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Plume overriding triggers shallow subduction and orogeny in the southern Central Andes

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ABSTRACT

Plate tectonic theory implies that mantle plumes may be eventually overridden by lithosphere during continental drift. These events have particular tectonomagmatic consequences for active margins and hence related orogenic processes. Since the first documentation of plume overriding and the definition of the plume-modified orogeny concept, only few examples have been recognized in the geologic record. In this study, we analyze the Neogene tectonic evolution of the Southern Central Andes between 35° and 38°S and its potential relation to the subduction of the Payenia plume as a recent analogue of this process. Through a series of tectonic reconstructions we show that progressive Payenia plume overriding correlates with Neogene arc-front migrations linked to slab shallowing, fold belt reactivation in the Main Cordillera and intraplate contraction in the San Rafael block. Additionally, Nazca slab tear determined from tomographic analyses and subsequent diachronous steepening of the subducted plate may also be an aftermath of plume subduction as often described in the final stages of plume-modified orogeny. Finally, we propose a modern analogue for processes previously described, dating back to the Mesoproterozoic, which provides further insights into these complex settings.

1. Introduction

Plume-subduction zone interaction is nowadays recognized as a relatively common geodynamic phenomenon and a direct consequence of plate tectonics (Murphy et al., 1998; Fletcher and Wyman, 2015; Mériaux et al., 2016; Chang et al., 2016). During this process weak mantle plumes may be suppressed and eventually destroyed if subduction-related mantle flow distorts the plume structure (Druken et al., 2014; Kincaid et al., 2013; Steinberger and O'Connell, 1998). Nevertheless, some plumes may evade subduction leaving particular tectonomagmatic imprints on the upper plate and associated non-collisional orogenic belts. To date, only few examples of this process have been identified in the geologic record (Murphy et al., 1998, 1999; Dalziel et al., 2000; Betts et al., 2009). In these cases introduction of a plume-related buoyant swell into a convergent margin may trigger changes in the slab angle leading to flat or shallow subduction (Murphy et al., 1998; Murphy and Keppie, 2005; Betts et al., 2009, 2015) (Fig. 1). Such subduction style produces upper plate contraction, a time-transgressive migration of orogenic and magmatic activity into the continental interior, and the eventual cessation of arc magmatism. Additionally, trench advance produced by plume-margin interaction may also contribute to crustal shortening in the overriding plate (Betts et al., 2012) (Fig. 1). Noteworthy, characteristic magmatic responses of mantle plumes, such as flood basalts and dyke swarms, may be inhibited during subduction because the plume is less likely to undergo adiabatic melting (Druken et al., 2014; Murphy, 2016) (Fig.1). Transient upper plate contraction produced by plume-slab contact at a convergent setting has been defined as “plume-modified orogeny” by Murphy et al. (1998). This peculiar process usually ends when the subducting oceanic lithosphere founders due to the buoyancy contrast between the plume and the overlying slab (Murphy et al., 1998, 1999; Dalziel et al., 2000) or breaks-off, which could be facilitated by the presence of weaknesses in the slab (Macera et al., 2008; Obrebski et al., 2010) (Fig. 1). The final stages of plume-modified orogenesis are usually followed by slab steepening, rollback, renewal of slab-pull and plume impact below the upper plate (Betts et al., 2009; Dalziel et al., 2000; Murphy et al., 1998; Oppliger et al., 1997) (Fig. 1). Among the few documented examples of plume-modified orogeny are the Laramide Orogeny potentially linked to the latest Cretaceous-Paleogene subduction of the ancestral Yellowstone plume (Murphy et al., 1998; Murphy, 2016), Middle to late Paleozoic Acadian orogeny in the northern Appalachians (Murphy et al., 1999; Murphy and Keppie, 2005), Neopaleozoic Gondwanic orogeny triggered by overriding of the Karroo plume (Dalziel et al., 2000) and regional contraction throughout eastern and central Mesoproterozoic Australia (Betts et al., 2009). Similarly to these examples, we suggest based on tectonic reconstructions, that recent tectonic activity associated with the Neogene reactivation of the Southern

