



Pre-Andean deformation and its influence on the shortening of the Southern Precordillera, Mendoza, Argentina

Milagros Gutierrez Seia^{a,*}, Pamela Jara^b, Macarena Bertoa del Llano^c, Andrés Richard^{d,e}, Lucas Lothari^c, Laura Beatriz Giambiagi^c

^a Carrera de Geología, Universidad Del Desarrollo, Las Condes, Chile

^b Mining Engineering Department, Faculty of Engineering, University of Santiago of Chile (USACH), Avenida Libertador Bernardo O'Higgins 3363, Estación Central, Santiago 9160000, Chile

^c IANIGLA-CONICET, Parque San Martín S/n, 5500 Mendoza, Argentina

^d CCT – CONICET, San Luis, Argentina

^e Departamento de Geología, UNSL, San Luis, Argentina

ARTICLE INFO

Keywords:

Southern precordillera
Fold-and-thrust belt
Paleozoic reactivation
Kinematic analysis

ABSTRACT

Andean structures preserve evidence of previous periods of deformation along the proto-Pacific margin of Gondwana. Particularly, the Southern Precordillera, in the southern Central Andes, presents a combination of different structural domains and a double vergence related to the reactivation of pre-Andean structures. This combination and the superposition of deformational events make it difficult to understand the stratigraphic systems and the evolution of the region. This contribution presents detailed information about the structures and evolution of the Southern sector of the Precordillera, focusing on the control exerted by Paleozoic structures over the recent Andean deformation, and the deformational styles of this fold-and-thrust belt. Three main structural domains are recognized. The western domain is characterized by high-angle back-thrusts that concentrate the highest amount of uplift. The central domain is composed of reverse double-vergence faults, and high-angle strike-slip faults. The eastern domain is characterized by pure contractional deformation and only east-verging structures. Four deformational events are recorded and analyzed along the Southern Precordillera at 32°30'S: (1) an Early Paleozoic compressional event, (2) a Late Paleozoic compressional event, (3) a Triassic extensional event, and (4) the Cenozoic Andean compressional event. Our model for the Cenozoic deformation of the Southern Precordillera is restricted to three stages of deformation. During the first stage, Paleozoic west-verging faults are reactivated. The second stage implies reactivation of Paleozoic and Permian-Triassic structures and the generation of reverse Andean faults. The final stage consists of the generation of NE-SW Andean thrusts.

1. Introduction

The Argentine-Chilean Andes correspond to a mountain range that resulted from the convergence between the Nazca and South American plates. This convergence between an oceanic plate and a continental plate underwent a dynamic change in the late Cretaceous, from a trench-retreat to trench-advanced dynamics (Ramos, 1988; Mpodozis and Ramos, 1989). These tectonic events give rise to each of the orogenic belts that form this mountain range and can be recognized in Cenozoic Andean structures, which also preserve evidence of previous periods of deformation along the proto-Pacific margin of Gondwana.

In central Chile and Argentina, the Southern Central Andes include,

from west to east, the following morphostructural units: Coastal Range, Principal Cordillera, Frontal Cordillera, and Precordillera (Fig. 1). The Precordillera, located in the central-western region of Argentina, is a fold-and-thrust belt that forms a north-south-trending mountain chain. In this contribution, we discuss how pre-Andean structures have controlled the development of this morphostructural unit. The study area is located in the Southern Central Andes at 32°30'S (Fig. 1), where the Precordillera constitutes the eastern mountain range of the Andean orogenic front (Jordan et al., 1983a, b; Mpodozis and Ramos, 1989; Kley et al., 1999).

Precordillera shows different deformation styles along its strike. The Northern and Central Precordillera (north of 32°S) are characterized by

* Corresponding author.

E-mail address: milagrosgutierrezseia@gmail.com (M. Gutierrez Seia).

a thin-skinned fold-and-thrust belt composed of north-south striking thrusts (Allmendinger et al., 1990; Cortés et al., 1997, 2005; Cristallini, 1998, 2006). However, the southern part of Precordillera shows a different deformation pattern, with a thick-skinned and block-style deformation in the west, and a thin-skinned deformation in the east (von Gosen, 1995; Folguera et al., 2001; Vergés et al., 2007). The study area is located at the transition from the thin-skinned north-south belt to the thick-skinned belt (Fig. 1). In this area, the recognized structures present orientations different from the typical north-south trending of the Northern and Central Precordillera, with north-northwest and north-northeast striking faults being the most common. Moreover, previous studies show that the Southern Precordillera presents a main tectonic transport towards the west, in its western sector, and towards the east, in its eastern sector. The double vergence of the Southern Precordillera has been related to the reactivation of pre-Andean structures (Cortés et al., 2006; Alonso et al., 2008; Giambiagi et al., 2010; Ariza et al., 2014). Although the superposition of deformational events has been proposed as the main cause of the complex structural pattern in this part of the Precordillera, the deformational mechanisms involved in this control remain unclear.

This contribution presents detailed geological and structural data collected from the Southern Precordillera at 32°30' S, focusing on the control exerted by Paleozoic structures on Miocene-to-recent deformation, and, specifically, on its kinematics. We present evidence for four different deformational events, showing the presence of Paleozoic and

Permian structures that were reactivated. Structural-field analysis and modelling allow us to identify the presence of a pre-existing lithospheric weakness zone that controls the location of the Permian–Triassic transtensional system and the deformation style of the fold-and-thrust belt. These findings, in combination with the newest correlations of Neogene foreland basin deposits in the Precordillera fold-thrust belt (Buelow et al., 2018; Jordan et al., 1996; Levina et al., 2014; Pinto et al., 2007; Mackaman-Lofland et al., 2020) and the Frontal Cordillera at these latitudes (Lossada et al., 2020a, 2020b), allow us to determine the structures that are reactivated and how they affect the structural evolution along the 32°30' latitude.

2. Tectonic setting

The study area is located in a transitional segment between a sub-horizontal subduction zone to the north (c. 5–10° dip at 100 km depth between 27° and 33°S) and a normal subduction zone to the south of 33°S. (Kley et al., 1999; Ramos, 1999; Ramos et al., 2002). This change in the tectonic configuration is responsible for multiple episodes of contraction, extension, and strike-slip deformation (Cristallini and Ramos, 2000; Cortés et al., 2005, 2006), associated with changes in the tectonic dynamics. Three large stages in the evolution of this morphostructural unit can be recognized (Fig. 2): 1) a first stage during which the active Gondwana continental margin was affected by the accretion and collision of exotic and para-autochthonous terrains during

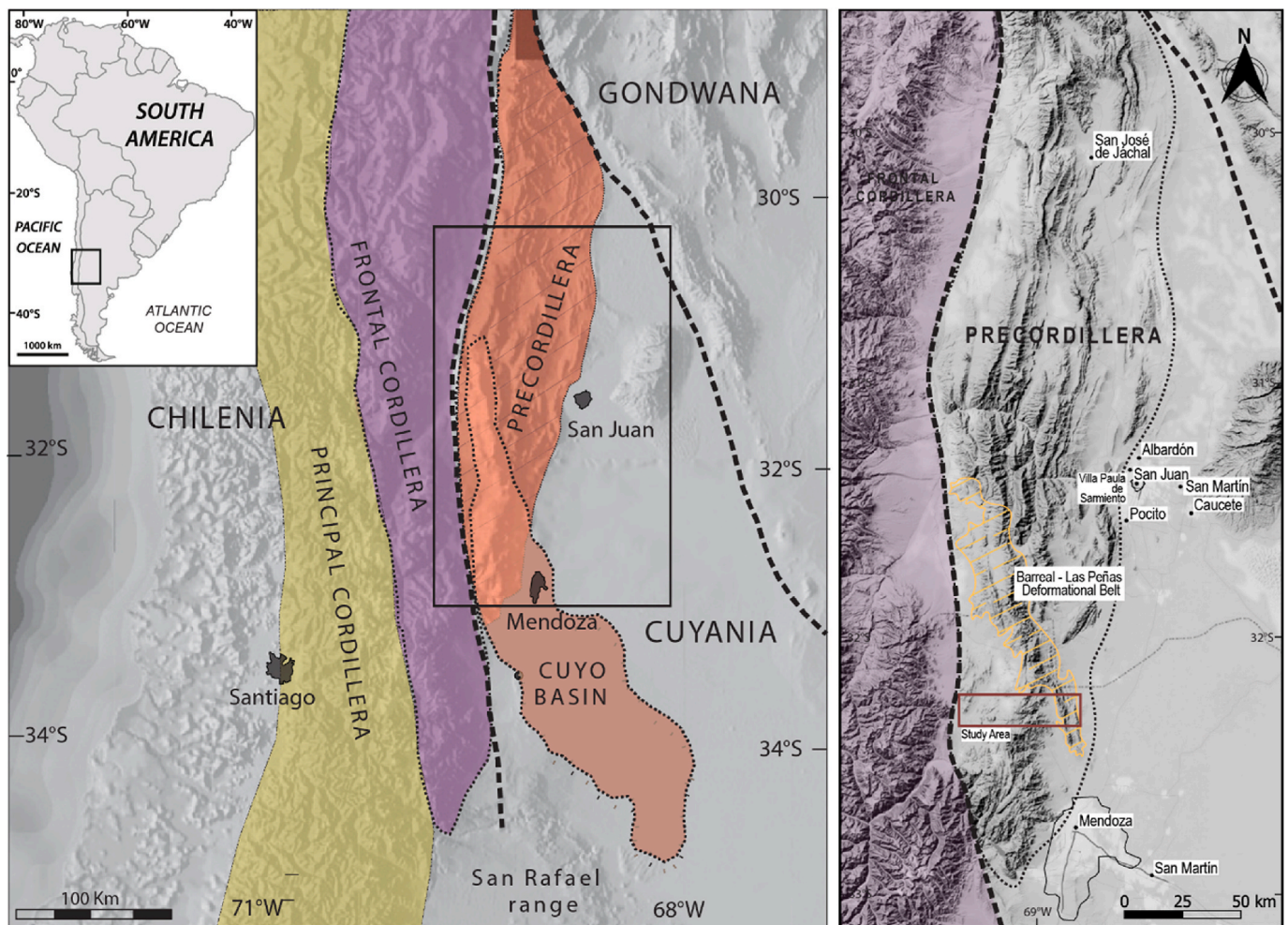


Fig. 1. Location map of the study area (modified from Giambiagi and Martínez, 2008), showing the morphostructural units of the Andes, between 28°S and 36°S latitude, the inferred boundary between exotic Chilenia and Cuyania terranes, and the boundary between Cuyania and western Gondwana (from Ramos, 2004). The black box indicates the location of the study area (Fig. 3).

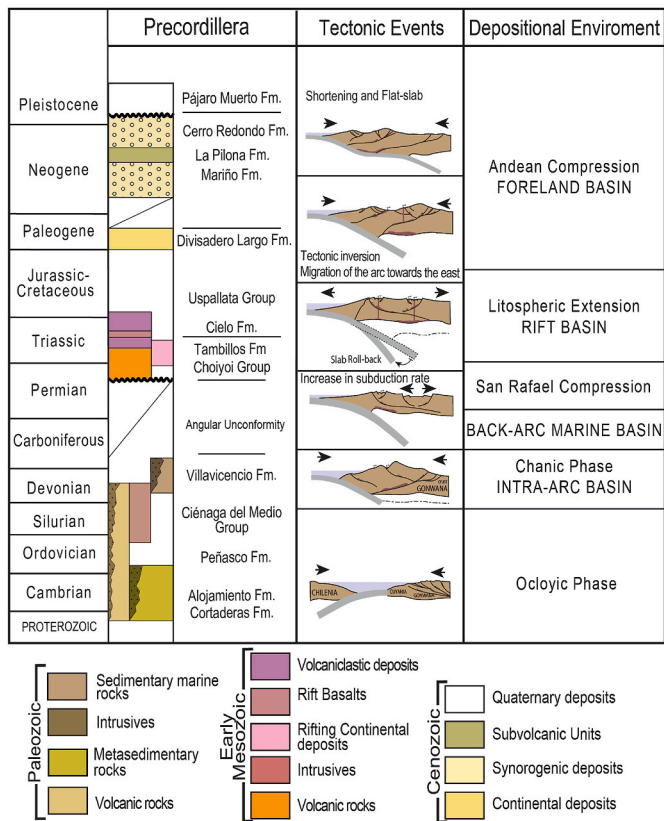


Fig. 2. Generalized stratigraphic column of the units that crop out in the study sector of the Southern Precordillera, associated with major tectonic events (Giambiagi et al., 2015; Charrier et al., 2007) and the depositional environment for each stage (Naipauer and Ramos., 2016). Fm.— formation.

the Paleozoic, 2) an intermediate stage, characterized by a predominantly extensive regime during the late Permian to lower Jurassic, and 3) a final stage, from the upper Jurassic to the present, characterized by a continuing subduction activity of oceanic crust beneath the South American continental margin (Ramos, 1988; Mpodozis and Ramos, 1989; Heredia et al., 2018) (Fig. 2). During this last stage, from the late Cretaceous to the present, the Andean orogenic cycle has taken place.

During the Cambrian, the Gondwana protomargin crust was thinned (González Menéndez et al., 2013; Boedo et al., 2013) and corresponded to a passive margin (Thomas and Astini, 2003). After this passive margin sedimentation, the Famatnian cycle took place, during the early Paleozoic. The beginning of this phase has been assigned to the inferred accretions of exotic terranes against the South American craton, associated with contractional deformational phases (Ramos et al., 1984; Turner and Méndez, 1975). These events gave rise to the formation of the Proto-Precordillera or Chanic orogen during the early Devonian to lower Carboniferous (Heredia et al., 2014). The structures formed during this process have been preserved as west-verging structures in the Southern Precordillera (Giambiagi et al., 2011; Heredia et al., 2012). During the late Carboniferous early Permian, the San Rafael orogenic event took place, associated with important cortical thickening (Llambías and Sato, 1990; Mpodozis and Kay, 1989). This orogeny is characterized by northwest-striking contractional structures.

