Contemporary recent extension and compression in the Central Andes

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Abstract

Although extension in the high Andes vs. compression in the lowlands has already been widely discussed in the literature, for the first time we recognized both extensional and contractional structures that developed contemporaneously during late Pliocene-Quaternary times in a wide area of the central Andean chain (about 90,000 km^2), where crustal earthquake data are missing. This area comprises north-eastern Chile, south-western Bolivia and north-western Argentina, and extends from the Puna Plateau to the Altiplano-volcanic belt. Late Pliocene-Quaternary folds, with hinge lines trending NNE-SSW to N-S, are mostly located along the westernmost part of the volcanic belt and the eastern part of the Western Cordillera. Locally, there are coeval reverse faults, parallel to the folds, which reach up to the surface; particularly, the Miscanti Ridge, Tolocha Fault and La Casualidad Ridge may be the morphostructural expression of tens-km-long fault-propagation folds, which locally show topographic scarps hundreds of meters high. North and east of the contractional structures, we found evidence of late Pliocene-Quaternary normal faults striking N-S in the southern part of the study area, and NW-SE in the northern part. Well-developed grabens are present in the higher areas of the volcanic belt and in the transition zone with the Puna Plateau. The surface rupture zones of normal fault swarms range 8 to 24 km in length, with single fault strands up to 18 km long, which are typical of tectonic structures. The distribution in space and time of the studied contractional and extensional structures indicates that they originated in the same time period; we thus address the challenging question regarding the possible origin of the stress sources, by analysing possible causes such as volcanotectonics, high topography, orogeny collapse, and gravitational spreading of the orogen, in relation also with the role played by inherited structures. We finally analyse the relations between the different structures and magma upwelling, and the potential for seismic hazard.

Key words: Andes, stress field, Plio-Quaternary, extension, contraction, orogeny collapse

1. Introduction

In areas of plate convergence, Andean-type tectonics have been regarded as a typical setting where subduction and related processes generate the thickening of the lithospheric wedge above the

Wadati-Benioff zone in a compressive regime (e.g. Kley et al., 1999; Cobbold and Rossello, 2003). This can be expressed by contractional tectonics with widespread folding and reverse faulting, whereby the stress field is given by horizontal greatest (σ_1) and intermediate (σ_2) principal stress. On the other hand, Nakamura and Uyeda (1980) suggested that the overall tectonics within a volcanic arc above a subduction zone can be transcurrent, with both the σ_1 and least principal stress (σ_3) in a horizontal orientation. Several authors recognized also the presence of normal faults, especially with outstanding examples found in Peru (Sébrier et al., 1988) and in other settings like the Himalayan region (Burchfiel and Royden, 1985). This prompted a long-lasting debate on the role played by high topography and crustal root in interacting with regional plate tectonic forces (Molnar and Lyon-Caen, 1988; Deverchère et al., 1989; England and Houseman, 1989; Wdowinski and Bock, 1994; Zoback, 1992; Gölke and Coblentz, 1996; Steinberger et al., 2001; Clark et al., 2005).

In South-America, most works about these topics involved mainly numerical modelling that used the World Stress Map as major source of information on the current stress field (e.g. Coblentz and Richardson, 1996; Meijer et al., 1997; Heidbach et al., 2008; Flesch and Kreemer, 2010; Ruch and Walter, 2010). However, focal mechanism solutions of crustal earthquakes in a wide area corresponding to the central part of the Andean Chain are missing, causing a formidable gap in the dataset used to conduct numerical modelling. There are only very few in-situ stress measurements that were done only at the topographic level (Schafer and Dannapfel, 1994) and thus do not represent reliable values of the crustal interior. We underscore that this area is particularly important for any attempts at understanding the relations between orogenic processes and their causes, because it represents a more complex setting than other regions of the Andes. The central Andes, in fact, are composed by the Altiplano/Puna Plateau, as well as a wide volcanic chain (missing in Peru, southern Ecuador and Venezuela, and much thinner and regular in southern-central Chile), the Cordilleras and the Subandean ranges, both marked by a complex topography and a very diverse distribution of geological units.

Besides the lack of reliable data on active crustal stresses in this region, also the studies on the geological structural evolution during Plio-Quaternary times are much less numerous than those dedicated to the older deformation phases, and are only related to local areas; the Plio-Quaternary tectonic evolution of some areas of the central Andes has been described as dominated by reverse faults and folds, or strike-slip faults (González et al., 2009; Eichelberger et al., 2015). Other works on the central Andes showed that faulting and folding fully developed in the Eocene-Oligocene and then ended (Jordan et al., 1997; Kraemer et al., 1999; Coutand et al., 2001; Carrapa et al., 2005; Mpodozis et al., 2005), or suggested that a maximum tectonic shortening was locally reached during the Neogene Quechua phase (Allmendinger et al., 1997). For Gubbels et al. (1993) and Cladouhos et al. (1994), the shortening phase ceased at 9-10 Ma in the southern Altiplano and northern Puna Plateau (PP), whereas for Gonzalez et al. (2009) it has been active as long as the Quaternary west of the PP.

In regards to extensional tectonics, other studies of the central Andes suggested the development of post-Miocene normal faulting with extension perpendicular or oblique to the orogen (Lahsen, 1982; Riller et al., 2001; Tibaldi et al., 2009; Schoenbohm and Strecker, 2009; Montero-Lopez et al., 2010; Zhou et al., 2013; Daxberger and Riller, 2015). Further studies indicated orogen-parallel or sub-parallel extension (Allmendinger et al., 1989; Marrett et al., 1994; Daxberger and Riller, 2015; Giambiagi et al., 2016), or extension just limited to parts of the PP (Cladouhos et al., 1994). Most of these papers focused on limited areas and do not allow to reach a regional view for the tectonics of late Pliocene-Quaternary times; as a consequence, several papers addressed only the extensional structures, whereas others only the contractional deformations. Moreover, a map of late Pliocene-Quaternary faults does not exist for the whole studied area. We have chosen to include different domains, such as cordilleras and Altiplano, in order to reach a regional perspective and locate possible boundaries between different recent tectonic deformation fields.

In view of the above, we wish to address a number of challenging scientific questions, as follow: *i*) the assessment of the actual deformation and related state of stress in the central Andes during late Pliocene-Quaternary times is of paramount importance for understanding its structural evolution and for conducting any reliable modelling of the recent geodynamics in western South-America. Can field data allow to draw a consistent picture of the recent tectonic evolution in the area? *ii*) Which are the origins of the forces responsible for the different deformation processes? *iii*) The identification of structures of Quaternary age is key to assessing seismic hazard; the region at the junction among Chile, Bolivia and Argentina is not densely populated but, nevertheless, several rural villages are present, made of buildings characterised by very poor structure and masonry, suggesting their high vulnerability. Are there recent, major structures in the central Andes that might be of interest for seismic hazard assessment? *iv*) Since the central Andes host tens of recent and active volcanoes, it is scientifically challenging also to understand the type of structures, kinematics and tectonic stresses that control magma upwelling and emplacement at shallow depth.

In order to tackle the above questions, we collected geological-structural data across a wide area of about 90,000 km^2 encompassing north-eastern Chile, south-western Bolivia and north-western Argentina, and extending from the PP to the east to the Altiplano-volcanic belt to the west (between 21°40’S-24°30’S, and 66°30’W-68°40’W) (Figs. 1A-B). The data were collected during field geological, structural and morphostructural surveys carried out over the past ten years, integrated with the interpretation of detailed satellite images. All data are originals apart from two graben structures already published in Bonali et al. (2012) and Tibaldi et al. (2008), here reviewed due to their importance. The surveys focused on the structures affecting deposits of Plio-Quaternary age, with special attention to defining the age, geometry and kinematics of deformations. We contribute to a better understanding of the recentmost geological-structural evolution of the central Andes with a regional perspective. The results indicate the presence of contemporary contractional and extensional structures distributed in different zones. Their distribution is analysed in terms of the local geological setting, topography, altitude and spatial position, with the purpose of assessing also the possible origin of the forces that caused deformation.