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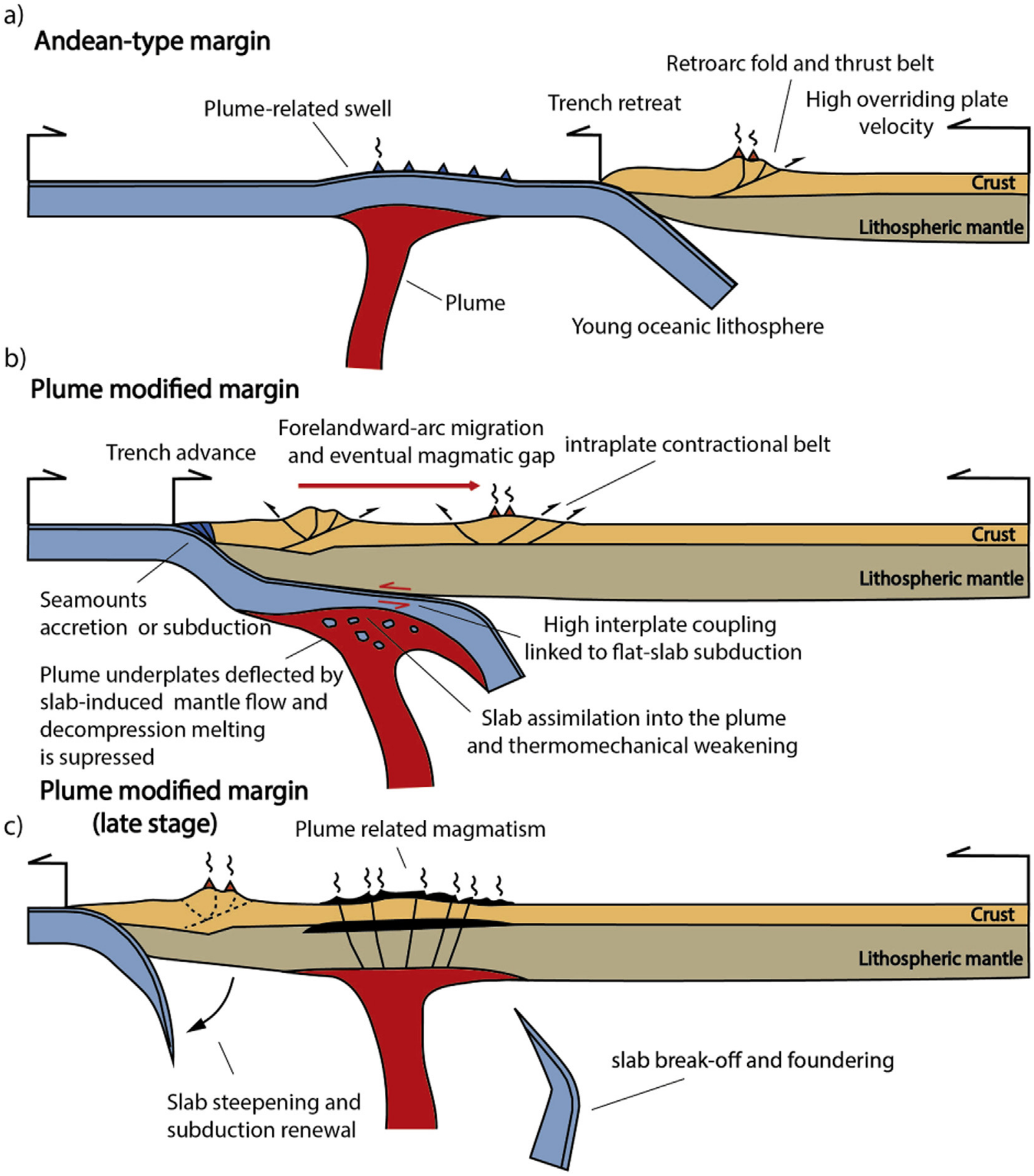

Fig. 1. Schematic tectonic diagram showing the process of plume-modified orogenesis in an Andean-type margin. Stages based on conceptual and numerical models from Murphy et al. (1998, 1999) and Betts et al. (2012, 2015). a) An Andean-type margin develops when overriding plate velocity becomes higher than trench retreat. It is characterized by a relatively stationary magmatic arc and a retroarc fold and thrust belt. A nearby plume impinges the oceanic lithosphere producing a topographic swell and seamounts that subsequently accrete or subduct beneath the active margin. b) Plume is overridden by the continent triggering trench advance and flat-subduction that in turn produce migration/cessation of arc magmatism and intraplate contraction. At this stage mantle decompression melting is suppressed and the plume enters in an incubation stage leading to assimilation and/or thermal erosion of the subducting slab. c) Subduction is reestablished after slab break-off, foundering and renewed decompression melting in the plume head.

Central Andes could have been modified when the South American margin overrode an ancient expression of the Payenia plume, a recently identified mantle anomaly beneath the Andean retroarc (Burd et al., 2014) (Fig. 2).

Neogene overriding of this plume by the South American plate explains a number of apparently unconnected tectonic events in the Andes between 35°S and 38°S that are not accounted by current tectonic models.

2. Geological setting

The Andes are the result of non-collisional orogenesis linked to the progressive overriding and subduction of the ancient Farallon plate and the current Nazca plate (Fig. 2a). Particularly, the Southern Central Andes between 35° and 38°S consist of a mostly thick-skinned fold and thrust belt constituted by different morphostructural units. From west to east, the most important are the Main Cordillera and an intraplate belt to the east known as the San Rafael block, which is separated from the cordilleran sector by the Neogene Río Grande foreland basin (Yrigoyen, 1993; Sagripanti et al., 2011; Giambiagi et al., 2012; Ramos et al., 2014) (Fig. 2b). Andean contraction at studied latitudes took place through tectonic inversion of the Mesozoic Neuquén Basin during two main deformational events, an older episode spanning from Late Cretaceous to Eocene (~98–55 Ma) and a younger Neogene event (18–5 Ma) (Cobbold and Rossello, 2003; Ramos et al., 2014; Fennell et al., 2015; Folguera et al., 2015a). Particularly, the last contractional episode produced an anomalous expansion of the orogenic front (~550 km away from the Chilean trench), deforming the continental interior and uplifting the basement-cored San Rafael block (Fig. 2b). Noteworthy, Andean reactivation and foreland contraction took place in concert

