Journal of Volcanology and Geothermal Research 201 (2011) 53–64

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

Payenia volcanic province in the Southern Andes: An appraisal of an exceptional Quaternary tectonic setting

Victor A. Ramos *, Andrés Folguera

Laboratorio de Tectónica Andina, FCEyN, Universidad de Buenos Aires, CONICET, Ciudad Universitaria, 1428 Buenos Aires, Argentina

ARTICLE INFO

Article history:
Received 13 April 2010
Accepted 3 September 2010
Available online 16 September 2010

Keywords:
monogenetic centers
intraplate basalts
steepening subduction zone
Mendoza
Neuquén

ABSTRACT

The Southern Volcanic Zone of the Andes has a Quaternary basaltic province along the retroarc which has a unique tectonic setting. The Payenia volcanic province covers an area larger than 40,000 km^2 between 33°30′ and 38° South latitudes, with an estimated volcanic volume of about 8387 km^3 erupted through more than 800 volcanic centers in the last ~2 Ma. The mainly basaltic province developed above the San Rafael Block is subdivided in three segments characterized by the Cerro Nevado, Llancanelo, Payún Matru, Tromen and Auca Mahuida volcanic fields, together with hundreds of minor monogenetic basaltic centers. The analysis of the different segments shows the formation of a common basalt plateau with intraplate signature from south to north between 2.0 and 1.7 Ma, which reached the 35°S to the north. Above this plateau monogenetic centers as Nihuil Vn. 1.433 Ma and Cerro Chato at 1.352 Ma are developed, followed by the large polygenetic center of Cerro Nevado (3980 m a.s.l.) at 1.320 Ma. This plateau was broken by a series of normal faults that produced volcanic cone alignments such as the NNW-trending Mancha Jarilla lineament in the central part at about 1.0 Ma. Extension shifted to the eastern margin of the San Rafael Block, which concentrates tens of monogenetic centers between 0.9 and 0.7 Ma. Extension then migrated towards the foothills in the west, where many monogenetic cones were erupted through NW-trending normal faults between 0.5 and 0.435 Ma. The collapse of the large Diamante Caldera at 0.445 Ma coincides with that period. Subsequent volcanism was concentrated in (1) the Payún Matru volcanic field, with the eruption of Cerro Payén between 0.272 and 0.261 Ma; the Payún Matru shield volcano, with polygenetic eruptions at least since the last 0.233 Ma and with the caldera formation bracketed between 0.168 ± 0.004 Ma and 0.082 ± 0.001 Ma, followed by several eruptions until 7000 yrs, and even historical ones; and in (2) the Tromen volcano, where younger than 0.2 Ma eruptions took place and historical eruptions were reported. The understanding of these eruptions in time and space, combined with geophysical data, indicates the geometry of an important crustal attenuation beneath Payenia, associated with a hot sublithosphere. The Late Miocene uplifted San Rafael Block collapsed in the Early Pleistocene as a consequence of the steepening of the subducted slab, and the injection of hot asthenosphere produced the Quaternary Payenia volcanic province. Melts of the lower crust along the Principal Cordillera at these latitudes are responsible for the Quaternary calderas, ignimbritic flows and rhyolitic volcanism that express the crustal delamination of the Andes. The Payún Matru volcanic field concentrates this asthenospheric flow in the Present.

1. Introduction

The presence of Payenia, a large Quaternary volcanic province of basaltic composition in the foreland region, behind the active volcanic arc is unique in the entire Andean chain from Colombia to Tierra del Fuego (Fig. 1). This volcanic province is developed between 33°30′ and 38°S over almost 40,000 km^2 parallel to the active volcanic arc of the Southern Volcanic Zone (Stern, 2004). The tectonic setting of the extra-Andean late Cenozoic lava and pyroclastic flows, cinder cones, and related rocks of basaltic composition is known since the early proposal of Jordan et al. (1983). These authors described the occurrence of these basalts in the retroarc area of a normal dipping (30°) subduction segment located in the southern segment of the Central Andes. This segment was analyzed by Ramos and Barbieri (1988) who attributed this exceptional setting to the young age of the subducted slab. However, the tectonic evolution of this exceptional geological province defined as Payenia by Polanski (1954) and González Díaz and Fauqué (1993), and partially described as the Complejo Efusivo Neógeno by Bettini et al. (1979) and Bermúdez (1987); as the Andino-Cuyana Basaltic Province by Bermúdez and Delpino (1990) and Bermúdez et al. (1993), is still a matter of debate.

The objectives of this paper are to review and evaluate the new chronological data on this basaltic province; to associate these data

---

* Corresponding author.
E-mail address: andes@gl.fcen.uba.ar (V.A. Ramos).

0377-0273/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2010.09.008

Fig. 1. Location of the Payenia volcanic province with the outline of the major volcanic fields. The main Quaternary volcanoes of the Southern Volcanic Zone are indicated as well as the Late Cenozoic volcanic gap further north related to the Pampean flat-slab segment (after Jordan et al., 1983; Stern, 2004).

with the new geophysical studies performed in the region; to reconstruct the structural history of the different segments; and to propose an integrated evolution of the region based on the hypotheses advanced on its genesis by several authors.

2. The Payenia geological province

Since the early studies of Polanski (1954) it was evident that a large Quaternary volcanic province dominates the foreland of the southern Mendoza and Northern Neuquén provinces of western Argentina (Fig. 1). Most of the previous work along the foreland was concentrated between 35°30′ and 37°30′S.

Two important volcanic fields were identified within these latitudes: the Llancanelo field with an extension of 10,700 km^2, and the Payún Matru volcanic field with approximately 5200 km^2 as part of the Andino-Cuyana basaltic province (Bermúdez et al., 1993, Risso et al., 2008). Some other authors include Payenia as part of the Patagonia mafic volcanic province, one of the largest retroarc mafic continental provinces of the Earth with near 200,000 km^2 (Kay et al., 2004), criteria partially followed by some later studies (Bertotto et al., 2006a,b, 2009). However, the geological and tectonic processes in the Paleocene to Quaternary Patagonian large mafic province are somewhat different from what is seen in Payenia, and therefore we prefer to keep the southern Mendoza and northern Quaternary Neuquén basaltic rocks as an independent unit.

Thus, following the early definition of Polanski (1954), we maintain the name of Payenia for this volcanic province. Payenia covers as a whole 39,638 km² between 33°30′ and 38°S and comprises more than 800 volcanic centers, being one of the densest volcanic provinces of South America (Risso et al., 2009). The region can be divided in three distinctive segments, which have different characteristics. The northern segment has isolated minor monogenetic fields; the central segment presents large volcanic fields with extensive lava flows; and the southern segment shows some large volcanoes with less extensive lava flows. The three segments together generated a volume of about 8400 ± 100 km^3, measured on a precise topographic DEM with a resolution of 90 m pixel.

2.1. Northern segment

The analysis of the Andean foothills south of the Pampean flat-slab segment, shows that the first monogenetic basalts are exposed south of the Manzano Histórico (33°37′S–69°23′22″W), where some 10 minor volcanic centers were described by Martínez (2005). A series of cinder cones and small monogenetic lavas of subalkaline basaltic composition were assigned to the Pleistocene in Arroyo de Las Pircas and in the Arroyo Grande del Portillo. They have calcalkaline signature and volcanic arc setting (Martínez, 2005).

Further south, between 34° and 34°30′S, monogenetic volcanoes of basaltic composition are described by Cortés and Sruoga (1998) emplaced in the piedmont and bajadas of the Frontal Cordillera (see Figs. 2 and 3). The volcanic centers are emplaced over the *Asociación Piroclástica Pumícea* of Polanski (1963), an extensive key bed of pumice pyroclastic deposits that represents large volumes of ignimbrites and