2. Geological-structural background

The central Andes, between 20.5°S and 24.5°S, are limited to the east by the Eastern Cordillera and Subandean zone that correspond to the front of imbricated thrust slices, mostly striking N-S and located in Bolivia, and to the west by the Western Cordillera of northern Chile, characterized by N-S to NNW-SSE folds and reverse faults. The region between these two cordilleras is represented by the Altiplano-PP, which extends from south-western Bolivia to north-western Argentina, and, more to the west, by the chain of volcanoes along the Chile-Bolivia and Chile-Argentina borders.

The studied area (Fig. 1) comprises the PP, the volcanic arc, and the region of transition to the Western Cordillera. The oldest rocks here are intrusive plutons of Paleozoic age. The oldest sedimentary deposits are marine rocks of Jurassic-late Cretaceous age, followed by early Miocene sedimentary rocks. These deposits crop out in a scattered way, and are mostly covered by Miocene lava flows and late Miocene ignimbrites. Several stratovolcanoes of late Miocene, Pliocene and Quaternary age have been identified in the study area (Tibaldi et al., 2009, 2017a). The younger lavas are interlayered with Pliocene and Pleistocene ignimbrites that were erupted in the main phases of caldera collapse, the largest structures being the Pastos Grandes (PG), La Pacana (LP), Panizos (CP), Vilama (VC), and Cerro Guacha (CG) calderas (Fig. 1B).

The Cenozoic tectonic evolution of central Andes has been dominated by contractional deformation (De Celles and Horton, 2003; Deeken et al., 2006; Strecker et al., 2007) caused by the convergence between the South-American and Nazca plates. Contraction has been accompanied by crustal thickening, followed by uplift and formation of the PP (Isacks, 1988; Allmendinger et al., 1997; Elger et al., 2005). Compressional deformation began in late Cretaceous west of the study area (Mpodozis et al., 1995; Bascuñan et al., 2015), and propagated eastward in the Eocene-Oligocene (Jordan et al., 1997; Kraemer et al., 1999; Coutand et al., 2001; Carrapa et al., 2005; Mpodozis et al., 2005). Local limited extension was detected in the Atacama rock succession, corresponding to a period of extensional relaxation during late Oligocene-early Miocene times (Pananont et al., 2004). Contraction resumed again and reached its climax in the Neogene Quechua phase of the Andean orogeny (Allmendinger et al., 1997). This shortening phase ceased at 9-10 Ma in the southern Altiplano and northern PP (Gubbels et al., 1993; Cladouhos et al., 1994), and at 2-4 Ma in the southern PP (Marrett et al., 1994), and shifted eastwards in the thin-skinned Subandean fold-and-thrust belt (Baby et al., 1995, Moretti et al., 1996; Echavarria et al., 2003). Following Gonzalez et al. (2009), contraction went on also during Pliocene and Quaternary times in the volcanic chain immediately west of the PP.

It has been demonstrated that extension affected this part of the central Andes as well, mainly in the PP and its close surroundings (review in Daxberger and Riller, 2015). A N-S, orogen-parallel extension was proposed by Allmendinger et al. (1989) and Marrett et al. (1994). The beginning of this phase was dated to the late Miocene-early Pliocene along the southern margin of the PP (Montero-Lopez et al., 2010). In this area, Zhou et al. (2013) found Quaternary (< 1 Ma) normal faults following a NE-SW to NNE-SSW extension direction, oblique to the local trend of the mountain belt. Along the southern margin of the PP, also Schoenbohm and Strecker (2009) documented extension oblique to the orogeny, but < 3.5-7 Ma. Cladouhos et al. (1994) showed the presence of < 9 Ma, minor normal faults in the northern part of the PP. A NE-SW directed phase of extension of late Pliocene-Quaternary age was suggested by Tibaldi et al. (2009) at some sites in the PP and more to the west in the volcanic chain. In the PP as a whole, various structures pointing to E–W to NW–SE Neogene-Quaternary extension were recently found by Daxberger and Riller (2015).

3. Methods

In order to date the structures, we used crosscutting relationships with the stratigraphic units, the age of which has been reconstructed by local geological surveys and all published radiometric datings. Most widespread stratigraphic markers are represented by the various ignimbrite flows outpoured by calderas: the Pujsa ignimbrite (5.6 ± 0.2 Ma; de Silva and Gosnold, 2007), the Atana-Toconao-La Pacana ignimbrite (4.0–4.5 Ma; González et al., 2009 and references therein), the Tucucaro-Patao ignimbrite (3.1–3.2 Ma; González et al., 2009 and references therein), the Talabre ignimbrite (2.52 ± 0.06 Ma; Barquero-Molina, 2003), and the Purico-Cajon ignimbrite (1–1.3 Ma; de Silva and Gosnold, 2007).

The presence of open fractures associated to a fault zone has been considered evidence of recent (late Pleistocene-Holocene) displacements: In fact, even in such an arid environment, the time from the base of the Eemian interglacial (126 ka BP) should have been long enough to enable filling ground fractures by wind deposits and possible failure of fracture edges. The fractures limited to a single slope have not been considered since they might have been influenced by local gravity slope deformation. For each fault, we defined its kinematics and we quantified its: *i)* strike; *ii)* dip direction; *iii)* dip angle; and *iv)* offset. The kinematics has been defined in the field, wherever possible, by combining offset of markers with recrystallized fibres and Riedel microfractures on slip planes. In very remote areas, the fault trace has been reconstructed also with the interpretation of Google-Earth^{TM} images. For each fold, the hinge line orientation and the fold vergence has been reconstructed. Since our paper focuses on late Pliocene-Quaternary tectonics, fault planes of this age have not been exhumed by erosion, also in consideration of the very low erosion rate of the studied region. As commonly done for geological-structural studies applied to recent faulting (McCalpin, 2009, and references therein), we reconstructed the components of kinematics based on the measurement of offset markers represented by surfaces and landforms. The vertical component of motions was measured based on the fault offset of the upper surface of the deposit, which usually coincides here with the topographic surface due to the very low erosion rate and recent age of the studied deposits. The strike-slip component of motions was reconstructed by means of measurement of lateral offset of deposits such as fluvial beds, or of landforms such as dry water gullies and water divides. The fault geometry has been reconstructed only in the case that a continuous fault can be followed in the field across not-flat terrains. The fault dip and inclination have thus been reconstructed based on the trace of the fault as followed on slopes perpendicular to the fault strike. The fault strike has been measured based on the average orientation of the fault scarp. Results from our field surveys have been integrated with information from published geological maps/papers. Although in the older part of the rock succession (pre-Pliocene), good fault striae are quite widespread, in the younger lavas and Quaternary ignimbrites, real striated tectonic planes are extremely rare. Moreover, several fault scarps affect loose deposits or hard rock covered by fine-grained sediments. The few available young fault planes with tectonic striae have been processed to determine the stress tensor by means of the SG2PS software (Structural Geology to Post Script Converter - http://www.sg2ps.eu; Sasvári and Baharev, 2014). For fissures and joints affecting deposits of Plio-Quaternary age, we measured attitude and the opening direction as well, as evidence of extension orientation. These structures have been measured only if they belong to long swarms as better explained below.

Slip planes can be produced by tectonics (i.e. remote regional stresses), gravity slope deformation, magma push, and lava flows. Since we focused on late Pliocene-Quaternary faulting, and erosion in the study area has been very limited during this time interval, the tectonic fault traces to be studied cannot have been exhumed by erosion and thus they represent the coseismic surface rupture length. Based on fault length-magnitude scale, a fault reaching the surface should have been associated to an earthquake sufficiently energetic to produce a length of the surface rupture zone > 7-10 km (Mark, 1977; Bonilla et al., 1984; Wells and Coppersmith, 1994; Leonard, 2010). As a consequence, we selected only those fault segments that belong to fracture swarms with total lengths > 7 km, which is more compatible with a tectonic origin, and the same approach has been used also for fissures and extensional joints.

