Coastal neotectonics in Southern Central Andes: uplift and deformation of marine terraces in Northern Chile (27°S)

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Abstract

Neotectonic observations allow a new interpretation of the recent tectonic behaviour of the outer fore arc in the Caldera area, northern Chile (27°S). Two periods of deformation are distinguished, based on large-scale Neogene to Quaternary features of the westernmost part of the Coastal Cordillera: Late Miocene to Early Pliocene deformations, characterized by a weak NE–SW to E–W extension is followed by uppermost Pliocene NW–SE to E–W compression. The Middle Pleistocene to Recent time is characterized by vertical uplift and NW–SE extension. These deformations provide clear indications of the occurrence of moderate to large earthquakes. Microseismic observations, however, indicate a lack of shallow crustal seismicity in coastal zone. We propose that both long-term brittle deformation and uplift are linked to the subduction seismic cycle.

Keywords: Brittle deformations; Quaternary marine terraces; Neogene shelf deposits; Andean fore arc tectonics

1. Introduction

Coastal neotectonic investigations are favoured by the presence of marine terraces. These morphological features provide a reference and chronological data of the sea levels and against which the progress of uplift and deformation can be traced. In active subduction margins, the study of Quaternary marine terraces has been indispensable for the calculation of uplift rates, and the determination of fault activity (e.g., Lajoie, 1986; Hanson et al., 1994). In general, coastal zones where Late Cenozoic sequences of terraces are registered allow a better understanding of recent tectonic evolution and deformation mechanisms.

The northern coast of Chile includes the most emerged parts of the Southern Central Andes fore arc closest to the trench. The pervasive hyperarid climatic...
conditions along with the good preservation state of the morphostratigraphic (e.g., marine terraces) and morphostructural (e.g., fault scarps) records favours studies in neotectonics. Late Cenozoic marine and continental basin sediments are well preserved and exposed in Antofagasta (23–24°S), Caldera (27–28°S) and La Serena (29–31°S) (e.g., Herm, 1969; Paskoff, 1970; Arabasz, 1971; Mortimer, 1973; Ota, 1986; Radtke, 1987a,b; Hsu et al., 1989) (Fig. 1).

Along this part of the South American Plate, subduction parameters have varied during the last 20 Ma. Convergence of the Nazca Plate has registered a variable obliquity of 30° to 23° and subduction long-term rates of 15 to 8 cm/year (Pardo-Casas and Molnar, 1987; DeMets et al., 1994; Somoza, 1998). During this time, the age of the subducting slab decreased (Soler and Bonhomme, 1990) and several ridges or seamount chains have been subducted (Gutscher et al., 2000; Yáñez et al., 2002). The present instantaneous convergence direction is N77°E, with an obliquity of 13°, and a rate of about 7–8 cm/year (DeMets et al., 1994; Angermann et al., 1999).

Within this non-accretive active margin, the maximum depth of seismogenic contact is estimated at 50–60 km (Comte et al., 2002). The intense seismicity and large thrust events along the seismogenic zone show a strong seismic coupling at the

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![Fig. 1. (a) Topography index map from the fore arc of Southern Central Andes. Data are from GMT. Triangles indicate active volcanoes. CPT is the Chile–Peru trench. Present day convergence vector is from Somoza (1998). (b) Morphostructural sketch map along 110 km of coast between 27°S and 28°S.](image)
interplate contact zone. The shallow part (<60 km) of
the subduction zone, as throughout a great part of the
Chilean subduction zone, dips to the east at an average
angle of about 20° (Suárez and Comte, 1993).

In the arid to hyperarid-arid Atacama Desert of
northern Chile, two longitudinal morphological units
are recognized: the Coastal Plain and the Coastal
Cordillera. The Coastal Plain, with 3 km average
width, is formed by a series of marine terraces,
partially covered by alluvial fans, which extends from
the present coastline to 300 m asl (Paskoff, 1989). The
Coastal Cordillera is considered a regular mountain
range with a variable width of 10–50 km and an
altitude of up to 2000 m (Mortimer, 1980). In the
major part of the north of Chile the Great Coastal
Escarpment separates the Coastal Cordillera from the
Coastal Plain (Paskoff, 1989).

The chronology, dynamics, style and control
mechanisms of Neogene and Quaternary tectonic
deformations in the Coastal Plain and Coastal
Cordillera are not well understood and remain subject
to debate. The Atacama Fault System is an example of
this debate. This structural system of Mesozoic origin,
N–S oriented between 20°30’S and 29°45’S (e.g.,
Thiele and Pincheira, 1987; Brown et al., 1993; Taylor
et al., 1998) presents, northward of 27°S, evidence of
Neogene and Quaternary activity (e.g., Arabasz, 1971;
Hervé, 1987; Riquelme et al., 2003). This activity is
mainly evidenced by vertical movements of tens to
hundreds of meters during the Late Cenozoic, allow-
ing calculation of the uplift rate of the Coastal
Cordillera. Nevertheless, its relation to the mecha-
nisms of subduction has been diversely interpreted
(e.g., Naranjo, 1987; Armijo and Thiele, 1990;
Wdowinski and O’Connell, 1991; Niemeyer et al.,
1996; Delouis et al., 1998; Adam and Reuther, 2000;
González et al., 2003).

In this paper, in order to better understand the
Neogene and Quaternary tectonic evolution of the fore
arc and its relations to subduction mechanisms, we
determine uplift rates and paleostresses in the Coastal
Plain at 27°S. This area has not been studied in detail
by recent works and is relevant to integrate novel
studies of more detail made in the northern and
southern part of it. Two types of indicators are used:
(1) the presence of morphological features such as
marine terraces, and (2) tectonic features, such as fault
planes and folds.

2. Geological framework

In the study area, the continental, littoral and
marine Late Cenozoic deposits overlie a basement
composed of Upper Paleozoic metamorphic and
Mesozoic plutonic rocks (Godoy et al., 2003; Blanco
et al., 2003). This basement is prefractured by NW–
SE and N–S to NNE–SSW predominating subvertical
structures. In this area the Coastal Plain reach a
maximum width of up to 10 km.

2.1. Neogene deposits

The Neogene continental and marine deposits form
sedimentary sequences that unconformably cover the
basement (Fig. 2).

The sedimentary sequences, assigned to the Lower
and Middle Miocene, are composed mainly of alluvial
or fluvial gravel and red angular pebbles (e.g.,
Copiapó River Gravels, Godoy et al., 2003) or of
grain supported clast gravel with varying degrees of
rounding (e.g., Quebrada Totoral Gravels, Blanco
et al., 2003). These continental deposits crop out mainly
in the large and deep valleys of this zone, where
Middle Miocene–Lower Pliocene marine sequences
cover them in erosional unconformity. These marine
sequences, grouped in the Bahía Inglesa Formation
(Rojo, 1985), are composed mainly of breccias,
conglomerates, coquinas, sandstone and mudstone.
They are interpreted as continental shelf partially
deltaic deposits and are restricted to basins present
only along the Coastal Plain. Remnants of ancient
wave-cut platforms (Agua Amarga Strata) onlap the
Coastal Cordillera, between 200 and 350 m asl. They
are composed of carbonated sands and coquinas, may
be equivalent to the upper part of the Bahía Inglesa
Formation.