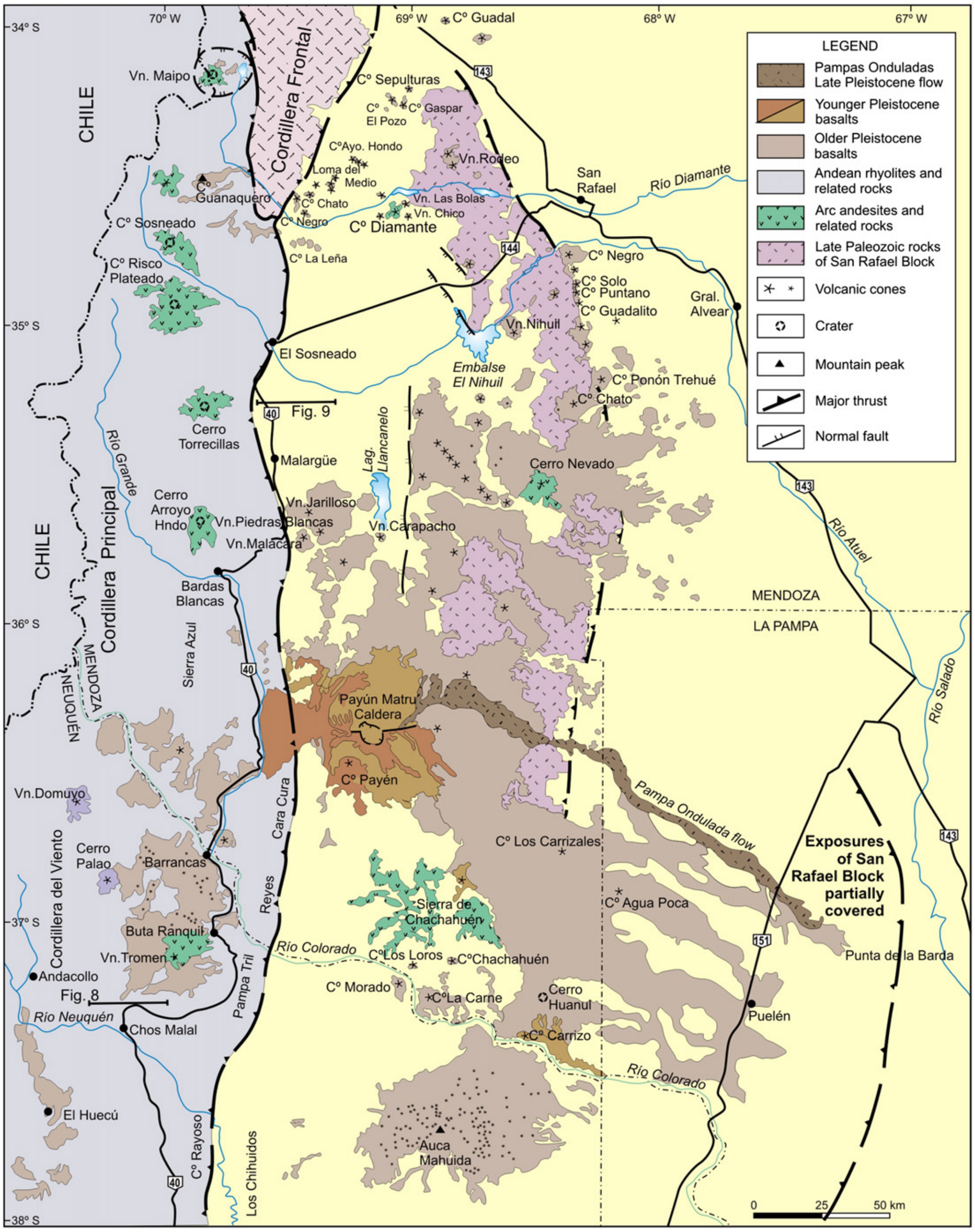

Fig. 2. Main volcanic centers and basaltic flows of the Payenia volcanic province. The relative extension of the volcanism from north to south is shown in detail in Figs. 3–5. Note the extraordinary length of the Pampa Ondulada flow based on Pasquare et al. (2008). The structure west of Rio Salado is based on Folguera and Zárate (2009).

ash-fall tuffs. These rocks were dated between 0.470 ± 0.07 Ma and 0.440 ± 0.008 Ma by Stern et al. (1984). These volcanic centers are aligned with piedmont fault scarps and bedrock escarpments, which correspond to normal faults interpreted by Cortés (2000) as associated with NW-trending trastensional lineaments. The ages of these monogenetic centers vary from 0.434 ± 0.3 Ma to 0.070 ± 0.004 Ma as reported by Folguera et al. (2009), in accordance with their stratigraphic relationship with the age of the substratum.

There are several small volcanic fields north of Río Diamante, like the Rodeo monogenetic volcanoes ranging in age from 0.705 ± 0.006 Ma to 0.590 ± 0.004 Ma, and isolated volcanoes like Cerro Guadal ranging from 0.530 ± 0.04 to 0.529 ± 0.04 Ma (Folguera et al., 2009).

South of the Río Diamante there are few small isolated volcanoes such as the Las Bolas field with ages between 0.505 ± 0.3 Ma and 0.495 ± 0.03 Ma and the Chico volcano with 1.164 ± 0.07 Ma and 0.484 ± 0.03 Ma. The large Diamante volcano has the youngest lavas between 0.082 ± 0.005 Ma and 0.076 ± 0.002 Ma (Folguera et al., 2009).

Further to the east along the eastern fault scarp of the San Rafael Block, there are several monogenetic volcanic centers with limited and small lava flows (González Díaz, 1972a). From north to south several ages have been reported with 0.801 ± 0.05 Ma in Cerro Negro; 0.932 ± 0.06 Ma north of Cerro Solo; 0.750 ± 0.05 Ma in Cerro Solo; 1.780 ± 0.11 Ma in Puntano volcano; and 0.805 ± 0.5 in Cerro Guadalito (Folguera et al., 2009). Several similar centers are aligned

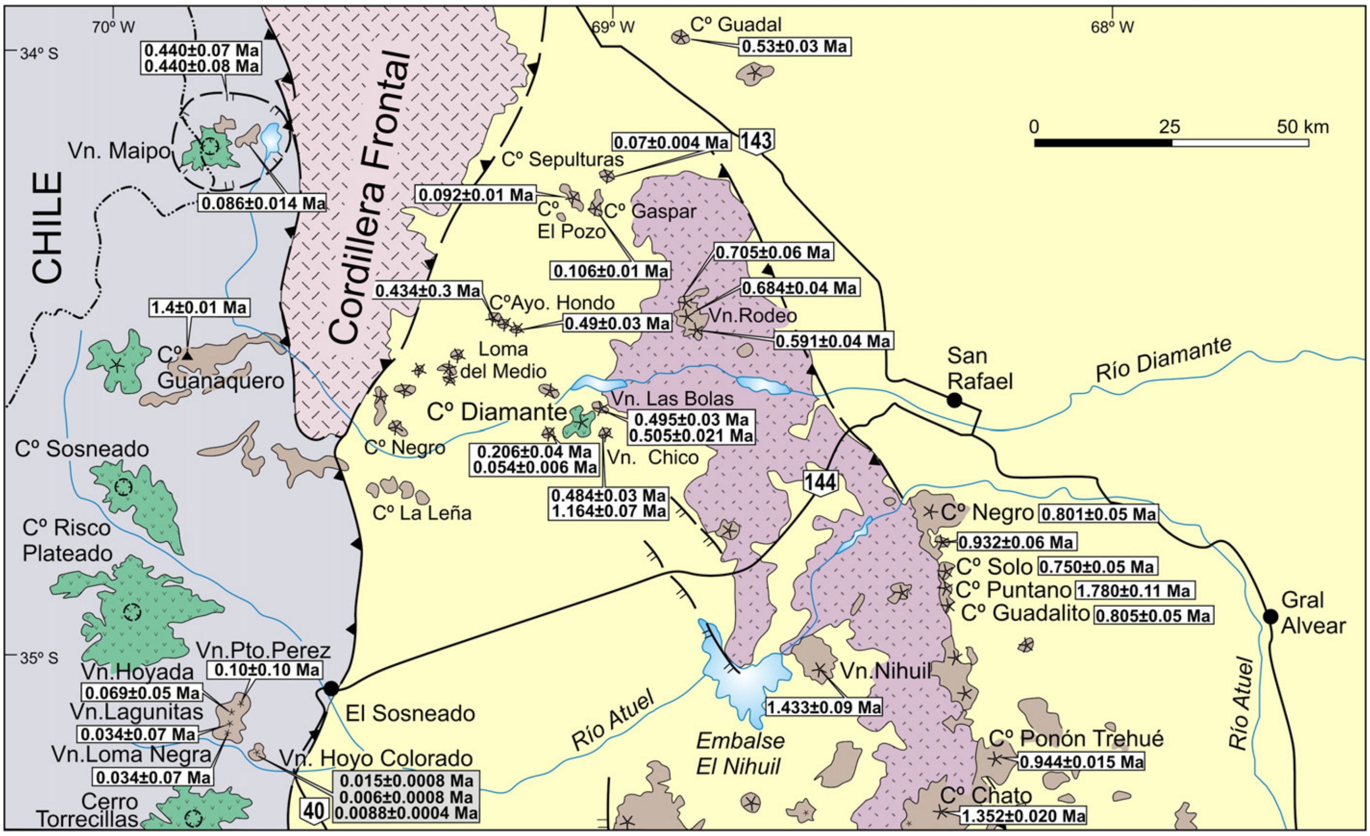

Fig. 3. Main volcanic centers of the northern segment with available ages. Chrono-logical data are mainly based on unspiked K–Ar data set of Folguera et al. (2009) and Sruoga et al. (1998); Naranjo et al. (1997) and Fuentes and Ramos (2008). Ages in gray are ^{3}He-cosmogenic dates from Marchetti et al. (2006). Legend as in Fig. 2.

further south along this fault-bounding margin. Reverse Pleistocene faults and monoclinal folds have been described along this margin of the San Rafael Block by Costa et al. (2004), and subsequent extensional collapse by Folguera et al. (2008).

The most recent volcanic activity is concentrated along the Andean orogenic front. Late Quaternary monogenetic volcanoes have been described by Naranjo et al. (1997) along Río Salado, recently examined by ^{3}He cosmogenic-exposures dating by Marchetti et al. (2006) yielding 0.0065 ± 0.0005 Ma and 0.0060 ± 0.0008 Ma. These ages are similar to the sequence of volcanic activity found further west with ages ranging from 0.100 to 0.005 Ma, reported by Folguera et al. (2009). These monogenetic volcanic centers are controlled by an important north-trending normal fault described by Kozlowski et al. (1993), and studied by Giampaoli and Dajczgewand (2005) along the valley of Río Salado.

This segment, although similar in size with the central and southern segments, concentrates less than 10% of the volcanic centers, being mainly scoria cones and small flows.

2.2. Central segment

This segment concentrates the most important volcanic activity, with three important volcanic fields (Fig. 4).

2.2.1. Cerro Nevado volcanic field

This volcanic field encompasses several monogenetic cones and a large estratovolcano developed over an early Pleistocene basaltic platform (Fig. 4). This platform is formed by the oldest basaltic flows that range in age from 1.83 Ma south of the Cerro Nevado to 1.71 Ma north of the Payún Matru (Fig. 4).

Cerro Nevado, the most important volcano (3980 m a.s.l.), is characterized by flows, lapilli beds and lapillitic breccias with high-K calcalkaline andesitic composition (Bermúdez, 1991). This author was the first to identify a large expansion of the volcanic arc as far as 500 km from the trench. Previous K–Ar ages of these volcanic rocks had large errors. The new K–Ar ages are more precise because the limit of detectability of the radiogenic Ar content is presently at 0.1%. This fact makes the Cassignol–Gillot technique especially suitable for very young dating as it allows obtaining K–Ar ages as young as 2 ka with only a few centuries uncertainty (Quidelleur et al., 2009). The new K–Ar ages of Cerro Nevado rocks vary from 1.324 to 1.320 Ma, which indicate a rapid eruption (Quidelleur et al., 2009). Slightly older ages have small centers as the Cerro Chato with 1.352 ± 0.02 Ma (Fig. 4).

