A abrupt increase in the coastal uplift and earthquake rate since ~40 ka at the northern Chile seismic gap in the Central Andes

José González-Alfaro a,⁎, Gabriel Vargas a, Luc Ortlieb b,⁎, Gabriel González c, Sergio Ruiz d, Juan C. Báez e, Magloire Mandeng-Yogo b, Sandrine Caquineau b, Gabriel Álvarez f, Francisco del Campo e, Ian del Río c

a Departamento de Geología, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Plaza Escorial 803, Santiago, Chile
b LOCÉAN,IRD, Sorbonne Universités, (CNRS, MNHN, IFR France-Nord), Bondy, France
c Departamento de Ciencias Geológicas, Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales (Cigiden), Universidad Católica del Norte, Avenida Angamos 0610, Antofagasta, Chile
d Departamento de Geofísica, Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile
e Centro Sismológico Nacional, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile
f Departamento de Ingeniería en Geomorfología y Geomática, Facultad de Ingeniería, Universidad de Antofagasta, Avenida Universidad de Antofagasta 02800, Antofagasta, Chile

ARTICLE INFO

Article history:
Received 28 May 2018
Received in revised form 15 August 2018
Accepted 22 August 2018
Available online xxxx
Editor: R. Bendick

Keywords:
rapid coastal uplift
MIS 3 earthquake geology
radiocarbon
northern Chile megathrust earthquakes

ABSTRACT

Over long-term geological scales, the position and vertical movements of the coast are considered to be among the most important effects resulting from first-order plate tectonics interactions in the subduction zones. However, the relationship between short-term vertical deformation driven by earthquakes and long-term coastal uplift in the Andean subduction contact of northern Chile has not been thoroughly elucidated to date. Based on precise radiocarbon dating and geomorphological analysis of littoral deposits in the Mejillones Peninsula at the southern edge of the major northern Chile seismic gap, we report a drastic increase in coastal uplift since marine isotope stage 3 (MIS 3) with uplift rates one order of magnitude more rapid than previously in the Late Pleistocene. Geomorphological evidence supplied by Holocene littoral deposits and marine terraces shows that this tectonic regime could be operating at present. Together with new geodetic data following the 2007 M W 7.7 Tocopilla event, these observations indicate that coastal uplift results from cumulative coseismic vertical displacement with low subsequent interseismic subsidence recovery driven by both deep-moderate and large megathrust earthquakes. We suggest that the accelerated coastal upriasing and earthquake rate over the past ~44 ka demonstrated in this work results from changes involving the entire subduction contact between the Nazca and South American plates in northern Chile.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

Resulting from large subduction earthquakes along the first-order tectonic margins, a strong vertical deformation driven by coseismic rebound is considered among the primary effects that contribute to coastal relief construction (Baker et al., 2013; Wesson et al., 2015; Melnick, 2016). Coastal uplift during large seismic events has been particularly well-documented since the 19th century along the subduction contact of the Nazca Plate beneath the South American Plate (Darwin et al., 1846; Ortlieb et al., 1996a, 2010; Vigny et al., 2011). However, although the link between vertical deformation and coseismic elastic rebound during recent megathrust earthquakes has been well-constrained (Vigny et al., 2011; Moreno et al., 2012), the relationship between the long-term uprisning of coastal areas and the subduction earthquake cycle is still a matter of controversy (Melnick, 2016). This controversy stems from the fact that interseismic processes generally reverse the coseismic uplift and that net long-term uplift is counterbalanced to a certain extent.

The Mejillones Peninsula (MP) is a conspicuous geomorphological feature located at the southern edge of the major northern Chile seismic gap, where the last large megathrust earthquake occurred in 1877 (Kausel, 1986; Comte and Pardo, 1991; Ruiz and Madariaga, 2018). This feature interrupts the straight hyper-arid coast with a length of ~1000 km along the Central Andes.
Fig. 1. Regional seismotectonic setting of the Mejillones Peninsula showing the rupture areas of the last historic megathrust earthquakes and the major northern Chile seismic gap. Color lines depict the slip distribution in centimeters for the last historic earthquakes, taken from Ruiz et al. (2014); the 1995 Antofagasta, 2007 Tocopilla, 1967 Tocopilla and 2014 Iquique and Pisagua events. The dashed red line corresponds to the hypothetical rupture of the 1877 large tsunamigenic megathrust earthquake, with a southern edge beneath the northern Mejillones Peninsula. Convergence rate given according to Angermann et al. (1999). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

des of northern Chile (Fig. 1). The morphostructure of this peninsula is composed of horst and half-grabens, linked to active crustal normal faults, as well as long wavelength folds with subaerial and submarine expression (Fig. 2a; Armijo and Thiele, 1990; Vargas et al., 2005, 2011a; Cortés et al., 2012). This structure is constituted by late Triassic–Lower Jurassic metamorphic (Calderón et al., 2017) and Jurassic–Cretaceous intrusive rocks together with late Cenozoic sedimentary deposits (Cortés et al., 2007), exhibiting marine terraces, paleo-beach ridges, fault escarpments and coastal cliffs that resulted from its uplift since $\sim$3 Ma at long-term rates on the order of 0.2–0.5 m/kyr (Ortlieb et al., 1996b; Victor et al., 2011; Nielsen, 2013).

