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Geochronology of the late Pliocene to recent volcanic activity in the Payenia back-arc volcanic province, Mendoza Argentina

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ABSTRACT

Eighteen samples originating from monogenetic cones and larger complexes in the back-arc Payenia volcanic province, in Mendoza Argentina, have been dated by the $^{40}Ar/^{39}Ar$ method. Groundmass and plagioclase separates give plateau ages, ranging from 20.7 ± 0.5 to 0.06 ± 0.02 Ma. Payenia has been divided into six subfields based on the new and literature radiometric ages: Payún Matrú, Río Colorado, Llancanelo, and Nevado volcanic fields, the Northern segment and the Andes retro-arc group. Fifteen samples are younger than 2.83 Ma and show correlation between geographic position and age. Eruption centres younger than 0.5 Ma are concentrated to the west of 69° W with few exceptions among new and literature data. This westward shift of activity supports the rollback theory for the subducting Nazca plate since the late Pliocene. Furthermore, a northward progression of volcanism on the San Rafael block from 2.8 Ma to around 0.5 Ma is recognized. We conclude that rollback was initiated in the southern part of Payenia in the early Pliocene and progressed >200 km northwards during the Pliocene-Pleistocene period creating conditions for hydrous magma generation beneath the eastern part of Payenia. The long lived activity of the Payún Matrú complex is ascribed to the presence of a thermal anomaly in the underlying asthenosphere which could be plume-like.

1. Introduction

The volcanic development of the 60,000 km^2 Payenia back-arc province in Argentina has been suggested to be linked to the differential movements of the subducting Nazca plate and the overriding South American plate (e.g. Muñoz et al., 1989; Kay et al., 2006a; Mazzarini et al., 2008; Folguera et al., 2009; Ramos and Folguera, 2011). However, any detailed correlation of volcanism with crustal tectonic evolution and changes in lithosphere–asthenosphere relations depends on the characterization in time of volcanism. We present new ^{40}Ar–^{39}Ar age information from volcanic rocks of Payenia and model the evolution since the late Pliocene. The volcanic activity in the back-arc of the transitional southern volcanic zone of South America (34°34′S–37°25′S) is an example of a back-arc volcanism in a continental setting. The area lies east of the main Andean Cordillera in the Argentinean provinces of Mendoza, Neuquén and La Pampa. The volcanic activity of interest is the most recent, the Payenia volcanic province (Polanski, 1954; Munoz and Stern, 1988; Bermúdez et al., 1993; Søager et al., in prep.). The volcanic province was named the Andino-Cuyana Basaltic Province by Bermúdez et al. (1989). The name Payenia volcanic province, given to the area by Polanski (1954), has been used in more recent papers (e.g. Germa et al., 2010; Kay et al., 2006a; Ramos and Folguera, 2011; Ramos and Kay, 2006) and will be used here. According to e.g. Bermúdez (1988) the activity in Payenia is concentrated in two volcanic fields, the Llancanelo volcanic field and the Payún Matrú volcanic field (Fig. 1). The activity in the area is represented by large composite volcanoes such as Payún Matrú, Payún Liso and Cerro Nevado that have produced evolved volcanic material including the large caldera forming eruptions of Payún Matrú (Llambías, 1966; Bermúdez, 1988; Ramos and Kay, 2006; Folguera et al., 2009; Germa et al., 2010). Surrounding the larger volcanoes there is a field of monogenetic scoria cones of almost exclusively basaltic composition often aligned and concentrated in small clusters (Fig. 1). The number of monogenetic vents is not known precisely but most likely amounts to more than 800 eruption centres (Inbar and Risso, 2001; Risso et al., 2008).

Volcanism in Payenia encompasses activity onwards from the Miocene (Kay and Copeland, 2006; Lambías et al., 2010; this paper). Detailed radiometric age studies were few up until a few

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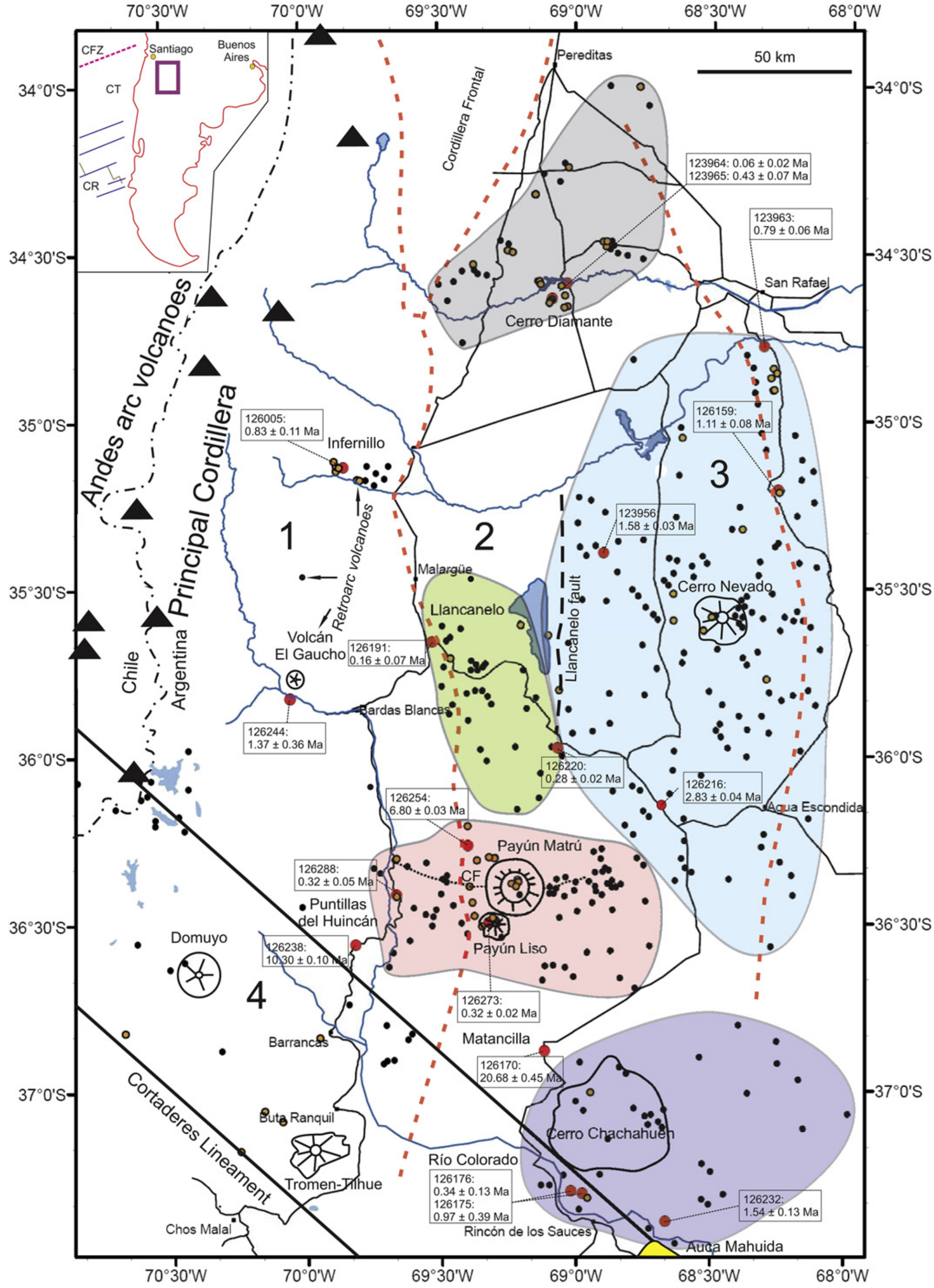