At the end of this compressional phase clockwise rotations took place between 280 and 265 Ma. This was followed by Permian-Triassic extensional deformation and extrusion of the Choyoi volcanic rocks (Rapalini and Vilas, 1991). Paleomagnetic evidence for these crustal block rotations has been found in the Uspallata-Callingasta Valley and was attributed to dextral strike-slip movements parallel or subparallel to the continental margin. After this strike-slip event, during the late

Permian to Triassic, intracontinental rift basins were generated, which are associated with the reactivation of weakened crustal zones (Legarreta et al., 1992) and the use of Paleozoic suture zones of the accreted terranes (Ramos and Kay, 1991). This stage is considered the Gondwanic cycle and is characterized by intense acidic magmatic activity associated with the Choyoi Group deposits. During the early to late Triassic, the crust was stretched with a north-northeast extension (Giambiagi et al., 2011) and the Cuyo basin opened (Uliana et al., 1989).

The Andean orogeny has affected the southern Precordillera from the Miocene to the present. This deformation is characterized by the reactivation of pre-Andean faults and the generation of new Andean structures (Cortés et al., 2006). The current deformation of the Southern Precordillera began during the late Miocene (Walcek and Hoke, 2012; Buelow et al., 2018). As the Southern Precordillera accommodates the deformation and since the orogenic front migrates eastward, the foreland basin sediments were incorporated into the fold-and-thrust belt (Fig. 2). The last event of this evolution corresponds to the migration of the orogenic front towards the Sierra de las Peñas-Las Higueras thrust system (Cortés and y Costa, 1996; Richard, 2020). Finally, the deformation of the Southern Precordillera is still ongoing and is evidenced by the record of interplate and intraplate earthquakes (Smalley and Isacks, 1990; Ramos, 1988; Smalley et al., 1993; Gutscher et al., 2000; Ramos et al., 2002) as well as neotectonic activity (Costa et al., 2000; Costa et al., 2006a,b; Cortés et al., 2008, 2016; Richard, 2020).

3. Stratigraphic background

The stratigraphy of the study area is represented by Precambrian and Lower Paleozoic metamorphic and sedimentary rocks; late Permian-early Triassic volcanic and volcanoclastic rocks, Triassic clastic sequences associated with the Cuyo basin deposits; and Cenozoic foreland sequences (Fig. 3). Neoproterozoic rocks are considered the basement of the stratigraphic sequence and consist of low-grade metamorphic rocks grouped into the Cortaderas Formation. The Cambrian - Devonian rocks correspond to metacarbonates, metashales, and metasandstones that crop out across the area in north-south trending belts. From west to east, these sedimentary rocks are grouped into the Ciénaga del Medio Group (Silurian- Devonian), the Peñasco Formation (Late Cambrian - Early Devonian), and the Alojamiento Formation (Cambrian). The Ciénaga del Medio Group consists of two units, Tontal Formation, and Sandalio Formation, the former corresponds to volcanic rocks with shale intercalations, while the latter consists of shales and metasandstones (Cortés, 1992). Metasandstones corresponding to the Peñasco Formation, consist of medium-grained metasandstones intercalated with metapelites. The Alojamiento Formation corresponds to silicified gray limestone and dolomite. These rocks are intruded by different mafic bodies. The combination between the presence of fossil fauna and flora and U-Pb ages allowed several authors to distinguish two extensional stages: a Late Neoproterozoic and a Middle Ordovician-Early Devonian one (von Gosen, 1995; Giambiagi et al., 2014; Heredia et al., 2018); the metamorphism recognized in the area can be related to the approach and collision of the Chilenia terrane against West Gondwana (Fig. 2) (Boedo et al., 2021). In the eastern sector of the study area, a sequence of quartz-sandstones, metashales, and metacarbonates are grouped into the Villavicencio Formation, which is dated Early Devonian at its base (Rubinstein and Steemans, 2007). This unit overlies the late Paleozoic sediments by an angular unconformity that is attributed to the Chanic orogeny (Ahumada, 2010). Carboniferous and Permian granitoids intrude the Villavicencio Formation and the Carboniferous successions (Fig. 3).

These previously deformed Paleozoic sequences are overlaid by the Permo-Triassic pyroclastic and volcanoclastic rocks of the Choyoi Group, which also cut the Paleozoic rocks by shallow batholiths and dikes. The subalkaline to alkaline signature of the upper Choyoi Group is consistent with a post-orogenic extensional magmatic arc (Llambías and Sato, 1990; Llambías, 1999).

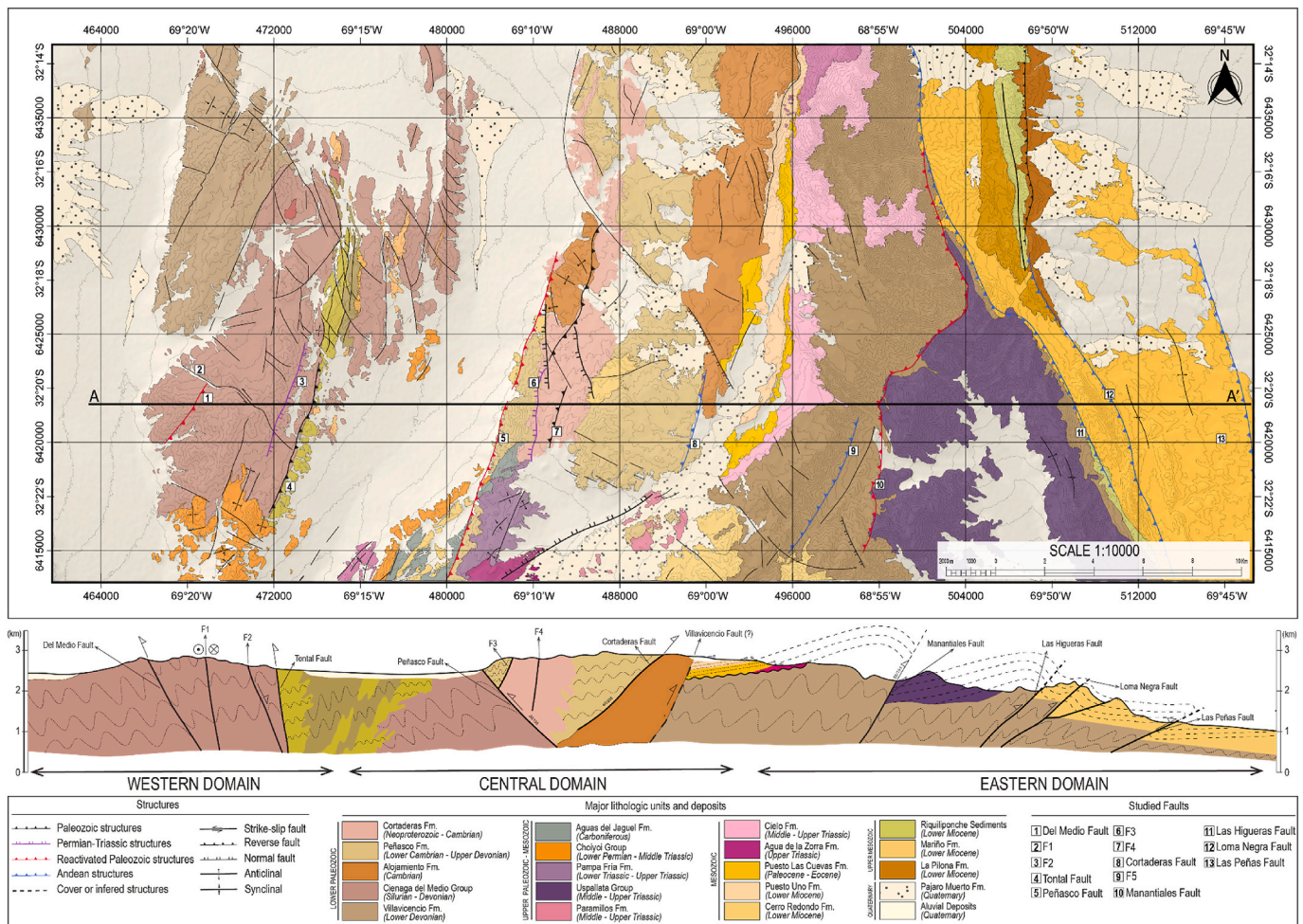


Fig. 3. Geological-structural map of the southern sector of the Precordillera, southern Central Andes, Argentina. The polyphase deformational history of this sector of the Andes is outlined by the generation time of the structures (different colors represent different deformational phases). A-A' is the cross-section presented for the study area. The area has been divided into three domains, western, central, and eastern; represented in the structural section. Faults: 1- Del Medio, 2- F1, 3- F2, 4- Tontal, 5- Peñasco fault, 6- F3, 7- F4, 8- Cortaderas, 9- F5, 10- Manantiales, 11- Las Higueras, 12- Loma Negra, 13- Las Peñas. Modified from Hoja Yalguaráz and Hoja Uspallata (Cortés et al., 1997).

The extensional event, associated with the opening of the Cuyo Basin, is represented by Early to Late Triassic clastic non-marine sediments of the Uspallata Group. These sediments unconformably overlay Paleozoic sequences and consist of continental deposits and volcanic rocks interbedded with basaltic lavas and sills associated with the Las Peñas depocenter. The Uspallata Group tapers toward the west, where low-energy deposits and volcanoclastic rocks are attributed to a period of regional subsidence (Fig. 2). In the study area, the Uspallata Group is correlated with the Cielo Formation, a Triassic sequence that consists of sedimentary breccias, brown and red sandstones, and gray conglomerates (Fig. 3).

As a consequence of the Main and Frontal Cordillera uplift, during the Miocene (Lossada et al., 2020), a foreland basin was developed and was filled with a clastic succession. From base to top, these sequences are represented in the study area by the Puesto Las Cuevas, Puesto Uno, Mariño, and La Piona Formations. They consist of sandstones, limestones, and some evaporite sediments. Later, during the Quaternary, uplift, and erosion associated with tectonics allowed for the deposition of alluvial and foothill sediments grouped into the Pajaro Muerto Formation (Fig. 3).

4. Structural setting

At 32°30'S, Southern Precordillera is divided into two structural

domains: Western and Eastern (Giambiagi et al., 2010) (Fig. 3), which are tectonically bounded by the Villavicencio fault. This structure bounds Triassic and Devonian sequences (Cortés et al., 1992; Folguera et al., 2004; Giambiagi et al., 2011). The western domain is characterized by north-south to north-northeast trending faults with tectonic transport towards the west (Giambiagi et al., 2011, 2014, 2015; Orellano et al., 2020). The eastern domain is characterized by north-south and northeast-trending double-vergence faults and northwest and east-west Triassic faults of normal dextral kinematics (Giambiagi et al., 2011, 2014, 2015; Orellano et al., 2020).

The Southern Precordillera, characterized by oblique structures, presents a zone of deformation that extends between 31°30'S and 32°30'S, the oblique deformation zone Barreal – Las Peñas orogen (BLP-DZ) (Cortés et al., 2005b, 2006). This north-northwest trending deformational belt is made up of five overlapping thrusts with tectonic transport towards the east and echelon geometry, spreading towards intramontane basins (Terrizzano et al., 2010; Schmidt et al., 2011b; Salomon et al., 2013; Costa et al., 2006).

The Quaternary faults present a north-northeast trend and occur throughout the study area, concentrating in the foothills and, cutting unconsolidated deposits where Reidel structures are recognizable in addition to minor folds (Siame et al., 2005; Cortés et al., 2016).

5. Methodology and data collection

Field analysis consisted of detailed geological and structural data collection of the Southern Precordillera around 32° 30' S. A geological transect is presented to illustrate the major structures affecting the upper crust. Field data were collected for most of these major structures and complemented with photo interpretation and published data. Structural measurements include fault orientation, slip direction, and the amount and sense of displacement. These observations are presented in 136 structural measurements taken at 7 stations. Strike, dip, striae and sense of movement were measured in mesoscale faults (less than 5 m of displacement) and regional scale faults (more than 5 m of displacement), using kinematic indicator criteria on slip planes, such as mineral fibers, Riedel fractures, and mineral precipitation in shadows (Petit, 1987; Doblas, 1998).

The age constraints of the fault activity is determined by the ages of rock units affected and unaffected by faulting, as well as cross-cutting relationships. In this way, faults that only affected the Neoproterozoic to Devonian units and Carboniferous to lower Permian units are considered of Devonian or Permian age, respectively. Faults affecting the Permian-Triassic Choiyoi Group and the Triassic Uspallata clastic sequences but not the Cenozoic sedimentary rocks are inferred to be of Permian-Triassic age. Faults affecting the lower Miocene sequence but not the Pliocene-Quaternary units are considered of Miocene age; and lastly, faults that are affecting unconsolidated sediments or Pliocene-Quaternary strata are classified as active faults and represent the neo-structural arrangement. If no cross-cutting relationships are recognized, or the information is not enough to assign an age, the consistency of the calculated kinematic axes obtained from mesoscale faults with regional kinematic data was taken into consideration.

Paleozoic deformation was investigated by measuring structures affecting Paleozoic rocks, where ductile and brittle deformations are recorded in meso- and macro-scale. We obtain the principal axes of shortening (λ_3) and extension (λ_1) for the incremental strain tensor from fault-slip data analysis (Marrett and Allmendinger, 1990; Twiss and Unruh, 1994). Using the software FaultKin 8.1 of Allmendinger (1998), the tensor summation method is used to obtain the principal strain axes. The fault analysis determines an average kinematic solution for each structural station where using linked Bingham distribution statistics, the directional maxima of the λ_3 and λ_1 strain axes for the fault arrays (Marrett and Allmendinger, 1990) are estimated.

Due to the limited or absent subsurface data in the western and central part of the study area, forward modeling was the method selected for the construction of the balanced structural section. Based on field observations, such as regional structures, strike and dip data, and surface mapping, a kinematic forward model is constructed using the MOVE software by PETEX. The cross-section restoration is based on area conservation. The cross-section was imported into 2D Move, where we back-tilted the Permian–Triassic volcanic rocks and the Triassic continental strata to the horizontal position. The initial state of the kinematic forward model considers the Paleozoic and Permo-Triassic deformations (pre-Andean). The forward modeling applies a number of algorithms to calculate fault-related deformation (Suppe, 1983). We used a trial-and-error method with multiple combinations of detachment level, ramp angle, and algorithm to achieve the best fit of the original data and surface mapping. The two chosen algorithms are the fault-parallel-flow and the combination of trishear and inclined shear algorithms (Erslev, 1995). The fault-parallel-flow algorithm maintains the length of the beds and is more useful to model stratified units; while the trishear-/inclined shear combination maintains the area and is more appropriate to model an unstratified basement block. We have chosen the trishear-/inclined shear algorithm to model the basement blocks and the fault-parallel-flow algorithm to model the backthrust faults.

