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# Paleomagnetism and geochemistry from the Upper Cretaceous Tres Picos Prieto locality (43ºS), Patagonian Plateau Basalts

**Claudia Beatriz Zaffarana[1], Silvia Leonor Lagorio[2], Rubén Somoza[1, 3]**

[1] *Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Intendente Güiraldes 2160, Ciudad Universitaria, Pabellón II (C1428EGA), Capital Federal, Buenos Aires, Argentina.*
*zaffarana@gl.fcen.uba.ar*
[2] *Servicio Geológico Minero Argentino (SEGEMAR), Av. Julio Argentino Roca 651, piso 10 - (C1067ABB) Capital Federal, Buenos Aires, Argentina.*
*slagor@minplan.gov.ar*
[3] *Instituto de Geociencias Básicas, Aplicadas y Ambientales (IGEBA) del Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Intendente Güiraldes 2160, Ciudad Universitaria, Pabellón II (C1428EGA), Capital Federal, Buenos Aires, Argentina.*
*somoza@gl.fcen.uba.ar*

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**ABSTRACT.** A paleomagnetic study on nine samples from lavas from the Upper Cretaceous Tres Picos Prieto locality (43º50'S and 70º3'W), Patagonian Plateau Basaltic Province, revealed that a *ca*. 300 m thick pile of basalts accumulated during three discrete (*i.e*., temporally separated) volcanic episodes. The chemistry of these lavas shows characteristics compatible with both subduction and intraplate magmatism, with the former having a more important contribution in the younger lavas. Overall, we interpret these rocks to be transitional basalts generated in a supra-subduction environment. The Late Cretaceous to Cenozoic Patagonian Plateau Basaltic Province crops out from eastern Patagonia to the cordillera, and their genesis have been associated with different tectonic processes, even for spatially separated rocks of the same age. Considering that the development of the magmatic province is contemporary with the stage of westward drift of South America, we propose that magma generation and upwelling due to rapidly shearing asthenosphere inducing circulatory flow associated to asperities in the lithosphere-asthenosphere interface (shear-driven upwelling) can be evaluated as a further potential mechanism to account for many outcrops of these backarc to intraplate lavas.

*Keywords: Patagonian Plateau Basaltic Province, Late Cretaceous, Paleomagnetism, Geochemistry, Argentina.*

**RESUMEN. Paleomagnetismo y geoquímica en la localidad de Tres Picos Prieto (43ºS), Cretácico Superior, Basaltos de Plateau de Patagonia.** Un estudio paleomagnético sobre nueve lavas en la localidad de Tres Picos Prieto (43º50'S, 70º3'W), perteneciente al Cretácico Superior de la Provincia Basáltica de Plateau de Patagonia, mostró que *ca*.300 m de lavas fueron acumuladas durante tres episodios discretos de volcanismo. La composición química de esas lavas muestra características compatibles con magmatismo relacionado con subducción y también de intraplaca, con creciente contribución del primero en los términos superiores. Las rocas son interpretadas como basaltos transicionales en ambiente de supra-losa. La Provincia Basáltica de Plateau de Patagonia se desarrolló durante el Cretácico Tardío y el Cenozoico, con sus afloramientos ocupando desde el este de la Patagonia hasta la cordillera. La génesis de estas lavas ha sido asociada a diferentes procesos tectónicos, incluso para rocas contemporáneas aflorando en distintas áreas. El desarrollo de esta provincia magmática es coetáneo con la etapa de deriva de América del Sur. Se propone que el modelo de ascenso de magmas relacionado con cizalla sublitosférica ('shear-driven upwelling') ofrece un mecanismo geodinámico que puede ser considerado al explorar la petrogénesis de casi la totalidad de las rocas que componen esta provincia máfica con características mixtas entre retroarco e intraplaca.

*Palabras clave: Basaltos de Plateau de Patagonia, Cretácico Tardío, Paleomagnetismo, Geoquímica, Argentina.*

## 1. Introduction

Patagonia has been the locus of widespread basaltic volcanism since the Late Cretaceous, the products of which constitute an important factor in forming the characteristic plateau landscape that dominates in the region. Barker *et al*. (1981) proposed that the composition of the Patagonian back-arc basalts evolved through time with strong dominance of tholeiitic basalts in the Late Cretaceous, alkali basalts in the Paleogene, and finally mostly alkali basalts and basanites in the Late Cenozoic. However, recent studies have shown a more complex scenario, proposing different driven mechanisms to account for the melting that originated the Patagonian back-arc lavas. In general, models involving subduction processes are numerous, although they fail to explain some aspects such as the presence of Quaternary basalts more than 500 km away from the trench, as may be observed in Patagonia.

Some Patagonian basalts have been associated to slab windows related to subduction of oceanic ridges (*e.g*., Ramos and Kay, 1992; Espinoza *et al*., 2005). Plate reconstructions (Cande and Leslie, 1986; Somoza and Ghidella, 2005) support this model for the origin of Eocene and Late Cenozoic basalts, but its application in other times seems to be tectonically untenable. The origin of other Oligo-Miocene basalts in central Patagonia has been related to a thermal anomaly associated to either slab-dynamics during times of plate reorganization (De Ignacio *et al*., 2001; Kay *et al*., 2007; see also Muñoz *et al*., 2000) or a transient mantle plume (Kay *et al*., 1992, 1993; Ntaflos *et al*., 2002). Bruni *et al*. (2008) proposed that intraplate magmatism in central Patagonia is related to the rising up of the asthenosphere to compensate a westward drift of the mantle wedge attached to South American lithosphere. Espinoza *et al*. (2010) suggest that the genesis of middle Miocene basalts and andesites cropping out in the foreland at 47°S is related to an event of slab shallowing. On the other hand, Parada *et al*. (2001) conclude that extensional tectonics is likely the explanation for the origin of the Late Cretaceous volcanism in the Aysén region in southern Chile. Thus, proposed models allow regarding the backarc basalts in Patagonia as a long lived, polygenetic magmatic province. Whatever their origin, the voluminous and wide distribution of the Late Cretaceous - Cenozoic basalts led to postulate that the Patagonian mantle has been on the verge of melting since the Mesozoic breakup of Gondwana (Kay *et al*., 2004).