Fig. 1. Map of the Payenia volcanic province. Red dots - Location of new age determinations, small orange dots – literature age determinations, black dots - volcanic cones (mainly from Llambías et al., 2010), triangles – Andes arc volcanoes. The volcanic fields are: green - Llancanelo, pink - Payún Matrú, lavender – Río Colorado, light blue – Nevado, grey – Northern Segment; also indicated is the Andes Retroarc. Orange dashed lines outline the major thrust fronts. Numbers refer to the main structural elements: 1) Malargüe fold and thrust belt (from the western thrust front to the Principal Cordillera), 2) Río Grande foreland basin (between the western thrust front and the Llancanelo fault, 3) San Rafael block (between the Llancanelo fault and the eastern thrust front), 4) Tromen–Domuyo belt (between the two black lines of which the lower coincides with the Cortaderas Lineament). Dotted line marked CF is the Carbonilla fault at Payún Matrú. The inset shows the location of the studied area in South America; CR is the Chile Ridge, CFZ the Challenger fracture zone, and CT the Chile trench. Data sources: this work, Kay et al. (2006a), Folguera et al. (2009), Germa et al. (2010) Quidelleur et al., 2009, and Españon (2010). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

years ago. Recent papers have published ages from different segments of the province (Folguera et al., 2009; Germa et al., 2010; Kay et al., 2006a, 2006b; Quidelleur et al., 2009). We present 18 new radiometric ages obtained by the $^{40}Ar/^{39}Ar$ method on rocks from the whole volcanic province with special focus on spatial and temporal trends in the volcanic activity for the last ~3 Ma. The Miocene samples are presented but this early part of Payenia volcanism is not discussed in this paper. Together with the existing radiometric age data from Payenia, we will assess the geochronology of Payenia and present a model for the volcanic evolution of Payenia in relation to plate tectonic and asthenospheric processes.

2. Geological setting

The volcanism in the Transitional Southern Volcanic Zone of the Andes (TSVZ) at 34.5–37° S west of Payenia is a manifestation of subduction of the Nazca plate under the South American continent. The convergence rate of the Nazca and the South American plates is about 85 mm/yr and the Nazca plate subducts to the east under the SVZ inclined at c. 30° and with seismicity on average at depths of 90–100 km under the volcanic arc (Yañez et al., 2002). North of the SVZ, volcanism is absent in the Andes over the Pampean/Chile flat-slab segment at 26–33° S (Yañez et al., 2002; Stern et al., 2007). South of the studied area, marking the southern limit of the TSVZ, is an NW-trending structural basement discontinuity called the Cortaderas lineament, reaching into the Andean cordillera (Cobbold and Rossello, 2003; Ramos, 1981; Ramos and Barbieri, 1988). The lineament is marked by the Tromen–Domuyo belt of volcanism including the Auca Mahuida volcanic field south of Río Colorado (Llambías et al., 2010) (Fig. 1). North of this lineament Cenozoic volcanism occurs in the far back-arc whereas to the south of it, volcanism has been nearly absent during the Cenozoic. The Cortaderas lineament also marks the southern limit of the Miocene shallow subduction zone and therefore this change in subduction angle is partly responsible for the back-arc magmatic activity (Ramos and Kay, 2006).

In the study area north of the Cortaderas lineament (between 34° S and 37.30° S), Fig. 1, the main morphological features from west to east are the principal cordillera, the Malargüe Fold and Thrust Belt (Malargüe FTB), the Río Grande foreland basin, the San Rafael basement block and the Pliocene to Holocene volcanoes of the Payenia Volcanic Province (Ramos and Kay, 2006; Llambías et al., 2010). The tectonic evolution of the back-arc area is a history of compression and extension controlled by the interaction of the subducting and overriding plate (Ramos and Kay, 2006; Folguera et al., 2011). In the late Oligocene the subduction of the Nazca plate was initiated, and trench rollback in general caused extension in the back-arc (Kay and Copeland, 2006). Volcanic rocks found in the back-arc from this period are from the Matancilla area south and south east of Payún Matrú (Fig. 1) (Kay and Copeland, 2006). These early Miocene volcanic rocks have been assigned to the Palauco formation (González Díaz, 1979). During the middle to late Miocene the subduction regime changed to a more shallow subduction, initiating the advance of deformation of the Malargüe FTB and forming a broader volcanic arc (Giambiagi et al., 2008; Ramos and Kay, 2006). Uplift of the Sierra de Chachahuén and the San Rafael block and the arc like signature of volcanic rocks found in these regions are indicators of the shallow subduction zone (Kay et al., 2006b; Ramos and Kay, 2006; Litvak et al., 2008; Spagnuolo et al., 2011). The Malargüe FTB had its major thrusting phase between 10.5 and 9 Ma (Giambiagi et al., 2008). Tectonic activity in the Malargüe FTB after 8 Ma was recognized as minor displacements along the Sosneado fault until 1 Ma ago (Giambiagi et al., 2008). Volcanism in the Malargüe FTB was ongoing throughout the whole period of thrusting and folding mainly in two eruptive cycles known as the HuincánI and HuincánII ocurring in the retro-arc zone (Combina and Nullo et al., 2000; Kay et al., 2006a,b; Giambiagi et al., 2008; Spagnuolo et al., 2011). The front-arc-like HuincánII Formation volcanism was contemporaneous with the main thrusting phase of the Malargüe FTB, with activity in the northern part around the Río Salado Valley at 10.5 to 5 Ma and in the southern Malargüe FTB at around 10.3 Ma (Baldauf et al., 1992; Nullo et al., 2006; Giambiagi et al., 2008; this study). In the southernmost part of the Payenia region the subducting slab apparently returned to a steeper path already in the latest Miocene resulting in the end of arc-like magmatism at around 5 Ma in the Chachahúen region (Kay et al., 2006a; Ramos and Kay, 2006). In contrast, the arc-like volcanism on the San Rafael block continued through the Pliocene and early Pleistocene, most extensively in the Cerro Nevado volcano (Søager et al., in prep.). According to Folguera et al. (2008, 2009) and Ramos and Folguera (2011) extension dominated the Payenia back-arc in this period as deduced from fracturing of the San Rafael block and normal faulting along its western limits and formation of the Las Loicas trough in the main Andes. The Río Grande foreland basin runs approximately N–S east of the Malargüe FTB and is limited in the east by the Llancanelo fault. North of Cerro Diamante the Río Grande foreland basin merges with the northern San Rafael block while in the south it fades out south of Payún Matrú. In the basin around 1000 m of continental Cenozoic deposits have been accumulated of which the late Miocene syn-orogenic sediments are the most important (Yrigoyen, 1993, 2000). South of Payún Matrú the volcanoes rest directly on the Mesozoic sediments of the Neuquén basin.