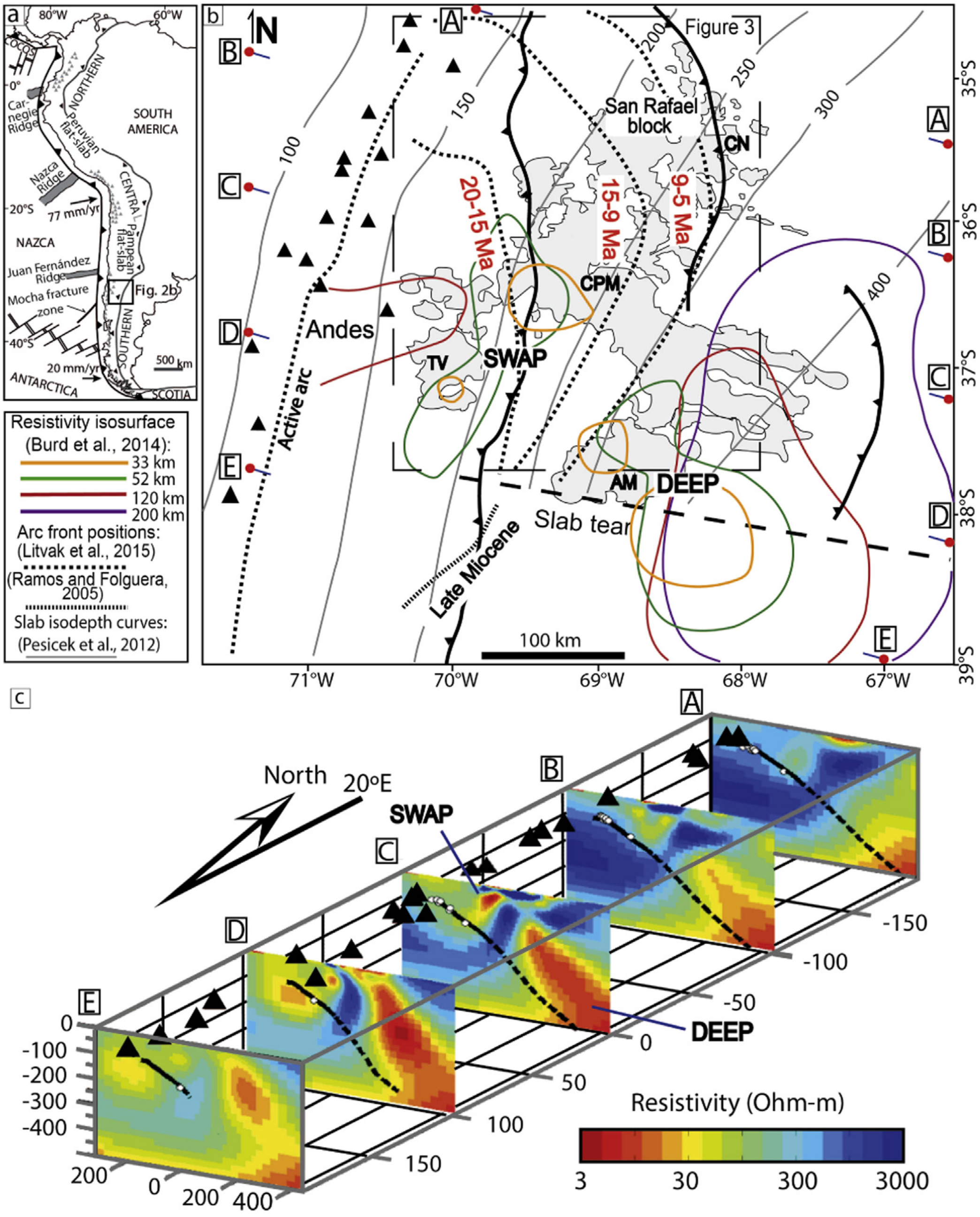

Fig. 2. a) Tectonic setting of the Andes. Modified from Horton and Fuentes (2016). b) Sketch map showing the Southern Central Andes between 35°S to 39°S, the Payenia volcanic complex (grey area) and the arc-front paleopositions during Neogene times (based from Ramos and Folguera 2005, Ramos et al., 2014 and Litvak et al., 2015). Also, contours corresponding to 35 Ohm-m isosurface of upper part of DEEP and SWAP mantle plumes at 33, 52, 129, and 200 km are presented (modified from Burd et al., 2014). Abbreviations are TV: Tromen volcano, CPM: Payún Matrú Caldera, CN: Cerro Nevado volcano, AM: Auca Mahuída volcano. c) Resistivity model modified from Burd et al. (2014) showing the structure of SWAP and DEEP mantle plumes. Profile C was used for 2-D reconstruction in Fig. 4. Solid and dashed black lines on profiles A to E indicate the subducted Nazca slab and white circles are slab seismicity.

with a stepwise eastward migration of arc magmatism that reached as far as ~300 km from the current arc front (Figs. 2b and 3) (Kay and Copeland, 2006; Ramos et al., 2014; Sagripanti et al., 2015a). These features have been attributed to a shallow subduction configuration that expanded the arc-front into the foreland sector with an average speed of at least 3 cm/yr (Kay et al., 2006a, 2006b; Spagnuolo et al., 2012; Dyhr et al., 2013a, 2013b; Ramos et al., 2014; Litvak et al., 2015). Slab shallowing of the subduction zone is thought to have occurred between ~20–19 and 5 Ma (see Litvak et al., 2015 for a synthesis) (Fig. 3). In Pliocene times the shallow slab destabilized and a series of complex tectonomagmatic events followed this process. Steepening of the Nazca slab produced arc retreat and asthenospheric injection that in the last two million years gave place to the huge basaltic flooding (~ 40,000 km^2) of the Payenia volcanic complex (Fig. 2b) (see Ramos and Folguera, 2011 for a review). Spatial distribution of the different pulses that constructed the Payenia volcanic plateau shows a progression of the intraplate magmatism to the west and north, interpreted as a diachronous steepening of the slab (Gudnason et al., 2012). Through a magnetotelluric survey, Burd et al. (2014) recently identified two resistivity anomalies interpreted as mantle plumes impinging below the southern sector of the Payenia volcanic complex (Fig. 2b and c). These are, a shallower plume below the Payún Matrú and Tromen volcanoes called SWAP and a deeper anomaly below the Auca Mahuída shield volcano named DEEP (Fig. 2b and c).