In this paper we report paleomagnetic and geochemical data from a basaltic section in the type locality of the Tres Picos Prieto Formation (Franchi and Page, 1980), which is one of the main Cretaceous localities of the mafic igneous province.

The goal of the paleomagnetic study is isolation of thermoremanent magnetization, which is acquired when igneous rocks cool from above the Curie temperature of their Fe oxides, which then record the direction of ambient geomagnetic field. The drift of the geomagnetic field is much slower than the rate of cooling of lavas, making the thermoremanent magnetization in these kinds of rocks to be a temporal fingerprint for a single volcanic event formed by either one or several eruptions. The potential resolution of the method, 100s years, makes paleomagnetism to be a powerful tool for correlating physically unconnected outcrops of lavas and ignimbrites (*e.g*., Magill *et al*., 1982; Somoza *et al*., 1999; Pluhar *et al*., 2005) as well as to estimate the amount of time and the number of events represented in a volcanic succession (*e.g*., Weiss *et al*., 1989; Knight *et al*., 2004; Somoza, 2007; Jarboe *et al*., 2008).

On the other hand, geochemical discriminant diagrams based on empirical observations show systematic chemical differences in the source of basic magmas erupted in different tectonic settings. Concentrations and ratios of selected elements in igneous rocks are then used to distinguish among different tectonic environments (*e.g.*, Wood, 1980; Pearce and Peate, 1995; Pearce, 1996).

Our results indicate that more than 300 m of lavas in the lower section of the Tres Picos Prieto Formation were accumulated during three volcanic events. As in other localities from the Patagonian Plateau Basalts, the studied lavas show signatures of both subduction and intraplate environments.

## 2. Paleomagnetism: Sampling and Results

Franchi and Page (1980) described the Tres Picos Prieto Formation as an Upper Cretaceous succession of basalts with intercalations of conglomerate, ignimbrite and tuffaceous sandstones. This unit corresponds to the Cretaceous section of the Patagonian flood-basalts of Barker *et al*. (1981). Samples were collected in Puesto Comerci (43º48’38’’S; 70°3’36’’W, Fig. 1), which is the main

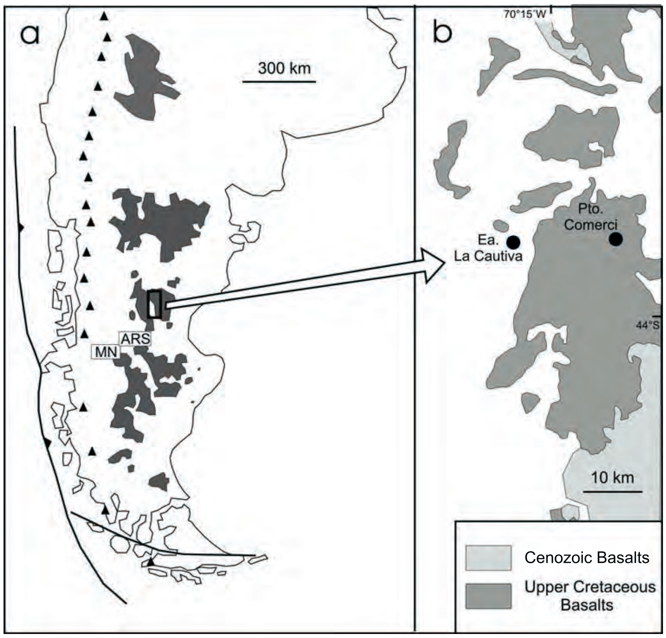



FIG. 1. **a.** Map of Southern South America and main outcrops of Patagonian Plateau Basalts. Triangles schematically represent the present day volcanic front (taken from Cembrano and Lara, 2009). The studied region is enclosed in the black rectangle. **ARS**: Alto Río Senguerr; **MN**: Morro Negro localities; **b.** Distribution of Cretaceous and Cenozoic basalts in the studied area, for details of the regional geology see Silva Nieto (2005).

locality in the type area of the Tres Picos Prieto Formation (Franchi and Page, 1980).

The section in Puesto Comerci (Fig. 2e) includes, from bottom to top, a porphiritic basalt, a meter scale conglomerate composed of basaltic boulders, and a succession of at least five basaltic flows. Above these basalts a ~20 m thick ignimbrite with decimeter scale pumice blocks crops out, followed by a thinner basaltic level which locally tops the plateau. From this succession we drilled six to seven samples from each of six different lavas in the lower part of the section (sites 3PA to 3PF in Table 1), covering a stratigraphic thickness of ~320 meters. Additionally we drilled twelve samples from eleven basaltic boulders in the conglomerate.