To avoid collection of data possibly linked to gravity slope deformation, comprising deep-seated gravity slope deformations or shallower landslide phenomena, we again focused on long fracture swarms that cross different slopes. In regards to magma-related deformations, several recent papers have showed that dykes propagating horizontally or vertically can produce surface faulting (e.g. Ruch et al., 2016; Ágústsdóttir et al., 2016), as well as also shallow magma chambers can produce surface brittle deformation (review in Tibaldi, 2015). For magma-related graben formation, we checked the width of the studied grabens (1-4 km wide) since those induced by diking are quite narrow, mostly in the order of tens of meters to 500-800 m (Ruch et al., 2016) and up to 1.5 km at the large Hawaii volcano-tectonic rifts (Jackson et al., 1975). Then we payed special attention to the location of possible Plio-Quaternary magma chambers, and thus we did not consider the structures located in correspondence of the calderas of that age. Although we are aware that especially shallow magma intrusions can also induce long faults, we highlight that by the above described approaches we tried to minimize the possible data collection of structures of non-tectonic origin.

We wish to stress that special attention must be given when collecting striae and other tectogliphes at lava and ignimbrite flows: Tibaldi (1996) demonstrated that in these rocks special criteria should be used to collect reliable fault slip indicators due to the possible presence of slickensides produced by sectors of the flow moving at different speeds that are very similar to textures induced by actual tectonic slip. For this reason, each site was evaluated using Tibaldi (1996)'s methods. This method consists in locating the slip plane respect to the possible presence of a lava flow and its flow direction, and to evaluate its vertical persistence. By comparing these data, it is possible to establish if the slip plane has been induced by lava motions. The method also considers the presence of specific features on the slip planes, called "burrs", which develop only on lava flow slip planes and not on tectonic fault planes (Tibaldi et al., 2017b).

4. Results

4.1 Compressional tectonic structures

The main compressional structure that can be observed in the studied area is the Miscanti Ridge (MR) (Figs. 1B and 2A, Table 1), named after Gonzalez et al. (2009), which extends from Latitude 23.13°S southward as far south as the Chile-Argentina border. The ridge is locally discontinuous due to covering of clusters of volcanic edifices, and thus it might be difficult to recognize it along its entire lengths on satellite images. As a consequence, we also used field checks and detailed topographic maps to survey its whole spatial development. It is composed of a northern part (north Miscanti Ridge in Table 1), made of two segments for a total of 40 km, plus a southern part with a length of 35 km. In its northern part, the MR trends N10° and can be observed at the surface as a morphological symmetric high; the two ridge slopes are tens of meters up to 150 m higher than the surrounding areas. Farther south, it becomes more asymmetric, with a gentle western slope and a steep scarp facing east. The height of the western slope is in the order of 100-150 m, whereas the eastern scarp reaches a maximum height of 350 m north of the border between Chile and Argentina. The MR is crossed by a few river valleys that enable studying its inner structure given by strongly deformed pre-Pliocene sedimentary strata, above which are younger deposits usually showing angular unconformities at the base. It is difficult to attribute a precise age to the older strata; they are red beds of possible Cretaceous age (Purilactis Group) or more recent sediments of Neogene age (San Pedro Formation). The younger deposits are represented by ignimbrites, dated in this area to 3.1-3.2 Ma (Tucucaro-Patao Ignimbrite, Gonzalez et al., 2009 and references therein) and younger lavas. These deposits are affected by reverse faults (Fig. 2B) and folding deformation. Near Lake Miscanti, there are several lava flows, which were affected by folding, such as for example some of the Pliocene flows of the Meñiques Volcano that now are located on the ridge top (Fig. 2A; Gonzalez et al., 2009), and a younger flow (possibly dating back to the Pleistocene) from the same volcano, whose frontal lobe was uplifted about 10 m along the eastern scarp of the MR (Fig. 2C).

Seventeen km south of Miscanti Lake, the MR is obscured by a volcano (site *A,* Fig. 1 - *67°48'58"W, 23°56'4"S*) that sits on top of a NNE-trending, 13-km-long, asymmetric ridge; strata gently dip to the NW along the western side of the ridge, whereas a steeply-dipping scarp offsets Pliocene lavas along the opposite side. The volcano shows a flank collapse towards the SE, suggesting a possible influence of the movements of the underlying fold.

A main reverse fault, here named Toloncha Fault (TF), crops out 14 km to the west, where it offsets the Plio-Pleistocene Toloncha volcano (TV) (see Figure 1 for location) and the 3.1-3.2 Ma Tucucaro-Patao Ignimbrite, and transitions northward to an anticline (total length 39 km). The fault strikes N00°-10°, dips to the west, and can be followed southward for 27.3 km, whereby it apparently disappears approaching a huge group of recent volcanoes. To the west there is a swarm of folds and east-dipping reverse faults (Gonzalez et al., 2009) that we consider backthrust splays of the main TF; the dominant shortening direction is N95°.

Further 13 km southward, at the Chile-Argentina border, another very high ridge reappears with pre-Pliocene folded strata giving rise to an east-vergent, NNE-SSW to N-S asymmetric fold, here named La Casualidad Ridge (LCR) (Fig. 1). The western morphological slope shows a topographic difference up to 300 m, and the eastern scarp is as much as 850 m high. A lava flow with preserved flow structures, but of difficult absolute age attribution, is tilted along the ridge at site *B* (Fig. 1 - *68°3'21"W, 24°44'36"S*). Another lava flow produced by a volcano located on top of the ridge, is affected by a 20-40 m offset at the base of the ridge scarp (site *C,* Fig. 1 - *68°12'53"W, 25°5'1"S*). The latter lava flow has been dated to the Plio-Pleistocene (SERNAGEOMIN, 2003) and lies above an ignimbrite unit (named Archibarca/Caballo Muerto) of 3.6 Ma BP (Brandmeier, 2014 and references therein). Although ages are not well constrained here, it is possible that also the Argentinian section of the ridge has moved during the late Pliocene-Quaternary times, and given a maximum age of 3 Ma for the offset lava, the minimum slip-rate is 0.01 mm/yr. In correspondence of the LCR, DeCelles et al. (2015) showed the presence of a main thrust dipping to the west. The total length of this swarm of ridge structures in Chile and Argentina is about 200 km; however, further studies would be needed to fully understand which segments of the ridges moved in recent times.

At a distance of 14 km northwest of Miscanti Lake, there is a series of minor NNW-SSE to N-S trending folds that affect the Tucucaro-Patao ignimbrite (3.1–3.2 Ma; Gonzalez et al., 2009 and references therein) (Fig. 1, Table 1). They are expressed by deposits with local opposite dips that indicate anticline structures. The average shortening direction is N85°. Most are asymmetrical with eastward vergence, and locally give place to reverse faults mostly dipping west (Gonzalez et al., 2009).

More to the south, 10 km west of Miscanti Lake, there is another series of folds with more curvilinear hinge lines and a convex side to the east in plan view, and associated reverse faults, characterised by dominant vergence to the east (site *D* in Fig. 1 - *67°54'15"W, 23°43'29"S*). The average shortening direction is N90°. They affect the Tucucaro-Patao ignimbrite and lavas of Plio-Pleistocene age (Gonzalez et al., 2009).

