Review

The Farallon-Aluk ridge collision with South America: Implications for the geochemical changes of slab window magmas from fore- to back-arc

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ABSTRACT

The collision of a divergent ocean ridge may evolve into two end cases: in the continuity of ocean-floor subduction, or in the detachment of the subducted plate. The northern Patagonia active plate margin has the unique situation that in Cenozoic time it has been subjected to two divergent ridge collisions, each one representing one of the end members. The Neogene Antarctica-Nazca divergent ridge collision evolved as a continuous ocean-floor subduction system, promoting a magmatic hiatus at the arc axis, the obduction of part of the ridge ocean-floor in the fore-arc, and basaltic volcanism in the back-arc. In contrast, the Paleogene Farallon-Aluk divergent ridge collision evolved into a transform margin, with the detachment and sinking of the Aluk plate and the development of a large slab window. As in the previous case, this collision promoted a magmatic hiatus at the arc axis, but the tectono-magmatic scenario changed to postorogenic synextensional volcanism that spread to the former fore-arc (basalt, andesite, rhyolite) and former back-arc (bimodal ignimbrite flare-up, basalt). Geochemistry of this slab window synextensional volcanism shows more MORB-like basalts towards the former fore-arc, and MORB-OIB-like basalts towards the former back-arc. Instead, an isolated undeformable crustal block in the former back-arc, with an "epeirogenic" response to the slab window and extensional regime, was covered by OIB-type basalts after uplift. Major elements show that slab window basalts reach TiO_2 values up to 3 wt%, as compared with the top value of 1.5 wt% of arc magmas. Besides, the MgO with respect to $(FeO^t + Al_2O_3)$ ratio helps to distinguish slab window magma changes from the former fore-arc to the former back-arc and also with respect to the "epeirogenic" block. Higher contents of HFS elements such as Nb and Ta also help to distinguish this slab window from arc magmas and also, to distinguish slab window magma changes from the former fore-arc to the former back-arc and "epeirogenic" block settings. The isotope compositions of slab window magmatism show a disparate coeval array from MORB to crustal sources, interpreted as a consequence of the lack of protracted storage and homogenization due to the extensional setting.

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1. Introduction

The long lived continental active margin of the Americas from Alaska to Patagonia shows significant along-strike and through-time changes of tectonic styles, including transform margins alternating with subduction segments that change from flat to normal subduction styles and obduction episodes (Barazangi and Isacks, 1976, 1979;

Forsythe and Nelson, 1985; Atwatter and Stock, 1998). These differences can be explained mainly by the existence of changes in the convergence geometry and rates, ocean-floor topography, the arrival of active ocean ridges, and the fission of ocean plates. The continental counterpart in the active margin is subjected, in most cases, to compression during subduction and relaxation during transform episodes. In addition to the thick or thin skin tectonic approach, the variety of tectonic responses to these compression-relaxation episodes within heterogeneous continental crust (close to the arc axis or far behind the back-arc) is caused by rheology differences mainly due to the accretion of wet and/or poorly consolidated sediments, the development of large batholiths along the arc axis and the presence of accreted terranes of much older or stabilized crust.

In general, the spreading ridge subduction along the continental margin may show fore-arc magmatism (calc-alkaline and tholeiitic), a lack of magmatism in the arc axis, and a large variety of back-arc magmatism (calc-alkaline, tholeiitic and alkaline) (Armstrong et al., 1985; Rogers et al., 1985; Forsythe et al., 1986; Saunders et al., 1987; Gans et al., 1989; Fitton et al., 1991; Kempton et al., 1991; Cole and Basu, 1992, 1995; Ramos and Kay, 1992; Nelson et al., 1993; Lagabrielle et al., 1994; Hawkesworth et al., 1995; Gorring et al., 1997; D'Orazio et al., 2001; Gorring and Kay, 2001; Hamilton and Dostal, 2001; Benoit et al., 2002; Bradley et al., 2003; Breitsprecher et al., 2003; Cole et al., 2006; Madsen et al., 2006; Kay et al., 2007; Cole and Stewart, 2008). Also, magmatism can show adakitic affinities (Kay et al., 2002; Chang et al., 2010) or transitions from shoshonitic to adakitic affinities (Eyuboglu et al., 2011a,b, 2012).

In Patagonia, two ridge collision episodes occurred during the Cenozoic (Cande and Leslie, 1986; Pardo Casas and Molnar, 1987; Somoza and Ghidella, 2005). One was the Neogene Nazca-Antarctica ridge collision with geometry almost parallel to the trench, along with the obduction of part of the ridge, the subduction of the divergent Antarctica plate, and the end of magmatism in the arc axis, and basaltic magmatism in the back-arc (Forsythe and Nelson, 1985; Nelson et al., 1993; Gorring et al., 1997; Gorring and Kay, 2001; Kay et al., 2002, 2004, 2007). The other was the Paleogene collision of the Farallon-Aluk active ridge (also with geometry almost parallel to the trench) that affected a subduction/supra-subduction system that had been active since the late Jurassic. In this case, the divergent Farallon plate could not be subducted and it was coupled to the continental crust along a transform fault as the Aluk plate was detached, causing the development of a slab window system that lasted 30 Ma (Kay et al., 2002, 2004; Aragón et al., 2011a). The Paleogene slab window resulted in the termination of the magmatic activity at the former-arc axis, accompanied by a landward migration (to the former back-arc) of calc-alkaline magmatism, with change to large volumes of synextensional bimodal volcanism of rhyolitic ignimbrites and interbedded andesites, and tholeiitic/alkalic basalts. At a mature stage (late Oligocene–early Miocene), the magmatism spread broadly through the former fore-arc, arc, and back-arc areas (Rapela et al., 1983, 1987, 1988; Kay and Rapela, 1987; Kay et al., 2002, 2004, 2007; Aragón et al., 2011a). This resulted in MORB-intraplate and arc signatures being developed by mantle upwellings in the slab window, and mantle wedge upwellings inherited from the former-arc, respectively. Besides the slab window model, the Oligocene fore-arc magmatism has been interpreted to be caused by slab roll-back (Muñoz et al., 2000; de Ignacio et al., 2001), and the migration of magmatism from the arc to the back-arc by shallowing the subduction zone geometry (Folguera and Ramos, 2011).

This paper reviews the collision of active ridges with continental plates as a major cause of abrupt changes of convergence geometry and rates that can lead to slab window development, and presents the tectono-magmatic changes that occurred along the profile of the mature Paleogene slab window system of northern Patagonia from the former fore-arc to the back-arc.

2. Active ridge collision

An active ridge is a first order rheological discontinuity in the oceanic crust. It is highly buoyant since it is composed of hotter oceanic lithosphere, and has divergent growth vectors. Therefore, the development of a ridge-trench triple junction by the collision of a divergent ridge with a trench can be one of the most efficient mechanisms to produce subducted ocean-slab detachments and the development of slab windows along a mature, well developed, subduction system. There are many cases in the present time where active ridge-continent collision (triple junction) is known to be occurring (e.g. Rivera triple junction, Mexico; Mendocino triple junction, northwest United States; Woodlark Basin, Solomon Islands; Taitao triple junction, Chile), and in the geological record as well (e.g. Kula-Farallon ridge beneath the Aleutian Islands; Kula-Pacific ridge beneath Japan; Farallon-Aluk ridge beneath Patagonia). Here we provide a brief review of the principles by which this mechanism operates in order to illuminate the existence of two end cases in Patagonia.

Since plates move along the surface of a sphere, the simplest model of a single ocean-continental plate interaction depends essentially on the relative location of the Euler pole of the ocean plate with respect to the continental plate margin. Two usual cases are: (a) the situation that the active plate margin may have the oceanic plate's Euler pole located in a position in which rotation only allows convergence (Fig. 1a). In such a case the only change is an increase of convergence rate as the distance to the Euler pole increases; (b) Fig. 1b shows the situation in which the ocean plate's Euler pole may be located in a position where rotation allows a parallel movement of the oceanic plate with respect to the continental plate. In such a case, along-strike plate interaction may change from the development of a marginal basin, to a transform plate margin, and finally to a subduction plate margin.

A more complex system introduces changes with time, such as the arrival (collision) of an active ridge. In such a situation, there are two possible relationships between the Euler poles of the ocean plates at each side of the active ridge that will determine if subduction is interrupted or not.