About three kilometers east-northeast from the main section there is a small hill, where three basaltic levels were identified (from young to old: sites 3PG, 3PH and 3PI, Table 1), and seven to eight samples were collected from each one. The conglomerate is not very thick in the main section, and it is absent in the nearby hill (Fig. 2e). Farther east, however, similar conglomerates show tenths meters thickness (see also Franchi and Page, 1980). All samples

**TABLE 1. PALEOMAGNETIC RESULTS.**

| Site | n/N | Decl. | Incl. | $\alpha_{95}$ | k |
|---|---|---|---|---|---|
| 3PA | 6/6 | 133.1 | 65.9 | 4.3 | 240 |
| 3PB | 5/5 | 139.2 | 66.3 | 4.9 | 240 |
| 3PC | 6/7 | 141.7 | 69.1 | 3.5 | 293 |
| 3PD | 5/6 | 156.1 | 59.0 | 4.8 | 185 |
| 3PE | 6/6 | 16.5 | -59.7 | 4.6 | 169 |
| 3PF | 7/7 | 312.5 | -41.9 | 2.2 | 942 |
| 3PG | 6/6 | 150.9 | 63.2 | 4.0 | 785 |
| 3PH | 7/9 | 36.5 | -57.6 | 5.4 | 195 |
| 3PI | 6/7 | 315.6 | -38.5 | 3.3 | 205 |

**n/N** denotes number of samples used in statistics/number of samples collected; **Dec., Incl.** are declination and inclination of paleomagnetic vector in geographical coordinates; $\boldsymbol{\alpha_{95}}$ is cone of 95% confidence level around mean direction; **k** is the fisherian precision parameter.

were oriented using magnetic and solar compasses. Differences between magnetic and solar compass measurements were only evident in the upper basalt from the small hill, heralding the presence of an unusually strong remanent magnetization in the site 3PG, quality that was confirmed during laboratory routines (see below).

The Tres Picos Prieto Formation at Puesto Comerci dips very gently (~2º) towards the southeast. Whole-rock K-Ar ages of 80±3 Ma for the upper lava flow in the hill and of 72±3 Ma for a basaltic level overlying the ignimbrite in the main section have been previously determined by Di Tommaso (1978) and reported by Franchi and Page (1980).

Both stepwise thermal and alternating field (AF) demagnetization in samples from all but one (3PG) of the studied sites were successful in isolating a high coercivity, high temperature component of magnetization mostly carried by titanomagnetite (Fig. 2a, b). Some samples from site 3PG, however, showed extremely high intensity of magnetization associated to a bicomponent paleomagnetic behavior with an almost complete overlap in coercivity spectra. It is likely that these samples underwent an isothermal remanent magnetization due to lightning which could not be successfully removed, hampering then the direct observation of the primary, thermoremanent magnetization. We then combined observed components from some samples and demagnetization circles from others to compute the mean direction for site 3PG (Fig. 2c). The extracted paleomagnetic vectors are listed in table 1 and shown in figure 2d.

Paleomagnetic results allow a very good correlation between the sampled lavas in the main section and those from the small hill (Fig. 2d, e). Paleomagnetic vectors from sites 3PF and 3PI (Figs. 2d, e) are indistinguishable from each other, strongly suggesting that they belong to the same lava. Likewise, identical directions observed in sites 3PA, 3PB and 3PC in the main section suggest that these successive lavas cooled within a very short time interval (years to a few 10s years), and probably one of them is the same lava flow that is represented by site 3PG in the hill (Fig. 2d). The paleomagnetic direction from site 3PE in the main section is statistically distinguishable from that of site 3PH in the small hill (angular distance between them 10°±5°; Fig. 2d). However, regarding their mutual proximity, their similar direction contrasting with the one of the expected time-averaged direction (star in Fig. 2d) and the stratigraphic position of the corresponding lavas in the volcanic succession (Fig. 2e), it is likely that these sites represent lavas erupted within a short time interval. The same analysis can be done for site 3PD versus sites 3PA, B, C (Fig. 2d). Overall, the results allow to identify three main volcanic events (Fig. 2d) which accumulated a pile of ~300 meters of basalts in the lower part of the Puesto Comerci section (Fig. 2e). Two early events occurred during times of normal polarity paleomagnetic field, whereas the late event produced at least four successive lavas that cooled under a reversed polarity paleofield (Figs. 2d, e). Paleomagnetism suggests that more than 200 m of lavas were accumulated within a time span of 10s to 100s years for this late event. The three events detected in the main section are also present in the nearby hill (Fig. 2c), allowing a direct correlation of unconnected outcrops of basalts (Fig. 2e).

Samples from the conglomerate show univectorial paleomagnetic behavior and are characterized by having lower values of both bulk susceptibility and magnetization intensity than those observed in the underlying basalt. The distribution of isolated components (Fig. 2f) gave a negative conglomerate test. However the results from the lavas clearly indicate that they carry primary magnetizations, pointing that the failure to statistically support a random distribution from remanences of the boulders is likely related to unresolved overlap of magnetizations. This is likely due to pervasive oxidation in these boulders, possibly related to the emplacement of the overlying basalt.

Both the K-Ar age of the basalt from site 3PG (80±3 Ma) and its reversed polarity point out that the upper basalts in the sampled section cooled during chron C33r (from 83 to 79.1 Ma; Cande and Kent, 1995). This constrains the eruption of the lower basalts (showing normal polarity) to have occurred late during the Cretaceous Superchron of Normal Polarity, which covers the entire Aptian to Santonian time span. Taken at face value the age from site 3PG (~80 Ma) and considering the upper bound age for the underlying basalts carrying normal polarity remanences (~84 Ma), the data suggests the occurrence of a period of at least 3 m.y. of tectonic and volcanic quiescence between the intermediate and the younger eruptive episodes. This has been also observed in other Late Cretaceous to Cenozoic Patagonian localities where the plateau basalts were constructed by discrete episodes of volcanism, spanning several million years from each other (*e.g.*,