For the shortening calculation, the strain integration technique from Woodward et al. (1986) was used, through which the original length and the current deformed length give the percentage of shortening in the

section. It is important to take into consideration some assumptions and limits of the proposed mode, should be considered. For simplicity's sake, we only consider the Neogene-Quaternary deformation. For this reason, the Paleozoic strata were modeled as a single internally deformed block where Paleozoic folding, as well as micro- and mesoscale deformation, have not been modeled. This results in the calculation of a minimum shortening rate. Moreover, erosion has affected the hanging-wall cutoffs of the Triassic and Cenozoic strata, and thus, the actual line lengths of the thrust sheets are unknown, and the modeled lengths represent a minimum value. As a result, minimum bed lengths are used in the cross-section to minimize shortening. All mapped thrusts were extended to depth from the surface to merge with a detachment level proposed by Richard (2020) in the area immediately to the east.

6. Structural domains

Based on the study of surface information, three structural domains can be distinguished: Western, Central, and Eastern (Fig. 3). These domains are characterized by three basement blocks overlaid by Triassic deposits filling the sub-basin Las Peñas, which forms a half-graben limited by the Las Higueras fault. This depocenter is uplifted by the regional reverse faults: Tontal, Peñasco, Villavicencio (cover), Manantiales, and Santa Clara faults (Fig. 3).

6.1. Western domain

The western domain is characterized by high-angle faults with tectonic transport towards the west. These structures are part of a Paleozoic structural system that uplifts the Cerro del Medio hill. This system consists of reverse faults with north-northeast orientations, as well as both normal and strike-slip faults with northwest orientations. In this domain, only Paleozoic rocks outcrop, sometimes covered by Quaternary sediments. South of the transect, Carboniferous-Permian strata, as well as Permian structures, can be recognized. The faults that are part of the western domain are: Del Medio, F1, F2, and Tontal faults (Fig. 3). The Del Medio fault is a north-northeast striking reverse fault. This west-verging structure uplifts the Ciénaga del Medio metasedimentary rocks, which show internal deformation, such as tight isoclinal folds that present a north-south and northwest general strike, usually showing northeast vergence. The F1 fault is a west-northwest strike-slip fault, which displaces approximately 100 m of the metasedimentary rocks of the Ciénaga del Medio Group. Through satellite imagery analysis a sinistral displacement could be inferred. Because of the lack of cross-cutting relationships, the faulting age of these structures is yet to be determined but the kinematic analysis and the deformational axis suggest a Paleozoic age for both structures. The F2 fault is a normal fault, having a north-northeast strike and dipping toward the east. This fault puts in contact a Paleozoic block of the Ciénaga del Medio Group against the Permian-Triassic volcanic rock of the Choiyoi Group and, towards the south, Permian - Triassic strata unconformably covers the structure, constraining the fault age to the Paleozoic. The Tontal fault is a north-south reverse fault with tectonic transport towards the west. This fault juxtaposes the Ordovician-Silurian sequences of the Sandalio Formation on top of the Devonian metasedimentary rocks of the Tontal Formation. Both formations are internally deformed, presenting cleavage planes and tight folds. This structure extends towards the south but it does not affect the Permian sequences of the Choiyoi Group.

6.2. Central domain

The central domain shows a complex structural framework with the interaction of different structural systems. In this domain, Paleozoic, Triassic, and Cenozoic rocks are recognized, forming hills and filling small basins. The structures are predominantly reverse faults with a general north-northeast strike. The reverse faults are: the Peñasco, F3, F4, Cortaderas, and Villavicencio faults (Fig. 3). The main vergence of

these structures is towards the east, except for the Peñasco fault. The Peñasco fault is a regional high-angle reverse structure with a north-northeast strike and tectonic transport towards the west, that juxtaposes the Cambrian-Devonian metasedimentary rocks (Peñasco Formation) on top of both the Carboniferous marine rocks (Aguas del Jagüel

Formation) and the volcanoclastic deposits (Choiyoi Group), south of the transect. Towards the north, the fault puts in contact Cenozoic sequences with the Paleozoic strata and is covered by Quaternary sediments. The fault dips 50–55°E, and fault-slip measurements indicate a sinistral movement. The kinematic relationships show a possible

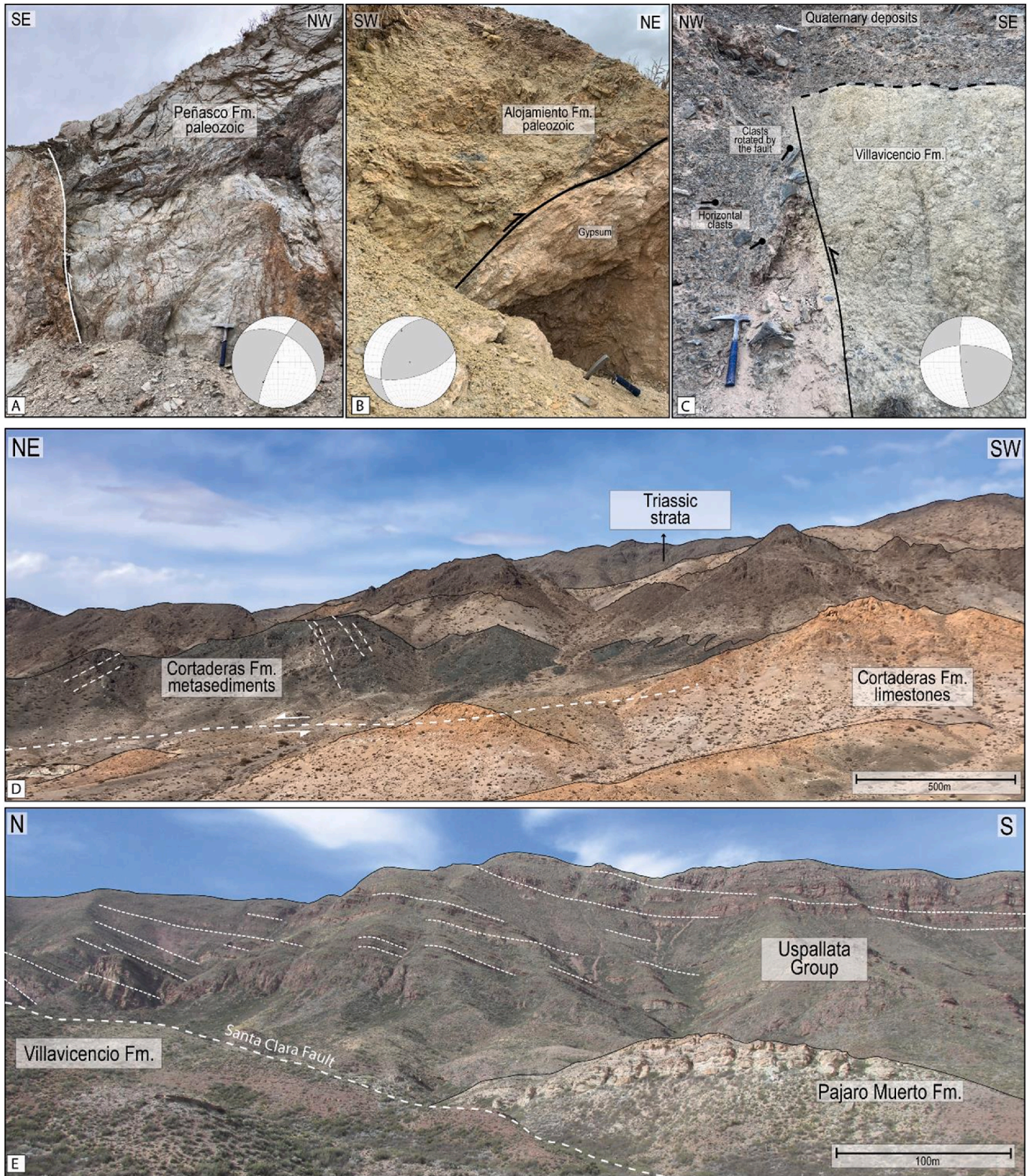


Fig. 4. Reverse and oblique-slip reverse Paleozoic faults reactivated during the Andean compression. (A) Peñasco fault. (B) Cortaderas fault. (C) Manantiales fault. Intraformational Paleozoic fault in the Cortaderas Formation (D). Unconformity between the Permian–Triassic Uspallata Group continental rocks and the late Paleozoic Villavicencio metasedimentary rocks folded (E).

Paleozoic age and due to the extension, orientation and cross-cutting relationships a Cenozoic reactivation is proposed; but because of the displacement observed on the Permian-Triassic and Cenozoic strata, less activity is suggested for the reactivation of the structure (Fig. 4A).

The north-south striking fault, F3, verging towards the east, uplifts the Cambrian-Devonian metasedimentary rocks (Peñasco Formation) on top of the Neoproterozoic metamorphic rocks (Cortaderas Formation). Data obtained from nearby stations indicate normal faulting. South of the study area, the structure cuts the Triassic Pampa Fría Formation, suggesting a Permian-Triassic age for the structure. F4 is a reverse structure that uplifts the Peñasco Formation on top of the Alojamiento metasedimentary rocks. In particular, the Alojamiento Formation shows tight folding and crenulation, suggesting that Lower Paleozoic shear zones were later reactivated as strike-slip structures (Fig. 4. B). This structure can be seen cutting through Cenozoic continental strata which, in combination with the kinematic analysis and the internal deformation of the Peñasco and Alojamiento sedimentary rocks suggests that these faults were generated by the reactivation of Paleozoic reverse structures during the Cenozoic compression. South of the section, northwest-striking normal faults with polarity towards the southwest are recognized. These structures only affect the Permian-Triassic volcanic rocks of the Choiyoi Group, so they can be associated with the Permian-Triassic extensional event.

6.3. Eastern domain

The eastern domain corresponds to east-vergent faults, which represent the actual deformation front. This front is composed of two Andean faults and one reactivated Pre-Andean fault system. This domain is composed of Early-Paleozoic rocks, Triassic clastic sequences, and foreland Cenozoic sediments, all exposed due to the activity of the structural systems. The structures that characterize the area are predominantly reverse and strike-slip faults with north-northeast and north-northwest strikes. These faults are the Manantiales, Las Higueras, Loma Negra, and Las Peñas faults (Fig. 3).

The Manantiales fault is a north-south structure (Cortes et al., 1999a, 1999b), also mapped as the Santa Clara Thrust (Harrington, 1971). The fault puts the metasedimentary rocks of the Villavicencio Fm. On top of the clastic deposits of Uspallata Group. Along the cross-section, it presents an important change of strike towards the south-west. The Manantiales fault shows a large area of damage that affects Quaternary sediments and where imbricated Paleozoic clasts can be recognized. The recent activity on the Manantiales fault shows oblique sinistral kinematics. Quaternary activity is also registered by Cortes et al. (1999; 2011b) south-west of the section. The kinematic analysis presented in this work shows that the Manantiales fault registered a contractional axis that can be related to the Paleozoic and Permian-Triassic events (Fig. 4. C).

In the Sierra de las Peñas area, the main style of deformation consists of a series of north-northwest striking faults, which make up Cenozoic thrusts that deform the rocks of the Mariño Formation in east-vergent folds with a basal detachment in the Devonian rocks. Although all faults share similar kinematic characteristics, their ages are different. The Las Higueras fault is associated with the Cenozoic compressional event based on the deformation of Pleistocene-Holocene sediments south of the cross-section (Paredes y Perucca, 2000; Perucca et al., 2008). The Loma Negra fault shows evidence of Quaternary deformation along the alluvial terraces. Other authors (Ahumada y Costa, 2009; Ahumada, 2010; Costa et al., 2015) mapped this structure north of the study area as a thrust that propagates onto alluvial deposits. Las Peñas fault is recognized as the westernmost thrust and neotectonics evidence is recognized as alluvial deposits that are folded and fractured (Cortes et al., 2014) (Fig. 4E).

7. Kinematic analysis

To analyze the deformational events that have taken place during the

uplift of the Precordillera fold-and-thrust belt, field data was collected and organized into seven structural stations showing four principal deformation events during different periods of time: Early Paleozoic, Late Paleozoic, Triassic, and Cenozoic.

7.1. Early Paleozoic deformation

Early Paleozoic deformation was responsible for the deformation in the western sector of the study area, and the deformation and uplift of the proto-Precordillera (von Gosen, 1995; Cortés et al., 1997). To evaluate subsequent reactivations of the early Paleozoic structures during the Early Permian, Late Permian-Triassic, and Cenozoic deformational events, we studied the structural grain of these rocks. In the study area, two major Early Paleozoic contractional deformation events can be recognized, affecting only the Cambrian-Devonian rocks.

The first phase is recorded in ductile shear structures and metamorphic foliations in Neoproterozoic to Devonian marbles and meta-carbonatites. The metapelites and limestones of the Alojamiento Formation are characterized by asymmetric, tight to isoclinal folds with sub-vertical axial planes, with general north-south strikes, with north-northeast and north-east variations. Axial plane cleavage is exhibited, controlling the arrangement of veinlets of irregular quartz indicative of pressure dissolution and transfer of mass during deformation. The shales of the Villavicencio Fm. Present a distinguishable pervasive foliation which provides evidence for a ductile deformation event with a northwest-southeast shortening axis and east tectonic transport. This phase was previously recognized by von Gosen (1995) in the Uspallata area affecting the Cambrian-Ordovician metasedimentary rocks, and the described structures match with the microscopic crenulation cleavage described by Heredia et al. (2012) and the mesoscale data south of the cross-section collected by Giambiagi et al. (2014).

A different deformational pulse is recorded on the limestones of the Alojamiento Fm. That shows two sets of brittle structures: high-angle structures striking north-northeast with tectonic transport towards the west and reverse structures striking east-west with tectonic transport towards the north. The kinematic analysis indicates a contractional regime with a shortening axis orientation north-south (Az 187°) (Fig. 5e); this evidence contributes to defining a second brittle contractional phase.