2.1. Subduction not interrupted

In the situation that both Euler poles are aligned with respect to the trench strike (Fig. 2), the arrival and collision of the active ridge
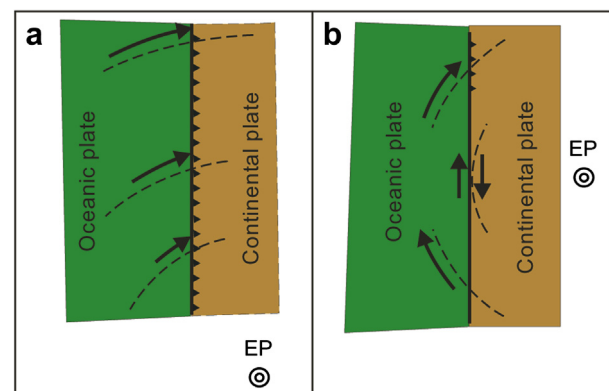

Figure 1. Schematic ocean-continental relative plate motion with respect to the oceanic plate Euler pole location. (a) The strike of the active margin under consideration is closely aligned with respect to the oceanic plate Euler pole location; (b) The strike of the active margin under consideration is located almost perpendicular with respect to the oceanic plate Euler pole location.
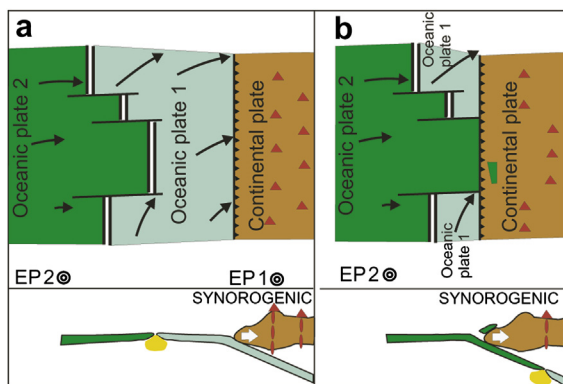
Figure 2. Schematic active ridge collision with continental plate in the situation that the Euler poles of both oceanic plates are relatively well aligned with respect to the strike of the active margin. (a) Pre-collision stage, (b) post-collision stage. Bottom windows show the profile with the subducting oceanic plate's behaviour, the magmatic activity location, and the synorogenic character of magmatism through all conditions.

Figure 3. Schematic active ridge collision with continental plate in the situation that the Euler pole of the oceanic plate 1 is relatively well aligned with respect to the strike of the active margin, and the oceanic plate 2 to arrive has an Euler pole close to perpendicular to the strike of the active margin. (a) Pre-collision stage, (b) post-collision stage. Bottom windows show profiles with the subducting oceanic plate's behaviour, the magmatic activity location and the orogenic character. Notice the development of a slab window as the subducted oceanic plate 1 is detached, and the change to postorogenic magmatism.

with the continental plate (Fig. 2b) does not interrupt subduction or compression at the subduction front, and the magmatism continues as synorogenic. The only changes introduced are to convergence angle and rates. Such a case is presented by the Taitao Peninsula (Nazca/Antarctica/SAM triple junction in southern Chile), where collision has caused a magmatic gap at the arc axis, intra-plate (OIB-like) basaltic magmatism in the back-arc (Gorring and Kay, 2001; Kay et al., 2002, 2004), and the obduction episode of the young and thin ocean crust of the ridge such as the Taitao Peninsula ophiolites (Forsythe and Nelson, 1985; Nelson et al., 1993).

Some authors (e.g. Gorring and Kay, 2001) have referred to this type of ridge subduction as a special type of slab window, but in this end case, there is no large slab detachment (only a small portion is obducted), the system continues to be synorogenic, and magmatism differs from that produced when a slab is detached and sinks by itself. Nevertheless, both types of ridge subduction share the fading and/or extinction of magmatic activity at the arc axis as described in the next case.

2.2. Subduction interrupted

The other possibility is that the first oceanic plate has an Euler pole aligned to the active margin strike, but the divergent oceanic plate 2 Euler pole is located perpendicular with respect to the active margin strike (Fig. 3). In such a case, a dramatic change from subduction to a transform plate margin takes place — as the active ridge collides with the continental plate (Fig. 3b), compression is replaced by intense extension at both fore- and back-arc, and the tectonic character of magmatism changes to postorogenic, such as in western USA with San Andreas transform fault system (Pacific/Farallon/NAM triple junction), and Basin and Ranges Province (Atwatter and Stock, 1998). The subducted slab is detached and the divergent ocean-floor slab becomes coupled to the continent along a transform fault. The sinking slab leaves a slab window behind. As in the previous case, magmatism diminishes in the arc axis to almost extinction, but magmatic activity diverges from the former-arc axis towards the former fore-arc (Dickinson and Snider, 1979; Cole and Stewart, 2008), and towards the former back-arc, with the development of large volumes of synextensional bimodal volcanism (ignimbrite flare-up and basalts) (Gans et al., 1989; Kempton et al., 1991; Hawkesworth et al., 1995).
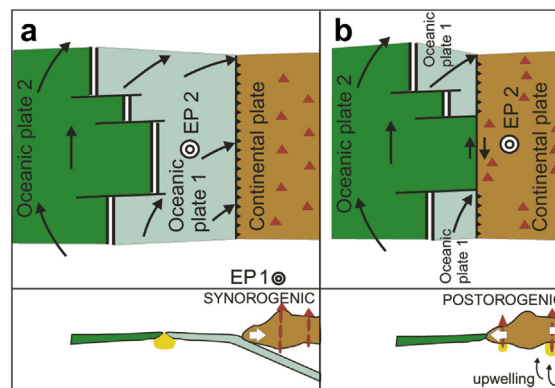
3. Magmatism related to a transform margin and slab window developed by an active ridge collision

From the above observations of present continental/ocean active plates transform margins, it can be stated that once the collision of a divergent ridge enables the coupling of the divergent ocean-floor to the continental crust through a transform fault, then the subducted plate detaches (or unzips), leaving a slab window behind. This new situation should result in extension and uplift in the overriding former fore- and back-arcs on the continental plate. However in practice much of the former-arc areas and some isolated thick crustal blocks in the former back-arc show uplift only (Fig. 4). These features allow the recognition of two settings where a significant amount of crustal thinning can be added to the effect of upwelling, and decompression is initiated in the upper mantle by sinking of the detached slab in the former fore- and back-arc areas. Thus, it is in these two settings where most of the slab window volcanic activity is concentrated. Nevertheless, the nature and volume of the volcanism in the former fore-arc may be quite different from the volcanism at the former back-arc. This can be attributed to the fact that the participation of subduction-modified subcontinental mantle may be insignificant in the former fore-arc compared to that expected in the former back-arc (Fig. 4). Yet a third situation of significant additional decompression is produced beneath the isolated thick rigid blocks in the former back-arc (Fig. 4). These large crustal blocks are subject to rapid buoyant uplift after the detached subducting plate decouples from the continental lithosphere, emerging as plateaux showing an elevation higher than 500—700 m with respect to the surrounding back-arc surface (Aragón et al., 2010, 2011a). After uplift is completed, basaltic flows cover the plateaux.