2.2. Quaternary deposits

The Quaternary continental and coastal deposits
are associated with morphostratigraphic units as
alluvial fans, dunes, fluvial and marine terraces. They
cover Neogene deposits and basement rocks in ero-
sional unconformity (Fig. 2).

The Quaternary marine terraces, which are dis-
tributed over an extensive area of the coast, are
grouped in the informal unit denoted the Caldera
Strata, defined on the basis of their lithologic and geomorphologic characteristics. These terraces allow a calculation of coastal uplift rates and, together with the evidence of brittle deformation; they record recent tectonic activity in this part of the fore arc.

3. Marine terraces and coastal uplift

Preserved Quaternary marine terraces in convergent margins are the product of the combination of two phenomena, sea-level changes and tectonic uplift. Their formation during interglacial maxima (high sea-level stands) is linked to regional vertical motions, which may preserve them from subsequent coastal erosion. The geometrical characteristics, presence of associated sediments and their preservation, depend on a series of geological, climatic and oceanographic parameters.

In the arid coastal region of the study area the emerged marine terraces are partially covered by alluvial deposits. Reduced precipitation limited the erosion and alteration of the former coastal sediments. A general recognition of the Quaternary marine terraces along 110 km of the coast between 27°S and 28°S, allows the Caldera and Bahía Inglesa localities to be defined as two interesting areas for neotectonic studies (Marquardt, 1999; Marquardt et al., 2000a). Here the marine terraces, well preserved, have been partially dated and are cut by normal faults (Fig. 3).

3.1. Method for estimating uplift rates

To estimate and quantify the Coastal Plain uplift, we determined the altitude at which Quaternary high sea-level stands were registered. This approach consists in measuring the maximum height reached by the sea during each interglacial or sub-stage (Lajoie, 1986). Practically, we used available isotopic data of ages of marine terraces in the area, complemented with paleontological studies carry out during this work, and we compare the present-day position of the marine terraces with published Quaternary high sea-
Fig. 3. Distribution of Quaternary marine terraces in Caldera and Bahía Inglesa area (27°S). Surface profiles with altitude (120±10 m) of the shoreline angle of marine scarps are shown. See text for further details.
level stands. We measure by barometric altimeter profiles the base of marine-originated scarps (shoreline angle) that limit inland marine terraces (internal limit) and evaluate their possible ages. The age assignments of each terrace are tentatively correlated with the respective Quaternary interglacial maxima and associated odd numbers of marine isotope stages (MIS) (Shackleton and Opdyke, 1973; Chappell and Shackleton, 1986).

The uplift rates are estimated by subtracting the altimetry value of each terrace from the sea level of the interglacial maximum assigned and then dividing this value by the age assigned to the terrace (MIS odd number).

3.2. Sequence of marine terraces of Caldera and Bahía Inglesa

The height and lateral continuity of the internal limit of each Quaternary marine terrace were measured over both the pre-Cenozoic basement and Neogene deposits. The deposits, ranging in thickness from 1 to 3 m, are mainly composed of gravel, coquinas, sandy coquinas and/or sand, and their degree of preservation varies. Locally beach–ridge sequences are preserved. The fossil content of the Pleistocene marine terraces comprises mainly extant molluscs, of the same species as those presently living in the area. The Neogene molluscan assemblages are quite distinct from the Quaternary assemblages, except for the transition period. In this period we follow Herm (1969) who considered that Concholepas concholepas and Argopecten purpuratus are diagnostic of Pleistocene units (Guzmán et al., 2000). No particular difference was found in the fossil content of the Pleistocene marine terraces, except for one terrace assigned to the MIS 11 (ca. 430 ka). The presence of relatively warm-water species (e.g., Donax peruianus and Trachycardium procerum) suggest at least episodical warm water conditions (Ortlieb, 1995; Ortlieb et al., 1996a, 1997, 2003; Guzmán et al., 2000).

3.2.1. Caldera sequence

The Caldera sequence includes up to 7 terraces, with shoreline angles at elevations between 0/+3 and +200 m asl (Profile A, Fig. 3). (i) The currently formed terrace comprises a sandy beach. Toward the north, this beach is limited by a small scarp, with a shoreline angle at 3 ±1 m asl, that we consider as a possible limit to the terrace. (ii) The second older terrace is internally limited by a scarp with an irregular trace or a beach ridge, at a maximum elevation 25 ±5 m asl. (iii) The terrace at 44 ±5 m asl has a reduced width and is preserved mainly where there is a rocky substrate. Although its scarp is well marked it may be mistaken for the scarp that limits the lower terrace. These geomorphologic features suggest that this terrace was partially eroded by the sea during the formation of the posterior 25 ±5 m asl platform. (iv) The internal limit of the following terrace is marked by a tenuous and eroded scarp whose shoreline angle is at 67 ±7 m asl. (v) The following older platform has an internal limit formed by a conspicuous scarp at a height of 110 ±3 m asl. (vi) The terrace at 162 ±10 m asl has a faunal association including a few warm-water molluscs (D. peruianus and T. procerum). This platform is covered by a moderately preserved beach–ridge sequence whose internal limit appears to be constituted by a large beach ridge and not by a marine scarp. (vii) The oldest terrace with Quaternary fauna, reaches 205 ±10 m asl.

3.2.2. Bahía Inglesa sequence

The Bahía Inglesa sequence includes up to 8 terraces, with respective shoreline angles between 0/+3 and +200 m asl (Profile B, Fig. 3). (i) The terrace currently formed, as in Caldera Bay, is a sandy beach that can extend with a slight increase in slope towards the interior. A scarp found at 3 ±1 m asl, is considered as the internal limit of this terrace. (ii/iii) The following two terraces are limited internally by marine scarps whose bases are estimated at 10 ±5 and 31 ±5 m asl. Both scarps are preserved mainly in the northern part of the bay. (iv) The next older level is limited internally by a small scarp or beach ridge with an irregular trace at 40 ±5 m asl. (v) The following platform, partially covered by a moderately preserved beach–ridge sequence, has an internal limit formed by a conspicuous high scarp at 78 ±7 m asl. (vi/vii) The next two terraces reach 115 ±5 and 139 ±10 m asl. Both are covered by beach–ridge sequences. In the deposits associated with the terrace located at 139 ±10 m asl, a single fossil shell was found of D. peruianus, a warm water species. (viii) The oldest deposits with Quaternary fauna are found at a height of 210 ±20 m.
3.3. Chronostratigraphic interpretation and uplift rates

In order to estimate the age of the Quaternary marine terraces, the following criteria were considered: (a) altimetric position and lateral correlation of each marine terrace; (b) identification of warm water bivalves which permit tentative assignment to MIS 11 (430±30 ka); (c) quantitative results (U/Th and ESR) obtained in areas neighbouring Caldera by Radtke (1987a) and Leonard et al. (1994); and (d) graphic comparison of relative spacing between the terraces of each sequence.

