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Invited Review Article

Transient plate contraction between two simultaneous slab windows: Insights from Paleogene tectonics of the Patagonian Andes

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ABSTRACT

Plate kinematic reconstructions show that the Farallon-Phoenix (Aluk) spreading center subducted under South America sometime between the Late Cretaceous and the Paleogene periods. Geological studies have supported a ridge-trench interaction in Patagonia during Paleocene to Eocene times mostly based on the documentation of slab window magmatism and Andean arc-quiescence. However, a revision of most recent works dealing with the Paleogene tectonic evolution of Central Patagonia between 39 °S to 50 °S highlights inconsistencies in this model. Particularly, the existence of two discrete areas with simultaneous slab window-related magmatism separated by a sector with plate-wide contraction, along with a spatio-temporal mismatch between magmatism location and ridge kinematics, preclude a single ridge-trench interaction. With the purpose to better understand this complex tectonic setting, we integrated this updated geological evolution into a plate kinematic model. We propose that the oblique collision of a segmented Farallon-Phoenix/Aluk mid-ocean ridge would explain the latitudinally variable tectonomagmatic evolution of Patagonia during early Paleogene times. Finally, this work adds resolution to geodynamic processes in active margins where complex midocean ridge-trench interactions take place.

1. Introduction

Plate kinematic reconstructions in the southeast Pacific Ocean indicate that the Farallon-Phoenix (or Aluk) mid-ocean ridge should have subducted someplace beneath South America during Late Cretaceous to Paleogene times (Cande and Leslie, 1986; Somoza and Ghidella, 2012; Eagles and Scott, 2014) (Fig. 1). However, the precise location and geometry of this oceanic feature through time remains somehow uncertain (Somoza and Ghidella, 2012). Geological constraints based on the finding of a Paleocene-Eocene arc shut-off and intraplate magmatism with geochemical signatures compatible with slab window development allowed placing this interaction in Patagonia south of 43–44 °S (Ramos and Kay, 1992; Kay et al., 2004), supporting previous inferences of Cande and Leslie (1986). More recently, Aragón et al. (2011a, 2013) argued that ridge collision took place further north, between 36 °S to 44 °S, based on geochemical and seismic tomography evidences of Paleocene-Eocene Phoenix/Aluk slab detachment. Additional complexity has been provided by recent works showing that certain sectors experienced intermittent arc activity in Eocene times (Pankhurst et al., 1999; Fernández Paz et al., 2018) and even intraplate contraction from Paleocene to Eocene times, contrarily to what is expected in slab window settings (Navarrete et al., 2015; Gianni et al., 2015a,b, 2017).

The geological record gives us information about the potential past locations and kinematics of mid-ocean ridges, even when oceanic plates have been totally subducted (e.g. Atwater, 1990; Breitsprecher et al., 2003). In this study, with the aim to better understand this complex tectonic setting, we carry out a revision of latest works dealing with the Paleogene tectonic evolution of Central Patagonia between 39 °S to 50 °S (Fig. 1). Then, this updated evolution is used as constraint in a plate kinematic model to put forward a hypothetical scenario that explains enigmatic features in Paleogene times, such as simultaneous slab-window synextensional magmatism at two different latitudes and subduction orogenesis between them.

2. Brief tectonic setting of the Patagonian Andes

The configuration of the Patagonian Andes at the analyzed latitudes is linked to the eastward subduction of the Nazca and Antarctic plates beneath the South American plate (Fig. 1a). The three plates interact in the Chile triple junction at 46° 30′ S. At this location the active Chile slab window develops to the south beneath Patagonia producing late Miocene to Pleistocene magmatism and dynamic uplift (Guillaume et al., 2010) (Fig. 1a). The Chile triple junction is linked to a major

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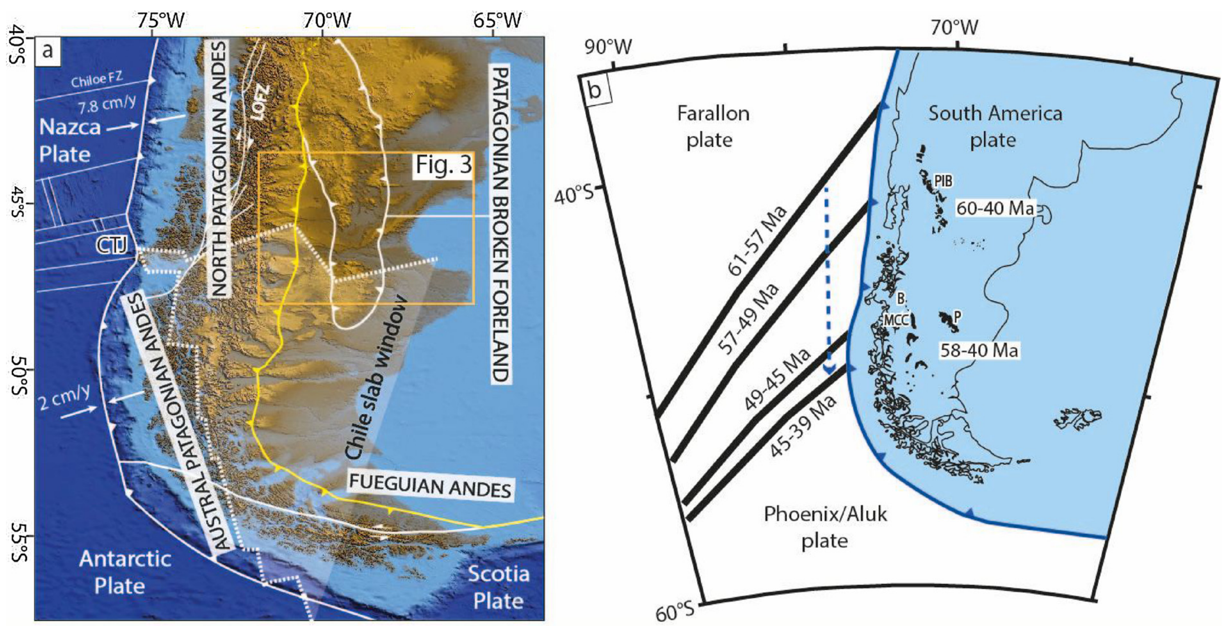

Fig. 1. a) Tectonic setting of the Patagonia showing the North and Austral Patagonian Andes, and the broken foreland area. Abbreviations are CTJ: Chile triple junction, LOFZ: Liquiñe-Ofqui fault zone, DM: Deseado Massif and NPM: North Patagonian Massif, FTB: Fold-thrust belt. b) Southward sweeping of the Farallon–Phoenix/Aluk mid-ocean ridge during Paleogene times according to the recent reconstruction of Eagle and Scott (2014) and as previously suggested by Cande and Leslie (1986). Slab window related magmatism is represented in black poligons. Abbreviations are: PIB: Pilcaniyeu magmatic belt, P: Posadas basalt, MCC: Meseta de Chile Chico basalts, B: Balmaceda basalts. See Fig. 2 for references to geochronological data.

topographic break that separates the North Patagonian Andes from the Austral Patagonian Andes. To the east, in an intraplate position, a ~700–800 km long orogenic belt known as the Patagonian broken foreland is located in a weak lithospheric zone (elastic thickness < 10 km) that absorbed 3–4% of intraplate contraction during Andean orogenesis (Echaurren et al., 2016; Gianni et al., 2017) (Fig. 1a).

3. Paleogene geology of Central Patagonia

In this section we briefly review the main geological features of the Paleogene history of Central Patagonia. We organized our analysis by making a geological synthesis of three different segments at 39°–44 °S, 45°–46°30′S and 46°30′–50 °S.

3.1. Paleocene-early Miocene geology of the 39 °S to 44 °S Andean segment

In this orogenic segment the Paleogene evolution is marked by the appearance of voluminous synextensional magmatic activity developed from the Pacific to the Atlantic coasts (Fig. 2). It is mainly represented by the Pilcaniyeu, El Maiten and Coastal volcanic belts, and the Somuncura basalts (Rapela et al., 1983, 1987; Rapela and Kay, 1988; Kay et al., 2007; Muñoz et al., 2000; Aragón et al., 2011a,b) (Figs. 2 and 3).