It is generally considered that the MP behaves as a tectonic boundary for the propagation of megathrust seismic ruptures nucleated to the north and to the south thereof (Victor et al., 2011; Schurr et al., 2012; Fuenzalida et al., 2013; Béjar-Pizarro et al., 2013). In fact, the most recent moderate 1995 Mw 8.1 Antofagasta and 2007 Mw 7.7 Tocopilla earthquakes encompassed the plate contacts underneath its southern and northern portion, respectively, uplifting the coast by several decimeters each (Schurr et al., 2012; Ortlieb et al., 1996a; Delouis et al., 1998; Pritchard and Simons, 2006). However, it is unclear how notably large tsunamigenic earthquakes, such as the last 1877 Mw $\sim$8.8 event, the rupture length of which would have spanned at least 400 km along this hyper-arid margin and stopping either to the north of the MP or beneath its northern portion (Figs. 1, 2b), can contribute to long-term uplift and constructive coastal relief processes.

In this work, based on radiocarbon dating of marine deposits together with geomorphological and geodetic observations following the 2007 Tocopilla earthquake, we estimate Late Quaternary to modern uplift rates and propose that long-term uplift of the MP resulted from the contribution of both deep-moderate, i.e., moderate magnitude earthquakes located in the deep plate interface, and large megathrust earthquakes coupled with low interseismic subsidence recovery. This coastal uprising has increased in the last $\sim$44 ka, i.e., since marine isotopic stage 3 (MIS 3).

2. Methods

2.1. Multiannual time series data from continuous geodetic GPS antennas

We report nine years of corrected time series data following the deep-moderate 2007 Mw 7.7 Tocopilla earthquake from the geodetic GPS antennas in three permanent stations located nearest to the rupture zone (Figs. 1, 2b; Centro Sismológico Nacional, CSN). The GPS data were collected at 15-s intervals. To analyze the short-term vertical deformation following the main shock, we used the data available from these 3 GPS antennas (Fig. 2b). Geodetic data were processed using Bernese GNSS software 5.2 (Dach et al., 2015) considering ITRF 2008 and South America fixed (Supplementary A) and following the procedure described in Bedford et al. (2016). We used the extended linear trajectory model (Bévis and Brown, 2014) to estimate the linear rate of GPS displacement by filtering out components associated with annual and semi-annual seasonal trends, instrumental changes, and a transient logarithmic trend resulting from viscoelastic relaxation following the 2007 Tocopilla earthquake. The vertical errors for the time series are represented by standard deviations on the order several millimeters (Supplementary A).

Annual subsidence rates for the interseismic period following the 2007 Tocopilla earthquake were estimated from a simple linear regression after the postseismic period that was considered until the end of 2009 according to the transient logarithmic trend since the main shock.

2.2. High-precision geomorphological positioning from differential GPS observations

Trigonometric topographic profile data used to determine the mean altitude of MIS 3 littoral outcrops in northern MP with respect to the present-day sea level in the area were obtained perpendicular to the coastal cliff that surrounds Mejillones Bay between Playa Grande and La Rinconada (Fig. 2a). In general, the leveling processes are intended to measure the vertical distance between one point located on the surface of the Earth and a reference level, which is normally the mean sea level (MSL). This distance is referred to as “high level”. To determine the MSL, we used the “clock tide” method adopted by the Servicio Hidrografico y Oceanográfico de la Armada (SHOA; http://www.shoa.cl) for the year 2012. The altitudes of geomorphic coastal features in Punta Lobería (C3; Fig. 2a) and Caleta Michilla (Fig. 1) were determined using a differential global positioning system (GPS; Trimble R-4 double frequency).

2.3. Radiocarbon analyses and mineralogical SEM and XRD observations from shells

We analyzed the stratigraphy and facies of Late Quaternary littoral deposits located on the coastal cliff of the northern MP and
Fig. 2. Geodynamic and morphotectonic setting of the Mejillones Peninsula at the southern edge of the northern Chile seismic gap showing the location of MIS3 outcrops. (a) Geological configuration of the northern MP showing subaerial and submarine tectonic features (Cortés et al., 2007; Vargas et al., 2005, 2011a). MF limits tectonic blocks of Morro Mejillones horst and Pampa Mejillones half-graben. Dark blue lines depict the location of uplifted paleo-beach ridges associated with MIS 5e and MIS 11 (Ortlieb et al., 1996a; Herr, 1969). C1, C2, C3 and C4 indicate the location of outcrops of MIS 3, including the mean calibrated radiocarbon ages (BP) obtained in this work from littoral deposits. (b) Seismotectonic setting of Mejillones Peninsula. Dots correspond to the 2007 Mw 7.7 Tocopilla earthquake aftershocks occurring to the north (red) and south (blue) of the seismotectonic section (Fuenzalida et al., 2013).
obtained marine shell samples for dating. Late Pleistocene and Holocene marine deposits include well-preserved fossil shells of peliocypoda and gastropoda species (Supplementary B).

Using LS and AMS radiocarbon analyses, and from an initial total number of 43 samples, 10 radiocarbon results yielded infinite ages and 33 yielded conventional radiocarbon ages obtained from well-preserved or unaltered fossil shells (Supplementary B), which were subsequently calibrated through Calib Rev 7.0.4 (Stuiver et al., 2013) using a 2-sigma confidence interval and previous estimates of the marine regional reservoir effect (Vargas et al., 2007; Ortlieb et al., 2011). From these data, 25 conventional radiocarbon ages yielded consistent results between 31 and 46 ka BP. From the overall package at La Rinconada, we defined a calibrated age range of 34–47 Cal. ka BP, supported by 18 radiocarbon results (Supplementary B). Four conventional radiocarbon results yielded Holocene ages (3.7 ± 0.1, 4.3 ± 0.1, 6.2 ± 0.1, and 6.8 ± 0.1 Cal. ka BP), and 4 conventional radiocarbon results yielded modern ages of 830 ± 30, 680 ± 30, 510 ± 30 and 460 ± 30 yrs. BP, which resulted in a single calibrated age range of 193 ± 92 Cal. yrs. BP (Supplementary B).