At the latitude of the Talabre village (Fig. 1), 12 km west of the northern termination of the MR, ignimbrite deposits referred to the 2.0-2.3 Ma old Talabre Formation (Gonzalez et al., 2009) show an outcropping reverse fault that dips towards the west (site *E* in Fig. 1 - *67°49'21"W, 23°18'15"S*). The surface fault trace is 9 km long and has a sinuous trace in plan view compatible with a shallow dip. The average strike is N-S.

North of San Pedro de Atacama, there is a major anticline that involves in its nucleus red beds of possible Cretaceous-Neogene age, above which, in discordance, there is a series of ignimbrite deposits (site *F* in Fig. 1 - *68°9'10"W, 22°35'45"S*). The younger deposit here has been dated 4-4.14 Ma BP (Puripicar Ignimbrite) (Brandmeier, 2014). The fold is 9.5 km long, with the hinge line trending NNE-SSW. The fold limbs are quite symmetric as far as the uppermost deposits are concerned.

4.2 Extensional tectonic structures

Immediately south of the Ollague volcano (*68°10'46"W, 21°18'36"S*) (OV in Fig. 1B), there is a swarm of NW-striking normal faults, mostly dipping to the SW, which affect lavas of Plio-Pleistocene age, and ignimbrite deposits of Pliocene age. The fault swarm has a total length of 8 km and runs across slopes of different orientation, thus excluding a gravity slope origin. At the Pastos Grandes Caldera in Chile (PG in Fig. 1B), there is a swarm of NW-SE normal faults that in part border the caldera, and in part are nested within the centre of the caldera floor. These structures should be genetically related to the collapse of this volcano-tectonic structure and to a resurgent dome, respectively.

West of the Pastos Grandes Caldera (PG), another, 19 km long, major system of NW-striking normal faults runs from the Aguilucho volcano to north of the Inacaliri volcano (Chile) (Figs. 1 and 3) (Table 1). Two major faults, 10 and 18 km long, have converging dips, thus producing a symmetric graben. The graben floor is 50-150 m lower than the shoulders, which range in altitude from 4600 m to 5200 m a.s.l. The graben floor is affected by other minor normal faults, each from 2 to 4 km long. The faults have dips between 50° and 70° and a rectilinear trace in plan view, which is consistent with their steep dip. They offset a series of NW-SE-aligned stratovolcanoes of Pliocene age (Sernageomin, 2003) and lava flows dated 1.1±0.2 Ma BP (Mercado et al., 2009). The longest fault bounding the graben to the northeast is sealed by a lava dome (Pabellon) dated at 80-130 ka BP by Ar-Ar (Tibaldi et al., 2009) and 50±10 ka by K-Ar (Urzua et al., 2002).

East of Inacalari volcano (Bolivia) eruptive fissures, punctuated by aligned vents, of Quaternary age striking NW-SE are present, suggesting that a NE-SW-directed extension has been active (Fig. 4 and site *G* in Fig. 1 - *67°49'17"W, 22°00'30"S*). Parallel to these fissures there are also normal faults such as those affecting the De Jorcada Pliocene volcano (Fig. 4 - *22°02'10"°S, 67°45'40°W*): this fault swarm is 13 km long and one single fault segment, with a very sharp and poorly eroded scarp, is 6 km long. This fault faces to the SW and the topographic offset amounts to a maximum of 40 m.

Farther south, in Bolivia, there is another swarm of recent normal faults, here labelled as Sol de Mañana Graben (Figs. 1B and 5A). Here, a series of NW-striking faults with fresh scarps are present and offset the Tatio ignimbrite deposit of 1.9 ± 0.8 Ma BP (de Silva and Gosnold, 2007) and a younger series of lavas emitted by effusive centres located along the same fault swarm (Figs. 5A-B). The swarm is 13 km long in total and made of fault strands each long up to a maximum of 6.8 km. The trace in plan view is quite rectilinear, consistent with a steep dip of the faults (e.g. Figs. 5C-D). The maximum offset is 30 m along the master fault facing NE, and up to 30-50 m along the opposite master fault facing SW (Figs. 5A-D).

Farther south, there is another swarm of normal faults with a total length of 24 km, here termed Laguna Verde Graben (Bolivia, Figs. 1 and 6). They strike more NNW-SSE in the northern part where they affect volcanoes of Pliocene-Quaternary age (Fig. 6A). Towards the south and east, the faults strike NW-SE and affect a Neogene stratovolcano and a Neogene-Quaternary dome (more probably of Pleistocene age) (Figs. 6A-C). Since these volcanoes are completely cut by the faults, it is possible to observe in section view the fault traces from an altitude of 5085 m down to 4360 m; they show a clear sub-vertical dip angle (e.g. Figs. 6B-C), thus consistent with normal faulting architecture. The longest fault segment is 9.45 km long.

The area between the Licancabur volcano and the ALMA observatory is composed of an ignimbritic plateau affected by a 18 km long swarm of N-S fractures (Figs. 1 and 7A). The trace of all these fractures is rectilinear in plan view, suggesting they have a vertical to sub-vertical attitude. The swarm is crossed by a road section that allows to clearly recognize their attitude and offset (e.g. Figs. 7B-C). Most are extensional fractures, filled with loose deposits (Figs. 7B-C). Some are partially empty, suggesting a young age. The opening direction, based on offset piercing points, indicates an overall E-W trending σ_3. A few of these structures show dip-slip normal motions (e.g. Fig. 7B). At the surface of the ignimbrite, the water gullies crossed by these fractures do not show any strike-slip offset, suggesting pure extensional motions. More to the SW, just north of the ALMA observatory, the same ignimbrite plateau is offset by a N-S-striking fault zone with a very fresh morphology (Fig. 7D). Water gullies are vertically offset, indicating pure dip-slip motions. The fault zone, with a total length of 8.6 km, is composed of six close fault segments, with vertical scarps facing west. The fault traces are rectilinear in plan view suggesting a steep attitude of the planes. In proximity of these scarps there is no bulging of the ignimbrite succession, giving rise to a step-like geometry typical of extensional fault settings. On the contrary, the Quaternary reverse faults that here we studied are almost always associated to bulging and folding of the rock succession. The N-S normal faults affect an ignimbrite plateau composed of the 1-1.3-Ma-old Purico Formation (de Silva and Gosnold, 2007).

It is worth mentioning that other swarms of NW-SE-striking, main Quaternary normal faults are present, but they belong to the resurgent domes in the interior of the Guacha and La Pacana calderas (e.g. Fig. 1), and thus they are not of pure tectonic origin and have to be interpreted in terms of the action of magma forces.

Southeast of the La Pacana caldera, there is a graben with N-striking normal faults (Figs. 1 and 8A). The whole structure is 7.8 km long, with a maximum width of 3.5 km. The bounding faults have converging dips and define a symmetric graben (Fig. 8A). The offsets of the westernmost master fault are mostly in the 5-8 m range; the maximum observed offset is 16 m (e.g. Fig. 8C); at the easternmost master fault, most offsets are as much as a few meters, up to 14 m (e.g. Fig. 8D). The faults offset ignimbrites of the Atana Member (3.96 ± 0.02 Ma BP, de Silva and Gosnold, 2007) and a series of lava flows of Pliocene age (Sernageomin, 2013). Considering that, in the middle of the graben floor, we discovered empty extensional fractures striking N-S with opening in the order of 35 cm (Fig. 8B), we must conclude that some recent (latest Pleistocene-Holocene) deformation occurred here.