Evidence for the present tectonic setting in the area based on GPS measurements shows an E–W crustal shortening rate of ~ 10 mm a^{-1} at the latitude 36–37 S (Klotz et al., 2001; Wang et al., 2007) which agrees well with evidence for crustal shortening during volcanism in the Tromen and Auca Mahuida volcanoes (Rosello et al., 2002; Cobbold and Rossello, 2003; Galland et al., 2007) and the recent reverse movements in the eastern thrust front of the San Rafael block (Costa et al., 2004, 2006). Initiation of compression has been proposed to be as early as in the early Pleistocene (Mazzarini et al., 2008). However, some authors claim that extension is currently active (e.g. Bermúdez et al., 1993; Folguera et al., 2006, 2009). Since the late Miocene, volcanism in the back-arc of the TSVZ has thus occurred in an area which has been subjected to alternating extension with active subsidence and compression (Bermúdez et al., 1993; Cobbold and Rossello, 2003; Folguera et al., 2006, 2009; Kay, 2001a, 2001b; Kay et al., 2006a; Mazzarini et al., 2008; Ramos and Kay, 2006).

In contrast to the partition into two large volcanic fields proposed by Bermúdez et al. (1993), the Payenia volcanic province is here divided into six subfields as used by Søager et al. (in prep.) and in agreement with the division suggested by Ramos and Folguera (2011) (Fig. 1). The Payún Matrú volcanic field of Bermúdez et al. (1993) is divided into the Payún Matrú volcanic field, including the Payún Matrú volcanic complex, Payún Liso and the cones and flows erupted around these volcanoes, and the Río Colorado volcanic field, including the cones and flows erupted in the Río Colorado valley and the area surrounding the Chachahuén volcano. The Llancanelo volcanic field of Bermúdez et al. (1993) is divided into the Llancanelo volcanic field occurring in the Río Grande foreland basin north of the Payún Matrú volcanic field west of the Llancanelo fault, and the Nevado volcanic field situated on the San Rafael block east of the Llancanelo fault. The northern segment includes the volcanoes north and west of San Rafael, and the last group, the Andes retro-arc group, comprises the volcanoes occurring in the Andean foothills west of the Llancanelo and Payún Matrú volcanic groups.

3. Analytical methods

Eighteen samples were selected for ^{40}Ar/^{39}Ar analysis. These were 17 groundmass separates and 1 plagioclase separate. The samples were collected from lava flows and scoria cones in the Payenia volcanic province. The advantage of analysing the monogenetic eruption centres is that they give insight into the more regional temporal and spatial trends in volcanic activity. Selection criterions for samples included representativity for the volcanic events in an area and that each sample has approximately a pristine state of conservation. For some areas the geology and morphology suggested that volcanism was Holocene and of undetectable age by the ^{40}Ar/^{39}Ar analysis of groundmass, and dating was not attempted. For such occurrences at Infernillo, Los Volcanes, Pampas Negras and Payún Matrú we rely on the published age results from other methods. Analyses of groundmasses were preferred to ensure a high degree of degassing of any inherited argon from the magmas before crystallization of the analysed material.

The selected samples were crushed in a jaw crusher and the material sieved. The 200–300 μm fractions were further processed in a Frantz magnetic separator and by handpicking under binocular microscope. The samples were irradiated in the TRIGA reactor at Oregon State University, Corvallis USA. The flux gradient during irradiation was monitored with the FCT-3 biotite of assumed age 28.03 ± 0.01 Ma (2σ) (Baksi et al., 1996). The samples were analysed by the incremental heating method. The samples were heated in 10–15 steps from 400 or 500 °C–1400 °C with a CO_2 integrated laser. The gasses released were cleaned in Zr–V–Fe and Zr–Al getters before being introduced into the MAP 215-50 mass spectrometer. Each measurement series includes 10 steps of measurements of the isotopes ^{36}Ar, ^{37}Ar, ^{38}Ar, ^{39}Ar and ^{40}Ar. Blanks were measured between every 3 to 4 increments. Along with blank corrections interfering reactions between neutrons and isotopes of Ca, Ka and Cl were corrected for (McDougall and Harrison, 1999). The ArArCALC program (Koppers, 2002) was used to process the data and the initial ^{40}Ar/^{36}Ar ratio assumed as 295.5 (Steiger and Jäger, 1977). Age was calculated for each increment and is presented with uncertainty of 2σ, further analytical and instrumental details for the laboratory have been published by Duncan and Hogan (1994).

All samples yielded a plateau age according to criteria after Fleck et al. (1977), *i.e.* representing at least 50% of the released ^{39}Ar and calculated from at least three adjacent increments and overlapping in age within the uncertainty at the 2σ confidence level. Isochrons from ^{36}Ar/^{40}Ar vs. ^{39}Ar/^{40}Ar indicate ages overlapping with the plateau ages and confirm that the non-radiogenic Ar within error is atmospheric. Total fusion age was calculated from the sum of all increments and weighted according to the amount of released ^{39}Ar. The mean squared weighted deviation (MSWD) was calculated for plateau and isochron ages (Koppers, 2002). The results are presented in Table 1.

4. Geochronological results

Ages calculated from the ^{40}Ar/^{39}Ar analysis of the 18 samples range from 20.68 to 0.06 Ma (Table 1). Examples of age plateaus and inverse isochron diagrams are shown in Fig. 2. The full dataset is available in the online Appendix A. The 3 oldest samples are all from the Middle Miocene Palauco Formation according to the geological map (Narciso et al., 2001) but the obtained ages range from early to late Miocene. The fifteen samples from the Plio-Pleistocene Payenia are from the Llancanelo, Nevado, Payún Matrú, Río Colorado and Andes retro-arc groups and the northern segment, and range in age from 2.83 to 0.06 Ma. In this paper we focus mainly on the development since the Pliocene.

4.1. Río Colorado volcanic field

From the Río Colorado volcanic field three samples from the area around the Río Colorado river were analysed in this study. All samples yielded a Pleistocene age and range from 1.54 ± 0.13 to 0.34 ± 0.13 Ma.

El Águila (126232): 1.54 ± 0.13 Ma. The Río Colorado volcanic field is dominated by monogenetic cones and lava flows. El Águila is from the group of older cones furthest to the east along the river and the age is thought to be representative also of the neighbouring cones, *e.g.* La Yegua.

Cerro Morado (126175): 0.97 ± 0.39 Ma. To the north of the Río Colorado and the town of Rincón de los Sauces is a volcanic plateau with 5 eruption centres. The sample is taken on the western side of the Cerro Morado in a 30 m thick lava flow underlying both the Cerro Morado and Cerro Carne which together form a small polygenetic complex. The apparent age of the sample is of similar age as

Table 1
Results of ^{40}Ar/^{39}Ar analysis of groundmasses and plagioclase from the Payenia volcanic province.

