Counterclockwise rotation during the Cenozoic in the northwestern end of the Sierras Pampeanas, Argentina

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Abstract

Investigations on the Andean orocline revealed that it is characterized to the north by counterclockwise rotation of about 37° and, to the south, due to an clockwise rotation of about 29°. This rotation would have begun in the Upper Eocene as a consequence of the convergence of the Nazca and South American plates. In the transition zone between the Puna and the Sierras Pampeanas show a pattern of clockwise rotations. Our paper shows that the NE convergence of the plates generated the counterclockwise rotation of the NW end of the Sierras Pampeanas. The counterclockwise rotation of the mountain blocks of approximately 20° would have occurred on a horizontal plane within 10 to 15 km of depth favored by the caloric rise during magmatic activity at 13 Ma. The rotations of this set of mountain ranges generated local stress tensors with NE and NW strike that conditioned the development of valleys, basins, mineralized dikes, mineral deposits and disassociated alluvial fans from their origins. The Atajo fault had a ductile and brittle behavior. Its reverse vertical component disposes a mylonitic belt of the Sierra de Aconquija on the rocks of the Ovejería Block and the Farallón Negro Volcanic Complex and, its dextral horizontal component, developed curvatures that gave rise to pull apart basins and positive zones. It is probable that towards the Lower Miocene the Santa María valley, the Campo del Arenal, the Hualfín valley and the Pipanaco salt flat formed a large basin, barely interrupted by hills of very little relief.

Keywords: Neotectonic, Counterclockwise rotation, Andes, Sierras Pampeanas, Transcurrent faults, Morphotectonic

1 Introduction

The study area is located in the northwestern end of the Sierras Pampeanas of Argentina, on the continental edge of the retroarc, on the 150-175 km depth lines of the Wadatti-Benioff zone (Yañez and Ranero 1999), where the Farallón Negro Volcanic Complex gave rise to porphyry Cu-Au and epithermal Au deposits (Mn, Ag, As, Pb, Zn) (Figs. 1a y 1b). In accordance with the depth of the Wadatti-Benioff zone, most of the seismic foci occur between 150 and 300 km deep, and others less frequent, between 70 and 150 km deep (Fig. 1b).

The Sierras Pampeanas extend between 27º and 33º LS, where the Nazca plate sinks below the continent at low angles of 5° to 10° (Isacks et al. 1982), reaching an approximate length of 750 km from the Oceanic trench. To the north of 27° S the Nazca plate tilts with a higher angle (Isacks et al. 1982), registering in the Cenozoic a period of oblique convergence, trending NE (Cande 1983). The Sierras Pampeanas forms a chain of mountains in the Andean foreland, are attached to the Puna and Cordillera Oriental in the north and are separated from the Andean chain by the Desaguadero river valley in the south (Fig. 1a). González Bonorino (1950b) considers that the Sierras Pampeanas derive from the Puna by the dismemberment or subdivision of the blocks building them. It is probable that the Pampean horizontal subduction is related to two simultaneous collisions of aseismic mid-ocean ridges; the Copiapó ridge could control the northern limit of the horizontal subduction zone as does the Juan Fernández ridge in the southern region (Álvarez et al. 2014).

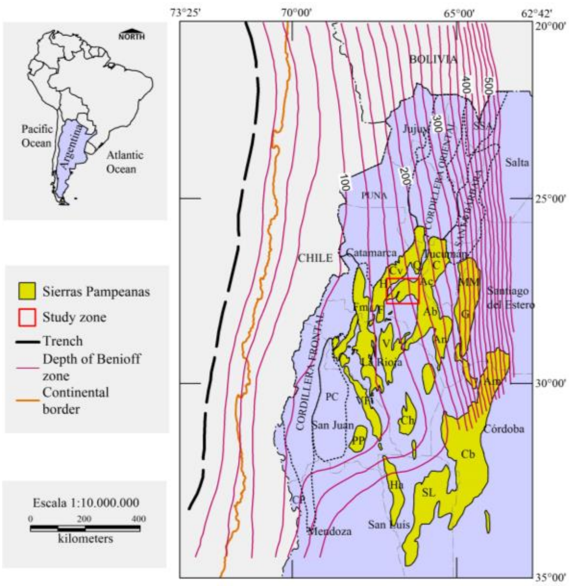

Figure 1a: Regional scheme of the Sierras Pampeanas and other Geological Provinces, NW Argentina and location of the study area. SSA: Sierras Subandinas. PC: Precordillera. CP: Cordillera Principal. Q: Quilmes range. Cv: Las Cuevas range. H: Hualfín range. F: Fiambalá range. V: Velazco range. Fm: Famatina. VF: Valle Fértil range. PP: Pie de Palo range. Ha: La Huerta range. C: Cumbres Calchaquíes. Ac: Sierra de Aconquija. Ab: Ambato. An: Ancasti range. Ch: Chepes range. MM: Dorsal Mujer Muerta. G: Guasayán range. Am: Ambargasta range. Cb: Sierras de Córdoba. SL: San Luís range.

From a spatial perspective, as a whole, the Sierras Pampeanas have an elongated morphology in a NNW strike, which contrasts notably with the NS strike of the Andean chain. (Fig. 1a). They are made up of mountains with NS, NNW and NNE strike, separated by large sedimentary basins and megafractures with dextral and sinestral horizontal displacement, evidencing sinestral rotation of the smaller mountain ranges (Gutiérrez 2000; Zampieri et al. 2012). (Fig. 1a). The Ambato Block is an example of counterclockwise horizontal rotation of the mountain ranges, it was displaced to the east by the convergence of plates in the Cenozoic, with its rotation center in the north, compressing against the Sierra de Aconquija (Gutiérrez 1999; Gutiérrez and Mon 2008; Gutiérrez et al. 2019). The deformation of the Andean foreland and the eastward rotation of the Sierras Pampeanas on a vertical axis (Miocene-Plio-Pleistocene) have been linked to the interaction of the Nazca plate (Isacks et al. 1982; Pilger 1984; Marrett et al. al. 1994; Yañez and Ranero 1999; Gutiérrez 2000; Jordan et al. 2001; Ramos et al. 2002; Somoza et al. 2002; Gutiérrez et al. 2002; Gutiérrez and Mon 2017a). The tectonic forces that deform a region act on a crust with inhomogeneities and particular physical-chemical properties, influenced, among other variables, by the temperature that enables the plasticity of quartz (Voll 1961; Passchier 2005) and by magmatic heat supply that weakens the rocks (Schilling et al. 2006; Sawyer 2008; Sawyer et al. 2011) favoring the development of ductile shear zones (Rosenberg and Handy 2000; Holtzman et al. 2003).

Planar subduction of the Nazca plate beneath the South American plate during the Miocene exhumes igneous-metamorphic basement blocks in the Andean foreland, where the Sierras Pampeanas form basement thrusts, which possibly cut the entire crust (Jordan and Allmendinger 1986; Kley et al. 1999). Previous work elaborated different models to relate the deformation of the foreland with the thermal structure and the mechanical properties of the South American lithosphere (Isacks 1988), with the geometry of the subducted plates (Barazangi and Isacks 1976; Jordan et al. 1983; Pilger 1981) and with previous stratigraphic and structural inhomogeneities (Allmendinger et al. 1983; Allmendinger and Gubbels 1996). Ramos et al. (2002) interpret that the thick - skinned basement uplift of the Sierras Pampeanas is due to the thermal weakening of the crust associated with eastward migration of arc magmatism that acted to elevate brittle-ductile subsurface de'collments.

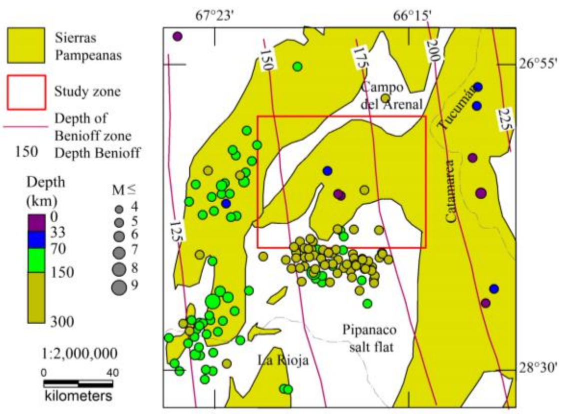

Figure 1b: Sketch showing the study area in the context of the depth lines of the Wadatti - Benioff plane together with the position of the seismic sources points and their magnitudes.

The continental sector of South America, east of the Andes, is characterized by a north-south compression, perhaps due to the collision with the Caribbean plate and which would have originated the Andean orocline, in a tectonic scheme of east-west compression (Assumpcao 1992). The Andean orocline (Carey 1955) is of the secondary type, where the crust and the lithospheric mantle are involved (Johnston et al. 2013), characterized to the north by a counterclockwise rotation of about 37° (the Peru orocline) and, to the south, due to an clockwise rotation of about 29° (the Arica orocline), which would have begun in the Upper Eocene as a consequence of the convergence of the Nazca and South American plates (Taylor et al. 1998; Coutand et al. 1999; Arriagada et al 2008; Johnston et al 2013). Magnetostratigraphic study and paleomagnetic data from Cretaceous and Neogene rocks from the transition zone between the

Puna and the Sierras Pampeanas (Hualfín – Santa María) show a pattern of clockwise rotations (Butler et al. 1984; Aubry et al. 1996). Dextral strike slip along the transition between the Puna and the Sierras Pampeanas is demonstrated by structural studies (Jordan et al. 1983; Allmendinger 1996; de Urreizteita et al. 1993); however, this transition was interpreted as sinestral, considering morphotectonic expressions and paleomagnetic data (Gutiérrez 2000; Gutiérrez and Mon 2017b; Peña Gómez 2012). The clockwise rotation pattern in the Andes of northern Chile (Precordillera and Cordillera Frontal) extends up to 29° S, showing that, at this latitude, the Incaic deformation ends, which would have begun in the Paleogene (Peña Gómez 2012).

Our study is a contribution to the knowledge of the neotectonic deformation of large mountainous blocks formed above flat-lying subductions zones and intense magmatic activity. (Figs. 1a, 1b and 2). The sinestral rotation of this set of mountain ranges is demonstrated, which, pushed by the convergence of plates, collided with the Sierra de Aconquija and, to accommodate the deformation, they had to rotate counterclockwise, favoring the process by the thermal weakening of the crust generated by the magmatic rise. During this tectonomagmatic process the following events occurred:

- Gravity faults and transcurrent faults with vertical displacement components were generated that accommodated the displacements of the ranges
- Intramontane basins were developed and magmatic intrusions were produced with the formation of mineral deposits
- Alluvial fans are disconnected from their riverbeds.

In the study area, a set of mountain ranges (Cerro Pampa, La Ovejería, del Venado, Talayacu, Carrizal and Algarrobal) which in this paper we call the Ovejería Block, are separated by the Atajo fault of the ranges (Capillitas, Santa Bárbara, Yacochuyo, Amanao and the El Durazno, Atajo and Huayco hills), which constitute the southern end of the Sierra de Aconquija (Fig. 2). The NE strike of the mountain ranges that make up the Ovejería Block contrasts markedly with the NS strike of the Andean chain and the NNW regional strike of the Sierras Pampeanas (Fig. 1a). The region is known in the literature mainly for the Farallón Negro Volcanic Complex (Llambías 1972), which was active between 13 Ma and 5 Ma (Sasso 1997) (Fig. 2).

2 Literature review

2.1 Regional geology

The study area was mapped by the geological Map of Capillitas (González Bonorino 1947). The oldest units are represented by metamorphic rocks of the Suncho Formation, attributed to the Upper Precambrian – Lower Cambrian (Mirré and Aceñolaza 1972). The rocks of the Granito Capillitas (González Bonorino 1950a), with a wide areal distribution, intruded into the metamorphic rocks in the Upper Ordovician – Lower Silurian (Mc Bride et al. 1975; Durand 1980). On the eastern edge of the Atajo fault, from Cerro Atajo to the Amanaos range, in the south, a mylonitic zone extends about 1,000 meters wide (Aceñolaza et al. 1982) (Fig. 2). The Atajo fault disposes the metamorphic rocks onto the tertiary sedimentary units to the northwest of the Cerro Atajo and generated a thrust of mylonitic metamorphic rocks to the south of the same hill (Rasuk 2012) (Fig. 2). The granitic and metamorphic rocks are discordantly overlain by Paleogene continental sediments, that were intruded by the rocks of the Farallón Negro Volcanic Complex (González Bonorino 1950a), on which Neogene continental sediments were subsequently deposited (González Bonorino 1947 - 1950a; Llambías 1970 - 1972) (Fig. 2). The dominant extrusive units in the Farallón Negro Volcanic Complex are volcanic-tuffaceous andesitic breccias (purple breccias and polymictic breccias), made up of poorly stratified dacitic and basaltic hornblende-pyroxene andesite breccias, with a gray, violet-gray or greenish-gray matrix (Llambias 1970).