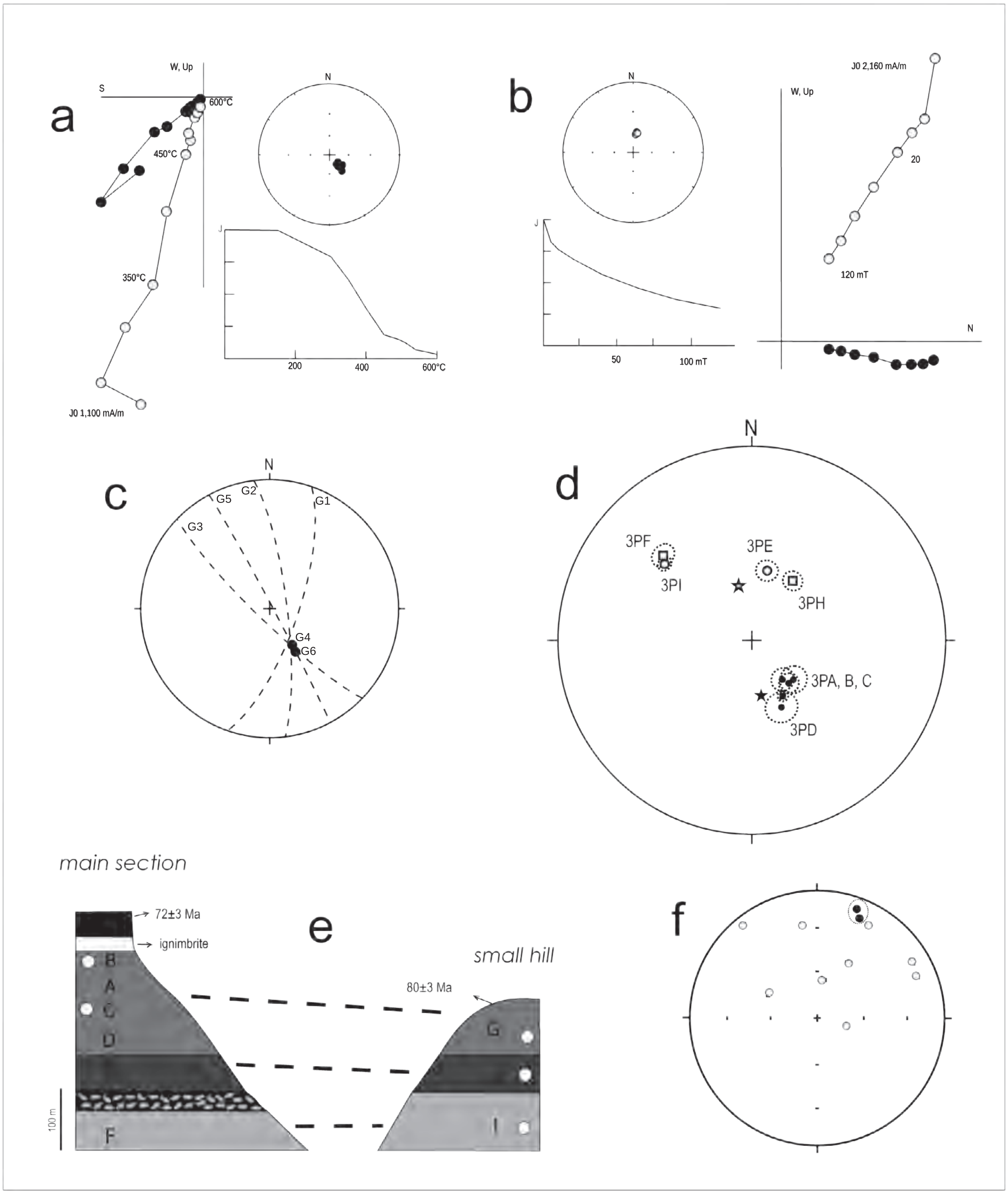



FIG. 2. **a.** Paleomagnetic behaviour of the samples when subjected to thermal demagnetization; **b.** Alternating field demagnetization; **c.** Demagnetization circles and isolated components used in determination of characteristic magnetization at site 3PG; **d.** Site-mean directions and Late Cretaceous expected directions (star symbol) for normal and reversed polarities. Note excellent correlation between lowermost sites (3PF and 3PI), very good correlation between intermediate sites (3PE and 3PH) and the cluster of reversed remanences defined by results from the upper lavas; **e.** Correlation of volcanic levels in the studied area; **f.** Visually negative conglomerate test, statistically corroborated by applying the test of Shipunov *et al.* (1998) by comparing the remanences in the boulders with the mean direction from the overlying 3PE site. The test yields ρ=0.606 whereas a random distribution at 95% confidence level should give ρ≤0.319 (critical value for n=10). Remanences enclosed by dotted line arises from the same boulder.

Brown *et al*., 2004; Espinoza *et al*., 2005; Guivel *et al*., 2006; Demant *et al*., 2007).

## 3. Petrography and geochemistry

Samples from the upper lavas (sites 3PB, C and G; Fig. 3a) show microporphyritic to porphyritic texture made up of microphenocrysts and few phenocrysts of altered olivine set in a pilotaxitic groundmass with clinopyroxene and opaque minerals. Samples from the intermediate level (site 3PH and 3PE, Fig. 3b) are porphyritic lavas with plagioclase and orthopyroxene phenocrysts plus scarce altered olivine microphenocrysts, set in a hyalophitic groundmass composed of orthopyroxene, clinopyroxene and opaque minerals. Plagioclase crystals measure up to 4.5 mm in length and occasionally show sieve texture; few olivine microphenocrysts show incipient orthopiroxene reaction rims.