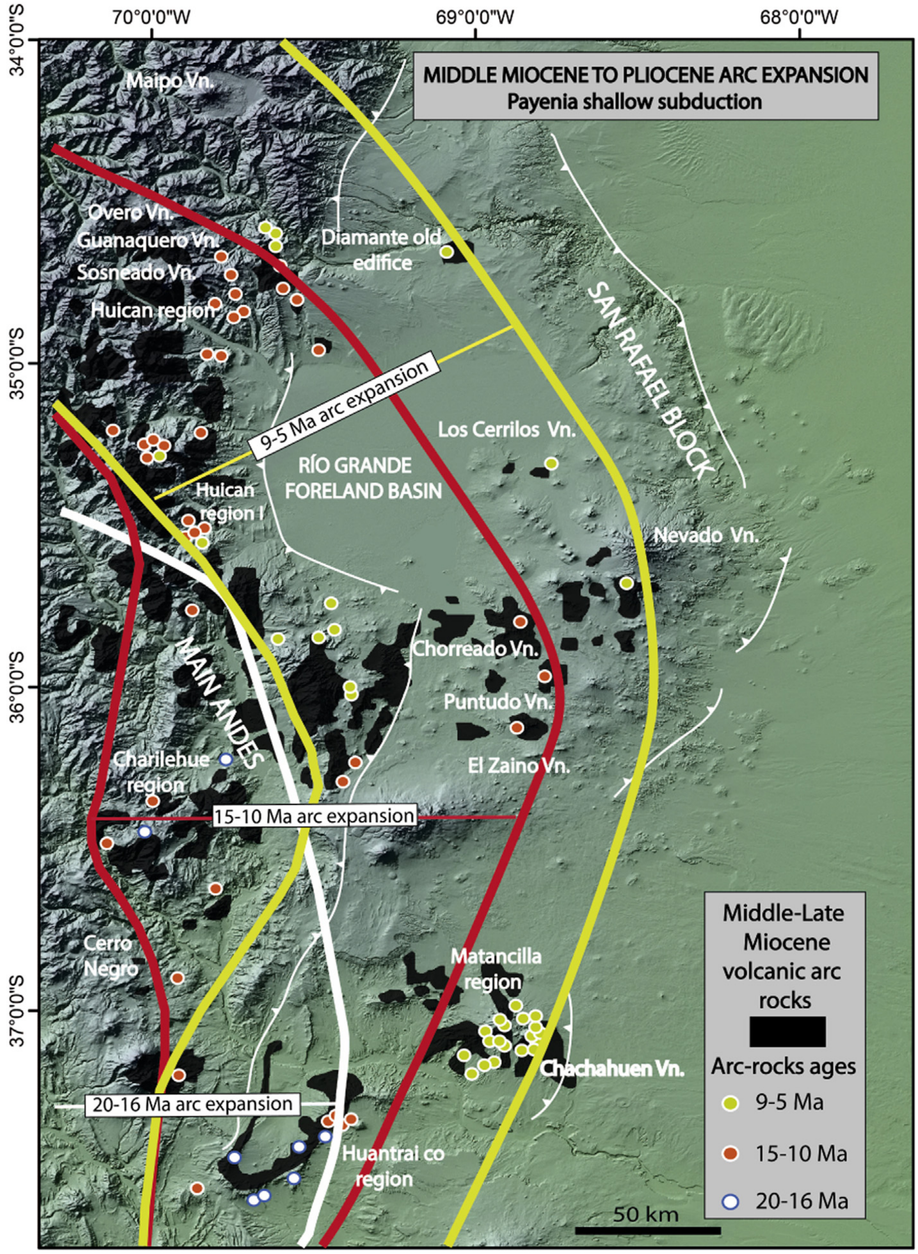

Fig. 3. Spatial distribution of radiometric ages of calcalkaline rocks between 34°30′ and 37°30′S showing a progressive eastward expansion of the middle Miocene to early Pliocene arc [modified from Folguera et al. (2015a) and Litvak et al. (2015, 2017)]. Age compilation is from Nullo et al. (1993, 1999, 2002), Ramos and Barbieri (1989), Ostera et al. (1999), Cobbold and Rossello (2003), Giambiagi et al. (2005), Kay and Copeland (2006), Kay et al. (2006a, 2006b), Folguera et al. (2009), Spagnuolo et al. (2012), Dyhr et al. (2013a, 2013b) and Ramos et al. (2014).

Notably, it is not clear whether the DEEP rises from near the top of the mantle transition zone or from the lower mantle due to the lack of resolution of the magnetotelluric profile at depth (Burd et al., 2014). The presence of an EM1 OIB-type mantle source in the Southern Payenia rocks and a MORB-like South Atlantic mantle source in the northern Payenia basalts are a striking expression of the complex mantle structure beneath the retroarc sector of the study area (Søager et al., 2013; Holm et al., 2016).

Burd et al. (2014) proposed that the SWAP and DEEP plumes may have been connected in Miocene times, but that the uppermost part of the DEEP was decapitated to form the SWAP when shallow north-westward mantle flow resumed during late Pliocene steepening of the slab. In addition, Pesicek et al. (2012) based on a seismic tomography study proposed a late Pliocene slab tearing episode in the Nazca plate at 38°S (Fig. 2b). Currently, the Andean retroarc at studied latitudes is under contraction as indicated by presence of structures that accommodate shortening in younger than 2 Ma strata (Galland et al., 2007; Sagripanti et al., 2015b; Gianni et al., 2014; Branellec et al., 2016).