Sample	Location	Plateau age				Isochron age			Total fusion age	Geographical position	
		N/N^{tot}	Age ± 2σ Ma	^{39}Ar (%)	MSWD	Age ± 2σ Ma	^{40}Ar/^{36}Ar	MSWD	Age ± 2σ Ma	°S	°W
Río Colorado volcanic field											
126176	Cerro Carne	8/10	**0.34** ± **0.13**	95.9	2.0	0.32 ± 0.19	296.4 ± 11.9	2.3	0.20 ± 0.28	37 18.647′	68 58.545′
126175	Cerro Morado	11/11	**0.97** ± **0.39**	100	0.4	0.35 ± 0.58	301.8 ± 7.5	0.1	1.09 ± 0.43	37 18.253′	69 01.104′
126232	El Águila	8/10	**1.54** ± **0.13**	90.3	0.9	1.51 ± 0.25	295.8 ± 2.4	1.0	1.62 ± 0.22	37 23.688′	68 39.951′
Payún Matrú volcanic field											
126273	Payún Liso	7/11	**0.32** ± **0.02**	91.4	0.4	0.30 ± 0.04	297.7 ± 4.3	0.3	0.32 ± 0.02	36 30.118′	69 19.277′
126288	Los Volcanes	6/12	**0.32** ± **0.05**	85.4	0.1	0.31 ± 0.16	296.2 ± 7.0	0.2	0.49 ± 0.10	36 25.115′	69 39.715′
Nevado volcanic field											
123963	Cerro Negro	9/12	**0.79** ± **0.06**	90	0.3	0.82 ± 0.19	293.8 ± 10.8	0.3	0.85 ± 0.08	34 46.667′	68 18.926′
126159	Ponon Trehue	5/10	**1.11** ± **0.08**	83.7	2.2	1.20 ± 0.17	284.0 ± 20.4	2.1	1.09 ± 0.09	35 12.622′	68 15.565′
123956	Cerro Colorado	10/10	**1.58** ± **0.03**	100	0.5	1.57 ± 0.04	296.7 ± 2.3	0.5	1.59 ± 0.06	35 23.861′	68 53.862′
126216	Cerro Chacaico	6/12	**2.83** ± **0.04**	89.6	0.1	2.82 ± 0.09	297.3 ± 13.0	0.1	2.84 ± 0.06	36 09.088′	68 41.364′
Llancanelo volcanic field											
126191	Cerro Jarilloso	8/8	**0.16** ± **0.07**	100	0.6	0.21 ± 0.21	308.2 ± 20.9	0.5	0.17 ± 0.08	35 39.781′	69 31.501′
126220	Las Ovejas	6/11	**0.28** ± **0.02**	89.3	0.1	0.28 ± 0.07	295.5 ± 10.5	0.1	0.42 ± 0.08	35 58.838′	69 03.924′
Andes retro-arc group											
126005	Infernillo, Mesillas volcano	10/13	**0.83** ± **0.11**	92.7	0.0	0.82 ± 0.21	295.5 ± 5.8	0.0	1.02 ± 0.19	35 08.352′	69 50.960′
126244	El Gaucho -plagioclase	5/10	**1.37** ± **0.36**	72.4	1.2	1.33 ± 0.36	334.6 ± 66.7	1.0	1.65 ± 0.38	35 49.751′	70 03.011′
Northern segment											
123964	Cerro Diamante	3/12	**0.06** ± **0.02**	75.8	0.0	0.06 ± 0.25	296.2 ± 80.9	0.0	0.08 ± 0.05	34 38.269′	69 05.090′
123965	Cerro Diamante	5/13	**0.43** ± **0.07**	70.4	0.3	0.40 ± 0.34	300.4 ± 66.6	0.4	0.53 ± 0.07	34 35.539′	69 01.858′
Miocene volcanoes											
126254	Cerro Fortunoso area	11/15	**6.80** ± **0.03**	89.4	0.6	6.80 ± 0.05	294.6 ± 13.9	0.7	6.83 ± 0.04	36 16.267′	69 23.854′
126238	Puntilla del Huincán	11/12	**10.30** ± **0.10**	91.5	1.1	10.77 ± 0.62	288.7 ± 8.9	0.9	10.21 ± 0.11	36 33.918′	69 49.003′
126170	Matancilla area	11/11	**20.68** ± **0.45**	100	0.6	20.81 ± 0.64	289.4 ± 28.1	0.7	20.61 ± 0.57	36 53.026′	69 07.067′

Bold ages are the plateau ages which are the accepted ages for the samples. Also given are: number of increments included in age calculation, % of ^{39}Ar released from the sample included in age calculation, mean squared weighted deviation (MSWD). For the inverse isochron calculation the ^{40}Ar/^{36}Ar ratio is reported along with the MSWD and the inverse isochron age. Total fusion age is given and the geographic position in degrees decimal minutes (dd mm mmm').

