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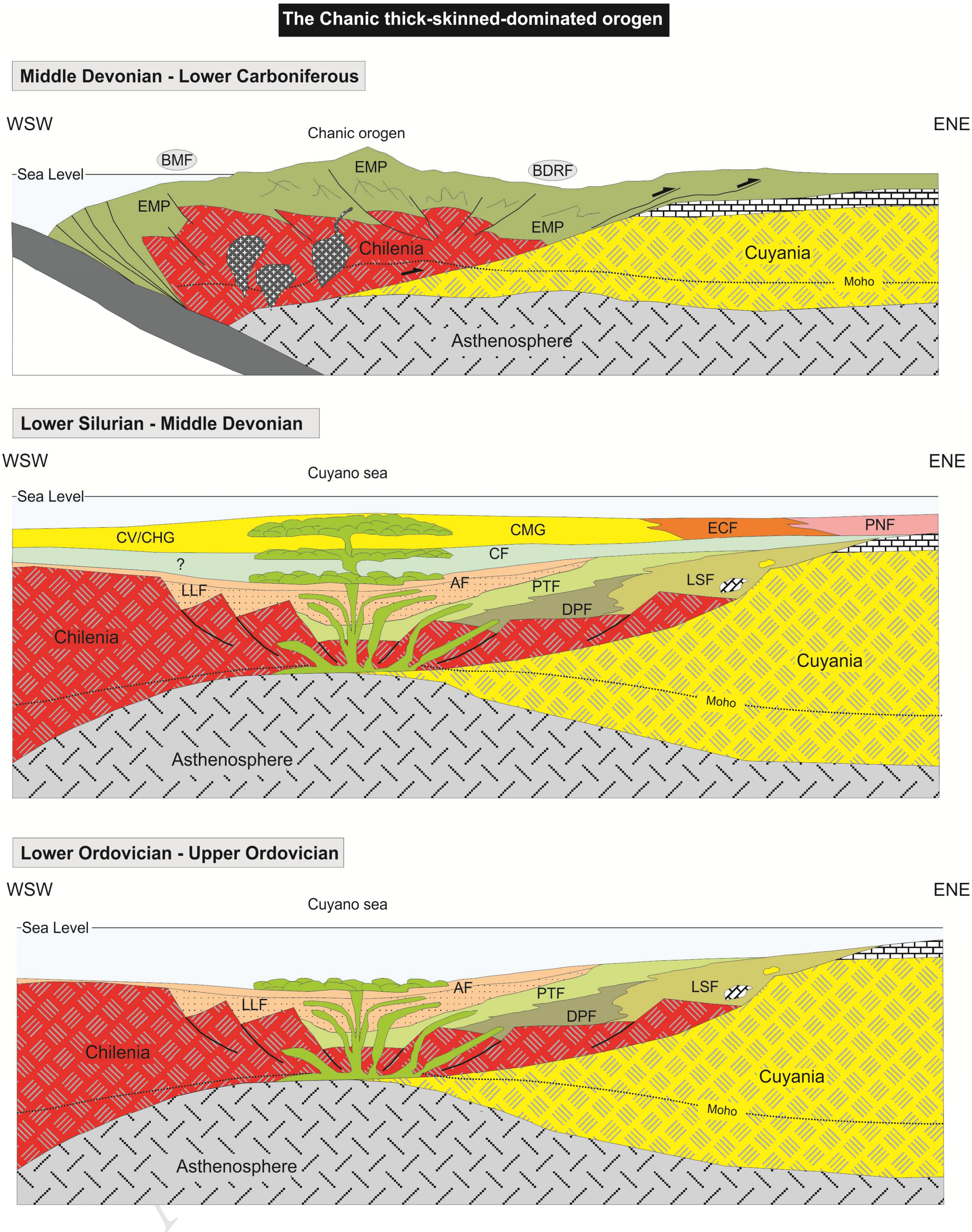

The Chanic thick-skinned-dominated orogen
Middle Devonian - Lower Carboniferous
WSW
ENE
Chanic orogen
Sea Level
BMF
EMP
BDRF
EMP
EMP
Chilenia
Cuyania
Moho
Asthenosphere
Lower Silurian - Middle Devonian
WSW
ENE
Cuyano sea
Sea Level
CV/CHG
CMG
ECF
PNF
CF
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LLF
AF
PTF
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Structural setting of the Chanic orogen (Upper Devonian) at central-western Argentina from remote sensing and aeromagnetic data. Implications in the evolution of the proto-Pacific margin of Gondwana

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Abstract

The basement of the Central Andes located in central-western Argentina (31º20'S - 69º22'W) is composed by the Cuyania and Chilenia terranes which were amalgamated to Gondwana in the Early-Mid Paleozoic. Between the Precordillera (Cuyania) and Frontal Cordillera (Chilenia) there are exposures of marine metasedimentary rocks associated with mafic rocks with an E-MORB chemical signature that represent the remnants of an extensional basin developed between both terranes. The stratigraphic features and the distribution of the Early-Mid Paleozoic units along the Western Precordillera were constrained by remote sensing techniques. This allowed us to identify two stages in the evolution of the sedimentary in-fill of the marine basin: an initial stage (Mid-Late Ordovician) marked by widespread extensional tectonics and a finning-upwards sequence interbedded with volcanic-plutonic mafic rocks; and a Late Ordovician?-Devonian where the sedimentation was characterized by the development of coarsening-upwards sequences with low participation of mafic rocks. Flattened parallel folds associated with pre-Andean thrusts have locally a top-to-the SW vergence. These pre-Andean (Late Devonian) structures are the relics of the Chanic orogen whose double vergence is the result of the control exerted by previous structures related to the ordovician rifting. This is constrained by the residual and regional magnetic anomalies which reflect an important correlation between deep and surface structures. We propose the inception of a subduction zone with an eastward polarity on the proto-Pacific margin of Gondwana as the responsible for the compressive geotectonic framework that led to the closure of the Western Precordillera basin during the Late Devonian and the development of the Chanic thick-skinned-dominated orogen.

Key words: Ophiolite, Thick-skinned-dominated orogens, Band ratios, Aeromagnetic anomalies, Argentine Western Precordillera

1. Introduction

Between the Neoproterozoic and Middle Paleozoic the current Pacific margin of South America experienced a long story of orogenic processes which has been preserved in the stratigraphic and structural record of the Central Andes.

The oldest orogenic events are related to the collision of several continental blocks (Pampia, Arequipa-Antofalla, Cuyania, Chilenia, among others, Fig. 1a) against the Gondwana margin (Ramos et al., 1986; Dalla Salda et al., 1992; Ramos, 1999; Ramos, 2009). During Late Cenozoic times, the Pampean flat-slab subduction segment (27°-33°30’S, Barazangi and Isacks, 1976) favoured the generation of dominant eastward vergent imbricated thrust sheets in the Frontal Cordillera, Central and Western Precordillera and the uplift of basement blocks due to the activity of back-thrusts in the Eastern Precordillera and Sierras Pampeanas in the front of the Andean orogen (Barazangi and Isacks, 1976; Jordan et al., 1983; Jordan et al., 1993). In this sector, an E-W cross section exhibits different tectonostratigraphic domains corresponding to the previously amalgamated continental blocks and their respective suture zones (Ramos, 1988). These suture zones are coincident with highly deformed and metamorphosed areas with strong positive gravity anomalies (Chernicoff and Zappettini, 2004; Martínez and Giménez, 2005; Alvarez et al., 2012) that are the key to study the particular features of the ancient orogenies.

The study area (Fig. 1a-b) is located in western-central Argentina (31º20'S-69º22'W) and comprises the central part of the Western Precordillera ophiolitic belt. There, Early Paleozoic metasedimentary rocks (slope and abyssal plain facies, Astini, 1992) host mafic igneous rocks with an E-MORB (Enriched-Mid Ocean Ridge Basalt) geochemical signature (Haller and Ramos, 1984; Kay et al., 1984; Davis et al., 1999; Fauqué and Villar, 2003; González- Menéndez et al., 2013; Boedo et al., 2013; Pérez et al., 2014). This ophiolitic belt records an important deformation phase with structures with northeastward and south-westward vergence (von Gosen, 1992; 1995; Davis et al., 1999; Alonso et al., 2008; Giambiagi et al., 2010) associated to greenschist facies metamorphism (Ramos et al., 1986; von Gosen, 1995; Davis et al., 1999; Robinson et al., 2005; Boedo et al., 2016). A Mid to Late Devonian metamorphic age is based on K-Ar and Ar-Ar on white mica and Lu-Hf on garnet ages (Cucchi, 1971; Buggisch et al., 1994; Davis et al., 1999; Willner et al., 2011). This structuration phase is related to the generation of the Chanic orogen as a result of the collision of the Chilenia terrane against the western margin of Gondwana (Ramos et al., 1986).This orogen controlled the distribution of sediments from Gondwana to the proto-Pacific basin during Late Paleozoic times (Sessarego, 1988; Alvarez et al., 2011; Hervé et al., 2013).