Although the Neogene shallow subduction event and its tectonothermal impact in the Southern Central Andes are well established, a satisfactory explanation for its cause has eluded researchers. Ramos et al. (2014) and Litvak et al. (2017) suggested that it was caused by the subduction of a buoyant aseismic ridge, similarly to other flat-slab segments in the Andes (Fig. 2a). On the other hand, Spagnuolo et al. (2012) and Folguera et al. (2015a, 2015b) inferred the existence of a mantle plume during initial slab shallowing in Neogene times based on the observation of voluminous mesosilicic rocks disposed in a NE trend resembling a plume track. However, to date a causal relation between plume subduction and Neogene slab dynamics has not been demonstrated.

3. Reconstructions of plume-Andean margin interaction

To analyze the spatial relation between the Payenia plume and the South American margin in Neogene times we carried out a series of tectonic reconstructions. According to Burd et al. (2014), the ancient Payenia plume was located immediately to the east of the shallow Nazca slab in the Neogene. However, a simple 2-D reconstruction of the subduction system at 37°S during the slab shallowing stage depicts a different spatial relation between these features (Fig. 4). To reconstruct the potential paleoposition of the subduction system at full slab shallowing development stage at ~10 Ma we followed the next steps. First, we reconstruct slab geometry during late Miocene times following a similar approach to Wu et al. (2016), based on the flexural unfolding of the subducted slab by flattening a mid-slab line to the earth surface.

This method is suitable for upper mantle slabs that are relatively undeformed such as the Nazca slab, as depicted by seismic tomography in the study area (Pesicek et al., 2012). To calculate the amount of subducted slab to unfold, we used de following constraints: Seismic tomography studies between 36°S and 38°S show that the Nazca slab extends at least ~800 km into the mantle, with a normal angle of ~30°E and presents a relatively uniform thickness of ~100 km (Pesicek et al., 2012; Fig. 2) (Fig. 4a). Convergence rate between the Nazca and South America plates at 10 Ma was around 100 mm/yr (Pardo-Casas and Molnar, 1987; Somoza, 1998) while the modern rate is about 74 mm/yr in the same direction (DeMets et al., 2010). Considering these two subduction rates, we estimate that the first 870 km of the seismically imaged Nazca slab at 37°S (Pesicek et al., 2012) have been subducted in the last 10 Ma (Fig. 4a). Once the 870 km of the Nazca slab were unfolded to a horizontal position to the west of the trench, the angle of the Nazca slab was restored from the current normal angle to two possible configurations: a shallow angle (Kay et al., 2006a) and to a flat-slab geometry recently proposed by Dyhr et al. (2013b) (Fig. 4b). It is worth noting that we did not take into account volume loss in the slab due to density changes (e.g. Wu et al., 2016), which considering the relatively constant thickness would yield a longer shallow slab. The position of the trench at 10 Ma was reconstructed 350 km east of the current location using an average upper plate velocity of 3,5 cm/yr following Somoza and Ghidella (2012) (Fig. 4b). As demonstrated by the latter authors, upper plate velocity of South America during Cenozoic times is highly variable depending on the used hotspot reference model. Nevertheless, taking into account the Cenozoic kinematic in the South Atlantic mid-ocean ridge, it is reasonable to consider a South American absolute motion between ~3 and ~4 cm/yr since ~40 Ma (Somoza and Ghidella, 2012). The reconstruction shows a slab restricted to the shallow upper mantle consistent with previous proposals of Yañéz et al. (2001) and recent numerical modeling of Neogene Nazca slab subduction (Quinteros and Sobolev, 2013). Then, using as constraint the current positions of SWAP and DEEP anomalies (Burd et al., 2014; Fig. 14), we located in our 2-D reconstruction the inferred geometry of the Payenia plume in late Miocene times (Burd et al., 2014; Fig. 15c) (Fig. 4b). Interestingly, the final 2-D reconstruction shows that the uppermost part of the Payenia plume overlaps with the slab and more importantly, its main body locates below the shallowly dipping Nazca slab (Fig. 4b). It is important to note that this spatial relation could be enhanced if we consider a complete flat-slab geometry (Dyhr et al., 2013b) instead of a shallow configuration (Kay et al., 2006a). We interpret this spatial relation as a likely plume impingement beneath the shallow subducting slab.

In order to evaluate a spatio-temporal relation between changes in slab angle (reflected on migrations of arc-front position) and plume subduction (e.g. Murphy et al., 1998, 1999; Betts et al., 2009), we utilized a recent global plate reconstruction model (Müller et al., 2016)