Summing up, the data collected can be associated with two Early Paleozoic contractional events: a ductile one, with a general north-south contractional direction, and a brittle one characterized by fault planes indicating a north-south shortening direction and different tectonic transports (Buggisch et al., 1994; von Gosen, 1995). This last event is better registered south of the cross-section (Giambiagi et al., 2011). The faults affecting the metasedimentary rocks of the Alojamiento Formation, located to the west of the Villavicencio fault, present tectonic transport towards the northwest; while those affecting the Villavicencio Fm. Rocks, located to the east of this fault, present tectonic transport towards the southeast. This suggests that the deformation had different vergences west and east of the Villavicencio fault.

7.2. Late Paleozoic deformation

Late Paleozoic deformation is recorded on Paleozoic rocks of the Peñasco Fm. And on Cambrian calcareous units of the Cortaderas Fm., where mainly inverse and strike-slip brittle structures. This deformation does not affect Permian or Early Triassic rocks that can be recognized immediately to the south but it does cut through Carboniferous strata of the Aguas de Jagüel Fm. The structures associated with this deformational event present two main structural characteristics: faults that strike northwest and overlap Cambrian-Devonian metasediments on top of carboniferous marine calcareous deposits; and northeast striking faults that put in contact calcareous early Paleozoic rocks with Devonian metasediments; both type of structures dipping towards the east.

The kinematic data obtained from three structural stations and the

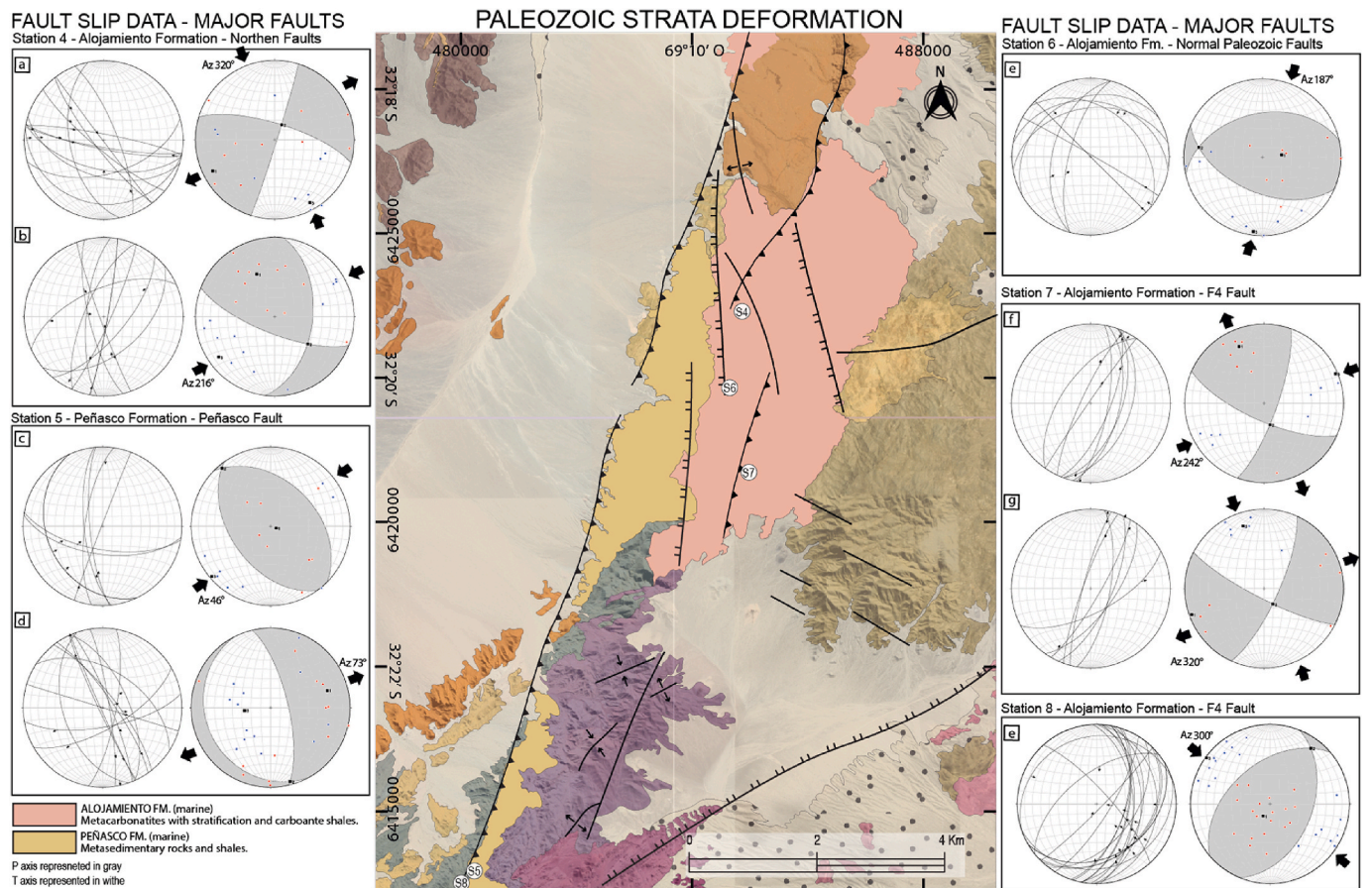


Fig. 5. Structural map highlighting the Paleozoic outcrops where Early and Late Paleozoic structures can be recognized, as well as Andean reactivations. (a–e) Kinematic data of meso and major-scale structures from the central and eastern domains representing Paleozoic and Mesozoic deformation. The data from the same station were separated into sets of structures corresponding to different deformation events, generating one or two families of structures with different shortening and stretching axes. In this way, the same structural station can show superimposed pulses of deformation. (S4–S8) Sites of kinematic measurements or structural stations.

cross-cutting relationships south of the cross-section suggest a Late Paleozoic northeast (Az 229°) shortening direction (Fig. 5). The high-angle structures present an oblique-slip reverse component with a sinistral movement, suggesting a transpressional movement in the northwest-striking structures and a transtensional movement in the northeast-striking structures. Considering the most recent deformational events, the unrotation via the unfold method resolves a transpressive regime for the Late Paleozoic deformation, with a northwest shortening axis (Az 242°) (Fig. 5b), and fault striking preferentially north-northeast. Taking the latter into consideration, the Late Paleozoic deformation presents a relationship with the Permian San Rafael phase, which was responsible for the deformation of Carboniferous-Early Permian sedimentary rocks and older rocks, and the generation of the angular unconformity that separates them from the Late Permian - Triassic volcanic and volcanoclastic rocks of the Choiyoi Group. Although this stratigraphic relationship was not observed in the study area, an angular unconformity is observed between the rocks of the Devonian Villavencio Fm. and those of the Triassic Cielo Fm. In the central domain near Cerro Cielo, which was used as a criteria for the analysis of the age of the structures.

The integration of these data suggests that the Paleozoic rocks are affected by a Late Paleozoic contractional deformation pulse. This brittle deformation is represented by fault planes striking northwest, with tectonic transport towards the west.

7.3. Triassic deformation

Fault-slip data, collected from the sedimentary rocks of the Uspallata Group, the Cielo Fm. (Fig. 6. a Fig. 6c and Fig. 6. d), and Paramillos Fm. (Fig. 6b), indicates a homogenous orientation of northeast maximum stretching direction (Fig. 7), in agreement with previous data collected by Japas et al. (2008). The fault planes present west-northwest to northwest strikes. The fault population registered in the Uspallata Group (Fig. 6d) indicates the syn-rift stage, where a concentration of structures towards the base of the strata indicates that the deformation was not concentrated in a single structure at this stage of deformation (Fig. 7b). In addition to the data obtained on Triassic rocks, it can be interpreted that a subset of the data obtained at station 4 (Fig. 5a), affecting Paleozoic rocks, records an extensional event where fault planes, striking northwest, and east-northeast, present kinematic results of an east-northeast maximum stretching axis direction. The interpretation of a major fault in this station indicates the presence of oblique-slip normal faults, with a sinistral component, related to this deformational event.

The integration of the data suggests that the Triassic and older rocks are affected by the regional Late Permian-Triassic extensional event, characterized by a stretching axis in the north-northeast direction (Giambiagi and Martinez, 2008) (Fig. 6).

7.4. Andean deformation and neotectonics

The Cenozoic contractional pulses are registered mostly in the Neogene sedimentary rocks, but also in the Pliocene-Quaternary

FAULT SLIP DATA - MESOSCALE

PERMO-TRIASSIC STRATA DEFORMATION

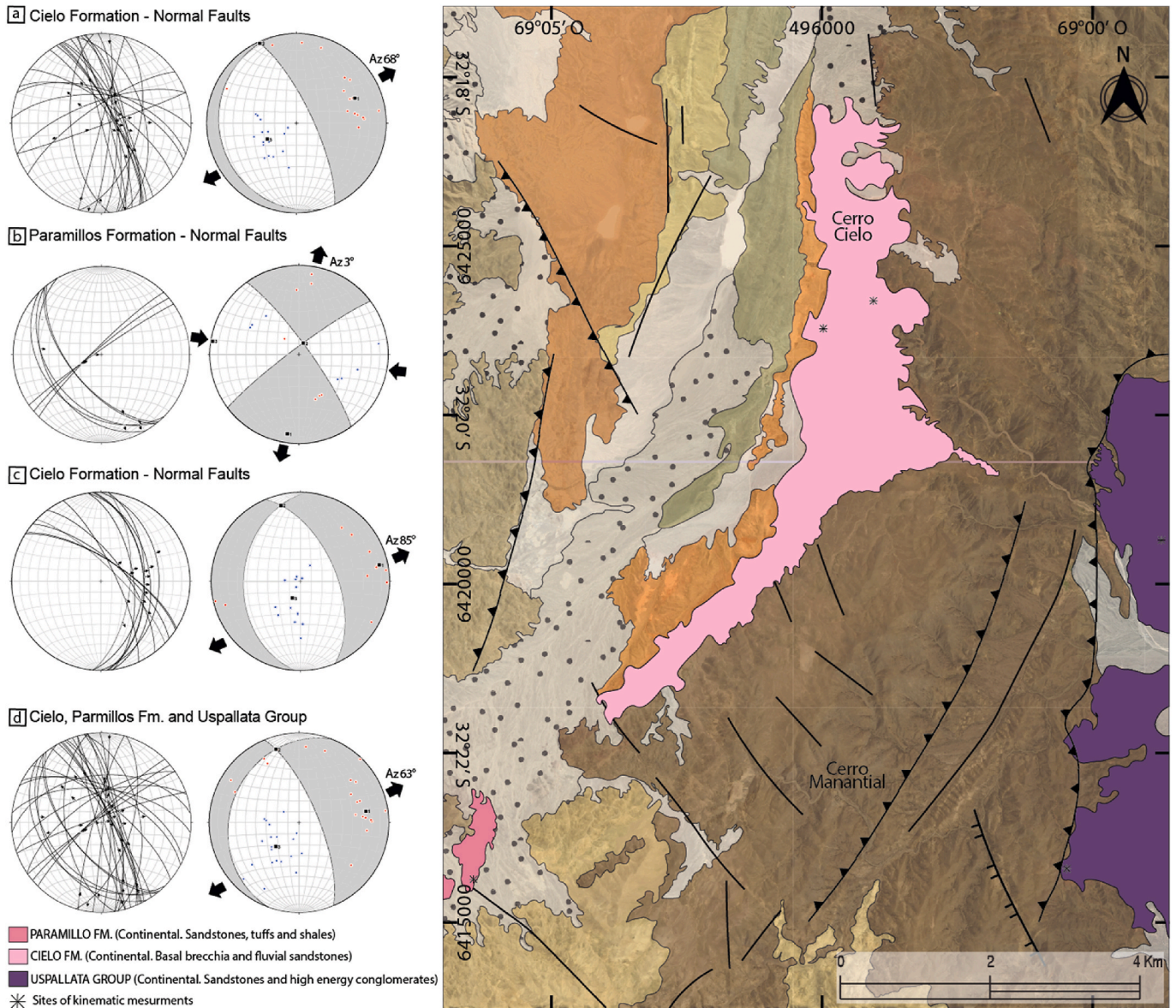


Fig. 6. (A) Structural map highlighting the Permian - Triassic deformation on the Cielo Formation and Uspallata Group. (B) Kinematic data of brittle Permian - Triassic structures from the central and eastern domain.

deposits (Cortés et al., 2005; Richard, 2020). The evidence collected from different structural stations (Fig. 5) shows two different sets of structures; one striking northeast and another one with northwest to north-northwest strike. The first one corresponds to inverse structures generated during Andean deformation. Their kinematic analysis indicates an east-west shortening axis orientation (Az 280°) (Fig. 5c and Fig. 5e). The second set of structures corresponds to Permian-Triassic and Paleozoic structures that were reactivated as reverse faults. The Permian-Triassic structures show sinistral displacements with a contractional component, suggesting a sinistral transpressive regime with a shortening axis east-southeast (Az 216°) (Fig. 5b); whereas the early and late Paleozoic faults are mainly inverted structures with a transtensional component (Fig. 5d and Fig. 5g).

Based on the data collected in the study area, the maximum shortening axis for the Early Miocene deformation can be associated with Andean tectonics and can be characterized by north-northeast and north-northwest faults with tectonic transport towards the east. It is observed that during this episode of deformation, the Paleozoic faults

with orientation favorable to reactivate under the Andean contractional axis were reactivated as inverse structures. Instead, the Permo-Triassic extensional structures register oblique-slip reverse components. In conclusion, the hybrid character of the Southern Precordillera fold and thrust belt is the result of the reactivation of pre-Andean structures that exert control in the elevation of the basement, as well as in the orientation of neotectonic deformation.

Finally, a fault plane recorded in the Quebrada Manantiales, which is associated with a minor branch of the homonymous fault, was studied in order to analyze the neotectonics in the area (Fig. 4C). This oblique-slip normal fault presents a sinistral component with an extension direction northeast (Az 46°) (Fig. 5b), indicating a current sinistral transpressive deformation in the study area. This structure would represent a normal Triassic fault that has been reactivated during the Andean compression, acquiring sinistral kinematics.