The samples from the lower basaltic lava (sites 3PI and 3PF, Fig. 3c) show porphyritic texture with plagioclase (up to 3.4 mm in size), altered olivine and scarce opaque minerals phenocrysts set in an intersertal groundmass with clinopyroxene, altered olivine and opaque minerals. These rocks can be distinguished from the upper ones by the absence of orthopyroxene and by the larger amount of olivine in the groundmass, difference also evident in the geochemistry. The boulders in the overlying conglomerate (Fig. 2) are volcanic rocks very similar to the lava of site 3PF. They are porphyritic basalts made up of plagioclase and olivine phenocrysts, both displaying occasional rims of iron oxides. The groundmass is strongly altered by iron oxides, with intersertal texture including altered olivine, plagioclase, clinopyroxene and opaque minerals.

Major-and trace-element analyses were measured on five representative samples by ICP-MS at ACTLABS Ltd. (Activation Laboratory, Ancaster, Ontario, Canada), in accordance with the 4B2-RES protocol. The fused samples were diluted and analyzed by Perkin Elmer Sciex ELAN 6000, 6100 or 9000 ICP-MS (for more details see the website http://www.actlabs.com). The results are shown in Table 2. Three of the samples belong to the uppermost level (3PB, 3PC and 3pG, Fig. 2e), one of the samples belongs to the intermediate level (sample 3PH) and the remaining sample was collected from the basal lava flow (sample 3PI). LOI content of the samples is below 3,5 wt%, so all of them are considered to yield suitable information on the primary geochemistry (*e.g*., Polat and Hofmann, 2003).

Rocks plot in the basaltic andesites field of the TAS diagram (Le Bas *et al*., 1986), showing a subalkaline character and belonging to the medium-K calcalkaline magma series (Figs. 4a, b, c). There are some chemical differences between rocks from the lowermost level (represented by site 3PI), and those from the other ones (sites B, C, G and H). In the TAS diagram (Fig. 4a), the lowermost lava plots in the boundary with the basaltic trachyandesite field, whereas some of the remainder lavas plot in the boundary with andesite field. The two groups have different normative composition; while the intermediate and upper levels are Quartz normative (Q=3-7%, Table 2), the lowermost level is Hypersthene normative (Hy>Ol). The latter is also characterized by lesser MgO content and higher $Al_2O_3$, $TiO_2$, $Fe_2O_3$, CaO and $K_2O$ values than the

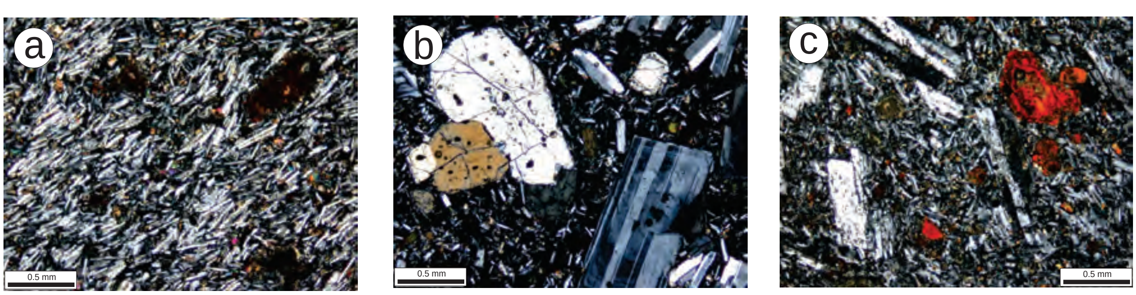



FIG. 3. **a.** Olivine phenocrysts and microphenocrysts altered to iddinsgite in a pilotaxitic matrix. Basaltic andesite (Q-normative), uppermost level; **b.** Plagioclase and orthopyroxene phenocrysts in hyalophitic matrix. Basaltic andesite (Q-normative), intermediate level; **c.** Plagioclase and olivine altered to iddinsgite in intersertal groundmass with iddinsgitized olivine. Basaltic andesite (Hy-normative), lower level. Crossed polars, 5x.