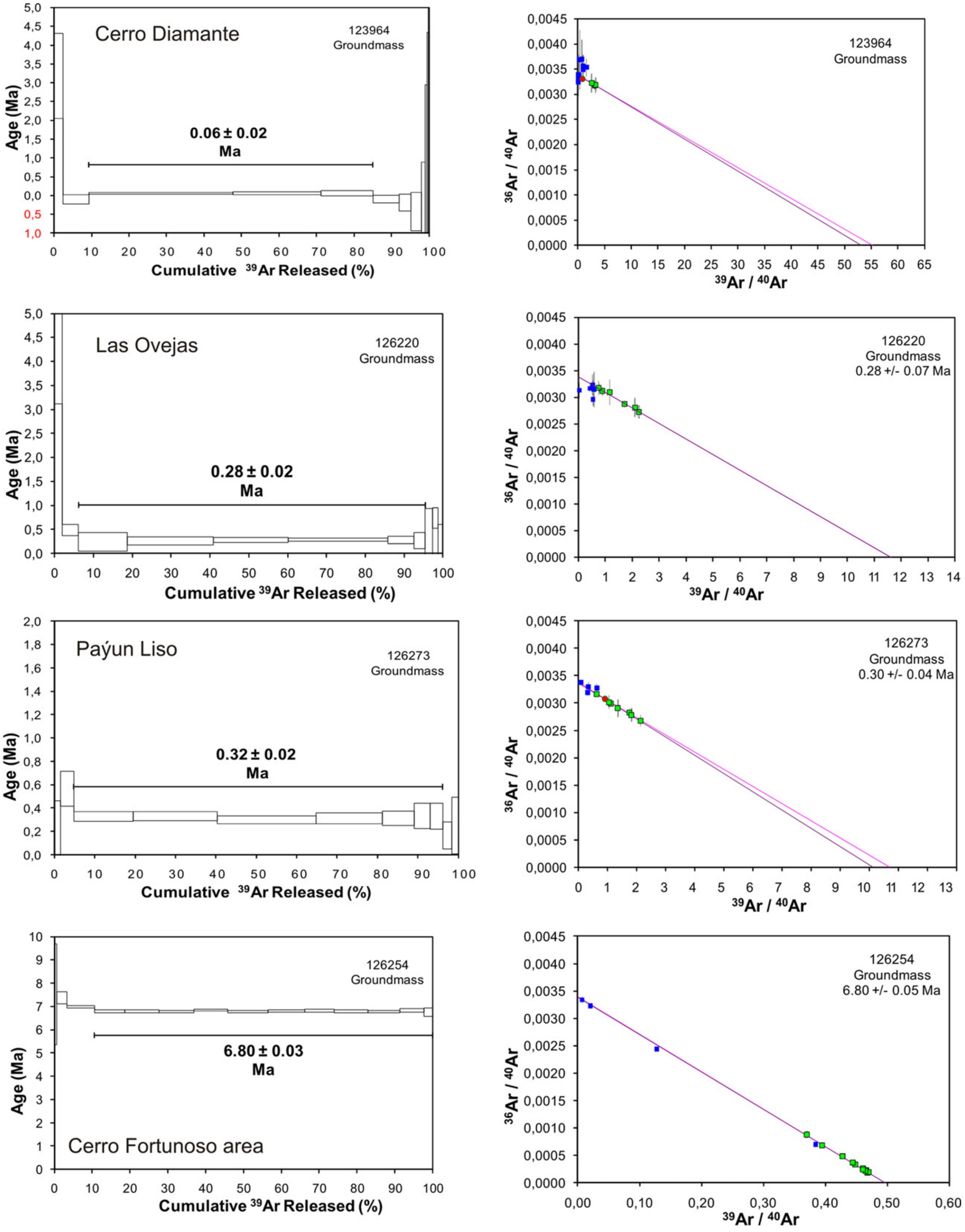

Fig. 2. Results of $^{40}Ar/^{39}Ar$ analysis for selected samples from Payenia. Plateau diagrams (left) and inverse isochron diagrams (right). The increments included in age calculation in the plateau diagrams are indicated with horizontal lines, and for isochrons with green data points. Calculated ages are reported with a 2σ uncertainty. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the Cerro Méndez scoria cone (1.23 ± 0.17 Ma) 3 km to the east (Kay et al., 2006a).

Cerro Carne (126176): 0.34 ± 0.13 Ma. The Cerro Carne scoria cone overlies the same volcanic plateau and the Cerro Morado lavas. This is a monogenetic volcanic centre with scoria and lava flows and the sample is from the latest erupted lava sampled east of the crater opening. The volcanic activity in Cerro Carne is one of the youngest in the Río Colorado volcanic field. Only Cerro Chico in the southern part of this plateau was interpreted morphologically as slightly younger.

4.2. *Payún Matrú volcanic field*

Rocks from the Payún Matrú volcanic complex were dated by Germa et al. (2010). They recorded ages between 168 ± 8 ka and Holocene for the trachytic Payún Matrú caldera and constrained the Mollar basalts from the Pampas Negras area (Llambías, 1966) to be >26 ± 4 ka according to dating of a younger ignimbrite from the Payún Matrú caldera. A lava from the Los Volcanes area with similar degree of alteration as the Mollar basalts from the Pampas Negras area had a similar age of 26 ± 10 ka which is probably representative for the youngest of the Los Volcanes flows reaching the Rute 40. The youngest activity in the Pampas Negras and Los Volcanes area is known as the Media Luna basalts (Llambías, 1966) of Late Holocene age (Españon, 2010). A few scattered occurrences of older lava flows in the area north of Los Volcanes and Pampas Negras are found and one was dated by Quidelleur et al. (2009) to 1.72 ± 0.05 Ma. Also the basaltic activity in the eastern part of the Carbonilla fracture has apparently continued since before 0.4 ± 0.1 Ma according to the age of the Carrizales flow which was derived from this fracture (Melchor and Casadío, 1999; Pasquaré et al., 2008).

Los Volcanes (126288): 0.32 ± 0.05 Ma. The Los Volcanes area displays a high intensity of volcanism with a sequence of basaltic lava flows of considerable volume. The sample dated from Los Volcanes is from the basal flow in a lava sequence of at least four lavas along Rute 40. It represents the early eruptions and indicates that activity in the area has been ongoing at least since Late Pleistocene. The apparent age of the sample is in good agreement with a reported age of 0.233 ± 0.22 Ma for a younger lava in the same flow sequence (Germa et al., 2010).

Payún Liso (126273): 0.32 ± 0.02 Ma. Payún Liso is a large composite volcano that rises 1700 m above the surroundings south of Payún Matrú. The sample is from a lava flow on the west flank of the volcano. This lava flow is most likely erupted at an early stage in the development of Payún Liso, but the stratigraphic relations of the volcano are poorly known. Other radiometric ages from locations close to the top and on the north side of the volcano are younger and range from 0.27 ± 0.01 Ma to 0.26 ± 0.08 Ma (Germa et al., 2010). Together, the reported ages indicate that the volcano was build up during relatively short time and that activity has been quiescent since around 0.26 ± 0.08 Ma.

4.3. *Nevado volcanic field*

The Nevado volcanic field is represented by four samples. The resulting ages range from late Pliocene (2.83 ± 0.04 Ma) to middle Pleistocene (0.79 ± 0.06 Ma) and corroborates with the existing ages from the area by Folguera et al. (2009) and Quidelleur et al. (2009). In the centre of this volcanism stands the large composite volcano Cerro Nevado with two identical K–Ar analyses of 1.32 ± 0.04 Ma (Quidelleur et al., 2009).

Cerro Chacaico (126216): 2.83 ± 0.04 Ma. Cerro Chacaico is from the southern part of the Nevado volcanic field and is the oldest hitherto dated sample from Nevado volcanic field. The sample is from a lava flow sampled at the flanks of the volcano. The eruption centres north of Cerro Chacaico, e.g. the Cerro Bayo, show the same erosional features and are likely to be of similar age.

Cerro Colorado (123956): 1.58 ± 0.03 Ma. The volcano is a monogenetic eruption site which is part of a chain of volcanoes forming an NW–SE lineament to the east of Lake Llancanelo, the Mancha Jarilla fracture. It is positioned west of Cerro Nevado in the northern part of the fracture. The 1.02 ± 0.03 Ma age obtained for the Perro Atado cone in the southern part of the fracture (Quidelleur et al., 2009) and the here reported age confirm the conclusions of the morphological study of Inbar and Risso (2001) who considered the northern part of the cones on the fracture to be much older than the southern part.

Ponon Trehue (126159): 1.11 ± 0.08 Ma. Ponon Trehue is a polygenetic eruption centre positioned NNE of Cerro Nevado at the southern end of the Malvinas fault (Bastías et al., 1993) which is the eastern thrust front of the San Rafael block. The sample is from a sequence of lava flows on the western slopes of the volcano. The apparent age of the sample is in accordance with a previously published analysis from the volcano of 0.94 ± 0.03 Ma (Quidelleur et al., 2009).

Cerro Negro (123963): 0.79 ± 0.06 Ma. South of the town of San Rafael is Cerro Negro, a monogenetic eruption centre with lava flows in all directions from a central crater forming a shield. It is one of the Malvinas group volcanoes marking the Cerro Negro and Malvinas faults (González Díaz, 1964, 1972). To the north, the lava flows are cut by the Río Atuel where flow sequences are visible. The apparent age is in good agreement with a previously published analysis from Cerro Negro of 0.801 ± 0.102 Ma (Folguera et al., 2009).

4.4. *Llancanelo volcanic field*

The obtained ages from the Llancanelo volcanic field are younger than the dated rocks from the Nevado volcanic field and this is in accordance with the Middle-Late Pleistocene age estimated from morphology by Bermúdez et al. (1993) and from two previous age determinations of 0.40 ± 0.14 Ma and with an age below detection (Españon, 2010). An age of 1.7 ± 0.6 Ma reported by Españon (2010) for Cerro Coral just east of Lake Llancanelo is considered to belong to the Nevado volcanic field.