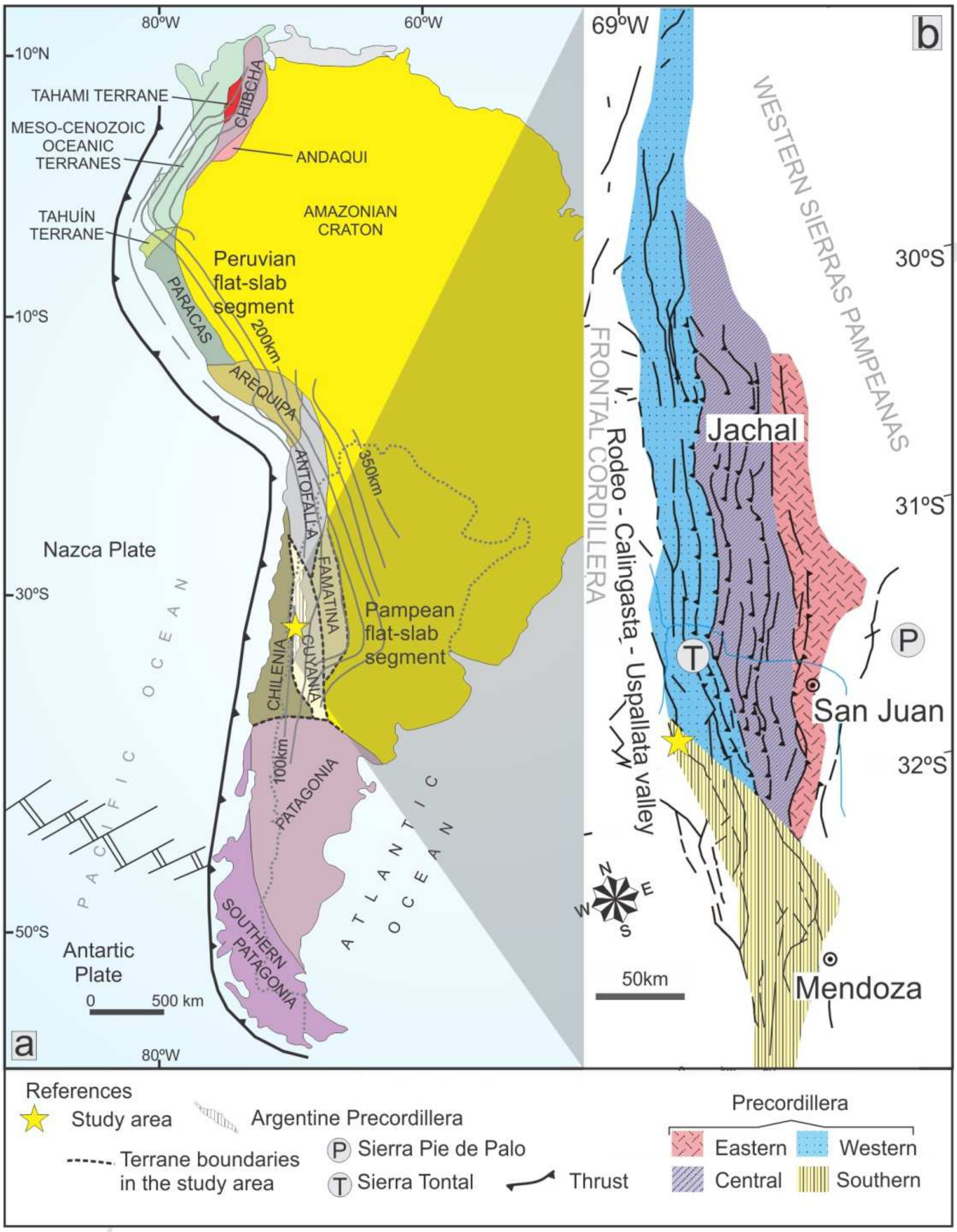

Figure 1: Location map of the study area. a) Location of the Argentine Precordillera in the context of the terranes docked to the western margin of Gondwana (current South America Plate, modified from Ramos, 2009). b) Subdivision of the Argentine Precordillera on the basis of its stratigraphic and structural features proposed by Baldis and Chebli (1969), Ortiz and Zambrano (1981), Baldis et al. (1982) and Cortés et al. (2006).

Currently, there is controversy about the origin of the aforementioned terranes (see discussion in Ramos, 2004). The Middle Proterozoic basement of Cuyania is exposed in several places (the Sierra Pie de Palo range and the San Rafael and Las Matras blocks). The continuity of this basement to the west (under the Argentine Precordillera) is confirmed by the presence of Grenville-aged xenoliths (1118 ± 54 Ma and 1101.8 ± 5.8 Ma, Abbruzzi et al., 1993; Kay et al., 1996; Rapela et al., 2010) hosted in neogene igneous rocks located in different sectors of the Precordillera (Leveratto, 1968; Gallastegui et al., 2008). In contrast, the exposure of the Chilenia basement is rare (Polanski, 1958; Ramos and Basei, 1997). A gneiss with an age of 1069 Ma was documented by Ramos and Basei (1997) in the Frontal Cordillera. Based on age similarities, these authors proposed that the Cuyania and Chilenia basements could be similar. Nevertheless, Kay and Abbruzzi (1996) had postulated that the terranes do not share the same isotopic signature based on isotopic signals on tertiary volcanics.

In this scenario, the following questions arise: what was the shape of the Early-Mid Paleozoic basin developed between the Chilenia and Cuyania terranes on the western margin of Gondwana? What were the mechanisms that led to the closure of the basin developed between them? What was the geotectonic setting in which the Chanic orogen (and the structural grain of the Western Precordillera) were developed?

Different geotectonic models have been proposed to provide answers to these questions (Ramos et al., 1986; Dalla Salda, 1992; Loske, 1994; Davis et al., 2000; Lopez and Gregori, 2004; Ramos and Dalla Salda, 2011; González Menéndez et al., 2013; Boedo et al., 2013). We present the results of the structural and lithological mapping based on remote sensing techniques and field work which were constrained by applying filtering techniques to the aeromagnetic data available in the area. Moreover, we propose an alternative geotectonic model to explain the Early Paleozoic evolution of the proto-Pacific margin of Gondwana on the basis of the results presented here.

2. Geological setting

2.1 The Early-Mid Paleozoic stratigraphy of the Western Precordillera

This paper focuses on the stratigraphic aspects of the Early-Mid Paleozoic units exposed in the study area (the Don Polo, Alcaparrosa, Calingasta and El Codo formations). All of these units were deposited in the Western Precordillera basin.

Don Polo Formation. This is the oldest unit recognized in the study area and it is represented by metasedimentary rocks that can be grouped into three main lithofacies. Massive coarse-grained metasandstones dominate the lower lithofacies, while the upper lithofacies is characterized by thin layers of fine-grained metasandstones and metapelites (Fig. 2a-c). The contact between them is a transitional lithofacies which is dominated by medium-grained metasandstones. The age of the Don Polo Formation is currently under discussion because its paleontological content is scarce. The finding of crinoids assigns this unit to the Ordovician *s.l.* (Turco Greco and Zardini, 1984).

Alcaparrosa Formation. This is the more widespread unit among the study area whose outcrops were exploited for sulphate minerals at the beginning of the 1900s (Angelelli and Trelles, 1938). The Alcaparrosa Formation is represented by hirnantian metasedimentary rocks (Brussa et al., 2003; Abre et al., 2012) that host mafic igneous rocks (meta-basaltic sills, dikes and pillow lavas, Fig. 3a-f). We recognized two members: a lower sandy member composed of coarse- to medium-grained metasandstones interbedded with metasiltstones; and the upper shaly member mainly composed of sets of green and purple shales. The plutonic and hipabisal mafic bodies (dikes and sills, Fig. 3d-f) are restricted to the metasedimentary rocks of the sandy member, while metabasaltic pillow lavas are restricted to the shaly member.

Figure 2: Lithofacies of the Don Polo Formation. **a)** Outcrops located to the north of the San Juan river headwaters. Coarse-grained metasandstone beds with thicknesses around 1 m corresponding to the lower lithofacies. **b)** Medium-grained metasandstones with beds thicknesses of 50 cm, corresponding to the transitional lithofacies located at the San Juan river headwaters. **c)** Folded metasandstone and metamudstone beds from the upper lithofacies (UL) at the northern part of the Sierra de Hilario. ECT: El Carrizal Thrust, Oa: Alcaparrosa Formation.

Calingasta Formation. This unit is represented by layers of purple and green shale, whose coarsening-upwards pattern is defined by the presence of metasandstone layers at the top of the sequence (Fig. 4a-c). Cone-in-cone structures, which were deformed by simple shear, are present in the fine-grained levels (Fig. 4b). The Calingasta Formation is assigned to the Silurian according to the presence of *Tropilodeptus sp.* and *Clarkeia sp*. (Furque and Cuerda, 1979). This record was questioned by Cingolani et al. (1987) and Peralta (1990) because there is no fossil description. On the other hand, Stephens et al. (1995) point to a mid-Ordovician age for these rocks on the basis of metamorphic ages presented by Buggish et al (1994).

Mafic magmatism

In the study area, the presence of metabasaltic dikes, sills and pillow lavas is restricted to the Alcaparrosa and Calingasta formations.

The mafic rocks have porphyritic texture with euhedral plagioclase and pyroxene phenocrysts in a microcrystalline matrix of the same composition. Apatite and ilmenite are frequent accessory minerals. Some bodies exhibit quartz and alkaline feldspar in a micrographic texture. This primary assemblage is partially replaced by a very low- to low-grade metamorphic assemblage that consists of chlorite, albite, white mica, epidote, titanite, calcite and clay minerals (González Menéndez et al., 2013; Boedo et al. 2013, 2016, Pérez 2015).

Geochemically, the mafic rocks exposed along Western and Southern Precordillera have great similarities showing an N- to E-MORB geochemical signature (Kay et al., 1984; González Menéndez et al., 2013; Boedo et al., 2013). However, at the Sierra de la Invernada locality, Pérez (2015) recognized relative increase in alkalinity towards the east.