The oldest magmatic event, related to the Paleocene–Eocene Pilcaniyeu belt, is composed of bimodal calc-alkaline volcanic rocks (basalt–rhyolite) with large amounts of ignimbrites and a subordinate andesites and basalts toward the top of the sequence (Rapela et al., 1987). Most radiometric ages in these volcanic rocks range from ~60 to 42 Myr (González Díaz, 1979; Rapela et al., 1983; Mazzoni et al., 1991; Aragón et al., 2011b; Iannelli et al., 2017) (Fig. 2). These rocks present an intraplate signature as indicated by a relatively elevated content of HFSE reflecting low percentages of mantle melting and a lack of contribution of slab fluids (Ba/Ta = 1.84–378.75, La/Ta = 0.36–32.89 and Nb/Yb = 0.42–29.72) (Aragón et al., 2011a, b). According to Iannelli et al. (2017), closer to the inner orogenic sector younger outcrops of the Pilcaniyeu Belt magmatism (~44 Ma) present an alkaline-like tendency with an arc-like signature. Recently, Savignano et al. (2016) documented a Paleogene exhumation event between 41 °S to 43 °S in the foreland region. However, it was wrongly attributed to contractional tectonics as evidenced by field documentation of syn-extensional volcanosedimentary wedges (Echaurren et al., 2016) and geochemical data indicating crustal thinning at that time (e.g. Aragón et al., 2011a, 2013). Subsequent magmatism is linked from west to east to the Coastal volcanic belt, El Maiten belt, and the Somuncura basalts (Fig. 3). The Coastal Magmatic Belt between 40 °S to 43 °S is composed of basaltic to dacitic lava flows with a variable geochemical signature defined by a mixture of slab signal and pristine mantle source and presents ages ranging from ~39 to 18 Myr (Muñoz et al., 2000; Henriquez Ascensio, 2016). To the east, contemporaneous magmatic activity took place in the El Maitén Belt assigned to the ~37–20 Myr time interval (Oligocene-lower Miocene) based on K-Ar and U-Pb ages (Rapela et al., 1983, 1988; Kay et al., 2007; Fernández Paz et al., 2018). As a whole the entire magmatic belt presents a mostly andesitic composition (Rapela et al., 1988). Particularly, the oldest outcrops (37 Ma) include mainly tholeiitic basaltic and andesitic lava flows (Fernández Paz et al., 2018). Subsequent, Oligocene magmatic activity is largely composed of calc-alkaline andesites (Rapela et al., 1988). Finally, this volcanism ends up with ~22–20 Myr tholeiitic basalts interbedded with marine deposits and alkaline lava flows (Bechis et al., 2014; Litvak et al., 2014). Geochemical data on these rocks show a time-progressive signal of slab-derived components with Ba/Ta, La/Ta and Nb/Yb ratios comparable with the present-day Andean arc (Fernández Paz et al., 2018). The El Maiten magmatism was erupted under an extensional setting as revealed by the presence of syn-extensional wedges and geochemical evidence of extrusion in a relatively thin crust (Bechis et al., 2014; Echaurren et al., 2016; Fernández Paz et al., 2018). Further east in an intraplate position, volcanic rocks of the Somuncura basalts that range in age from ~29 to 17 Myr, erupted almost coetaneous to the arc-related Coastal and El Maitén belts (Kay et al., 2007) (Fig. 3). These include late Oligocene pre-plateau flows of alkaline basalts and hawaiites, plateau flows of dominantly hypersthene normative basalt and basaltic andesites and post plateau mainly alkaline olivine basalts and hawaiites (Kay et al., 2007). This magmatic activity was characterized by La/Ta and Ta/Hf ratios characteristic of intra-plate settings (La/Ta = 9.04–19.84 and Ta/Hf = 0.14–1.03) with a major pulse

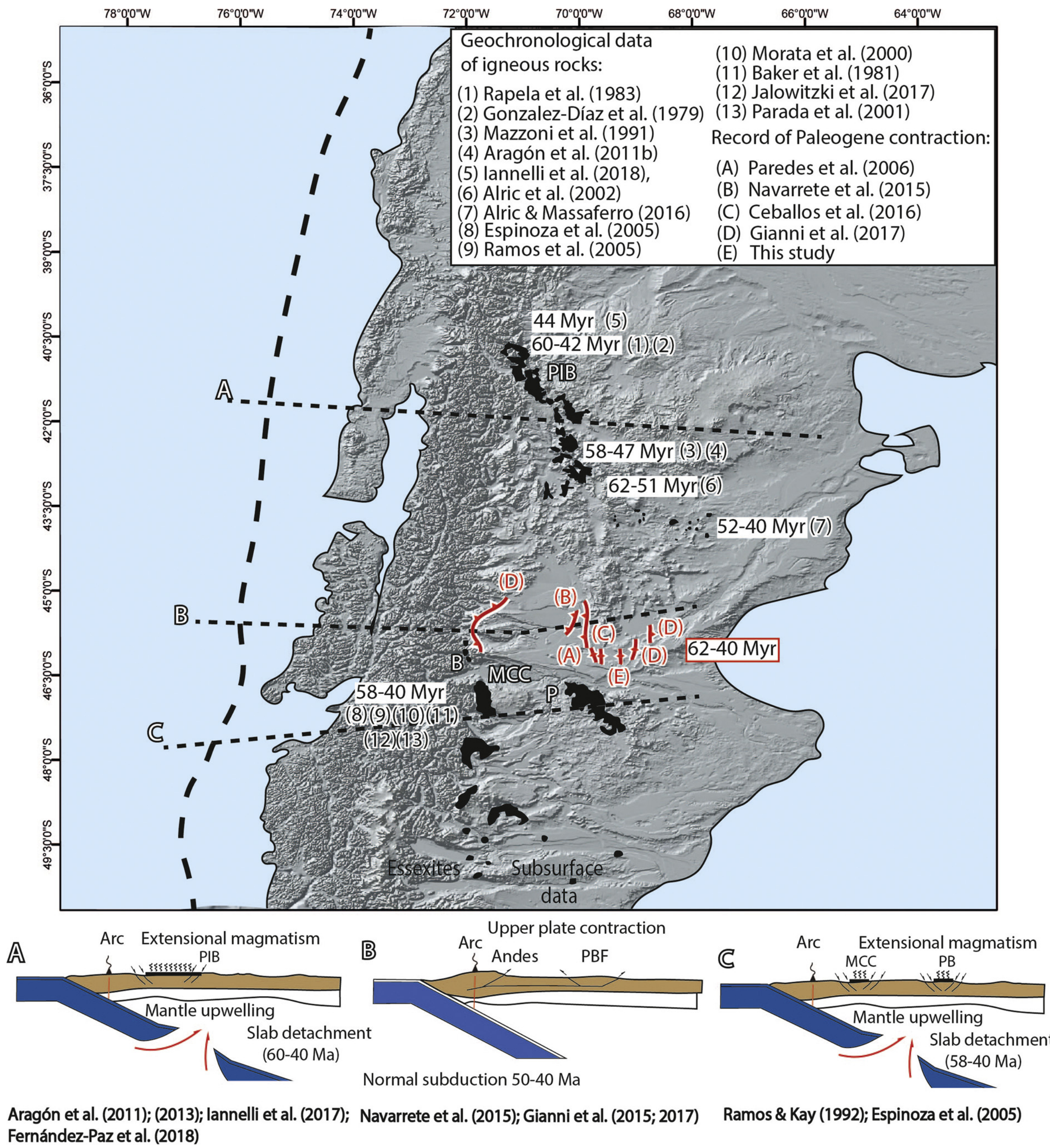

Fig. 2. Tectonic setting of Patagonia during the ~60 to 40 Myr time interval from 39°30′S to 50 °S. Synextensional within-plate igneous rocks were mostly emplaced in two segments, one at 39 °S to 44 °S and the other from 46°30′S to 50 °S. In between the latter segments, contraction from the plate margin to the intraplate area took place at those times and within-plate magmatic activity was practically absent. A to C are three schematic cross sections summarizing the proposed geodynamic contexts between 60-40 Myr. Abbreviations are: PIB: Pilcaniyeu magmatic belt, P: Posadas basalt, MCC: Meseta de Chile Chico basalts, B: Balmaceda basalts, PBF: Patagonian broken foreland (Alric et al., 2002).

presenting higher concentrations of mobile elements indicating slab influence in the mantle source (Ba/ Ta = 88.10–713.75, Ba/ La = 8.97–40.29) (Kay et al., 2007; Remesal et al., 2012).