3.3.1. Ages of the Caldera and Bahía Inglesa sequences

The lateral continuity of the marine platforms, or of the scarps that limit them, cannot be established in the field, because of erosion. Morphostratigraphic arguments must thus be used on the base of altimetric criteria and aerial photograph analysis (see segmented lines, Fig. 3).

The terraces with warm-water faunal association, and correlated with MIS 11, are found respectively at 162±10 and 139±10 m asl in Caldera and Bahía Inglesa sequences. We infer that the lower terraces correspond to MIS 9, 7 and 5, respectively.

Leonard et al. (1994) carried out two U/Th radiometric measurements in Morro Copiapó, a close-by locality (Profile B, Fig. 3), in a terrace comparable in height and faunal content to those assigned to MIS 11 (430±30 ka). One of these results (480+/−145 ka) is compatible with our assignment, although the other result (515+/−15 ka) would suggest an older age (MIS 13 or 15).

Radtke (1987a) obtained ages (U/Th and ESR) on shell material from the two lowest terraces of the area. The results are compatible with our assignment of the
marine terraces located at 25±5 and 44±5 m asl in the Caldera Bay sequence, and those located at 10±5, 31±5 and 40±5 m asl in Bahía Inglesa to the MIS 5 high sea stands. The radiometric dating method is not able to discriminate the substages 5a, 5c or 5e.

For the terraces found at 67±7 and 78±7 m asl in Caldera and Bahía Inglesa sequences, respectively, the dates obtained by Radtke (1987a) indicate minimal ages compatible with the penultimate interglacial stage (MIS 7, 210±10 ka).

Based on these data and having carried out a graphic comparison of relative spacing between the terraces of each sequence with the interglacial maxima of the sea-level variation curves, morpho-chronostratigraphic ages are proposed for the terraces. This tentative age assignment is based on the double hypothesis: (1) that within each sequence of terraces the uplift has been homogeneous in space, and (2) that the uplift rates did not vary significantly between any given interglacial and its neighbours.

The Quaternary marine terraces older than MIS 11 could not be dated by any means: their age is comprised between 2 and 0.5 Ma.

3.3.2. Uplift rates of the Caldera and Bahía Inglesa sequences

The following estimated uplift rates are proposed considering correlations of estimated maximum heights of marine terraces for the last 430 ka (Fig. 4, Table 1). For the emerged terraces assigned to the last four Marine Isotopic Stages (MIS 11, 9, 7, 5), average uplift rates of 0.34±0.06 m/ka were obtained, considering paleo sea level elevations (height sea level, HSL, Fig. 4) relative to present mean sea level (Shackleton and Opdyke, 1973; Chappell and Shackleton, 1986; Hanson et al., 1994; Muhs et al., 1994; Gallup et al., 1994). The presently forming marine terrace with a possible scarp foot at 3±1 m asl, is considered as a Holocene terrace. We estimated Holocene uplift rates by considering that the high sea level occurred at 6±2 ka (Gallup et al., 1994; Bezerra et al., 1998).

4. Tectonic deformation and fault-slip analysis

In order to better understand the neotectonic features, a study of the Late Cenozoic tectonic evolution is made. For estimating stresses we analysed the strike and sense of slip from fault planes that cut Neogene and Quaternary marine and continental deposits. Later, seismic data are displayed to characterize the seismicity of this region and to propose a tectonic model of deformation.

4.1. Methods for estimating stresses

The determination of the state of stress is based on microstructural analysis of the fault rake. This analysis assumes that slip vectors on each fault plane are parallel and in the same sense as the shear stress. It further considers that deformation is small and occurs as relative displacements of rigid blocks (Anderson, 1951; Wallace, 1951; Bott, 1959). Additionally, it is assumed that a tectonic event is characterized by a unique tensor of homogeneous stress at the outcrop scale (Carey and Mercier, 1987; Angelier, 1994).

Several populations of striated fault planes are analysed by means of the numeric inversion algorithm proposed by Etchecopar et al. (1981). This method

<table>
<thead>
<tr>
<th>Marine number</th>
<th>Isotopic Stages (MIS)</th>
<th>Caldera max. height (m)</th>
<th>Bahía Inglesa max. height (m)</th>
<th>Estimated uplift rates (m/ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>age (ka)</td>
<td>SLH (m)</td>
<td></td>
<td>Caldera</td>
</tr>
<tr>
<td>11</td>
<td>430±30</td>
<td>0±10</td>
<td>162±10</td>
<td>0.38±0.04</td>
</tr>
<tr>
<td>9</td>
<td>330±10</td>
<td>4±4</td>
<td>110±3</td>
<td>0.32±0.02</td>
</tr>
<tr>
<td>7</td>
<td>210±10</td>
<td>3±4</td>
<td>67±7</td>
<td>0.33±0.04</td>
</tr>
<tr>
<td>5c</td>
<td>125±5</td>
<td>5±3</td>
<td>44±5</td>
<td>0.31±0.05</td>
</tr>
<tr>
<td>5c</td>
<td>100.5±5</td>
<td>–14.5±2.5</td>
<td>25±5</td>
<td>0.39±0.06</td>
</tr>
<tr>
<td>5a</td>
<td>83.3±3</td>
<td>–15.5±5</td>
<td>–</td>
<td>0.31±0.07</td>
</tr>
<tr>
<td>1</td>
<td>6±2</td>
<td>1±1</td>
<td>3±1</td>
<td>0.33±0.26</td>
</tr>
</tbody>
</table>

SLH: former sea-level height. See text for further details.
allows calculation of four of the six parameters which define the stress tensor: the orientation of the three principal axes ($r_1, r_2, r_3$) and the stress ellipsoid shape ratio $R=(\sigma_2-\sigma_3)/\sigma_1$, with $0 \leq R \leq 1$. The reliability of the results, as well as its improvement, are defined with respect to: (a) the number and distribution of fault planes in space, (b) the histogram of angular differences between calculated and measured striations, and (c) the localisation of the fault-plane poles in a Mohr circle (Etchecopar and Mattauer, 1988; Ritz and Taboada, 1993).

The populations of faults in which slip-vector could not be measured or the inversion method analysis could not be used are analysed by the right dihedra method (Angelier and Mechler, 1977; Angelier, 1994). This graphical method permits calculation of the potential orientations of the principal stress axes from one or several faults. The results and stereo-plots are obtained from the computer program FaultKin (Marrett and Allmendinger, 1990; Allmendinger et al., 1990).