4. The northern Patagonia case

Since the late Jurassic, the northern Patagonia has shown a protracted active margin history, with sharp spatial (Figs. 5 and 6) and compositional changes, time related to varied interaction with the Aluk, Farallon and Nazca plates. This can be summarized in three main tectono-magmatic stages (Aragón et al., 2011a): (a) late Jurassic—Cretaceous subduction of the Aluk plate with emplacement of the North Patagonian batholith (NPB) (Pankhurst et al.,
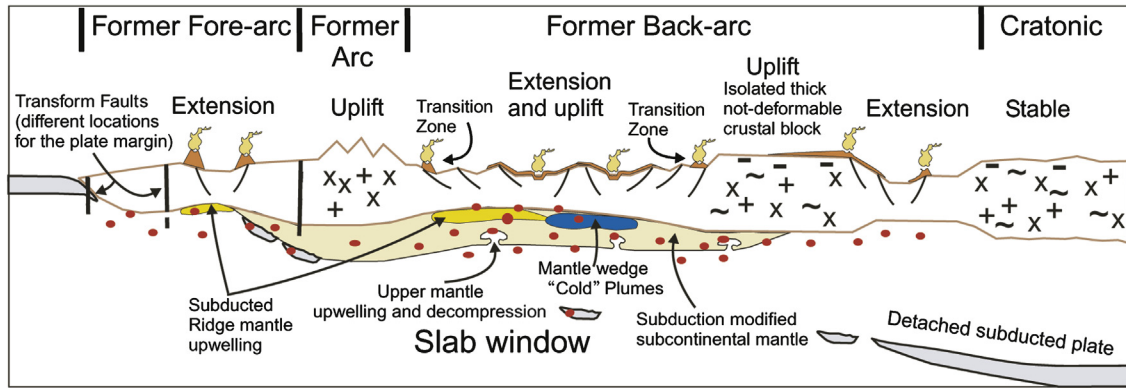
Figure 4. Schematic tectono-magmatic cross section for a mature slab window system developed from the collision of an active ridge and the detachment of the subducted plate. The transform fault margin is developed at the former fore-arc. Meantime in the former back-arc the continental crust deformability is heterogeneous with thin extensional crust and the presence of a thick solid not-deformable crustal block. Three sources of upwelling are identified; one is the subducted-ridge mantle upwelling, the second is the upper mantle upwelling from beneath the detached subducted plate, and the third is the mantle wedge "cold" plumes upwelling (of the subducted mélanges). The first two can account for the basalts generation, and the third can account for the large volumes of silicic magmatism (Castro and Gerya, 2008; Castro et al., 2010). These "cold" plumes would be remnants from the previous subduction episode, accumulated in the back-arc lithosphere.

1999; Vaughan and Pankhursts, 2008) at the southern Andes axis; (b) a Paleogene to early Miocene Farallon-Patagonia transform plate margin, with synextensional and voluminous volcanism that ignited Patagonia from the Pacific to the Atlantic coasts, as represented by the Pilcaniyeu, El Maiten, and Coastal volcanic belts and the Somún Curá basaltic plateau (Rapela et al., 1983, 1987; Kay and Rapela, 1987; Rapela and Kay, 1988; Kay et al., 1993, 2004; Muñoz et al., 2000; Aragón et al., 2011a,b); (c) late Miocene subduction of the Nazca plate, with tectonic inversion, reactivation of the North Patagonian batholith, and Pliocene—Holocene arc volcanoes along the southern Andes axis, as represented by the North Patagonian batholith (NPB) epizonal plutonism (Rapela and Kay, 1988; Aragón et al., 2011a), followed by the Pleistocene to recent volcanic arc represented by the southern Andes volcanic zone (SVZ) (Hickey-

Vargas et al., 1986, 1989; López-Escobar et al., 1992, 1993, 1995; Mella et al., 2005). To the south of the reviewed area, the Eocene Posadas basalts have also been suggested to be related to the Paleogene ridge collision by Ramos and Kay (1992), Kay et al. (2002), and Ramos (2005).

The northern Patagonian crust did not behave homogeneously with respect to alternating compression and extension. During the Paleogene extension, two regions suffered little deformation other than uplift — the Andean batholitic blocks in the former-arc and the North Patagonian massif in the former back-arc. Instead, the former fore-arc and most of the back-arc have been subjected to extension, crustal thinning and uplift (Aragón et al., 2011a).

It is important to emphasize that this isolated undeformable crustal block in the former back-arc has suffered as much as 1200 m
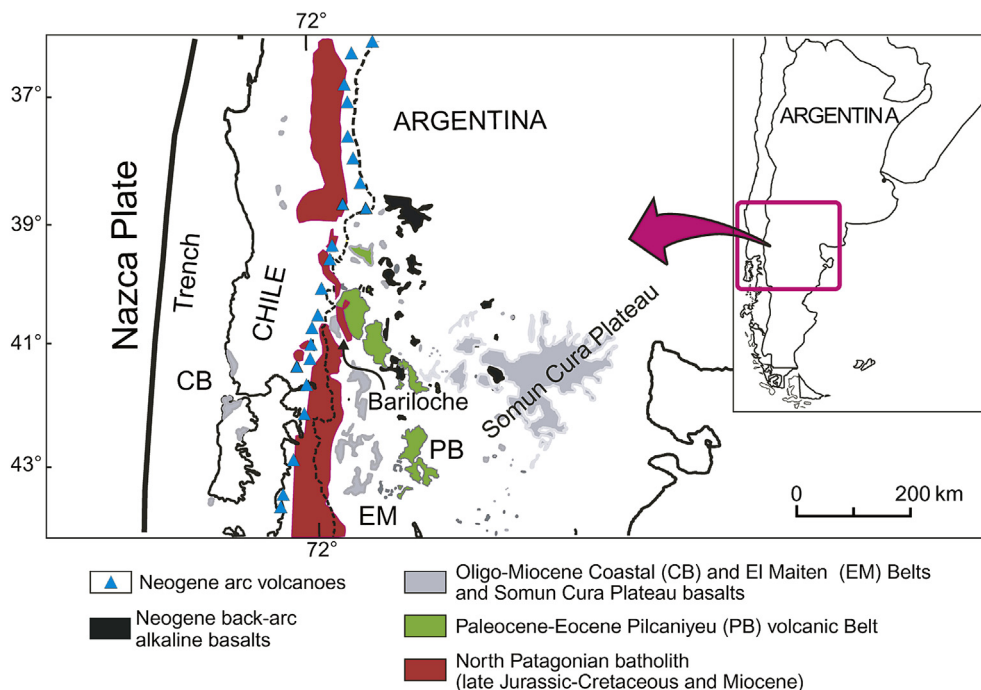

Figure 5. Distribution of late Jurassic—Cretaceous to present day major magmatic units in northern Patagonia. Slab window magmatism is restricted to the Eocene—early Miocene rocks.
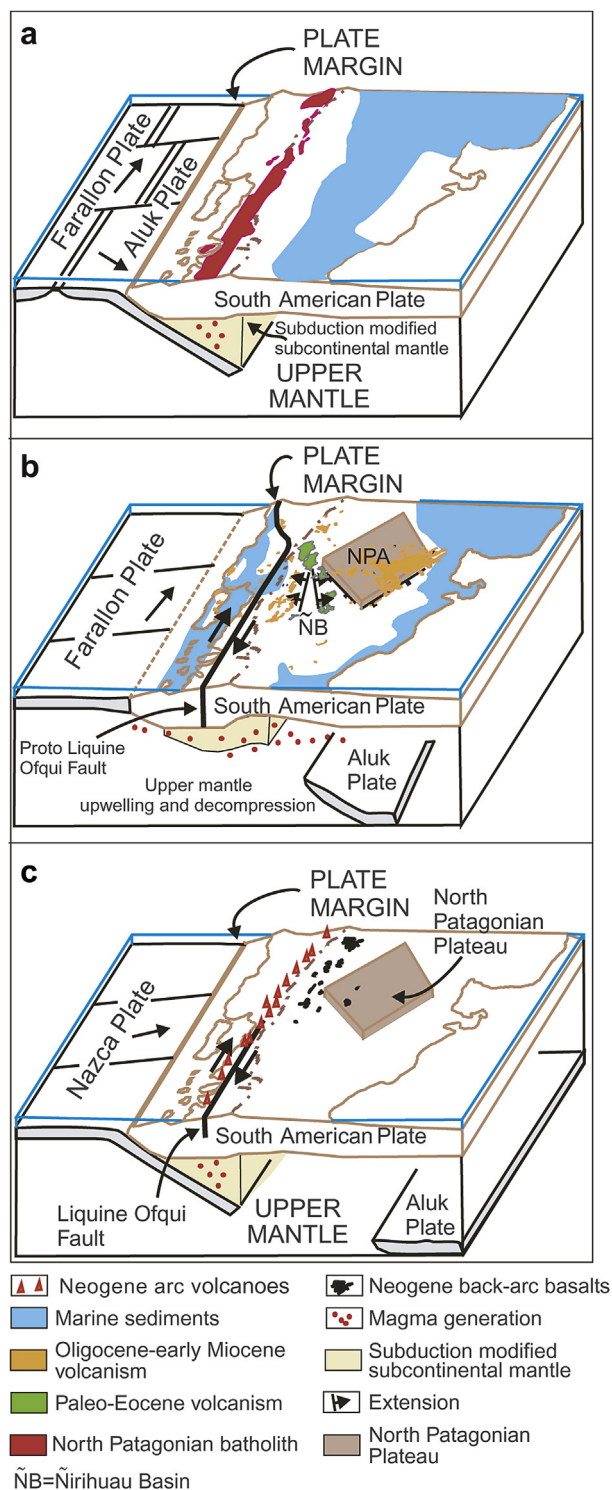
Figure 6. Schematic tectono-magmatic 3D models of northern Patagonia. (a) The northern Patagonian batholith during Aluk plate subduction and the Maastrichtian-Danian marine transgression along the back-arc. (b) The Farallon-South America is a transform plate margin at northern Patagonia latitude, volcanism changes to bimodal synextensional in the Eocene—Oligocene—early Miocene. The northern Patagonian massif is subject to strong uplift, so as to build a plateau, and subsequently basaltic flows spill from its top. During the late Oligocene—early Miocene interval broad marine transgressions came from the Pacific and the Atlantic oceans. (c) Tectonic inversion and arc volcanism in the Neogene due to major plate rearrangement, as the Farallon plate splits into Cocos and Nazca plates, and convergence angle changes to almost perpendicular.