To support our radiocarbon analyses from Late Quaternary shell samples, we previously investigated the preservation state of the shell minerals at the micrometric scale via scanning electron microscopy (SEM) and X-ray diffraction measurements.

SEM observations were performed on carbon-coated fragments of the shell layers from a fossil shell discovered in a life position within the MIS 3 littoral deposits (MG9927-a and MG9927-b; Figs. 3a–d and e–f, respectively). We clearly observed the characteristic prismatic calcitic structure of the outer layer (Fig. 3a, b, c, e) with a regular arrangement of well-preserved prisms (Fig. 3d, f). No traces of diagenetic alteration were observed, such as dissolution or secondary crystallization (Dauphin et al., 2011; Faylona et al., 2011).

The mineralogical composition of the internal and outer layers for 3 samples was determined by X-ray diffraction analysis (XRD) using a Siemens D500 diffractometer with Ni-filtered CuKα radiation at 40 kV and 30 mA. All of the samples were placed in a rotating aluminum sample holder and scanned over 2θ values from 2° to 70° with counting for 2 s every 0.02°. Samples were ground with an agate mortar and pestle prior to bulk mineralogical analyses. Semi-quantitative estimations of aragonite and calcite mass percentages were performed using calibration curves established from samples with known concentrations of both mineralogical phases. XRD analyses from the shells showed that the outer layer (Fig. 3g) consists of 100% calcite, whereas the inner layer (Fig. 3h) consists of 100% aragonite, except for MG9927-c observations in which traces of calcite (~1%) were found in the analysis of the inner layer (Supplementary B).

The reliability of our radiocarbon age estimations is supported by consistent results obtained separately from aragonite and calcite mineralogical phases in addition to SEM observations showing pristine crystals of carbonate in mollusk shells as well as the absence of any traces of dissolution or secondary carbon recrystallization, as in the case of sample MG9927-a, b (Fig. 3; Supplementary B). Thus, contamination and consequent radiocarbon age-rejuvenation, eventually associated with the precipitation of younger carbon after shell death (e.g., Busschers et al., 2014), can be discarded from these results.

Considering the limitations in accuracy of the radiocarbon method when considering age results from samples formed during the MIS 3-time span, such as those analyzed in this work (47–34 ka BP), we do not claim a detailed or chronostratigraphic precision but a whole consistency in radiocarbon age determinations supporting tectonic inferences from each study site.

3. Results

3.1. Cosismic uplift and interseismic recovery of the 2007 Mw 7.7 Tocopilla earthquake

The geodetic time series shown in this work evidence nine years of recorded data following the November 14th 2007 Mw 7.7 Tocopilla earthquake. The interseismic, coseismic and postseismic positions are shown by 3 GPS antennas located in the study area, corresponding to MCLA, PMEJ and JGRN (Figs. 2b, 4). The coseismic vertical rebound was on the order of few decimeters, with a maximum vertical displacement at PMEJ of 340 mm (Fig. 4a). For the Mw 7.7 deep-moderate earthquake, we considered that nine years of both postseismic and interseismic geodetic data are representative of the subsequent period of coseismic elastic rebound recovery. The latter is reinforced by the total horizontal coseismic recovery that all GPS antennas underwent in the north and east-time series components at rates of 22–35 mm/yr (Fig. 4a).

The preseismic up-time series show less than one year of data acquisition for the three GPS antennas of the CSN network (Fig. 4a), with no records older than these being available. Therefore, we did not estimate any tendency for the preseismic period because it encompasses a few months of GPS records that are not sufficient to support annual vertical velocity rate estimations.

The first two years following the main shock could correspond to the postseismic period, which was characterized by a first stage of rapid increase and a subsequent decrease in uplift that can be adjusted by a logarithmic trend line (all up-time series; Fig. 4a). The PMEJ GPS antenna record exhibits the fastest uplift increase, with a total of ~60 mm in two years (Fig. 4a).

The interseismic periods show low subsidence rates in all of the up-time series, with a vertical recovery increasing to the southwest of the main shock rupture area (MCLA: −0.40 ± 0.07 mm/yr; PMEJ: −1.31 ± 0.12 mm/yr; JGRN: −3.10 ± 0.08 mm/yr; Fig. 4b). This difference in signal behavior is expected because from north to south, the MCLA GPS antenna is located farther from the trench than is JGRN (Fig. 2b). The GPS antennas further away from the trench are expected to experience less influence from the coupled plate “unstable” domain and therefore minimal or null interseismic subsidence, as shown at MCLA (Figs. 2b, 4b), which exhibits an almost unchanged up-time series during the interseismic period. The latter could be taken as evidence for permanent coseismic uplift in the MCLA area. If we consider no variations in the interseismic linear regression trend over time (Fig. 4b), with PMEJ as the most representative GPS antenna of the seismic rupture area beneath northern MP, then the 2007 Tocopilla earthquake coseismic uplift could be recovered in ~250 yr. The lack of other deep-moderate subduction earthquakes affecting the study area over at least the last 140 yr after the 1877 large megathrust earthquake (Ruiz and Madariaga, 2018) tends to support the last estimation.

The subsidence rates following the Tocopilla main shock (0 to ~3 mm/yr) are slower (Fig. 4b) than the ~10 mm/yr estimated for the Arauco Peninsula area for a complete seismic cycle, encompassing the period between 1835 and 2010 in the Maule segment of central southern Chile (Wesson et al., 2015).