The volcanic activity migrated towards the west where NW-trending extensional faults concentrate a series of monogenetic cones of basaltic composition as the Cerro Mancha Jarilla (Bermúdez et al., 1993). New ages obtained in cones located along these lineaments yielded ages of 1.044 to 1.022 Ma (Quidelleur et al., 2009).

The last activity in the Cerro Nevado volcanic field shifted towards the margin of San Rafael Block. There, prominent basaltic volcanoes as the Cerro Ponón Trehue were erupted aligned with discrete NW-trending extensional faults identified by Núñez (1979). The basalts of Cerro Ponón Trehue have an age of 0.944 Ma (Quidelleur et al., 2009), similar to the volcanic trend between Cerro Negro and Cerro Guadalito (0.801–0.932–0.805 Ma, Folguera et al., 2009), developed along the eastern margin of the San Rafael Block (Fig. 3).

2.2.2. Llancanelo volcanic field

This volcanic field was recently studied by Risso et al. (2008), who characterized this as a series of monogenetic volcanic centers of high cone density, with three kinds of volcanic cones: tuff rings, tuff cones and scoria cones. The volcanic centers frequently show phreatomagmatic characteristics, which indicate that magma–water interaction

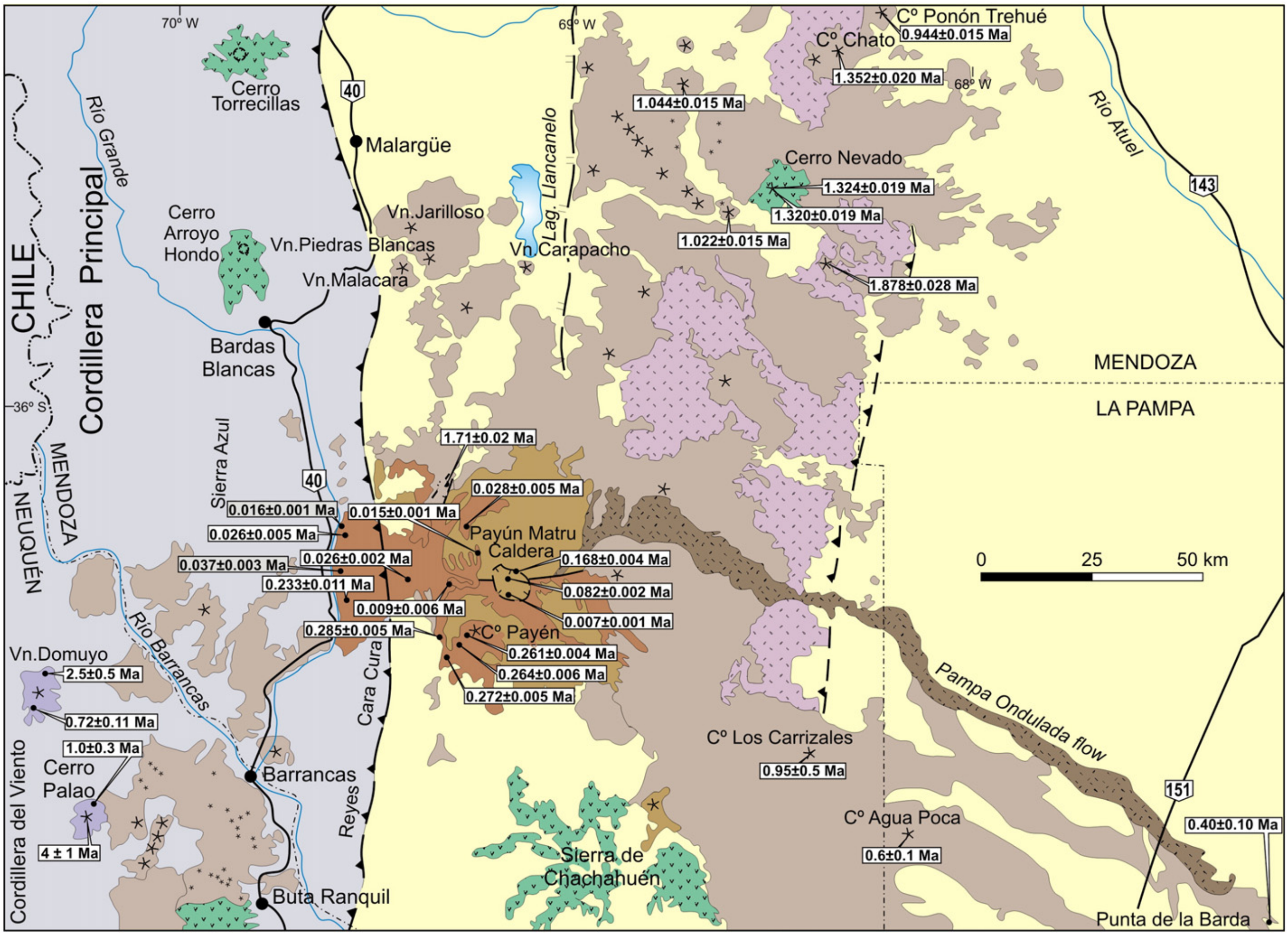

Fig. 4. Main volcanic centers of the central segment with K–Ar ages using the Cassignol–Gillot technique for the Cerro Nevado volcanic field based on Quidelleur et al. (2009) and the Payún Matru volcanic field based on Germa et al. (2010); isolated ages south of the Pampa Ondulada flow are standard K–Ar ages based on Melchor and Casadío (1999). The ages from Domuyo and neighboring areas are from Miranda et al. (2006) and Folguera et al. (2007c). Ages in grey are ^{3}He-cosmogenic dates from Marchetti et al. (2006). Legend as in Fig. 2.

played an important role in the construction of the volcanic edifices. This fact is confirmed by the recent studies of Violante et al. (2010) who proved that the surface of the present Llancanelo Lake was much more extensive at the time of these eruptions, based on geophysical grounds and shallow drillings of the uppermost sedimentary sequences.

The tuff cones in this volcanic field are controlled by NW-trending lineaments, similar to the main fractures of the Cerro Nevado volcanic field. This set of fractures has cross-cutting relationships with ENE-trending lineaments as seen in Jarilloso and Malacara-Piedras Blancas trends depicted by Risso et al. (2008). The present depression of the Llancanelo Lake is controlled by a half-graben structure, east-bounded by a normal fault already described by Polanski (1963) and Folguera et al. (2008).

There are a few old K–Ar ages in Llancanelo which indicate a Late Pleistocene age (Linares and González, 1990), but they are not reliable. The age of this field is poorly constrained and could be as young as Holocene, since historic activity is quoted by Risso et al. (2008).

2.2.3. Payún Matru volcanic field

This field has the most important volcanic activity of the Payenia volcanic province. The volcanoes are developed on a basaltic plateau of about 1.71 ± 0.02 Ma (Quidelleur et al., 2009), with large basaltic flows erupted to the east for tens of kilometers. These eruptions seem to have originated in a large east–west fissure and their ages are poorly constrained. They are prior to 0.95 ± 0.5 Ma and 0.6 ± 0.1 Ma, based on the ages of Cerro Los Carrizales and Cerro Agua Poca, two volcanic centers reported by Melchor and Casadío (1999) and Bertotto (2000) developed above these lava flows (see Fig. 4).

The Payún Matru shield volcano (3691 m a.s.l.), characterized by the high-K basalts and the trachytic composition of the younger products, has been studied by Llambías (1966) and González Díaz (1972b), who established a complex volcanic stratigraphy, including the formation of its large caldera and the post-caldera volcanic products. The geochemical composition indicates a backarc–intraplate setting (Kay et al., 2006). The age of the earlier stages is not established and could be as old as 0.233 ± 0.011 Ma, but recent studies constrained the formation of the caldera between 0.168 ± 0.004 Ma (pre-caldera rocks) and the age of the first post-caldera in 0.082 ± 0.001 Ma (Germa et al., 2010). These authors reconstruct the original volume of the shield volcano in 240 km^3, prior to the collapse, and a subsequent volume removed by the caldera forming eruption in about 25 km^3.

The Payén stratovolcano exposed to the south of the caldera has intermediate composition and was built between 0.272 and 0.261 Ma (Germa et al., 2010).

The Payún Matru shield volcano could also be the source of large basaltic lavas that flowed to the west and trapped the Río Grande valley, dated at about 0.233 Ma (Quidelleur et al., 2009). An exceptional single flow produced during this episode of basaltic eruption has an individual tongue-like shape with a length of 181 km and therefore is one of the longest known individual Quaternary lava flow on Earth (Pasquare et al., 2008). The age of the Pampas Onduladas flow is poorly constrained. Along the escarpment of Punta de la Barda, one of the basalt flows was dated by K–Ar in 0.40 ± 0.10 Ma by Melchor and Casadío (1999). The Pampas Onduladas flow does not reach Punta de la Barda, and it should be younger than 400 ka (see relationships in Fig. 4).

The post-caldera eruption comprises more evolved acidic rocks and basalts (González Díaz, 1972b). The basalts range in age from 0.026 to 0.028 Ma, with the last trachytic intra-caldera products in 0.007 Ma (Germa et al., 2010). Some new ages obtained in the basalts that temporarily dammed the Río Grande valley yielded ^{3}He cosmogenic ages ranging from 0.044 ± 0.002 Ma to 0.037 ± 0.003 Ma (Marchetti et al., 2006). A water polished bedrock knob on a fluvial strath of this area yielded 0.016 ± 0.001 Ma by the same dating method.