5. Discussion

5.1 The time-space distribution of deformation

The surveys carried out in Chile, Bolivia and Argentina allowed us gain a major insight into the distribution of the recent-most deformation pattern in space and time. Our data show the presence of both extensional and contractional deformations, which developed within the same late Pliocene-Quaternary time window; this observation was not completely put forward by the previous literature, since in the study area previous papers highlighted the presence of just contractional or only extensional structures during the last phase of deformation, ignoring or minimizing the presence of the other type of structures. For example, the paper by Gonzalez et al. (2009) described the presence only of young shortening structures in part of the area studied here, in the form of folds and reverse faults, and did not consider the presence of extensional structures. Other authors mentioned the presence of extensional faults but suggested they are of no significance, and may have formed as a result of slope instability (e.g. Arriagada et al., 2006). Other authors, on the contrary, such as for example Lahsen (1982), suggested that compressional structures do not affect deposits younger than 4 Ma BP in the whole northern Chilean Andes, which in turn are just offset by N-S normal faults. A paper by Allmendinger et al. (1989) recognized the presence of contemporaneous extensional and contractional deformations, but suggested that normal faults are only present in the PP, and shortening shifted in the Quaternary east of the PP at the foreland thrust system.

Our data instead, put forward that late Pliocene-Quaternary tectonics is in general more important than previously thought in the studied area, and that contraction and extensional deformations can develop contemporaneously at very short distance each other. In regard to contractional structures, in Table 1 it is possible to notice the age of the deposits involved in the younger compressional phase: the folds and reverse faults affect strata dated up to 2.0 Ma BP by radiometric dating or to the Pleistocene by stratigraphic methods. This indicates the presence of a compressional phase that was active in late Pliocene and Quaternary times. If we look at the youngest extensional structures, they involve deposits up to the Pliocene (2.4 Ma) and Quaternary (0.7 Ma). From the point of view of the time window, these data indicate that contractional and extensional deformations formed contemporaneously. The occurrence of diverse types of deformation during the same time implies a rotation of stress tensor in space. In the study area, Quaternary strike-slip motions have been documented at a few faults, such as at the NNE-striking Bequeville fault (Marrett et al., 1994) located in the eastern, lower corner of our study area, whereas the Calama-Olacapato-El Toro fault shows Quaternary slip only in the eastern-most part of our study area (Fig. 1) (Bonali et al., 2012; Lanza et al., 2013). Also the geometry and distribution of Quaternary folds is consistent with dominant pure shear ductile deformation; in fact, the pattern of folds with a typical en-échelon arrangement or other evidence of main Quaternary shear zones is lacking in the study area. In conclusion, during late Pliocene-Quaternary times, the studied area has been characterised by two main domains, one with horizontal σ_1 and σ_2 and the other one with horizontal σ_3 and σ_2, whereas transcurrent motions were very local along the eastern border of the area.

From the point of view of the distribution in space, the late Pliocene-Quaternary contractional deformations are concentrated along the MR, TF and LCR, in Chile. The northernmost evidence of compression along the MR has been indicated at Latitude 22.98°S (7 km south of the Chile-Bolivia border) by Gonzalez et al. (2009). More to the west, late Pliocene-Quaternary contractional structures have been found south of the ALMA observatory (23.07°S), and more to the north, such as the fold at Latitude 22.42°S. The claim for extensional deformations between the latter fold and the northern termination of the MR is based on the discovery of extensional fissures and normal faults between the Licancabur volcano and the ALMA observatory (Fig. 7A). This swarm of extensional fractures and minor normal faults is composed of parallel N-S-striking planes, perfectly rectilinear in plan view, that indicate high-angle fracture planes, confirmed by the section view along road cuts (Figs. 7B-C). The measurement of opening directions shows an overall homogeneous E-W extension. All deposits of this ignimbritic plateau and the topography do not show any bulging that might indicate folding. Therefore, we need to rule out that this swarm of structures might be the expression of extension at the extrados of a fold. The main normal fault located immediately southwest of the fracture swarm (north of ALMA) is also characterised by a rectilinear trace in plan view, which is compatible with a sub-vertical fault attitude (Fig. 7D). This geometry of the fault trace, and the regular planar topography and faulted deposits, is completely different from the setting at the reverse fault located north of the Talabre village (see Fig. 1): This reverse fault, in fact, is characterised by a bulging in correspondence of the hanging-wall block and by a sinuous shape of the fault surface trace in plan view, confirming the different kinematics.

5.2 Origin of deformation

The coexistence of extensional and contractional deformations in the same section of an orogen needs to be adequately explained. First of all, several swarms of NW-SE-striking, extensional faults, are located in the interior of calderas, namely the La Pacana, Pastos Grande, and Guacha. They show very similar structural features, represented by series of parallel, up to 20 km long, NW-SE-striking main normal faults, and minor NE-SW-striking normal faults. They bound the caldera margin, such as in the case of La Pacana, or they affect only the caldera centre. Although they have lengths of fault surface rupture that are compatible with tectonic seismogenic faults (e.g. Wells and Coppersmith, 1994), the movements along the NW-SE faults at these calderas are here interpreted as produced by magma inflation and deflation linked with caldera activity, as already suggested for La Pacana by Gardeweg and Ramírez (1987). The NW-SE geometry of these faults, instead, may have been guided by pre-existing regional structures: this area, in fact, has been affected, in pre-Quaternary times, by transcurrent motions along NW-SE regional faults, as suggested in previous literature (Riller et al., 2001; Matteini et al., 2002; Mazzuoli et al., 2008; Tibaldi et al., 2009).

Other recent normal fault swarms are not related with calderas and thus their origin should be different. These fault swarms are from 7.8 to 24 km long and contain single, continuous fault segments up to 18 km long. The lengths of the measured outcropping normal fault swarms are fully compatible with the typical surface rupture length of tectonic seismogenic faults, as shown in the databases of Wells and Coppersmith (1994) and several other authors. This means that the surveyed structures may represent the topographic rupture of faults originated during prehistoric earthquakes. Although we are aware that the extremely arid climate can play a major role in preserving the morphologies, the very sharp appearance of some of these faults, such as the structure north of ALMA observatory, and the local presence of empty large ground fractures, suggest possible recent movements of late Quaternary age.

Regarding their origin, most of these normal faults affect areas with a flat horizontal to sub-horizontal morphology, such as in the case of the Sol de Manana graben (Fig. 5), the Laguna Verde graben (Fig. 6), the fracture swarm south of Licancabur, the fault north of ALMA (Fig. 7), and the graben at the Argentina-Chile border (Fig. 8). The only exception is given by the Inacaliri graben that rests on top of a volcano row (Fig. 3). The latter setting can be the evidence of a gravity force responsible for the formation of the graben, possibly in connection with volcano spreading. Spreading is here a possible factor, due to the huge mass of the volcanic row and the possible presence of clay-salty deposits below it, given the vicinity with a *salar* deposit. In all the other cases, we have to exclude similar effects or the possible influence of slope gravity. Based on the above, and the lengths of the single fault segments as well as the entire fault swarms, we conclude that the studied extensional structures are tectonic in origin.

The average altitude of the areas affected by the folds and reverse faults of late Pliocene-Quaternary age is 3941 m, whereas the areas affected by the extensional structures have an average altitude of 4520 m (Table 1). These data suggest that topographic loading has an effect on the stress tensor and thus on the type of deformation (Fig. 9); our results are consistent with the study of Sébrier et al. (1988) for the Andes of central Peru, which showed that a compressional stress field with horizontal σ_1 dominates at an average elevation < 4000 m, whereas a vertical σ_1 is expected above this average altitude. In fact, the majority of normal faults considered in this study (82%) are locate in areas with an elevation > 4000 m (Fig. 10).