3.2. Paleocene-early Miocene geology of the 45 °S to 46°30′S Andean segment

At these latitudes the Central sector of the foreland area is characterized by the presence of the intraplate San Bernardo fold-thrust belt, which is separated ~150–200 km from the North Patagonian Andes by a mostly undeformed zone (Fig. 4). Contrarily to the northern and southern segments, in this segment magmatic activity is significantly restricted and the Cenozoic record presents a comparably larger volume of sedimentary rocks (Figs. 2 and 4).

The Cenozoic history in the North Patagonian Andes at analyzed latitudes begins with Paleocene to Eocene olivine-phyric Balmaceda flood basalts (e.g. Parada et al., 2001). The latter, mainly took place at 46 °S as localized extrusions erupted between ~60–46 Myr (Baker et al., 1981; Butler et al., 1991; Demant et al., 1996; Morata et al., 2000; Parada et al., 2001) (Fig. 2). These are peridotite xenolith-bearing alkaline basalts characterized by HIMU-like OIB signature with a marked positive Nb–Ta anomalies and negative anomalies in highly incompatible and fluid-mobile elements (Rb, K, Pb, and Sr) (Jalowitzki et al., 2017).

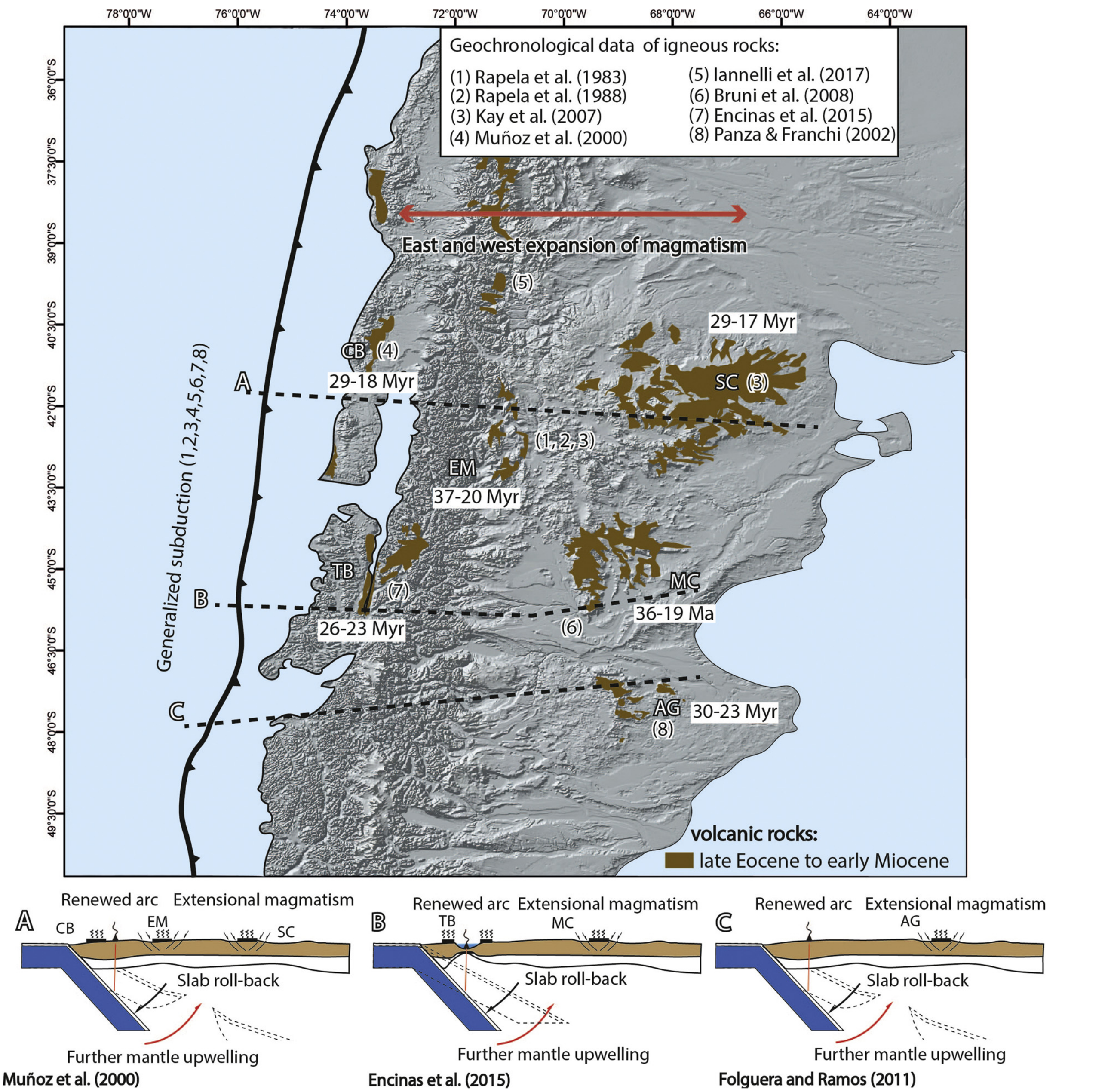

Fig. 3. Tectonic setting of Patagonia during ~36 to 18 Myr from 39°30′S to 48 °S. At this time synextensional magmatism spread in an east and west direction from the intraplate area to the forearc zone. A to C are three schematic cross sections summarizing the proposed geodynamic contexts between ~36 to 18 Myr. Profiles A, B, and C are the general models for the latest Eocene to early Miocene time interval, where tectonomagmatic activity has been linked to mantle upwelling induced by slab-roll back during rapid and orthogonal plate convergence. Abbreviations are CB: Coastal magmatic belt, TB: Traiguen Basin, MC: Meseta Cuadrada basalts, EM: El Maitén magmatic belt, AG: Alma Gaucha basalts and SC: Somuncura basalts.

To the east, in the surroundings of the San Bernardo FTB the Cenozoic sedimentary cycle in the foreland region began with the record of the first Atlantic marine ingression in Danian times (Fig. 4).

In the late Paleocene, the marine environment was replaced by the synorogenic fluvial to lacustrine deposits of the Río Chico Group (Raigemborn et al., 2010; Karusse et al., 2017) (Fig. 4). The Rio Chico Group is made up of four units spanning the ~62–42.8 Myr time interval (Clyde et al., 2014; Krausse et al., 2017). From base to top these units are the Las Violetas, Peñas Coloradas, Las Flores and Koluel-Kaike Formations. The synorogenic nature of the Río Chico Group has been indicated based on field and geophysical evidences of a syntectonic control on the deposition of this unit (Fig. 5). Paredes et al. (2006); Navarrete et al. (2015); Gianni et al. (2015a) recognized syncontractional growth-strata in several structures of the San Bernardo fold-thrust belt from seismic lines during deposition of the complete section of the Paleocene to Eocene Río Chico Group (Fig. 5a and b). Similarly, from the analysis of seismic lines and a subsidence curve in the anticlinal Aguada Bandera, Cevallos and Villar (2016) suggested that at least 25% of the total shortening was absorbed during late Paleocene times (Fig. 5c). Recently, Gianni et al. (2017) documented the presence of numerous contractional structures preserving growth-strata in the uppermost unit of the Río Chico Group (Koluel Kaike Formation) dated in 46-42.2 Myr through U/Pb detrital zircon ages (Krausse et al., 2017) (Fig. 5d). To the west, in the North Patagonian Andes in the Meseta de Chalía area, Paleogene deformation has been recently inferred from the recognition of syncontractional growth-strata in the beds dated in 39.9 ± 0.6 Ma (Gianni et al., 2017) (Fig. 5e and f).