As a whole the Payún Matru volcanic field encompasses more than half of the total volume erupted in Payenia. It has the largest plateau lavas, the major volcanoes, a unique late Pleistocene caldera, the longest single flow, and concentrates the younger activity and more voluminous eruptions.

2.3. Southern segment

This segment encompasses two large volcanic fields, the Auca Mahuida and the Tromen basaltic fields. There are also several small basaltic volcanoes such as Cerros Morado, La Carne, Carrizo, among many others monogenetic cones and flows along the Río Colorado valley. Cerro Los Loros stands as a different siliceous tuff ring in the proximities (Németh et al., 2009). Further to the east over the basalt plateau, there is a shield volcano, the Cerro Huanul, described by Bertotto (2002) as a Hawaiian eruptive basalt center of possible Quaternary age.

2.3.1. Auca Mahuida volcanic field

This large basaltic shield volcano stands at 2253 m a.s.l., 100 km east of the orogenic front with a well-preserved central crater and an andesitic plug. It has been surveyed by Holmberg (1964) who assigned most of the lavas to the Pleistocene, except the lowermost flow that he assigned to the Pliocene. An angular unconformity separates the volcanic rocks from the gently dipping Cretaceous beds. Recent Ar–Ar data indicate that most of the lavas range in age from 0.8 to 1.7 Ma (Fig. 5), with the only exception of the lowermost flow that yielded 2.03 ± 0.03 Ma (Ar–Ar plateau age of Rossello et al., 2002). Recent dating by Ar–Ar presented by Kay et al. (2006) yielded ages of 1.78 ± 0.1 Ma, 1.55 ± 0.07 Ma and 1.39 ± Ma for the plateau basalt flows. The geochemical characteristics indicate that the volcanic rocks vary from hawaiites to mugearites in the lava flows with some more evolved trachytes in the final products. Both types fall in the backarc–intraplate fields (Kay et al., 2006).

2.3.2. Tromen volcanic field

This region was recently described as the Tromen volcanic plateau by Kay et al. (2006), Galland et al. (2007), and Folguera et al. (2008) who present new geochemical data and Ar–Ar and K–Ar dates that established a precise stratigraphy of the volcanic field.

Geochemical studies have shown that most of the sequence that forms the Tromen volcanic plateau comes from typical intraplate melts, with no slab connection.

Only the basal-less voluminous products around 4 Ma would have an arc affinity (Kay et al., 2006). On the other hand, the Tromen volcanic plateau has been recently considered to have been emplaced in a compressive tectonic setting, mainly due to its location into the Chos Malal fold and thrust belt and to the finding of folding affecting Quaternary lavas (Galland et al., 2005). New field and seismic data from the Tromen plateau show striking evidence of normal faulting affecting Quaternary basaltic flows (Folguera et al., 2008).

The Tromen volcanic field developed an extensive basaltic plateau with ages ranging from 1.8 to 1.6 Ma that support monogenetic

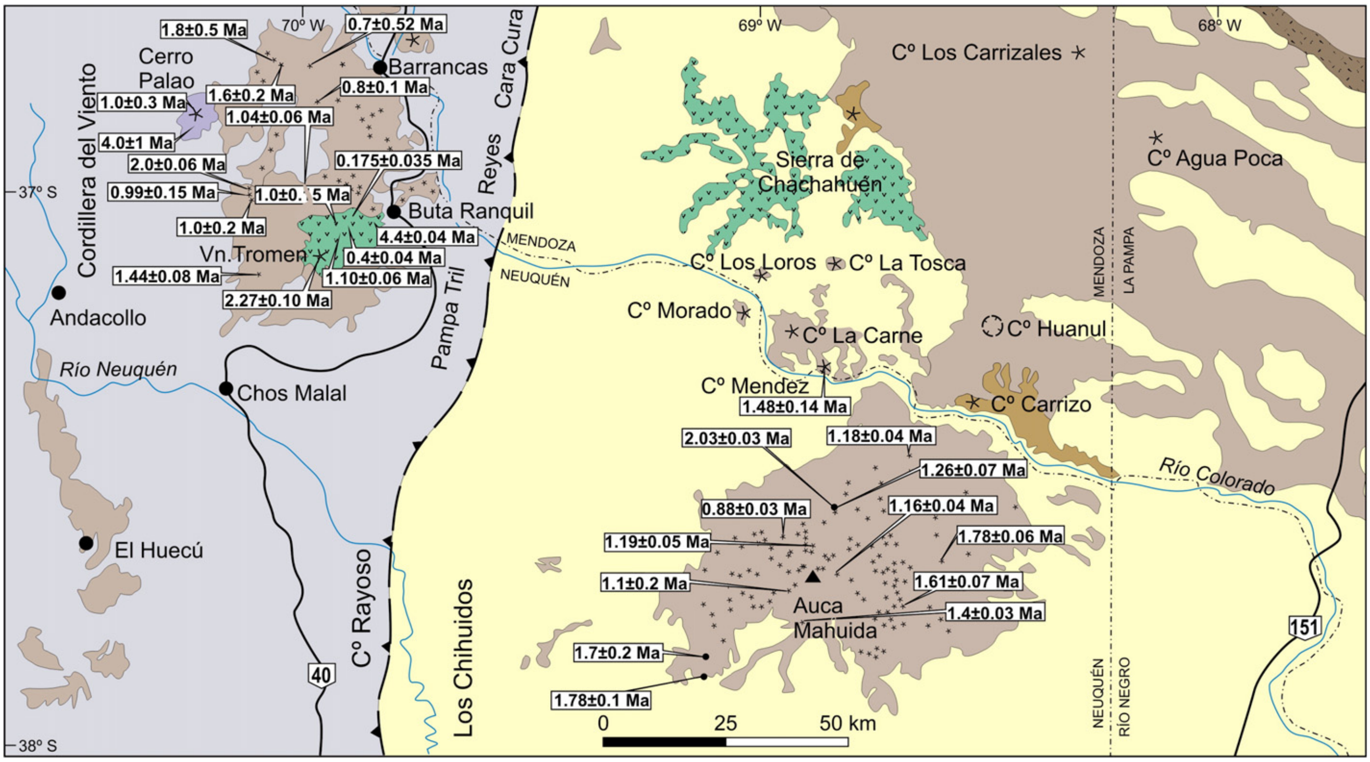

Fig. 5. Main volcanic centers of the southern segment with Ar–Ar ages of the Auca Mahuida volcanic field based on Rossello et al. (2002); the ages in the Tromen volcanic field and surrounding areas are based on Kay et al. (2006), Miranda et al. (2006), Galland et al. (2007) and Folguera et al. (2008). Legend as in Fig. 2.

volcanoes and the younger Tromen volcano with its summit at 3969 m a.s.l. (Folguera et al., 2008). This basaltic platform is supporting volcanic cones such as the Wayle volcano (1.04 ± 0.06 Ma), Cerro Polco (0.8 ± 0.1 Ma and 0.7 ± 0.2 Ma), and basalt flows ranging in age from 1.0 ± 0.2 Ma to 0.99 ± 0.15 Ma near Tricao Malal (Folguera et al., 2008). Ar–Ar ages in the southern sector of the platform yielded 1.31 ± 0.12 Ma and 1.83 ± 0.06 Ma (Galland et al., 2007). The intraplate lavas of the Tromen stratovolcano range in age from 2.27 ± 0.1 Ma to 0.04 ± 0.04 Ma (Ar–Ar) showing a long lasting volcanic activity (Kay et al., 2006; Galland et al., 2007).

Several monogenetic late Quaternary basaltic cones and lavas described by Bermúdez (1985) are emplaced in the present Rio Colorado valley, immediately to the east of the Tromen plateau, northeast of Buta Ranquil.

3. Determination of magma source and tectonic setting from geophysical studies

During the last years a considerable amount of geophysical studies were carried out with the common objective of determining the origin of the Payenia flood sequences emplaced in the retroarc region. The first studies were gravimetric surveys and indicated that theoretical computations of Moho, based on different isostatic models, did not reproduce adjustably Bouguer anomalies (Diez Rodríguez and Introcaso, 1986). These studies were performed at the southernmost part of the Payenia basalt flood eruptions at 38°–39°S latitudes on the eastern side of the Andes. Latter combination of isostatic-thermal models was advocated in order to reproduce the Bouguer anomaly in the region (Pacino, 1997). This thermal root would be confirmed for the eastern side of the Andes at the southern Payenia volcanic field by magnetoteluric surveys. These studies identified highly conductive pockets, interpreted as reservoirs of magma and/or volatiles, hosted in the crust beneath the flood basalt area (Brasse and Soyer, 2001).

Receiver function analyses performed by Yuan et al. (2006) highlighted an attenuated crust (~33 km) beneath the eastern Andean slope in coincidence with the southernmost part of the flood eruptions (Fig. 6). 2D density models based on Yuan et al. (2006) lower crustal geometry and Brasse and Soyer (2001) highly conductive reservoirs reproduced Bouguer anomalies (Folguera et al., 2007a). Hence, the early hypotheses that considered a thermal component in order to explain the lack of correlation between isostatic models and measurements were confirmed.

Gilbert et al. (2006) based on the data of Wagner et al. (2005) produced the first insights into the subcrustal seismic velocity structure in the central area of flood eruptions (~36°S), between major volcanic centers such as Cerro Nevado and Payún Matru volcanoes (Fig. 6a). Receiver function analyses and computation of S-wave anomalies revealed multiple crustal low velocity zones interpreted as partial melting pockets beneath the retroarc volcanic centers. A subcrustal low velocity zone is determined as a 20 km thick (vertical dimension), hosted between 40 and 60 km in depth, and at least 250 km wide (horizontal dimension) volume, coinciding with the extension of Quaternary flood eruptions in the retroarc area.