3.2. Evidence of Holocene uplift

Morphostratigraphic evidence of rapid and abrupt Holocene uplift were observed along the coastline of northern MP at Punta Lobería and Playa Grande (Fig. 2a) as well as at Caleta Michilla, which is located nearly 50 km to the north (Figs. 1, 5 and 6).

At Punta Lobería, we found littoral deposits constituted by well-rounded conglomerates with marine shells (Fissurella sp., Echinodermata sp.) and a coarse sandy matrix located at an altitude of 4.5 m a.s.l. at the base of an abandoned sea cliff (Fig. 5a, b). We
Fig. 3. Microstructure of the outer calcitic layer (SEM images) of samples MG9927-a (a–d) and MG9927-b (e–f). XRD spectra of the outer (g) and inner (h) layer of shell samples with mineralogical reference from the PDF database for calcite (red bars) and aragonite (blue bars). The asterisk (*) indicates the diffraction peak due to the sample holder.
interpret the latter deposits as a paleo-beach berm or eventually as tsunami deposits located at a paleo-wave cut notch of a recently uplifted coastline. These deposits can be associated with uplifted marine terraces located at 1.5 m a.s.l. in a manner similar to that of the present-day geomorphologic configuration between the littoral deposits and submerged marine terrace in the area (Figs. 5a–c).

Four radiocarbon results from marine shells taken from these deposits yielded conventional age values between 460 ± 30 and 830 ± 30 yr BP (Supplementary B), with a single age of 193 ± 92 Cal. yr BP (1665–1949 CE; Fig. 5c), which is coincident in time with the last large tsunamigenic 1877 Mw ~8.8 megathrust earthquake.

In Mejillones Bay, a conspicuous coastal cliff is visible as a limit of the modern beach, similar to the one at Punta Lobera. Along the bay, this cliff presents active and inactive segments (Fig. 2a). The active segment of this coastal cliff is located proximal to the Mejillones Fault (MF), a conspicuous N–S normal fault system cutting alluvial fans in the northern MP (Figs. 2a, 7a) at La Rinconada, whereas the inactive segment is located to the east of the embayment (Figs. 2a, 5d). The active segment at La Rinconada is characterized by a cliff reaching 10 m a.s.l., with a narrow (<15 m) or absent beach (Fig. 7a). In contrast, the inactive segment, such as at Playa Grande, which is located 20 km NE from La Rinconada, is characterized by a cliff reaching 22 m a.s.l. and is covered by eolian sands (Fig. 5a). The base is located at least 100 m away from the modern coastline, with a marine terrace ~60 m in width constituted by uplifted littoral deposits of sandy (intertidal) facies reaching 7.1 m a.s.l. (Figs. 5d–e). Radiocarbon results of marine shells from these littoral sediments yielded ages of 3.7 ± 0.1 and 4.3 ± 0.1 Cal. ka BP (Fig. 5e; Supplementary B).

Further north of MP, at Caleta Michilla, which is located 30 km north of Playa Grande (Fig. 1), we found littoral marine deposits forming a terrace located up to 7 m a.s.l. (Fig. 6a). These deposits are constituted by intercalation of well-rounded gravels and sandy layers with abundant mollusk shell fragments (Fig. 6b). From these deposits, we obtained stratigraphically consistent radiocarbon ages of 6.8 ± 0.1 and 6.2 ± 0.1 Cal. ka BP from intact mollusk shells (Fig. 6c; Supplementary B). These ages are in addition to the 7.0 ± 0.2 Cal. ka BP that can be deduced from the previous conventional age of 6.7 ± 0.3 ka BP reported by Leonard and Wehmiller (1991) from the same deposits.

3.3. Marine isotopic stage 3 coastal records

Littoral marine sediments are well exposed along the coastal cliff that surrounds the Mejillones Bay at the northern portion of the MP, overlying the uplifted marine abrasion platforms carved on igneous rocks and Neogene deposits in the area (Fig. 7b). These sediments record a transgressive sequence, which has been dated in this work using radiocarbon determinations obtained from four locations (C1, C2, C3 and C4; Fig. 2a). The deposits are well exposed on the previously mentioned sea cliff, which reaches 10–22 m a.s.l. from the western (La Rinconada) to the eastern (Playa Grande) portion of the Mejillones embayment (Fig. 2a). At
La Rinconada, these deposits overlay both an angular unconformity carved on semi-consolidated Neogene marine sediments (C1; Figs. 2a, 7b) and a non-conformity carved on Jurassic igneous gabbroic rocks (C2; Figs. 2a, 7b), respectively. The deposits at the La Rinconada embayment reach up to ~7 m a.s.l. in the coastal cliff located on the tectonic block of Pampa Mejillones hemi-graben (Figs. 7, 8a). In this location, a 9.6 m a.s.l. stratigraphic column exposes marine to continental sedimentary facies from bottom to top (Figs. 8a, b). In the bottom portion of the stratigraphic column outcrops, a layer ~0.6 m thick of bioclastic orthoconglomerate composed of well-rounded cobbles and boulders, intact bivalves in life positions and mollusk shell fragments is embedded within coarse-medium sandy matrix (Fig. 8b). Over this layer, we found a gray sandy marine deposit ~0.3 m in thickness overlaid by a semi-consolidated coquina ~0.7 m in thickness. This structure is overlaid by a deposit ~0.25 m in thickness of semi-consolidated in situ Balanus sp. with pebbles and shell fragments (Fig. 8b). The last layer is overlaid by sandy facies with low-angle subhorizontal cross-lamination interbedded with well-rounded gravels and abundant shell fragments, which are located up to ~6.5 m a.s.l. The overall package of littoral deposits is characterized by normal vertical grain size gradation, evidencing a transgressive sea-level fluctuation (Fig. 8b). These marine layers are overlaid by 3 m of alluvium with supralittoral sheets interbedded within its lower portion, which can be associated with the progradation of the alluvial system into the marine basin subsequent to the transgressive episode (Figs. 8b, c). The thickness of the alluvium is variable, ranging from almost 0 up to ~26 m close to the mountain front, where the MF is located (Fig. 7).