Hence, according to the age of syntectonic deposits (~62-40 Myr),

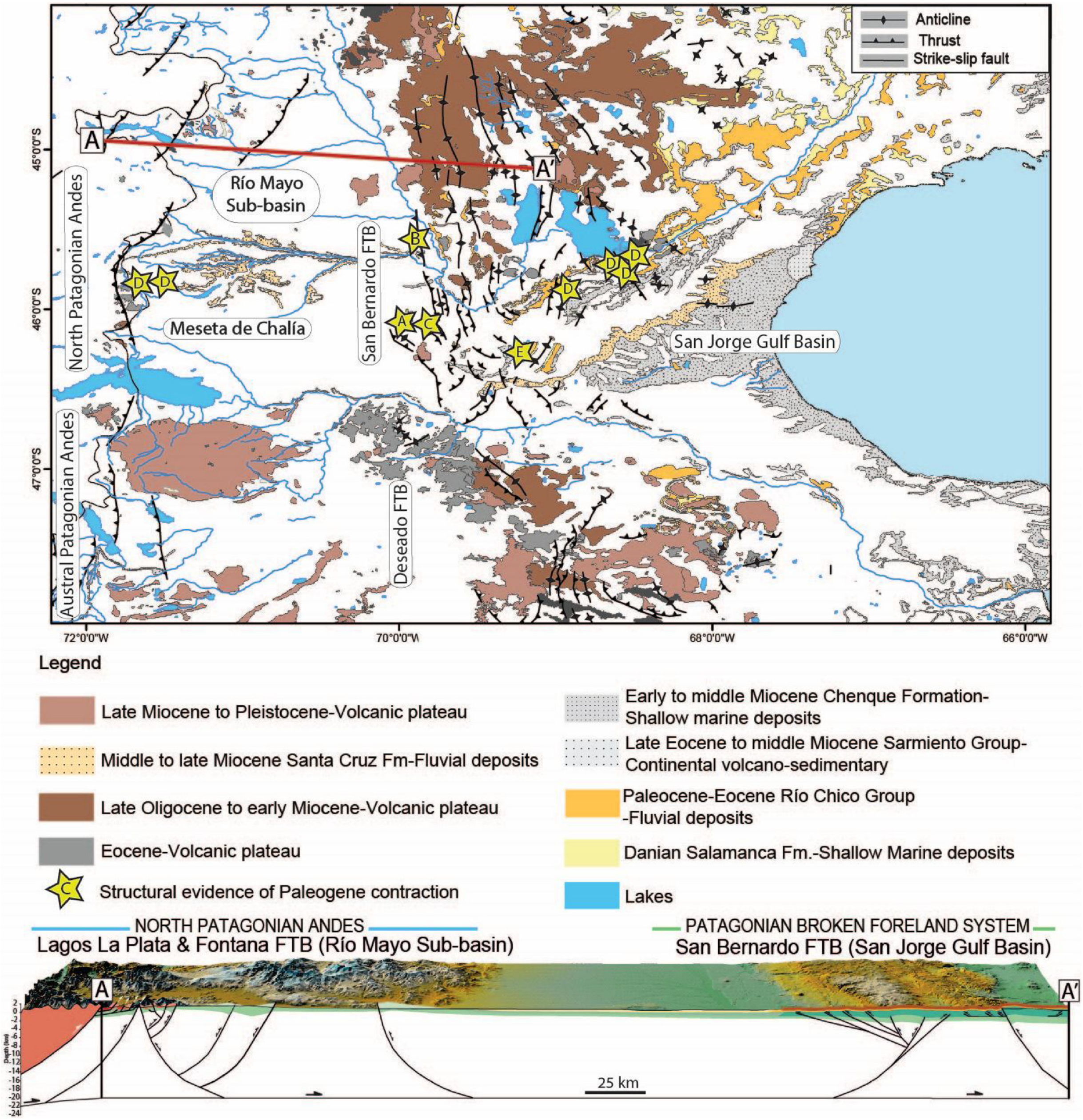

Fig. 4. Geological sketch map showing the main morphostructural units and Cenozoic formations from Patagonia between ~44° to 48 °S. Modified from Gianni et al. (2017). Yellow stars are locations were structural evidences of Paleogene contraction have been documented in field and/or seismic reflexion surveys. References in the stars are. A: Paredes et al. (2006), B: Navarrete et al. (2015), C: Cevallos and Villar (2016), D: Gianni et al. (2017), E: This study (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Central Patagonia between 45 °S to 46°30′S was under compression in late Paleocene to Eocene times with contraction affecting from the plate-margin to the intraplate zone (Figs. 2, profile B and 5). Partially coetaneous to Andean contraction from 45 to 39 Myr metaluminous and calc-alkaline plutonic rocks with arc signature intruded over the western flank of the North Patagonian Andes (Pankhurst et al., 1999). During the latest Eocene to early Miocene, the San Bernardo fold-thrust belt was first intruded by 36 to 33 Myr alkaline rocks and subsequently covered by extensive 27 to 18 Myr basanites, trachybasalts, alkaline and subalkaline basalts and basaltic andesites with a within-plate geochemical signature (Bruni et al., 2008; Sciutto et al., 2008) (Fig. 3 and 4). Eocene to Miocene magmatic activity coexisted with deposition of pyroclastic materials reworked by fluvial systems belonging to the Sarmiento Group (Fig. 4). Over the San Bernardo fold and thrust belt volcanic rocks were extruded through extensional faults and fissures (Gianni et al., 2017). To the west, despite local mafic outcrops in the Andean foothills ranging in age from 29 to 25 Myr (Dal Molin, 1998; Morata et al., 2005), Oligocene to early Miocene magmatism mostly concentrated in the Traiguén–basin in the forearc region (Hervé et al., 1995) (Fig. 3). This basin was characterized by a thinned crust and extensive pillow basalts dated between 26 to 23 Myr with arc-like signature that were extruded syn-extensionally in a deep marine environment (Hervé et al., 1995; Encinas et al., 2015).

3.3. Paleocene-early Miocene geology of the 46°30′S to 50 °S Andean segment

In the foothills of the Austral Patagonian Andes extensive alkaline basalts with typical OIB signature, known as the Posadas basalt, were extruded between ~53 to 40 Myr (Ramos and Kay, 1992; Kay et al.,