If we consider topography as a proxy to crustal thickness, which for the central Andes has been demonstrated by Beck et al. (1996), the lithosphere below areas of higher altitude that suffered from intense crustal thickening, may be subject to thinning and extension with mass removal towards the foreland, where the crust is thinner (Fig. 9) (Schoenbohm and Strecker, 2009, and references therein). The presence of a high heat flow below the volcanic chain and the PP (Springer and Forster, 1998) facilitates this mass transfer due to the low crustal strength below these regions. A readjustment of mass transfer at depth is accompanied by uplift and collapse of some sectors of the orogen (Tibaldi et al., 2009; Bonali et al., 2012; Lanza et al., 2013; Giambiagi et al., 2016). We prefer this interpretation to the gravitational spreading of the orogen, because of the presence of orogen-perpendicular extension in the whole study area; in fact, the orogen orientation changes from N-S to NW-SE at the same latitude where we found a rotation of the normal fault strike (Fig. 9), whereas the gravitational spreading model implies often orogen-parallel extension (Daxberger and Riller, 2015). In the studied area, it is interesting to note that the decrease in the frequency of tectonic normal faults from north to south correlates with the decrease in crustal thickness in the same direction: in the northern part of our study area, Prezzi et al. (2009) shows that the Moho depth is in the range -55 to -75 km and in the southern part (south of 23°20”) is from -50 to -65 km, and McGlashan et al. (2008) indicate for the same areas a crustal thickness of 67-80 km and 42-59 km respectively. This suggests that gravity flow in the crust and orogenic collapse is more probable in the northern part, consistent with the distribution of surface extension.

A recent (< 10 Ma BP) broad uplift of the Altiplano-PP has been put forward by several authors (Garzione et al., 2008, and references therein). We suggest that at the surface, this uplift may have been accommodated by motions along normal faults with two different directions of extension. In the northern part of the study area, a preferentially NE-SW-directed extension, whereas, to the south a dominant E-W extension. This may be due to the effect of inherited structures produced by previous phases of transcurrent motions along NW-SE planes in the northern part (Tibaldi et al., 2009, 2017a) and along N-S to NNE-SSW structures in the southern part. These structures are suitably oriented with respect to the extensional vectors induced by the orogen collapse. This view is consistent with the numerical study of the gravitational potential energy of the Central Andes by Flesch and Kreemer (2010) that shows an orogen-perpendicular σ_3 rotating from NE-SW in northernmost Chile (north of 22°S) to E-W more to the south, as resulting also from our field-based analysis.

As an alternative, or complementary hypothesis to the above, we emphasize the importance of the MR, TF and LCR that represent a major (100 to 200 km long) corridor made of fault-propagation folds, with the main slip planes dipping west. The abrupt re-orientation of the extensional structure strike from NW-SE to N-S at the latitude of the northern MR may also signify that the N-S normal faults and the MR-TF-LCR structures are genetically linked: the MR-TF-LCR allow overthrusting of the Western Cordillera tectonic units towards the volcanic chain. The thickening in the overthrusting area produces an overload on the crust with the possible formation of a flexure eastward, which in turn produces at the surface extensional structures striking around N-S, parallel to the flexure trend (Fig. 11). Anyway, this scheme fails to explain the several graben structures located far away from the compressional ridges, and thus we favour more the high-topography/orogenic collapse explanation.

5.3 Structure kinematics, stress tensor and volcanism

The whole area of the volcanic belt east and north of the MR and LCR, comprising the studied part of the PP, is affected by normal faults of late Pliocene-Quaternary age, which show two main directions of extension: NE-SW north of the northern termination of the MR, and E-W more to the south. This stress configuration in the Andean chain and in the PP facilitates the use of NW-SE-striking fractures as magma paths in the northern part of the study area, and N-S-striking structures in the southern part. This interpretation is consistent with the recent findings on the space-time distribution of volcanic centers and their morphometric characteristics by Tibaldi et al. (2017a).

These authors, in fact, put forward that the morphometry and alignments of hundreds of volcanic centers in the same area as the one documented here, are compatible with NW-SE-striking magma paths in the northern part of the area, and with N-S-striking magma paths in the southern part. Some scattering of magma path orientations exists, but this reflects the complexity of shallow magma plumbing systems in the interior of volcanic edifices, where the magma conduit can be controlled also by a number of parameters different from the tectonic stress state or regional fractures (for a review of these topics see Tibaldi, 2015).

Based on the data here presented on the late Pliocene-Quaternary normal faulting, the magma paths of the volcanoes of the same age located near these structures benefitted from both the σ_3 and σ_2 being horizontal, a stress tensor orientation that is classically considered to favour magma upwelling to the surface. On the contrary, the older volcanoes that are located in the northern part of the studied area may have been controlled by previous tectonic phases characterised by transcurrent motions along the NW-SE faults, consistent with the strike-slip kinematics observed, for example, by Acocella et al. (2007), Bonali et al. (2012) and Lanza et al. (2013). For example, during the Neogene, about 20 km of left-lateral displacement took place along the Calama-Olacapato-El Toro fault (Allmendinger et al., 1983). Such a stress configuration, characterised by horizontal σ_3 and σ_1, has been increasingly regarded as also favourable to magma upwelling (Tibaldi et al., 2010; Spacapan et al., 2016). A more general control of the NW-SE faults on volcanism, and especially on caldera development in the Puna Altiplano, was suggested also by Riller et al. (2001, 2006), Caffe et al. (2002), Chernicoff et al. (2002), Petrinovic et al. (2005), and Ramelow et al. (2006).

As we have seen, during late Pliocene-Quaternary times other zones within the study area have also been affected by a compressive regime. This stress state, with horizontal σ_1 and σ_2, has been classically regarded as unfavourable to magma upwelling, and magma movements have been mostly suggested to occur along horizontal planes, being the σ_3 axis vertical (e.g. Cas and Wright, 1987; Glazner, 1991; Hamilton, 1995; Watanabe et al., 1999). Nevertheless, in the study area several Pliocene-Quaternary volcanoes are located exactly in correspondence of reverse faults and folds of the same age. For example, along the Miscanti Ridge, several volcanoes are located near the fault-propagation fold in the hanging-wall block or in the footwall block. Some of these edifices are aligned exactly in correspondence of the crest of the fault-propagation fold, as the example on the La Cusualidad Ridge portrayed in Figure 12, and have been partially involved in the compressional deformation process. This clearly suggests a direct control of contractional structures on volcano location and growth, as will be detailed below. Some volcanoes sitting atop of folds, also show evidence of huge lateral failure, as sector or flank collapse. This suggests a further possible direct connection between the folding process and volcano development, as the fault-propagation fold growth may have contributed to volcano slope instability. This is also attested to by the fact that the collapsed volcanoes have the failed flank pointing in the direction of the scarp created by the process of the fold's asymmetric growth. This pattern is consistent with the findings of other authors obtained by way of analogue modelling (Galland et al., 2007; Tibaldi, 2008; Ferrè et al., 2012) or by field data in other areas (Tobisch and Paterson, 1990; Martì et al., 1992; Ferrè et al., 2002; review in Tibaldi et al., 2010).

We suggest that, in a contractional setting, magma can rise along ramp segments of reverse faults, although these are not oriented normally to σ_3, consistent with previous similar suggestions by Tibaldi (2005) and Cembrano and Lara (2009). This may be explained in terms of the different forces necessary for magma intrusion in intact host rocks (or poorly fractured rocks) versus rocks affected by continuous long faults; dyking can occur through intrusion into a newly formed fracture if magmatic pressure (p_m) exceeds the lithostatic pressure (p_l), plus the horizontal compressive stress in the host rocks perpendicular to the dyke, plus the host rock tensile strength (Gudmundsson, 1995, 2006, 2012). If, on the contrary, the host rock has already been affected by well-developed mechanical discontinuities (usually faults) produced by previous deformation events, these planes have no cohesion (or very poor cohesion in the case of sealing effects) and magma propagates along them if magmatic overpressure ($p_o = p_m - p_l$) exceeds the compressive stress perpendicular to that plane. In the case of a ramp structure, the component of the stress acting perpendicularly to the plane is a fraction of σ_1, plus a component due to the overburden. This means that a weakness zone, such as a ramp structure, can represent a suitable magma pathway under an active compressional stress state. Once magma reaches the interface between the volcano and the substratum, magma upwelling to the crater zone may be facilitated by a local stress state linked with the volcano morphology (see Tibaldi, 2008), with previous intrusions that modified the stress pattern (Chaput et al., 2014), or with stretching at the outer-arc of a fold (Gonzalez et al., 2009; Gürer et al., 2016).