of uplift during regional extension in a short time as demonstrated by the Danian marine sediments that now stand at that altitude with no deformation. Furthermore, late Oligocene—early Miocene basalts cover the Danian marine sediments and fall from the top of the plateau to the surrounding lower land, showing a close relationship between extension, massif uplift and basalt generation.

5. Geochemistry

This section attempts to summarize the major and trace elements variations, and isotopic variations of the Paleogene igneous rocks encountered in a cross section (Fig. 4) in the northern Patagonia mature slab window system that lasted for about 30 Ma. The cross section extended from near the trench in the former fore-arc, to the back-arc (more than 1000 km from the former trench (Fig. 4)). The back-arc has been subdivided into two regions: one was subject to extension, crustal thinning and uplift; and the other one that was not affected by extension but remained as a thick crustal block, was only subject to uplift.

Geochemical major and trace element data were compiled from various sources of published data of northern Patagonia and western United States. Such large compilation of diverse trace element selections has limited the amount of coincident published trace elements types through fore-arc and back-arc, which can be used in discrimination diagrams. The data of northern Patagonia are from López-Escobar et al. (1976), Rapela et al. (1983, 1987), Hickey-Vargas et al. (1986), Parada et al. (1987), Gerlach et al. (1988), Tormey et al. (1991), López-Escobar et al. (1992), Kay et al. (1993), Pankhurst et al. (1999), Muñoz et al. (2000), Mella et al. (2005), Saraceno (2010), Aragón et al. (2011a,b), and of western United States from Kempton et al. (1991), Fitton et al. (1991), Hawkesworth et al. (1995), Cole and Stewart (2008).

Major element geochemistry shows the presence of calc-alkaline and tholeiitic basaltic-gabbroic rocks in the former fore-arc, arc and back-arc settings. In contrast, alkali basalts are present in the former back-arc, as large plateau lavas on the uplifted non-deformable thick crustal block, and synextensional bimodal (rhyolite ignimbrite flare-up and basalt flows) on the uplifted and thinned crust areas. Moreover, no significant pluton emplacement is detected in the former-arc axis until subduction was re-established around 23 m.y. ago. The first plutonic rocks emplaced at the arc axis are 19 Ma gabbros which differ from the NPB and SVZ basic rocks in their much lower SiO_2 wt% (down to 47 wt%) (Aragón et al., 2011b).

The major elements K_2O, and TiO_2 of slab window magmatism show differences compared to the present (SVZ) and ancient (NPB) arc axis magmatism at the same latitude (Fig. 7). The K_2O wt% (for siliceous rocks) reaches higher values at the back-arc settings with respect to the arc (NPB, and SVZ). The Ti_2O wt% for basaltic rocks of the SVZ and NPB never surpasses the 1.5 wt%, as in most orogenic basaltic andesites (Gill, 1981). Instead the basalts and basaltic andesites in the former fore- and back-arc reach higher values (up to 3 wt% in some cases), but are restricted to rocks with less than 55% SiO_2, which are comparatively rare in the former-arc rocks.

Significant variations are also found in the MgO-FeO^t-Al_2O_3 diagram (Fig. 8) for basalts and basaltic andesites in the silica range SiO_2 51—56 wt% calculated dry in rocks that have less than 2 wt% LOI. Also, the selected rocks have not been subject to metamorphism to avoid Al_2O_3 enrichment and MgO loss (the increase of Al_2O_3 ratio in some basaltic andesites may be indicative of a fractionation process). Even though the ratio of MgO with respect to ($FeO^t + Al_2O_3$) shows a very narrow range, the SVZ rocks plot well within the island arc and active continental margin field (Fig. 8A) with few samples that reach the boundary with MORB field. If the slab window rocks are compared to the arc rocks, then the former
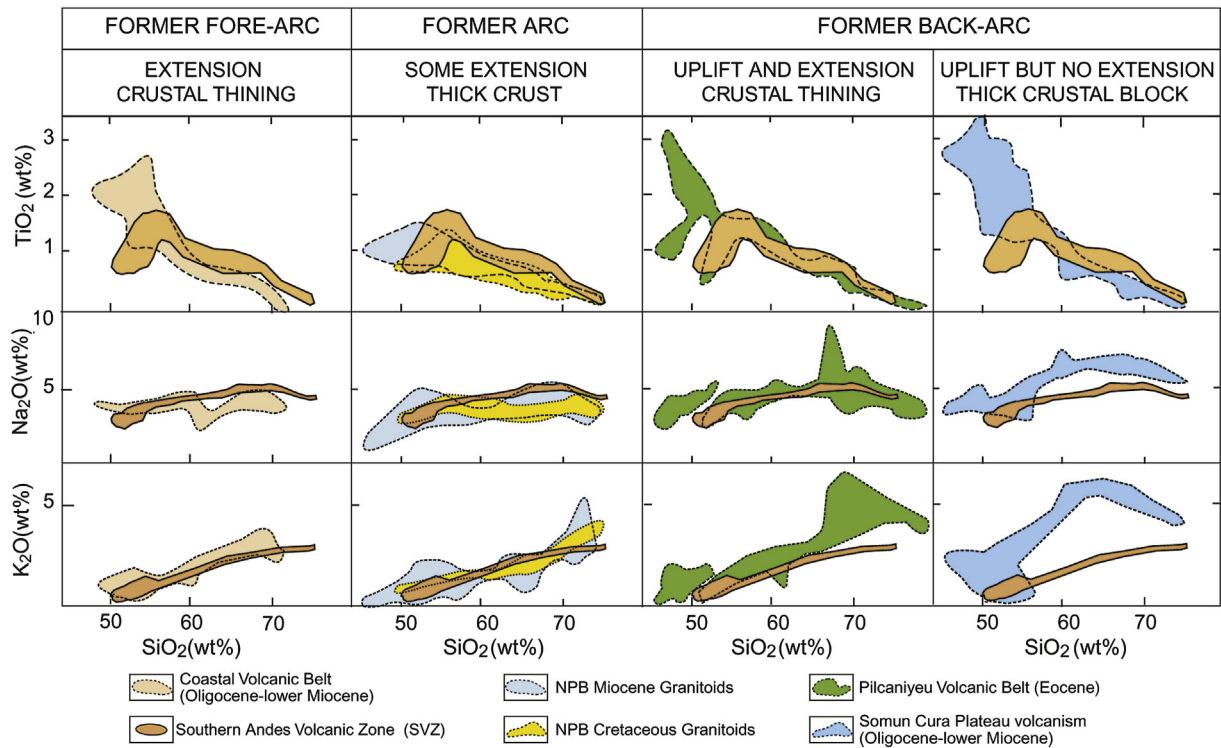
Figure 7. Diagrams showing selected major element variations with respect to silica for igneous rocks in the former fore-arc, arc, and back-arc of northern Patagonia developed during the Paleogene Aluk plate detachment and slab window opening. Diagrams of the former-arc also show rocks of the Cretaceous (NPB) North Patagonian batholith and the Miocene (NPB) reactivation. The orange field shows the southern Andes volcanic zone (SVZ) rocks (Neogene volcanic arc) at the same latitude, plotted as reference in all diagrams. Data of the Coastal volcanic belt is from Muñoz et al. (2000). Data of SVZ is from Hickey-Vargas et al. (1986), Gerlach et al. (1988), López-Escobar et al. (1976), Tormey et al. (1991), López-Escobar et al. (1992) and Mella et al. (2005). Data of the northern Patagonian batholith is from Pankhurst et al. (1999), Parada et al. (1987) and Aragón et al. (2011b). Data of El Maiten and Pilcaniyeu belts is from Rapela et al. (1983, 1987) and Aragón et al. (2011a). Somuncura plateau basalts are from Kay et al. (1993) and Saraceno (2010).

back-arc "extensional crust" rocks plot in the MgO poor side of that field, and many of them plot along the boundary with spreading centres islands (e.g. Iceland). Instead, the neighbouring back-arc basalts of the undeformable thick crustal block (Somuncura plateau basalts, Fig. 8A) show increased MgO-FeO ratios which plot in the ocean-island-continental fields. Besides, Coastal Belt basalts, which represent the magmatism at the former fore-arc, have higher MgO-FeO ratios which plot close to the MORB-continental basalts boundary. Coastal belt basaltic andesites richer in Al_2O_3 and SiO_2 may have undergone fractionation.