The 18 calibrated radiocarbon results obtained from shell samples collected at La Rinconada from both the hanging wall (C1) and the footwall (C2) of the MF (Figs. 2a, 7, 8b) yielded an age range of 45–34 Cal. ka BP with a mean age of 40 ± 3.6 Cal. ka BP (Supplementary B), which were assigned by this study to MIS 3. The
11 kyr scatter obtained from these 18 radiocarbon results (Fig. 8b; Supplementary B) could be the result of the low precision and moderate accuracy accepted from radiocarbon dates from this time span. As an example, AMS radiocarbon results obtained from a single specimen of *Choromytilus chorus* collected in the live position within littoral sandy facies overlaying a non-conformity carved on Jurassic rocks in the footwall of the MF (Fig. 7b) yielded 6 calibrated ages between 45.7 ± 1.6 and 34.5 ± 0.4 Cal. ka BP (sample MC9927—a–c; Supplementary B).

Ten of our conventional radiocarbon results obtained from marine shells from La Rinconada yielded infinite age values (Supplementary B), which can be interpreted as reworked material deposited during previous marine isotopic stages. This observation could also offer an explanation for older ages previously reported from U/Th analyses from the same sedimentary packages, which gave results of 124 and 162 ka (Víctor et al., 2011) and 106 ka (Radtke, 1989). We interpret this reworking of material as the result from coastal reoccupation and partial erosion of previous deposits (e.g., MIS 5), at the time of MIS 3.

MIS 3 deposits were also identified at Playa Grande and Punta Lobera (Figs. 2a, 5), reaching altitudes of 22 m and 12.5 m a.s.l. on the crest of the sea cliffs at the eastern and western blocks of the MF, respectively (Figs. 2a, 5). Radiocarbon results from mollusk shell fragments yielded mean ages of 38.3 ± 0.9 and 38.5 ± 0.8 ka Cal. BP at each site, respectively, confirming the same time span for the La Rinconada record (Supplementary B).

**4. Discussion**

**4.1. Subduction earthquakes and short-term coastal uplift**

Short-term vertical deformation affecting the MP was evidenced for the first time by geodetic and geological observations following the 1995 *M* *w* 8.1 Antofagasta earthquake, which ruptured the subduction contact 200 km from the southern MP to the south (Fig. 1; Ruegg et al., 1996; Delouis et al., 1998). During this earthquake, the southern MP underwent a coseismic uplift of approximately 0.15–0.80 m (Ortlieb et al., 1996a). Additionally, due to this earthquake, the northern MP experienced aseismic pulses during five years of postseismic afterslip movement on the order of few centimeters in both their vertical (uplift) and horizontal components (Pritchard and Simons, 2006).

The last large event that affected the northern MP in 1877 (*M* *w* ∼ 8.8) was the only historical earthquake (*M* > 7) reported in the last 130 yr to rupture the study area (Ruiz and Madariaga, 2018) before the 2007 *M* *w* 7.7 Tocopilla event. The well-preserved littoral deposits and marine terraces at Punta Lobera at the western coast of the northern MP (Figs. 2a, 5a–c) could be taken as coherent evidence for a strong coseismic uplift that likely occurred during the last 1877 *M* *w* ∼ 8.8 megathrust earthquake. Indeed, this last large tsunamiogenic earthquake could have at least partially ruptured the plate contact beneath the MP, similar to the 1.3 ± 0.2–2.6 ± 0.6 m of coastal uplift observed in the Arauco Peninsula during the 2010 *M* *w* 8.8 Maule earthquake in Central Chile (Farías et al., 2010; Vargas et al., 2011b; Vigny et al., 2011).

The geodetic evidence following both the 1995 *M* *w* 8.1 and 2007 *M* *w* 7.7 earthquakes shows aseismic slip-pulses that affected the northern MP (Pritchard and Simons, 2006; Bejar-Pizarro et al., 2010; Schurr et al., 2012). Furthermore, during the postseismic period following the 2007 Tocopilla earthquake, much of the aftershocks remained confined to the coseismic rupture area despite the decrease of Coulomb stress (Schurr et al., 2012). The latter suggests that the rupture area of the 2007 Tocopilla earthquake is subjected to a partially and/or temporally “conditionally stable” regime, which might slip in a stable or unstable manner (Schurr et al., 2012). Considering that the 1995 Antofagasta and the 2007 Tocopilla afterslip pulses affected the areas beneath and offshore of the northern MP, it is possible to suggest that the narrow “conditionally stable” domain could have an up-dip limit underneath this peninsula (Fig. 2b) that is shallower than that of the remainder of the region where it was located roughly parallel to and near the coastline (i.e., 35–40 km depth on the seismogenic zone; Bejar-Pizarro et al., 2010; Schurr et al., 2012; Melnick, 2016). Effectively, a partially locked slab beneath the coastline and northern MP is a better explanation for our observations of nearly null and low interseismic vertical recovery in the static GPS antennas (Fig. 2b).