5.4 Are there active faults?

Among the criteria to assess the presence of faults capable of producing earthquake hazard, the age and area (surface length for field data) of the slip plane are of paramount importance. Holocene fault slip is regarded as a prerequisite for establishing the potential for new earthquakes along a given structure. Anyway, there are several pieces of evidence that suggest quiescence times that are longer than the Holocene (Grützner et al., 2017; Williams et al., 2017, and references therein). At an active convergence zone like the Andes, where geodynamics is dominated by the presence of effective subduction between the Nazca plate and the South American plate, tectonic stresses may be transmitted to the crust above the Wadati-Benioff zone. Although stress transmission may be attenuated by thermal processes, great crustal thickness, etc., we cannot rule out the possibility that low magnitude stresses may accumulate in the upper crust over time and may be accommodated elastically until the shear stress along the fault reaches a threshold value that will cause rare events of surface fault rupture to happen. This hypothesis is consistent on one side with the scarcity of crustal seismicity in the studied area, and on the other side by the presence of several faults that show evidence of surface rupture in Quaternary times. Moreover, there is clear evidence of Quaternary folding that might hinder reverse blind faults.

Although a more detailed chronology of the most recent movements along the studied structures is not available, there are clues that further studies are required to assess if there is a possible seismic potential. We highlight, in particular, the great length of some of the studied structures: the main compressional features are the Miscanti Ridge (MR), which is made of different segments totalling about 75 km, the 39-km-long Toloncha Fault and associated fold, and the about 100-km-long La Casualidad Ridge, also showing a segmented pattern. Also the coeval normal fault swarms, although shorter than the compressional structures, are characterised by important lengths, in the order of 8-24 km. Based on published databases that put in relation earthquake magnitude with surface rupture lengths of seismogenetic faults (Geller, 1976; Mark, 1977; Bonilla et al., 1984; Wells and Coppersmith, 1994; Leonard, 2010), it can be noted that these lengths are compatible with surface ruptures linked to paleo-earthquakes. The main problem in the studied area is that stratigraphy resolution is not accurate enough to enable assessing a late Pleistocene or Holocene age of the latest slip along these structures, which might aid in determining their potential seismic hazard. The presence of very fresh morphologies along the fault scarps, including very sharp fault edges, river offsets, and especially empty fissures, cannot be considered conclusive due to the very poor erosion rate of the region. However, based on the length and large number of the structures here described, we suggest that it may be worth conducting further studies, possibly integrated with paleoseismological investigations by trenching.

6. Conclusions

Our geological-structural data have been collected in a wide region, as large as 90,000 km^2, at the border among Chile, Bolivia and Argentina, comprising part of the Western Cordillera, the volcanic belt and the Altiplano-Puna Plateau. The approach of our study is focused on the collection of data relative to surface folding and faulting of late Pliocene-Quaternary age that must comply with series of parameters that allow to consider only structures that have a higher probability of tectonic origin. The parameters for faults are scaling relationships between the length of the surface rupture zone of tectonic faults and their capability of breaking the surface, the relationships with slope attitude (in order to exclude slope deformations), and the possible influence of local magma inflation/deflation phases. Focusing only on faults that can be attributed to young coseismic tectonic events, allows a more reliable assessment of the late Pliocene-Quaternary deformation field and related stress state, which represents the foundation for a better comparison with results coming from other methods.

Respect to previous authors, we conclude by two major points: 1) late Pliocene-Quaternary tectonics is here in general more important than previously thought, and 2) within the recent tectonics, there is a division in space of the dominant deformation kinematics. In fact, the eastern part of the Western Cordillera and the westernmost part of the volcanic belt are characterised by the presence of late Pliocene-Quaternary folds, with hinge lines trending NNE-SSW to N-S, and parallel reverse faults which reach the surface. The main compressional structure is the Miscanti Ridge (MR) that runs N10° from the border Chile-Bolivia southward with a series of segments totalling about 75 km. At its apparent southern termination, the MR is covered by a dense array of Plio-Quaternary volcanoes, but further south a similar ridge reappears in Argentina with a more NNE strike and contraction is transferred more to the west along the N-S-striking, 39 km long Toloncha Fault and associated fold. Farther south, a series of main fold/fault segments give rise to the La Casualidad Ridge, totalling about 100 km with a NNE-SSW to N-S trend. These three main structures are interpreted as fault-propagation folds, which locally show evidence of late Pliocene-Quaternary motions, both in the Chile and Argentina sections. Several coeval minor folds and reverse faults are present west of these structures. The important length of some of these structures and their age claim for further studies to assess if there is a possible seismic potential.

East and north of the MR, several swarms of normal faults are also present. They strike NW-SE north of the MR and N-S at the latitude of the MR. They affect deposits dated to Pliocene-Quaternary times on a stratigraphic basis, or radiometrically dated at 2.4-0.7 Ma BP. The normal fault swarms have length in the order of 8-24 km, and they are mostly located in flat areas, giving rise to graben structures. These data enable ruling out the hypothesis of a genesis linked to slope gravity effects, suggesting they are tectonic faults. Other NW-SE normal fault swarms are linked to caldera failure and resurgence.

These data allow us to underscore that the central Andean chain has been subject to the development of coeval contractional and extensional structures of regional importance. The average altitude of the areas affected by the late Pliocene-Quaternary folds and reverse faults is 3941 m, whereas the areas affected by the extensional tectonic structures have an average altitude of 4520 m. This is consistent with the interpretation that the normal faults here might have been induced by orogen collapse.

The change in strike of the normal faults from NW-SE to N-S at the latitude of the northern termination of the MR, may be explained as resulting from orogen-perpendicular collapse and by the inheritance of pre-existing structures that reactivated under the new extensional stress field.

This extensional structural setting is favourable to the transfer of magma to the surface especially within the core of the chain. Nevertheless, several volcanoes are located also ontop of compressional features such as folds and reverse faults, indicating that magma can rise also along paths subjected to a compressional stress state.

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FIGURE CAPTIONS AND TABLE

Figure 1. (A) Inset shows the location of the study area with the Northern Volcanic Zone (NVZ), the Central Volcanic Zone (CVZ), the Southern Volcanic Zone (SVZ), and the Austral Volcanic Zone (AVZ). (B) Structural map of the study area with main late Pliocene-Quaternary faults, folds, and calderas, based on new data from this work and previous papers and geological maps (Marsh et al., 1992; Servicio Geológico Nacional, 1996; Salfity and Monaldi, 1998; Sernageomin, 2003; González et al., 2009; Tibaldi et al., 2009; Bonali et al., 2012). Black boxes show location of corresponding figures. Letters *A* to *G* refer to geological sites cited in the main text. CP-Cerro Panizos caldera, COT-Calama-Olacapato-El Toro fault, GC-Guacha caldera, LV-Licancabur volcano, JV-Juriques volcano, LCR-La Casualidad Ridge, LP-La Pacana caldera, MR-Miscanti Ridge, OV-Ollague volcano, PG-Pastos Grandes caldera, SPA-San Pedro de Atacama, TV-Plio-Pleistocene Toloncha volcano, VC-Vilama caldera.

Figure 2. (A) Structural sketch map of the northern sector of the Miscanti Ridge (Chile), showing the main late Pliocene-Quaternary compressional structures (modified after Sernageomin (2003) and González (2009)); location in Figure 1. (B) Photo of reverse faults accompanied by folding of Pliocene ignimbrite deposits (Tucucaro-Patao ignimbrite, 3.1–3.2 Ma); location in Figure 2A. (C) Photo of a lava flow of estimated Pleistocene age whose frontal lobe is offset and uplifted along the Miscanti Ridge. Rose diagrams of strike is shown for the five normal faults and for the four reverse faults; stereo plot for field-surveyed reverse faults, with kinematics, is reported.