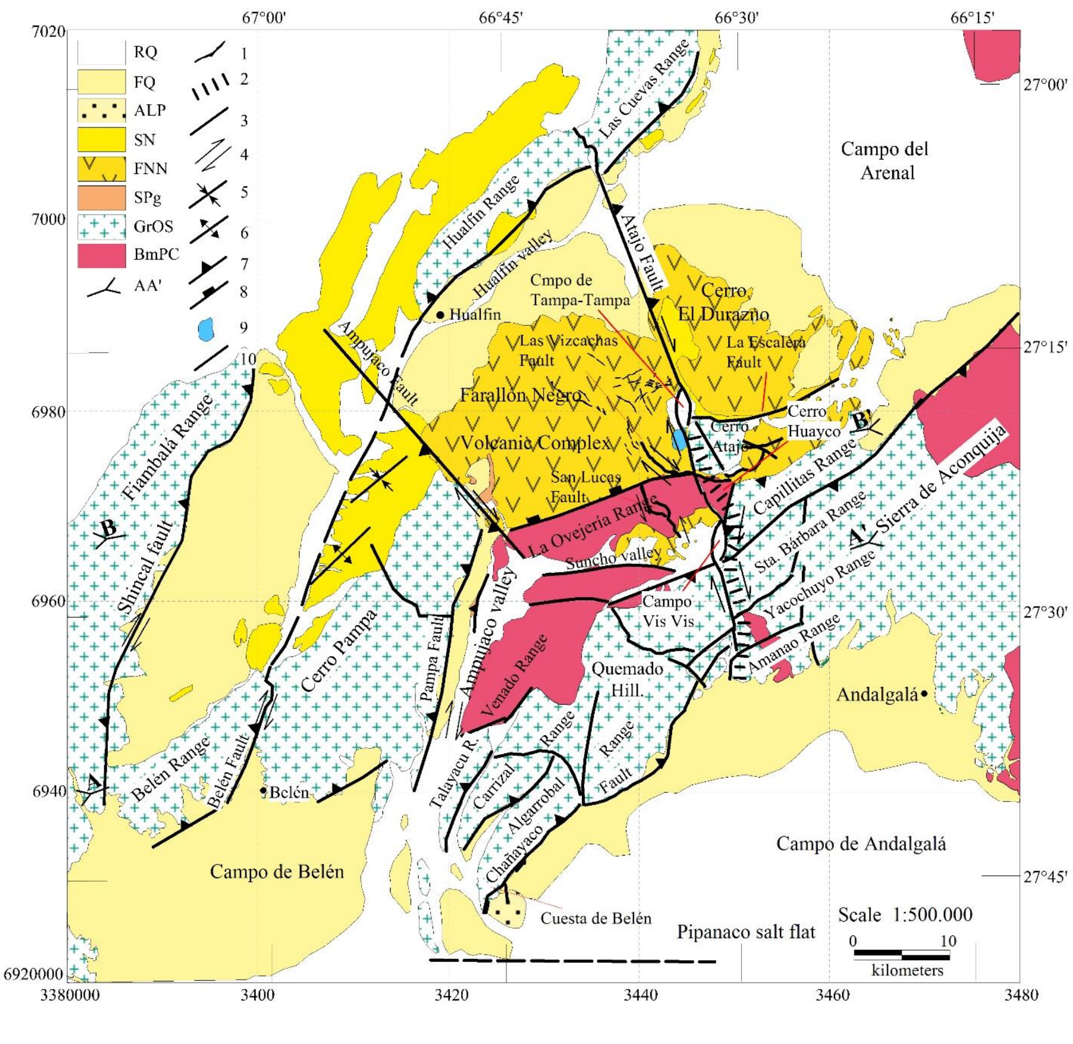

Figure 2: Geological map of the study area. RQ: Recent sedimentary deposits. FQ: Foothill deposits, Quaternary. ALP: Alluvial fan, Lower Pleistocene. SN: Sedimentary rocks, Neogene. FNN: Complejo Volcánico Farallón Negro, Neogene. SPg: Sedimentary rocks, Paleogene. GrOS: Granito Capillitas, Upper Ordovician - Lower Silurian. BmPC: Metamorphic basement, Upper Precambrian - Lower Cambrian. 1: Mineralized dikes (8.59 – 5.95 Ma). 2: Mylonitic belt. 3: Lineaments. 4: Transcurrent fault. 5: Syncline. 6: Anticline. 7: Reverse fault. 8: Normal fault. 9: Natural dam. 10: Blind fault.

Intrusive rocks and dike swarms take proper names (Dacita Arroyo Alumbrera, Andesita El Durazno, Diques Cerro El Durazno, Riolita Las Casitas, Andesita La Chilca, Diques El Águila, Dacita Agua Tapada, Riodacita Macho Muerto y Riolita Los Leones) according to its particular characteristics and emplacement age, dated (Ar/Ar) between 12.56 Ma and 5.9 Ma (Sasso 1997; Sasso and Clark 1999).

A detailed analysis of the stratigraphy and geometry of the Tertiary sedimentary basins of the surrounding region was carried out by Bossi and Muruaga (2009a), who point out that the initial Paleogene fill, made up of the Hualfín and Saladillo formations, appears associated with asymmetric depocenters controlled by normal faults. The El Morterito Formation is considered equivalent to the Calchaquense-Araucanense and is attributed to the Miocene due to the presence of fossils vertebrate (Turner 1962) and discordantly disposed on the igneous-metamorphic basement (Durand 1980). Galli et al. (2012) characterized the red banks deposited by fluvial systems corresponding to the Hualfin Formation (Eocene - Lower Miocene?) and the clastic, volcaniclastic accumulations and interbedded primary volcanic deposits of the Farallón Negro Volcanic Complex (Upper Miocene - Pliocene). Lacustrine sedimentites, similar to the San José Formation (Miocene) that crop out in the Santa María Valley, were identified and described on the eastern slope of Cerro Pampa. For Ruskin et al. (2011) there is no evidence that the Paraná seaway during the Miocene flooded the promontory in the Sierras Pampeanas of Argentina, the period of climate change that resulted in lake deposit is equally likely. Ancient alluvial fans, affected by faults, were described in the Ampujaco Valley and in the southern end of the Sierra del Venado (Herazo et al. 2017). The Quaternary is represented by conglomerates, gravels and sands with components of volcanic rocks and by sandy and silty aeolian deposits (Penck 1920; Bossi and Muruaga 2009a). Thick alluvial fans of the Las Cumbres Formation were identified on the western edge of the Velazco range and were attributed to the Early Pleistocene (González Bonorino 1972; Sosic 1972; Bossi et al. 2009b). These units reach 600 m in thickness and their Pleistocene age is confirmed by the presence of fossil dacipodid plates found in the lacustrine layers and they are correlatable with the conglomerates of the Guanchín Formation (Bossi et al. 2009b) in the Bolsón de Fiambalá (Bossi et al. 1989; Sosa Gómez et al. 1993). These conglomerates of the northwestern Pampean ranges are related to the climax of the ascent of mountain blocks such as the Punaschotter (Penck 1920; Bossi et al. 2009b). The conglomerates of the Las Cumbres Formation and the conglomerates of the Guanchín Formation can be correlated with the conglomerates of the Yasyamayo Formation in the Santa María valley (Toselli et al. 2018), which has an age between 2.9 and 1.5 Ma (Strecker 1987; Bossi et al. 2001).

2.2 Tectonic scheme

International research on crustal deformation and mountain building in order to understand the morphotectonic evolution of the central Andes used different methodologies and data that helped to establish shortening direction and kinematic models. Riller and Oncken (2003) suggest a model of the upper crust segmented by rhomboid-shaped domains on whose edges differential horizontal displacements occur as a result of the shortening in the NW and ENE strike. Throughout the Puna, changes in the direction of shortening were dated between 9 Ma (Cladouhos et al. 1994), 4 to 1 Ma (Marrett and Strecker 2000) and in the Pleistocene (Marrett et al. 1994; Allmendinger et al. 1989). In the Eastern Cordillera, curved structures and vertical uplifts were attributed to NS strike stress components generated by oblique shortening during Miocene-Pliocene deformation (Mon 2001). The decoupling surface from where the basement blocks of the eastern Andean edge rise on one or both of its flanks has various hypotheses based on surface and subsoil studies, which place it at 25 km and between 10 and 15 km deep (González Bonorino 1950b; Vergani y Starck 1989; Comínguez and Ramos 1991; Grier et al. 1991; Zapata and Allmendinger 1996; Mon and Drozdzewski 1999). The deformation and uplift of the sierras should have started at 13 Ma (Pilger 1984), registering important uplifts between 7.6 - 6 - 4 – 2.97 Ma, continuing until 0.6 Ma and after 630 BP (Strecker 1987; Jordan and Alonso 1987; Strecker et al. 1989; Kleinert and Strecker 2001; Carrera and Muñoz 2008; Gutiérrez et al. 2021). The Sierra de Aconquija experienced 10–13 km of vertical rock uplift, ~4–5 km of peak surface uplift, and 6–8 km of exhumation since around 9 Ma (Löbens et al. 2013) and, in the Holocene (630a BP), the thrusting of the Cumbres Calchaquíes on the Sierra de Aconquija occurs (Gutiérrez et al. 2021). Mortimer et al. (2009) document the evolution of the El Cajón-Campo del Arenal basin in an initial undeformed state, starting at 11 Ma. The internal deformation of the basin begun at 6 Ma, together with the exhumation of the northern Quilmes range. Towards the Middle Pliocene, the total uplift of the Quilmes range has separated the El Cajón-Campo del Arenal basin of the the Santa María basin. The Farallón Negro Volcanic Complex is located to the north of the studied area (Fig. 2) and is limited to the east by the Atajo fault. It has an elliptical geometry whose major axis strike to NW and its current morphology is due to the collapse of the volcanic structure that reached 6 km in height (Llambías 1972). Rossello et al. (1996) interpret that the elliptical geometries of the cartographic features of the Bajo La Alumbrera deposit and the Cerro Galán volcanic caldera are related to Andean deformation and constitute kinematic indicators.

In the study area and surrounding regions, earthquake focal mechanisms and fault geometries indicate NE and other NW-trending compressive tectonic stress (Jordan et al. 1983; Allmendinger 1996; Proffet 2003; Somoza and Ghidella 2005; Lavenu 2006). In the Bajo La Alumbrera deposit, the presence of normal faults with horizontal displacement components indicates NE extension processes, before 6.75 Ma (Sasso and Clark 1999). The dikes and subvolcanic intrusives of the Farallón Negro Volcanic Complex were emplaced following a structural pattern that, at the beginning of the volcanic activity, had a preferential NE strike. The following change to a NW position, between 8.59 - 5.0 Ma, as a result of the rotation of the deformation in this sense has great influence on the formation of porphyry copper and epithermal deposits (Gutiérrez et al. 2002). South of the La Ovejería range, Palacio et al. (2005) identified a calderic structure in the Vis Vis field, which is associated with the Miocene volcanic event of the Farallón Negro district (Fig. 2). Seggiaro et al. (2014) determine four successive Andean deformational events for this region and, Gutiérrez and Mon (2017a) recognize a fold belt 100 to 200 km wide, which extends from the northern end of the Precordillera to the Santa Bárbara System and evidences a NNE compression, limited by the Salta and Tucumán lineaments. In this belt, the Neogene and Quaternary tectonic evolution of the Ampujaco valley, among others, was produced by the reactivation of a previous structural geometry (Gutiérrez and Mon 2017b).