**4.2. Late Quaternary sea level position and geometric-conceptual model for long-term uplift**

The global sea level position during the MIS 3 has been established by several researchers as between −31 and −95 m (Fig. 8c; Arz et al., 2007; Siddall et al., 2008; Pico et al., 2016). Because of this wide range, we compare the sea level curves of Arz et al. (2007), which is based on ice volume changes due to Northern Hemisphere climatic variability, and Pico et al. (2016), which considers glacial isostatic adjustments during 57–37 ka (Figs. 8c, 9; for the geometric-conceptual model build-up see Supplementary C).

**Uplift history according to the Arz et al. (2007) sea level curve.** Considering our radiocarbon results, we interpret that the 6 m of littoral deposits and sedimentary facies located at La Rinconada (Fig. 8a,b) resulted from an important transgression that occurred between 40 and 38 ka (Fig. 8c; Arz et al., 2007; Siddall et al., 2008). This transgression raised the sea level by ~30 m in less than 2 ky, beginning with its position at −95 m at 40 ka and concluding with its stabilization at −65 m at 38 ka (Figs. 8c, 9a). Taking the difference in altitude between the MIS 5e and MIS 3 littoral deposits at Pampa Mejillones (~50 m; Fig. 9c), we need to infer a subsidence rate of ~0.17 m/kyr for the period 125–40 ka (Fig. 9a) to explain the 2 m/kyr uplift rate since 38 ka (Figs. 9b, c; Supplementary D).
Uplift history according to the Pico et al. (2016) sea level curve. According to these authors, an important transgression during MIS 3 occurred between 70 and 44 ka, when the sea level rose by ~32 m from −70 m to −38 ± 7 m (Figs. 8c, 9e). Taking the same geometric considerations as in the previous case, we infer an uplift rate of 0.07 m/kyr for the period 125–44 ka (Fig. 9d), followed by an increase to 1.14 m/kyr since 44 ka (Fig. 9e; f; Supplementary D).

Both models can explain the current stratigraphic and geomorphological configuration of littoral deposits that are well exposed at La Rinconada. However, according to Pico et al. (2016), the important transgression period during MIS3 encompassed ~26 kyr – in contrast with the 2 kyr proposed by Arz et al. (2007) –, which can better explain the thickness of the MIS 3 system track. Furthermore, the position for the lower bathymetric location of the unconformity associated with the LGM on the shelf in Mejillones Bay (MIS 2), as well as the slope of the bay bottom that resulted from both geometric-conceptual models (Fig. 9c, f), fits better with the bathymetric and stratigraphic submarine observations (Vargas et al., 2005, 2011b), taking the sea level curve from Pico et al. (2016) rather than taking the sea level curve from Arz et al. (2007).

Thus, we assigned an age of ~44 ka for the maximum high stand sea level position (38 ± 7 m b.s.l.) during the MIS 3 period, according to Pico et al. (2016). From this, we estimate uplift rates of between 0.98–1.30 m/kyr and 1.45–1.77 m/kyr for the MF hanging wall and footwall, respectively, at La Rinconada (Fig. 7; Supplementary D). For the 64–78 m of uplift estimated for the footwall block during the last ~44 kyr, only 4 m of this accumulated uplift can be explained by the MF elastic rebound from the 0.5 m/kyr slip rate deduced for the activity of this fault (i.e., 20 m of vertical slip since 44 ka; Fig. 7b). If we consider that 20% of fault displacement is linked to footwall block uplift (Stein et al., 1988), then, the uplift rate for the footwall block taking out the fault activity would be 1.36–1.68 m/kyr.

In addition, the accelerated Middle to Late Pleistocene coastal uplift has also been inferred by Binnie et al. (2016) through the study of marine terraces at Morro Mejillones (Fig. 2a) using 10Be cosmogenic dating. Those authors inferred a period of rapid uplift...
Fig. 9. Geometric conceptual models for the Late Quaternary uplift history at the La Rinconada area. (a–c) Uplift history considering the sea level curve from Arz et al. (2007). (d–f) Uplift history considering the sea level curve from Pico et al. (2016). The vertical dashed lines 1, 2 and 3 correspond to the inferred inner edges of the Holocene, MIS3, and MIS5c (or 5a) transgressions, respectively.

at a time within the last 200 kyr, with estimated rates of $0.60 \pm 0.06$ m/kyr over the last 480 kyr and $0.53 \pm 0.18$ m/kyr for the time period 480–269 ka. This rapid coastal uplift, which occurred post-200 ka according to Binnie et al. (2016), could be mostly represented by the $\sim 44$ ka increased coastal uplift that we deduced from our geometric-conceptual model (Figs. 9d–f).

Additionally, from the in situ littoral deposits with intertidal facies dated as $3.7 \pm 0.1$ and $4.3 \pm 0.1$ ka Cal. BP located at 7.1 m a.s.l. at Playa Grande (Fig. 5d–f), it is possible to estimate an uplift rate of $1.79 \pm 0.18$ m/kyr, likely recording a recent pulse of coastal uprisiing. Similarly, considering the age of littoral deposits located at a maximum altitude of 4–6 m a.s.l. at Caleta Michilla, 50 km to the north of Mejillones City and dated at $6.2 \pm 0.1$ and $6.8 \pm 0.1$ ka Cal. BP, it is possible to estimate an uplift rate of $0.61 \pm 0.11$ m/kyr (Fig. 6). The latter suggests that rapid coastal uplift also occurred during the Holocene and that this is a regional process rather than an exclusive one constrained to the MP area. Thus, our new Late Quaternary coastal uplift rate estimates are much higher than those previously considered as 0.1–0.5 m/kyr in the same region (Ortlieb et al., 1996;
Victor et al., 2011). We propose that the uplift regime prevailing since MIS 3 was initiated following a period of almost zero coastal uplift between MIS 5e and ~44 ka.