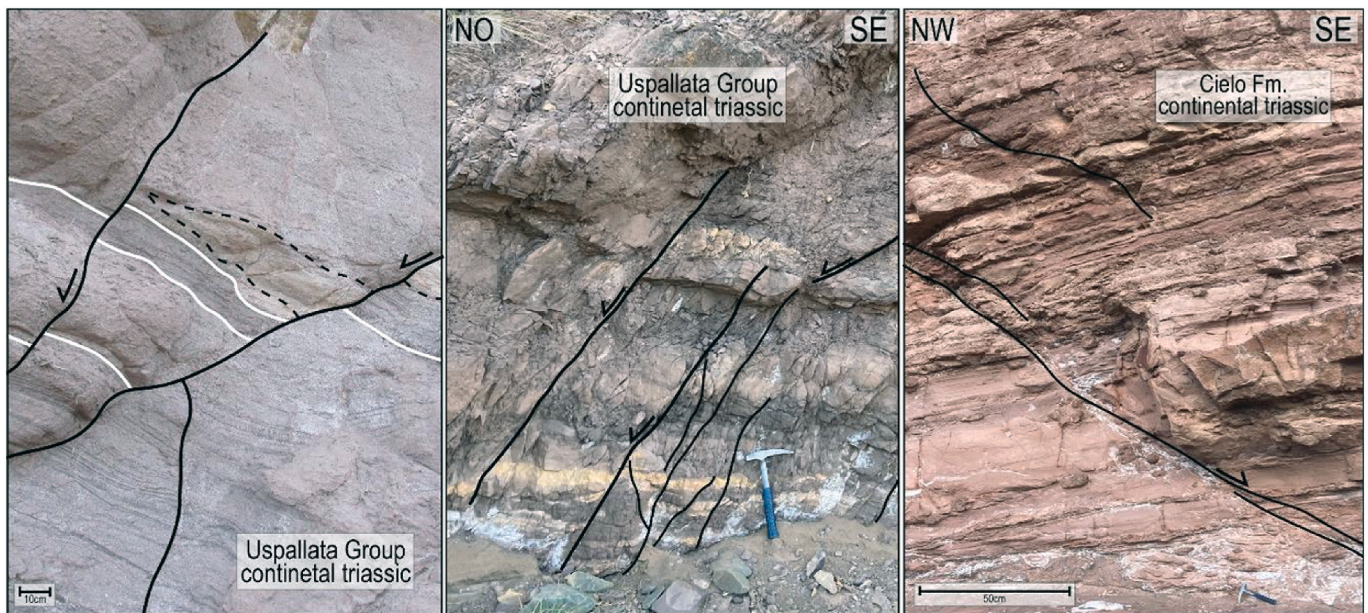


Fig. 7. Permian - Triassic deformation. (A) Normal structures affecting the Triassic Uspallata Group and interfingering of the finer sedimentary layers. (B) Normal faulting in the base of the Uspallata Group is recognized as a bigger number of fragile structures related to an early stage of the deformational stage. (C) Mesoscale normal faulting in the Triassic Cielo Fm. Strata.

8. Structural model

To understand the temporality and the structural relationships of the structures analyzed in this contribution, a structural forward model of the selected cross-section is presented. This model allowed us to propose a probable evolution of the recognized structures in the cross-section from an initial no-deformation state. The proposed decollement depth (10 km) was taken from Richard (2020), who studied the easternmost sector of the southern Precordillera, and from the regional cross-section at 32.4°S from Giambiagi et al. (2022). The age constraint of the model is set between 15 Ma and the present. This time span has been separated into three deformational stages. The age constraint is determined based on the beginning of the uplift of the Cordillera Frontal (Buelow et al., 2018), followed by the uplift of the Precordillera (Ramos et al., 1996; 2002; Buelow et al., 2018; Richard, 2020), when deformation in the Aconcagua fold-and-thrust belt, located in the Cordillera Principal, vanished and migrated towards the east (Ramos et al., 1996). This sequence of uplift is supported by thermochronological data (Fosdick et al., 2017; Lossada et al., 2017; Buelow et al., 2018; Mackaman-Lofland et al., 2020), which suggests that the Cordillera Frontal has uplifted since 15 Ma. Sedimentological evidence, such as the transition between the middle and upper Mariño Formation and the increase in green lithic arenite derived from the Devonian Villavicencio Formation, suggests the incorporation of the eastern Precordillera into the thrust system from 15 Ma to 8.5 Ma. The second stage is constrained based on the detrital zircon populations in the upper part of the La Pizona Formation determined by Iverson et al. (2012), which suggests that this sector received contributions from Frontal Cordillera 8.5 Ma ago; while the provenance analysis performed by Buelow et al. (2018), indicate that the western sector of the Southern Precordillera, was up at that time. This suggests that the uplifted ranges corresponded to the Cordillera del Tigre (Frontal Cordillera) and the western Precordillera; while the eastern Precordillera, the Sierra de Las Peñas-Las Higueras, was not yet a positive relief, or at least it did not constitute a barrier that prevented the arrival of sediments from the Cordillera Frontal and western Precordillera (Iverson et al., 2012; Buelow et al., 2018). Seismic interpretations show progressive unconformities in the sedimentary sequences younger than 4.5 Ma, suggesting that deformation was beginning in the eastern sector (Vergés et al., 2007; Quiroga, 2014; Richard, 2020). The third stage is

determined based on the deposition of the Mogotes Formation (3.5–1 Ma), east from the cross-section. The sediments of this unit suggest that the Sierra de las Peñas-Las Higueras, together with the Alojamiento and Cerro Cielo ranges, constitute a positive relief for this period.

Based on the structural interpretation and the strata thickness obtain in the field, we proposed an initial condition, previous to the Andean deformation, where three uplifted blocks, composed of Paleozoic rocks in the central domain, are identified (Fig. 8). From previous structural models (Giambiagi et al., 2014; Richard, 2020) and the generation of different scenarios the Paleozoic blocks are considered as a mechanic basement with rigid behavior; while the Mesozoic and Cenozoic rocks present internal deformation. Clastic continental rocks from the Cielo Formation fill a Triassic depocenter, corresponding to a sub-basin of the Las Peñas depocenter, representing the late syn-rift facies. This unit has 300 m in thickness and interfingers towards the west with the Uspallata Group. On top of the Triassic sequences, the early Cenozoic deposits reached up to 1000 m thick. From this starting point, an area-balanced section is proposed, with three deformational stages responsible for the uplift and deformation of the Southern Precordillera.

- The first stage of deformation occurs between 15 and 8.5 Ma (Late Middle Miocene) and is responsible for the uplift of the Ciénaga del Medio Group and the Peñasco Formation. This stage presents the main uplift of the Southern Precordillera FTB and consists of a period in which the deformation is concentrated in the western and central domains. The uplift generated by these faults is calculated to be 3 km approximately with a minimum shortening rate of 0.72mm/yr. The in-sequence north-south to north-northeast Paleozoic faults which are connected in depth to a first-order detachment level and have a favorable orientation with respect to the Andean shortening axis, are reactivated. The deformational sequence begins with the reactivation of the Del Medio fault and continues further east with the reactivation of the Paleozoic Peñasco and Cortaderas faults. These faults are generated as back thrust faults with high dipping angles, allowing for an increase in the thickness of the basement sequences and generating positive reliefs, such as the Cerro del Medio, Cerro Redondo, Cerro Blanco, and Cerro Cortaderas hills. After the movement of these faults, the inversion of the Manantiales fault (Paleozoic with Triassic reactivations) takes place,

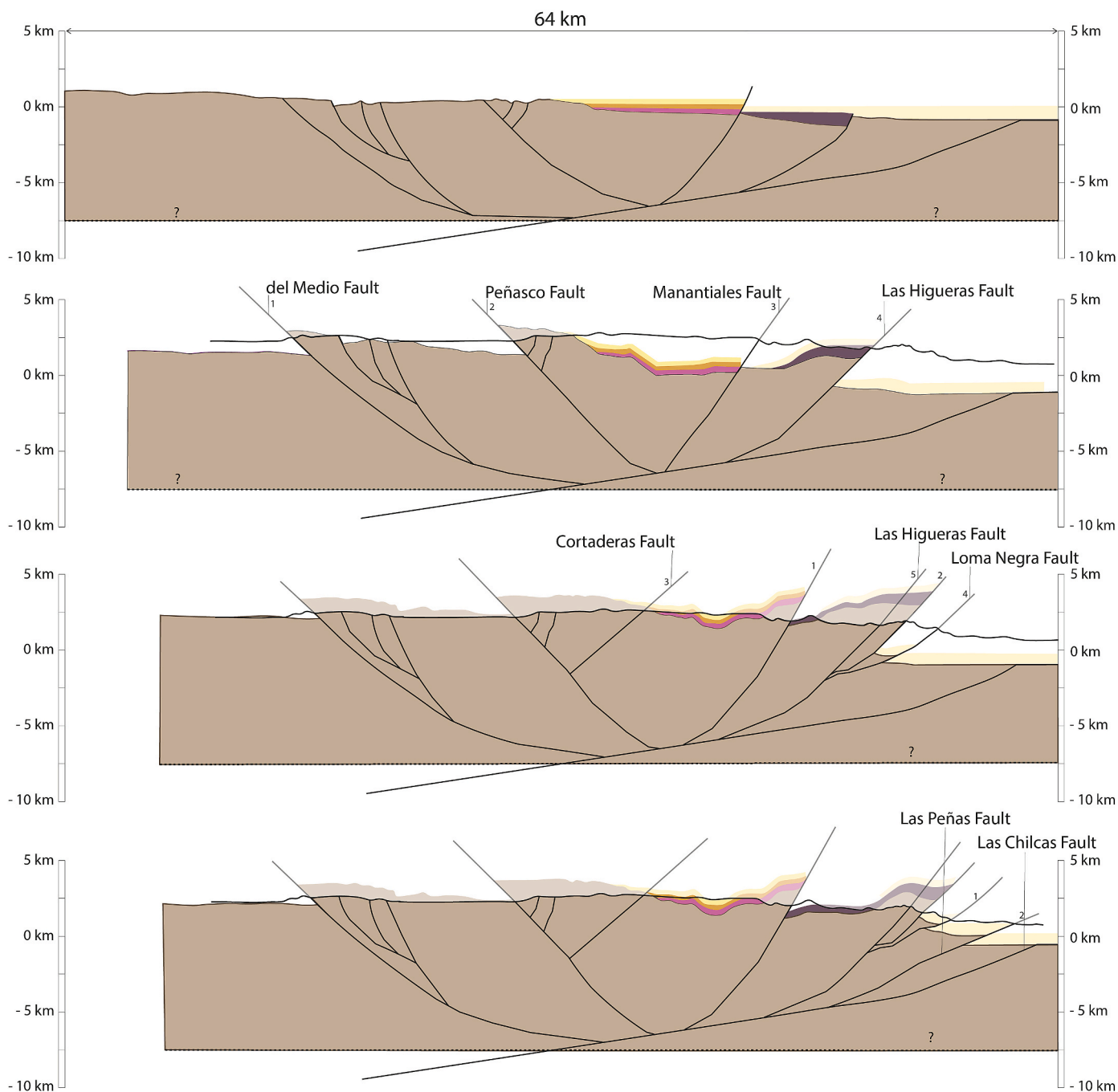


Fig. 8. Reconstruction and evolution of the cross-section in Fig. 4 (A) Initial conditions at 15 Ma, previous Andean compression. (B) First stage of deformation, between 15 Ma and 8.5 Ma. Shortening rate in the section: 0.72 mm/ry. Active faults in sequence: Middle fault, Peñasco fault, Manantiales fault. (C) Second stage of deformation between 8.5 Ma and 3.5 Ma. Shortening rate in the section: 1.04mm/yr. Active faults in sequence: Cortaderas, Las Higueras, Loma Negra. Active faults out of sequence: Santa Clara. (D) Third stage of deformation between 3.5 Ma and the Neotectonics. Shortening rate in the section: 0.86mm/yr. Active faults: Springs, Las Peñas. Numbering (1, 2, 3, 4, and 5) corresponds to the chronological order of fault movement. Stratigraphic unit colors stratigraphic correspond to those indicated in Fig. 2. Numbers in faults indicate order of reactivation.

simultaneously with the deposition of the Cielo Formation. Based on the obtained surface data, this fault has a sub-vertical dip, which indicates that, by the time of its Cenozoic reactivation, the fault presented dips greater than 45° (Fig. 8).

- The second stage of deformation occurs between 8.5 and 3.5 Ma, and it is focused towards the east, concentrating on the strata of the Uspallata Group and the Mariño Formation. It starts with the generation of the Cortaderas reverse fault deforming the basement. Eastwards, the Las Higueras Triassic normal fault is inverted, with

high dips angles. Afterward, with more shortening, the Loma Negra fault is generated as a footwall shortcut fault in the recumbent block. The generation of these faults implies an increase in the angle of the Las Higueras fault and the generation of a pair of syncline-anticline. This stage of deformation presents a minimum shortening rate of 1.04mm/yr; concentrating the highest rate of shortening for the Southern Precordillera FBT. More shortening is involved as the deformation evolves, the system gets stalled, and the Santa Clara fault is generated as an out-of-sequence fault, which uplifts the

Villavicencio Fm. basement without excessively shortening the section (Fig. 8).

- The last stage of deformation is presented from 3.5 Ma to the present. In this stage, contractional deformation migrates further east, with the generation of the Las Peñas fault. This fault corresponds to a low-angle in-sequence reverse fault that connects in depth with the first-level detachment. The flexure along the fault plane explains the deformation of the strata of the Mariño Fm. This episode is characterized by a strong shortening and mostly thin-skinned deformation; with a minimum shortening rate of 0.86mm/yr (Fig. 8).

9. Discussion

9.1. Influence of pre-Andean structures over the Cenozoic Andean deformation

Pre-existing major faults can generate upper-crustal mechanical weaknesses, favorable for reactivation during subsequent deformational

events. These planes of weakness can strongly influence the structural evolution of orogenic belts (Allmendinger et al., 1997; Carrera et al., 2006; Eichelberger and McQuarrie, 2015; Martínez et al., 2020). Different authors have proposed that numerous fault and shear processes can lead to the weakening of pre-existing structures (Handy, 1989; Rutter et al., 2001). These processes include the generation of pre-existing cohesionless fractures, grain refinement processes, especially grain size reduction, and/or thermal perturbations, which are some of the processes leading to long-term weakening.