Las Ovejas (126220): 0.28 ± 0.02 Ma. South of Lake Llancanelo is the Las Ovejas scoria cone, a monogenetic eruption centre that produced lava flows and scoria. The sample is from a lava flow from a smaller crater on the side of the central vent. The nearby Cerro Fiero shows a similar degree of erosion and may be of similar age.

Cerro Jarilloso (126191): 0.16 ± 0.07 Ma. West of Lake Llancanelo the volcanic centres produced large lava plateaus and scoria cones and some of the centres were formed in phreatomagmatic eruptions (Risso et al., 2008). The volcanic formations in the area are young in appearance and show minimal signs of erosion; some are only just being buried by Aeolian sediments. The sample dated for this study is from a lava flow from Cerro Jarilloso and is thought to be representative in age for much of the volcanic activity in the area. This is confirmed by the Ar/Ar ages of Españon (2010) of 0.12 ± 0.13 Ma and 0.40 ± 0.07 Ma for the dated Llancanelo lavas sampled west of the Lake Llancanelo.

4.5. *Andes retro-arc*

The retro-arc samples are from the Andean foreland; these two volcanic areas occur geographically separated from the Payún Matrú and Llancanelo volcanic fields and are situated within the Malargüe Fold and Thrust Belt (Giambiagi et al., 2008; Ramos and Folguera, 2011). This arc-type volcanism is also geochemically distinct from the back-arc volcanism (Søager et al., in prep.). The two samples presented here were erupted in the final waning stages of activity in the Malargüe Fold and Thrust Belt (Turienzo, 2010).

El Gaucho (126244): 1.37 ± 0.36 Ma. The El Gaucho volcano is situated around 20 km west of Bardas Blancas. Both groundmass and plagioclase separate were analysed from this sample. The groundmass separate did not yield an acceptable age plateau according to Fleck et al. (1977) but the calculated age supports the age obtained from the plagioclase analysis. This sample does not represent the latest eruption event in the volcano, but it is believed to be a good approximation as the sampled lava is high in the lava sequence.

Infernillo, *Mesillas volcano* (126005): 0.83 ± 0.11 Ma. The Infernillo volcanism occurs in two separate areas: The young Hoyo Colorado volcano, and the volcanoes of varying age north of the Niña Encantada lake: Mesillas, Loma Negra, Lagunitas and Hoyada volcanoes (Naranjo et al., 1999; Folguera et al., 2009). The age result of 5–6 ka by the ^{3}He method of Marchetti et al. (2006) appears to be of the Hoyo Colorado volcano as this location is indicated in Fig. 3 of Folguera et al. (2009). The position of the volcanic edifices in the two areas is believed to be controlled by the N–S trending Infernillo fault system in the Malargüe Fold and Thrust Belt (Giampaoli et al., 2002). The dated sample has the oldest published age available from the area, and constitutes a significant extension of the period of volcanic activity in this area. The age of this sample may also be representative of the Mal Barco and Laguna Blanca flows north and northeast of the Mesillas volcano. Folguera et al. (2009) presented six K–Ar age determinations from the Niña Encantada group which all yielded calculated ages below the detection limit of one to two hundred ka. We therefore propose that this area has experienced at least two separate volcanic periods.

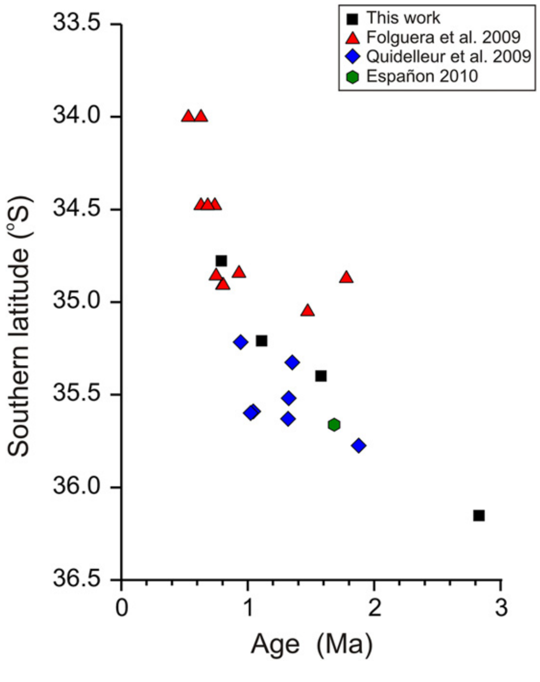

Fig. 3. Northwards temporal progression is evident in the eastern Nevado volcanic field and Northern segment. Ages plotted are: Black, this study - samples: 126216, 126159, 123956, 123963; blue, Quidelleur et al. (2009) - samples: CN03, CN07, CN10, CN11, CN34, CN36, CN42; red, Folguera et al. (2009) - groups: Aisol Volcano, Guadal Volcano, Las Malvinas and Los Tolditos; green, Españon (2010) - sample LL1, Cerro Coral. All samples are located east of 69° W, except for LL1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.6. Northern segment

Cerro Diamante (123965): 0.43 ± 0.07 Ma and (123964): 0.06 ± 0.02 Ma. Cerro Diamante is found in the northern part of the Río Grande foreland basin. Two samples from the volcano are presented. In the area around the volcano are scattered monogenetic cones while Cerro Diamante shows signs of repeated eruptive events that are now constrained in time. The older sample is from a plateau lava underlying the volcano sampled to the north where it is exposed at the Río Diamante. Underlying the lava is an ignimbrite from the formation of the Diamante caldera in the high Andes. The ignimbrite has been dated to 0.47 and 0.44 Ma by Stern et al. (1984) which agrees well with the 0.43 Ma age obtained from the basal Cerro Diamante lava. The age of 7.38 ± 0.86 Ma from this area is from the pre-Payenia basement (Folguera,et al., 2011) and not relevant for the present discussion. The younger sample from Cerro Diamante is from the top of the volcano representing one of the latest volcanic events and this age conforms well with the ages obtained by Folguera et al. (2009) for other samples from this edifice. The two samples therefore constrain the volcanic activity of Cerro Diamante in time indicating an active period of around 0.37 Ma. The two ages obtained for the neighbouring cone Cerro Chico by Folguera et al. (2009) are apparently both from the same sample, since the sample numbers were given as 10A and 10B. The two ages are very different, 0.484 ± 0.06 Ma and 1.164 ± 0.146 Ma, which is highly unlikely, also because Cerro Chico is apparently a monogenetic cone. We therefore choose to disregard these ages in our further discussion. Other results from the Cerro Diamante volcanic group (Folguera et al., 2009) are within the activity period indicated above, which seems well described by the combined data.

4.7. Miocene samples

La Matancilla (126170): 20.68 ± 0.45 Ma. The oldest of our dated samples is from the Matancilla area between Payún Matrú and Chachahuén. It is sampled from the top flow of this large hawaiite lava plateau of unknown origin. The Matancilla lavas were assigned to the early Miocene Palauco formation by González Diaz (1979). Kay and Copeland (2006) published an ^{40}Ar/^{39}Ar age of 23.76 ± 0.08 Ma and compiled previously published K–Ar ages between 16 ± 5 and 26 ± 2 Ma from the Matancilla area (see compilation in Kay and Copeland, 2006). The age reported here agrees well with the published ages and places the alkali basalts from the Matancilla area in the early Miocene period prior to the eruption of the Palauco basalts in the Sierra del Palauco.