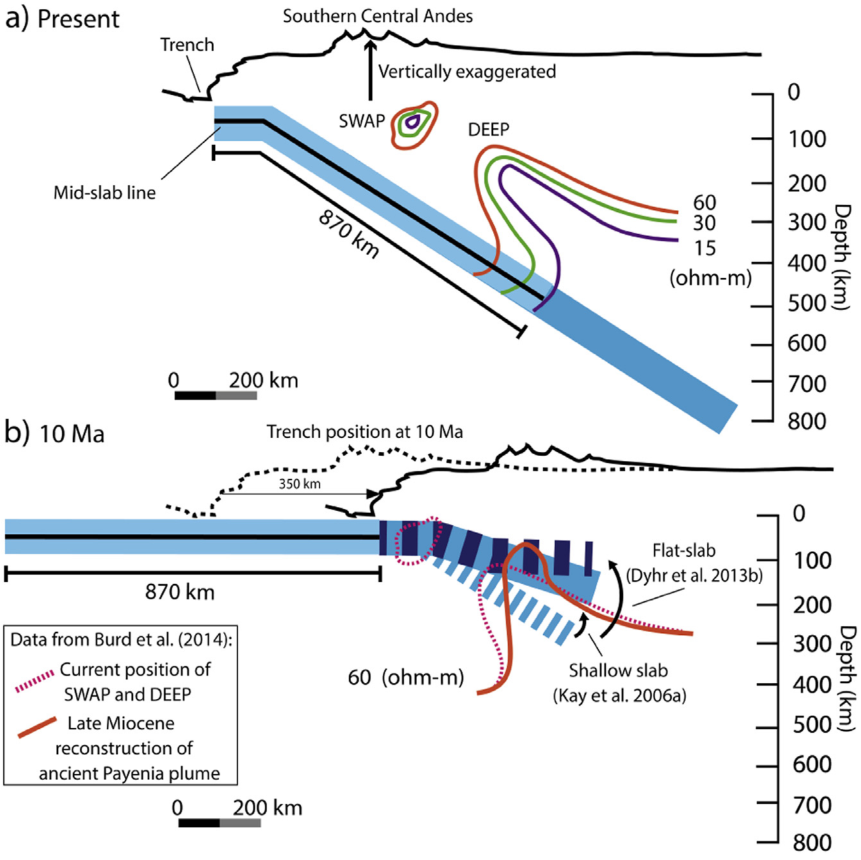

Fig. 4. a) Present configuration of the convergent margin at 37°S. Nazca slab geometry at 36°S is from Pesicek et al. (2012) and 60, 30, and 15 Ohm-m isoresistivity contours at the same latitude for SWAP and DEEP are from Burd et al. (2014). b) Reconstruction of the convergent margin at 10 Ma. Mid-slab line in the Nazca plate restored to the surface by flexural unfolding, and reconstruction of trench position, and ancient Payenia plume in late Miocene.

using the free-access Gplates software (www.gplates.org). The use of other plate reconstruction models (e.g., Seton et al., 2012) does not substantially change the proposed history of plume subduction and leads to same conclusions. Similarly, to the global study of plume-subduction interactions of Fletcher and Wyman (2015) and the reconstruction of the nearby Juan Fernandez hot-spot (Yañéz et al., 2001), we assumed that the Payenia plume could have existed previously to the Miocene. This assumption seems reasonable since hot-spots directly linked to mantle plumes (French and Romanowicz, 2015) beneath the Nazca and South American plates are pre-late Miocene and mostly Cretaceous in age (e.g., Kerr and Tarney, 2005; Gibson et al., 2006; O'Connor et al., 2012). In addition, we considered that the Payenia plume was fixed in a hot-spot reference frame similarly to the analysis of Murphy et al. (1998) and Fletcher and Wyman (2015). Noteworthy, it is known that mantle plumes may experience some degree of displacement respect to the vertical direction due to convective asthenospheric currents, direct motion of their source pushed by spreading slabs above the core-mantle boundary or by subduction-induced toroidal flow (Steinberger and O'Connell, 1998; Mériaux et al., 2016; Hassan et al., 2016). The latter factor would be particularly influential on the proposed Neogene setting of the ancient Payenia plume nearby the Andean active margin. Nevertheless, we consider valid the assumption of a fixed Payenia plume since Mériaux et al. (2016) demonstrated through analogue modeling that subduction-induced toroidal flow is not particularly effective for short slabs transiting the upper mantle as observed in the South American subduction zone (see Appendix S2.1 in Mériaux et al., 2016). Moreover, this effect on the ancient Payenia plume motion could be further ruled out by taking into account the existence of a short slab in Neogene times as reconstructed in Fig. 4a and recognized in numerical simulations of the subduction of the Nazca slab in the last 20 Ma (Quinteros and Sobolev, 2013). The existence of a shorter slab in the Neogene has been attributed to a previous slab detachment event (e.g. Yañéz et al., 2001) or to highly oblique convergence that produced limited subduction in pre-Miocene times (Quinteros and Sobolev, 2013). Since the Payenia plume is currently dismembered in SWAP and DEEP anomalies, these were reconstructed to a paleoposition in which the SWAP is located over the upper part of the DEEP anomaly, as suggested by Burd et al. (2014) (Fig. 5a). In order to do this, first the DEEP anomaly was restored from its southwestward deflection, observed in the isoresistivity curves shown in Fig. 2b (Fig. 5a). Then, the SWAP anomaly was placed on top of DEEP. Overlap of the shallowest parts of SWAP and DEEP at ~50 km of depth resulted in a minimum upper plume diameter of ~200 km that was utilized in the plate reconstruction (Fig. 5a, b). Additionally, we show arc-front positions from Oligocene-Miocene (Folguera et al., 2015a) to Miocene-Pliocene (Litvak et al., 2015). Fig. 5b shows that the ancient Payenia plume was completely subducted between ~20 and 16 Ma, when the first magmatic arc expansion was registered and at about the time of commencement of contraction Southern Central Andes (Kay et al., 2006a, 2006b; Litvak et al., 2015; Folguera et al., 2015a) (Fig. 5b). Continued plume subduction from 16 to 5 Ma closely correlates with the documented late stages of arc expansion that lead to the full development of the shallow subduction configuration and intraplate contraction in the San Rafael block (Fig. 5b). Finally, it is worth to note the close relation between plume paleopositions and the area where the slab teared at 38°S in Pliocene times (5–3 Ma).