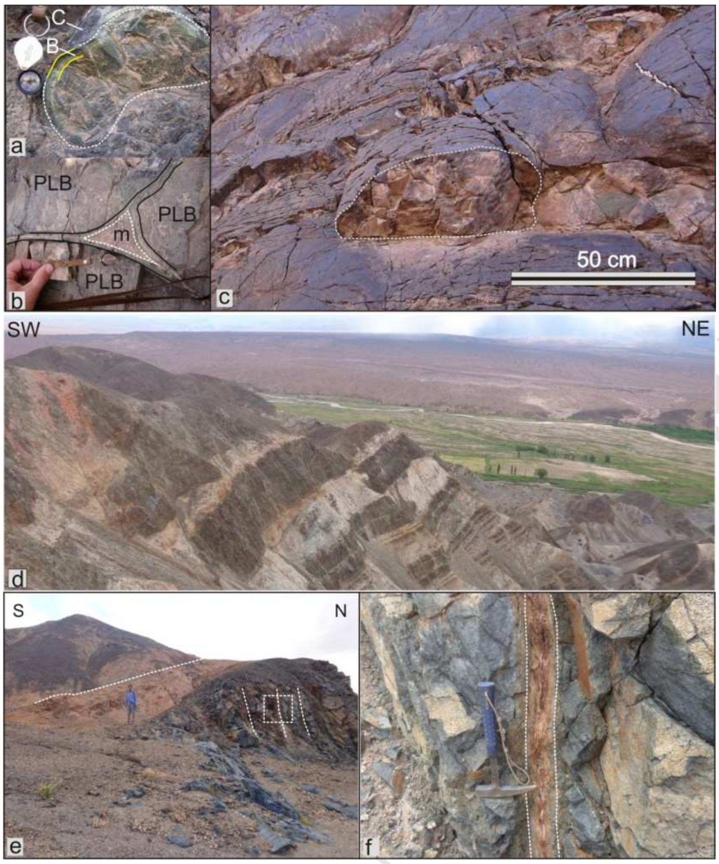

Figure 3: Mafic igneous rocks hosted in the Alcaparrosa Formation. **a)** Pillow lavas. The contour (dashed white line) is an irregular surface which adapts to the morphology of the lower and surrounding pillow lavas corresponding to a previous magmatic effusion. On the surfaces of each pillow is common the development of bread crust (C) and glassy borders (B). **b)** The triangular area (dashed white line) represents a cavity between three pillow lava basalts (PLB) which has been filled by a matrix (m) of minerals such as calcite, epidote, opaque minerals and amorphous silica (chalcedony?). Figures **a** and **b** were taken at the SE of the San Juan river headwaters. **c)** Pillow lava metabasalt exposed at the synclinal of the El Rincón. **d)** Layers of weakened and altered metasandstones interbedded with metabasaltic sills. **e)** Metagabbro dikes hosted in metasandstone beds. Several (meta)gabbro intrusions can be recognized in the field. White dashed lines represent the position of the stratification planes (upper left) and dikes (centre-right). The box indicates the area of Figure f. **f)** Metagabbro body formed by several pulses showing a texture resembling a sheeted structure. Contacts between each dike are represented by thin

alteration zones (brown strip bounded by white dashed lines). Figures **d** to **f** were taken at the Sierra Bandeada area..

El Codo Formation. This unit is mainly composed of green medium to fine metasandstone and green metasiltstone-metaclaystone with subordinate levels of metaconglomerate. Petrographically, the metasandstone shows affinity with the rocks of Central Precordillera (Sessarego, 1988). The El Codo Formation palinomorphs content documents a givetian-frasnian age (Sessarego, 1988; Amenábar and di Pascuo, 2008). In accordance, this unit is unconformably covered by the Del Raton Formation (Lower Carboniferous).

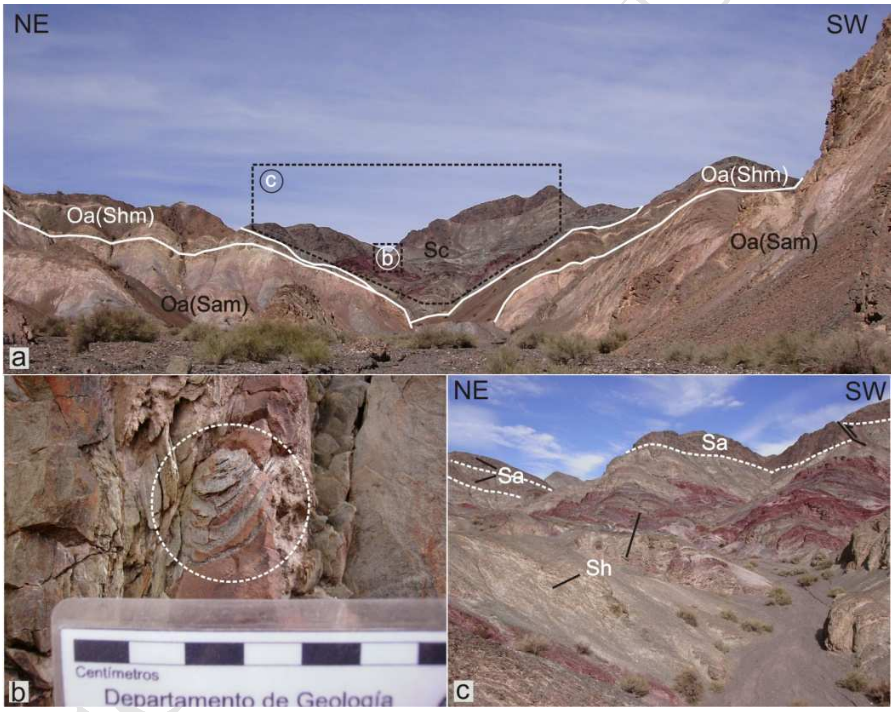

Figure 4: Stratigraphic features of the Calingasta Formation at the El Rincón synclinal. a) Panoramic view of the contact zone between the Alcaparrosa (Oa) and the Calingasta (Sc) formations. The black dashed line represents the location of figures b and c. Sam: Sandy member; Shm: Shaly member. b) Cone in cone structures preserved in layers of fine metasandstone of the Calingasta Formation. The cones are affected by parallel-to-the beds simple shear. c) Calingasta Formation. Green and purple shales (Sh) at the bottom and metasandstones at the top (Sa) are in contact through a transition zone.

2.2 Local structure

The geological setting of the study area consists of overimposed folds and faults. Folding can be observed at different scales. Thrusts are grouped according to their orientation, vergence and relative age, among other features. The two following thrust systems show evidences of neogene activity.

Thrust systems

Thrust systems were separated into two main groups, T1 and T2, based on the orientation and length of their traces, dip direction, vergence and relative age of deformation.

Thrust system T1. This group is represented by NW-SE thrusts with NE dipping planes and top-to-the SW vergence (Fig. 5a-c). Thrust traces rarely exceed 10 km in length because its oblique orientation produces truncation against thrusts from T2 group. The T1 group mainly affects lower Paleozoic rocks. However, there are places where lower Paleozoic rocks are over-thrusted on Triassic and Neogene rocks. The dipping angles are higher to the northeast, where the thrusts reach nearly vertical dips or are even overturned to the west-southwest (Alonso et al., 2008).

At a local scale, these thrusts are associated with minor folds whose wavelength ranges from 5 to 10 m and in some cases as much as 50 m. These folds present thickened hinges and NW-SE axial plane cleavage. Both thrusts and minor folds have a top-to-the SW vergence. Major folds, as will be described below, are closely related to the T1 thrusts. In this case they share the same orientation with variations in the dip-angles and dip-directions.

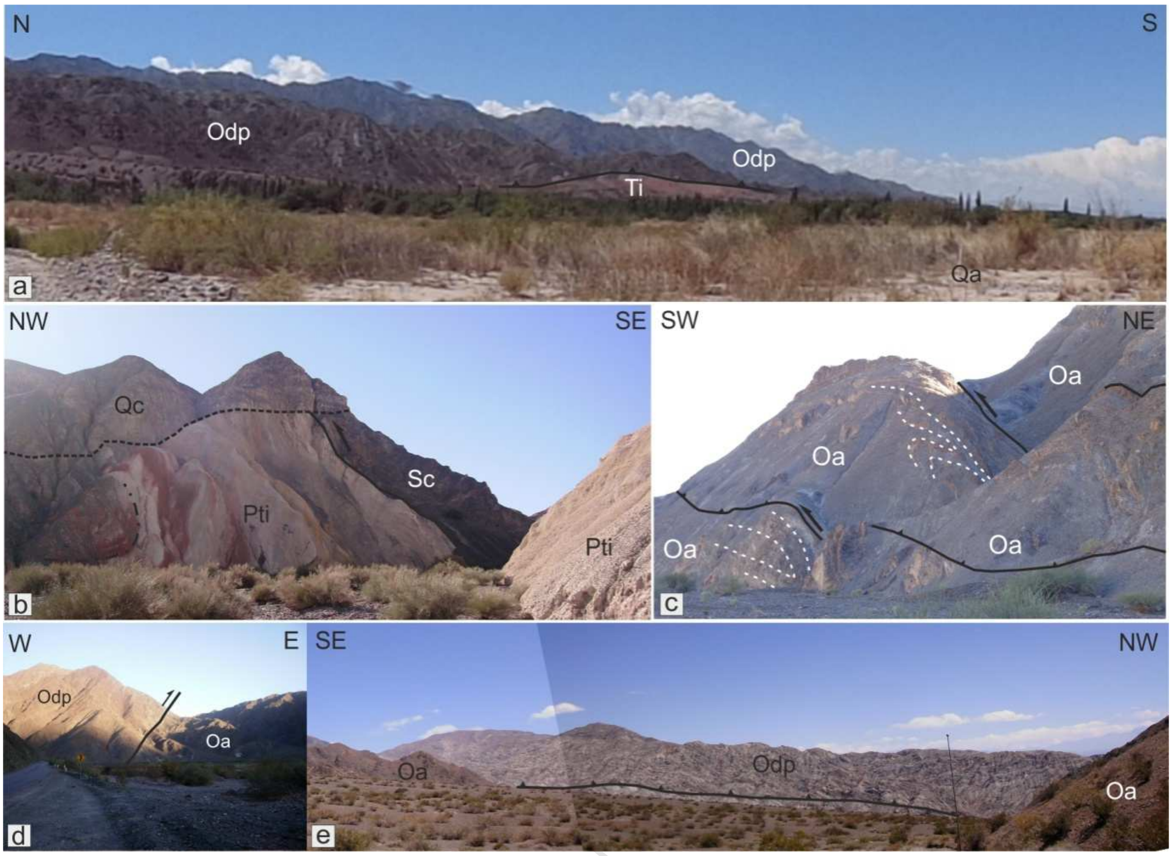

Figure 5: a-c) Thrust system T1. d-e) Thrust system T2. a) Panoramic view of the western foothill of the Sierra de Villa Corral where neogene beds (Ti) are overthrusted (T1 thrusts) by Early Paleozoic rocks (Odp: Don Polo Formation). b) Triassic rocks are overthrusted by rocks of the Calingasta Formation (Sc), while quaternary strata (Qc) are not affected by this deformation. c) Tectonic repetitions of the Alcaparrosa Formation (Oa) by the T1 thrusts. d) The El Carrizal thrust at the latitude of the San Juan river where the Alcaparrosa Formation is overthrusted by the Don Polo Formation. e) The El Carrizal thrust (T2) on the eastern flank of the Sierra de Hilario range. The Alcaparrosa Formation (Oa) is overthrusted by the Don Polo Formation (Odp).