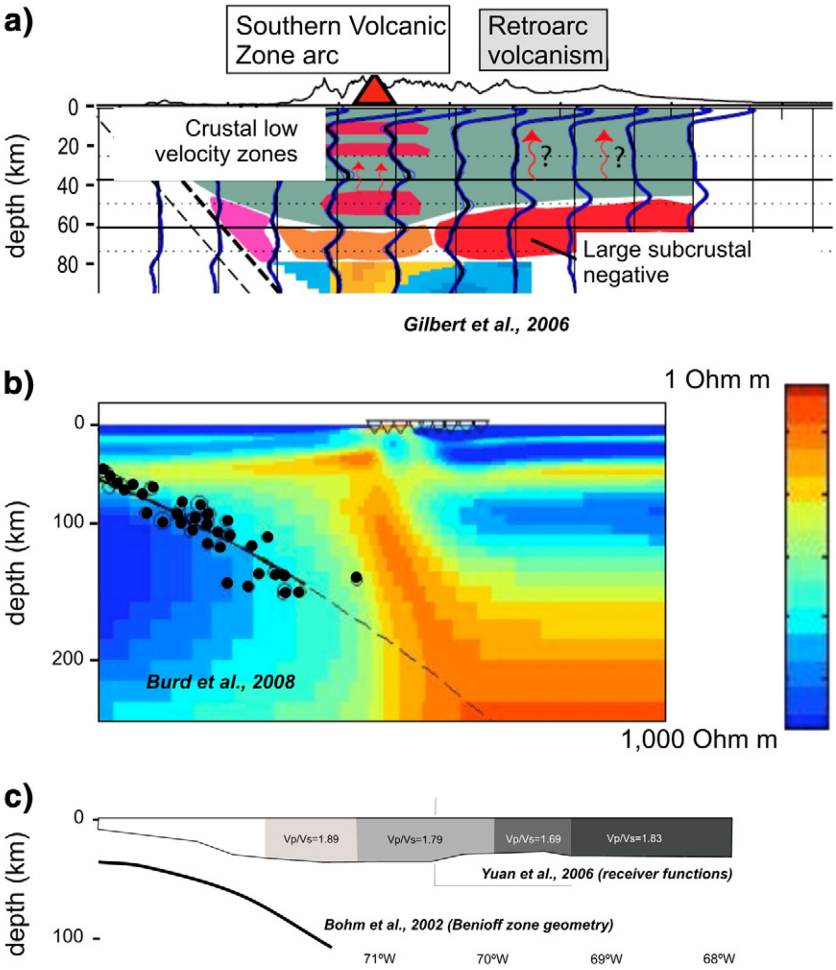

Fig. 6. Geophysical constraints for the retroarc region between 35° and 39°S that show a) large subcrustal negative arrivals beneath the northern Payenia volcanic field (Gilbert et al., 2006); b) low resistivity plume-like zone (Burd et al., 2008), and c) crustal attenuation phenomena at the southernmost part (Yuan et al., 2006). See location of these surveys in Fig. 7.

Folguera et al. (2007b) modified the 3D density model of Tasarova (2004) with new constraints for the retroarc area with the aim of determining the source of long wavelength and positive gravity residual anomalies at the area of flood eruptions (Fig. 7). Residual gravity anomalies were calculated in order to eliminate the pronounced regional signal from the observed Bouguer anomaly. This low long-wavelength regional field is caused by the large mass deficit of the Andean root. The long-wavelength gravity field, defined by the EIGEN-GL04S1 satellite derived model, was used to represent the regional field. The residual anomalies were calculated by subtracting the corresponding regional fields from the observed Bouguer anomaly. Long wave-length gravity highs are located above the western sector of the Agrio fold and thrust belt, the eastern sector of the Malargüe fold and the thrust belt and the eastern San Rafael Block (Fig. 7).

A crustal attenuated area (Moho up to 30 km), 200–250 km wide, was obtained in the density model through the retroarc zone, coincident with the crustal low velocity area determined from seismic studies (Wagner et al., 2005; Gilbert et al., 2006) and the positive residual gravity anomalies. Then, the positive residual anomaly depicted in Fig. 7 is interpreted as the result of the upward deflection of the crustal density layering due to stretching. Hence, this model provides a picture of the lower crust through the central and southern parts of the Payenia volcanic field.

Finally, Burd et al. (2008) made a conductive model for the first 500 km and performed a magnetoteluric survey at the latitudes of the Payenia volcanic field and adjacent eastern slope of the Andes (36.5°S) (Fig. 6b). Here a steeply-dipping conductive feature was identified as rising beneath the Payún Matrú Volcanic Field. This "plume" is rooted deeper than 200 km and is just above the projected Nazca Slab (Burd et al., 2008).

4. Late Cenozoic structural evolution

The geologic map of Fig. 2 shows two major thrust systems developed by the end of the Miocene: (1) The orogenic front at the foothills of the Cordillera Principal, which is the thrust front of the complex Malargüe fold and thrust belt. It was formed as a thick-skinned belt by tectonic inversion of normal faults favored by thermal weakening during the expansion of the magmatic arc (Ramos and Folguera, 2005); and (2) the major thrust that uplifted the San Rafael Block during the Late Miocene. This thrust is well exposed at the latitude of San Rafael, and continues from Cerro Negro to Cerro Ponón Trehue (González Díaz, 1972a; Núñez, 1979), where is covered by the basalt flows from Cerro Nevado field. Further to the south, it can be tracked along the eastern margin of the exposures of the late Paleozoic rocks up to north of Cerro Carrizales, where the basaltic platform obliterates its trace. The basement block continues to the south, east

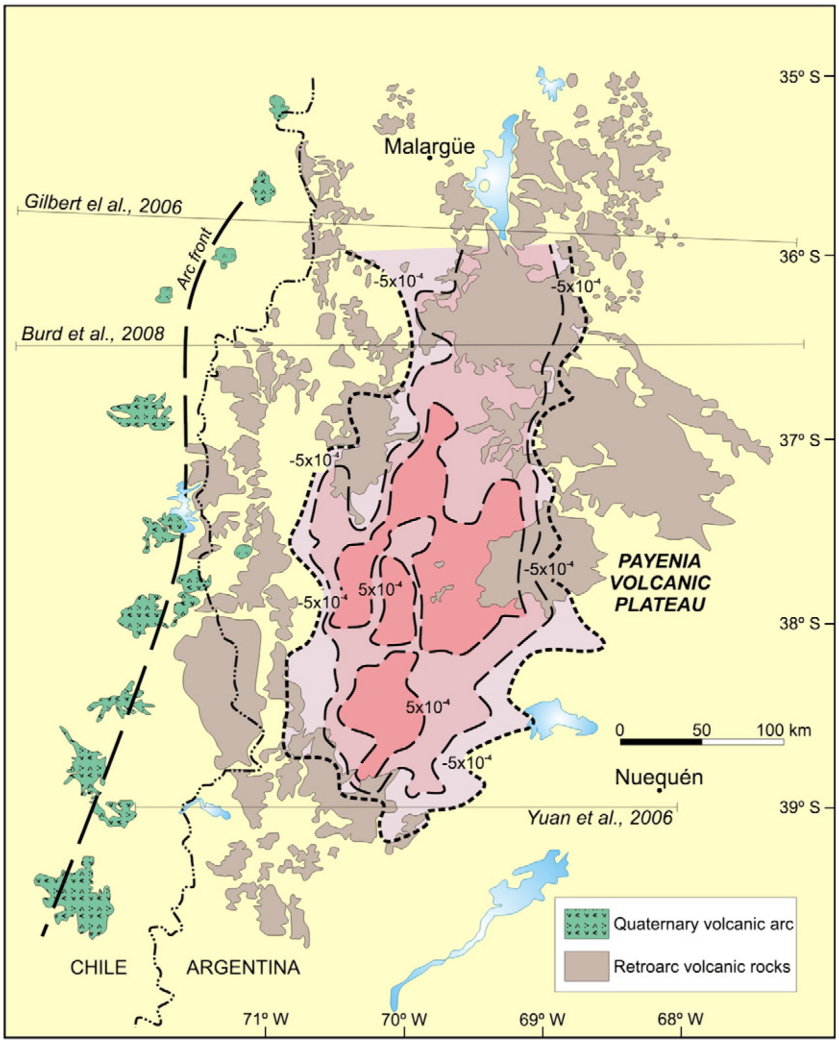

Fig. 7. Residual gravity anomalies in the retroarc zone between 36° and 39°S (after Folguera et al., 2008). The positive values are interpreted as related to the upwardly deflected density crustal structure produced by lithospheric stretching. Isocontours are expressed in miligals. Note location of geophysical surveys displayed in Fig. 6.

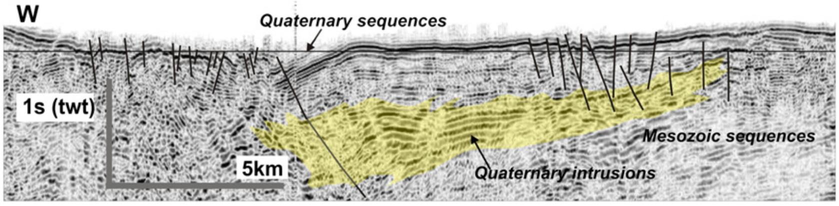

Fig. 8. Extensional deformation, associated roll over structure and Quaternary half-graben in the Tromen volcanic field from 2D seismic line (modified from Folguera et al., 2008). These structures are controlling the eruption of the western Tromen volcanic field.

of the Sierra de Chachahuén, where a fault uplifts the Neocomian limestones more than 1 km above the regional basin level. On the other hand, the topographic elevation model clearly shows that heights like the Cerro Nevado (3980 m a.s.l.), Payún Matru (3691 m), and Auca Mahuida (2253 m), besides the volcanic edifices, have their bases built on an uplifted basement block where the Late Miocene peneplain can be reconstructed (González Díaz, 1972a).