3 Methodology

The analysis of the tectonic morphology and the interpretation of morphotectonic processes was carried out with the visual interpretation of ASTER, LANDSAT, SENTINEL and SRTM (Topographical Radar) (ESA; USGS) satellite images. These images were also used for the elaboration of thematic cartography. With these tools the morphotectonic features of the region could be interpreted and tectonic deformation processes could be elucidated. They also served to locate suitable places to find kinematic indicators and make measurements of structures that could document the tectonic processes that shaped the current landscape. The field data was collected during campaigns carried out over several years, from which 193 measurements of fractures and faults are recovered, 101 measurements of schistosity planes in metamorphic rocks, 27 measurements of stratification planes in Tertiary sedimentary rocks, 31 measurements of planes of pseudostratification in volcanic rocks and 31 measurements of bedding planes in Quaternary conglomerates. These data were processed with the Stereonet v11 software (Allmendinger et al. 2012; Cardozo and Allmendinger 2013) to determine the most frequent orientations from the population, that respond to a state of local effort.

4 Results

4.1 Current morphotectonic scheme

The NE-striking compressive strain of the Andean tectonics (Somoza and Ghidella 2005; Lavenu 2006) acted on a morphostructural landscape with a dominant NS orientation, generates submeridian striking structures. The mountain ranges were uplifted during the Pliocene by reverse faults located on one of its edges (González Bonorino 1950b). Continental deformation, from north to south, in the Sierras Pampeanas, owes its origin to the Juan Fernández ridge, which reached the area of the Farallón Negro Volcanic Complex 9 to 10 Ma ago (Pilger 1981; Cross and Pilger 1982). During the Quaternary, the Andean compressive tectonics also generated extensive and transpressive processes that shaped the current morphology, segmenting and/or redirecting the Andean structures and affecting Pleistocene sediments and producing anomalies in the drainage network (Gutiérrez 1999-2000; Mon 1999; Gutiérrez and Mon 2004-2008; Gutiérrez and Mon 2017c; Gutiérrez et al. 2019; Gutiérrez et al. 2021).

During the Cretaceous, the retroarc zone was controlled by extensional processes that generated rift basins. Neogene and Quaternary tectonic activity in the study area could also have evolved by reactivation of some previous structures associated with the Cretaceous Rift, as occurred in neighboring areas (Gutiérrez et al. 2019; Gutiérrez et al. 2021). The previously uplifted terrain favored the development of reverse faults, transcurrent faults and magmatic ascent (Gutiérrez and Mon 2017b). To the north of the La Ovejería range, the Farallón Negro Volcanic Complex (Llambías 1970) developed between 12.5 and 5.1 Ma (Sasso and Clark 1999) (Fig. 2). The uplift of the marginal blocks would have started at 13 Ma (Pilger 1984), but the current morphostructural landscape in the Sierras Pampeanas, whose deformation has records at 7.6 - 6 - 4 and 2.97 Ma and continuing until 630 BP (Strecker 1987; Strecker et al. 1989; Carrera and Muñoz 2008; Gutiérrez et al. 2021), is represented by mountain ranges and mountainous blocks dismembered into smaller mountain ranges with different strikes.

4.1.1 Morphostructure

The work area is located between the Sierra de Aconquija to the east and the Sierra de Fiambalá to the west. To the north are the Hualfín – Las Cuevas ranges. To the northeast it borders the Campo del Arenal and to the south are the fields of Belén, Andalgalá and the Pipanaco salt flat (Figs. 2 and 3). The Fiambalá, Hualfín - Las Cuevas and Belén ranges are tilted to the northwest by reverse faults on their eastern edges and separated from the study area by the Hualfín valley (Fig. 3). The Fiambalá range strike NNE and the Hualfín and Las Cuevas ranges strike NE. This set of ranges is cut to the north by the Atajo fault and to the south by the Ampujaco fault, through which they had a dextral displacement (Figs. 2 and 3). The Hualfín valley widens to the south, between the Fiambalá and Pampa hills, and is encased between the Belén range and Cerro Pampa (Figs. 2 and 3).

4.1.1.1 Ranges and hills: The Atajo fault forms a regional structure through merging morphostructural units that experienced different behaviors during the Andean tectonics. To the east of the Atajo fault are the ranges that constitute the southern foothills of the Sierra de Aconquija (Cerros Atajo, Huyaco and the Capillitas, Santa Bárbara, Yacochuyo and Amanao ranges) (Fig. 3). The Cerro El Durazno is a remnant promontory of the cone of the Farallón Negro volcano that was cut by the Atajo fault. The Cerro Atajo has scars that show the sliding and collapse of its SW flank, corresponding to at least ¼ of its Surface. Cerro Huayco has a triangular morphology whose western side joins the eastern edge of the La Ovejería range (Figs. 2 and 3).

To the west of the Atajo fault are the ranges that make up the Ovejería Block and the Farallón Negro Volcanic Complex (Figs. 2 and 3). To the north of the La Ovejería range, between 13 and 5 Ma, the magmatic activity in the region triggered the emplacement of a volcano, which may have reached 6,000 m in height (Sasso 1997); its geological units were called the Farallón Negro Volcanic Complex and gave rise to vein-like Au (Mn, Ag, As, Pb, Zn) and Cu-Au porphyry mineral deposits (Llambías 1970). The caldera of the volcano has an oval morphology with NW strike and occupies an approximate area of 166 km^2, but the extrusive volcanic units cover a larger area (Fig. 2).

The La Ovejería range is made up mainly of metamorphic rocks, is 24.5 km long, about 7 km wide and reaches 3,100 meters above sea level. The Venado range represents a 45.4 km long block, 23.6 km wide and rises 2,700 ma.s.l.; It is made up almost entirely of granitic rocks. The Belén range-Cerro Pampa, 57.4 km long and 16.6 km wide, is made up of granitic rocks and the northern end reaches 3,200 ma.s.l. (Fig. 2). South of the Venado range, separated by the Talayacu River, are the Carrizal and Algarrobal ranges, which, in turn, are separated by the La Agüita River. The Carrizal range is about 14 km long and the Algarrobal range about 22 km long. The Carrizal and Algarrobal ranges join to the north with Quemado Hill; Together they form a block of NE strike, made up of granitic rocks, about 40.5 km long and 14 km wide (Fig. 2).

4.1.1.2 Valleys and fields: Between the Venado range to the east and the Cerro Pampa to the west, the Ampujaco valley extends with a NNE strike; at its widest part it reaches 8 km in length (Fig. 4a). Towards the north, this valley connects with the narrower Suncho valley, which strike E-W, separating the Ovejería and Venado ranges, through which the Suncho river flows towards the Ampujaco valley (Figs. 2, 3 and 4a).

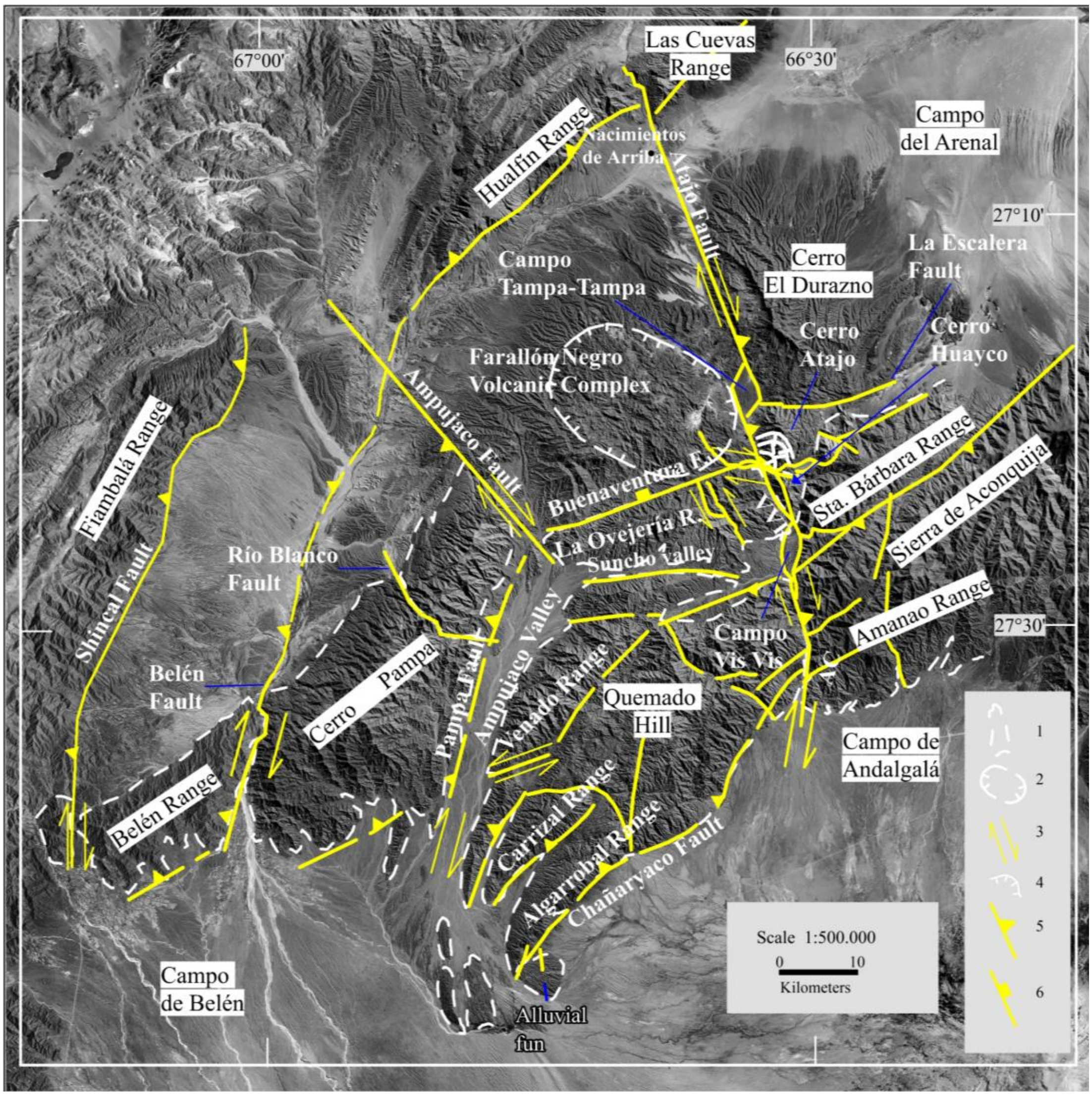

Figure 3: Current morphotectonic scheme of the study region. Structures are marked with yellow lines. The blue lines are indicators of place names. 1. White cut lines mark the outline of the ranges. 2. White cut line with hatched and oval shape indicates the Farallón Negro caldera. 3. Transcurrent fault. 4. Landslides. 5. Reverse fault. 6. Normal fault. VVR: Vis Vis river.

The Tampa Tampa (to the north) and Vis Vis (to the south) fields are located on the western edge of the Atajo fault and occupy areas of 8.6 km^2 and 6 km^2, respectively. These fields were identified as calderic structures with which mineralized zones are associated (Llambías 1970; Palacio et al. 2005) (Figs. 2 and 3).

4.1.1.3 Alluvial fans of the Ampujaco Valley: On the eastern flank of Cerro Pampa there are alluvial fans with particular morphological characteristics that differentiate them from other adjacent ones, identified as the second level of the area (Fig. 4a). To the south of the Ampujaco river valley, half-buried remains of alluvial fans can be seen, between 4 and 6 km long and up to 2 km wide, similar to those on the eastern flank of Cerro Pampa (Figs. 2 and 4a). One of these piedmont deposits (Figs. 4a and 5a) is made up of sandstone from base to top with intercalation of lenticular conglomerates with matrix support. Towards the top it passes into fine stratified conglomerates, with a predominance of metamorphic clasts, granites and vulcanites. The distal zone of the fan was eroded, leaving terraced levels approximately 5 meters thick. Laterally, this deposit is covered by a poorly selected conglomerate facies, load-bearing clast with a fine matrix, gravel-sized clasts of granitic, metamorphic and scarcely volcanic composition; the blocks are larger, sub-angular, approximately 50 cm in diameter, predominantly granitic in composition, compared to the underlying fan. In the distal zone, to the north, the conglomerate disappears below a stratified cenoglomerate at the base (35º NW dip), in contact with the Morterito Formation (very cohesive orange-brown sandstones with 58º W dip of the strata) (Fig. 5b).