Thrust system T2. This second group of thrusts comprises N-trending structures that control the design and orientation of the main ranges in the Western Precordillera. Thus, the length of the T2 thrusts exceeds the study area and frequently ordovician-to-neogene rocks are involved in this deformation (Fig. 5d-e), where the T2 planes are overlapped towards the E with varying angles. The Del Tigre fault, located a few kilometres to the northeast of the study area, belongs to the T2 system. This is a dextral strike-slip fault whose neotectonic activity is well documented (Siame et al., 1996; 1997; Cortés et al., 1999; Fazzito et al., 2013; among others).

Fold systems

The Early-Mid Paleozoic rocks have different orders of folding whose geometric features are recognized at different scales. Non-parallel folding is recorded by increasing hinge thicknesses (Fig. 6a-b) corresponding to classes 1C and 2 according to Ramsay (1967). Generally, they are tight and isoclinal folds that are often spatially associated with T1 thrusts. The dominant trend of their axial planes is NW-SE and their dip angles are high (Figs. 6c). Thus, a WSW main shortening direction (257°, Fig. 7) can be interpreted. Folds of opposite vergence can be observed within a major fold. The structural scheme could be summarized as a succession of strongly asymmetric small folds within major anticlines and synclines (Fig. 6c). Small scale structures depict drag folds and minor complications, whose design resembles the S-M-Z pattern described by Ramsay (1967).

Minor structures. Most of the internal deformation associated to the aforementioned flexural slip folds occurs within the less competent layers (fine-grained rocks), developing an axial plane cleavage (S_1) parallel to the stratification plane (S_0). Most of the competent layers undergo only pressure solution and micro-fractures. While the axial plane cleavage (S_1) is usually divergent fanning, the spaced fractures developed in more competent layers are convergent fanning. Shear displacements are sometimes observed along these planes.

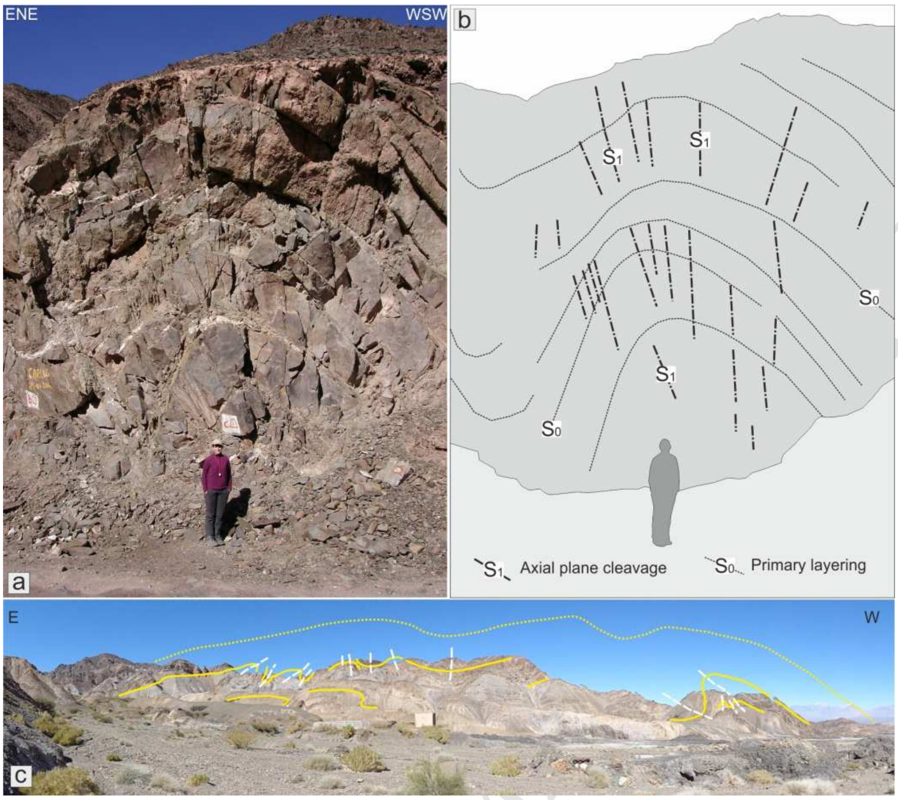

Figure 6: Scales and geometry of the folds. a) Folds of lesser-scale in metasandstone layers (Don Polo Formation). b) Scheme based on Figure a, where S_0 and S_1 surfaces are shown. c) Panoramic view of the southern Sierra Alcaparrosa area. The image shows a first order anticline fold (wavelength is greater than 500m). Folds of second and third order with variable vergence are present in the flanks and core of the main structure. Yellow solid lines represent primary layering (S_0), while the white dotted lines represent the fold axial planes.

3. Data, methods and results

3.1 Remote sensing

Landsat 7 ETM satellite data used in this work was acquired through the Global Land Cover Facility website (http://glcf.umiacs.umd.edu) which belongs to the University of Maryland and NASA (National Aeronautics and Spatial Administration). The date of acquisition of the selected image (path: 232, row: 082) corresponds to 3rd December 1999. The images used have high spatial resolution, high spectral range, radiometric calibration and provide information in the near infrared and visible channels (NIR), short wave infrared (SWIR), thermal infrared (TIR) and panchromatic. The image width is 183 km and its spatial resolution is 28.5 m in bands 1 to 5 and 7; 15 m in band 8; and 60 m in band 6.

Satellite imagery processing were performed using the software ENVI 4.5.

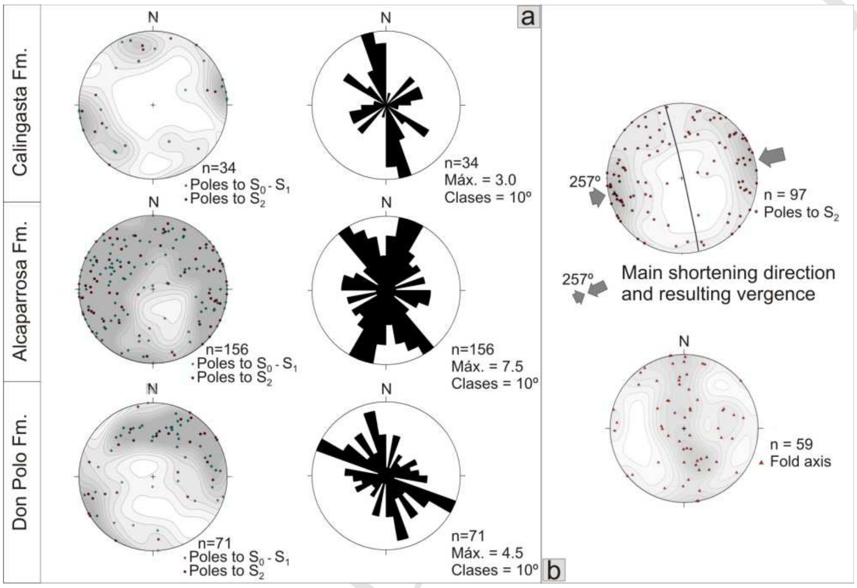

Figure 7: Structural data. a) (Left) Lower hemisphere, equal area stereo-plots of the tectonic structures preserved in the Early-Mid Paleozoic rocks. S_0: stratification plane, S_1: Axial plane cleavage; (right) Rose diagram of fold axial planes and stratification planes. b) (Upper) Fold axes. Gray arrows indicate the main shortening direction. The NE dip-direction of the average plane indicates a WSW vergence (257º). (Lower) Poles to the axial plane cleavage (S_1).

Combination of bands: variations suffered by the electromagnetic waves through their reflection on earth's surface are directly related to the nature and composition of the materials. Combination of bands allows performing a preliminary lithological differentiation between the formations that outcrop in the region. However, there are certain limitations mainly related to the spectral homogeneity that presents each geological unit (Fig. 8a).