This basement uplift was collapsed during Quaternary times when several normal faults were developed as described in detail by Polanski (1963) and Folguera et al. (2008). The new geochronological data constrain the timing of this collapse. A large basaltic plateau was formed during the latest Pliocene and Early Pleistocene. The existing data shows that oldest basalt flows are in the Auca Mahuida field from 2.03 ± 0.03 Ma to 1.78 ± 0.06 *Ma, and in the Tromen plateau from 2.0 ± 0.06 Ma, persisting up to 1.8 ± 0.5 Ma and 1.6 ± 0.2 Ma (see Fig. 5). At the central segment the old plateau lavas are preserved northwest of the Payún Matru with a 1.7 ± 0.02 Ma age in a remnant broken by normal faults (Fig. 4). At the Cerro Nevado volcanic field the plateau lavas have 1.828 ± 0.028 Ma (Fig. 4). Further north in the northern segment, the basalts of Cerro Puntano (1.780 ± 0.11 Ma) are the only evidence of this age as the plateau was not developed there.

This plateau formed from south to north, and the best evidence of its collapse is derived from the Tromen plateau (Fig. 8). There, north of the Lago Huaraco, about 12 km west of Barrancas, 1.8 to 1.6 Ma plateau basalts are affected by normal faults (Fig. 5), which are covered by undeformed basalts of 0.8 ± 0.1 Ma (Folguera et al., 2009).

Further north in the Cerro Nevado field, the timing of the collapse can be identified in two discrete episodes. Bermúdez (1991) identified the first evidence of structures that affect the 1.83 Ma plateau, represented by northwest-trending normal faults where the Mancha Jarilla volcano and other similar cones were emplaced (Fig. 4). Two new ages constrained these cones between 1.044 and 1.022 Ma (Quidelleur et al., 2009). The second episode is related to extension along the main Late Miocene thrust that bounded the San Rafael Block, with monogenetic centers developed between 0.810 and 0.944 Ma (Fig. 3).

West of the Cerro Nevado volcanic field, the Río Grande foreland basin records minor normal faults at the subsurface of the Lago Llancanelo area (Fig. 9) where the Late Miocene and Pliocene deposits are accumulated. The Tertiary deposits are affected by extensional deformation beneath the Nihuil and Llancanelo lows, close to the western edge of the San Rafael Block, where field studies have identified normal faults.

This extensional deformation is also controlling the eruption of monogenetic basaltic centers in the Llancanelo volcanic field, where Risso et al. (2008) already described the tectonic control.

The extension localized at the northern segment, along the eastern margin of the San Rafael Block, migrated also to the west from 0.9 to 0.7 Ma. A series of monogenetic cones installed since 0.500–0.435 Ma in the Main Andean foothills and along NW-trending faults with an extensional component (Fig. 3). At this stage the large Diamante Caldera collapsed between 0.470 ± 0.07 Ma and 0.440 ± 0.08 Ma (Stern et al., 1984), where the resurgent Maipo Volcano was later emplaced.

The structural evolution described above indicates that after the Late Miocene uplift of the San Rafael Block an extensional deformation started around 1.0 Ma, migrated to the east from 0.9 to 0.7, and finally retreated to the old orogenic front associated to caldera formation. The extension still persists in a series of very recent centers as the ones located along the Río Salado valley and widespread through the entire region. The Tromen volcanic center located in the foothills is still active as signaled by Havestadt (1752).

Based on the very low initial ^{87}Sr/^{86}Sr ratios of the basaltic products of the southern part of Payenia, even lower than the present volcanic arc in the SVZ, Ramos and Barbieri (1988) proposed that these ratios could be explained by the young age of the oceanic slab being subducted at these latitudes. However Stern et al. (1990) demonstrated using a larger data set that these basalts are the result of hot asthenosphere sources mixed with volatiles derived from the oceanic slab. This fact was interpreted by Kay et al. (2006) as the injection of hot asthenosphere during the steepening of the subducted slab and the limited interaction with the asthenospheric wedge in a backarc–intraplate setting. Some authors have also agreed that the arc signature of the Pliocene–Pleistocene can have been caused by slab fluids added to the mantle wedge at the time of subhorizontal subduction of the Nazca plate in the late Miocene (Bertotto et al., 2006a,b).

The petrological characteristics of the basalts, the distribution in time and space, together with the structural evolution are coherent with the hypothesis of a steepening of the oceanic slab (Fig. 10) at these latitudes (Folguera et al., 2006; Kay et al., 2006, Ramos and Kay, 2006).

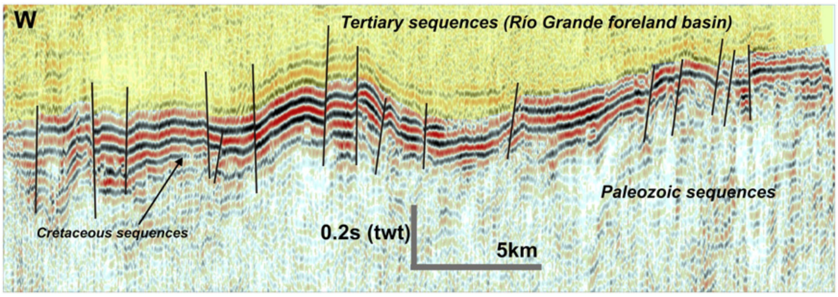

Fig. 9. Extensional deformation affecting Mesozoic to Tertiary deposits in the Río Grande foreland basin near Llancanelo depocenter as registered in a 2D seismic line (see location in Fig. 2).

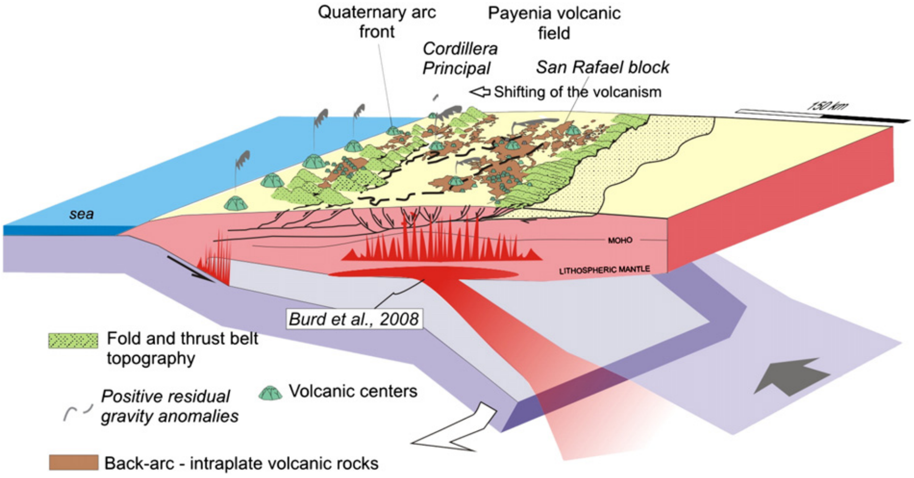

Fig. 10. Proposed model for the evolution of the Payenia volcanic province related to a steepening of the subducted slab and injection of hot asthenosphere, responsible for the extensional deformation and shifting of the volcanism toward the trench (modified from Ramos and Folguera, 2005). Near trench Benioff zone geometry after Bohm et al. (2002).

5. Concluding remarks

Research performed in the calcalkaline volcanic rocks of the Cerro Nevado and Chachahuén volcanic field demonstrated that subduction related arc rocks were formed as far as 500 km away from the present oceanic trench (Bermúdez, 1991; Kay et al., 2006). Subsequent studies demonstrated that similar rocks were formed along a belt parallel to the San Rafael Block, which represents the Middle to Late Miocene volcanic arc associated with an important period of deformation, crustal thickening, expansion and migration of the volcanic arc (Litvak et al., 2008).

The subsequent extension, evidenced by normal faulting of the Late Miocene uplifted peneplain of the San Rafael Block (Folguera et al., 2007a, b, 2009), and the consequent basaltic volcanism of Quaternary age are associated with steepening of the subducted slab (Ramos and Folguera, 2005). The time of the migration of the volcanic arc (Ramos and Kay, 2006), as well as the development of the Payenia basaltic province, is constrained by new geochronological data between 18 and 6 Ma, and 2 Ma and the present, respectively. The present analyses of the structural evolution and the basaltic activity permitted to reconstruct the back and forward displacement of the magmatic activity.

Both the geological and geophysical evidence point out to the existence of extensional deformation systematically developed at the areas of crustal attenuation and subcrustal low velocity zones described above. This attenuation is associated with an abnormal hot asthenosphere beneath the Payenia volcanic province. The asthenospheric flow, presently concentrated beneath the Payún Matru caldera, is associated with the steepening of the oceanic slab as depicted in Fig. 10. The area concentrates the volumetrically most important activity erupted in the last 200,000 years, and lasting to historical times.

The Quaternary eruptions of monogenetic basaltic fields, polygenetic volcanoes and caldera complexes that produced the basaltic rocks of the Payenia volcanic province are also associated in time and space with the Quaternary melting of the lower crust beneath the Cordillera Principal as proposed by Hildreth et al. (1984). This crustal delamination process is expressed by abundant rhyolites, ignimbritic flows, and caldera formation along the main volcanic arc during the Pleistocene.

Acknowledgements

Field work and logistics of the present study were financially supported by grants Ubacyt x182 and CONICET PIP 112/200801-00016. The authors kindly acknowledge the members of Laboratorio de Tectónica Andina for critical comments and support, as well as to Dr. Eduardo Llambías and an anonymous reviewer for the constructive comments.

References

Bermúdez, A., 1985. Los basaltos post pliocenos entre los 38° y 39° de latitud sur. Provincia de Mendoza. Argentina: 4° Congreso Geológico Chileno (Antofagasta), Actas, vol. 3, pp. 52–67.