4.2. Neogene and Quaternary deformation and stresses

Neogene deposits registered extensional and compressional tectonic events. Evidence of extension was observed in Quebrada Blanca, Puerto Viejo, Estación Monte Amargo and Quebrada Tiburón (Fig. 1), where normal faults of varied orientations, with centimetric to metric scale displacements are present. Evidence of compression was observed in the area of Morro Copiapó, where high-angle reverse NW–SE to NE–SW striking faults dip towards the west, and metric displacements along the fault plane are observed. These faults, probably related to the reactivation of basement structures with similar orientations, are sealed off by Quaternary deposits assigned to the last half million years. They cut only the continental and marine Neogene deposits.

Quaternary sediments showing brittle deformation are restricted to Caldera and Bahía Inglesa, where deformation is characterized by normal faults of varied orientations and centimetric to metric displacements (Fig. 3). These faults cut the Quaternary marine terraces generating well-defined fault scarps. These scarps can be mistaken for paleo shorelines (beach ridges or marine cliffs). Therefore, analysis of aerial photos and satellite images is fundamental in differentiating features caused by marine erosion from those caused by tectonic deformation. Old shorelines generally form sequences sub-parallel to the current coastline. In contrast to the altitude of the shoreline angle of marine scarps that generally remain the same, the altitude of the base of the fault scarps can vary considerably along their trace. Analysis of aerial photos and satellite images confirms that the Quaternary faults do not displace laterally morphological features such as beach ridges. Therefore, in cases of non-striated fault planes, assuming extensional faults with dip-slip is an approach that allows us to consider the “theoretical” direction of the main stress axes and apply microstructural analysis. Some Quaternary faults are located in zones of regional scale lineaments or are subparallel to them. Thus, the Quaternary faults may be related to the reactivation of pre-Quaternary basement structures.

4.2.1. Extensional deformation in Neogene deposits.

At Quebrada Blanca, east of Caldera, a set of small displacement normal faults cuts diatomites from the Bahía Inglesa Formation assigned, in this locality, to the Upper Miocene–Lower Pliocene (Tsuchi, 1992). These faults form a sub-parallel structural arrangement associated with diatomite breccias (Herm, 1969; Marquardt, 1999). These structures are presumably associated with the creation of fracturing and debris flows, similar to those processes described by Grimm and Orange (1997) in California, and related to the gravitational instability of these deposits. These high angles, NNE–SSW striking structures show centimetric scale displacements of up to 10 cm and are devoid of striations or other type of strike-slip component evidence. The few measurements available for these assumed dip-slip faults are compatible with a NW–SE extension (Fig. 5A, Table 2).

Along the cliff of Puerto Viejo, a set of normal faults cuts the Bahía Inglesa Formation deposits assigned, in this locality, to the Late Miocene–Pliocene (Marchant, 2000). Movements along these normal fault planes are of a decimetric scale order (up to 60 cm), and are marked by the displacement of well-cemented thick sandy layers, partly bioclastic, of subhorizontal attitude (Plate 1). These high angle NW–SE faults, without striations or evidence for strike-slip component, form a graben-type structural
arrangement and they are compatible with a NE–SW oriented extension (Fig. 5B, Table 2).

In the north side of the Copiapó River Valley, near Estación Monte Amargo, high angle normal faults cut subhorizontal deposits of gravel, sand and silt (Plate 1(B)). These deposits overlie an ash layer dated by the K/Ar method (biotite) at 6.4 ± 1 Ma (Godoy et al., 2003). This fault population can be separated in two conjugate sets, one oriented NW–SE with NE dip and the other striking NE–SW with SE to NW dip. Movements along these dip-slip faults are of a decimetric magnitude scale and generally without striations or strike-slip component evidence; they are compatible with an ENE–WSW to radial extension regime (extension in all directions of the horizontal plane) (Fig. 5C, Table 2).

At Quebrada Tiburón a set of high angle, N–S striking, normal faults displace deposits assigned to the Middle Miocene–Pliocene (Marchant, 2000). They are striated along dip of the fault planes, and they show decimetric to 1.5 m displacements (Plate 1(C)) and gypsum-filled tension cracks, sub-parallel to the fault planes. On the edges of some of these cracks striations were measured and their kinematics have been related to the normal fault plane set (Fig. 6A). The stress tensor calculated from the measured striated fault planes and cracks indicates an E–W to radial extensional regime, with $R=0.01$ (Fig. 6B).

4.2.2. Compressional deformation in Neogene deposits.

The southeast and northeast boundaries of the Morro Copiapó are characterized by two main reverse faults, striking NNE–SSW and NNW–SSE, that thrust Mesozoic plutonic rocks over the Neogene deposits of the Bahía Inglesa Formation (Fig. 7). They do not cut stratigraphic markers and thus the offset is difficult to measure. However, a minimal accumulated displacement of 15 m may be estimated considering the thickness of the deformed deposits in the southern part of the Morro. In this last locality a progressive unconformity in the Bahía Inglesa Formation is observed. Its footwall layers show a sedimentary wedge with rotative offlap (Plate 1(D)). Striated planes along the NNE–SSW main trace fault were measured in the central part of the Morro Copiapó. The obtained stress tensor defines an E–W compressional regime ($\sigma_1$: N269°E/49°; $\sigma_2$: N168°E/09°) with $R=0.28$ (Fig. 8), therefore inclined, with a grate uncertain, towards a uniaxial compression. This stress tensor load tilted around $\sigma_2$ towards the east can be explained by a low distribution of fault planes and by the localisation of some pole of planes near the Mohr circle ($\sigma_2$, $\alpha_3$), where the rotation of the principal axes compensates the sensibility of these plane rakes (slip direction) to the variation of $R$. In the southern part of the Morro Copiapó, the main fault trace appears in a small quarry. No stress tensor could be obtained.

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Fig. 5. The stereogram (Wulff net, lower hemisphere) illustrates the attitude of normal faults and their hypothetical slip vector data. Arrow attached to fault shows hanging wall movement. These faults deforming Neogene deposits in (A) Quebrada Blanca, (B) Puerto Viejo and (C) Estación Monte Amargo. Sites are located on Fig. 1. Divergent large arrows give azimuths of the minimum principal stress $\sigma_3$, obtained by the right dihedra method.
numerically by inversion of striated fault planes, nevertheless, a NW–SE principal compressional stress direction could be estimated from the right dihedra method (Fig. 9). Throughout most of the north eastern part of Morro Copiapó, the fold axis (N60° to 30°E) of the deformed layers of the Bahía Inglesa Formation (Fig. 7) is compatible with a N135°E to N89°E shortening direction (Figs. 8 and 9).

In Playa Chorrillos, south of Morro Copiapó, and in the east of the main fault, an ENE–WSW system of minor reverse faults of up to 4 m of offset is related to fault-propagation folds. They are found only at the base of the Bahía Inglesa Formation and are sealed off by the upper layers of this formation.

In the Las Tinajas area, in the south of the Morro Copiapó, a reverse fault cuts and folds deposits assigned to the Late Miocene (Plate 1(E)) (Marchant, 2000). This fault trends N–S, with an offset of up to 2.20 m, and is in accordance with an ENE–WSW to E–W compressional regime (Fig. 10).