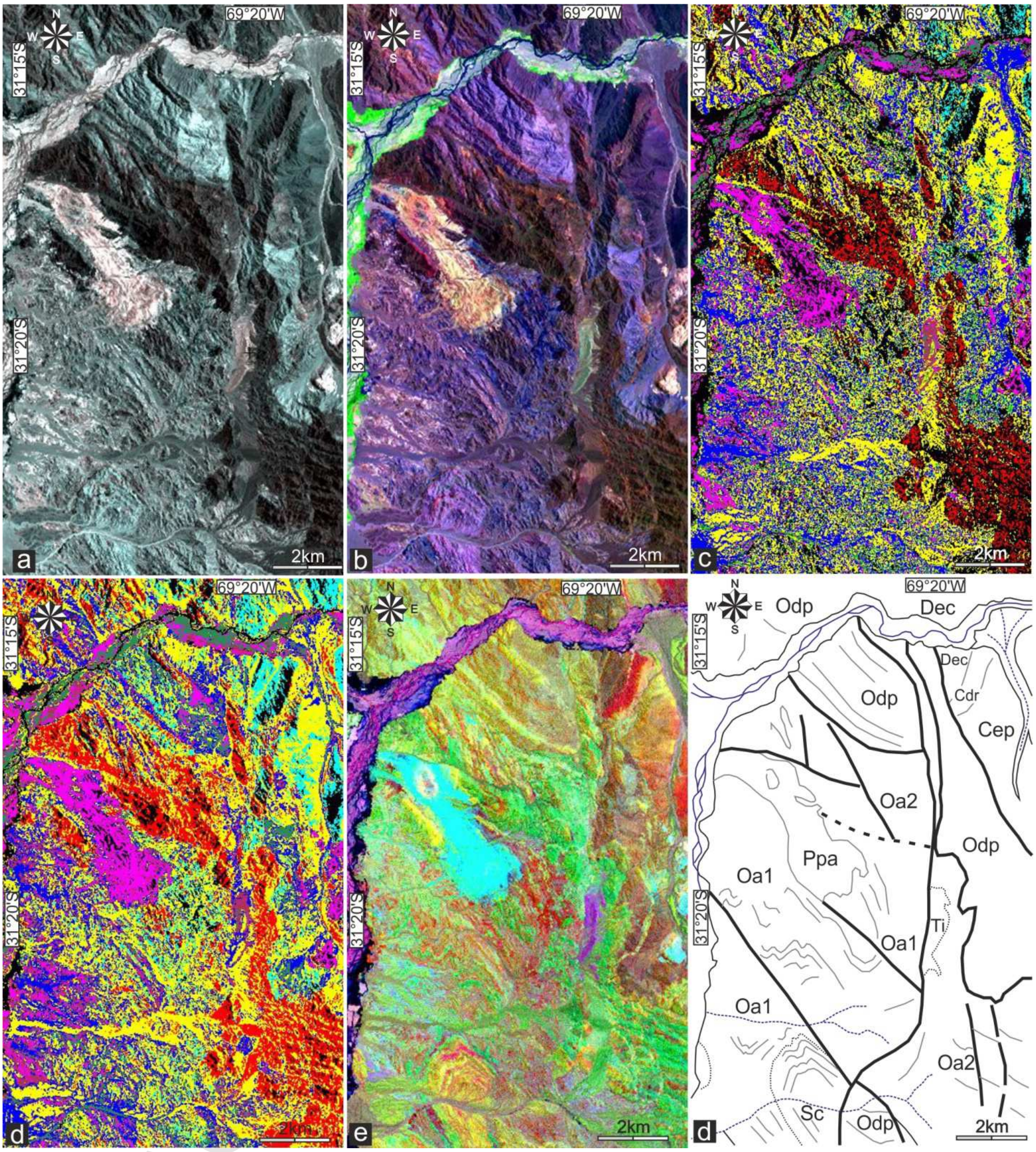

Figure 8: Processed satellite images of the study area. a) A R:3, G:2, B:1 image from the study area. b) A R:7 G:4 B:1 image. c) Supervised classifications by minimum distance. d) Supervised classifications by parallelepiped method. e) Band ratio R:7/5 G:5/4 B:3/1. Stratigraphic and structural interpretation based on the processed images and field work. Odp: Metasedimentary rocks of the Don Polo Formation, Oa: Alcaparrosa Formation (1) metasedimentary interbedded with mafic igneous rocks, (2) pillow lava

metabasalts and scarce shales. Sc: Metasedimentary rocks of the Calingasta Formation. Ppa: Alteration zone associated to the Alcaparrosa porphyry. Ti: undifferentiated tertiary deposits. Black thick lines represent thrusts and dash lines are minor faults while thin grey lines correspond to lithological breaks.

Spectral and supervised classifications: the first technique allows us to establish a classification criteria based on the spectral responses of different materials (Richards, 1999). The supervised classifications were carried out according to the minimum distance and the parallelepiped methods (Figs. 8b-c). In the former, pixels are grouped under the same colour based on the relative closeness between the spectral value previously established by the class and the pixel average spectral value. In the latter, each class is defined by a parallelepiped enclosing a range of reflectance within which each pixel can be grouped or rejected.

Band ratios: we applied the band ratio R:7/5, G:5/4, B:3/1, since it is suitable for discriminating between granites, mafic, sedimentary and metavolcanic rocks (Gad and Kusky, 2006).

Obtained results allowed us to recognize boundaries between different lithostratigraphic units and the distribution of each lithological domain (Fig. 8d). Each unit has defined variety of colors (Table 1), which contribute to outline the contacts (lithological breaks). The geometry of these contacts and their distribution allow the interpretation of secondary structures acquired by tectonic deformation (Fig. 8d). For example, at the central-southern sector of the study area, the lithological homogeneity of the Alcaparrosa and Calingasta formations in unprocessed satellite images inhibits the recognition of the folds (Fig. 8a). Classification and band ratio techniques allow to highlight the geometrical features of the folds and faults (Fig.8b-d).

Table 1: Comparative scheme with the results obtained by the different techniques (Combination of bands, supervised classification and band ratio) applied to satellite imagery of the study zone.

Technique **Lithology**	**Combination bands** **R7 G4 B1**	**Supervised classification**	**Band ratios** **R7/5 G5/4 B3/1**
Metasedimentary (**Don Polo Fm.**)	Bluish gray - dark brown	Blend of red, yellow and cyan	Brown to light green, yellow, red
Metasedimentary (**Alcaparrosa Fm.**)	Bluish gray - dark brown	Blend of yellow, green and cyan	Yellow, red
Mafic rocks (**Alcaparrosa Fm.**)	Undifferentiated	Red	Green, light blue
Metasedimentary (**Calingasta Fm.**)	Bluish gray - light violet	Blend of yellow, green and blue	Brown, yellow, red
Metasedimentary (**El Codo Fm.**)	Dark brown	Blend of cyan and yellow	Dark brown
Sedimentary rocks **Neopaleozoic**	Dark gray – pinkish Brown	Blend of magenta, cyan and yellow	Red, yellowish brown, white, fuchsia, light blue
Sedimentary rocks **Neogene**	Light violet - greenish brown	Fuchsia (not classified materials)	Violet, light violet
Unconsolidated deposits **Quaternary**	Greyish brown	Blend of green, magenta and black (not classified materials)	Violet, blue and pink

3.2 Geophysical data

Magnetism

Different filters have been applied to the high resolution magnetic database in order to characterize geological structures. The database was obtained from the Servicio Geológico Minero Argentino (SEGEMAR) and corresponds to Zone 17-Block II Precordillera Sur (Mendoza-San Juan). Measurements were collected by the acquisition company Sial Geosciences, with a nominal height of 120 m along N-S flight lines spaced every 1000 m and E-W flight control lines every 7500 m. This database was then corrected for the daily variation by the aforementioned company (Dobrin, 1976). Finally, the magnetic anomaly was calculated by subtracting from dataset the International Geomagnetic Reference Field (IGRF) for the acquisition date (Blakely, 1996). The levelling of the aerial magnetic data was performed following the methodology proposed by Cheesman et al. (1998) and Ruiz et al. (2011). This was carried out using terrestrial magnetic data which improves the resolution from a 5 x 5 km to a 250 x 250 m cell size. The obtained magnetic anomaly map is shown in Fig. 9a.

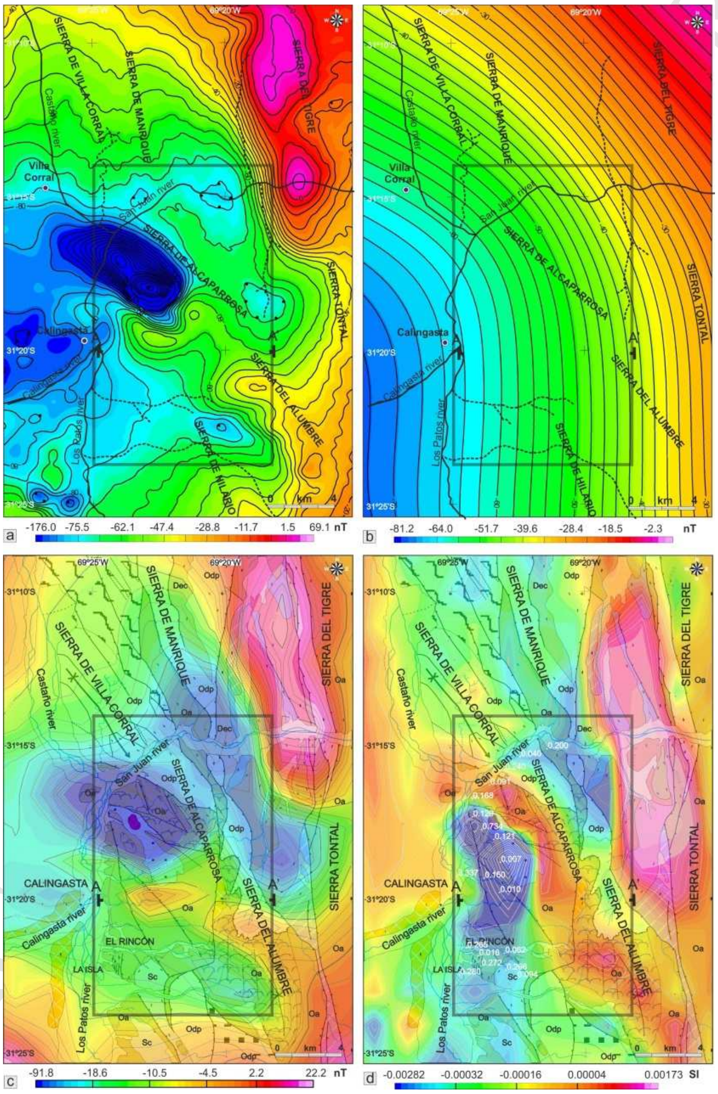

Figure 9: Magnetic maps in transparency layer over the simplified geological map (the box indicates the location of the study area). a) Magnetic anomaly field map (isolines every 5 nT). b) Regional magnetic anomaly field map corresponding to the upward continuation on a reference plane located at 7.5 km

(isolines every 2 nT). c) Residual magnetic anomaly field map onto the simplified geological map (isolines every 2 nT). d) Apparent magnetic susceptibility map onto the simplified geological map. The white numbers on the map correspond to measured magnetic susceptibility (x10^{-3}SI) in the outcropping rocks.