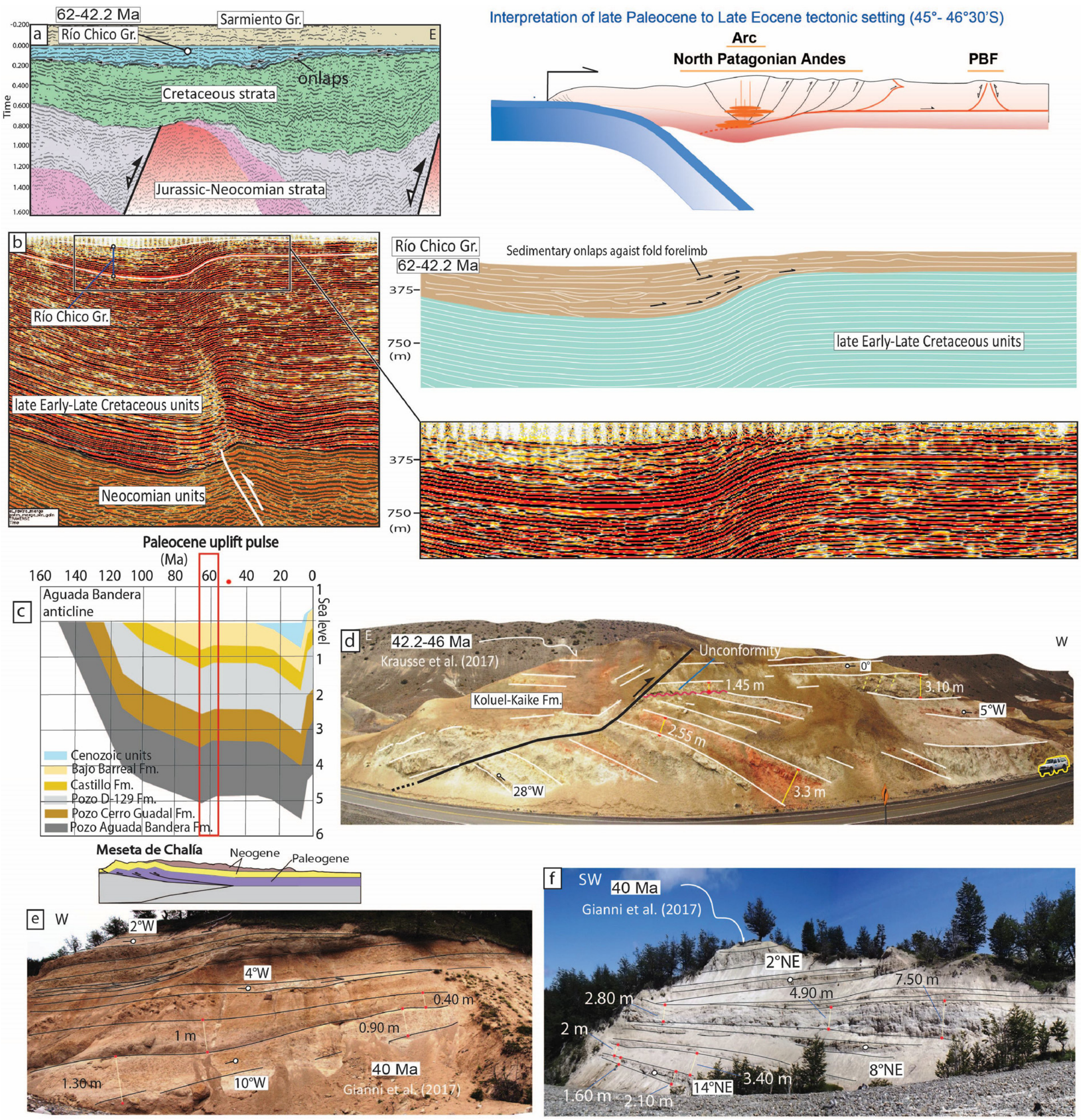

Fig. 5. Structural evidence of late Paleocene-Eocene contraction between 45 °S to 46°30′S. a) and b) are examples of late Paleocene-Eocene growth of contractional structures observed in seismic lines. a) is modified from Gianni et al. (2015a), b) is from this work. c) Subsidence curve of the Aguada Bandera anticline depicting an uplift stage during Paleocene times. Modified from Cevallos and Villar (2016). d) Eocene syncontractional growth-strata in the uppermost unit of the Río Chico Group (Koluel Kaike Formation). Modified from Gianni et al. (2017). e) and f) are syncontractional growth-strata documented in the Meseta de Chalía in the north Patagonian Andes dated in 40 Ma by Gianni et al. (2017). Abbreviation PBF: Patagonian broken foreland.

2004; Ramos, 2005 and references therein) (Fig. 2). The Posadas basalts have also been detected in the subsurface area of the Austral basin to the south (Ramos, 1982a,b), associated at surface with essexite dikes all along the Andean foothills between 46°30′S to 51 °S (Ramos, 2002) (Fig. 2). Coetaneous to intraplate magmatism, syn-extensional OIB-like flood basalts and some peridotite xenolith-bearing basanitic necks, belonging to the Meseta de Chile Chico, were erupted over the foothills of the Austral Patagonian Andes (Espinoza et al., 2005) (Fig. 2). The Posadas basalts and the oldest rocks from the Meseta de Chile Chico are nepheline- or hypersthene- normative, while younger rocks from the latter are more alkaline (> 5% normative nepheline) (Ramos and Kay, 1992). Geochronological data constrained the magmatic activity in these areas to the ~58–40 Myr time interval (Ramos and Kay, 1992; Morata et al., 2000; Espinoza et al., 2005, and references therein) (Fig. 2). At the same time of extensive magmatic activity at these latitudes, a magmatic null in subduction-related magmatism took place from 65 to 34 Myr between 46°30′– 48 °S (Ramos et al., 1982; Suárez and de La Cruz, 2001).

The Oligocene to early Miocene was characterized by significant magmatic activity linked to the poorly studied Alma Gaucha Basalts in the intraplate area (Fig. 3). These are characterized by the presence of extensive basalts flows, necks and dikes of melanocratic olivinic basalts and basanites ranging in age from 30 to 23 Myr (Panza and Franchi, 2002).

4. Paleogene geodynamic models for Central Patagonia

The geodynamic setting of the widespread magmatic activity between 39 °S and 44 °S has been associated with the southward sweep of the Farallon-Phoenix/Aluk mid-ocean ridge (Aragón et al., 2011a, 2013) that potentially interacted with the Patagonian margin in Paleogene times (Cande and Leslie, 1986) (Fig. 1b). According to Aragón et al. (2011a), the divergent Farallon plate could not be subducted and it was coupled to the continental crust along a transform fault. As the Phoenix/Aluk plate was detached it produced a slab window event and asthenospheric upwelling that lasted ∼30 Myr. As stated by Aragón et al. (2011a, 2013), from the ∼60 to 40 Myr time interval, the slab window resulted in the development of an arc-shut-off, accompanied by the eruption of large volumes of syn-extensional bimodal volcanism of the Pilcaniyeu belt in an intraplate setting (Fig. 2, profile A). However, more recently Iannelli et al. (2017) and Fernández Paz et al. (2018) indicated the presence of syn-extensional volcanic rocks with arc-like signature, suggesting the activation of incipient subduction at these latitudes during the last stages of this magmatic event between 44-37 Myr. Subsequently, in a more evolved stage during the Oligocene to early Miocene, Andean subduction became more active (Rapela et al., 1983, 1987, 1988) and further mantle upwelling produced a significant spreading of magmatism, presenting arc and MORB-intraplate signatures to the east and west, respectively (e.g. Muñoz et al., 2000; Kay et al., 2007; Aragón et al., 2011a, 2013, 2017; Alric and Massaferro, 2016) (Fig. 3). After the latest Eocene onset of incipient subduction, significant mantle upwelling inferred at this stage could also have been aided by a coetaneous slab rollback (Muñoz et al., 2000; de Ignacio et al., 2001) likely facilitated after Phoenix/Aluk slab detachment (Fig. 3, profile A). However, intraplate mantle upwelling related to the Somuncura basalts has been alternatively related to a transient hot-spot or a delamination event (Kay et al., 2007; Remesal et al., 2012), and hence, its origin remains under discussion. Noteworthy, the slab window model at these latitudes is independently supported by seismic tomography in Patagonia indicating a subduction gap manifested in an absence of fast anomaly continuity in the tomographic model (Aragón et al., 2011a,b). Based on kinematic calculations these authors interpreted the discontinuity in the imaged slab as the detachment of the Phoenix/Aluk slab in Paleogene times. Noteworthy, the subduction of this ridge has been associated with Late Cretaceous intraplate volcanism to the north (35°30′S), implying a southward younging trend of retroarc eruptions in which the Pilcaniyeu Belt could have been part (Iannelli et al., 2018).

To the south, the Paleogene geodynamic setting of the Andes between 45 °S to 46°30′S was also related by Parada et al. (2001) to the interaction of the Alluk/Farallon ridge based on the presence of small outcrops of the OIB Balmaceda basalts in the Andean foothills (see also Jalowitzki et al., 2017) (Fig. 3). However, at these latitudes, magmatic activity is very restricted, extensional activity is lacking and in contrast to the above described segment, strong contractional activity affected from the plate-margin (Patagonian Andes) to the intraplate sector (San Bernardo fold-thrust belt). As previously mentioned, the late Paleocene to Eocene contractional deformation documented in the entire region was associated with ∼62 to 40 Myr synorogenic deposition (Paredes et al., 2006; Cevallos and Villar, 2016; Navarrete et al., 2015; Gianni et al., 2017) (Figs. 2 and 5). According to Gianni et al. (2017), the compressional stress-field originated in an active margin to the west as indicated by the record of partially coeval subduction-related magmatic arc activity between ∼45 to 39 Myr (Figs. 2, Profile B and 5). Noteworthy, Pankhurst et al. (1999) related this stage of ∼45–39 Myr arc magmatism to a period of rapid orthogonal convergence. The virtual absence of Paleocene arc magmatism has been interpreted as produced by a shallow slab angle at that time (Suárez and de La Cruz, 2001; Gianni et al., 2018).