**TABLE 2. GEOCHEMICAL DATA.**

| **Site** | **3PB** | **3PC** | **3PG** | **3PH** | **3PI** | **Site** | **3PB** | **3PC** | **3PG** | **3PH** | **3PI** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rock-Type** | **BA** | **BA** | **BA** | **BA** | **BA** | **Rock-Type** | **BA** | **BA** | **BA** | **BA** | **BA** |
| $SiO_2$ | 56.87 | 57.14 | 55.72 | 56.66 | 52.81 | La | 21.9 | 17.1 | 18.0 | 20.2 | 12.9 |
| $TiO_2$ | 1.16 | 1.16 | 1.14 | 1.22 | 1.53 | Ce | 42.6 | 38.3 | 37.9 | 46.4 | 30.4 |
| $Al_2O_3$ | 17.42 | 17.46 | 17.61 | 17.50 | 19.52 | Pr | 5.49 | 4.79 | 4.48 | 5.88 | 3.98 |
| $Fe_2O_3$ | 6.91 | 6.93 | 6.79 | 7.01 | 8.26 | Nd | 21.5 | 18.4 | 17.4 | 22.6 | 16.9 |
| MnO | 0.11 | 0.10 | 0.12 | 0.13 | 0.14 | Sm | 4.7 | 4.0 | 3.8 | 5.0 | 4.3 |
| MgO | 4.74 | 4.57 | 5.41 | 4.71 | 4.06 | Eu | 1.44 | 1.33 | 1.27 | 1.55 | 1.43 |
| CaO | 7.47 | 7.44 | 7.83 | 7.24 | 8.16 | Gd | 4.7 | 3.9 | 3.7 | 4.8 | 4.4 |
| $Na_2O$ | 4.09 | 3.88 | 4.05 | 4.09 | 4.05 | Tb | 0.8 | 0.7 | 0.6 | 0.8 | 0.7 |
| $K_2O$ | 0.96 | 1.03 | 1.02 | 1.02 | 1.18 | Dy | 4.4 | 3.7 | 3.4 | 4.5 | 4.3 |
| $P_2O_5$ | 0.25 | 0.28 | 0.30 | 0.40 | 0.30 | Ho | 0.9 | 0.7 | 0.7 | 0.9 | 0.9 |
| sum | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | Er | 2.6 | 2.1 | 2.0 | 2.4 | 2.5 |
| | | | | | | Tm | 0.36 | 0.31 | 0.29 | 0.35 | 0.37 |
| L.O.I. | 1.28 | 1.70 | 1.60 | 1.93 | 3.03 | Yb | 2.3 | 1.9 | 1.8 | 2.2 | 2.2 |
| | | | | | | Lu | 0.33 | 0.26 | 0.26 | 0.32 | 0.33 |
| Q (CIPW) | 5.72 | 7.09 | 3.18 | 5.75 | 0.00 | Hf | 3.9 | 4.9 | 3.7 | 5.5 | 3.9 |
| Hy (CIPW) | 15.35 | 15.39 | 16.57 | 16.21 | 14.48 | Ta | 0.8 | 0.7 | 0.8 | 0.9 | 0.7 |
| Hy/Ol (CIPW) | | | | | 16.84 | Pb | 17 | 10 | 9 | 7 | 6 |
| | | | | | | Th | 2.6 | 2.6 | 2.7 | 2.5 | 1.8 |
| Cr | 130 | 130 | 140 | 100 | 50 | U | 0.7 | 0.6 | 0.6 | 0.7 | 0.5 |
| Ni | 70 | 70 | 70 | 80 | 70 | | | | | | |
| V | 124 | 148 | 150 | 142 | 174 | Ba/La | 9.45 | 12.57 | 12.22 | 9.55 | 14.65 |
| Rb | 17 | 17 | 20 | 22 | 14 | La/Ta | 27.38 | 24.43 | 22.50 | 22.44 | 18.43 |
| Ba | 207 | 215 | 220 | 193 | 189 | (La/Yb)cn | 6.42 | 6.07 | 6.74 | 6.19 | 3.95 |
| Sr | 550 | 554 | 569 | 472 | 567 | La/Nb | 3.13 | 2.44 | 2.57 | 2.02 | 1.61 |
| Nb | 7 | 7 | 7 | 10 | 8 | Ba/Nb | 29.57 | 30.71 | 31.42 | 19.3 | 23.62 |
| Zr | 159 | 201 | 164 | 230 | 152 | Sr/Y | 22.92 | 26.38 | 28.45 | 18.88 | 22.68 |
| Y | 24 | 21 | 20 | 25 | 25 | Ti/V | 56.08 | 46.99 | 45.56 | 51.51 | 52.71 |
| | | | | | | Zr/Hf | 40.76 | 41.02 | 44.32 | 41.82 | 38.97 |

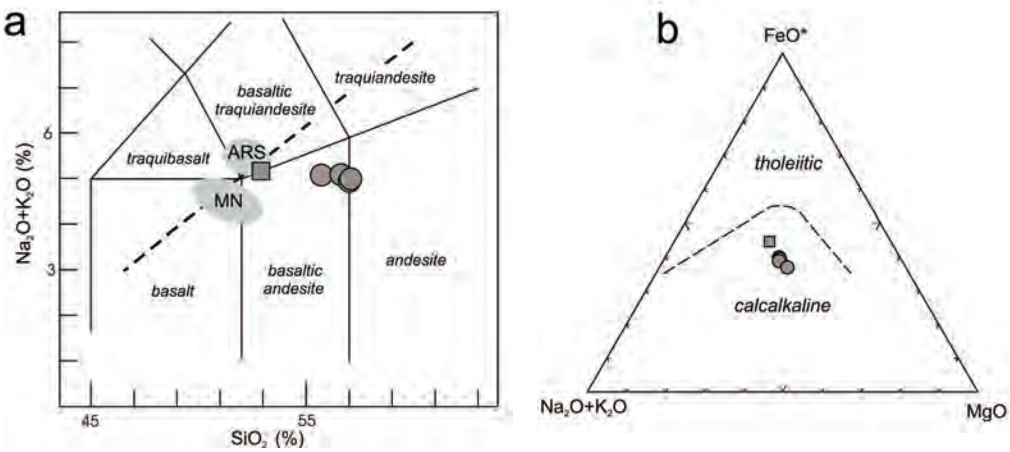
**Note**: Major elements recalculated to 100% on volatile free basis. CIPW-normative compositions assuming $Fe_2O_3$/FeO = 0.15 **Q**, **Hy** and **Ol** = CIPW-normative quartz, hypersthene and olivine, respectively; **BA** = basaltic andesite; **cn** = chondrite normalized (Boynton, 1984).

quartz-normative basaltic andesites (Table 2). Notably the Hy-normative rock also has lower contents of La, Ce, Nd, Zr, Th, Rb and Ba.

The Q-normative rocks of the intermediate level (sites 3PH and 3PE) are characterized by higher contents of $P_2O_5$ and Zr as well as lower Sr values than the upper rocks (sites 3PB, C and G, Table 2). In the chondrite-normalized ('cn'; Boynton, 1984) REE diagram (Fig. 5a), samples display a moderate slope pattern, in congruence with low light REE/ heavy REE fractionation. The Hy-normative rocks have the lowest contents of light REE (LREE), evident in the La/Yb ratios ('cn' 3.95 from site 3PI against 6.07-6.74 from the other sites, Table 2). In normalized to primordial mantle (Sun and McDonough, 1989) multi-elemental diagrams the rocks show a similar behaviour, characterized by negative Nb and Ti anomalies and a positive Pb peak (Fig. 5b).