Filtering of anomalies. Analytical continuation of potential fields has been widely used as a filter in frequency domain. Specifically, upward continuation allows to evaluate the potential field on a surface (plane) different to the acquisition one ($h \neq 0$). This attenuates the high-wavenumbers from bodies emplaced on the upper crust (Dean, 1958; Blakely, 1996).

In present contribution many calculations for Upward continuations at different heights were tested. The optimum height chose is h= 7.5 km due to it is the best which attenuates the crustal short wavelengths (Fig 9b). The magnetic influence of deep regional sources is reflected on the regional magnetic field. As such as in other locations of the Precordillera (Ariza et al., 2017) the NW-SE inflection of the regional trend concordant with the E-W structural lineament along the San Juan river reveals the deep inception of that structure, probably located in the basement of the Precordillera.

The residual magnetic anomaly field was obtained by subtracting the regional anomaly to the magnetic anomaly (Fig. 9c). Minimum values of magnetic anomalies can be observed over Early Paleozoic rocks (Fig. 9c). This anomaly has an elliptical geometry and it is concentrically distributed around the metasomatic halo of the Alcaparrosa porphyry (Fig. 9c). However, the surface extension of that metasomatic halo is smaller than the associated magnetic anomaly (Geuna and Escosteguy, 2006; Ariza et al., 2015). Maximum values of magnetic anomalies to the NE of the study area correspond to the Late Paleozoic rocks. The dominant NW-SE trend of the anomalies is concordant with the main structural pattern of the area.

A magnetic station measured on field, is strongly influenced by main field, sun disturbances and the physical properties of rocks as such as the Magnetic Susceptibility and Remanence. Thus, once filtered the known effects (IGRF and Diurnal effect), is possible to obtain an estimation of the magnetic susceptibility by inversion of the magnetic anomaly.

The use of the magnetic susceptibility as a lithological indicator was especially useful for mapping units which are difficult to discriminate in the field (Ariza et al., 2014a).

In present contribution the investment method was applied on the residual magnetic anomaly. This operation was carried out from the Apparent Susceptibility Calculation module of the Oasis Montaj software, which uses the following equation:

$$L(r,\theta) = \frac{1}{2\pi F.H(r)\Gamma(\theta).K(r,\theta)}$$

With:

$$H(r) = e^{-hr}$$

$$\Gamma(\theta) = [sinI_{\alpha} + icosl.\cos(D - \theta)]^2$$

$$K(r,\theta) = \left[\frac{\sin(arcos\theta).\sin(arcos\theta)}{arcos\theta.arsin\theta}\right]$$

Where

I : Geomagnetic inclination

D: Geomagnetic declination

I_{α} : Reduction of the amplitude of the inclination of the pole

F : Total magnetic field (nT)

θ : Geographic latitude

h : Depth relative to the observation level for which the susceptibility is calculated

The apparent susceptibility map (Fig. 9d) was obtained from the following operations: 1- reduction to the magnetic pole; 2- downward continuation for the depth of the source; 3- correction for the geometrical effect of an infinite vertical prism, and 4- separation by the total magnetic field to produce susceptibility. Measured susceptibility data on the outcrops were compared with the apparent magnetic susceptibility map (Fig. 9d). Maximum values of magnetic susceptibility in the study area are oriented NW-SE (as the main structure of the area) and it correlates with the outcrops of the pillow lava metabasalts (shaly member) of the Alcaparrosa Formation.

3.3 Geological map of the Western Precordillera between 31°14'S – 31°24'S

The obtained results are combined in the geological map of the studied segment of the Western Precordillera (Fig. 10). All the Early-Mid Paleozoic units that outcrop in the study area are involved in large scale anticlinorium and synclinorium folds whose size and geometries are recognized in the satellite images (Fig.10).

The strike of the Don Polo, Alcaparrosa and Calingasta formations is predominantly NNW-SSE. The similarities found in the structural pattern (different-scale folding) of these units indicate that they were structured under the same tectonic phase. This conspicuous folding is dissected by the T1 and T2 thrust systems (Fig.10).

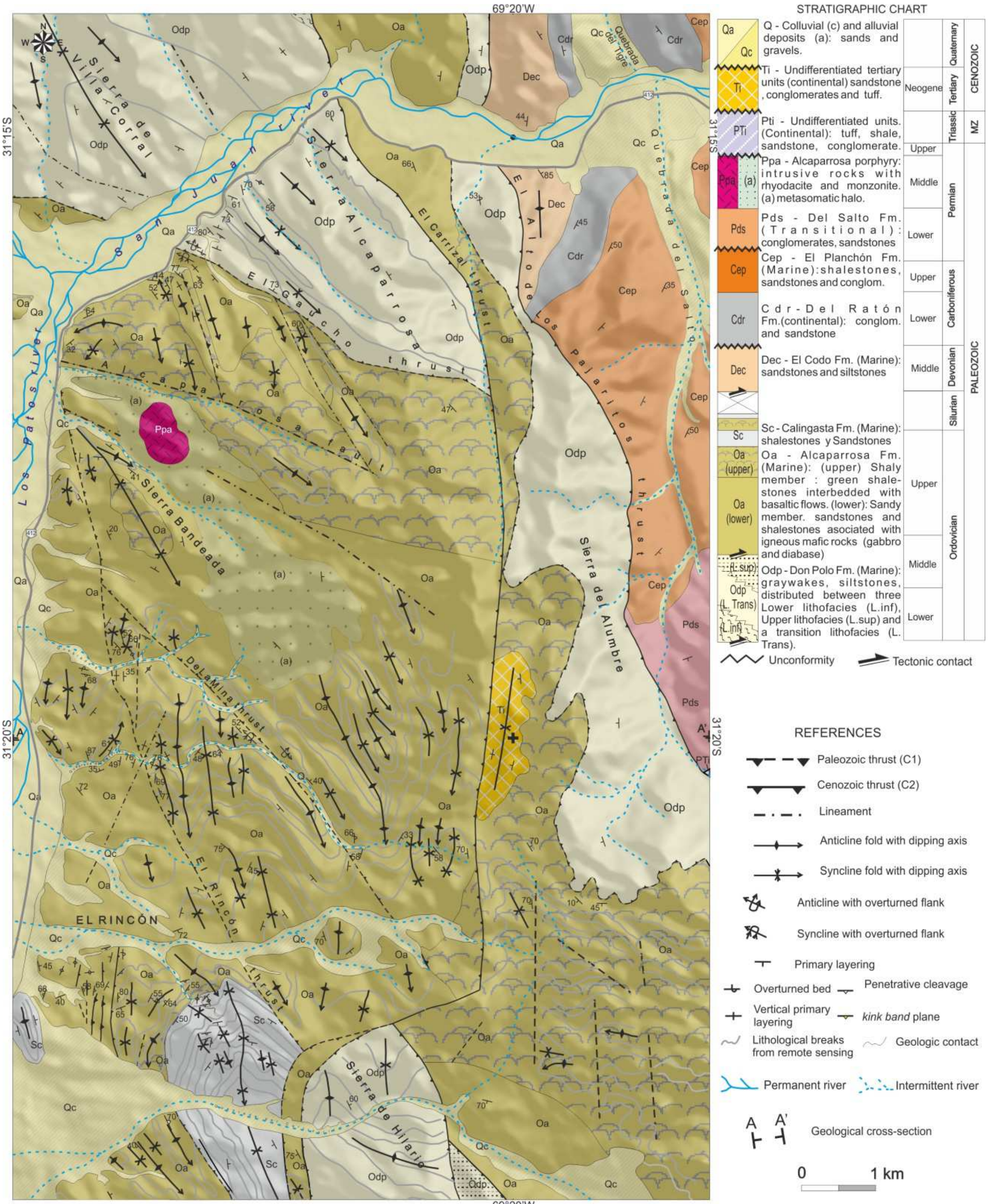

Figure 10: Geological map of the Western Precordillera between the Sierra Alcaparrosa and the Sierra de Hilario areas.

3.3.1 Geological cross-section along 31°20'S

Figure 11 presents a block diagram comprising an E-W cross-section along 31°20'S. The structure of this segment of the Western Precordillera is characterized by a folded belt (ductile deformation) that mainly affects the Early-Mid Paleozoic units with the development of a double-vergence system of thrusts (brittle deformation). However, the close relation between folds and T1 thrusts (similar strike and dip-direction of fold and thrust planes) allow us to interpret a common origin for these two structures. In contrast, the cutting relationship of the T2 thrusts over previous ductile folds and T1 thrusts indicates a younger age for T2.