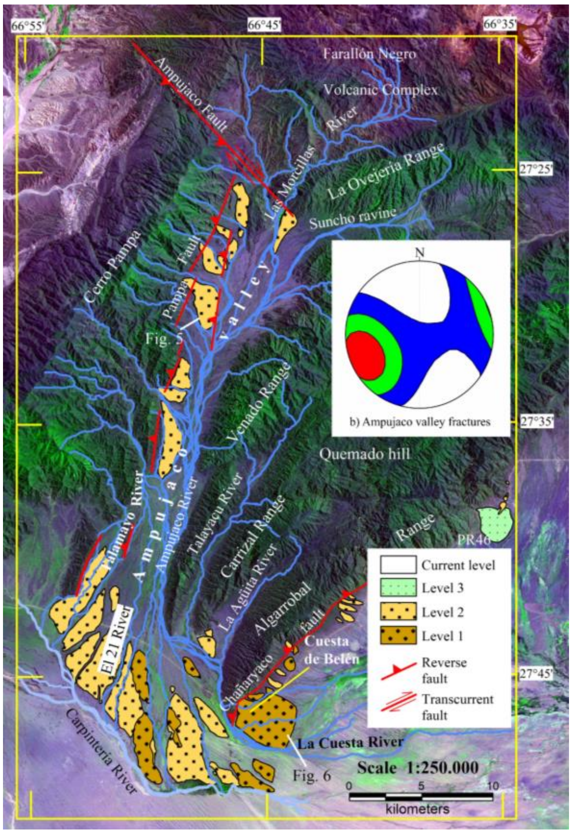

Figure 4: a) Scheme of the alluvial fans in the Ampujaco valley and eastern edge of the Algarrobal range. It is possible to distinguish 4 levels of alluvial fans. Fig. 5 and 6 are indicated in the map. b) Statistical diagrams of the fractures in Schmidt's equiareal network, lower hemisphere. PR46: Provincial route N° 46.

To the south of the outcrops of the Morterito Formation (Fig. 5b), below the cenoglomeradic-conglomeradic sequence, there is a sedimentary sequence approximately 11 meters thick, of stratified greenish-yellowish pellets (dip 35° NW), with concretions, which due to their lacustrine characteristics can be correlated with the San José Formation (Bossi and Palma 1982) of the Santa María Valley (Herazo et al. 2017) (Fig. 5c).

The different dips of these sedimentary units allow us to interpret the presence of a reverse fault, blind, verging to the east, which produced the dip to the west of the geomorphological surface of the terraced levels of the alluvial fans (Fig. 5a).

4.1.1.4 Alluvial fans of the Algarrobal range: At the southeastern end of the Algarrobal range, a geoform with an E-W strike represents an alluvial fan with a surface area of 12,500 m^2; the apex of the fan is located ca. 1,200 ma.s.l. and is partially affected by the Chañayaco reverse fault (Figs. 2 and 4). The Cuesta de Belén (PR46) crosses the northern end of the deposit, which corresponds to Level 1 of alluvial fans in the area (Figs. 4a and 6a). Towards the north and along the same flank of the range, remains of alluvial fans similar to the one described and others corresponding to the second level can be seen (Fig. 4a). The alluvial fan of the Cuesta de Belén has a typical morphology. It presents a raised relief and its geomorphological surface is wavy, dissected by the drainage network, evidencing intense water erosión. In the middle part to the north, the fans is segmented by faults. The fan consists predominantly of conglomerate, with decreasing grain size to up, generally well selected and cohesive, load-bearing clasts, gravel-sized and isolated blocks up to 1.5 meters in diameter. The matrix is sparse in the facies near the foothills and more abundant in the distal and lateral facies; bedding is tabular parallel (095°/55°), sloping towards the base and nearly horizontal towards the top (Fig. 6b). The clasts are rounded to subrounded, spherical, subprismatic and discoidal in shape; constituted by lithic fragments of gray and pink granite, porous volcanics and few clasts of metamorphic composition (Herazo et al. 2017).

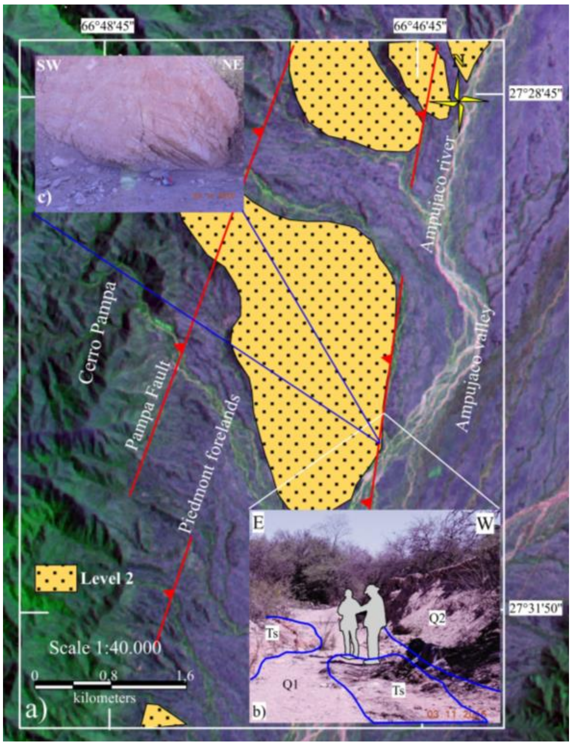

Figure 5: a) Detailed view of the piedmont deposits and its relations with the Pampa fault, in the Ampujaco valley. The reactivated, external fault is blind, but it is evident because it affects Tertiary sediments and Quaternary conglomerates. b) TS: Morterito Formation (Tertiary), reddish brown color (273°/58°) and consolidated quaternary conglomerate (Q2: 275°/35°) raised by the Quaternary reactivation of the Pampa fault. Q1: fluvial sediments and Quaternary terraced deposits. c) San José Formation.

The conglomerate deposit in some sectors lies on granitic basement or in contact with the undifferentiated Tertiary composed of brown, friable sandstones with abundant gypsum. In the contact between the latter, a continuous level of fault breccia with a 118º/55º strike, approximately 5 cm thick, is observed (Fig. 6b). The geomorphological characteristics of its surface and conglomeratic composition are very different from those of the adjacent fans (Levels 3 and 4). Levels 3 and 4 are modern alluvial deposits, coalescent, with a flat geomorphological surface, with an abundant sandy-silty support matrix (Herazo et al. 2017). To the NE of the Cuesta de Belén, the tectonic morphology of an alluvial fan (Level 1) of smaller dimensions than the previous one can also be observed, but also very consolidated and arranged on granite rock (Figs. 4a, 6a and 6c). This fan is far from the mountainous front and is affected by the Chañaryaco reverse fault, which disposes the conglomerate layers with a strong tilt to the SE (133°/48°) (Figs. 6a and 6c).

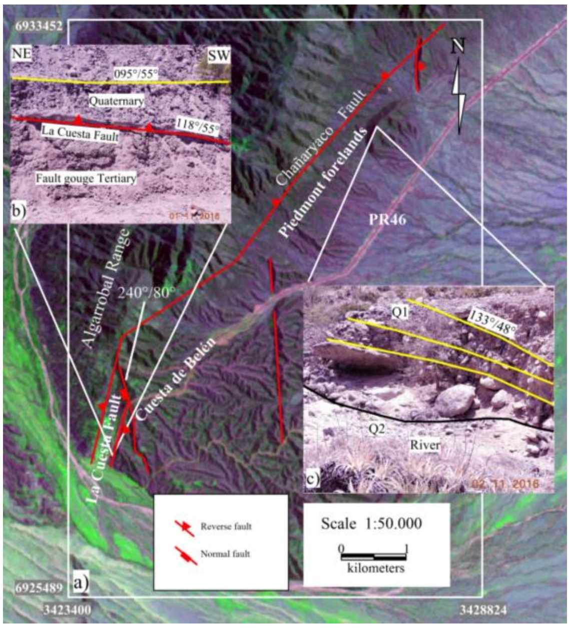

Figure 6: a) Detailed view of the neotectonic faults that are generated in the foothills and of the tectonic morphology of the alluvial fans raised by these faults. The new faults have a different orientation and inclination to the Chañaryaco fault and are generated far from the main fault. b) Stratigraphic sequence that alternates banks of thick, rounded conglomerates (the stratification is indicated by the yellow line: 095°/55°), with banks of coarse, brown, friable sandstone, with abundant sheets of gypsum. The reverse fault (indicated by the red line: 118°/55°) brings the sandbar into contact with the upper conglomerate bank. The fault plane is about 3 m thick. c) View of the counter slope of the alluvial fan made up of rounded pebbles (the yellow line indicates the stratification: 133°/48°). The Chañaryaco reverse fault disposes the conglomeratic layers with dip to the NE. The conglomerates that form the alluvial fan are arranged on granite rock. The contact between the quaternary units is indicated with a black line: Q1, conglomerates of the alluvial fan, older; Q2 river sediments.

The alluvial fans at the southern end of the Ampujaco River and the SE end of the Algarrobal range, corresponding to Levels 1 and 2 (Fig. 4a), are geoforms unrelated to the elements necessary for their formation (such as the raised relief at its head, the source area of the materials, a transport drainage, etc.), which managed to accumulate these volumes of rock that today are strongly consolidated and in an advanced erosion stage. The alluvial fans described present a coarse granular composition, high relief, deep dissection due to surface drainage, affected by faulting. This contrasts markedly with the younger alluvial fans (Level 3 and current level) (Fig. 4a), with little dissected reliefs. and not affected by faults. These characteristics of the alluvial fans of Levels 1 and 2 allow us to interpret that they could correspond to the Pliocene - Pleistocene.

4.1.2 Structures

4.1.2.1 Atajo fault: The Atajo fault, with NNW strike, measures 69.5 km in length (Figs. 2, 3 and 7a), has a reverse vertical component, dipping 60° and 80° to the east. In the northwest area of Cerro Atajo, this fault thrusts the granitic and mylonitic rocks over the Tertiary sedimentary rocks and over the volcanic rocks of the Farallón Negro Volcanic Complex (Figs. 2 and 8a) and, to the south of Cerro Atajo, the mylonitic rocks over metamorphic rocks (Figs. 2 and 7b). It also has a component of dextral horizontal movement, as revealed by the displacements between the Hualfín - Las Cuevas and La Ovejería - Cerro Huayco ranges (Figs. 2, 3, 7 and 11) and by the secondary conjugate structures that accompany it (Figuras 2, 7a and 8c). The Tampa Tampa and Vis Vis basins were identified as caldera structures with which mineral deposits are associated (Llambías 1970; Palacio et al. 2005) (Fig. 2). The morphology of the Atajo fault interpreted from satellite images, the data obtained in the field and the morphologies of the

Tampa Tampa and Vis Vis basins associated with mineralized zones, allow us to interpret that the fault generated releasing and restraining bend zones (Fig. 7). The releasing bend zones are associated with the Tampa Tampa and Vis Vis basins, and the restraining bend zone is associated with the western edge of Cerro Huayco (Fig. 7). The Tampa Tampa field is located on the northeast edge of the volcanic caldera, northwest of Cerro Atajo. It is about 8.6 km^2 and the overlap of faults is of the order of 4 km (Fig. 7a). The Vis Vis field is located south of the La Ovejería range, it is elongated, occupies an area of 6 km^2 and the overlapping of faults is of the order of 4.5 km (Fig. 7a). Between both pull-apart basins, the Atajo fault developed a restraining stepover, between the edges of La Ovejería range and Cerro Huayco, 4.2 km long (Fig. 7a). The Cerro Huayco was part of the La Ovejería range. The Atajo fault cut the northeast end of the La Ovejería range generating the dextral displacement of the Cerro Huayco, tilting the schistosity planes of the metamorphic rocks that compose them towards the west, in the La Ovejería range and, to the east, in the Cerro Huayco (Figs. 2 y 7a).