The deformation of the Southern Precordillera at 32°30'S, especially in its western and central domains, has been strongly influenced by Paleozoic to Triassic pre-Andean structures. Here, we propose that the reactivation of Paleozoic north-northeast structures and Permian-Triassic north-northwest structures, as reverse and strike-slip faults, respectively, are responsible for the thick deformational style of this fold-and-thrust system.

Paleozoic structures affecting the Southern Precordillera can be associated with two pre-Devonian compressive pulses (Fig. 9). These

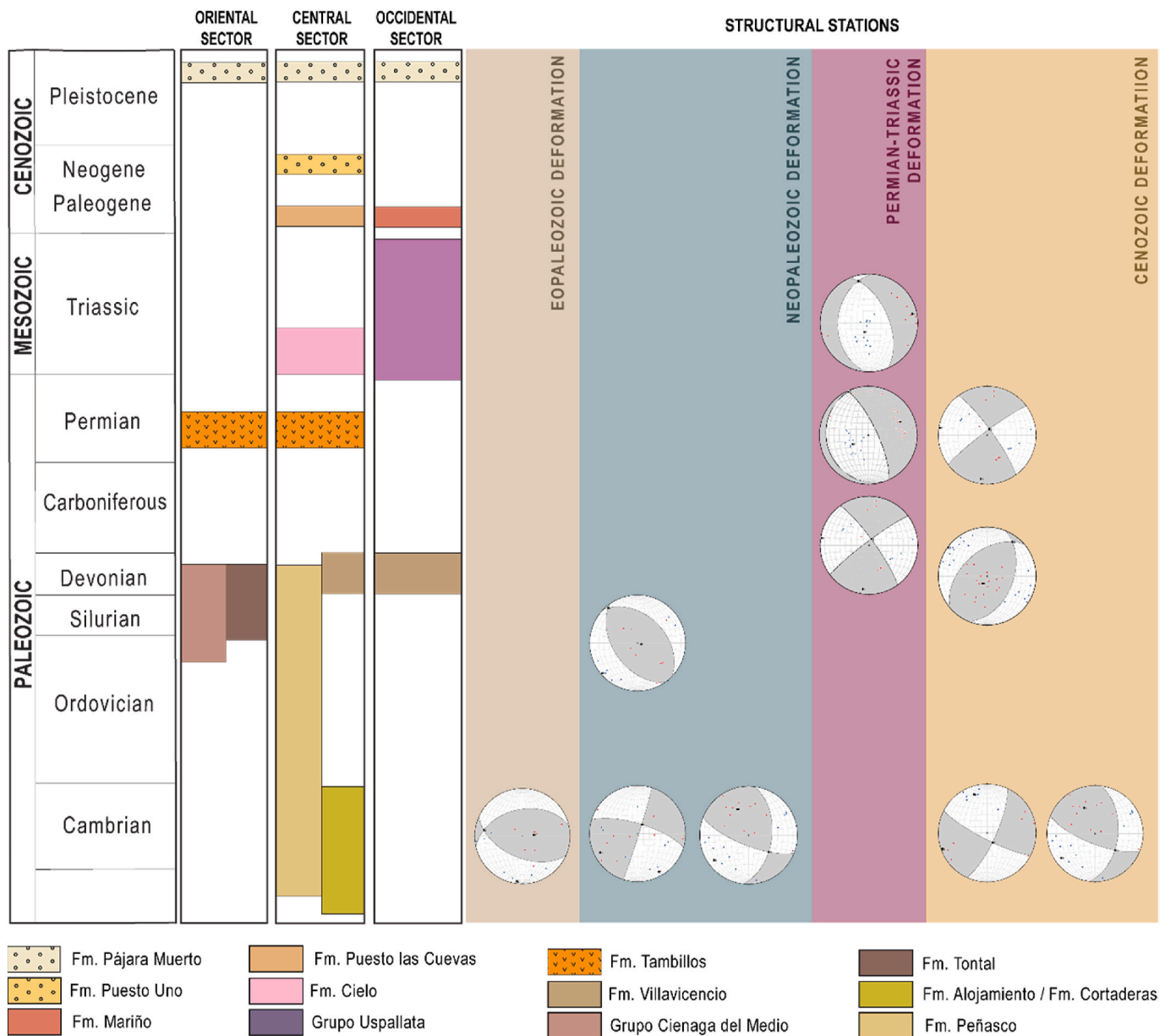


Fig. 9. Compilation of the kinematic results for each of the deformational events recognized in Southern Precordillera. The structural solutions represent the shortening and extensional axis for each event.

pulses have been related to the collision of different crustal blocks (Amos and Rolleri, 1965; Rolleri and Baldi, 1969; von Gosen, 1995; Davis et al., 1983; Giambiagi et al., 2014; Boedo et al., 2020). The kinematic of the mapped structures establishes that the last Paleozoic compression entails synchronous contractional and strike-slip events, under a transpressive regime, with a general north-south maximum shortening axis and double tectonic transport (Fig. 10). After these events, rocks in the study area were affected by a contractional northeast shortening pulse. This brittle deformation also presents a transpressive component with high-angle faults of both dextral and sinistral kinematics. These Paleozoic structures control the position of west-vergent Andean thrusts on the western part of the Southern Precordillera. The reactivation of these pre-existing structures was related to the kinematic evolution of the mountain belt. When the reactivation conditions were favorable, the west-verging structure became active. This led to the complex interaction of east- and west-vergent faults, characterizing a bivergent system.

Mesozoic normal faults, associated with master faults of the Cuyo basin, have been reactivated under the positive tectonic inversion (Fig. 9). These faults have north-northwest to northwest variable orientation and can be reactivated as high-angle reverse faults with a sinistral component (Fig. 10). These major faults present inflections along their strike. Additionally, due to these reactivations, transpressive kinematics are registered. The reactivation of these faults suggests the existence of a contractional axis with a similar orientation to the current east-northeast Andean contraction (Giambiagi et al., 2011). These features are observed in the Manantiales fault, where the thickness variation, the contact between the Paleozoic basement with the Quaternary deposits, and the rotation of the clasts in the fault zone allow for interpreting the faults as Mesozoic inverted normal fault (Giambiagi et al., 2003b, 2008). The strike-slip component is associated both with the superposition of deformational events and the relationship between

the contractional axis angle and fault geometry. This results in an oblique reactivation, with mainly sinistral transpressive components. Nevertheless, there are also reactivated opposing vergence faults. This difference can be linked to factors, such as changes in the type of basement rocks, the lack of Triassic coverage, and the geometric configuration of the faults.

Towards the east, a major rheological contrast exists between the Paleozoic basement and the Cenozoic cover (Mescua and Giambiagi, 2012). This rheological contrast causes the Cenozoic layers to decouple from the basement rocks, generating zones of detachments between the metamorphic basement and the sedimentary cover, which in turn generates the horizontal propagation of the faulting to the east, and consequently, the folding of the cover by fault bending. Andean east-verging structures are favored by this contrast, as can be recognized by the close proximity of the Las Higueras, Loma Negra, and Las Peñas faults to one another.

The geometry of the Southern Precordillera is restricted by basement-rooted reverse faults, inherited from Neopaleozoic and Permian deformational events (Fig. 10). The reactivation of these faults controls the west-vergence of the Southern Precordillera, in contrast with the general east-vergence of the Northern Precordillera.

9.2. Structural domain analysis and deformation sequence

Our new field kinematic data and our proposed structural model suggest that this sector of the Precordillera shows an important tectonic uplift to the west, while to the east, horizontal tectonic shortening is more important than tectonic uplift, characterized by several in-sequence thrusts with tectonic transport towards the east (Fig. 3). This characterization is correlatable with descriptions of the Precordillera at Southern latitudes (Giambiagi et al., 2011, 2014; Mescua and

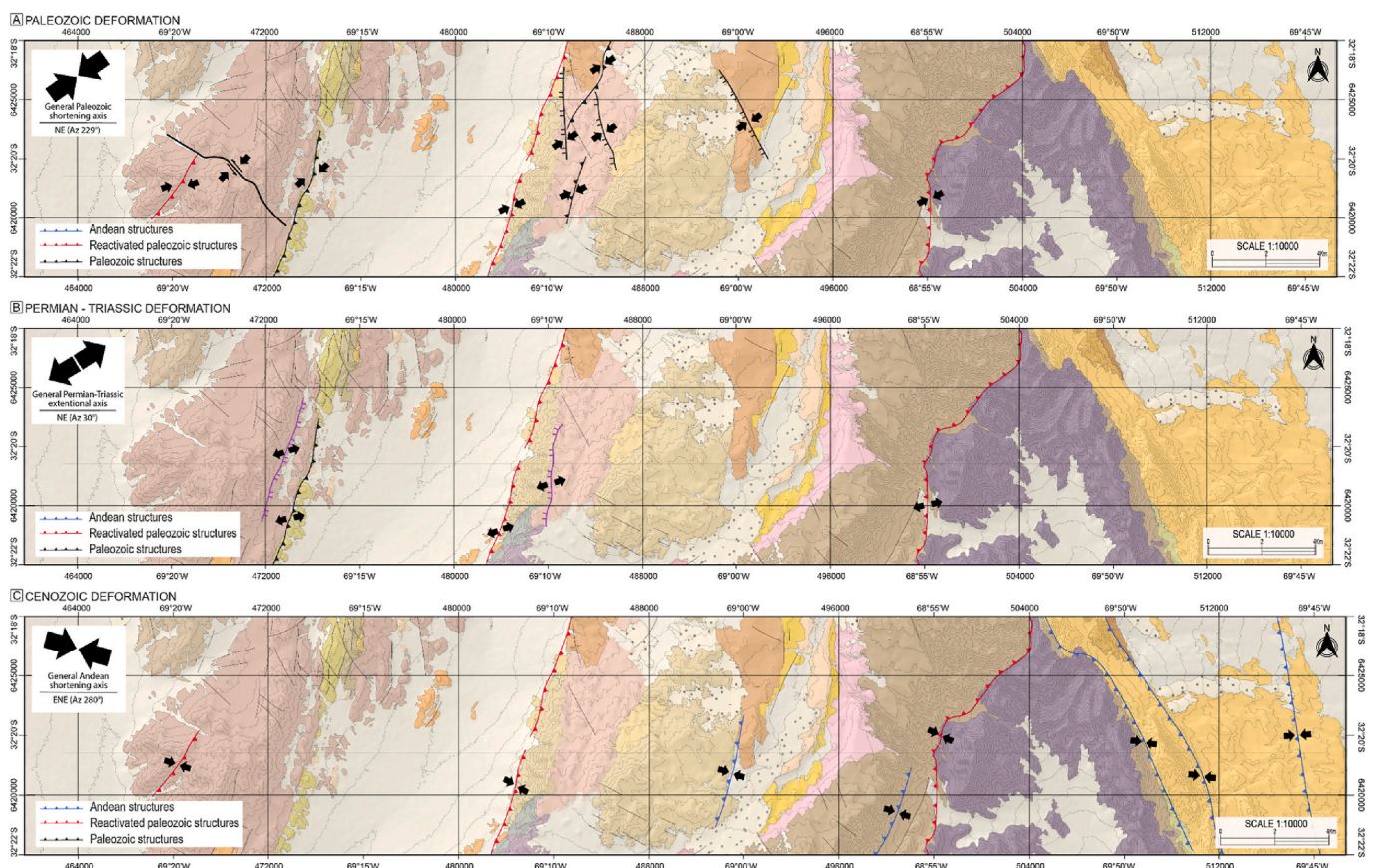


Fig. 10. Structural maps showing the structures associated with each deformational event. (A). Paleozoic contractional axis (B) Permian-Triassic extension axis (C) Cenozoic (Andean) contractional axis.

Giambiagi, 2012).

The involvement of the basement towards the west and the fault kinematics indicates a hybrid deformational style, with high-angle inverted faults, involving Paleozoic basement rocks, as well as the volcano-sedimentary Permian-Triassic cover, and medium to low-angle reverse faults involving the younger Cenozoic sedimentary units. The strata of the central sector are characterized by homogeneous dips (between 20° and 25°), and the structural model shows an overturned fold. In addition, in the eastern sector, tighter fault-controlled folds can be recognized as a consequence of the shortening associated with the Las Higuera fault (Fig. 3).

The development of this structural style was strongly controlled by the lower and upper Paleozoic structures affecting the western sector (Fig. 9). It can be established that the first episode of deformation of the Southern Precordillera is associated with the uplift of the Cordillera del Tigre, which main east-vergent fault system is connected to the Precordillera structures by a deep basement ramp, constrained between 17 and 12 Ma (Levina et al., 2014; Buelow et al., 2018; Lossada et al., 2020; Giambiagi et al., 2022), and it is recorded by the reactivation of Paleozoic and Triassic faults with north-south or north-northwest strikes. These reactivated faults uplift the different Paleozoic blocks, named Cerro Cortaderas, Cerro del Medio, and Cerro Peñasco. This process allows the tipping of the sedimentary sequences with the consequent exposure of the Villavicencio Fm. and the Uspallata Group. This deformation event also generated the folding of the Cielo, Puesto las Cuevas, and Puesto Uno strata. The previous proposal is consistent with the decrease in the contribution of Permo-Triassic zircons and the increase in the dominance of Carboniferous zircons from ca. 10 to ca. 8 Ma (Fosdick et al., 2015). Other evidence that supports the model is the increase of both the lithic clasts from the Villavicencio Fm. In the La Pizona Fm. and the sedimentation rates at the Mariño – La Pizona contact (Buelow et al., 2018); the sedimentation rate (compacted) increases from 0.16 mm/yr to 0.28 mm/yr, which is interpreted to represent increased orogenic exhumation due to eastward migration of the deformation front. The second episode of deformation occurs between ca. 8.5 and 3 Ma when a drastic increase in shortening and a generalized displacement is observed in thrusts that affect Paleozoic and Cenozoic sequences in the eastern sector of the transect (Levina et al., 2014; Fosdick et al., 2015; Suriano et al., 2017). The model suggests that, during this deformation, new north-northeast structures are generated, such as the Loma Negra fault, which is consistent with the west-northwest regional shortening axes. Additionally, the model suggests the reactivation of Paleozoic faults located in the eastern sector. This stage is characterized by the generation of folding and ductile structures in the strata of the Uspallata Group and the Mariño Formation. The easternmost expression of this deformation is the Sierra de las Peñas – Las Higuera, where the last event of this evolution and migration of the deformation is recorded (Cortés and Costa, 1996; Costa et al., 2000b, 2014; Richard, 2020). To accurately delimit the age of activity of the faults and the kinematic and geometric behavior of the structures, it is necessary to conduct thermochronology dating and sedimentological studies in further research.