In the southern vicinities of the Morro Copiapó, in the opening of the Quebrada La Higuera, layers of the Bahía Inglesa Formation are smoothly deformed constituting a wide monocline gently inclined to the ENE. East to ENE vergence slump structures are recognised in clay sediments located to the east of this flexure. They are probably associated with the compressional event that uplifted Morro Copiapó.

4.2.3. Extensional deformation in Quaternary deposits

Between Caldera and Bahía Inglesa (Fig. 3), a set of fault scarps up to 2 m in height and trending N20°E to N50°E, vertically cuts the old Quaternary coastlines. These faults, without lateral displacement, limit the NE–SW trending Caldera Graben. The foot of these scarps, characterized by the development of sag ponds, now dry, vary in altitude from the current sea level up to a maximum of 45 m asl. The normal faults that limit this graben towards the east form westward facing scarp surfaces. To the north of Bahía Inglesa, in a quarry located along the trace of one of these faults and at 9 m asl, a set of ENE–WSW roughly trending, 65°N dipping normal faults cut unconsolidated Quaternary deposits (Fig. 11A). The main fault (mF) offsets by 2 m the base of Quaternary deposits associated with the terrace assigned to MIS 5. The synthetic fault (sF), located in the footwall of the mF, displaces the base of the Neogene deposits by up to 1 m. The antithetic fault (aF), located in the hanging-wall of the mF, forms a wedge which displaces coastal layers assigned to MIS 5 up to 25 cm. A thin non-deformed alluvial layer seals these faulted deposits.

Towards the northeast, at an altitude of 13 m asl, the trace of this fault scarp was cut by a trench. Here, normal faults with a N75°E/88°N attitude and without striations displace at least 50 cm of deposits associated with the marine terrace assigned to MIS 5 (Fig. 11B). The normal faults that limit the Caldera Graben towards the west form east facing scarps (Fig. 3) that juxtapose Mesozoic plutons and Quaternary deposits (Fig. 11 C). To the west of Caldera, in two quarries located at 9 and 30 m asl and along the trace of this fault scarp, there is a set of normal faults with a N75°E/88°N attitude and without striations displace at least 50 cm of deposits associated with the marine terrace assigned to MIS 5 (Fig. 11B). The normal faults that limit the Caldera Graben towards the west form east facing scarps (Fig. 3) that juxtapose Mesozoic plutons and Quaternary deposits (Fig. 11 C). To the west of Caldera, in two quarries located at 9 and 30 m asl and along the trace of this fault scarp, there is a set of normal faults with a N75°E/88°N attitude and without striations displace at least 50 cm of deposits associated with the marine terrace assigned to MIS 5 (Fig. 11B).

The obtained stress tensor defines a NW–SE extensional regime ($\sigma_3$: N150°E/22°; $\sigma_2$: N060°E/01°) with $R=0.67$ (Fig. 12), therefore inclined towards an uniaxial extension.

In another trench, located at 40 m asl and 10 m eastward of the scarp which limits the Caldera Graben towards the east, a set of unstriated normal faults cut coastal deposits assigned to MIS 7 (Fig. 11D). The obtained stress tensor defines a NE–SW extensional regime ($\sigma_3$: N080°E/22°; $\sigma_2$: N310°E/01°) with $R=0.67$ (Fig. 12), therefore inclined towards an uniaxial extension.

<table>
<thead>
<tr>
<th>Site</th>
<th>Age of deformed unit</th>
<th>$n$</th>
<th>$\sigma_1$ Azimuth</th>
<th>$\sigma_1$ Dip</th>
<th>$\sigma_2$ Azimuth</th>
<th>$\sigma_2$ Dip</th>
<th>$\sigma_3$ Azimuth</th>
<th>$\sigma_3$ Dip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quebrada Blanca</td>
<td>Upper Miocene–Lower Pliocene</td>
<td>5</td>
<td>120°</td>
<td>67°</td>
<td>212°</td>
<td>01°</td>
<td>303°</td>
<td>23°</td>
</tr>
<tr>
<td>Puerto Viejo</td>
<td>Late Miocene–Pliocene</td>
<td>4</td>
<td>257°</td>
<td>68°</td>
<td>144°</td>
<td>09°</td>
<td>051°</td>
<td>20°</td>
</tr>
<tr>
<td>Monte Amargo</td>
<td>&lt;6.4 ± 1 Ma</td>
<td>11</td>
<td>246°</td>
<td>69°</td>
<td>156°</td>
<td>00°</td>
<td>066°</td>
<td>21°</td>
</tr>
</tbody>
</table>
These high-angle NE–SW faults have centimeter scale offsets. Some of the faults are synthetic normal faults while others are reverse antithetic and seem to readjust the faulted blocks, always compatible with a NW–SE extensional direction. No morphological features associated with these structures are generated at the surface, but a west facing buried fault scarp is preserved.

To the southeast of Bahía Inglesa a NNE–SSW fault scarp cuts the marine erosion scarp located 30 m asl and assigned to MIS 5 (Fig. 3). Its trace is formed by a system of normal subvertical faults, with centimeter to metric scale displacements (up to 4 m), which reach the surface and constitute structural features of graben- and horst-types (Fig. 13A). The dip of the main scarp face varies in direction, west in the northern sector and east in the southern sector, in a scissors effect. The general NNE attitude of the faults suggests a NW–SE direction of extension (Fig. 13B).

In Alto del Fraile, to the SE of Bahía Inglesa, there is a series of scarps that cut beach ridges assigned to
MIS 9, making it difficult to confirm whether the marine deposits of the MIS 7 are affected (Fig. 3). These scarps have three main directions, NE–SW, NW–SE and ENE–WSW, and although no fault planes are observed, they are considered to be of tectonic origin. Plate 1 (F) shows one of these scarps which could correspond to a vertical displacement of up to 4 m.

In the Estación Monte Amargo area, in the southern bank of the Copiapó River Valley, Segerstrom (1964, 1965a,b), Mortimer (1969) and Paskoff (1979a) interpreted the large N–S to NNE–SSW trending eastward facing scarp, as a Quaternary fault. We interpret this geomorphic marker as the result of a complex system of fluvial and alluvial scarps developed from Pliocene wave-cut platforms (Agua Amarga Strata), which appear at 280 m asl (Fig. 14).

4.3. Seismicity

Historic and locally recorded seismicity of the subduction margin of Caldera area was analysed by Comte et al. (2002). The zone has a very high interplate seismic activity with at least eight events with magnitude $M_s \geq 7.5$ during the last 200 years. Two events with magnitudes $M_s \geq 8.0$ are reported, the 1819 ($M_s = 8.3$) and the 1922 ($M_s = 8.5$) great earthquakes with associated tsunamis (Beck et al., 1997). Nevertheless, no significant historical crustal seismicity is associated with the fore arc at this latitude. The most superficial seismic activity registered corresponds to mining activity and there is no evidence of events that can be correlated with the trace of known active faults (Fig. 15).