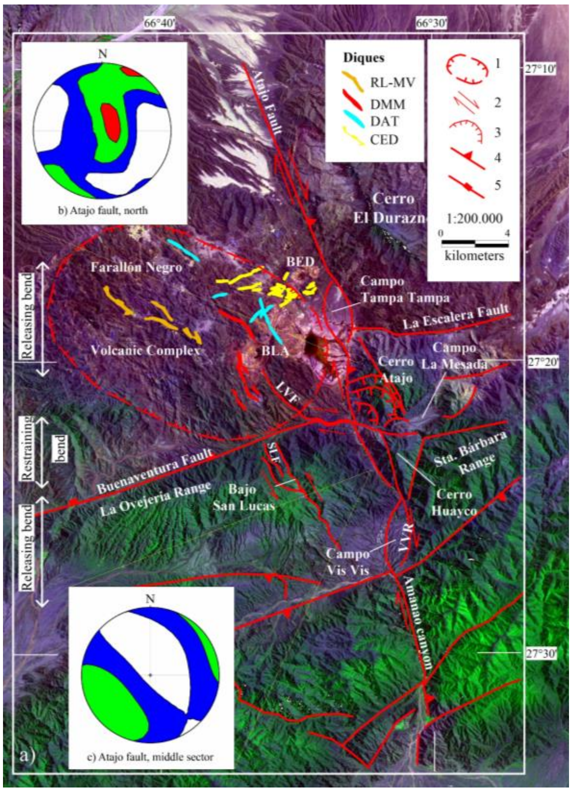

Figure 7: a) Morphotectonic diagram of the study area. The regional structures, the volcanic caldera, the mineralized dikes with different orientations and the main mountain ranges are shown. 1: Volcanic caldera. 2: Transcurrent fault. 3: Slip scars. 4: Reverse fault. 5: Normal fault. 6: Mineralized dikes. b) and c) Statistical diagrams of geological fractures y sus tensores de esfuerzos in Schmidt's equiareal network, lower hemisphere. RL-MV: Los Leones Rhyolite and mineralized veins (5 Ma). DMM: Dacita Macho Muerto (5.95-6.14 Ma). DAT: Agua Tapada Dacite (7.39 Ma). CED: Cerro El Durazno (8.10-8.59 Ma).

It is likely that the Atajo fault also had a normal horizontal displacement component, dipping to the east; On the eastern flank of the La Ovejería range, triangular facets, indicating normal faulting, dipping to the east, were carved into the metamorphic rocks.

The Atajo fault is also cutting the eastern edge of the Farallón Negro Volcanic Complex. To the NE the Cerro El Durazno form a remnant of the volcanic cone, so it would have played an important role in generating the collapse of the volcanic caldera. The fracture planes measured on the Atajo fault, west of the Cerro Atajo and Cerro Huayco, indicate main strikes to the NW and NNW, respectively, evidencing a close relationship with the main trace of the fault and its geometry (Figs. 7a, 7b and 7c).

4.1.2.2 San Lucas fault: The La Ovejería range is cut on its northeast side by the San Lucas fault and its northern edge is limited by the Buenaventura fault (Aceñolaza et al. 1982), which has a normal displacement and dips 70° to the NNW (Profett 2003) (Figs. 3 and 7a). The San Lucas fault, striking NW and 7 km long, shows sinestral horizontal displacement and formed a small pull-apart basin of 1.14 km^2. The basin is elliptical in shape with major axis oriented to the NW and a length of 1.7 km (Fig. 7a). Subvolcanic intrusives crop out in this depression, related to the Farallón Negro Volcanic Complex (Llambías 1970), which intruded into the igneous-metamorphic basement (Figs. 2 and 7a).

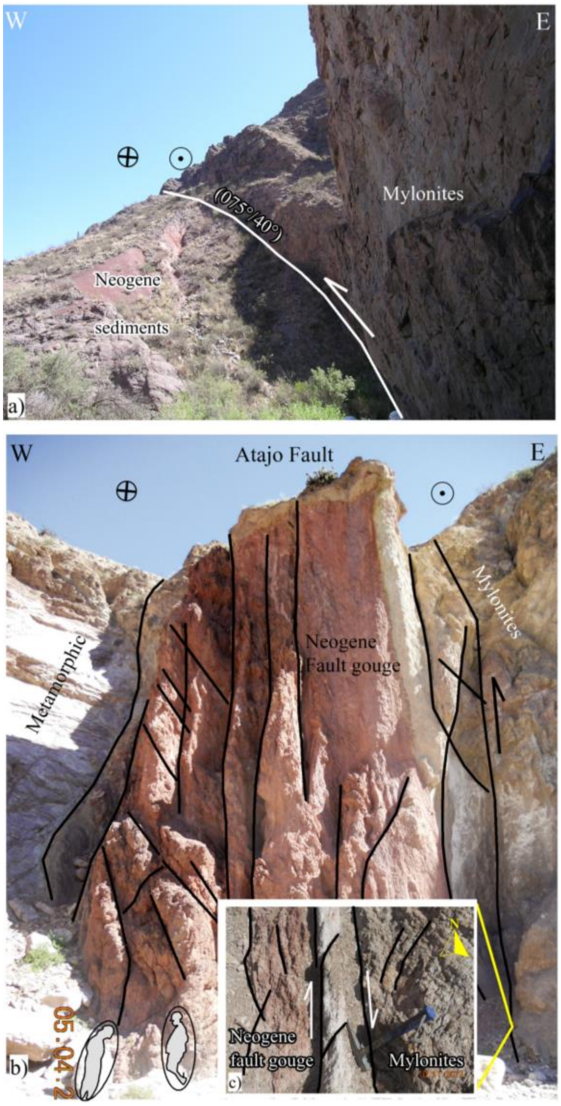

Figure 8: The dotted and cross circles indicate the dextral horizontal movement of the fault. Below are pointed the shape of people, as the scale of the outcrop. a) Mylonitic rocks thrusted on Neogene sediments through the Atajo fault. b) Mylonitic rocks thrusted on metamorphic rocks through the Atajo fault. The thickness of the fault gouge made up of neogenic sediments is observed. c) Image from the lower right corner of the figure b; secondary conjugate fractures are observed showing dextral horizontal displacement of the fault.

On the western side of the San Lucas fault, on a wall of metamorphic rocks, the fault plane (267°/52°) (Fig. 9a) and the striations (198°/05°) were measured, which show its horizontal displacement (Fig. 9b). In Fig. 9b conjugate fractures R are also observed, which supports the evidence of sinestral displacement of the fault. The fracture planes measured in the area strike preferentially to the NW, with the same direction as the San Lucas fault (Figs. 7a and 9c). In this area there are also normal faults that affect the metamorphic basement, cutting quartz dikes (Fig. 10).

4.1.2.3 Las Vizcachas fault: The geometry of this fault is curved, with a general NW strike and dextral horizontal displacement, it is about 15 km long (Figs. 7a and 11). To the east, it marks the limit between Cerro Atajo to the north and Cerro Huayco to the south and, to the northwest, it enters the caldera of the Farallón Negro volcano (Figs. 7a and 11). The fault is well defined in satellite images, but in the field the most representative evidence is the positive flower geometry that it generated in the volcanic rocks (Fig. 12).

The horizontal shear zones usually have extensive or compressive components, leading to transtension and transpression zones, respectively. In the transpression, structures with convex geometry are formed upwards, called "structures in palm tree" (Sylvester 1988). It is a fault zone, about 3 km wide, where the Las Vizcachas fault occupies the central zone and, on its sides, there are smaller structures, with the same strike (Fig. 11). Twenty-seven structural data were measured in the fault zone that, represented in the Schmidt's net with the Stereonet software (Allmendinger et al. 2012; Cardozo and Allmendinger 2013), clearly reflect the geometry of the Las Vizcachas fault zone (Figs. 11a and 11b). This fault cuts and displaces the Atajo fault and generates a cut and displacement in the northern end of Cerro Huayco (Fig. 11a). The fault also produces the dismemberment of the NE end of the La Ovejería range, generating a small valley 3 km long and 180 m wide, occupied by the Jejenes river (Fig. 11a).

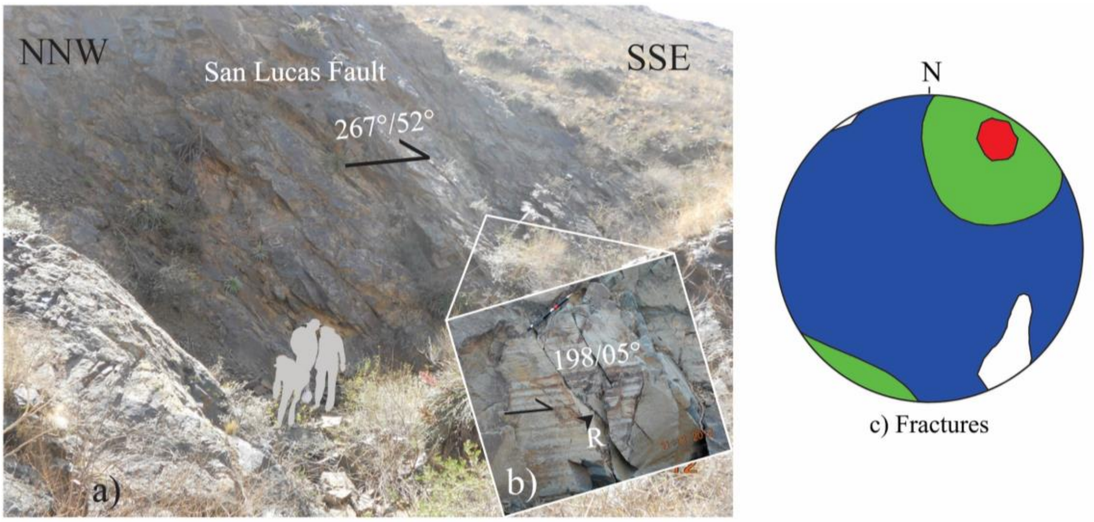

Figure 9: a) View of the San Lucas fault, carved in metamorphic rocks. b) Striations of the fault plane defining horizontal displacement. c) Statistical diagrams of the fractures in Schmidt's equiareal net, lower hemisphere. Shape of the people as reference scale for the outcrop.

4.1.2.4 Ampujaco fault: This fault represents a linear tectonic feature, with a NW strike, about 30 km long, visible in satellite images, where it shows components of reverse vertical displacement, with dip to the SW and dextral horizontal displacement (Gutiérrez et al. 2002) (Figs. 2 and 3). This fault places the granitic rocks of Cerro Pampa in contact with the rocks of the Farallón Negro Volcanic Complex and with the metamorphic rocks of La Ovejería range (Fig. 2). To the west, it marks the limit between the Fiambalá and Hualfín ranges (Figs. 2 and 3). The attitude of the fault plane measured at the northwest end of the La Ovejería range is 240°/80° (Fig. 2).

4.1.2.5 Belén fault: This fault strike NNE, is about 50 km long (Figs. 2 and 3) and is likely to have continuity with the fault on the eastern edge of the Hualfín – Las Cuevas ranges (Figs. 2 and 3). The fault divides the southern sector of a mountainous block made up of granitic rocks, generating a small valley limited to the west by the Belén range and to the east by the Cerro Pampa (Figs. 2 and 3). The valley opens towards the Belén field reaching a width of 3.20 km, where the town of Belén is located; to the north it connects with the Hualfín valley, where the fault does not outcrop (Figs. 2 and 3). This fault is reverse, dipping to the west; at its northern end its fault plane (245°/30°) disposes granitic rocks on Neogene sediments (320°/34°) (Fig. 13).

4.1.2.6 Pampa fault: The fault limits the western edge of the Ampujaco Valley (Figs. 2 and 3). It is a reverse fault, broken, about 29 km long, which lifts and tilts the Cerro Pampa to the west (Fig. 4a). The quaternary reactivation of this fault is manifested 2.4 km to the east of the main fault, as another reverse fault that raises the stratification planes of Tertiary sedimentites, orange-brown in color (273°/58°) and the deposits of alluvial fans formed by highly consolidated conglomerates, of possibly Early Pleistocene age (275°/35°) (Figs. 4a and 5). In tectonically active regions, Bull (2007) describes tectonic morphologies of this type as external faults, a product of fault migration, generating a piedmont foreland between the two faults. In the Tafí valley there are good examples of faults with different geometries, generated in the foothills, as a result of the reactivation of previous faults (Gutiérrez et al. 2021). Some fracture planes were measured on the western edge of the Ampujaco valley, registering a preferential NNW strike (Fig. 4b).