Subsequently, a change to extensional deformation at analyzed latitudes took place in latest Eocene at ∼36–33 Myr with alkaline intrusions over the San Bernardo fold-thrust belt (Bruni et al., 2008). The strongest manifestation of this stage occurred between Oligocene to early Miocene times, when widespread syn-extensional magmatism extended over the forearc region, the Patagonian Andes and the San Bernardo fold thrust belt (Fig. 3). In the San Bernardo fold thrust-belt, extensional activity was responsible for causing the partial collapse of previous orogenic relief (Rodriguez and Littke, 2001; Gianni et al., 2017). To the west, this extensional stage achieved its maximum expression in the forearc region with the development of the quasi-oceanic floored intraarc Traiguen Basin (Hervé et al., 1995; Encinas et al., 2015 (Fig. 3). According to Encinas et al. (2015), a slab rollback model in a context of high plate convergence (e.g. Pardo Casas and Molnar, 1987) accounts for all the characteristic features of this stage (Fig. 3, Profile B). In this sense, an accelerated asthenospheric-wedge circulation and the steepening of the subduction angle would explain the generalized extension and crustal thinning, as well as the widespread volcanism with a geochemical signature of mixed pristine mantle source and slab-fluids.

To the south, between 46°30′ and 50 °S, the Paleogene geodynamic evolution is somehow similar to the 39°–44 °S segment. From Paleocene to Eocene times, widespread plateaux basalts erupted from the Andean foothills to the intraplate sector under an extensional regime (Ramos and Kay, 1992; Espinoza et al., 2005) (Figs. 2 and 4). Collectively, the Paleocene to Eocene magmatic arc quiescence and the OIB-like magmatism described between 46°30′ to 52 °S, have also been interpreted as evidence of mantle upwelling linked to a slab-window formed during the Paleogene subduction of the Farallon-Phoenix/Aluk mid-ocean ridge (Ramos and Kay, 1992; Kay et al., 2004; Espinoza et al., 2005) (Fig. 2, Profile C).

Geochemical data from Oligocene to early Miocene mafic rocks at these latitudes are lacking so far, hampering any interpretation about its geodynamic setting. Nevertheless, based on the timing of magmatic activity and petrological similarities with other Oligocene-Miocene rocks in Patagonia, Folguera and Ramos (2011) related these outcrops to mantle upwelling produced by slab roll-back (Fig. 3, Profile C).

5. Discussion: proposed tectonic model for the Paleogene tectonic evolution of Central Patagonia

Central Patagonia between 39° to 50 °S presents striking latitudinal contrasts in its Paleogene geological record and consequently, in the interpreted geodynamic settings, specifically during the 60–40 Myr time interval.

As seen in Fig. 2, most of the ∼60–40 Myr slab window-related extensional magmatism was mainly circumscribed to two discrete zones at 39°–44 °S and 46°30′–50 °S. In between them, a segment coinciding with the Southern region of the North Patagonian Andes and the San Bernardo fold-thrust belt was characterized by a completely different tectonic regime at those times (Fig. 5). As reviewed in previous section, plate-wide contraction took place from late Paleocene to Eocene times (Paredes et al., 2006; Navarrete et al., 2015; Gianni et al., 2015a,b, 2017; Cevallos and Villar, 2016) and 60–40 Myr intraplate magmatism was almost absent with the exception of local basaltic outcrops in the Balmaceda area at 46 °S (Parada et al., 2001) (Fig. 2, profile B). Hence, as depicted in this revision, the Paleogene tectonic scenario of Central Patagonia is more complex than previously acknowledged. Particularly, the segmented nature of Patagonia from ∼60 to 40 Myr in terms of stress regimes (compressional vs. tensional) and magmatic activity does not seem to fit with the classic models proposing a single mid-ocean ridge collision-slab window event (e.g. Ramos and Kay, 1992; Espinoza et al., 2005; Aragón et al., 2011a) (Fig. 2). Slab window episodes are often related to the activation of generalized extensional to transtensional deformation, sometimes in the plate margin (e.g. see Sisson et al., 2003 for a synthesis; Scalabrino et al., 2010) and more commonly in the continental interior (see Thorkelson, 1996 and references therein). The latter prediction, is in stark contrasts with the contractional deformation described from the Andes to the intraplate area between 45 °S to 46°30′S (Figs. 2 and 5). Additionally, the fact that the same mid-ocean ridge is invoked to explain practically simultaneous intraplate

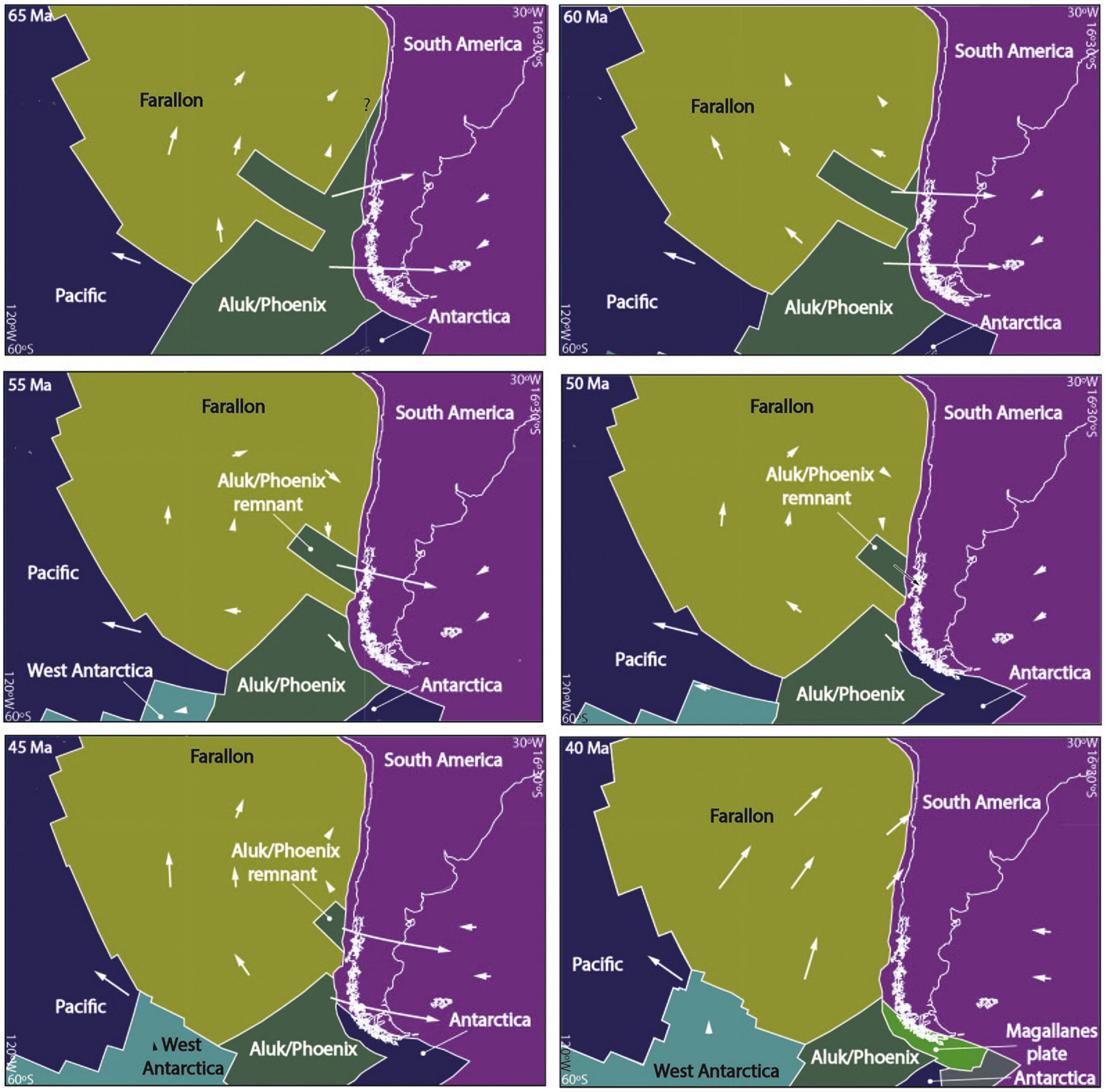

Fig. 6. Proposed reconstruction of the interaction of the Farallon/Aluk(Phoenix) mid-ocean ridge and the South American margin in Paleogene times shown in Mercator projection. The reconstruction was obtained by modifying previous model of Müller et al. (2016) by including the existence of a transient Aluk(Phoenix) plate remnant. The early Paleogene geological record of two potential slab windows at 39 °S-44 °S and 46°30′–48 °S, and plate-wide contraction linked to normal subduction between those segments were used as constraints in these reconstructions. The kinematic model is available at: http://doi.org/10.5281/zenodo.1311733.