Locally recorded data show a well defined Wadati–Benioff zone, in which the downgoing slab penetrates the mantle at a dip of 22° to the east, to depths of 130–150 km and at distances of about 320 km from the trench (Comte et al., 2002).

Along the interplate zone, at depths less than 70 km, the obtained stress tensor indicates a compressive regime (Comte et al., 2002; Pardo et al., 2002). The orientation of $\sigma_1$ is parallel to the convergence direction and dipping to the east about 23°, and $\sigma_3$...
is oriented N244°E with dip of 58°. Events located above the main decollement are in normal stress regime with $\sigma_3$ horizontally oriented parallel to the convergence direction. In addition, high-resolution bathymetric data and seismicity located above the thrust contact in front of Caldera suggest that seamounts are being subducted.

5. Tectonic interpretation and discussion

In the present work, we found differences in deformation style and magnitude during the Late Cenozoic in this part of the Southern Central Andes fore arc. Based on these differences and microstructural analysis, two Neogene–Early Pleistocene and Late Quaternary tectonic events were recognised.

Ten microstructural stations were analysed. In general, the studied fault populations are in the limit of application of the stress tensor calculation methods and only in three of these stations we could calculate the stress tensor. In the other stations, however, the estimated orientations of the principal stress axes are coherent for each one of the defined tectonic regimes.

**Fig. 7.** Structural map of the Morro Copiapó area, showing location of fault sites analyzed in this paper.
5.1. Neogene–Early Pleistocene events

Neogene deposits display a weak but well distributed extensional deformation and another, more important but local, compressional deformation. These events are approximately constrained in time between the Late Miocene to Early Pleistocene (Fig. 16). Nevertheless, at present, stratigraphic and tectonic data of the area are insufficient to specify their relation and timing.

5.1.1. Extensional deformation

The extensional deformation developed in the Neogene deposits is characterized by a reduced number of cracks and normal faults with centimetric scale displacements (<1.5 m). This weak deformation is distributed throughout most of the studied area. In some cases, such as Quebrada Blanca, the deposits are syntectonic and their instability was probably triggered by the seismic activity or by the sedimentary load. In other cases, dip-slip faults are compatible with an E–W to NE–SW extensional direction or with radial extensional regime. In this last case, as in Quebrada Tiburón where the stress ellipsoid shape ratio \( R \) is close to cero, contemporary uplift is a plausible mechanism to explain this kind of extension.

In the Mejillones Peninsula (23°S) a similar Neogene E–W extensional deformation was documented (Niemeyer et al., 1996; Hartley et al., 2000), followed by a weak E–W compressional probably Pliocene event (Marquardt et al., 2000b).

South of the study area, at Talinay (30–31°S), Navidad (34°S) and Arauco Peninsula (37–38°S), a similar Neogene E–W extensional deformation was documented (Paskoff, 1970; Lavenu and Cembrano, 1999).

In spite of the large coastal area in which this extension is recognized, its relation with the mechanisms of subduction is not well understood. Usually, it is associated with local gravitational instability and synsedimentary events, as earthquake shocks or sediment load readjustment. Studies along the AFS, inland between 24°S and 27°S, show an uplift of the Coastal Cordillera in relation to the Central Depression from tens to hundreds of meters during the Neogene (Hervé, 1987; Riquelme et al., 2003). This differential uplift, controlled by the activity of the AFS, is compatible with an E–W extensional deformation. Therefore, it seems reasonable to link part of the extensional deformation, which affects Neogene deposits throughout the coast, with regional subduction mechanisms.

5.1.2. Compressional deformation

Unlike the extensional deformation, compressional deformation of Neogene deposits is of greater

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**Fig. 8.** The stereogram (Wulff net, lower hemisphere) illustrates the attitude of reverse faults and their slip vector data. Arrow attached to fault shows the movement of the hanging wall block. These faults deformation Neogene deposits in Morro Copiapó central site, located on Fig. 7. Convergent large arrows give azimuths of the maximum principal stress \( \sigma_1 \), obtained by two methods: (A) right dihedra (black arrows) and (B) numeric inversion algorithm (grey arrows). The histogram and Mohr circle are satisfactory for all planes, validating the stress tensor solution obtained. Symbols as in Fig. 6.
A) Right diedra method, n=9
Principal stress axes
\( \sigma_1 \) Dir. 315 Dip 07
\( \sigma_2 \) Dir. 049 Dip 31
\( \sigma_3 \) Dir. 213 Dip 59

B) Etchecopar method

B.1) First iteration (n=9), partial result
Stress Tensor ± Error
\( \sigma_1 \) Dir.±Err. 348 ± 27 Dip ± Err. 18 ± 23
\( \sigma_2 \) Dir.±Err. 089 ± 40 Dip ± Err. 31 ± 07
\( \sigma_3 \) Dir.±Err. 232 ± 10 Dip ± Err. 53 ± 10
R±Err. = 0.79 ± 0.20

B.2) Second iteration (n=8), partial result
Stress Tensor ± Error
\( \sigma_1 \) Dir.±Err. 355 ± 11 Dip ± Err. 26 ± 14
\( \sigma_2 \) Dir.±Err. 105 ± 23 Dip ± Err. 35 ± 05
\( \sigma_3 \) Dir.±Err. 238 ± 07 Dip ± Err. 44 ± 12
R±Err. = 0.69 ± 0.16

B.3) Third iteration (n=5), partial result
Stress Tensor ± Error
\( \sigma_1 \) Dir.±Err. 034 ± 77 Dip ± Err. 29 ± 26
\( \sigma_2 \) Dir.±Err. 140 ± 73 Dip ± Err. 26 ± 28
\( \sigma_3 \) Dir.±Err. 264 ± 30 Dip ± Err. 49 ± 06
R±Err. = 0.95 ± 0.15

Fig. 9. Reverse faults deforming Neogene deposits in Morro Copiapó southern site. Symbols as in Fig. 8. Site is located on Fig. 7. (A) Convergent large arrows give azimuths of the maximum principal stress \( \sigma_1 \), obtained by the right dihedra method. (B) The stress tensors partially obtained in three iterations by numeric inversion algorithm method are shown. White circles represent fault-plane poles that are not satisfactory for the Mohr circle solution. They are localised in the area of sensitivity of \( R \) and therefore they are eliminated of the following iteration. Finally, the number of fault planes and Mohr circle representation are not satisfactory for calculate the stress tensor.