$MgO/(FeO^t + Al_2O_3)$ ratios for slab window basalts from the western United States (Fig. 8B), from the extensional former fore-arc (Coastal Range), back-arc (Basin and Range) and the eastern transition zone (Colorado Plateau), seem to show a trend much like that of Patagonia, although caution should be exercised, since few samples meet with the criteria that we have used for the plot.

The least evolved basalt samples in the former fore-arc exhibit light rare earth element depletion and enrichment patterns, similar to that of enriched mid-ocean-ridge basalts (E-MORB) (Fig. 9). In contrast, the least evolved basalt samples in the former back-arc exhibit light rare earth element patterns, similar to that of enriched mid-ocean-ridge basalts (E-MORB) and OIB (Fig. 9), which resemble plots of Iceland basalts (mid-ocean-ridge and hot-spot). Notice that the 19 Ma arc gabbros that represent the first magmas after subduction re-establishment have flat patterns and a positive Eu anomaly (Aragón et al., 2011b).

As noted and discussed by Rapela and Kay (1988) for the Paleogene back-arc, the magmatic rocks in the former fore- and back-arc have trace elements concentrations with small relative enrichment of some large-ion lithophile elements (Ba and Th), but

with a stronger relative enrichment in high field strength elements such as Nb, and Ta (Figs. 10 and 11) compared to the arc. In the arc axis, the Pliocene—recent SVZ shows Ba/Nb ratios in the range of 100—50 (Fig. 10). The Cretaceous rocks of the North Patagonian batholith reaches Ba/Nb ratios greater than 100, in contrast the first Miocene gabbros of the subduction re-establishment have lower Ba/Nb ratios (close to 30). The slab window magmatism in the Coastal Belt has Ba/Nb ratios in the range of 30 and greater. The magmatism in the former back-arc shows a very wide Ba/Nb ratios range, even though most rocks plot below Ba/Nb ratio of 30, but some of them have ratios in the range of arc rocks suggesting the strong arc inherited influence left in the upper mantle wedge by the Cretaceous subduction event. The lack of high Ba/Nb ratios in rocks of the former fore-arc shows more affinity with ocean-floor basalts and little interaction with arc fluids (Muñoz et al., 2000). On the other hand, rocks in the former back-arc show MORB and OIB-signatures but with strong arc influence (Fig. 10).

The Ta-Th-Hf/3 discrimination diagram (Fig. 11, after Wood, 1980) shows that SVZ rocks are Th rich and Ta poor, plotting well within the volcanic arc calc-alkaline basalts field. In contrast, for rocks of the Coastal Belt in the former fore-arc, the relative proportion of Ta increases gradually until it reaches the E-MORB within-plate tholeiites field. In the former back-arc extensional crust, the Paleocene—Eocene Pilcaniyeu belt rocks plot in the transition between arc, E-MORB and within-plate fields, the Oligo-Miocene El Maiten belt rocks plot in the transition between arc, E-MORB, N-MORB (Kay and Rapela, 1987; Rapela and Kay, 1988; Aragón et al., 2011a). On the other hand, in the former back-arc unextended thick crust, the Oligocene—Miocene Somuncura rocks plot in the within-plate basalts field and a few on the transition to
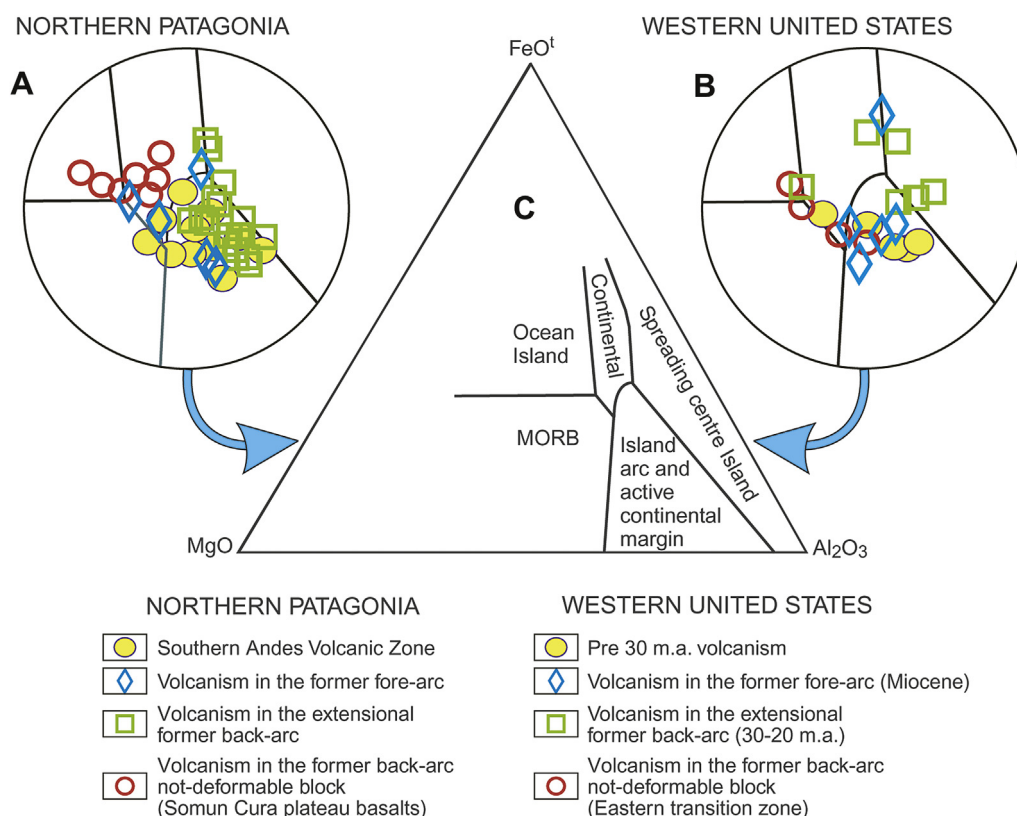
Figure 8. The MgO-FeO[t]-Al$_2$O$_3$ diagram. (A) Close-up of northern Patagonia Cenozoic volcanic unit's compositional variations. (B) Close-up of western Unites States Cenozoic volcanic unit's compositional variations. (C) From the tectonic settings discriminant boundaries (after Pearce et al., 1977), the discriminated fields are: MORB (ocean ridge and ocean-floor basalts); ocean-island basalts; continental basalts; volcanic arc and continental active margin basalts; spreading centre island basalts (e.g. Iceland, Galapagos). The diagram can only be used with subalkaline rocks in the silica range SiO$_2$ 51–56 wt% (calculated dry), and free of alteration or metamorphism (in this case we used rocks in that silica range that are free of CIPW normative Ne, have less than 2 wt% LOI loss and have not been subject to metamorphism). Data from Corbella (1982), Remesal and Parica (1989), Kay et al. (1993), Aragón et al. (2011a), Cole and Stewart (2008), Kempton et al. (1991), Fitton et al. (1991) and Hawkesworth et al. (1995).

arc. Published data for northern Patagonia tholeiitic and alkalic basalts in the former back-arc extensional setting show more affinity to MORB and OIB-type basalts (Kay et al., 2002, 2004; Aragón et al., 2011a). And the basalts in the former back-arc unextended thick crustal block show more affinity to a within-plate setting (Kay et al., 2002, 2004).