## 4. Petrogenesis and comparison with coeval basalts from Patagonia

The low values of MgO, Cr and Ni (Table 2) indicate that the rocks at Puesto Comerci do not represent primitive melts. The negative Nb anomaly (Fig. 5b) and the trace element ratio La/Nb>1 (Table 2) are characteristic of subduction-related magmas, in accordance with the calcalkaline nature



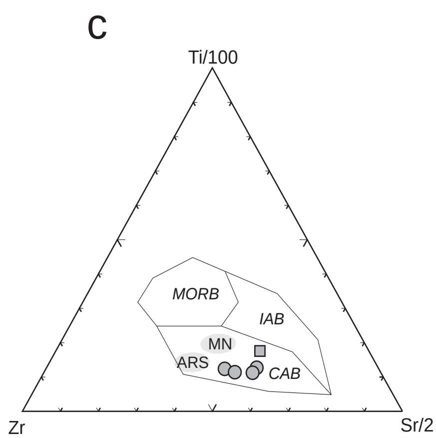




FIG. 4. Geochemical classification and tectonic diagrams for Tres Picos Prieto lavas. **a.** Total alkali-silice (TAS, Le Bas *et al*., 1986), the dashed line divides the alkalic and sub-alkalic fields (Irvine and Baragar, 1971); **b.** AFM; **c.** Zr-Ti-Sr diagram (after Pearce and Cann, 1973). MN and ARS show the geochemistry of the Morro Negro (Demant *et al.* (2007) and Alto Río Senguer (Barker *et al*., 1981) basalts, respectively. In b, though not shown, MN and ARS rocks also plot within the calcalkaline field.

of the studied rocks (Figs. 4b, c). Concordantly, it may be observed that patterns in the multi-elemental diagram including the positive Pb anomaly (Fig. 5b) are similar to those of type-2 basaltic samples from the Southern Volcanic Zone of the Andes (SVZ; López-Escobar *et al*., 1993; D' Orazio *et al*., 2003). It is worth noting that the Q-normative rocks show higher La/Nb ratio as well as La, Ba, Th and Rb contents than those observed in the lowermost, Hy-normative rocks. Though these features can be regarded as a consequence of differentiation processes, so frequent in arc settings, it should be noted that if crystal fractionation or assimilation with crystal fractionation were operative, a decrease in MgO, Cr and Ni contents of the Q-normative rocks should be expected. However, MgO and Cr contents are even higher than in the Hy-normative one while Ni shows no change. Therefore, the differences in the studied rocks would arise from slight differences in the source. An increasing subduction imprint in the source of the Q-normative rocks is considered to be more suitable to explain such differences. This is particularly illustrated by the positive correlation of the Ba *versus* La/Nb curve with lava-age (Fig. 5d).

However, Ba/La ratios<20 and Ta/La ratios<25 (Table 2) are not characteristic of arc rocks according to Kay *et al.* (2004). The same is suggested by Ba/Nb<40 (D' Orazio *et al*., 2004), Ti/V>20 (Shervais, 1982; Bruni *et al*., 2008) and Zr/Hf≥39 (David *et al*., 2000) ratios (Table 2, Fig. 5c), all of them indicating a within-plate component in the Tres Picos Prieto magmas. Nevertheless, it should be noted that La/Ta also shows an increase towards the uppermost level, with La/Ta=27.4, just compatible with arc magmatism, reinforcing the above mentioned increase of subduction signature with time.