Right diedra method, n=6
Principal stress axes
\( \sigma_1 \) Dir. 081 Dip 20
\( \sigma_2 \) Dir. 350 Dip 03
\( \sigma_3 \) Dir. 251 Dip 70

Fig. 10. The stereogram (Wulff net, lower hemisphere) illustrates the attitude of reverse faults and their slip vector data. Arrow attached to fault shows the movement of the hanging wall. These faults deforming Neogene deposits in Las Tinajas (Fig. 7). Convergent large arrows give azimuth of the maximum principal stress \( \sigma_1 \), obtained by the right dihedra method.
Fig. 11. Trench exposure showing displacement of Quaternary layers of sand (shades of gray) with gravels and mollusc fossils, buried fault scarps, and surface fault scarps associated with the faults that limited the Caldera Graben (Fig. 3). (A) Quarry exposed in the fault that limit this graben toward the east in Bahía Inglesa, near 9 m asl, with evidence of up to two fault movements during the last 125 ka. (B) Trench in the almost fault, near 13 m asl, with evidence of one fault movement during the last 125 ka. (C) Trench exposed in the fault that limit this graben toward the west in western Caldera, near 40 m asl, with evidence of up to two fault movements during the last 125 ka. (D) Trench exposed 10 m eastward of the fault that limit this graben toward the east in eastern Caldera, near 30 m asl, with evidence of one faulting event during the last 210 ka with two buried fault scarps. See text for further details.
magnitude and is concentrated in the vicinities of the Morro Copiapó. The development of reverse faults and folds, compatible with an E–W to NW–SE trending compression, characterizes this deformation. Those structures are generally synsedimentary during the deposition of the Pliocene upper section of the Bahía Inglesa Formation. There are no age estimates for the Neogene deposits first involved in the deformation. Nevertheless, this deformation does not affect Quaternary deposits assigned to MIS 11 (430 ka).

Same minor E–W compressional deformation has been found in the Mejillones Peninsula, where it was assigned to the Pliocene (Marquardt et al., 2000b). In the southern Peruvian fore arc and Bolivian High Andes, during uppermost Pliocene–lower Pleistocene time (3–2 Ma), an E–W compressional tectonics affected this region (Lavenu and Mercier, 1991; Mercier et al., 1992; Noblet et al., 1996).

During the Pliocene, in the fore arc zone of the Andes of Southern Chile, between 33°S and 34°S, a similar E–W compressional tectonic event occurred (Lavenu and Cembrano, 1999). This compression is linked to an apparently rapid convergence regime and important subduction coupling.

5.2. *Quaternary tectonics*

In the studied area, the Quaternary deposits display, during at least the last half-million years,
Fig. 13. (A) NNW–ESE schematic sections from north (above) to south (below) of a scissor fault displacing Quaternary deposits in Bahía Inglesa (Fig. 3). The lateral evolution of the fault scarps and its occasional coincidence with the marine scarps are also shown. (B) The stereogram (Wulff net, lower hemisphere) illustrates the attitude of these normal faults and their slip vector data.

Fig. 14. Geological map and section of the Estación Monte Amargo area, where Segerstrom (1965a,b) and Mortimer (1969) have proposed a Quaternary fault.
regional coastal uplift and localized extensional deformations.

5.2.1. Coastal uplift rates

In order to quantify vertical motions along coastal regions the emerged Pleistocene marine terraces must be dated and correlated with interglacial high seastands. The geochronological methods (U/Th and ESR) used in Caldera area by Radtke (1987a) and Leonard et al. (1994) give results that are consistent with our morphostratigraphic and paleontological analyses. No general consensus has been reached on the original global sea-level position at the time the terraces were formed (e.g., Hanson et al., 1994; Gallup et al., 1994; Zazo, 1999; Rostami et al., 2000).

The morpho-chronostratigraphic study of the marine terrace remnants in Caldera (27°S) suggests a relatively continuous uplift motion during the last 430 ka, with a mean value of 0.34±0.06 m/ka. Uplifted marine terraces located south of the study area, along 100 km to 28°S (Fig. 16), suggest minimum and maximum uplift rates of 0.23 and 0.39 m/ka, respectively, with an average of 0.31 m/ka for the same period. The lateral and/or temporal variation of the uplift rate is probably due to local faulting, as observed in the Caldera area. Available data on the number and position of more than 430-ka-old Pleistocene terraces (at 200 m high) suggests that the region has not been uplifted at the same rate during the whole Quaternary, a much slower uplift occurred during the Pleistocene, before the 1 Ma.

Along the coast of southern Peru, Pleistocene marine terraces are seldom higher than 200 m and regional uplift rates are of the order of 0.15–0.10 m/ka for the entire Quaternary (Ortlieb et al., 1996b). Where local tectonic activity is present, uplift rates of up to 0.3–0.46 m/ka were determined (Goy et al.,

Fig. 15. Epicentral distribution of the most superficial microseismicity determined using a temporary on- and off-shore network in Caldera (Comte et al., 2002). The colour of each circle is related to the different depth interval.
The highest uplift rates calculated in central southern Peru, of the order of 0.7 m/ka during the last million years, are directly associated with subduction of the aseismic Nazca Ridge (Macharé and Ortlieb, 1992). In the Chilean Hornitos area (23°S), uplift was continuous during at least the last 330 ka, with a mean value of 0.24 m/ka and small lateral variations due to local tilting (Ortlieb et al., 1996c). This uplift rate may be representative of the coastal sector extending to the north for more than 100 km, and probably 300 km (20°S). North of 20°S and above the Peruvian border (18°S) the Great Coastal Escarpment plunges directly into the sea (Paskoff, 1979b, 1989), so that no marine terraces are preserved and we lack evidence for any vertical motion.

In the eastern part of the Mejillones Peninsula (23°–23°30’S), an uplift of 0.15 m/ka was estimated at least during the last 330 ka (Ortlieb, 1995). It seems to increase northward and reach the uplift rate considered in the Hornitos area (Ortlieb et al., 1996a, 1996c). The western Pleistocene marine terrace sequences, abraded in the peninsula, suggest double uplift rates, with the same increase in uplift towards the northern part. These different uplift rates are linked to the presence of N–S normal faults (Armijo and Thiele, 1990; Hartley and Jolley, 1995; Delouis et al., 1998; Marquardt et al., 2002).

South of the Mejillones Peninsula, in the Antofagasta area (23°30’–24°S), the inferred mean uplift rate during the late Quaternary is of the order of 0.1 m/ka (Ortlieb, 1995). Between 24°S and 26°S, the Great

Fig. 16. Summary of tectonic settings along the coasts between 27°S and 28°S latitude. (A) Chronology and orientation of the compressional and extensional axis. (B) Microtectonic sites and localities where marine terrace sequences were logged. (C) Variation of elevation and correlation of the Quaternary marine terraces. Grey pattern: certain correlation (modified from Marquardt, 1999).
Coastal Escarpment plunges directly into the sea; no marine terraces are preserved along this coastal sector (Paskoff, 1979b, 1989). Between 26°S and the Caldera area (27°S), a narrow coastal plain develops at the foot of the escarpment and exhibits remnants of Pleistocene marine terraces (Mortimer, 1969, 1973; Mercado, 1978; Godoy and Lara, 1998, 1999). Probably the uplift rates determined for the Caldera area (27–28°S), should be representative for the coastal sector extending to the north, diminishing progressively until 26°S.