Puntilla de Huincán (126238): 10.30 ± 0.10 Ma. This sample is a sub-alkaline mugearite from a lava flow just north of lake Coipo Laufquén in the Andes retro-arc. Intense retro-arc volcanism in the late Miocene to the Miocene Pliocene boundary has been grouped in the HuincánII eruptive cycle (Combina and Nullo, 2000; Kay et al., 2006a,b). The activity dated by us coincides with the initiation of this volcanism which is of the same age as the main episode of deformation in the Malargüe Fold and Thrust Belt (Giambiagi et al., 2008).

Cerro Fortunoso area (126254): 6.80 ± 0.03 Ma. This sample is an alkaline latite from an NNE-SSW trending line of cones north of Pampas Negras (Fig. 1). This volcanism can also be included in the HuincánII eruptive cycle although it is alkaline in character. The age of this sample is of similar age as the final phase of thrusting in the Malargüe Fold and Thrust belt just west of the Fortunoso area (Baldauf et al., 1992; Giambiagi et al., 2008).

5. Discussion

5.1. The geochronological data base for Payenia

To establish a better understanding of the geochronological data set available from Payenia, the 18 new ages and existing data will be used to investigate spatial and temporal trends within Payenia. Published radiometric age data is from the northern part of the study area (Folguera et al., 2009), from the area around Cerro Nevado in the Nevado volcanic field (Quidelleur et al., 2009), from Payún Matrú volcano and the near vicinity (Germa et al., 2010) and from the Río Colorado volcanic field (Kay et al., 2006a, b). Literature age data from Payenia have mostly been reported with 1σ uncertainties (Folguera et al., 2009; Germa et al., 2010; Quidelleur et al., 2009). When comparing this data with our new data we cite 2σ uncertainties in order to ensure that interpretations are at the 95% confidence level.

5.2. Spatial and temporal variations

The collection of ages from the Nevado volcanic field in Fig. 3 shows an age progression with a northwards younging of the activity. The oldest dated volcanic activity in Payenia is from Cerro Chacaico at around 2.83 Ma, after which the volcanism progressed northwards, with a concentration of activity around Cerro Nevado between 1.6 and 1.0 Ma and in Ponon Trehue between 1.1 and 0.94 Ma. After that the activity further proceeded northwards to Cerro Negro and the Malvinas group volcanoes around 0.8 Ma. After the activity in Cerro Negro, volcanism moved towards the north and west and reached its northernmost extension in the Guadal Volcano around 0.5 Ma (Folguera et al., 2009). The northward progression extended over approximately 2.3 Ma and is illustrated in Fig. 3. After the northward progression in the Nevado volcanic field, volcanism shifted to the Río Grande foreland basin west of the Llancanelo fault. This is illustrated in Fig. 4 with the new data from Cerro Jarilloso, Cerro Diamante and Las Ovejas, 0.06–0.28 Ma, where the volcanic activity is considerably younger than east of the Llancanelo fault. Folguera et al. (2009) also recognised a westward progression in the volcanism of the northern part of the province north of 35° 30′S in *a.o.* the Papagayos (0.607–0.092 Ma) and Medio (0.449–0.136 Ma) groups. The shift in the position of the volcanic activity where volcanic rocks younger than 0.5 Ma are concentrated west of the Llancanelo fault around 69° W and older rocks to the east, with only minor exceptions (Fig. 4), is confirmed by the available radiometric age data from the literature. The volcanism younger than 0.5 Ma is found in the western part of the northern segment including the Cerro Diamante and the Llancanelo, Infernillo and Payún Matrú volcanic fields where the highly active Payún Matrú and Los Volcanes are responsible for the majority of the volcanic activity in the last 0.5 Ma. The older volcanism in Payenia is concentrated in the eastern volcanic fields of Nevado and Río Colorado. This indicates a trench-ward propagation of volcanic activity in Payenia the last 3 Ma. This is in accordance with Lara and Folguera (2006) who noted that back-arc volcanism was established in the near back-arc at 1.6 Ma around 39° S.

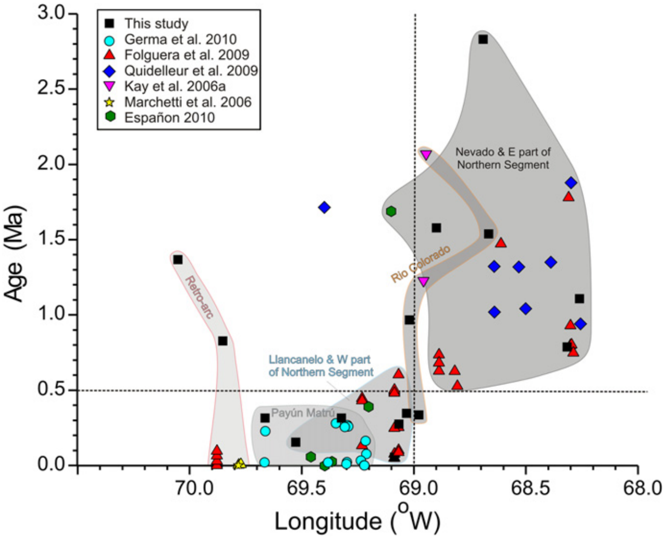

Fig. 4. Distribution of ages in the Payenia volcanic province. Samples west of around 69° W (the Llancanelo fault) are younger than 0.5 Ma and east of 69° W older, with only small deviations. The two samples dated for this study older than 0.5 Ma and west of 69° W are the Mesillas volcano at Infernillo and El Gaucho samples in the retro-arc. See text for discussion Sources for age data as for Fig. 1.

5.3. Implications

The age information available for Payenia is summarized in Fig. 5. The trends recognized here are the northwards progression in the Nevado volcanic field and the northern segment from around 2.83 Ma to around 0.5 Ma and the succeeding westward shift of volcanism with a concentration of the volcanic activity west of 69° W in the last 0.5 Ma. This systematic two-parted age progression must be related to changes of loci for generation of basaltic magma in the mantle and/or stress in the crust. The causal mechanisms for the back-arc volcanism in the Southern Volcanic Zone have been addressed in relation to geochemical characters of the erupted rocks (Kay et al., 2004, 2006a). On the basis of these studies it has been suggested that the widespread volcanism in Payenia during the Pliocene and Pleistocene is a result of the melting of a hydrated mantle over a steepening subducting slab (Kay et al., 2004, 2006a). The occurrence of high-K calc-alkaline back-arc magmatism up to 500 km east of the trench, in the southern regions of Chachahúen and Sierra de Huantraico from 15 to 5 Ma, was suggested to be the result of a shallowing of the subducting slab during the Miocene and a related broadening of the volcanic arc (Kay, 2001a, 2004; 2006a, 2006b; Folguera et al., 2008). When the subduction angle steepened here since the late Miocene, as evidenced by the 4.5 ± 0.5 Ma Parva Negra basalts (Ramos and Barbieri, 1988) with no slab input, widespread melting took place below the relatively thin lithosphere due to the influx of hot asthenospheric material into the mantle wedge and caused extensive basaltic eruptions in the Auca Mahuida and Río Colorado volcanic fields (Kay et al., 2006b).