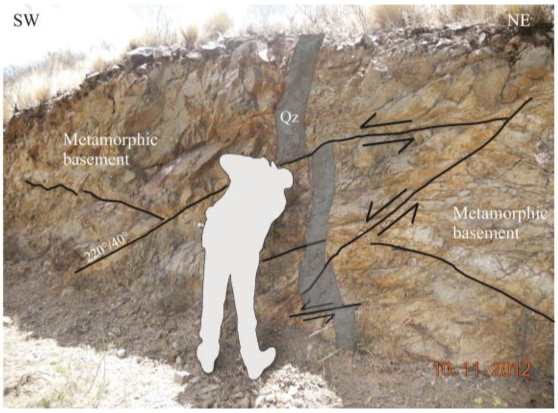

Figure 10: Normal faults affecting metamorphic basement rocks. They are cutting and displacing a quartz dike.

4.1.2.7 Chañaryaco fault: The fault strikes NE and is 39 km long (Figs. 2 and 3). Its morphotectonic expression is the uprising and tilting towards the west of the mountainous block constituted by the Venado, Talayacu, Carrizal and Algarrobal ranges and Quemado hill (Fig. 3). The Talayacu and Carrizal ranges, in turn, are limited on their eastern edge by smaller structures, verging to the east, which tilted them to the west (Figs. 2 and 3). In the foothills of this mountain block, east of the Chañaryaco fault, recent tectonics generated normal and reverse structures that are affecting highly consolidated alluvial fan deposits, which constitute Level 1 of these deposits (Fig. 4a), probably belonging to the Pliocene - Pleistocene (Fig. 6a).

These structures were formed by the reactivation of the Chañaryaco fault. Some of them have oblique orientations with respect to the strike of the Chañaryaco fault, generally NS strike and, opposite dip directions (Fig. 6a). The reverse fault La Cuesta (118°/55°), about 1,000 m long, tilted the alluvial fan, separating from the Algarrobal range and disposing of the conglomerate layers with a strong dip to the east (095°/55°) and eroding it (Figs. 6a and 6b). The fault occurs at the contact between the brown sandstone and the conglomerate deposits that constitute the alluvial fan (Fig. 6b).

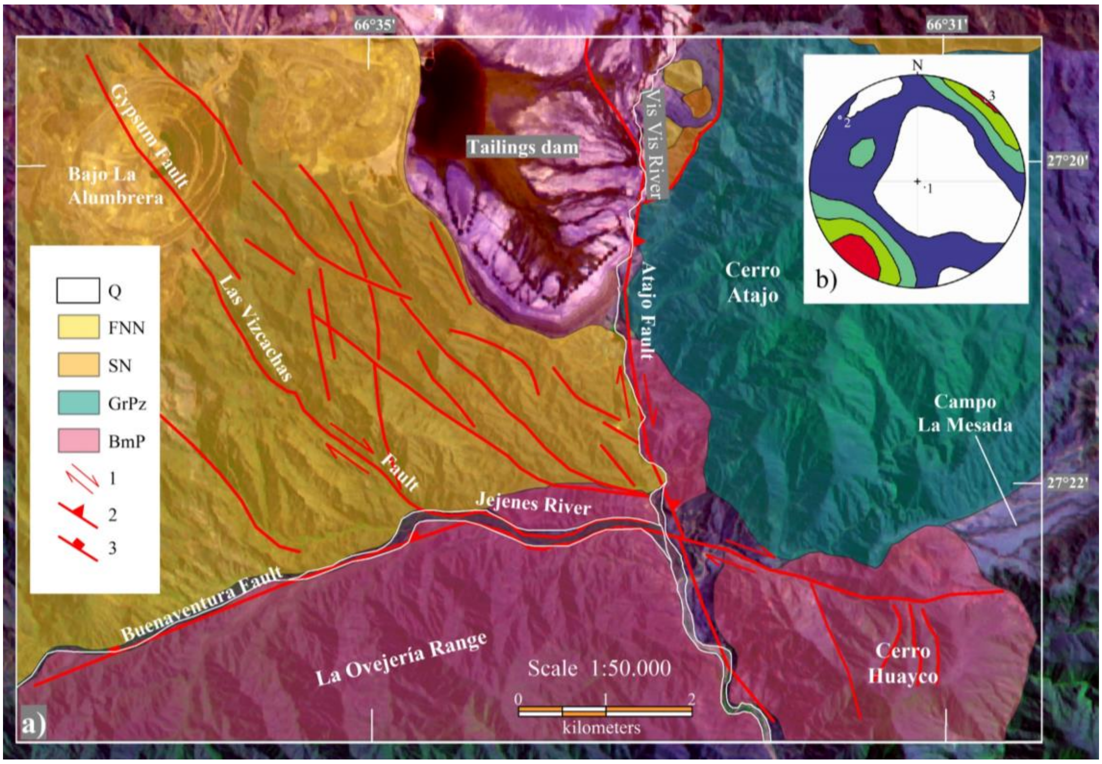

Figure 11: a) Structural diagram of the Las Vizcachas fault zone. The fault cuts the northern edge of Cerro Huayco and sierra La Ovejería and then enters the volcanic caldera of Farallón Negro. b) Statistical diagrams of geological fractures and their stress tensors in Schmidt's equiareal net, lower hemisphere.

To the north, where the flank of the Algarrobal range forms a strong curved inlet, concave to the east, the reactivation of the Chañaryaco fault also caused the tilting to the east and the dismember of another alluvial fan (Level 1, Fig. 4a), that could have occupied an area of about 3 km^2 (Figs. 6a and 6c). It is possible to see in the satellite image (Fig. 6a) the height of the counterslope of one of these residual deposits, which reaches about 90 m. This is the product of the tilting caused by the fault, which in turn arranged the conglomerate strata with strong SE dip (133°/48°) (Fig. 6c).

4.1.3 Mineralized dikes

Magmatic activity allowed the emplacement of the Farallón Negro Volcanic Complex towards the end of the Tertiary, giving rise to porphyry copper and epithermal deposits (Fig. 2). The dikes and subvolcanic intrusives were emplaced in the volcanic complex following a structural pattern that, at the beginning of the volcanic activity, had a preferential trend NE (CED: 8.10-8.50 Ma), later changing to a NW strike (DAT: 7.39 Ma; DMM: 5.95-6.14 Ma and RL-VM) (Gutiérrez et al. 2002) (Fig. 7a).

The internal fracturing of the volcanic complex also has a preferential NW trend (Fig. 11a). The sinistral rotation of the shortening axis controlled the tectono-magmatic evolution of the Farallón Negro Volcanic Complex (Gutiérrez et al. 2002).

4.2 Statistical treatment of structural data

The statistical diagrams of faults and fractures are represented in figures 4b (corresponding to the Ampujaco valley), 7b and 7c (along the Atajo fault), 9c (representing the San Lucas fault) and 11b (corresponding to the zone of Las Vizcachas fault). In all cases, a preferential NW strike of the structures is observed.

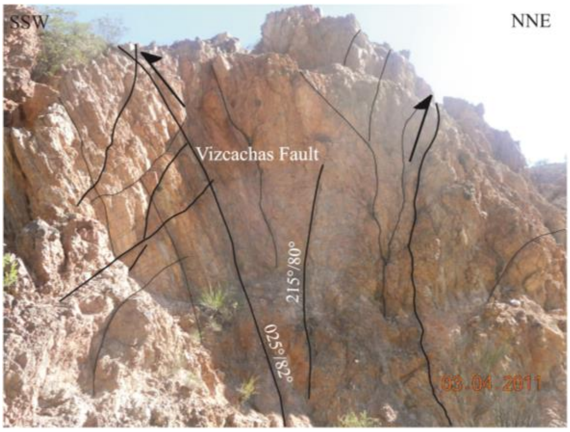

Figure 12: Positive flower structure of the Las Vizcachas fault, transcurrent and dextral.

Schistosity data were measured on the Atajo fault, on both banks of the Vis Vis River, mainly in the outcrops of the La Ovejería range and Cerro Huayco. The schistosity planes strike NW, dipping at a steep angle to the NE and SW (Figs. 2 and 14a).

The stratification planes of the Tertiary and Quaternary rocks and the pseudostratification planes of the volcanic rocks were measured on the Atajo fault, on both banks of the Vis Vis river, between the eastern edge of the volcanic caldera and the western flank of Cerro Atajo (Fig. 2). In all cases, subhorizontal NW strike is recorded (Figs. 14b, 14c and 14d).

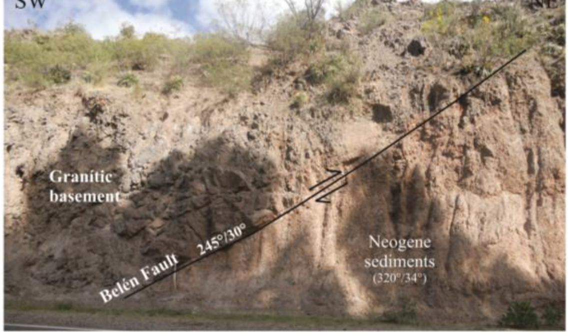

Figure 13: The Belén fault produces the thrust of granite rocks over the Neogene sedimentary rocks. Outcrop at the northern end of the fault, on National Route 40. The general strike of the fault is N-S but, in this area, it marks a break with a NW strike.

4.3 Recent tectonic activity

We found evidence of neotectonic activity in the Vis Vis ravine, in the Ampujaco valley and on the western edge of the Andalgalá field (Figs. 2 and 4a). At the southern end of the left bank of the Vis Vis river, the deposits of terraced Quaternary alluvial fans were raised between 70 and 100 m above the level of the current river channel, which shows the vertical reactivation of the Atajo fault (Fig. 2). Some of these Quaternary terraces, on the banks of the rivers that drain into the Vis Vis river, are affected by faults, as evidence of recent tectonic activity (Fig. 15).

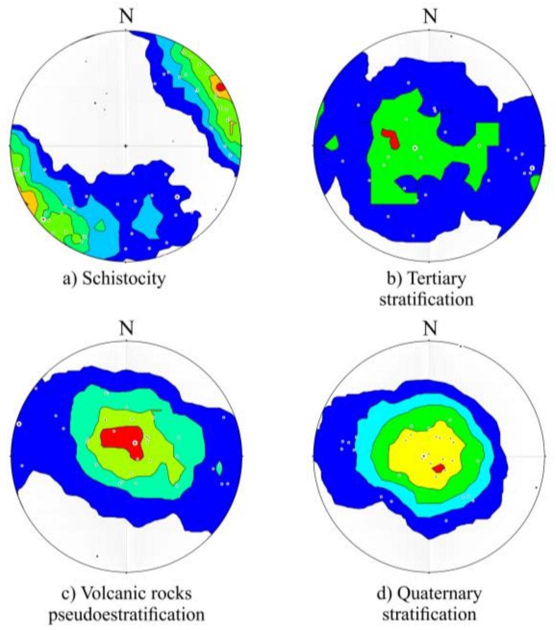

Figure 14: Statistical diagrams of the geological structures in Schmidt's equiareal network, lower hemisphere. a) Schistocity planes of the metamorphic basement. b) Stratification planes of tertiary sedimentary rocks. c) Planes of pseudostratification of volcanic rocks. d) Quaternary deposit stratification planes.

In the Ampujaco Valley (Fig. 3), both the stratification of the Tertiary sedimentary rocks (dipping 58° W; 35° NW) and that of the Quaternary conglomerate deposits (dipping 35° NW) are tilted to the west, revealing the presence of a reverse and blind fault, verging to the east, in the distal zone of the alluvial fans (Figs. 4a and 5).

On the eastern edge of the Algarrobal range (Fig. 3), alluvial fan deposits are detached from the source area and a channel that feeds them (Fig. 4a). These deposits are affected by faults. The reverse fault La Cuesta (118°/55°) disposes the stratification of the alluvial fan of the Cuesta de Belén with a dip of 55° to the east (Fig. 6b) and the reactivation of the Chañaryaco fault tilts towards the SE at a alluvial fan deposit (133°/48°) and separates it from the mountain front (Fig. 6c).

Figure 15: Reverse fault in the quaternary sediment terrace on the right bank of the Huayco River.