Bermúdez, A., 1987. Basaltos alcalinos terciarios en la Sierra de Palauco, Mendoza, Argentina: Simposio Internacional sobre Vulcanismo Andino, X|° Congreso Geológico Argentino (Tucumán), Actas, vol. 4, pp. 238–242.

Bermúdez, A., 1991. Sierra del Nevado. El límite oriental del arco volcánico neógeno entre los 35°30' y 36° L.S. Argentina: 6° Congreso Geológico Chileno (Santiago), Actas, vol. 1, pp. 318–322.

Bermúdez, A., Delpino, D., 1990. La provincia basáltica andino cuyana. Revista de la Asociación Geológica Argentina 44 (1-4), 35–55 (1989).

Bermúdez, A., Delpino, D., Frey, F., Saal, A., 1993. Los basaltos de retroarco extraandinos. In: Ramos, V.A. (Ed.), Geología y Recursos Naturales de Mendoza, 12° Congreso Geológico Argentino and 2° Congreso de Exploración de Hidrocarburos, Relatorio. Asociación Geológica Argentina, Buenos Aires, pp. 161–172.

Bertotto, G.W., 2000. Cerro Agua Poca, un cono basáltico cuaternario portador de xenolitos ultramáficos, en el oeste de la provincia de La Pampa, Argentina. Revista de la Asociación Geológica Argentina 55 (1–2), 59–71.

Bertotto, G.W., 2002. Cerro Huanul (37°170S; 68°320O), nueva localidad con xenolitos ultramáficos en basanitas cenozoicas del sur de Mendoza: 15°Congreso Geológico Argentino (El Calafate), Actas, vol. 3, pp. 66–70.

Bertotto, G.W., Cingolani, C., Berg, E., 2006a. Hawaiian and Strombolian style monogenetic volcanism in the extra-Andean domain of central-west Argentina. Journal of Volcanology and Geothermal Research 158, 430–444.

Bertotto, G.W., Orihashi, Y., Nagao, K., Motoki, A., 2006b. New K–Ar ages on retroarc basalts of Mendoza-La Pampa. Segundo Encuentro Científico del ICES Noviembre 2006, Buenos Aires.

Bertotto, G.W., Cingolani, C., Berg, E., 2009. Geochemical variations in Cenozoic back-arc basalts at the border of La Pampa and Mendoza provinces, Argentina. Journal of South American Earth Sciences 28 (4), 360–373.

Bettini, F.H., Pombo, R.A., Mombrú, C.A., Uliana, M.A., 1979. Consideraciones sobre el diastrofismo andino en la vertiente oriental de la Cordillera Principal, entre los 34°30′ y los 37° Lat. Sur. : 7° Congreso Geológico Argentino (Neuquén, 1978), Actas, vol. 1. Asociación Geológica Argentina, Buenos Aires, pp. 161–172.

Bohm, M., Lüth, S., Echtler, H., Asch, G., Bataille, K., Bruhn, C., Rietbrock, A., Wigger, P., 2002. The Southern Andes between 36° and 40°S latitude: seismicity and average seismic velocities. Tectonophysics 356, 275–289.

Brasse, H., Soyer, W., 2001. A magnetoteluric study in the Southern Chilean Andes. Geophysical Research Letters 28 (19), 3757–3760.

Burd, A., Booker, J.R., Pomposiello, M.C., Favetto, A., Larsen, J., Giordanengo, G., Orozco Bernal, L., 2008. Electrical conductivity beneath the Payún Matrú volcanic field in the Andean back-arc of Argentina near 36.5°S: insights into the magma source. 7th. International Symposium on Andean Geodynamics (Nice), Extended Abstracts, pp. 90–93.

Cortés, J.M., 2000. Fallas cuaternarias oblicuas al frente montañoso en la Cordillera Frontal de Mendoza (34°-34°30'S). Revista Cuaternario y Ciencias Ambientales: Publicación Especial, 4, pp. 57–62.

Cortés, J.M., Sruoga, P., 1998. Zonas de fractura cuaternarias y volcanismo asociado en el piedemonte de la Cordillera Frontal (34°30′LS), Argentina: 10° Congreso

Latinoamericano de Geología y 6° Congreso Iberoamericano de Geología Económica, Actas, 2, pp. 116–121.

Costa, C.H., Cisneros, H., Salvarredi, J., Gallucci, A., 2004. La neotectónica del margen oriental del bloque de San Rafael: Nuevas consideraciones: 12° Reunión sobre Microtectónica y Geología Estructural (Cafayate), Asociación Geológica Argentina, Serie D, Publicación Especial, 9, pp. 33–40.

Diez Rodríguez, A., Introcaso, A., 1986. Perfil transcontinental sudamericano en el paralelo 39°S. Geoacta 13 (2), 179–201.

Folguera, A., Zárate, M., 2009. La sedimentación neógena continental en el sector extrandino de Argentina central. Revista de la Asociación Geológica Argentina 64 (4), 692–712.

Folguera, A., Zapata, T., Ramos, V.A., 2006. Late Cenozoic Extension and the evolution of the Neuquén Andes. In: Kay, S.M., Ramos, V.A. (Eds.), Late Cretaceous to Recent magmatism and tectonism of the Southern Andean margin at the latitude of the Neuquen basin (36–39°S): Geological Society of America, Special Paper, 407, pp. 267–285.

Folguera, A., Bottesi, G., Zapata, T., Ramos, V.A., 2008. Crustal collapse in the Andean back-arc since 2 Ma: Tromen volcanic plateau, Southern Central Andes (36°40′–37°30′S). Tectonophysics (Special Issue Andean Geodynamics) 459, 140–160.

Folguera, A., Introcaso, A., Giménez, M., Ruiz, F., Martinez, P., Tunstall, C., García Morabito, E., Ramos, V.A., 2007a. Crustal attenuation in the Southern Andean retroarc (38°–39°30′ S) determined from tectonic and gravimetric studies: the Lonco–Luán asthenospheric anomaly. Tectonophysics 439, 129–147.

Folguera, A., Alasonati Tasarova, S., Hese, F., Hackney, R., Gotze, H., Schmidt, S., Ramos, V.A., 2007c. Crustal attenuation along the Andean retroarc zone 36°–39°S from gravimetric análisis. Latinoamerican Symposium 2007 Kiel, Abstracts, pp. 38–41.

Folguera, A., Ramos, V.A., Zapata, T., Spagnuolo, M.G., 2007b. Andean evolution at the Guañacos and Chos Malal fold and thrust belts (36°30′–37°S). Journal of Geodynamics 44, 129–148.

Folguera, A., Naranjo, J.A., Orihashi, Y., Sumino, H., Nagao, K., Polanco, E., Ramos, V.A., 2009. Retroarc volcanism in the northern San Rafael block (34°–35°30′S), southern Central Andes: occurrence, age, and tectonic setting. Journal of Volcanology and Geothermal Research 186, 169–185.

Fuentes, F., Ramos, V.A., 2008. Geología y estructura del Cerro Guanaquero, Alto río Diamante, Provincia de Mendoza. Revista de la Asociación Geológica Argentina 63 (1), 84–96.

Galland, O., Hallot, E., Cobbold, R., Ruffet, G., Brémond d'Ars, J., 2005. Coeval volcanic activity and tectonic shortening, Tromen volcano, Neuquén province, Argentina. VI° International Symposium on Andean Geodynamics, Extended Abstracts, pp. 293–296.

Galland, O., Hallot, E., Cobbold, P., Ruffet, G., Galland, O., Hallot, E., Cobbold, P., Ruffet, G., d'Ars, J., 2007. Volcanism in a compressional Andean setting: a structural and geochronological study of Tromen volcano (Neuquén province, Argentina). Tectonics 26, TC4010. doi:10.1029/2006TC002011.

Germa, A., Quidelleur, X., Gillot, P.Y., Tchilinguirian, P., 2010. Volcanic evolution of the backarc Pleistocene Payun Matru Volcanic Field (Argentina). Journal of South American Earth Sciences 29 (3), 717–730.

Giampaoli, P., Dajczgewand, D.M., 2005. Faja plegada y corrida de Malargüe: la estructura a la latitud del río Salado. Boletín de Informaciones Petroleras 1 (1), 6–17.

Gilbert, H., Beck, S., Zandt, G., 2006. Lithospheric and upper mantle structure of central Chile and Argentina. Geophysical Journal International 165 (1), 383. doi:10.1111/j.1365-246X.2006.02867.x.

González Díaz, E.F., 1972a. Descripción geológica de la Hoja 27d San Rafael, Provincia de Mendoza: Servicio Nacional Minero Geológico, Boletín, 132, pp. 1–127. Buenos Aires.

González Díaz, E.F., 1972b. Descripción geológica de la Hoja 30d Payún-Matrú, Provincia de Mendoza. : Dirección Nacional de Geología y Minería, Boletín, 130. Dirección Nacional de Geología y Minería, Buenos Aires, pp. 1–88.

González Díaz, E.F., Fauqué, L.E., 1993. Geomorfología. In: Ramos, V.A. (Ed.), Geología y Recursos Naturales de Mendoza, 12° Congreso Geológico Argentino and 2° Congreso de Exploración de Hidrocarburos, Relatorio. Asociación Geológica Argentina, Buenos Aires, pp. 1–88.

Havestadt, B., 1752. Mapa geográfico y diario del Padre Bernardo Havestadt (itinerario). En el cual se detallan las provincias, ciudades, sitios, días y leguas que en los últimos meses del año 1751 y primeros meses del año 1752 recorrió, viajando por los dominios de los indios chilenos, el padre Bernardo Havestadt, misionero de la Compañía de Jesús. (Available at http://es.wikisource.org/wiki/ Memorias_de_Bernardo_Havestadt).