Figure 3. (A) Geological map of the Inacaliri Graben area (Chile) (modified after Sernageomin, 2003, Tibaldi et al., 2009, and Tibaldi et al., 2017a); field-measured vertical offsets of normal faults that create the graben are reported. Rose diagram of strike is shown for the 36 faults, stereo plot of the main field-surveyed normal faults with kinematics is reported. (B) Note the presence of the late Pleistocene-Holocene Pabellon lava dome (21°50'20"S - 68°09'15"W) growth on the NW-striking normal fault (modified after Tibaldi et al., 2009).

Figure 4. Geological-structural map of the De Jorcarda volcano and nearby Pleistocene-Holocene aligned vents; rose diagram of strike is shown for the 13 mapped faults.

Figure 5. *(A)* Geological-structural map with new studied normal faults that highlight the "*Sol de Manana graben*" (Bolivia) (modified after Tibaldi et al., 2009, and Brandmeier, 2014). Arrows indicate the location of field-measured vertical offsets. Rose diagram of strike is shown for the 36 faults; stereo plot of the field-surveyed normal faults with kinematics is reported. *(B)* Panoramic view of offset lava flows of possible late Pleistocene-Holocene age with a maximum dip-slip amount of about 30 m. (C-D) Detailed views of fault scarps belonging to the SW and NE part of the graben.

Figure 6. *(A)* Geological map of the area located around Laguna Verde (Bolivia), just north of the Argentina-Bolivia border (modified after Sernageomin, 2003, Tibaldi et al., 2009 and Brandmeier, 2014). Newly mapped normal faults affecting the area are reported. North of the Licancabur and Juriques volcanoes, normal faults mainly strike NW-SE, whereas to the south normal faults and extensional fractures strike about N-S and offset ignimbrites of the Purico Formation, dated at 1-1.3 Ma by de Silva and Gosnold (2007). Field-measured vertical offsets are reported as well as rose diagrams of strike is shown for the 47 faults; stereo plot of the field-surveyed normal faults with kinematics is reported. *(B-C)* Photos of a normal faults studied in the area, location in Figure 6A.

Figure 7. *(A)* Geological map of the studied area with the newly studied normal faults and extensional fractures (geological units after Sernageomin (2003) and Brandmeier, 2014). Green dots locate the structural stations, the respective plane to pole plots of measured joints and extensional fractures are reported. The number in the centre of the pole plot indicates the number of measurements, white arrows indicate the estimated σ_{Hmin} direction based on the statistical contouring of the average opening direction from the whole data set of extensional joints collected at each site. Blue-green colours represent lowest density of contour, whereas red colour represents highest density of data. Rose diagram of strike is shown for the 76 faults. *(B)* Photo of an open, 30-cm-wide, N-S-striking extensional fractures that dips to the east and shows a small (few cms) vertical component. *(C)* Photo of a set of N10°-striking extensional fractures in the Purico Ignimbrite. *(D)* Panoramic view of the N-S striking normal fault affecting the Purico Ignimbrite north of the ALMA Observatory.

Figure 8. *(A)* Geological-structural map of the area with normal faults located at the border Chile-Argentina (redrawn after Bonali et al., 2012; Sernageomin, 2003; Brandmeier, 2014). Yellow dots locate the structural stations, the respective plane to pole plots of measured extensional joints and fractures are reported. The number in the centre of the pole plot indicates the number of measurements, white arrows indicate the estimated σ_{Hmin} direction based on the statistical contouring of the average opening direction from the whole data set of extensional joints collected at each site. Blue-green colours represent lowest density of contour, whereas red colour represents highest density of data. Rose diagram of strike is shown for the 83 faults as well as the stress tensor calculated on 11 fault planes. *(B)* Photo of a 35-cm-open, N-S-striking extensional fracture located in the middle of the graben of Figure 6A. *(C-D)* Photos of about N-S-striking normal faults affecting the volcanic unit of Miocene age in the western and eastern part of the graben, respectively. The dashed line represents an offset river gully.

Figure 9. 3-D sketch of distribution of the main late Pliocene-Quaternary stress states in the study area. Note that σ_1 is horizontal and trends about E-W in the low lands east and west of the volcanic arc-Puna Plateau, where crust is thinner, whereas σ_1 is vertical in the highlands. In the northern part

of the study area, extension is more common where crust is thicker and gravity orogenic collapse is more probable. Crust thickness from McGlashan et al. (2008).

Figure 10. Shaded view of the study area, dark grey zones represent areas with elevation > 4000 m a.s.l.; normal faults are reported as well as the rose diagrams of the fault strike for the entire set of extensional structures (212) and only for normal faults (174) located at an elevation > 4000 m.

Figure 11. 3-D sketch illustrating the effect of the piling of tectonic units that may produce flexuring in front of the advancing thrust. Flexuring, in turn, may determine extension at the extrados of the flexure with reorientation of σ_3 that becomes horizontal and normal to the thrust strike. The fault-propagation fold portrayed is the La Casualidad Ridge.

Figure 12. Example of a volcanic centre exactly located in correspondence of the crest of the fault-propagation fold (at *24°48'26"S, 68° 3'51"W*), here corresponding to the La Cusualidad Ridge. White lines show bedding attitude.

Table 1. List of localities characterized by late Pliocene to Quaternary deformation. Deformation type, shortening direction, age of involved deposits, altitude and total length of the structures are reported.

Locality	**Deformation type**	**Shortening direction**	**Age of involved deposits**	**Altitude (m a.s.l.)**	**Total length (km)**
Northern Miscanti Ridge (Chile)	Main fold	N100°	3.1-3.2 Ma	4200-5000	40
Miscanti Ridge – Lake Miscanti (Chile)	Main fold	N100°	Plio-Pleistocene	4142-4380	35
Unnamed (Chile)	Fold/reverse fault	N120°	Pliocene	3930-4400	13
Toloncha Fault (Chile)	Fault (+ fold)	N90°	Pleistocene	3400-4000	27.3 (+ 11.7)
La Casualidad Ridge (Argentina)	Fold/reverse fault	N90°-100°	Post-3.1 Ma	3700-4950	100
14 km NW of Miscanti Lake (Chile)	Folds	N85°	3.1-3.2 Ma	3000-3700	14
10 km west of Miscanti Lake (Chile)	Folds and reverse faults	N90°	3.1-3.2 Ma and Pleistocene	2900-3900	9.7
North of Talabre (Chile)	Reverse fault	E-W	2.0-2.3 Ma	3600-3740	9
North of San Pedro de Atacama (Chile)	Main fold	N100°	4-4.14 Ma	3900-4100	9.5
Locality	**Deformation type**	**Extension direction**	**Age involved deposits**	**Altitude (m a.s.l.)**	**Total length (km)**
SW of Ollague volcano (Chile)	Normal faults	NE-SW	Plio-Pleistocene	3950-4600	8
Inacaliri graben (Chile)	Normal faults	NE-SW	Pliocene	4510-5200	19

East of Inacalari volcano (Bolivia)	Normal faults	NE-SW	Pliocene	4700-5700	13
Sol de la Manana graben (Bolivia)	Normal faults	NE-SW	1.3-0.7 Ma	4800-5250	13
Laguna Verde graben (Bolivia)	Normal faults	NE-SW	Plio-Pleistocene	4360-5500	24
South of Licancabur (Chile)	Extensional fractures	E-W	1.35 Ma	3950-4100	18
North of ALMA (Chile)	Normal faults	E-W	1.35 Ma	3336-3500	8.6
SE of La Pacana caldera (border Argentina-Chile)	Normal faults	E-W	Post-2.4 Ma	4380-4510	7.8