In contrast, the calc-alkaline back-arc volcanism continued much longer in the central and northern Payenia region. Here this volcanism is also found up to 500 km east of the trench in the area of the Nevado volcanic field where it continued through the lower Pleistocene period, a.o. in the Cerro Nevado volcano. The volcanism progressed northwards from the southern San Rafael block in the late Pliocene to the Cerro Negro area in middle Pleistocene and finally to the northern segment where the slab is currently at a depth of ~180–190 km below the young Cerro Diamante volcano. According to Søager et al. (in prep.) the volcanism of the Nevado volcanic field and the northern segment is geochemically very similar to the high-K calc-alkaline Chachahuén magmas (Kay et al., 2006b) and the Miocene volcanism of the San Rafael block (Litvak et al., 2008) suggesting a similar mode of formation for these rocks. Moreover, the size of the Cerro Nevado volcano indicates that there was a substantial supply of hydrous fluids or melts from the slab in this area to generate this amount of magmas. This suggests that the slab was present below the San Rafael block during the

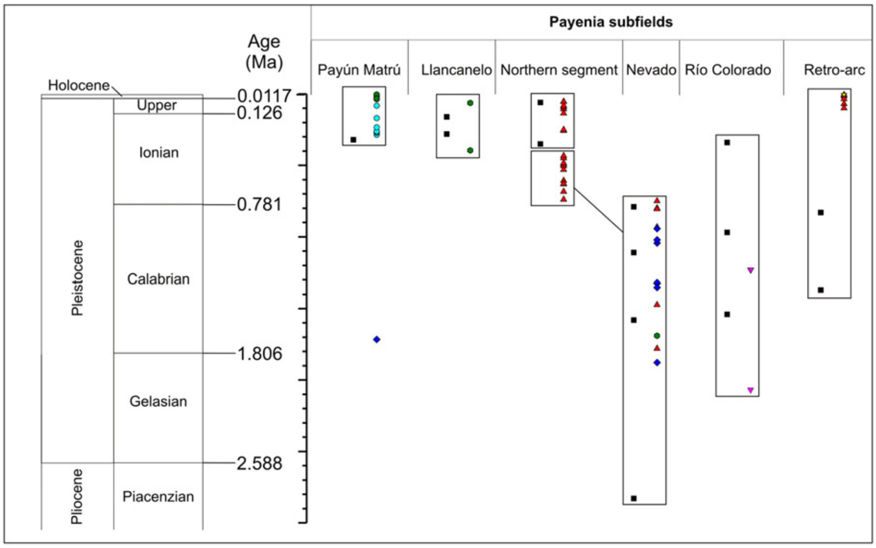

Fig. 5. Age of volcanic fields and temporal span of activity of individual segments. Data and symbols as in Fig. 4. The geological time scale is according to Gradstein et al. (2004).

early Pleistocene period and that the Nevado volcanism followed the retreating slab. Thus the slab rollback was not simultaneous from 37° S to 34° S but was initiated in the southern part and then propagated to the north. The Quaternary volcanic history of the northern segment does not go back further than ~700 ka and the northern transition between shallow and normal subduction during the Miocene-Pliocene period was probably positioned under this area. Due to the late Miocene to Recent development of the Pampean flat slab at ~30–33° S just north of the Payenia province (Yañez et al., 2002), the northern segment is now again positioned on the transition from the current Pampean flat slab to the normal subduction angle under the SVZ. Only now the transition marks the southern border of the present flat slab, whereas in the Miocene the area was positioned above the northern transition of the Payenia shallow subduction zone. Consequently, there must have been an interaction between the slab rolling back in the Payenia region and the simultaneous advancement of the Chile flat slab to the north. This can explain the continued volcanic activity in the western part of the northern segment until around 50 ka (Folguera et al., 2009).

Although this hypothesis can be supported with the progression of volcanism in the eastern and northern part of Payenia since the Upper Pliocene, it does not explain the long lived volcanic activity seen in Payún Matrú (Germa et al., 2010; Quidelleur et al., 2009; this study). The volcanic activity here shows a temporal span that is best explained by a sustained thermal or compositional anomaly beneath the volcano or a continuous addition of hydrous fluids or melts to the source mantle (Fig. 3). A long-lived thermal anomaly cannot be explained solely with the influx of hot astenospheric material during rollback of the slab but could be related to the plume-like structure rising from beneath 200 km above the subducting Nazca slab recognized by Burd et al. (2008). Geochemical studies of the volcanism in Payún Matrú, Payún Liso and Los Volcanes indicate that there is only a small influence from either slab fluids or lithospheric contamination in the magmas and that the volcanic rocks have an intraplate character (Pasquaré et al., 2008; Germa et al., 2010; Søager et al., in prep.). This supports the upper mantle plume suggestion of Burd et al. (2008) as being responsible for the excessive volcanism centred in the Payún Matrú volcanic complex and possibly also the Llancanelo volcanism. It furthermore indicates that the volcanism in Payenia the last 3 Ma was closely connected to the rollback of the slab, as it generated space for influx of material into the mantle wedge and created a window for mantle plume material rising from deeper parts of the mantle.

6. Concluding remarks

We present 18 new $^{40}Ar/^{39}Ar$ ages and a compilation of the geochronological data for the erupted rocks in Payenia. A new division of the volcanic province into six fields is suggested based on the temporal development: The Nevado volcanic field focussed on the San Rafael block with ages between 2.8 and 0.7 Ma, the Llancanelo volcanic field west and south of the Llancanelo lake with ages between 400 and 60 ka, the northern segment including the Cerro Diamante with ages between 700 and 50 ka, the Payún Matrú volcanic field with ages between 320 ka to recent and the Río Colorado volcanic field with ages 2.1–0.34 Ma.

The late Pliocene to Recent volcanism in Payenia shows spatial and temporal trends that supports the rollback hypothesis for the subducting Nazca plate. Since the late Pliocene to around 0.5 Ma the volcanism progressed from the southern to the northern Nevado volcanic field within the San Rafael block and presumably marks the withdrawal of the subducting slab towards the north. Then activity shifted towards the Río Grande foreland basin in the Llancanelo volcanic field and the Payún Matrú volcanic field which was the major outlet for magma in Payenia in the last 300 ka. Low volume volcanic activity over the last half of the Pleistocene period is also observed in the southern Río Colorado volcanic field, although it probably ended shortly after 340 ka. The westward shift in activity around 0.5 Ma has only a few exemptions. The shift occurs around 69° W and is coinciding with the Llancanelo fault and thus the western limit of the San Rafael block. The observed trends in volcanic activity are most likely the result of changes in the loci for melt generation in the mantle as the slab retreated towards the north and west and created space for the inflow of asthenosphere into the mantle wedge. The more sustained volcanism in the Payún Matrú volcano requires continued supply of magma which is probably generated by a plume-like upwelling of mantle beneath the lithosphere.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsames.2012.02.003.

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