magmatism and extensional activity in areas separated ~400 km from each other is also puzzling (Fig. 2). In this sense, according to most recent plate kinematic reconstructions of Eagles and Scott (2014), at the time the Meseta de Chile Chico-Posadas-Balmaceda basalts erupted (58–55 Myr), the Farallon-Phoenix/Aluk ridge was colliding with the Patagonian margin ~500 km to the north (Fig. 1b). On the other hand, if we consider previous reconstructions of Cande and Leslie (1986) and Somoza and Ghidella (2012), between 50-49 Myr the mid-ocean ridge collision took place at 37°'30′S about 1000 km to the north from the Meseta de Chile Chico-Posadas basalts. These inconsistencies indicate the necessity of further study to fully understand the causes of latitudinally contrasting tectonomagmatic episodes in Central Patagonia in early Paleogene times. Following, we make a first attempt to assess this complex geodynamic setting.

As mentioned above, the existence of two areas with simultaneous slab window-related magmatism separated by a sector characterized by plate convergence and contraction, precludes a single mid-ocean ridge-trench collision event (e.g. Ramos and Kay, 1992; Aragón et al., 2011a) (Fig. 2). A possible explanation for the simultaneous slab window magmatism may involve the propagation of a horizontal slab tear during Paleogene ridge subduction. In this regard, 2-D dynamic numerical models of Burkett and Billen (2009) have shown that the approach of an oceanic ridge leads to a slab detachment anticipating ridge subduction. This is because of both the increase of slab buoyancy and the progressive decrease on lithospheric strength. However, as proposed by Guivel et al. (2006) for the Chile slab window, slab detachment related to the Farrallon-Phoenix/Aluk ridge is predicted to take place to the east of the 39°–44 °S slab window, and not far to the south as seen in this case. Furthermore, as previously mentioned, intraplate magmatism at 46°30′–50 °S is largely simultaneous to within-plate magmatic activity at 39°-44 °S, not following the expected magmatic chronology in this process (Burkett and Billen, 2009). Alternatively, this latitudinally variable tectonomagmatic activity could be interpreted as the record of two coeval slab windows. In this sense, Thorkelson (1996) theorized about the possibility of the simultaneous formation of multiple slab windows separated by subducting plate remnants, termed *fraternal slab windows,* caused by oblique collision of a segmented mid-ocean ridge. Thus, a potential explanation for the Paleogene tectonic setting of Central Patagonia may be to considering the collision of a ridge segmented by transform faults as seen in nature, instead of a straight one, as is often sketched in plate kinematic reconstructions (e.g. Cande and Leslie, 1986; Eagles and Scott, 2014) (Fig. 1b). Indeed, segmentation of the Farallon-Phoenix/Aluk mid-ocean ridge has been previously inferred by Somoza et al. (2012), to explain latest Cretaceous arc shut-off, slab window magmatism, and deformation at 22 °S. Recently, Iannelli et al. (2018) also suggested a segmentation in the Aluk/Farallón(Phoenix) ridge to describe an incipient early Paleocene slab window at 36°30′S that coexisted with active subduction immediately to the south of this latitude. The hypothetical interaction of a ridge segmented by a combination of left and right-stepping transform faults, forming two eastward ridge offsets and one in the middle towards the west, would allow the development of two separate slab windows. Furthermore, it would also permit the transient existence of a small converging remnant plate in between. A similar configuration has been inferred for the Resurrection plate at 55–39 Myr in the northeastern Pacific Ocean (Madsen et al., 2006). In order to illustrate this process, and to adjust it to previously published plate kinematic scenarios, a recent global plate reconstruction model (Müller et al., 2016) is utilized in the free-access Gplates software (www.gplates.org). Müller et al. (2016) incorporated the model of Eagles and Jokat (2014) for the opening of the Scotia Sea, which in turn, utilizes finite rotation of Eagles and Scott (2014) for their reconstructions. Thus, this hypothetical ridge configuration was integrated by modifying the geometry of the straight Farallon-Phoenix/Aluk mid-ocean ridge in this model using as constraints the geological positions of the slab window-related magmatism and the convergent segment with plate-wide contraction. The ridge geometry was adjusted in order to reproduce the complete subduction of the Phoenix/Aluk remnant plate at ∼40-39 Myr at about the time when contraction ended (Gianni et al., 2017) and before magmatism with asthenospheric signature started in the San Bernardo fold-thrust belt at 36 Myr (Bruni et al., 2008).

Similarly, previous studies in North America have predicted the location of the Kula–Farallon ridge (for which there is no preserved evidence in the seafloor spreading record) based on following evidence of a slab window beneath western North American margin (e.g. Engebretson et al., 1985; Atwater, 1990; Breitsprecher et al., 2003; Madsen et al., 2006). The magnitudes in ridge offsets that yielded the most compatible kinematics with the geological record are within the scales observed in nature (up to ∼600–1100 km) and in those reconstructed in several plate kinematic models (e.g. Johnston and Thorkelson, 1997, Fig. 1; Madsen et al., 2006; Müller et al., 2016). Plate reconstructions are presented at analyzed latitudes from 65 Ma to 40 Ma covering critical times when the slab windows and contraction were fully developed (The kinematic model can be downloaded from an online repository: http://doi.org/10.5281/zenodo.1311733) (Fig. 6). Additionally, the hypothetical slab windows shapes were projected schematically for subhorizontal angles with the aim to compare with the spatial locations of slab window magmatism (Fig. 7). The latter is only used as a reference since thermal erosion can act on slab window edges to enhance a progressive enlargement of the lithospheric gap (e.g. Severinghaus and Atwater, 1990; Thorkelson and Breitsprecher, 2005). Furthermore, as currently seen in the Chile ridge slab window and recently modeled in laboratory experiments, mantle upwelling may flow laterally up to 130 km below the continent producing magmatism beyond the projected slab window (Guillaume et al., 2010) (see inset figure in Fig. 7).

Indeed, this might explain why intraplate magmatism of Meseta de Chile Chico-Posadas-Balmaceda is observed in Fig. 7 about 150–100 km to the north of the projected slab-window. As a result, the modeled position of the segmented Farallon–Phoenix/Aluk mid-ocean ridge with respect to South America correlates with onshore geological and geochemical evidence of ∼60 to 40 Myr slab window events and the existence of a transient convergent zone with contraction between them in Central Patagonia (Fig. 7). Although, narrow subduction zones have been recently associated with upper-plate extension (Schellart, 2008), the potential subduction of a buoyant plate linked to the remnant Phoenix/Aluk slab could be a satisfactory explanation for plate-wide contraction in a latitudinally restricted area (Fig. 6 and 7). In this regard, young oceanic lithosphere (< 10 Ma) tends be neutrally buoyant, being more resistant to subduction and hence, more likely to increase plate coupling (Cloos, 1993). Thus, a higher degree of plate coupling during rapid subduction of the buoyant Phoenix/Aluk remnant plate could have favored a short-lived inland transmission of compressional stresses (Fig. 6). Additionally, subduction of an oceanic plate resisting entrainment could explain the discontinuous nature of Paleogene arc magmatism between 44 °S to 47 °S (Pankhurst et al., 1999; Suárez and de La Cruz, 2001), which contrast with almost continued magmatic arc activity between 60 to 34 Myr in the Austral and Fueguian Andes to the south of 50 °S (Hervé et al., 1984, 2007) (Fig. 1a). The latter regions, to the south of the Meseta de Chile Chico-Posadas basalts slab window, record active orogenesis during Paleogene times, mostly south of 50 °S, with scarce or no evidence of intraplate magmatism (Nelson, 1982; Skarmeta and Castelli, 1997; Kraemer et al., 2002; Ghiglione et al., 2002; Malumián, 2002; Fosdick et al., 2014, among others). Noteworthy, the northward propagation of Aluk/Phoenix remnant plate subduction from 44 to 45 Myr observed in our reconstruction (Fig. 7) explains the influence of slab fluids in the youngest terms of slab window magmatism at 39–43 °S (Iannelli et al., 2017; Fernández Paz et al., 2018).