4. Discussion and conclusions

The Neogene evolution of the Southern Central Andes in the study area is associated with the westward drift of the South American plate, the eastward subducting Nazca plate and the presence of the Payenia mantle plume (Fig. 6). However, how the interplay between these features resulted in the complex tectonic evolution described in this region is still poorly understood. In this sense, a satisfactory explanation for Neogene shallow subduction and related orogenic activity in

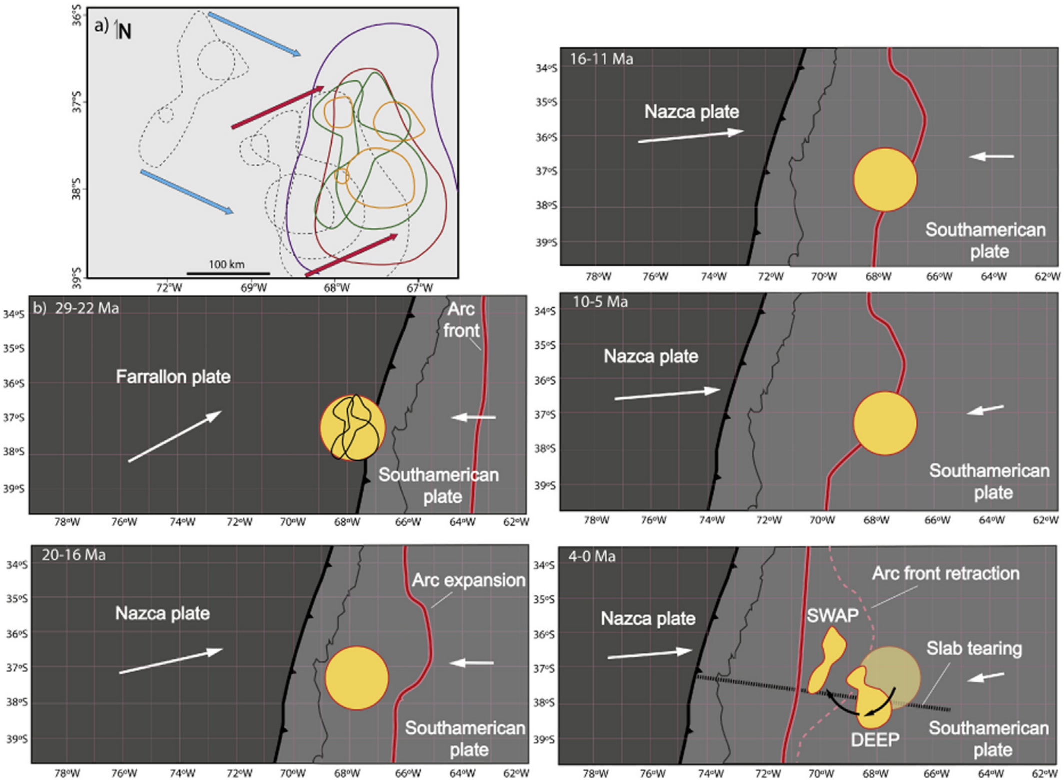

Fig. 5. a) Reconstruction of the ancient Payenia plume position previous to Pliocene separation of SWAP from DEEP. Blue and red arrows are directions of restoration for SWAP and DEEP plumes respectively. b) Reconstruction of plume-Andean active margin interaction in Neogene times using Müller et al. (2016) model on Gplates software. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