Along the coast of the La Serena–Talinay area (29°45′–31°S), Pleistocene marine terraces are seldom observed above 200 m and regional uplift rates are of the order of 0.1–0.2 m/ka for the Late Quaternary (Leonard and Wehmiller, 1992; Ota et al., 1995; Paskoff, 1995; Benado, 2000). Preliminary results from detailed mapping and lateral correlations between 28°S and 29°S show a narrow coastal plain that exhibits remnants of Pleistocene marine terraces up to 130 m elevation. In this area, the uplift rates are probably similar to those estimated in the Caldera area, although a reduction of the rates would be expected towards the La Serena–Talinay area.

The coastal areas of southern Peru and northern Chile were thus uplifted at rates varying between 0.4 m/ka and approximately zero. The variation of these vertical movements is thought to be relatively independent of the variation of some of the subduction parameters, as direction of convergence, convergence obliquity and age of the subducted plate (Macharé and Ortlieb, 1992).

The relationship between these Quaternary vertical movements and subduction induced seismic activity is now being studied. The effect of the coseismic phase on surface deformation was studied in the large $M_w$=8.1 Antofagasta subduction earthquake of 1995 (e.g., Ruegg et al., 1996; Delouis et al., 1997; Klotz et al., 1999; Debra et al., 1999). This earthquake showed that large subduction earthquakes produce vertical movement (uplift and subsidence) and extension in the coastal region. The co-seismic uplift motions are concentrated offshore, mainly some westernmost coastal localities (Ortlieb et al., 1996d; Pritchard et al., 2002).

Delouis et al. (1998) proposed a regional flexure of the outer fore arc that may be controlled by offshore subsidence caused by subduction erosion near the trench and by onshore uplift related to the under-plating of eroded low-density material beneath the Coastal Cordillera (Adam and Reuther, 2000).

5.2.2. Extensional deformation

The extensional deformation recorded in the Quaternary marine terraces is characterized by the development of high angle normal faults and associated scarps that evidence up to 4 m of dip-slip displacements. Considering the chronology of the marine terraces, three events of deformation are proposed. A first event, evidenced by the fault scarps developed in Alto del Fraile area, is bracketed between 330 and 210 ka. The direction of extension for this event is undeterminate. A second event would have happened between 210 and 125 ka and its related structures are moderately preserved in the vicinities of Caldera. Those dip-slip faults are compatible with a NW–SE extensional regime. A last event of deformation, reflecting a NW–SE extensional regime, which happened during the last 125 ka formed the Caldera Graben and the scissors type fault of Bahía Inglesa.

In northern Chile, Pliocene to Quaternary fault scarps has been recognized throughout the Coastal Plain and Coastal Cordillera between Taltal (25°S) and Salar Grande (21°S) (e.g., Arabasz, 1971; Okada, 1971). Nevertheless, it is in the Antofagasta zone (23–24°S) where a great number of studies have been made with the purpose of determining the age and kinematics of structures, and the deformation mechanisms (e.g., Naranjo, 1987; Armijo and Thiele, 1990; Hartley and Jolley, 1995; Niemeyer et al., 1996; Delouis et al., 1998). In this coastal area, the neotectonic data indicate that N–S trending faults are reactivated during the Quaternary under E–W extensional regime. This subduction extensional regime would correspond to an episodic process linked to the seismic cycle in the subduction zone. In effect, large subduction earthquakes could produce co-seismic E–W trending extension related to horizontal and vertical displacements of the coastal area and in the coastal area, the extension is reduced by interseismic contraction (Delouis et al., 1998). Nevertheless, this trench perpendicular near surface extension by normal faults has also been interpreted as extensional collapse of the slightly overcritical outer fore arc wedge (Adam and Reuther, 2000).
Therefore, they are two possible mechanisms to explain the Quaternary extension in the Caldera area, considering that it is located in a subducted plate without lateral constraints and where deformation is controlled by the subduction seismic cycle:

(1) **Co-seismic extension**, reduced by inter-seismic contraction due to the convergence. As in the case of Antofagasta, the occurrence of strong earthquakes \(M_w \geq 8.0\) could trigger formation or reactivation of faults (Delouis et al., 1998). According to the position and propagation of the earthquake, throughout the zone of subduction, the extension may be bounded within the coastal area (until the uplifting zones). The evidence of Quaternary faults in the Caldera area could demonstrate the nucleation of great earthquakes in this zone. This nucleation may be related to the subduction of seamounts observed offshore of this area (Comte et al., 2002).

(2) **Inter-seismic extension** directly linked to compressive boundary forces due to the convergence in the period separate two-subduction earthquakes. The Quaternary faults, compatible with a convergence direction subperpendicular to extension, could correspond to active arc-transverse normal faulting (e.g., Feuillet et al., 2001). This deformation must produce superficial crustal seismicity.

As many Quaternary normal faults having a different orientation of ENE–WSW trending, therefore extension perpendicular to the convergence does not be strongly supported. Nevertheless, in this zone and generally in the north of Chile, shallow seismicity has not been registered in the outer fore arc (Comte et al., 2002). As shown for the 1995 Antofagasta earthquake, co-seismic extension is expected to be subparallel to the convergence direction, which is not the main direction of extension finding (Figs. 12 and 13). Combinations of factors are contributing to the extensional stress regime and those factors should account for the tendency of the normal fault analysis towards radial extension. Therefore, we consider that Quaternary brittle deformation appears to be directly linked to co-seismic extension and uplift.

6. Conclusions

Moderate to high vertical uplift rate \((0.34 \pm 0.06 \text{ m/ka})\) and NW–SE extension characterize the Quaternary tectonics of the outer fore arc in the Caldera area. This latter tectonic behaviour occurred at least since Middle Pleistocene times. Large-scale Late Miocene to Pliocene deformation is characterized by a weak NE–SW to E–W extension and NW–SE to E–W compression. These last events are probably uppermost Pliocene in age. During the Neogene evidence of positive vertical movements is indirect and may be reflected in local radial extensional and compressional features.

This Neogene-to-Quaternary deformation pattern provides clear indications of the occurrence of moderate to large interplate or intraplate earthquakes. We propose that deformation in the outer fore arc is linked to the subduction seismic cycle. Compressional brittle deformation during the Upper Pliocene could have been produced during a more rapid convergence rate and subduction coupling than those from the Quaternary. In this case shallow crustal seismicity would be developed (interplate earthquakes, related to reverse faults). Neogene to Quaternary extensional brittle deformation and Quaternary uplift could be linked to large subduction earthquakes. Coastal co-seismic uplift and E–W extension should be produced after interseismic contraction periods, characterized by the absence of shallow crustal seismicity.

Acknowledgements

We thank B. Delouis, G. Gonzalez and Mr. Mather for their critical reviews of the manuscript. This research was supported by the Servicio Nacional de Geología y Minería-Chile, as part of its Geological Mapping of the Atacama Fault System and Coastal Belt between 26° and 28°S Project. It was also supported by Institut de Recherche pour le Développement (IRD) UR 154 (France) and by FONDECYT project # 1981145.

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