Our results suggest different shortening rates for each of the contractional episodes. Constraining deformation rates for the Paleozoic reverse structures in the western sector is complex due to the difficulty in interpreting the geometry at depth of the structure. The results yield shortening rates of 0.72 mm/yr for the first contractional event, 15–8.5 Ma, which involves the reactivation of these west-verging structures. However, as the deformation continues and advances towards the east, this rate increases to 1.04 mm/yr, 8.5–3.5 Ma. This corresponds to about 15%–21% of the most likely long-term shortening rates, 5–7 mm/yr, estimated for the complete width of the Precordillera and the Andean front region of 30–33°S by several different authors (Sarewitz, 1988; Cristallini and Ramos, 1997; Giambiagi and Ramos, 2002; Ramos, 2004; Vergés et al., 2007). However, for the last contractional episode, affecting mostly the eastern domain, shortening

rates decrease to 0.89 mm/yr. This value falls into the same range of shortening rates of recent studies (Costa et al., 2019) which present shortening rate values for the last ~200 ka ranging from 0.16 to 0.38 mm/yr, the higher value can be attributed to a difference in the spatial and temporal scales of observation. Other studies present higher shortening rates for Precordillera in the same time constraint, Schmidt et al. (2011) calculate shortening rates of ~1.2–2.0 mm/yr for the Holocene in a young splay of the Las Peñas; Costa et al. (2015), estimated shortening rates from 1.61 mm/yr to 2.18 mm/yr for the last 4495 ± 143 ka and slightly lower rates from 1.27 mm/yr to 1.79 mm/yr for the last 8245 ± 48 ka.

10. Conclusions

The Precordillera fold-and-thrust belt, located at the eastern part of the southern Central Andes, between 28° and 33°S, is regarded as a classical thin-skinned, east-vergent, N–S oriented thrust belt. However, its southern part has a more complex deformation style, with the basement involved in the deformation, bi-vergent tectonic transport, and NW to NE striking faults. In this sector, the reactivation of the Paleozoic and Triassic structures is a first-order control for the geometry and style of deformation. The orientation of basement reverse faults inherited from the compressive Paleozoic events and from the Permian-Triassic extensional deformation conditioned the evolution of this orogenic belt. The reactivation of these structures results in a complex structural relationship between west and east-verging structures.

Due to the presence of pre-Andean structures, the Southern Precordillera behaves as a contractionary deformation unit, characterized as a fold-and-thrust belt with a hybrid deformation style; thick-skinned with basement involved in the deformation and thin-skinned with detachment in the Paleozoic-Cenozoic sedimentary cover. Based on field observations and subsurface interpretations, three different structural domains were distinguished. The western domain is characterized by north-south and north-northwest striking, moderate to high-angle reverse faults that uplift the basement. The central domain presents structures like those on the western domain and also inverted normal with northwest strike, and reverse Cenozoic northeast faults of low angle. The eastern domain involves an inverted Triassic structure and inverse thrusts with a north-south to north-northeast strike.

Our proposed structural model for the Cenozoic deformation of the Southern Precordillera at 32°30'S involves oblique tectonic inversion where the greatest shortening rate is calculated to be 1.04 mm/yr and it is associated with the eastward migration of the deformational front.

6.

CRedit authorship contribution statement

Milagros Gutierrez Seia: Conceptualization, Data curation, Formal analysis, Software, Validation, Writing – original draft. **Pamela Jara:** Software, Validation, Writing – review & editing. **Macarena Bertoa del Llano:** Writing – review & editing. **Andrés Richard:** Software, Writing – review & editing. **Lucas Lothari:** Project administration, Resources, Writing – review & editing. **Laura Beatriz Giambiagi:** Software, Supervision, Validation, Funding acquisition, Project administration, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This work was supported by the Argentine ANPCyT (PICT-2019-0800) and the Argentine CONICET (PIP 11220200101409CO). We acknowledge Petex for the Academic Licence of the program MOVE to the Universidad del Desarrollo (Chile).

References

- Ahumada, E., 2010. Neotectónica del frente orogénico andino entre los 32°08'S – 32°19'S, provincias de Mendoza y San Juan, PhD Thesis, Depto. Geología, Univ. Nac. San Luis.
- Allmendinger, R.W., 1998. Inverse and forward numerical modelling of trishear fault-propagation folds. *Tectonics* 17 (4), 640–656.
- Allmendinger, R.W., Figueroa, D., Snyder, D., Beer, J., Mpodozis, C., Isacks, B.L., 1990. Foreland shortening and crustal balancing in the Andes at 308S latitude. *Tectonics* 9, 789–809.
- Allmendinger, R.W., Jordan, T., Kay, S.M., Isacks, B., 1997. The evolution of the Altiplano-puna plateau of the central Andes. *Annu. Rev. Earth Planet Sci.* 25, 139–174. <https://doi.org/10.1146/annurev.earth.25.1.139>.
- Alonso, J., Gallastegui, J., García-Sansegundo, J., Fariás, P., Rodríguez Fernández, L., Y Ramos, V., 2008. Extensional tectonics and gravitational collapse in an Ordovician passive margin: the Western Argentine Precordillera. *Gondwana Res.* 13, 204–215.
- Amos, A.J., y Rolleri, E.O., 1965. El Carbónico marino en el valle de Calingasta-Uspallata (San Juan- Mendoza), vol. 368. *Bol. Inf.Petrol. YPF. (Bs.As)*.
- Ariza, J.P., Martínez, M.P., Vujovich, G.I., Boedo, F.L., Alvarez, O.Y., Sanchez, M.A., 2014. Sensoramiento remoto y magnetismo aplicado al estudio de terrenos paleozoicos en la Precordillera Occidental (31°20'LS). *Geoacta* 39, 35–50.
- Boedo, L., Pérez Luján, S., Ariza, J.P., Vujovich, G.I., 2021. The mafic-ultramafic belt of the Argentine Precordillera: a geological synthesis. *J. S. Am. Earth Sci.* 110, 103354 <https://doi.org/10.1016/j.jsames.2021.103354>. ISSN 0895-9811.
- Boedo, F.L., Vujovich, G.I., Kay, S.M., Ariza, J.P., Pérez Luján, S., 2013. The E-MORB783 like geochemical features of the early Paleozoic mafic-ultramafic belt of the Cuyania 784 terrane, western Argentina. *J. S. Am. Earth Sci.* 48, 73–84.
- Buelow, E.K., Suriano, J., Mahoney, J.B., Kimbrough, D.L., Mescua, J.F., Giambiagi, L.B., Hoke, G.D., 2018. Sedimentologic and stratigraphic evolution of the Cacheuta basin: constraints on the development of the Miocene retroarc foreland basin, south-Central Andes. *Lithosphere* 10 (3), 366–391. <https://doi.org/10.1130/L1709.1>.
- Carrera, N., Muñoz, J.A., Sábat, F., Mon, R., Roca, E., 2006. The role of inversion tectonics in the structure of the Cordillera Oriental (NW Argentinean Andes). *J. Struct. Geol.* 28, 1921–1932.
- Charrier, R., Pinto, L., Rodríguez, M.P., 2007. Tectonostratigraphic evolution of the Andean Orogen in Chile. In: Moreno, T., Gibbons, W. (Eds.), *The Geology of Chile*. Geological Society, London, pp. 21–114.
- Cortés, J.M., 1992. Lavas almohadillas en el Grupo Ciénaga del Medio, extremo noroccidental de la Precordillera mendocina. *Rev. Asoc. Geol. Argent.* 47, 115–117.
- Cortés, J.M.Y., Cegarra, M., 2004. Plegamiento Cuaternario transpresivo en el piedemonte suroccidental de la Precordillera sanjuanina. *Asociación Geológica Argentina, Serie D: Publicación Especial* 7, 68–75 (Buenos Aires).
- Cortés, J., y Costa, C., 1996. Tectónica Cuaternaria en la desembocadura del Río de las Peñas. Bordo oriental de la Precordillera de Mendoza Decimotercer Congreso Geológico Argentino Actas 2, 225–238.
- Cortés, J.M., Vinciguerra, P., Yamín, M., Pasini, M.M., 1999a. Tectónica Cuaternaria de la Región Andina del Nuevo Cuyo (28°–38° LS). In: Caminos, En R. (Ed.), *Geología Argentina. Servicio Geológico Minero Argentino, Anales*, Buenos Aires, pp. 760–778, 29 (24).
- Cortés, J.M., Casa, A., Pasini, M., Yamin, M.Y., Terrizzano, C., 2006. Fajas oblicuas de deformación neotectónica en Precordillera y Cordillera Frontal (31°30'–33°30' ls): controles paleotectónicos. *Rev. Asoc. Geol. Argent.* 61, 639–646.
- Cortés, J.M., González Bonorino, G., Koukharsky, M.M.L., Pereyra, F., Brodtkorb, M., 1997. Hoja geológica 3369-09, Uspallata, provincia de Mendoza, Argentina, escala 1:250,000. *Servicio Geológico Minero Argentino (Inédito)*, Buenos Aires, p. 204.
- Cortés, J.M., González Bonorino, G., Koukharsky, M.L., Brodtkorb, A., Pereyra, F., 1999b. Hoja Geológica 3369-03 Yalguaraz, Mendoza. *Carta Geológica de la República Argentina Escala 1:100.000*, vol. 280. *Servicio Geológico Minero Argentino, Boletín*, p. 230 (Buenos Aires).
- Cortés, J.M., Terrizzano, C.M., Pasini, M.M., Yamin, M.G., Casa, A.L., 2016. Quaternary tectonics along oblique deformation zones in the Central Andean retro-wedge between 31°30'S and 35°S. *Geological Society, London, Special Publications* 399, 267–292.
- Costa, Carlos, Vázquez, Fabricio, Kröhlings, Daniela, 2015. Holocene shortening rates of an andean-front thrust, southern precordillera. *Tectonophysics* 664, 191–201. <https://doi.org/10.1016/j.tecto.2015.09.017>. Argentina.
- Costa, C.H., Gardini, C., Diederix, H., Cortés, J., 2000a. The andean orogenic front at Sierra de Las peñas-las Higuera, mendoza, Argentina. *Journal of South American Earth Sciences* 13 287–292.
- Costa, C., Machette, M.N., Dart, R.L., Bastías, E., Paredes, N.D., Perucca, L.P., Tello, G.E., Haller, K.M., 2000b. Map and database of quaternary faults and folds in Argentina. *United States Geological Survey Open-File Reports* 00-108 75p.
- Costa, C.H., Schoenbohm, L.M., Brooks, B.A., Gardini, C.E., Richard, A.D., 2019. Assessing Quaternary shortening rates at an Andean frontal thrust (32° 30'S), Argentina. *Tectonics* 38, 3034–3051. <https://doi.org/10.1029/2019TC005564>.
- Costa, C.H., Audemard, F.A., Bezerra, F.H.R., Lavenu, A., Machette, M.N., París, G., 2006a. An overview of the main Quaternary deformation of South America. *Rev. Asoc. Geol. Argent.* 61 (4), 461–479.
- Costa, C., Smalley, R., Schwartz, D., Stenner, H., Ellis, M., Ahumada, E., Velasco, M., 2006b. Paleoseismic observations of an onshore transform boundary: e Magallanes-Fagnano fault, Tierra del Fuego, Argentina. *Rev. Asoc. Geol. Argent.* 61 (4), 647–657.
- Cristallini, E., 1998. Introducción a las fajas plegadas y Corridas. Inédito. Curso teórico-práctico. Departamento de Ciencias Geológicas. Facultad de Ciencias Exactas y Naturales. Universidad de Buenos Aires, 2000. <http://aviris.gl.fcen.uba.ar/Bibliog>.
- Cristallini, E., Ramos, V., 1997. Estructura profunda de los Andes a los 32° de latitud sur (Argentina y Chile), presented at the 8th Congreso Geológico Chileno. *Acta* 3, 1622–1625.
- Davis, D., Suppe, J., Dahlen, F.A., 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *J. Geophys. Res.* 1153–1172. <https://doi.org/10.1029/JB088iB02p01153>, 1983.
- Eichelberger, N., McQuarrie, N., 2015. Kinematic reconstruction of the Bolivian orocline. *Geosphere* 11 (2), 445–462. <https://doi.org/10.1130/GES01064.1>.
- Erslev, E.A., 1995. Trishear fault-propagation folding. *Geology* 19 (6), 617–620. [https://doi.org/10.1130/0091-7613\(1991\)019](https://doi.org/10.1130/0091-7613(1991)019), 1991.
- Folguera, A., Etcheverría, M., Pazos, P., Giambiagi, L., Cortés, J.M., Fauqué, L., Fusari, C., Rodríguez, M.F., 2001. Descripción de la Hoja Geológica Potrerillos (1: 100.000). Subsecretaría de Minería de la Nación, Dirección Nacional del Servicio Geológico, p. 262.
- Fosdick, J.C., Grove, M., Graham, S.A., Hourigan, J.K., Lovera, O., Romans, B.W., 2015. Detrital thermochronologic record of foreland burial heating, sedimentary provenance, and orogenesis in patagonia. *Basin Res.* 27, 546–572.
- Giambiagi, L., Martínez, A.N., 2008. Permo-Triassic oblique extension in the Uspallata-Potrerillos area, western Argentina. *J. S. Am. Earth Sci.* 26, 252–260. <https://doi.org/10.1016/j.jsames.2008.08.008>.
- Giambiagi, L., Ramos, V., 2002. Structural evolution of the Andes in a transitional zone between flat and normal subduction (33°30'–33°45'S), Argentina and Chile. *J. S. Am. Earth Sci.* 15 (1), 101–116.
- Giambiagi, L.B., Tassara, A., Mescua, J., 2015. Evolution of shallow and deep structures along the Maipo-Tunuyán transect (33°40'S): from the Pacific coast to the Andean foreland. *Geol Soc Lond Spec Publ* 399, 63–82. <https://doi.org/10.1144/sp399.14>.
- Giambiagi, L.B., Alvarez, P., Godoy, E., Ramos, V.A., 2003. The control of preexisting extensional structures on the evolution of the southern sector of the Aconcagua folds and thrust belt, southern Andes. *Tectonophysics* 369, 1e19.
- Giambiagi, L.B., Bechis, F., García, V.H., Clark, A., 2008. Temporal and spatial relationships of thick- and thin-skinned deformation in the Malargüe fold and thrust belt, southern central Andes. *Tectonophysics* 459, 123e139.
- Giambiagi, L.B., Mescua, J., Folguera, A., Martínez, A., 2010. Estructuras y cinemática de las deformaciones pre-andinas del sector sur de la Precordillera, Mendoza. *Rev. Asoc. Geol. Argent.* 66, 5–20.
- Giambiagi, L.B., Mescua, J., Bechis, F., Martínez, A., Folguera, A., 2011. Pre-Andean deformation of the Precordillera southern sector, southern central Andes. *Geosphere* 7, 1–21.
- Giambiagi, L.B., Mescua, J., Heredia Carballo, N., Fariás Arquer, P.J., GarcíaSansegundo, J., Fernández, C.Y., Lössada, A., 2014. Reactivation of Paleozoic structures during Cenozoic deformation in the Cordón del Plata and Southern Precordillera ranges (Mendoza, Argentina). *J. Iber. Geol.* 40 (2).
- Giambiagi, L., Tassara, A., Echaurren, A., Julve, J., Quiroga, R., Barrionuevo, M., Liu, S., Echeverría, I., Mardónez, D., Suriano, J., Mescua, J., Lössada, A., Spagnotto, S., Bertoa, M., Lothari, L., 2022. Crustal anatomy and evolution of a subduction-related orogenic system: insights from the Southern Central Andes (22–35°S). *Earth Sci. Res.* 232, 104138 <https://doi.org/10.1016/j.earscirev.2022.104138>.
- González Menéndez, L., Gallastegui, G., Cuesta, A., Heredia, N., Rubio Ordóñez, A., 2013. Petrogenesis of Early Paleozoic Basalts and Gabbros in the Western Cuyania 930 Terrane: Constraints on the Tectonic Setting of the Southwestern Gondwana Margin.
- Gutscher, M.A., Spakman, W., Bijwaard, H., Engdahl, E.R., 2000. Geodynamics of flat subduction: seismicity and tomographic constraints from the Andean margin. *Tectonics* 19 (5), 814–833.
- Handy, 1989. Deformation regimes and the rheological evolution of fault zones in the lithosphere: the effects of pressure, temperature, grain size and. *Volumen* 163, 119–152 pages=.
- Heredia, N., Fariás, P., García-Sansegundo, J., Giambiagi, L.B., 2012. The Basement of the Andean Frontal Cordillera in the Cordón del Plata (Mendoza, Argentina): geodynamic Evolution. *Andean Geol.* 39 (2), 242–257.
- Heredia, S., Kaufmann, C., Mestre, A., Soria, T., Ortega, G., 2014. La edad de la base de la Formación La Cantera (Ordovícico) en la Precordillera Oriental, Sierra de Villicium, San Juan. In: *Congreso Geológico Argentino*, vol. 19, pp. S2–S13 (Córdoba).
- Heredia, N., García-Sansegundo, J., Gallastegui, G., Fariás, P., Giacosa, R.E., Hongn, F., Tubía, J.M., Alonso, J.L., Busquets, P., Charrier, R., Clariana, P., Colombo, F., Cuesta, A., Gallastegui, J., Giambiagi, L., González-Menéndez, L., Limarino, C.O., Martín-González, F., Pedreira, D., Quintana, L., Rodríguez Fernández, L.R., Rubio-Ordóñez, A., Seggiaro, R., Serra-Varela, S., Spalletti, L.A., Cardó, R., Ramos, V.A., 2018. The pre- andean phases of construction of the southern Andes basement in neoproterozoic-paleozoic times. In: *The Evolution of the Chilean and Argentinean Andes*.
- Jordan, T.E., Isacks, B., Ramos, V.A., Allmendinger, R.W., 1983a. Mountain building in the central Andes. *Episodes* 1983 (3), 20–26.
- Jordan, T.E., Isacks, B., Allmendinger, R., Brewer, J., Ramos, V.A., Ando, C., 1983b. Andean tectonics related to geometry of subducted plates. *Geol. Soc. Am. Bull.* 94 (3), 341–361.

