0.63 ± 0.03</td>
<td>0.32 ± 0.31</td>
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<td></td>
<td>+190 m 191 ± 4</td>
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<td>9c</td>
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<td>0.59 ± 0.03</td>
<td>0.24 ± 0.46</td>
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<td>405 ± 10</td>
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Previous studies

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<th>Duration (kyr)</th>
<th>Uplift rate (m/ka)</th>
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<td></td>
<td>500</td>
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<td>Plio-Pleistocene</td>
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Table 4: Slip rates inferred from the differentially uplifted marine terrace sequences of San Juan de Marcona. Mean slip rates are in m/ka.

<table>
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<tr>
<th>Marine terraces CEH</th>
<th>Marine terraces CTH</th>
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<th>MIS Age (ka)</th>
<th>Offset (m)</th>
<th>Mean slip rate (m/ka)</th>
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<td>+42 m</td>
<td>+41 m</td>
<td>5a</td>
<td>80</td>
<td>4</td>
<td>0.11 ± 0.02</td>
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<tr>
<td>+72 m</td>
<td>+55 m</td>
<td>5c</td>
<td>100</td>
<td>5</td>
<td>0.85 ± 0.23</td>
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<td>+105 m</td>
<td>+80 m</td>
<td>5e</td>
<td>122</td>
<td>7</td>
<td>0.21 ± 0.10</td>
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<td>+150 m</td>
<td>+131 m</td>
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<td>9c</td>
<td>321</td>
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<td>+177 m</td>
<td>11</td>
<td>405</td>
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</table>
Fig. 1
Fig. 2
Fig. 3
Fig. 4
Fig. 5
Fig. 6

Stair-cased marine terraces

A Cerro El Huevo

B Cerro Tres Hermanas

Marine terrace name

Marine isotopic stages

Uplift rates (m/ka)

Error bar on sea level

Highstands elevation and age
Fig. 7
Fig. 8
Fig. 9