5 Discussion

5.1 Current landscape

In the literature there are numerous references on the interaction of the Nazca and South American plates as being responsible for the deformation of the Andean foreland and on the displacement and rotation of the Sierras Pampeanas on a vertical axis (Isacks et al. 1982; Pilger 1984; Marrett et al.1994; Yañez and Ranero 1999; Gutiérrez 2000; Jordan et al.2001; Ramos et al. 2002; Somoza et al. 2002; Gutiérrez et al. 2002; Gutiérrez and Mon 2007a). In addition, the convergence of the Nazca and South American plates was attributed to the beginning of the rotation of the Andean orocline in the upper Eocene, counterclockwise about 37° north (Peru) and clockwise about 29° south (Arica) (Taylor et al. 1998; Coutand et al. 1999; Arriagada et al. 2008; Johnston et al. 2013). Magnetostratigraphic study and paleomagnetic data from Cretaceous and Neogene rocks, immediately NW of the study area, at the transition zone between the Puna and the Sierras Pampeanas (Hualfín – Santa María), show a pattern of clockwise rotations (Butler et al. 1984; Aubry et al. 1996). Different authors agree that the compressional strength that originated the Sierras Pampeanas were transmitted by the upper, rigid part of the crust, within 10 or 15 km of depth, which moves on more or less horizontal planes, rising the mountainous blocks by one of its flanks or by both, favored by thermal weakening of the crust (González Bonorino 1950b; Vergani and Starck 1989; Comínguez and Ramos 1991; Grier et al. 1991; Zapata and Allmendinger 1996; Mon and Drozdzewski 1999; Ramos et al. 2002). The deformation is influenced, among other things, by the rheology of the rocks and pre-existing faults (Rodgers and Rizer 1981; Ikeda 1983; Riller and Oncken 2003; Mon et al. 2005; Gutiérrez and Mon 2008: Zampieri et al. 2012; Gutiérrez et al. 2019).

However, other researchers also postulate NE compression and counterclockwise rotation in the Andean foreland. Assumpcao (1992) interprets that the continental part of South America, east of the Andes, influenced by a tectonic scheme of east-west compression, is characterized by north-south compression. Also, Gutiérrez and Mon (2017b) determine a NNE shortening that involves sectors of the Precordillera, Sierras Pampeanas, Famatina System, Cordillera Oriental and Santa Bárbara System, folding up to the Neogene stratigraphic units. Other studies, based on the interpretation of the regional tectonic morphology and measurement of structural data, showed counterclockwise rotation of some mountain ranges that make up the Sierras Pampeanas (Gutiérrez 2000; Zampieri et al. 2012). The Ambato Block is an example of counterclockwise rotation due to plate convergence in the Cenozoic (Gutiérrez 1999; Gutiérrez and Mon 2008; Gutiérrez et al. 2019).

The study area, in a regional morphotectonic scheme, as a whole (Fig. 1a), can be located at the southern end of a curved mountain range, made up of the Sierra de Aconquija and the Cumbres Calchaquíes, with NNE strike, which separate other mountain blocks with a NS strike (the Quilmes range to the north and the Ambato Block to the south) (Fig. 1a and 1b). In turn, the set of mountains that constitute the study area separates two large sedimentary basins; to the north, the Santa María valley - Campo del Arenal and, to the south, the Pipanaco salt flat (Fig. 1a and 1b). These two intermontane depressions (campo del Arenal and Pipanaco salt flat) are connected through the elevated Hualfín valley, whose drainage network begins to the northeast of the Nacimientos de Arriba town, makes its way through the Belén fault and discharges its waters in the Pipanaco salt flat (Figs. 1a,1b and 2). The presence of lacustrine sediments equivalent to the San José Formation (Miocene) in the Ampujaco valley (Herazo et al. 2017) could indicate a connection between the Santa María basins – campo del Arenal, Hualfín valley and Pipanaco salt flat, perhaps forming a large basin in the Lower Tertiary (Figs. 1b and 2). Mortimer et al. (2009) determine the division and deformation of the El Cajón-campo del Arenal basins by the uplift of the Quilmes range around 6 Ma, as a consequence of the uplift of the western edge of the Aconquija range.

Viewing the study area in greater detail, the morphotectonic scheme has another geometry. The southern end of the mountainous complex made up of the study area to the west (Bloque Ovejería) and Sierra de Aconquija to the east is broken by the Atajo fault (Figs. 2 and 3). To the west of the Atajo fault, three dismembered mountain blocks can be distinguished, separated by the Ampujaco and Suncho valleys, made up of the Belén range - Cerro Pampa, Venado - Carrizal - Algarrobo ranges and, La Ovejería range, with a general NNE and ENE strike, respectively, bounded on the north by a volcanic caldera (Figs. 2 and 3).

The Atajo fault, of reverse character with a NE dip and dextral horizontal displacement, generated two pull apart basins (Tampa Tampa and Vis Vis fields) and a step over (Cerro Huayco), cut the NE end of the Farallón Negro Volcanic Complex and produced the displacement between the Hualfín – Las Cuevas ranges and between the Ovejería Block – Sierra de Aconquija (Figs. 2, 3, 7 and 8). Then, through the Atajo fault, the counterclockwise rotation of the Ovejería Block took place, which broke off from the southern end of the Sierra de Aconquija (Fig. 3). The western edge of Cerro Atajo was cut by the Atajo fault, evidencing multiple landslides (Fig. 7) and disposing granitic and mylonitic rocks on Tertiary sedimentary rocks (Fig. 8a). The Atajo fault is responsible for the dismembering of the northern end of the La Ovejería range, separating it from the Cerro Huayco, displacing it and initiating it to rotate counterclockwise, coinciding with the step-over geometry (Figs. 2 and 7). Gapais et al. (1992) and Urreiztieta et al. (1993) highlighted that the El Durazno, Hualfín, Las Cuevas, Belén, and Aconquija ranges are deviated from the submeridional directions that the northern and southern ranges present. Sasso and Clark (1999) interpret a deviation of the regional compression to the NW towards the end of the volcanic activity. Based on the orientation of the subvertical dikes of the Farallón Negro Volcanic Complex, Gutiérrez (2000) and Gutiérrez et al. (2002) interpreted shortening axis rotation from NE (8.10 Ma) to NNW (5 Ma) (Fig. 7).

The block constituted by the Belén range – Cerro Pampa is divided by the Belén fault and rotated counterclockwise by the Pampa fault (Figs. 3 and 13). The northern edge of Cerro Pampa is limited by the Amanao fault, with NW strike and dextral displacement, which separates it from La Ovejería range (Figs. 2 and 3). The counterclockwise rotation of the Cerro Pampa gave rise to the Ampujaco and Suncho valleys (Figs. 2 and 3). At the southern end of the Algarrobal range, the presence of ancient conglomerates, corresponding to Level 1, forming extensive alluvial fans (Figs. 4, 5 and 6), some of which are today unrelated to a source area and a drainage channel (Figs. 4 and 6). This can only be explained considering a stage prior to the counterclockwise rotation of the mountains and the origin of the Ampujaco valley, with a single mountain block that provided sediments and transport channels for the formation of these piedmont deposits, in an active tectonic setting (Figs. 3, 6 and 3). Then, with the counterclockwise rotation of the mountains and the formation of the Ampujaco valley, other piedmont deposits would have been generated on the western flank of Cerro Pampa, distinguishing today at least three levels of piedmont deposits (Figs. 3 and 4). Recent tectonics is evidenced in the morphology of these piedmont deposits and in the Quaternary terraces that are tilted by faults (Figs. 5 and 6).

The morphological and stratigraphic characteristics of the conglomerate deposits corresponding to the alluvial fans of levels 1 and 2, in the Ampujaco valley and on the Cuesta de Belén, allow them to be correlated with the conglomerates known in the literature as Punaschotter and which take their own names in different places, identified as Las Cumbres Formation, Guanchín Formation and Yasyamayo Formation, described by Penck (1920); Gonzalez Bonorino (1972); Sosik (1972); Strecker (1987); Bossi et al. (1989 – 1989b - 2001); Sosa Gómez et al. (1993); Toselli et al. (2018).

5.2 Interpretation of counterclockwise rotation

Immediately to the north of the Pipanaco salt flat, on the 150-175 km depth lines of the Wadatti-Benioff zone (Yañez and Ranero 1999), a concentration of seismic foci is observed that occur between 150-300 km depth (Fig. 1b). Less frequently, earthquakes occur in the study area within the first 30 km of depth (Fig. 1b). The Farallón Negro Volcanic Complex, which gave rise to porphyry-type deposits of Cu-Au and epithermal Au (Mn, Ag, As, Pb, Zn) (Fig. 2), shows intense magmatic activity between 13 and 4 Ma (Sasso 1997). Both the compression exerted by the convergence of the Nazca and South American plates and the thermal weakening of the crust would have influenced the Sierras Pampeanas to produce a basal detachment between 10 and 15 km deep, moving in a plane more or less horizontal (González Bonorino 1950b; Vergani and Starck 1989; Comínguez and Ramos 1991; Grier et al. 1991; Zapata and Allmendinger 1996; Mon and Drozdzewski 1999; Ramos et al. 2002) (Figs. 16a and 16 b).

Evolution and movements along deeper faults, as suggested in 10-15 km, coincide with the startup of the plasticity of quartz, whose behavior changes drastically from at ca. 270-300° C, i.e. the brittle-ductile transition (Voll 1961; Passchier 2005). Therefore, the rock strength is reduced, rocks can be easier deformed and shear zones can be generated. In addition, the influence of additional, magmatic-controlled, thermal input can push this transition to upper levels, but also could lead to partial melting if the magma bodies are large and hot enough. It has long been known that partial melting in the form of a network or in layers reduces the strength of the rocks and thus can promote the initialization of faults (Schilling et al. 2006). Melt on grain boundaries weakens the rocks, too, and weak rocks deform faster (Sawyer et al. 2011). Although the volume of melts, formed by this process, are significant lower, than in lower crustal levels (>25 km) they should be able to support the initialization of ductile faults. In addition, if the melt volume is large enough, the partial melts are channelized through increased deformation (Sawyer 2008) and thus support the development of ductile shear zones, too (Rosenberg and Handy 2000; Holtzman et al. 2003).

The experimental results show the development of rotations, faults and folds as a product of the presence of a rigid block in the fault path, which also depends on the size of the rigid block. When this rigid block is large, it does not rotate and is cut by strike-slip faults, which suggests that it is easier and less energy consuming to cut the rigid block by faults than to achieve its rotation (Nalpas et al. 2011). The interposition of larger granitic bodies in the deformation trajectory even leads to the formation of transcurrent structures with opposite kinematics (Zampieri et al. 2012).

In figure 3, the edges of the mountain ranges and the center of the volcanic caldera were delimited with broken white lines, in order to have a current morphotectonic frame of reference. Considering this current tectonic morphology, the geometry of the mountain ranges and the structural relationships between them, a scheme was drawn up that represents the tectonic morphology prior to the general uplift of the mountain ranges and the counterclockwise rotations (Fig. 17). To elaborate this scheme, the contour of the mountain ranges located to the west of the Atajo fault (Bloque Ovejería) and the contour of the southern end of the Sierra Aconquija, to the east of the fault, were drawn (Fig. 17).