The volcanic rocks of the former fore-arc, arc and back-arc have Nd and Sr isotope compositions that range from those close to the mid-ocean-ridge basalts with $\varepsilon_{Nd}(t)$ as high as +6 and $(^{87}Sr/^{86}Sr)_0$ values as low as 0.7030 (Fig. 12a, b) to crustal influence compositions with $\varepsilon_{Nd}(t)$ as low as −2 and $(^{87}Sr/^{86}Sr)_0$ values as high as 0.7057. In contrast, the Cretaceous NPB shows a time-dependent isotopic array with increasing $\varepsilon_{Nd}(t)$ and decreasing $(^{87}Sr/^{86}Sr)_0$. And the SVZ shows a much more constrained isotopic composition with $\varepsilon_{Nd}(t)$ values in the range of +5 to +2 and $(^{87}Sr/^{86}Sr)_0$ values in the range of 0.7035–0.7045 (Fig. 12) (compilation in Aragón et al., 2011b references therein).

6. Comments

The northern Patagonian margin unusually experienced two active ocean ridge collisions during the Cenozoic. Moreover, these two collisions are end-member cases as described in Section 2 ("Active ridge collision"). Subduction continued in the case of the Pliocene to recent Antarctica-Nazca ridge collision (Taitao Penin-sula), whereas in the case of the Paleogene Farallon-Aluk ridge (northern Patagonia) the arriving ocean plate coupled to the continental plate by means of a transform fault, and the subducted

plate detached and continued to sink, opening a large window. Both collision types share the particularity that magmatic activity at the arc axis decreases to a hiatus, but differ in many tectono-magmatic features. In the first case, where subduction continues, compression continues, synorogenic magmatism is restricted to the back-arc, it is basaltic (tholeiitic, alkalic, adakitic), and has an OIB-type affinity (Kay et al., 2002). Meantime at the fore-arc, obduction of the ridge ocean-floor may occur, such as the Taitao ophiolites (Forsythe and Nelson, 1985; Nelson et al., 1993). In the other case, where the subducted plate is detached and subduction is inter-rupted, broad extension is developed in the former fore- and back-arc, postorogenic magmatism spreads through the former fore- and back-arc, and is basaltic, andesitic and rhyolitic (calc-alkaline, tholeiitic and alkalic). The synextensional basalts in the former back-arc have lower MgO/(FeO[t] + Al$_2$O$_3$) ratios than the basalts from the undeformed thick crustal block and those from the extensional former fore-arc (Fig. 8A) and plot in the discriminant field of spreading centre island basalts (e.g. Iceland, Galapagos) (Fig. 8C). The same lower MgO ratio is also found in western United States (WUS) when the basalts from the extensional setting of the Basin and Range (in the former back-arc) are compared to the basalts from the Coastal Range (in the former fore-arc) (Fig. 8B).

These MORB, OIB and Iceland OIB-type affinities have also been recognized in trace element behaviour. The synextensional basalts in the former back-arc have MORB-OIB affinities (Iceland type) but with LILE concentrations that indicate an upper mantle source enriched by the preceding subduction process; as it is shown in Eocene basalts of northern Patagonia (Aragón et al., 2011a), and in
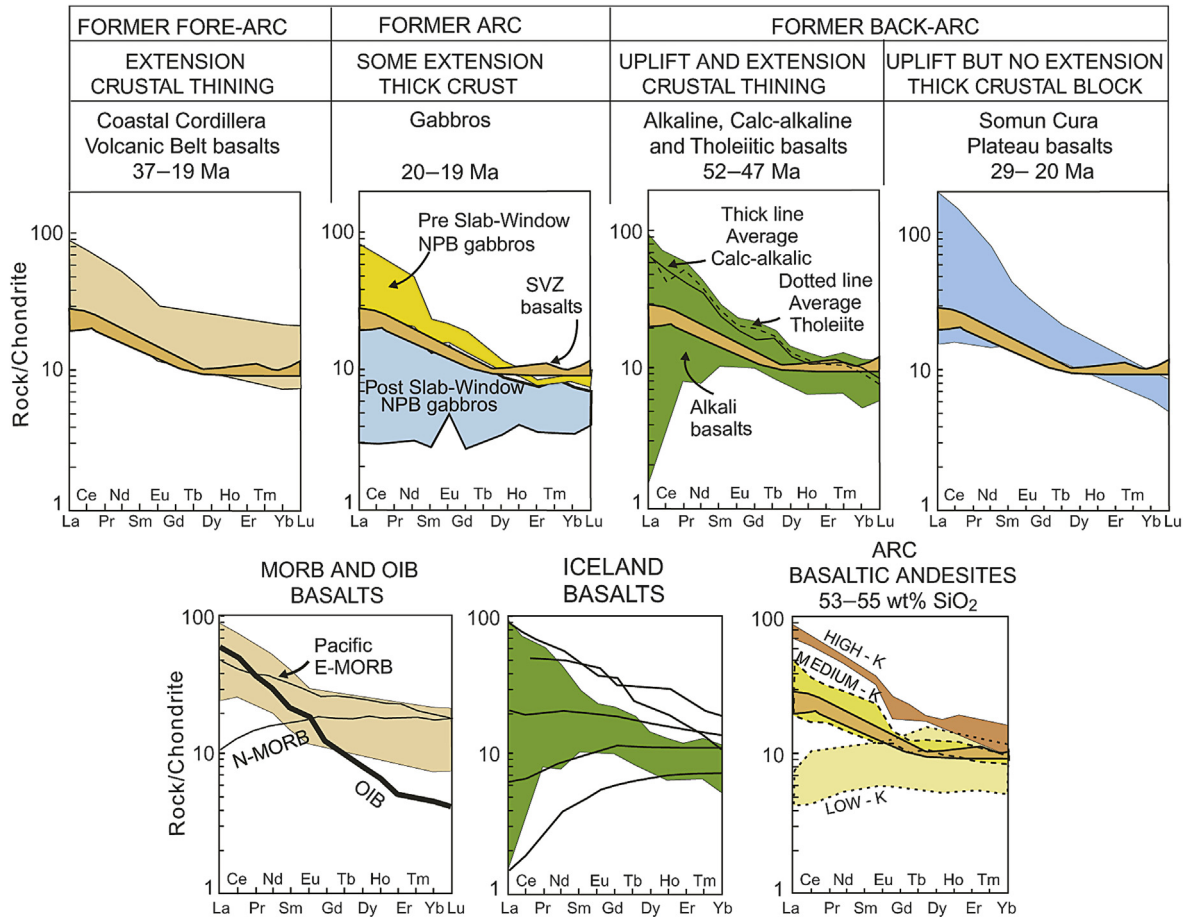
Figure 9. Chondrite-normalized REE patterns for basalts and gabbros of the former fore-arc, arc, and back-arc of northern Patagonia show the different behaviour of the calc-alkaline, tholeiitic and alkalic mafic rocks at the same latitude, and the differences along time at the arc axis. Orange field is for SVZ basalts, plotted as reference in all REE diagrams. Field for the SVZ volcanic front is represented by data from Hickey-Vargas et al. (1986) and Gerlach et al. (1988), samples data references in Fig. 7. Bottom row shows for comparison average chondrite-normalized REE patterns for N-MORB, E-MORB, OIB (after Saunders, 1984 and references therein) with respect to Paleogene basalts in the former fore-arc, and Iceland (MORB and OIB) (after Saunders, 1984 and references therein) with respect to Paleogene basalts in the former back-arc, and for low-K, medium-K and high-K basaltic andesites after Gill (1981) with respect to SVZ arc basalts.

Eocene basalts of central Patagonia (Kay et al., 2002). In contrary, the basalts in the former fore-arc have an ocean-like or MORB affinity (Muñoz et al., 2000), with little input of slab-derived hydrous fluids into the mantle source region. The western United States Neogene basalts in the near trench zone (former fore-arc) are also MORB-type (Cole and Stewart, 2008).

The volcanism in the former fore-arc is characterized by isolated volcanic centres. On the other hand the volcanism in the former back-arc is characterized by large volcanic fields, is synextensional and bimodal, with an early large ignimbrite flare-up and a late stage of tholeiitic and alkalic basalts (Aragón et al., 2011a). The volume of magma eruption as ignimbrites is comparable to the volume of cordillera batholiths. The other example of this type of ridge collision and subducted plate detachment found in WUS Farallon-Pacific ridge late Oligocene collision also shows in the former back-arc the Basin and Range synextensional ignimbrite flare-up and late basalts (Gans et al., 1989; Fitton et al., 1991; Kempton et al., 1991; Axen et al., 1993; Hawkesworth et al., 1995; Rogers et al., 1995).