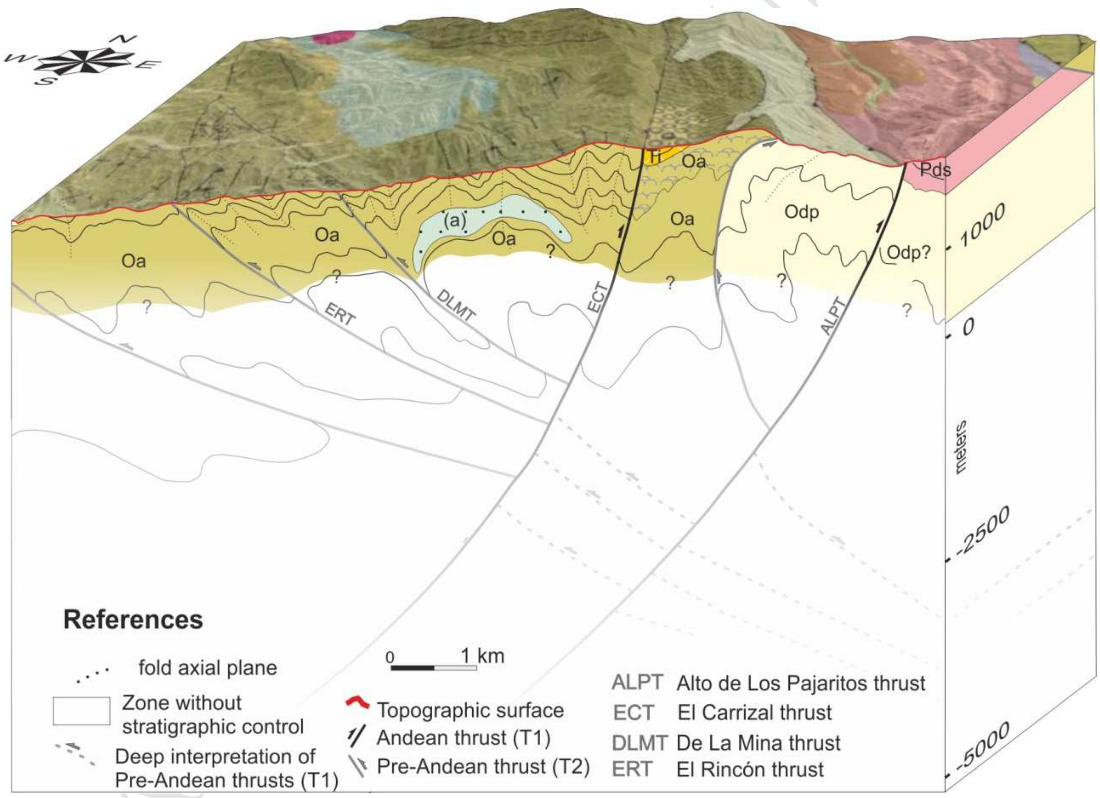

Figure 11: Block diagram of the geological E-W cross-section along 31º20' (A-A'). The image shows the surface trace of mapped structures and their interpretation in depth.

4. Interpretation of results and discussion

4.1 Spreading and closure of the Western Precordillera basin

The Western Precordillera ophiolite belt represents the vestiges of a continental margin in transition to an ocean floor (Davis et al., 1999; Alonso et al., 2008; González Menéndez et al., 2013; Boedo et al., 2013). Indeed, this belt represents the suture zone between the Cuyania and Chilenia terranes (Haller and Ramos, 1984; Ramos et al., 1986; among others). The high gravimetric gradients located along the Rodeo-Calingasta-Uspallata valley confirm the presence of a first order discontinuity in the lithosphere that would correspond to this suture (Martínez and Giménez, 2005).

Despite the fact that the basement of the Western Precordillera basin remains unknown, the WNW-ESE deep-structural lineament recognized in the study area from aeromagnetic data (Fig. 9b) correlates with the structural setting of the Cuyania basement (e.g. Sierra Pie de Palo) (Oriolo et al. 2014).

Scarce outcrops of metamorphic rocks exposed in the Frontal Cordillera have an U-Pb age of 1069 Ma (Ramos and Basei, 1997). This rock is comparable in age with those from the Cuyania basement (Abbruzzi et al., 1993; Kay et al., 1996; Rapela et al., 2010). The geochronological similarities between the Cuyania and Chilenia basement rocks suggest the existence of a common lithosphere between them (Ramos y Basei, 1997; Jones et al., 2015).

The oldest stratigraphic record from the northern part of the Western Precordillera (Calingasta-Rodeo) corresponds to ordovician metasedimentary rocks. Until now, there is no record of pre-Ordovician sedimentation as it does ocurr in the Southern Precordillera and the Frontal Cordillera where a late neoproterozoic-cambrian sedimentation is registered (Davis et al., 2000; López and Gregori, 2004; López de Azarevich et al., 2009;Willner et al., 2011;Gregori et al., 2013; Boedo et al., 2017). Sedimentation during Ordovician times in the Western Precordillera marine basin developed in an extensional context, as it is evidenced by the presence of normal faults related to the deposition of the Don Polo and Alcaparrosa formations (Alonso et al., 2008; Ariza et al., 2014b). This is also suggested by the turbidite sedimentation and the presence of olistostromic sequences to the east of the study area (the Los Sombreros Formation and equivalent units, Benedetto and Vaccari, 1992; Banchig and Bordonaro, 1994; Albanesi et al., 1995). The units described in this paper are compatible with the development of a shallow marine basin as proposed by several authors (Basilici et al., 2003; Boedo et al., 2013; Heredia et al., 2014, among others). A deepening of this basin could be evidenced by the sedimentation represented in the upper member of the Alcaparrosa Formation during the late Ordovician. Sedimentation within a similar context continued along the western margin of the Precordillera during the Silurian and part of the Devonian (the Calingasta and El Codo formations).

The provenance studies performed in ordovician-silurian silicoclastic sequences indicate a common source area located to the east for the Precordillera (Sessarego, 1988; Baldis y Peralta, 1999; Abre et al., 2012). A change in the sedimentation conditions would be related to the accretion of the Cuyania terrane against the western margin of Gondwana during the Mid-Late Ordovician (Thomas and Astini, 2003; Abre et al., 2012, among others).

Mafic rocks with an E-MORB chemical signature are present along the western margin of the Precordillera (Haller and Ramos, 1984; Kay et al., 1984; Cortés and Kay, 1994; Davis et al., 1999; González Menéndez et al., 2013; Boedo et al., 2013; K. de Brodtkorb et al., 2015). This magmatism is associated with the Western Precordillera marine basin spreading, which could have been active up to the Silurian-Devonian according to U-Pb ages on metabasalts and flora contents (Cortés, 1992; Davis et al., 2000).

The belt records an event of intense deformation and associated low-grade metamorphism known as the Chanic orogeny. This event is related to the collision of the Chilenia terrane against the Gondwana margin during Middle-Late Devonian times (Ramos et al., 1986; von Gosen, 1992; 1995; 1997; Davis et al., 2000). This is documented by the Lu-Hf on garnet age that would represent the climax (390 ± 2 Ma, Willner et al., 2011) and the K-Ar and Ar-Ar on white mica cooling ages (Cucchi, 1971; Buggisch et al., 1994; Davis et al., 1999). These ages are consistent with the angular unconformity recognized in the study area between the Del

Raton Formation (Early Carboniferous) and the El Codo Formation (Mid Devonian). This orogenic event would involve the closure of the marine basin and the consequent continentalization of the western edge of Gondwana (Ramos et al., 1986; Astini, 1992; Davis et al., 1999; among others).

Some authors (Ramos et al., 1986; von Gosen, 1992; 1995; this work) proposed that the closure of the oceanic basin developed through the passage from a passive to an active continental margin with a subduction zone dipping eastwards based on top-to-the west devonian structures. However, top-to-the-east structures are also described and on this basis some authors (Davis et al., 1999; Gerbi et al. 2002; Sellés Martínez and Azcurra, 2010a-b; Heredia et al., 2014) postulate a westward dipping subduction zone. The double-vergent systems are typical of collisional orogenic systems (Kearey et al., 2009; Nemcok et al., 2013; Iaffa et al., 2013) and are consequence of the control exerted by previous structures. Such control is consequence of a contrast in the behaviour of the lithosphere between a rigid and a weakened sector through the presence of inherited anisotropies (Kearey et al., 2009). In the case of the Argentine Precordillera (Fig.12), these structures are probably associated with the rifting of the basin which have begun from south to north in neoproterozoic-cambrian times (Ariza et al., 2014b; Heredia et al., 2014; Vujovich, 2016). Thereby the tectonic inversion of normal faults with both eastward and westward dipping directions would have conditioned and controlled the development and propagation of thrusts through the sedimentary cover (Fig.12).

4.2. Model proposed

In the study area, the stratigraphic record suggests that the Western Precordillera basin (Fig.12) would have reached a temporary extension of about 95 Ma from Floian (the Los Sombreros Formation, Ortega et al., 2014) to Frasnian times (the El Codo Formation, Amenábar and di Pascuo, 2008). However, to the south of the study area (current Southern Precordillera and Frontal Cordillera) there are mafic bodies and metasedimentary rocks of late neoproterozoic-early cambrian ages (Davis et al.,2000; López and Gregori, 2004; Willner et al., 2008; Lopez de Azarevich et al., 2009; Gregori et al., 2013) that evidence an older rifting process probably related to the detachment and drift of the Chilenia (and Cuyania?) terrane from Laurentia (Benedetto and Astini, 1993; Ramos, 1995; Astini et al., 1995, Naipauer et al., 2010; Thomas et al., 2011, 2012, among others).

The chemistry of the interbedded mafic rocks indicates that their emplacement took place on a thinned continental lithosphere (González Menéndez et al., 2013; Boedo et al., 2013). Therefore, it is unlikely that the sector of the Western Precordillera basin studied here would have reached the enough expansion to then develop a subduction zone and a magmatic arc (Ernst, 2010).