Finally, we suggest that these two slab windows would have coalesced into a larger slab detachment after the final subduction of the Phoenix/Aluk remnant plate beneath South America after ∼40–35 Myr. This process, could have favored sub-slab poloidal flow enhancing slab roll-back and extension (Guillaume et al., 2010; Fennell et al., 2018), and intraplate magmatism during latest Eocene to early Miocene times (Muñoz et al., 2000; de Ignacio et al., 2001; Bruni et al., 2008; Folguera and Ramos, 2011; Encinas et al., 2015; Fernández Paz et al., 2018).

6. Conclusions

A revision of most recent studies dealing with the Paleogene tectonic evolution of Central Patagonia highlights a latitudinal contrast in the tectonomagmatic evolution of the Patagonian Andes and foreland region. Between 45 °S to 46°30′S the North Patagonian Andes experienced contractional tectonics that produced fold and thrust belt development from the Andean sector to the intraplate area between ∼62 Ma to 40 Myr. Subsequently, a switch in the tectonic regime to extension mainly initiated at ∼36-33 Myr and generalized between ∼27 to 19 Myr when mafic magmatic activity extended from the fore-arc region to the intraplate sector. Integration of the latter tectonic evolution with Paleogene histories immediately to the north (39 °S-44°30′S) and south (46°30′-52 °S) depicts a complex geodynamic scenario. In those areas, Paleocene to mid-Eocene tectonic evolution share similar features, a prolonged magmatic arc quiescence to the west and the eruption of ∼60–40 Myr OIB, OIB-like, and MORB-like syn-extensional mafic and/or bimodal igneous rocks to the east. Geochemical signatures in these rocks have been previously interpreted as the testimony of Farallon-Phoenix/Aluk mid-ocean ridge subduction and slab-window development. As discussed in this study, the existence of two discrete areas with simultaneous slab window-related magmatism separated by a convergent sector with contraction, along with a spatio-temporal incompatibility between magmatism location and Farallon-Phoenix/Aluk ridge kinematics, hamper invoking a single mid-ocean ridge/slab window event.

In this study provide a first attempt to explain this challenging geodynamic scenario in which the latitudinally variable tectonomagmatic activity is interpreted as the record of two coeval slab windows. As shown in the presented kinematic reconstruction, the hypothetical interaction of a segmented mid-ocean ridge would fit best the

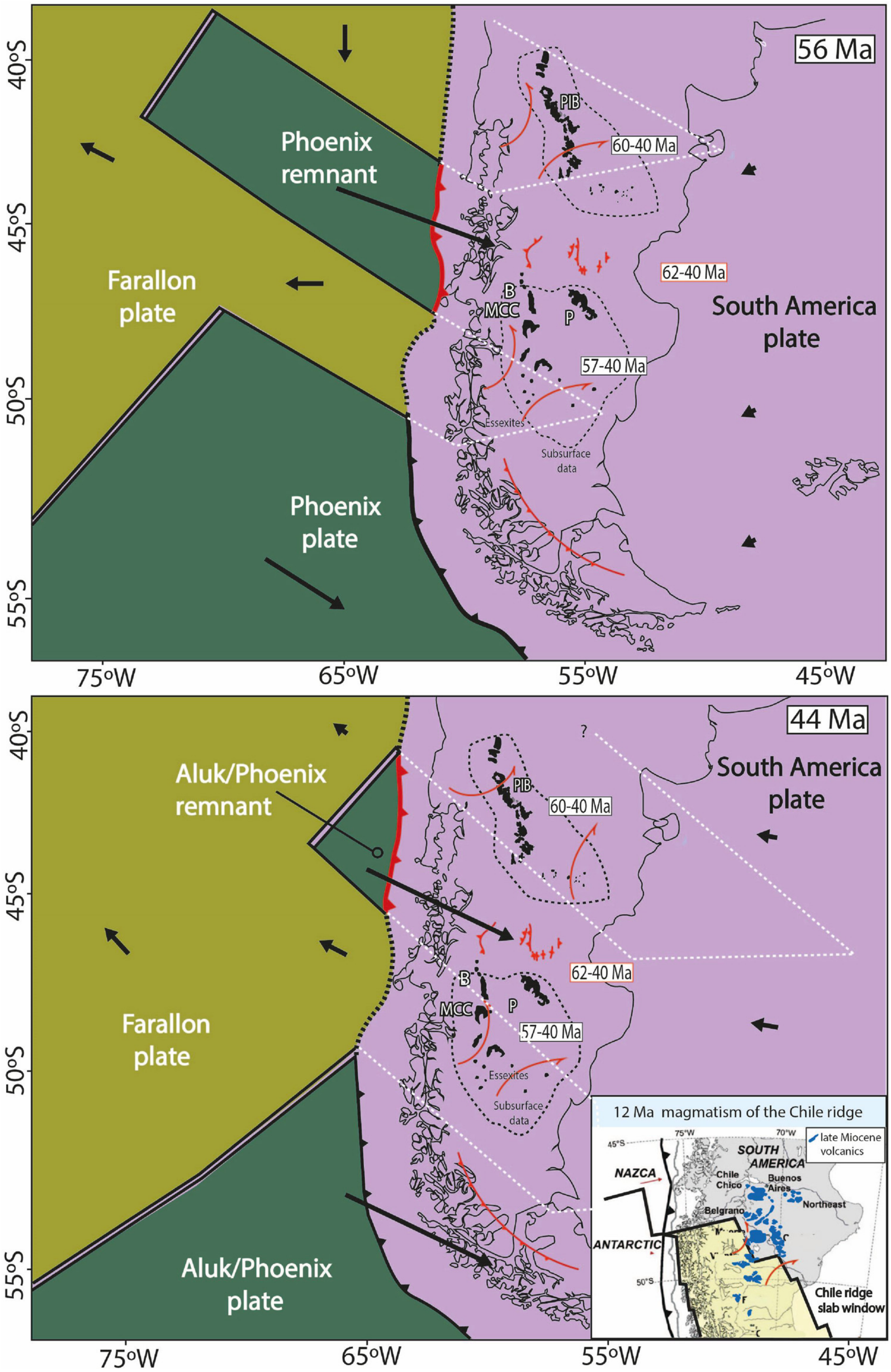

Fig. 7. Proposed geodynamic setting for Patagonia during 60-40 Myr time interval. Inset figure in image below is an example of 12 Ma magmatism beyond the extent of the projected Chile slab window (Breitsprecher and Thorkelson, 2009; Guillaume et al., 2010), used here as an analog for the Balmaceda-Meseta de Chile Chico-Posadas slab window magmatism.

Paleogene geological record. In this regard, two eastward-directed ridge offsets would have allowed the early formation of coeval slab windows to the north at 39°–44 °S and to the south 46°30–50 °S. On the other hand, a westward-directed ridge offset would have permitted the existence of a converging remnant Phoenix/Aluk plate. Subduction of young and neutrally buoyant oceanic lithosphere related to this remnant plate would explain intermittent arc activity and transient plate-wide contraction from the Andes to the intraplate sector between 45 °S to 46°30 °S. These two slab windows would have coalesced into a large slab detachment after the final subduction of the Phoenix/Aluk plate beneath South America at ~40–35 Myr. This could have taken place in a context of orthogonal convergence and slab roll-back, possibly enhancing extension and intraplate magmatism during latest Eocene/Oligocene to early Miocene. Testing the feasibility of this hypothesis will require additional constraints on the geochronology and geochemistry of igneous rocks along the 39 °S-50 °S Andean segment.

Finally, the Paleogene tectonic evolution of Patagonia may help to better understand tectonomagmatic segmentations in the upper-plate of ancient convergent settings, where ridge subduction is expected to have commonly taken place throughout its evolution.

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