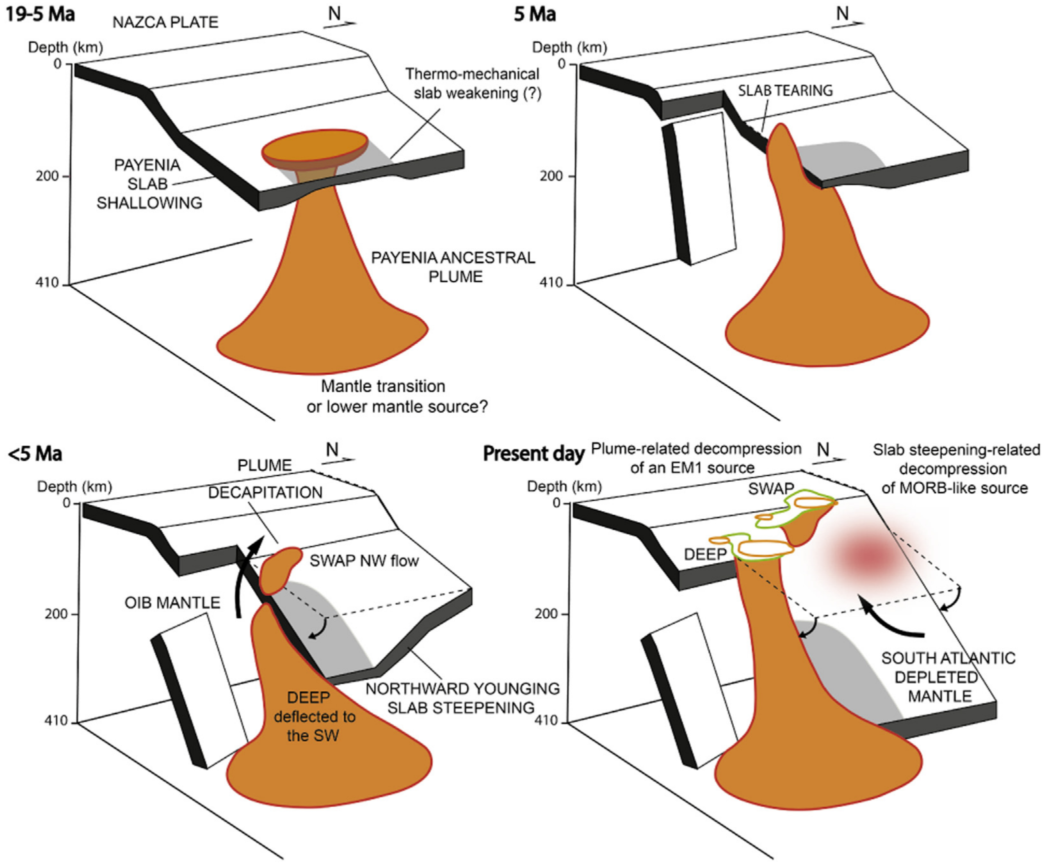

Fig. 6. Proposed tectonic model linking, Payenia plume subduction, slab shallowing, and later oceanic plate tearing, steepening and plume decapitation. 19–5 Ma: Payenia plume subduction and shallowing of the Nazca plate. 5 Ma: Tearing of the Nazca slab due to plume-related thermo-mechanical lithospheric weakening. <5 Ma: Upward flow of the Payenia plume during plate steepening from beneath the slab through the teared area. During this process the plume was separated into SWAP and DEEP mantle anomalies. Present day: Normal subduction and current location of both mantle anomalies in the Andean retroarc.

the Andes between 35°S and 38°S is lacking. Ramos et al. (2014) suggested that low angle subduction was triggered by the potential subduction of an aseismic ridge. However, no evidence for the existence of this ridge has been provided so far.

Similarly, Litvak et al. (2017) suggested that the Juan Fernandez ridge, classically related to the Pampean flat-slab (33°S–27°30S, Fig. 2a), somehow influenced the slab buoyancy in the south triggering shallow subduction between 35° and 38°S at the study area. Nevertheless, the effect of this ridge as a driving mechanism for Pampean flat-slab, has been disregarded based on recent kinematic reconstructions (Skinner and Clayton, 2013) and its origin has been linked to other causes (e.g., hydrodynamic suction, Manea et al., 2012). This fact precludes any possible genetic connection between the Juan Fernandez ridge and the Neogene shallow subduction to the south discussed in this study. Furthermore, numerical modeling studies assessing the effects of subduction of thick oceanic crust indicate that a buoyant impactor is not sufficient to yield a shallow or flat subduction configuration (Gerya et al., 2009; van Hunen et al., 2004).

As shown in the 2-D reconstruction of the convergent margin in the Southern Central Andes at 10 Ma the Payenia plume possibly located below the Nazca plate during the slab shallowing stage. Furthermore, the Neogene plate kinematic reconstruction supports a potential connection between Payenia plume overriding and slab shallowing development. This is indicated by a close spatio-temporal relation between the suggested progressive plume subduction and stepwise arc-front migrations to the foreland area. In the light of the data presented, we propose that Neogene fold and thrust belt reactivation and intraplate deformation in the Southern Central Andes may constitute a potential case of plume-modified orogeny (Murphy et al., 1998). Moreover, this proposal provides a unified model that accounts for apparently unconnected tectonic events in Neogene times.

In this sense, suggested Pliocene slab tearing event at 38°S after shallow subduction and later steepening could also be a consequence of Payenia plume subduction (Murphy et al., 1998; Dalziel et al., 2000; Betts et al., 2009) (Fig. 6).

According to Pesicek et al. (2012), slab tearing localized in a major oceanic discontinuity known as the Mocha fracture zone (Fig. 2a). Nevertheless, the observed ESE-WNW direction of the slab tearing (Fig. 2b) is not coincident with the NE- direction of the Mocha fracture zone (Fig. 2a), which weakens the straightforward genetic relation proposed by Pesicek et al. (2012). As noted in Fig. 4b, at the time when slab tearing developed (~5–3 Ma), the Payenia plume partially overlapped the sector where vertical tearing took place. Because plumes usually have some degree of difficulty in breaking through the subducting lithosphere, during subduction plume material may pond at the base of the slab entering in incubation stage (Betts et al., 2012; Murphy, 2016) and leading to progressive assimilation and/or thermal erosion of the oceanic lithosphere (Murphy et al., 1998; Obrebski et al., 2010). As a matter of fact, this could explain the presence of eclogite bodies of possibly recycled MORB detected in the source (SWAP and DEEP) of the southern Payenia basalts (Søager et al., 2013). Hence, we alternatively propose that plume-related thermo-mechanical weakening (Macera et al., 2008; Obrebski et al., 2010) linked to ponding of the Payenia plume at the base of the slab may have facilitated slab tearing.

According to Burd et al. (2014), slab tearing created a window for the asthenosphere to flow during the slab steepening process (Ramos and Folguera, 2011) detaching and pushing the upper part of the ancient Payenia plume (SWAP) towards the NW. If our reconstruction is right, this slab window may have allowed the plume to escape from below the Nazca slab to locate at the base of the South American plate (Fig. 6). Similar processes have been proposed in other plume-slab interaction cases based on seismic tomography surveys and predicted by numerical modeling (Obrebski et al., 2010; Liu and Stegman, 2012). Noteworthy, it is compatible with the proposed northwestward flow during plume decapitation signaled by Burd et al. (2014) (Fig. 6). Furthermore, this scenario explains the diachronous character of slab steepening; starting from the south, where the ancient Payenia plume was firstly located and the tearing took place, and progressing to the north (Gudnason et al., 2012). Also, it is consistent with the presence of different mantle sources in the south (EM1 OIB-type mantle) and north (Depleted MORB-like mantle) of the Payenia volcanic province (Søager et al., 2013; Holm et al., 2016) (Fig. 6).

Finally, it is worth noting that plume-modified orogeny may be difficult to recognize in old contractional belts, especially in those subjected to recurrent tectonic activity. In this sense, we consider that the well preserved evolutionary stages of this peculiar process in the Southern Central Andes and their related deformational effects could facilitate identification of similar events in such complex settings.

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