Hildreth, W., Grunder, A., Drake, R., 1984. The Loma Seca Tuff and the Calabozos Caldera: a major ash-flow and caldera complex in southern Andes of central Chile. The Geological Society of America 95 (1), 45–54.

Holmberg, E., 1964. Descripción geológica de la Hoja 33d, Auca Mahuida, Provincia del Neuquén, Boletín, 94. Dirección Nacional de Geología y Minería, Buenos Aires, pp. 1–88.

Jordan, T., Isacks, B., Ramos, V.A., Allmendinger, R.W., 1983. Mountain building model: the Central Andes. Episodes 1983 (3), 20–26.

Kay, S.M., Gorring, M., Ramos, V.A., 2004. Magmatic sources, setting and causes of Eocene to Recent Patagonian plateau magmatism (36°S to 52°S latitude). Revista Asociación Geologica Argentina 59 (4), 556–568.

Kay, S.M., Burns, M., Copeland, P., 2006. Upper Cretaceous to Holocene magmatism and evidence for transient Miocene shallowing of the Andean subduction zone under the northern Neuquén Basin. In: Kay, S.M., Ramos, V.A. (Eds.), Evolution of an Andean Margin: A tectonic and magmatic view from the Andes to the Neuquén Basin (35–39°S): Geological Society of America, Special Paper, 407, pp. 19–60.

Kozlowski, E., Manceda, R., Ramos, V.A., 1993. Estructura. In: Ramos, V.A. (Ed.), Geología y Recursos Naturales de Mendoza, 12° Congreso Geológico Argentino and 2° Congreso de Exploración de Hidrocarburos, Relatorio. Asociación Geológica Argentina, Buenos Aires, pp. 235–256.

Linares, E., González, R.R., 1990. Catálogo de edades radimétricas de la República Argentina 1957–1987. Asociación Geológica Argentina, Publicaciones Especiales Serie B, Didáctica y Complementaria 19, 1–628.

Llambías, E.J., 1966. Geología y petrología del volcán Payún Matrú, Mendoza. Acta Geológica Lilloana 7, 265–310.

Litvak, V., Folguera, A., Ramos, V.A., 2008. Determination of an arc-related signature in Late Miocene volcanism over the San Rafael Block, Southern Central Andres (34°30″–37°) Argentina: the Payenia shallow subduction zone. 7° International Symposium on Andean Geodynamics, Niza, Extended abstracts, pp. 289–291.

Marchetti, D.W., Cerling, T.E., Evenson, E.B., Gosse, J.C., Martínez, O., 2006. Cosmogenic exposures ages of lava flows that temporarily dammed the Río Grande and Río Salado, Medoza Province, Argentina. Backbone of the Americas, Patagonia to Alaska, Asociación Geológica Argentina, Serie D, 9, p. 66.

Martínez, A., 2005. El volcanismo del Choiyoi en la región del Manzano Histórico, Tunuyán, Mendoza. Ph.D. Thesis, Universidad de Buenos Aires (unpublished), 274 pp., Buenos Aires.

Melchor, R.N., Casadío, S., 1999. Hoja Geológica 3766-III, La Reforma, Provincia de La Pampa. Servicio Geológico Minero Argentino, Boletín, 295. Servicio Geológico Minero Argentino, Buenos Aires, p. 73.

Miranda, F., Folguera, A., Leal, P., Naranjo, J., Pesce, A., 2006. Neogene deformation in the retroarc area (36°30′–38°S) based on the study of Upper Pliocene–Lower Pleistocene volcanic complexes of the Southern Central Andes of Argentina. In: Kay, S.M., Ramos, V.A. (Eds.), Evolution of an Andean Margin: a tectonic and magmatic view from the Andes to the Neuquén Basin (35–39°S): Geological Society of America, Special Paper, 407, pp. 287–298.

Naranjo, J., Lara, L., Mazzoni, M., 1997. Late Quaternary monogenetic volcanoes along Río Salado, Southwest Mendoza Province. Acta Geologica Hispánica 32, 113–122.

Németh, K., Risso, C., Nullo, F.E., Smith, I.E.M., 2009. Silicic pumiceous tuff ring of Los Loros in Mendoza (Argentina). IAVCEI–CVS–IAS, 3° International Maar Conference (Malargüe), Abstracts. 2 pp.

Núñez, E., 1979. Descripción geológica de la hoja 28d Estación Soitué, provincia de Mendoza: Servicio Geológico Nacional, Boletín, 166, pp. 1–67. Buenos Aires.

Pacino, M., 1997. The Andean elevation in Argentina–Chile at 39°S from gravity data. Geoacta 22, 91–102.

Pasquare, G., Bistacchi, A., Francalanci, L., Bertotto, G.W., Boari, E., Massironi, M., Rossotti, A., 2008. Very long pahoehoe inflated basaltic lava flows in the Payenia volcanic province (Mendoza and la Pampa, Argentina). Revista de la Asociación Geológica Argentina 63 (1), 131–149.

Polanski, J., 1954. Rasgos geomorfológicos del territorio de la provincia de Mendoza. : Ministerio Economía, Instituto Investigaciones económicas y tecnológicas, Cuadernos de investigaciones y estudios, 4. Ministerio de Economía del Gobierno de Mendoza, Mendoza, pp. 4–10.

Polanski, J., 1963. Estratigrafía, neotectónica y geomorfología del Pleistoceno pedemontano, entre los ríos Diamante y Mendoza. Revista. Asociación Geologica Argentina 17 (3-4), 127–349 (1962).

Quidelleur, X., Carlut, J., Tchilinguirian, P., Germa, A., Gillot, P.Y., 2009. Paleomagnetic directions from mid-latitude sites in the southern hemisphere (Argentina): contribution to time averaged field models. Physics of the Earth and Planetary Interiors 172, 199–209.

Ramos, V.A., Barbieri, M., 1988. El volcanismo Cenozoico de Huantraico: edad y relaciones isotópicas iniciales, provincia del Neuquen. Revista de la Asociación Geológica Argentina 43 (2), 210–223.

Ramos, V.A., Folguera, A., 2005. Tectonic evolution of the Andes of Neuquén: constraints derived from the magmatic arc and foreland deformation. In: Veiga, G., et al. (Ed.), The Neuquén Basin: a case study in sequence stratigraphy and basin dynamics: The Geological Society, Special Publication, 252, pp. 15–35.

Ramos, V.A., Kay, S.M., 2006. Overview of the tectonic evolution of the Southern Central Andes of Mendoza and Neuquén (35°–39°S latitude). In: Kay, S.M., Ramos, V.A. (Eds.), Evolution of an Andean Margin: a tectonic and magmatic view from the Andes to the Neuquén Basin (35–39°S): Geological Society of America, Special Paper, 407, pp. 1–18.

Risso, C., Németh, K., Combina, A.M., Nullo, F., Drosina, M., 2008. The role of phreatomagmatism in a Plio–Pleistocene high-density scoria cone field: Llancanelo Volcanic Field (Mendoza), Argentina. Journal of Volcanology and Geothermal Research 169, 61–86.

Risso, C., Németh, K., Nullo, F., 2009. Field Guide to Payún Matru and Llancanelo volcanic fields, Malargüe - Mendoza. 3IMC. 3° International Maar Conference (Malargüe), 28 pp.

Rossello, E.A., Cobbold, P.R., Diraison, M., Arnaud, N., 2002. Auca Mahuida (Neuquén Basin, Argentina): a Quaternary shield volcano on a hydrocarbon-producing substrate. 5th International Symposium on Andean Geodynamics (Toulouse), Extended Abstracts, pp. 549–552.

Sruoga, P., Llambías, E.J., Fauqué, L., Schonwandt, D., Repol, D.G., 1998. Volcanological and geochemical evolution of the Diamante Caldera–Maipo volcano complex in the southern Andes of Argentina (34°10′S). Journal of South American Earth Sciences 19 (4), 399–414.

Stern, C.R., Amini, H., Charrier, R., Godoy, E., Hervé, F., Varela, J., 1984. Petrochemistry and age of rhyolitic pyroclastic flows which occur along the drainage valleys of the río Maipo and río Cachapoal (Chile) and the río Yaucha and río Papagayos (Argentina). Revista Geologica de Chile 23, 39–52.

Stern, Ch.R., Frey, F.A., Zartman, R.E., Peng, Z., Kyser, T.K., 1990. Trace element and Sr, Nd, Pb and O isotopic composition of Pliocene and Quaternary alkalic basalts of the Patagonian Plateau lavas of southernmost South America. Contributions to Mineralogy and Petrology 104 (94), 308.

Stern, C.R., 2004. Active Andean volcanism: its geologic and tectonic setting. Revista Geologica de Chile 31, 161–208.

Tasarova, Z., 2004. Gravity data analysis and interdisciplinary 3-D modelling of a convergent plate margin (Chile, 36–42°S). Dissertation, FB Geowissenschaften, FU Berlin, http://www.diss.fu-berlin.de/2005/19/.

Violante, R., Osella, A., Vega, M., de la Rovere, E., Osterrieth, M., 2010. Paleoenvironmental reconstruction in the western lacustrine plain of Llancanelo Lake, Mendoza, Argentina. Journal of South American Earth Sciences 29 (3), 650–664.

Wagner, L., Beck, S., Zandt, G., 2005. Upper mantle structure in the south central Chilean subduction zone (30° to 36°S). Journal of Geophysical Research 110, B01308. doi:10.1029/2004JB003238.

Yuan, X., Asch, G., Bataile, K., Bohm, M., Echtler, H., Kind, R., Onchen, O., Wölbern, I., 2006. Deep seismic images of the Southern Andes. In: Kay, S.M., Ramos, V.A. (Eds.), Late Cretaceous to recent magmatism and tectonism of the Southern Andean Margin at the latitude of the Neuquen Basin (36–39°S): Geological Society of America, Special Paper, 407, pp. 61–72.