The Upper Ordovician magmatic centre along the Western Precordillera basin would be compatible with an incipient (Kay et al., 1984) and slow ocean ridge spreading basin. This hypothesis would explain why in the study area the mafic rocks are restricted to the Alcaparrosa and Calingasta formations and equivalent units and why they are scarce or absent in other units (e.g. the Don Polo Formation) (Fig.12).

Moreover, the oceanic lithosphere generated in the western side of the Chilenia-Cuyania block as the result of their separation from Laurentia (Hyppolito et al., 2014) would have reached an estimated age of 140-160 Ma at the Mid Devonian. A lithosphere of these features (older and denser) is more likely to develop an active subduction margin (Kearey et al., 2009). Therefore, it is feasible that the subduction zone related to the closure of the Western Precordillera basin was developed on the western margin of the Chilenia terrane with an eastward polarity in a similar configuration to the current Andean margin. The evidences presented by Kato et al. (2008) and Martínez et al. (2012) suggest the continuity of this subduction margin to the south (41ºLS).

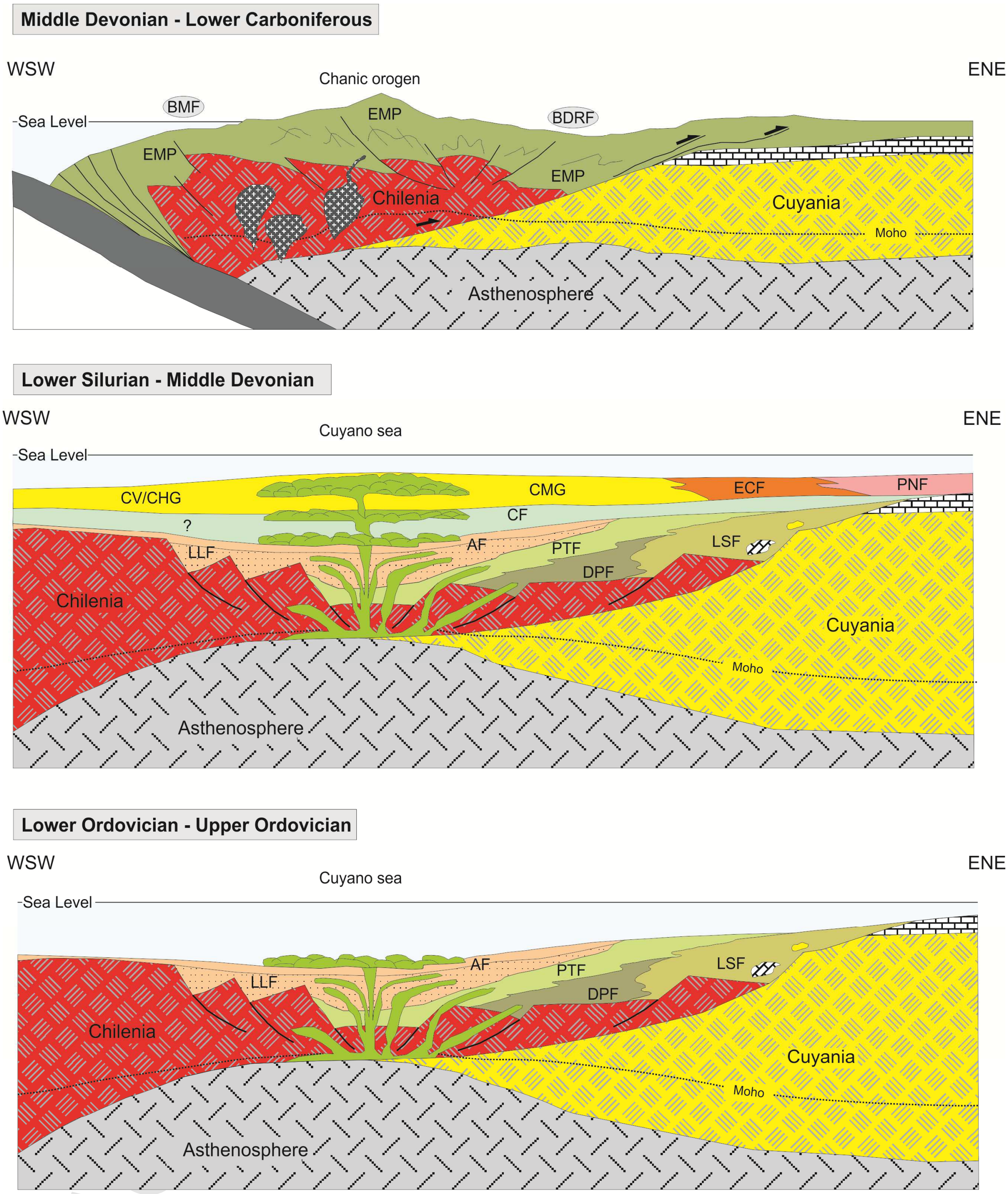

Figure 12: Geological evolution proposed for the central sector of the Western Precordillera from its initial stages to its closure (Chanic Orogeny) during Middle-Late Devonian times. DPF: Don Polo Formation, PTF: Portezuelo del Tontal Formation, LSF: Los Sombreros Formation, AF: Alcaparrosa Formation, CF: Calingasta Formation, CMG: Ciénaga del Medio Group, ECF: El Codo Formation, PNF: Punta Negra

Formation, CHG: Chinguillos Group, CV: Capas Vallecito (informal unit), EMP: Undifferentiated Early-Mid Paleozoic, BMF: Basin of Maliman Formation, BDRF: Basin of Del Raton Formation.

An active subduction zone with these characteristics along the western margin of the Chilenia terrane (Fig.12) allows us to explain the following facts:

- The presence of plutonic rocks of Early Devonian to Early Carboniferous age (monzogranites and granodiorites) emplaced along several sections of Frontal Cordillera (Chilenia) (Caminos et al., 1979; Tickyj et al., 2009a; b; García Sansegundo et al., 2014, Tickyj et al., 2017), San Rafael Block (Cingolani et al., 2003) and the northernmost part of the Argentine Precordillera (Frigerio et al., 2012) The calc-alkaline signature of these plutons indicates that they formed in a magmatic arc.

- Such subduction process would be related to a compressive strength at the upper plate (Chilenia and Cuyania). Thus, the closure of the Early Paleozoic basin took place at the Late Devonian - Early Carboniferous. The double vergence of the Late Devonian deformation would be the result of the control exerted by previous structures and would be related with the Early Paleozoic rift, in accordance with different authors (von Gosen, 1995; Alonso et al., 2008; Heredia et al., 2014; Ariza et al., 2014b).

- The compressive tectonics associated with subduction is evidenced by the presence of syntectonic plutonic rocks from the Early-Late Devonian (Tickyj et al., 2009a; Frigerio et al., 2012, Tickyj et al., 2017). Such compression was transferred to an upper plate constituted by an association of mafic and sedimentary rocks hosted in a thinned continental lithosphere. Based on the low P-T metamorphism relation present in the study area, the generated structures (double vergent flattened parallel-folds and pre-Andean thrusts) would be the result of the interaction between the Cuyania and Chilenia terranes in a compressive tectonic context controlled by ancient anisotropies (thick-skinned-dominated Chanic orogen).

To the south of the study area, in the Guarguaraz region (Frontal Cordillera) and in the Cordón del Peñasco (Sothern Precordillera) metasedimentary and mafic-metaigneous rocks deformed under high pressure-mid temperature conditions (Massonne and Calderón, 2008; Willner et al., 2011; Boedo et al., 2016) represent the final closure of the basin between Chilenia and Cuyania.

5. Conclusions

We recognized two finning-upward sequences (the Don Polo and Alcaparrosa formations). They represent talus and abyssal plain settings of a shallow basin. The mafic dikes, sills and pillow lavas hosted at different levels of the Alcaparrosa Formation are related to the spreading of the Western Precordillera basin. The structure of the Chanic orogen is represented by folds and thrusts. Major folds have NW-SE trend and axial planes dipping to NE, which have been generated under a NE-SW direction of maximum compression. The minor structures associated to the folds indicate mechanisms of flexural-slip folding with partial recrystallization and development of axial plane cleavage (S_1). The record of non-parallel folds would indicate a transition zone between flexural-slip folds and flattening folds (flexural-slip-flattened folds).

The compatibility between the aforementioned folds and T1 thrusts allow us to interpret a common deformation age (Mid-Late Devonian) for both structures. Whereas the geometric and kinematic features of the T2 thrusts and their cut-relations with devonian structures and tertiary rocks confirm their andean age.

Aeromagnetic maps presented here represent a new contribution to the geophysical knowledge of the region. They reveal the influence of deep structural configuration on surface structures, such as the WNW-ESE deep structures located in the Pie de Palo range that could continue to the west in the Argentine Precordillera basement. Dominant NW-SE trending anomalies show a similar pattern to the predominant structural pattern (chanic structural grain) of the study area.

The origin of the Western Precordillera basin in the study area is linked to an extensional process related to the separation between the Cuyania and Chilenia terranes during the Ordovician. This extensional context could be related to the extensional process that has begun south of 32ºS (current Southern Precordillera and Frontal Cordillera) in the late Neoproterozoic-Cambrian. This interpretation involves the existence of a common basement whose origin and provenance is currently a subject of discussion. The inception of an eastward dipping subduction zone west of the Chilenia terrane during the Early-Mid Devonian would have provided the compressive geodynamic framework that led to the closure of the Western Precordillera basin and the consequent development of the thick-skinned-dominated Chanic orogen.

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Research highlights

- An asymmetric marine basin was developed between the Chilenia and Cuyania terranes
- The Chanic orogen was a thick-skinned-dominated orogen on the proto-pacific margin of Gondwana
- Geophysical data evidence the structural features of the Western Precordillera basement
- Andean structures are strongly controlled by inherited pre-Andean anisotropies