A closer look at the former back-arc shows the presence of the North Patagonian massif which behaved as an isolated undeform-able epeirogenic thick crustal block (Corbella, 1984) during the slab window development (resembling an epeirogenic island in the former orogenic belt foreland) (Aragón et al., 2011a). Once subject

to uplift in late Eocene—early Oligocene (in the range of 1200 m, Aragón et al., 2010), the large Somuncura plateau basalts spilt from the uplifted block top to the surrounding back-arc. These basalts have stronger within-plate affinity than coeval basalts in the former back-arc, but they still show some arc components (Kay et al., 1993, 2004). They also have a higher $MgO/(FeO^t + Al_2O_3)$ ratios than the basalts from the surrounding extensional former back-arc, but plot in the OIB-continental basalts field (Fig. 8A). A similar situation can be recognized in WUS Neogene slab window system with, the late Miocene—Pliocene uplift of the Colorado Plateau in the foreland followed by the Plio-Pleistocene Colorado Plateau basalts volcanism (eastern transition zone basalts) (Wenrich et al., 1995). In summary, it can be stated for the Patagonia E—W slab window profile (Fig. 4) that a MORB-like signature is important in the former fore-arc and present in the extensional part of the former back-arc, but absent in the rigid part of the latter. In contrast, there is a slight arc influence in the former fore-arc that increases towards the former back-arc (extensional uplift area) and diminishes in the former back-arc (non-extensional uplift area). Finally the OIB-signature in basalts is recognized in the alkali basalts of the former back-arc (extensional uplift area) and is important in the former back-arc (non-extensional uplift area). Thus the former back-arc (extensional uplift area) is a unique area having coeval basaltic magmas with MORB, OIB (Iceland type) and arc affinities.
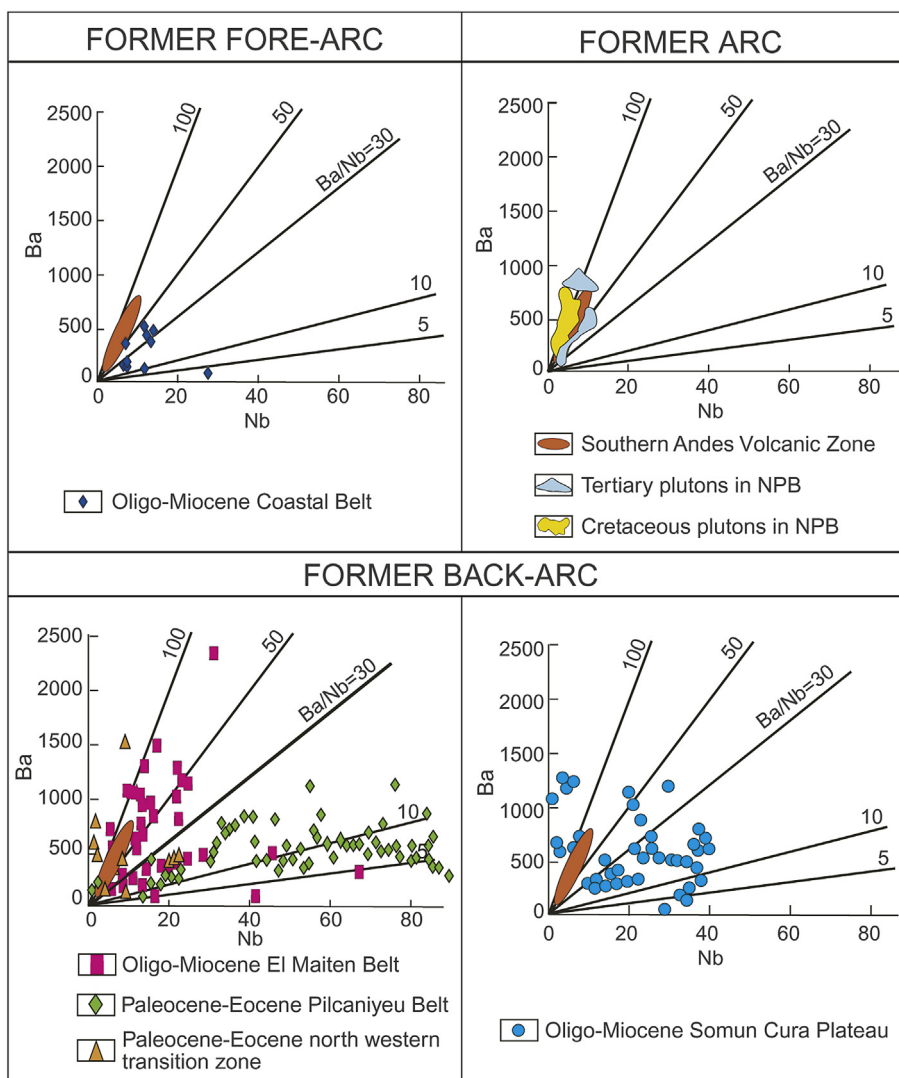
Figure 10. Diagram showing Ba variations with respect to Nb for igneous rocks (full silica range) in the former fore-arc, arc, and back-arc of northern Patagonia, to illustrate the spatial variations of slab window volcanic rocks at the same latitude. The rocks in the former-arc plot include; the SVZ rocks for reference and comparison with the other slab window locations and also the Cretaceous and Miocene rocks of the North Patagonian batholith to show the differences along time at the arc axis. The Paleocene–Eocene north western transition zone of the former back-arc is an area very close to the former-arc axis. Samples data references as in Fig. 7.

Even though it is difficult to distinguish between arc or slab window tholeiitic and calc-alkaline basalts, andesites and rhyolites, some distinctions can be made. Perhaps the most outstanding of these differences is that the basalts of slab windows reach values of TiO_2 higher than 1.5 wt% (top value for arc basaltic andesites, Gill, 1981), and as much as 3 wt% (Muñoz et al., 2000; Cole and Stewart, 2008). Another feature of the slab window basalts is that these reach lower SiO_2 contents than arc basalts. It is of interest to notice that the first arc gabbros to be produced when subduction and arc magmatic activity is re-established also have lower SiO_2 contents than normal arc gabbros (Fig. 7). Another interesting observation is that K_2O contents of basalts, andesites and rhyolites can reach higher values in slab window than in arc conditions, even in the former fore-arc. The slab window basalts also show significant $MgO/(FeO^t + Al_2O_3)$ ratio changes from the former fore-arc to the former back-arc (Fig. 8) that may be related to the MORB or OIB-type influence for their magma generation process (Pearce et al., 1977). The least evolved basalts in the former fore-arc plot on the MORB boundary, instead the least evolved basalts of the former back-arc extensional crust plot on the spreading ridge island

boundary, and the basalts of the former back-arc with a not extensional thick crust plot on the ocean-island-continental fields (Fig. 8A).

Trace elements seem to be most useful to distinguish between arc and slab window magmatism. The increased content of HFS elements (Nb, Ta) in slab window derived magmas with respect to arc magmas when plotted in tectono-magmatic discrimination plots show that slab window magmas plot in the transition area between typical arc and typical MORB and within-plate magmas (Fig. 11).