### 4.3. Megathrust earthquake contribution to long-term coastal uplift

The long-term uplift that affected the northern MP since ~44 ka can be explained as the result of coseismic uplift by at least two types of subduction earthquakes: one nucleating along the deepest portion of the plate contacts, such as the deep-moderate 2007 Mw 7.7 Tocopilla earthquake, and large megathrust tsunamigenic events, such as the 1877 Mw ~8.8 earthquake. From the analysis of cracks that would have been generated by this last type of earthquakes, an ~300-yr recurrence period has been inferred for its occurrence at geological time scales (Baker et al., 2013), which is roughly consistent with paleo-seismic evidence from laminated sediments in Mejillones Bay, suggesting the occurrence of an important event that caused erosion and local reworking of material within the embayment close to 1409–1449 CE (Vargas et al., 2005). Thus, as a first-order estimation, we can consider that 1877-type earthquakes could occur every 300–400 yr. In spite of the scarce available historic data, the null occurrence of a deep-moderate earthquake (M > 7) in the study area following the 1877 episode and before the last 2007 Tocopilla event suggests a recurrence time interval greater than 130 yr and up to 250 yr as inferred from geodetic estimations – providing that low vertical recovery rates prevail unchanged over time –, for such episodes in the northern MP. This observation implies that both deep-moderate earthquakes (e.g., 2007 Tocopilla, 0.34 m of coseismic uplift; PMEJ; Figs. 2a, 4, 10a) and large megathrust earthquakes (e.g., 1877, 1.2 m of coseismic uplift inferred at Punta Lobera; Figs. 5a, 10a) have contributed on the order of 236 m of coastal uplift as a minimum amount in the northern MP since ~44 ka. Considering the sea level at that time (Pico et al., 2016), as well as the present-day position of the top of MIS 3 deposits that would be located at 33 m a.s.l. in the footwall of the MF at La Rinconada (presently situated at 21 m a.s.l. for the base of the MIS 3 deposits on the footwall and ~12 m of MIS 3 littoral deposit inner edge; Fig. 7), the long-term subsidence rate would be on the order of 69–75%, resulting in a large contribution of megathrust earthquakes to constructive coastal relief processes (25–31%), which is even higher than for Santa María Island, considering a complete seismic cycle (i.e., 15–22% of permanent vertical deformation; Wesson et al., 2015). Moreover, our uplift rate estimates since MIS 3 in northern MP are in the range of that reported for the Arauco Peninsula by Jara-Muñoz et al. (2015) (Fig. 10b). This uplift rate estimation does not consider the vertical contribution of the MF activity in the footwall.

Such an increase in coastal emersion could have been driven by increased megathrust earthquake production, implicating an onset of the modern seismic regime since MIS 3 at multi-millennial time scales and reflecting the beginning of long-term earthquake clustering. The deep-moderate earthquakes, such as the 2007 Tocopilla event, would control the coastal uplift evolution as a first-order process and likely trigger permanent deformation affecting the “conditionally stable” domain, which appear to be acting beneath the northern MP and Coastal Cordillera in northern Chile (Béjar-Pizarro et al., 2010; Schurr et al., 2012; Melnick, 2016). Additionally, the MP is situated above the limit between the “unstable” and “conditionally stable” domains (Pritchard and Simmons, 2006; Béjar-Pizarro et al., 2010, 2013; Schurr et al., 2012), suggesting the involvement of the tsunamigenic large megathrust earthquakes such as the 1877 event that ruptured the entire seismogenic zone beneath the northern MP.

### 4.4. Role of active crustal faults in permanent deformation

The MP is characterized by active upper crustal normal faults (Figs. 2a, b), and among these, the most remarkable structure is the MF (Figs. 2a, 7). The late Quaternary activity of this fault system has been well constrained from submarine and subaerial paleo-seismological analyses, yielding a mean vertical slip rate of 0.5 m/kyr over the last ~40 kyr (Vargas et al., 2011a; Cortés et al., 2012). Considering the consistency of our age results obtained from samples taken at both block sides of this fault (footwall and hanging wall), together with an age of ~44 ka for the littoral deposits cut by this geological structure and our precise estimations for the altitude of these deposits, it is possible to estimate a mean vertical slip rate value of 0.47 m/kyr, which closely matches previous independent results (Vargas et al., 2011a; Cortés et al., 2012). The MIS 3 deposits are embedded on both the hanging wall and footwall blocks of this fault, implying that the regional uplift has outpaced the subsidence that particularly affects the hanging wall during the activation of this fault and discounting the notion that the observed uplift is dominated by normal fault
tectonic blocks (von Huene and Ranero, 2003). Considering 20 m of vertical displacement for the MF, the horizontal extension rate can be estimated as 0.12 m/kyr for the last ~44 kyr, which is in agreement with the extensional rates estimated as 0.06–0.18 m/kyr by Allmendinger and González (2010) in the study area since the early Miocene and early Pliocene. The latter implies negligible lithospheric isostatic rebound as a response to crustal stretch, which would not contribute significantly to the northern MP uplift. Additionally, the MF exhibits offset alluvial surfaces with maximum ages of 35–40 ka (Vargas et al., 2011a; Cortés et al., 2012), indicating that the activity of this fault started roughly concomitantly with the increased coastal uplift since ~44 ka. Therefore, we propose that MF acts as a structural hinge that differentially accommodates the vertical deformation triggered by the uplift.