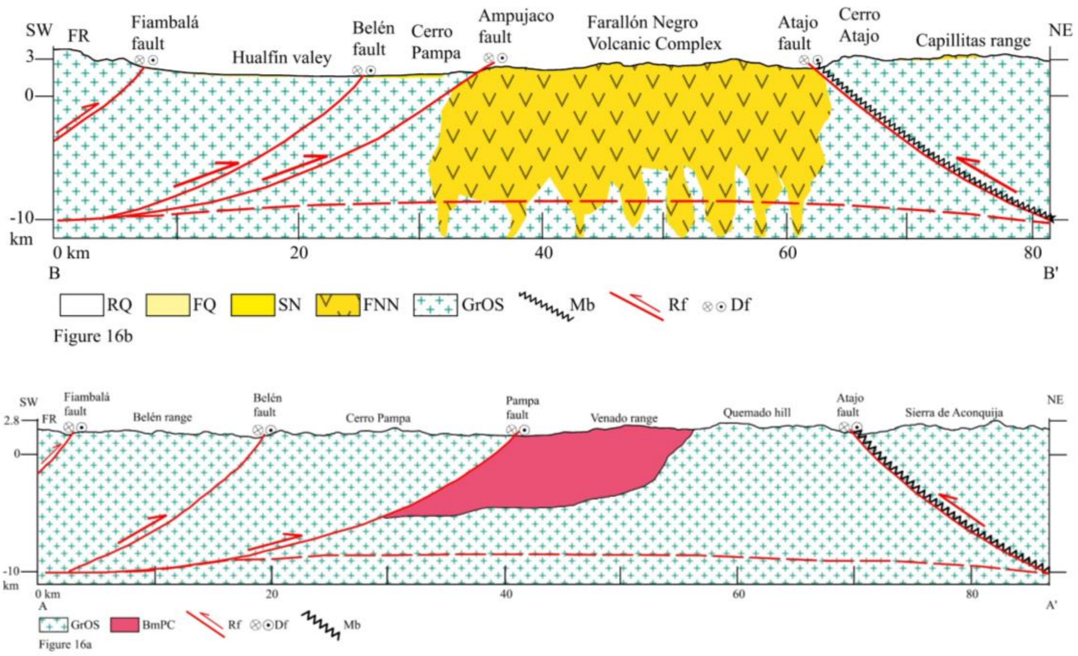

Figure 16: **a**: Schematic section to show the depth of the basal detachment. The location of the profile is indicated in figure 2. GrOS: Granito Capillitas, Upper Ordovician - Lower Silurian. BmPC: Metamorphic basement, Upper Precambrian - Lower Cambrian. Mb: Mylonitic belt. Rf: Reverse fault. Df: Dextral fault. **b**: Schematic section to show the depth of the basal detachment. Note that, in both figures (16a and 16b), the zone of crustal weakness, where the counterclockwise rotation occurs, coincides with the location of the metamorphic basement of the La Ovejería range and the Farallón Negro Volcanic Complex, between the Atajo, Pampa and Ampujaco faults (Figs 2 and 3). Location of the profile in figure 2. RQ: Recent sedimentary deposits. FQ: Foothill deposits, Quaternary. SN: Sedimentary rocks, Neogene. FNN: Farallón Negro Volcanic Complex, Neogene. GrOS: Granito Capillitas, Upper Ordovician - Lower Silurian. Mb: Mylonitic belt. Rf: Reverse fault. Df: Dextral fault.

The silhouette of the Ovejería Block was turned clockwise, and the contour of the southern end of the Sierra de Aconquija moved to the south, following the reverse path that tectonics would have used to configure the current landscape (Figs. 3 and 17). This scheme seems to be a possible morphology, prior to the deposition of lacustrine sediments during the lower Miocene in the Ampujaco valley, where the Belén, La Ovejería, Venado, Carrizal, Algarrobal ranges and Quemado hill formed a chain with the same NE strike than the Santa Bárbara, Amano and Aconquija ranges (Figs. 3 and 17). In this initial state, it is probable that the Santa María valley, the campo del Arenal, the Hualfín valley and the Pipanaco salt flat were connected, constituting a large basin, interrupted by hills of little relief. The Atajo fault would have already existed as a structural element in the southern end of the Sierra de Aconquija and, probably, some faults are inherited from the Cretaceous Rift (Fig. 10), which limited depocenters that housed Paleogene sedimentary units (Bossi and Muruaga 2009a).

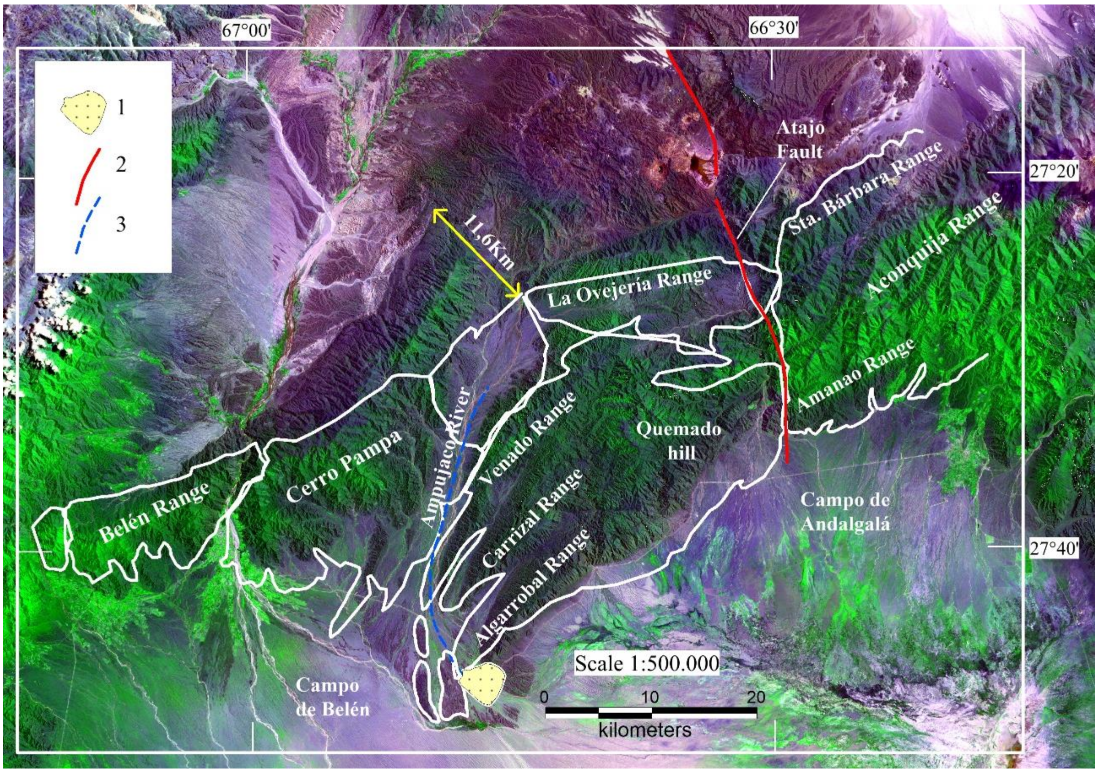

Figure 17: Morphotectonic scheme at the beginning of the deformation. The white lines draw the silhouettes of the ranges in their initial position, prior to deformation. 1. Alluvial fan of the Cuesta de Belén. This alluvial fan would have been deposited during the initial uplift of the Ovejeria Block, before the rotation of the mountains. 2. Atajo fault. This fault would have already existed, before the raising and rotation of the Ovejeria Block, marking the limit with the Sierra de Aconquija. 3. Location and direction of runoff that the Ampujaco River would have had to deposit the conglomerates that formed the alluvial fan of the Cuesta de Belén. These alluvial fans have rounded, granitic and volcanic pebbles, which show a long journey whose origin could have coincided with the northern end of the pampa hill.

We consider that the mountainous block formed by the Sierra de Aconquija and Cumbres Calchaquíes, made up of granitic bodies of batholithic dimensions, constitute a rocky, rigid, impassable massif, against which other mountainous blocks collided, displaced by the convergence of plates and weakened by the magmatic ascent, breaking up into smaller mountains. In the case at hand, this rocky massif played a fundamental role in the counterclockwise rotation of the mountains in the study area. Towards the Middle Miocene, the Sierra de Aconquija constituted a positive element, limited to the south by the Atajo fault, against which the Ovejería Block began to collide and rise. (Fig. 15).

At 13 Ma, magmatic activity generates volcanic activity at Farallón Negro. At 8.10 - 8.59 Ma, the Cerro El Durazno dikes originate, with a NE strike and then, at 7.39 Ma, the mineralized dikes related to the intrusive Agua Tapada Dacite originate in a NNW strike (Sasso 1997; Gutiérrez et al. 2018). These dikes, with a NE – NNW strike, indicate the beginning and the evolution of the counterclockwise rotation of the Ovejería Block. Between 5.95 and 6.14 Ma, the Macho Muerto Dacite dikes originated, with NW and WNW strike (Sasso 1997). The Las Vizcachas fault zone (Fig. 7), which has the same NW strike as the Macho Muerto Dacite dikes, would also have been generated between 5.95 – 6.14 Ma. Around 5 Ma, the mineralized dikes associated with the Los Leones Rhyolite intrusive originate and the mineralized veins continue in later events, all with a marked NW strike (Sasso 1997; Gutiérrez et al. 2018). After these last subvolcanic intrusives, towards the end of the Pliocene and with the maximum uplift of the mountain ranges that make up the Ovejería Block, the conglomerates of the alluvial fans of Level 1 would have been deposited. The conglomerates of the alluvial deposits of Level 2 would have been deposited in the Pleistocene, after the formation of the Ampujaco and Suncho valleys with the end of the counterclockwise rotation.

The tectonic process of counterclockwise rotation of the mountains occurs on both sides of the southern end of the Sierra de Aconquija; the Ambato Block to the SE (Gutiérrez et al. 2019) and the Ovejería Block, to the SW (Figs. 3 and 15).

6 Conclusions

1. It is probable that towards the Lower Tertiary the Santa María valley, the Campo del Arenal, the Hualfín valley and the Pipanaco salt flat were connected, constituting a large basin, interrupted by hills of little relief, on which the lacustrine sediments, equivalent to the San José Formation, were deposited.

2. After the deposition of the Lower Miocene lacustrine sediments, the thrusting of the Sierra de Aconquija on the Ovejería Block appened by the Atajo fault, evolving the deformation in the counterclockwise rotation of the Ovejería Block. The counterclockwise rotation of the mountain blocks occurred on a horizontal plane within 10 to 15 km of depth (Figs. 16a and 16b) where the rigid crust sliding over the lower crust, favored by the caloric rise during magmatic activity at 13 Ma.

3. It is then verified that, as a result of the NE convergence of the Nazca and South American plates, the counterclockwise rotation of the Ovejería Block occurs. The

tectonic deformation and counterclockwise rotation of the mountain ranges were accommodated through the Atajo, Pampa and Belén faults (Fig. 2).

4. The NE transpressive compression configured the current landscape, displacing the Belén range about 11.6 km to the NW and giving it a counterclockwise rotation of approximately 20°. The La Ovejería range would have moved about 6 km to the NW at its northern end and 2 km at its southern end, and the Venado range 6.4 km to the NW, approximately (Figs. 3 and 17). The Cerro Huayco, currently located to the east of the Atajo fault, was part of the eastern end of the La Ovejería range, it would have turned 6º to the left and would have moved about 5 km to the NNW (Figs. 3 and 7).

5. The Atajo fault had a ductile and brittle behavior in its geological history (as evidenced by the mylonitic strip on its eastern edge), generate the thrusting of the Sierra de Aconquija on the Ovejería Block. The kinematics of the Atajo fault show normal, dextral and reverse displacement with west vergence. In the middle section of the Atajo fault, kinematics are recorded that generated pull apart basins such as the Tampa Tampa and Vis Vis fields and a step-over on the western border of Cerro Huayco (Fig. 7).

6. The rotation of the Ovejería Block was responsible for the local rotation of the stress tensors in the study area, from NE to NW, between 13 - 5 Ma. The mineralized dikes of the Farallón Negro Volcanic Complex, originating between 8.10 Ma in a NE strike and 5.0 Ma in a NW strike, show the magnitude of the transpressure exerted by the rotation of the Ovejería Block (Fig. 7). The geometry of the Las Vizcacha fault zone (Figs. 7a, 11a, 11b and 12) allows us to infer that its development correlates with the emplacement of the Macho Muerto Dacite dikes between 6.14 – 5.95 Ma.

7. In the initial hypothetical morphotectonic scheme (Fig. 17), the alluvial fan of the Cuesta de Belén now has the necessary elements to generate the processes that gave rise to it. They were deposited by the Ampujaco River that drained the Belén range – Cerro Pampa (Figs. 4 and 17). The alluvial fans corresponding to Level 1 of the Cuesta de Belén would have been deposited towards the Pliocene - Pleistocene.

8. With progessive deformation, the Belén range - Cerro Pampa continued their counterclockwise rotation, detaching from the La Ovejería range and forming the Ampujaco valley, where the Level 2 alluvial fans were deposited during Pleistocene (Figs. 3, 4, 5, 17).

9. The Andean deformation due to the convergence of plates is not only accommodated by vertical shortening EW, but also by horizontal displacements, product of the rotation of the ranges on a vertical axis and, in some cases, also generates a shortening in the NNE strike.

10. Finally, the statistical results of the sedimentary, volcanic and Quaternary structures show the collapse of the volcanic caldera postulated by Llambías (1970) (Figs. 14b, 14c and 14d).

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no confict of interest.

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