The isotope composition shows coeval variations that range from those similar to the mid-ocean-ridge basalts (Fig. 12), to those demonstrating some crustal influence. The isotope composition also helps to distinguish and understand the slab window process with respect to the arc process. Coeval arc magmas of the same locality have a constrained isotopic composition, and if changes occur, these will be time-dependent, showing that arc magmas have a good homogenization mechanism (Fig. 12). Instead, slab window volcanism in the former fore-arc, arc and back-arc have coeval samples of the same locality with disparate Nd and Sr
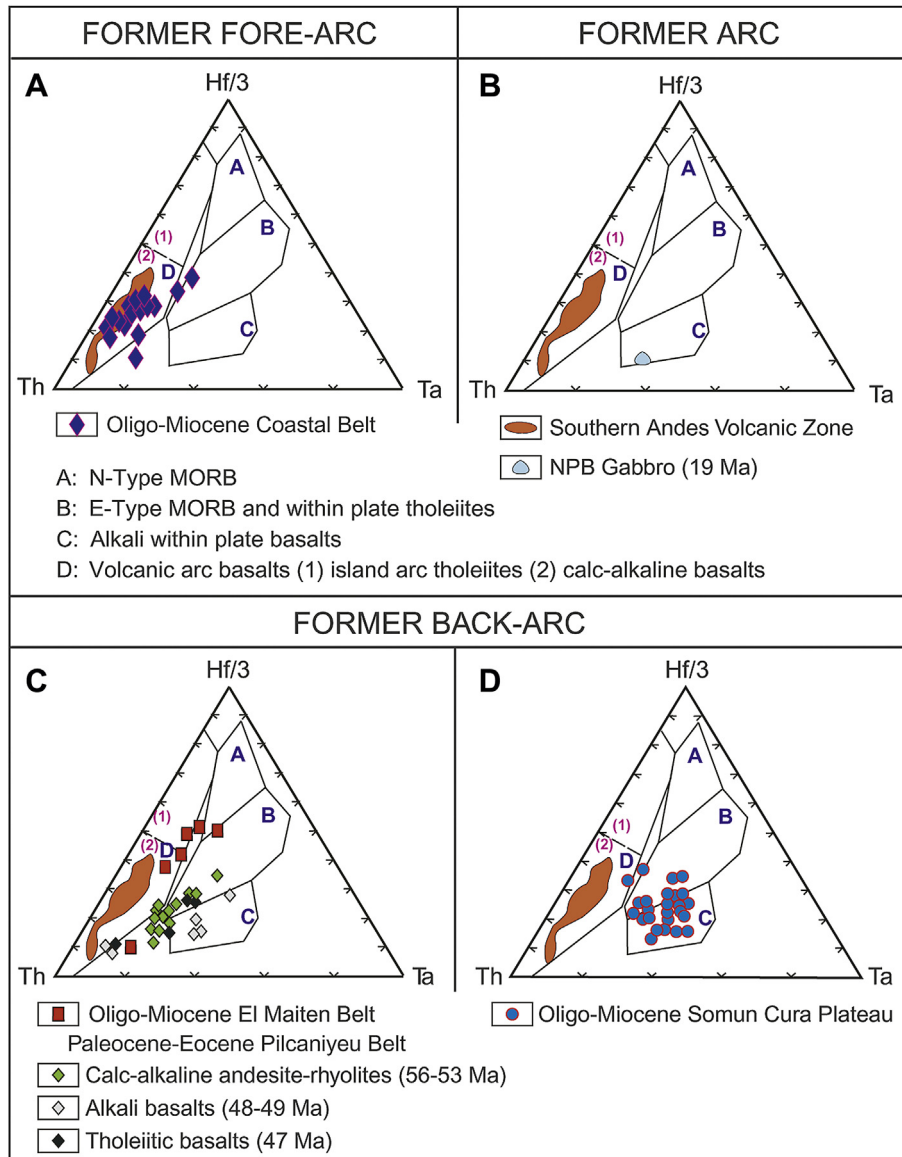
Figure 11. Graph showing Ta-Th-Hf/3 discrimination diagram (after Wood, 1980) for rocks (all silica range) of the former fore-arc, arc, and back-arc of northern Patagonia to show the different behaviour of the calc-alkaline, tholeiitic and alkalic volcanic rocks at the same latitude, and the differences along time at the arc axis. Samples data references as in Fig. 7.

isotope compositions (Fig. 12) (Aragón et al., 2011b), showing that slab window derived magmas have no homogenization or protracted storage, probably as a consequence of the extreme extensional conditions developed in the former fore- and back-arc during the subducted slab detachment.

Finally, from the above-mentioned statements, it seems probable that changes from the former fore-arc to the former back-arc may reflect end-member magma generation processes similar to those of MORB (active ridge) or OIB (hot-spot). In such a scheme, the sinking of the detached plate would be responsible for the mantle upwelling above it (a hot-spot like effect), and the active ridge subduction would be responsible for the MORB-like effect. Although in order for the subducted-ridge upper mantle to continue to produce MORB-like basalts it would have to rise to the shallower depths beneath the extensional continental crust. On the other hand, magma generation beneath the thick undeformed "epeirogenic" block in the foreland only produced OIB-like basalts and is most likely to have been influenced by hot-spot like mantle upwelling above the slab window (Kay et al., 2007), dehydration of

β-phase olivine (Motoki et al., 2005) and the decompression caused by the 1200 m (epeirogenic?) crustal uplift (Aragón et al., 2010). Beneath such thick crust the MORB-type upper mantle process seems no longer to have any influence (Figs. 3 and 4).

The other mentioned end case is the one in which the colliding active ridge is subducted, compression continues and no detachment of the subducted plate occurs. The fact that Antarctica-Nazca ridge subduction has only produced OIB-type basalts in the back-arc (Kay et al., 2002, 2004), seems to show the impossibility of the subducted-ridge upper mantle to rise to the shallower depth beneath the back-arc crust when ocean-slab subduction and compression continue (Fig. 2).

Most of the arguments in this work dealt with basaltic magma types, but this is an incomplete perspective since much of the magmatism in the former back-arc is made of great volumes of silica-rich volcanic rocks (e.g. ignimbrite flare-up). With respect to this it would be important to consider in future works the role of the lower continental crust and "cold" plumes accumulated in the back-arc during the previous subduction episode that may participate in
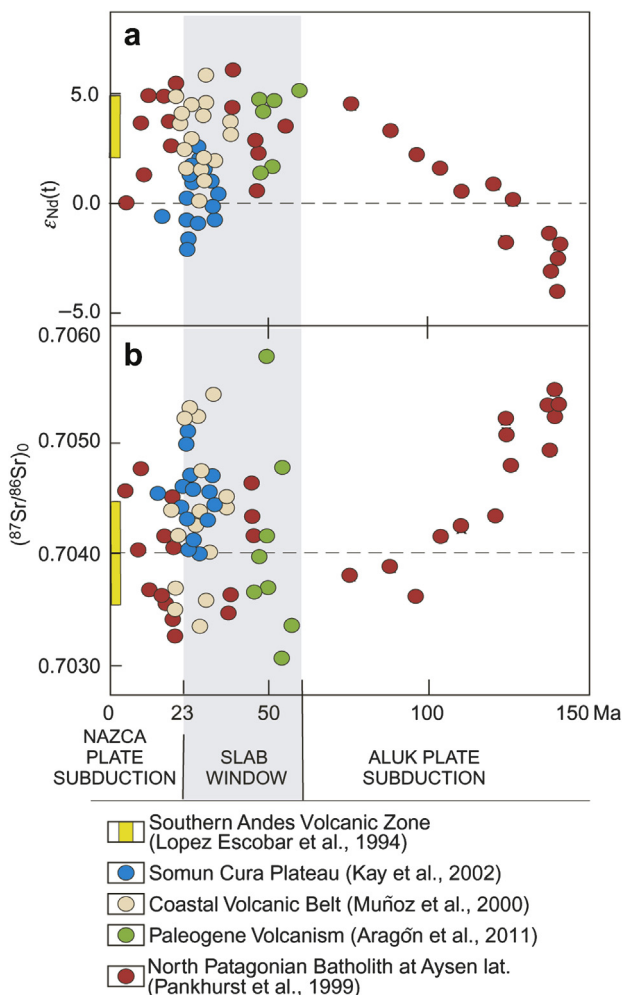
Figure 12. (a) $\varepsilon_{Nd}(t)$ and (b) $(^{87}Sr/^{86}Sr)_0$ ratio versus crystallization age for North Patagonian batholith granitoids and Paleogene volcanism, modified from Pankhurst et al. (1999) and Aragón et al. (2011b). The shaded field shown is for the slab window event suggested to have lasted from Paleogene Farallon-Aluk ridge collision (Cande and Leslie, 1986; Muñoz et al., 2000; Somoza and Ghidella, 2005) to the 23 Ma major plate reorganization (Lonsdale, 2005) (Farallon plate break-up to form Nazca and Cocos plates).

silica-rich magma generation. A cold plume is a melange of subducted MORB basalt and sediment in the mantle wedge well up in upper mantle conditions (Castro and Gerya, 2008; Castro et al., 2010). These metamorphosed MORB/sediment upwelling pockets may be stored in the back-arc to produce silica-rich magmas during the extension, decompression and mantle upwelling developed by the slab window in the former back-arc (Fig. 4).

Acknowledgments

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