A possible crustal scale west-verging thrust splay fault has been proposed from crustal deformation analyses from the aftershocks following the 2007 Tocopilla earthquake (Fuenzalida et al., 2013). This local splay fault, recognized only offshore of the northern MP (Fig. 2b), could explain both the uplift and the presence of normal faulting activity as a response to deformation on the fold hinge. It has been proposed that changes in the coastal uplift rates could be linked to random thrust splay fault activity over time (Nicol et al., 2009; Mouloupolou et al., 2016). Despite this observation, if intraplate faults have importantly contributed to the uplift history, it cannot be taken as evidence of an unessential contribution of the megathrust earthquake activity. The empirical evidence of the 2010 Maule earthquake has shown that intraplate faulting activity was directly linked with a Coulomb stress change produced on the continental margin by the main shock (Farías et al., 2011; Aron et al., 2013). Similar examples of intraplate faulting activity linked to large megathrust earthquakes have occurred in the context of the 2004 Sumatra-Andaman and 2011 Tohoku-Oki earthquakes (Andrade and Rajendran, 2011; Delescluse et al., 2012; Obana et al., 2012).

The main problem in explaining regional coastal uplift with this type of splay faulting activity is that it does not comply with the regional tectonic setting of the continental wedge characterized by frontal margin collapse due to subduction erosion (von Huene and Ranero, 2003; Sallares and Ranero, 2005), and it is in disagreement with a critically tapered Coulomb wedge theory for the inner portion of the continental margin (Wang and Hu, 2006). In addition, the two largest aftershocks (Mw 6.3 and Mw 6.8) following the 2007 Tocopilla earthquake were nucleated on this possible splay fault (Schurr et al., 2012), but the elastic rebound effect of these aftershocks resulted in a downward movement of the northern MP (Béjar-Pizarro et al., 2010), which is in contradiction with our observations of dominant coastal uplift. In agreement, the presence of uplifted Holocene littoral deposits at Michilla located 50 km to the north of the MP suggests that coastal uplift is a regional rather than a local process restricted to the northern MP. Nevertheless, the uplift rates estimated at Caleta Michilla are lower than those from the northern MP, perhaps because the Caleta Michilla area is only affected by vertical build-up deformation associated with deep-moderate earthquakes (Melnick, 2016), and instead, the northern MP is affected by both deep-moderate and large megathrust earthquakes.

According to annual geodetic data and late Quaternary geomorphological feature observations, it seems that the most plausible mechanistic explanation for constructive permanent vertical coastal deformation in northern MP is related to subduction earthquake processes, where the mechanistic transition represented by the “conditionally stable” domain in the plate contact could be the manifestation of a overthrusting and folding deformation zone in the lower part of the continental plate resulting in crustal thickening, which would imply extensional strain and uplift response on the upper crust (Fig. 2b; González et al., 2003; Melnick, 2016).

Other explanations to both the uplifting and stretching of the crust are linked to subductsed aseismic ridges (Hartley and Jolley, 1995), accumulated coseismic crustal extensional deviatoric stresses (Delouis et al., 1998) and basal subduction erosion with associated tilting-block rotations together with sediment underplating (von Huene and Ranero, 2003). The main problem with these last hypotheses is that they do not explain our geodetic data, MIS 3 football stratigraphic position and Holocene uplifted littoral deposits and marine terraces.

Accordingly, we propose that the nearly concomitant increase in coastal uplift of the northern MP (Fig. 10b) and neighboring localities is a product of regional-scale changes involving the entire subduction plate contact between the Nazca and South American plates in northern Chile.

### 5. Conclusions

Radiocarbon results from MIS 3 and Holocene deposits together with precise geomorphological measurements and stratigraphic observations in the northern Mejillones Peninsula at the southern edge of the northern Chile megathrust seismic gap support uplift rates on the order of 1.4 to 1.7 m/kyr, which are one order of magnitude higher than those prevailing previously in the area, demonstrating an acceleration in regional coastal uprising in the last ~44 kyr. In this context, active crustal faulting such as that occurring along the Mejillones Fault is responsible for the absorption of differential uplift (0.47 m/kyr of vertical slip in the last ~44 kyr) and block tectonics at the scale of the Late Quaternary. High uplift rates can be explained as the result of subduction megathrust earthquakes breaking underneath the northern portion of MP, similar to those during the deep-moderate 2007 Mw7.7 Tocopilla event as deduced from geodetic measurements, and during the large megathrust tsunamiigenic 1877 Mw8.8 episode, as inferred from geological observations.

We propose that accelerated coastal uplift along this segment of the Central Andes since the Late Pleistocene is most probably associated with the onset of a modern seismic regime set after ~44 ka as the result of enhanced endogenous processes encompassing the entire subduction contact between the Nazca and South American plates in northern Chile.

### Acknowledgements

The authors thank the Fondo Nacional de Desarrollo Científico y Tecnológico projects #1161547 and #1140846. For a number of analyses, the authors benefited from IRD support from the Laboratoire de Mesure du Carbone 14 (LMC14, CNRS–CEA–MCC–IRD–IRSN). The first author acknowledges support from doctoral CONICYT scholarship #20010102. Geodetic data from the GPS antennas were supplied by Centro Sismológico Nacional. We thank Diego Salazar and reviewers for their useful comments.

### Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2018.08.043.

### References