- Kley, J., Monaldi, C., Salfity, J., 1999. Along-strike segmentation of the Andean foreland: causes and consequences. *Tectonophysics* 301, 75–94.
- Legarreta, L., Kokogian, D.A., Dellape, D.A., 1992. Tertiary structure of the Cuyan Basin: how much tectonic inversion? *Revista - Asociacion Geologica Argentina* 47, 83–86.
- Levina, M., Horton, B.K., Fuentes, F., Stockli, D.F., 2014. Cenozoic sedimentation and exhumation of the foreland basin system preserved in the Precordillera thrust belt (31–32°S), southern central Andes, Argentina. *Tectonics* 33, 1659–1680.
- Llambías, E., Sato, A., 1990. El Batolito de Colangüil (29–31°S) cordillera frontal de Argentina: estructura y marco tectónico. *Rev. Geol. Chile* 17 (1), 89–108.
- Llambías, E.J., 1999. Las rocas ígneas gondwánicas. El magmatismo gondwánico durante el Paleozoico Superior-Triásico. In: Caminos, R. (Ed.), *Geología Argentina*, vol. 29. Instituto de Geología y Recursos Minerales, Anales, pp. 349–363.
- Mackaman-Lofland, C., Horton, B., Fuentes, F., Constenius, K., Ketcham, R., Capaldi, T., Stockli, D., Ammirati, J.B., Alvarado, P., Orozco, P., 2020. Andean Mountain building and foreland basin evolution during thin- and thick-skinned neogene deformation (32–33°S). *Tectonics* 39, e2019TC005838. <https://doi.org/10.1029/2019TC005838>.
- Marrett, R.A., Allmendinger, R.W., 1990. Kinematic analysis of fault-slip data. *J. Struct. Geol.* 12, 973–986.
- Martínez, F., López, C., Parra, M., 2020. Effects of pre-orogenic tectonic structures on the cenozoic evolution of andean deformed belts: evidence from the salar de Punta Negra basin in the central Andes of northern Chile. *Basin Res.* 1441, 1462. <https://doi.org/10.1111/bre.12436>.
- Mescua, J.F., Giambiagi, L.B., 2012. Fault inversion vs. new thrust generation: a case study in the Malargüe fold-and-thrust belt, Andes of Argentina. *J. Struct. Geol.* 35, 51e63.
- Mpodozis, C., Ramos, V.A., 1989. The Andes of Chile and Argentina. In: Ericksen, G.E., Cañas, M.T., Reinemund, J.A. (Eds.), *Geology of the Andes and its Relation to Hydrocarbon and Energy Resources; Circum-Pacific Council for Energy and Hydrothermal Resources*, vol. 11. American Association of Petroleum Geologists, Earth Science Series, Houston, Texas, pp. 59–90.
- Orellano, A.P., Winocur, D., Rubinstein, N., Tassinari, C., 2020. Age and origin of the Paramillos DE Uspallata Pb-Zn-Ag vein deposit in the Cuyo Basin, Argentina: constraints from structural controls and isotopic evidence. *Ore Geol. Rev.* 122, 103524. <https://doi.org/10.1016/j.oregeorev.2020.103524>.
- Pinto, L., Hérial, G., Fontan, F., Parseval, P., 2007. Neogene erosion and uplift of the western edge of the Andean Plateau as determined by detrital heavy mineral analysis. *Sediment. Geol.* 195, 217–237.
- Ramos, V.A., 1988. The Tectonics of the Central Andes, 30° to 33°S Latitude, vol. 218. Geological Society of America Special Paper, pp. 31–54.
- Ramos, V.A., 1999a. Las Provincias Geológicas del Territorio Argentino. In: Caminos, R. (Ed.), *Geología Argentina. Subsecretaría de Minería de la Nación, Servicio Geológico Mínero*. Argentino, Instituto de Geología y Recursos Minerales.
- Ramos, V.A., Cristallini, E.O., Pérez, D.J., 2002. The pampean flat slab of the central Andes. *J. S. Am. Earth Sci.* 15, 59–78.
- Ramos, V.A., Jordan, T., Allmendinger, R., Kay, S., Cortés, J., Palma, M., 1984. Chilenia: un terreno alóctono en la evolución paleozoica de los Andes Centrales. 9° 1047 Congreso Geológico Argentino. S.C. Bariloche, Argentina, pp. 84–106.
- Ramos, V.A., Y Kay, S., 1991. Triassic rifting and associated basalts in the Cuyo basin, central Argentina. In: En Harmon, R., y Rapela, C. (Eds.), *Andean Magmatism and its Tectonic Setting*, vol. 265. Geological Society of America, Publicación Especial, pp. 79–91.
- Rapalini, A.E., Vilas, J.F., 1991. Preliminary paleomagnetic data from the Sierra Grande Formation: tectonic consequences of the first mid-Paleozoic paleopoles from Patagonia. *J. S. Am. Earth Sci.* 4 (1–2), 25–41.
- Richard, A., 2020. Modelado cinemático aplicado a Neotectónica en el frente orogénico andino entre 32°10' S–32° 40' S, provincias de Mendoza y San Juan. Tesis Doctoral. Universidad de San Luis.
- Rolleri, E., Baldi, B., 1969. Paleogeography and Distribution of Carboniferous Deposits in Argentina Precordillera. *Gondwana Stratigraphy, UNESCO Symp.* vol. 2. UNESCO, Paris, pp. 1005–1024 (Mar de Plata, 1967).
- Rubinstein, C., Steemans, P., 2007. New palynological data from the devonian Villavicencio Formation, precordillera de mendoza, Argentina. *Ameghiniana* 44, 3–9.
- Rutter, E.H., Holdsworth, R.E., Knipe, R.J., 2001. The nature and tectonic significance of fault Zone weakening. *Geol. Soc. Lond. Spec. Publ.* 186, 1–11.
- Salomon, E., Schmidt, S., Hetzel, R., Mingorance, F., Hampel, A., 2013. Repeated folding during late holocene earthquakes on the La Cal thrust fault near Mendoza City (Argentina). *Bull. Seismol. Soc. Am.* 103 (2A), 936–949.
- Sarewitz, D., 1988. High rates of late Cenozoic crustal shortening in the Andean foreland, Mendoza Province, Argentina. *Geology* 16, 1138–1142.
- Schmidt, S., Hetzel, R., Mingorance, F., Ramos, V.A., 2011. Coseismic displacements and Holocene slip rates for two active thrust faults at the mountain front of the Andean Precordillera (~ 33° S). *Tectonics* 30 (5).
- Siame, L.L., Bellier, O., Sebrier, M., Araujo, M., 2005. Deformation partitioning in flat subduction setting: case of the Andean foreland of western Argentina (28°S–33°S). *Tectonics* 24, TC5003. <https://doi.org/10.1029/2005TC001787>.
- Smalley Jr., R., Isacks, B.L., 1990. Seismotectonics of thin and thickskinned deformation in the Andean foreland from local network data: evidence for a seismogenic lower crust. *J. Geophys. Res.* 95, 12 487– 12 498.
- Smalley Jr., R., Pujol, J., Regnier, M., Chiu, J.-M., Chatelain, J.-L., Isacks, B.L., Araujo, M., Puebla, N., 1993. Basement seismicity beneath the Andean Precordillera thin-skinned thrust and fold belt and implications for crustal and lithospheric behaviour. *Tectonics* 12, 63–76.
- Suppe, J., 1983. Geometry and Kinematics of fault-bend folding. *Am. J. Sci.* 283, 684–721.
- Suriano, J., Mardonez, D., Mahoney, J.B., Mescua, J.F., Giambiagi, L.B., Kimbrough, D., Lossada, A., 2017. Uplift sequence of the Andes at 30°S: insights from sedimentology and U/Pb dating of synorogenic deposits. *J. S. Am. Earth Sci.* 75, 11–34. <https://doi.org/10.1016/j.jsames.2017.01.004>.
- Terrizzano, C.M., Fazzito, S.Y., Cortés, J.M., Rapalini, A.E., 2010. Studies of Quaternary deformation zones through geomorphic and geophysical evidence. *Tectonophysics.* <https://doi.org/10.1016/j.tecto.2010.05.006>.
- Thomas, W.A., Astini, R.A., 2003. Ordovician accretion of the Argentine Precordillera 1085 terrane to Gondwana: a review. *J. S. Am. Earth Sci.* 16, 67–79.
- Turner, J.C.M., Méndez, V., 1975. Geología del sector oriental de los Departamentos de Santa Victoria e Iruya, Provincia de Salta, República Argentina. *Boletín de la Academia Nacional de Ciencias de Córdoba* 51 (1- 2), 11–24.
- Twiss, R.J., Unruh, J.R., 1994. Kinematics of a contractional strike-slip duplex inferred from inversion of the seismic P and T axes, 1989 Loma Prieta aftershock sequence (abstract). *Eos Trans. AGU* 75 (44). Fall Meet. Suppl., 180, 1994.
- Uliana, M.A., Biddle, K.T., Y Cerdán, J., 1989. Mesozoic extension and the formation of Argentine sedimentary basins. In: TANKARD y, A., BALKWILL, H.R. (Eds.), *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*, vol. 46. AAPG, Memoir, pp. 599–614.
- Verges, J., 2007. Drainage responses to oblique and lateral thrust ramps: a review. *Special Publ. Int. Assoc. Sedimentol.* 38, 29–47.
- von Gosen, W., 1995. Polyphase structural evolution of the southwestern Argentine Precordillera. *J. S. Am. Earth Sci.* 8, 377–404. [https://doi.org/10.1016/0895-9811\(95\)00021-7](https://doi.org/10.1016/0895-9811(95)00021-7).
- Walcek, A.A., Hoke, G.D., 2012. Surface uplift and erosion of the southernmost Argentine Precordillera. *Geomorphology* 153–154, 156–168. <https://doi.org/10.1016/j.geomorph.2012.02.021>.