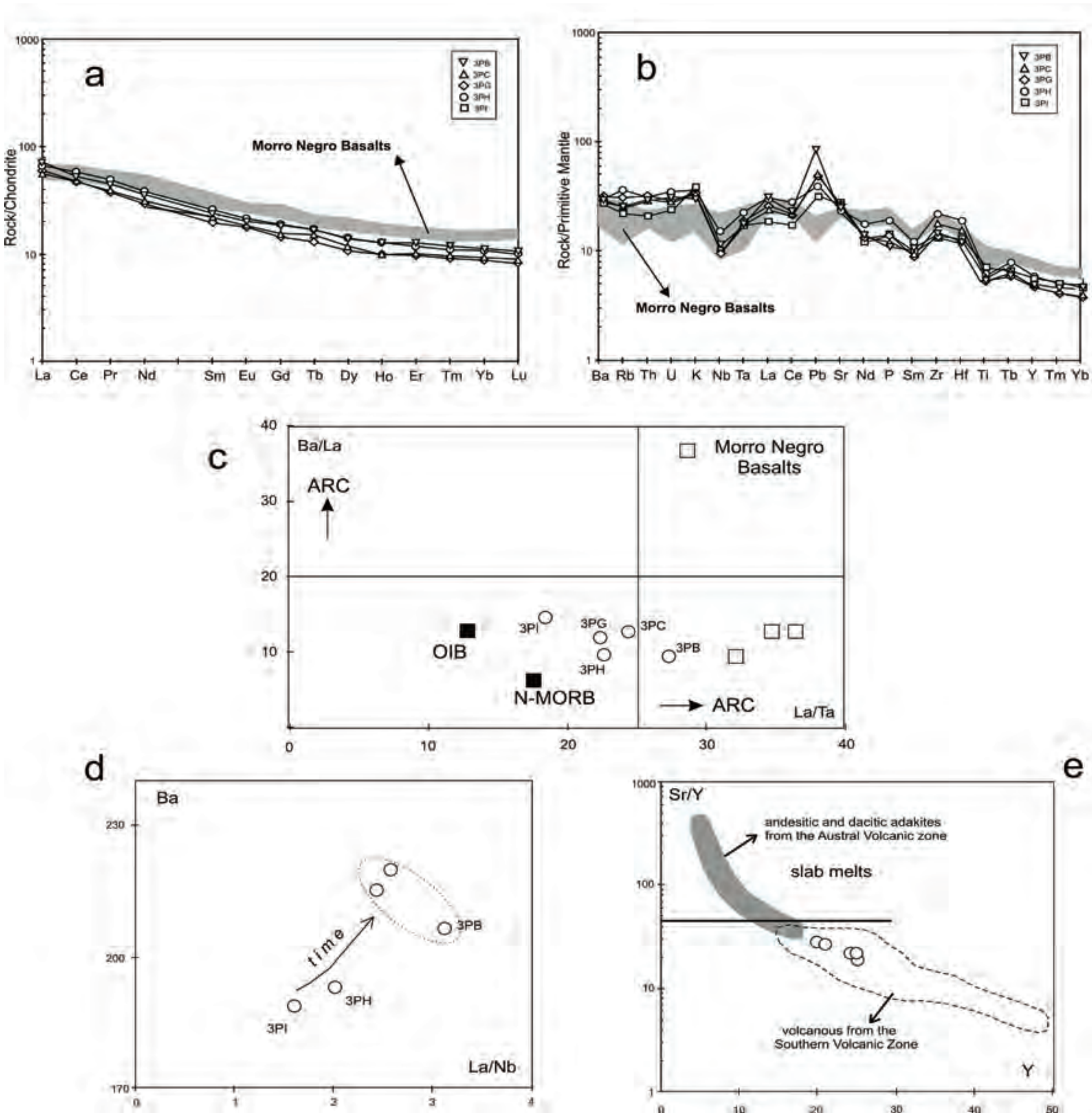



FIG. 5. **a.** Chondrite-normalized (Boynton, 1984) REE diagram for Tres Picos Prieto lavas; **b.** Normalized primitive Mantle (Sun and McDonough, 1989) multi-elemental diagram. Grey fields correspond to Morro Negro basalts (Demant *et al.*, 2007) plotted for comparison; **c.** La/Ta *versus* Ba/La diagram; lines defining arc field ratios according to Kay *et al.* (2004), OIB and MORB mean values are from Sun and McDonough (1989), open squares are the results from Morro Negro basalts (Demant *et al.*, 2007); **d.** La/Nb *versus* Ba plot pointing out the evolution trend through time; **e.** Y *versus* Sr/Y diagram showing no slab melts participation in the mantle source of Tres Picos Prieto; compositional fields and limits are from D'Orazio *et al.* (2003) and references therein.

From the previous discussion, the Tres Picos Prieto basaltic lavas represent an intermediate case between subduction-related and within-plate volcanism. This kind of volcanic rocks has similarities with the 'transitional' type defined by Stern *et al*. (1990) in southern South America, which display characteristics between the cratonic basalts (OIB-type magmas) and the arc basalts. Some examples of this particular type of basalts in Patagonia were described in Cenozoic rocks from Meseta de la Muerte (Gorring *et al*., 1997), from Meseta de las Vizcachas, Camusú Aike (D'Orazio *et al*., 2004, 2005), from Cerro Ante (Bruni *et al*., 2008) and from the Zeballos Volcanic sequence (Espinoza *et* *al*., 2010). Kay *et al*. (2006) also suggested mixing between continental mantle and slab components to explain the chemistry of Oligo-Miocene basalts in central Patagonia.

Although the position of the 80-60 Ma magmatic arc for latitudes of the study area is not well constrained, all of the dated plutonic rocks showing similar age crop out west of the studied locality (*e.g*., the 81.7 Ma±1.3 Teta granodiorite, Rolando *et al*., 2002) suggesting that the studied rocks may correspond to a proximal back-arc area. In this context, basalts of transitional type could be the consequence of a decrease in the amount of incompatible elements derived from the dehydratation of the subducting slab together with the consistent lower degree of partial melting that determines a change from arc to back-arc volcanism (*e.g*., Hickey-Vargas *et al*., 1986, 1989; Stern *et al*., 1990).

This is in accordance with the geological framework, as Tres Picos Prieto lavas uncomformably overly Jurassic to Lower Cretaceous mesosilicic and acid volcanic rocks that are typical of arc settings. Hence, the transitional character of Tres Picos Prieto rocks must therefore reveal the change from arc to back-arc setting as mentioned above. Nevertheless, the increase in the subduction signature towards the top of the sequence points out that arc conditions tend to be reinstalled.

The main localities of Late Cretaceous Patagonian Plateau Basalts define a ~200 km, NNE-SSW trending line with the Tres Picos Prieto occuping the northernmost position and the Morro Negro basalts (*e.g*., Demant *et al*., 2007) occuping the southernmost possition (Fig. 1). Available geochemical data (Barker *et al*., 1981; Demant *et al*., 2007; this study) show that all of these Late Cretaceous basalts plot in the calcalkaline field (Fig. 4b and c). Some differences, however, come from the TAS diagram, with basaltic trachyandesitic type characterizing the Alto Río Senguerr rocks, while basalts and basaltic andesites prevail in the localities of Morro Negro and Tres Picos Prieto, respectively (Fig. 4a). Hypersthene normative lavas are overlain by quartz normative ones in both the Tres Picos Prieto and Morro Negro localities (Demant *et al*., 2007; this study). Likewise, both locations show similar, moderate to rather flat chondrite-normalized patterns (Fig. 5a), although the Tres Picos Prieto lavas display slightly lower REE contents, higher $(La/Yb)_{cn}$ ratios (3.9-6.7 *versus* 3.8-4.2) and $(Yb)_{cn}>(Lu)_{cn}$. Also multi-elemental diagrams normalized to primordial mantle are quite similar (Fig. 5b), with the exception of the positive Pb anomaly shown by the Picos Prieto lavas. As observed in the Tres Picos Prieto locality, the lavas from Morro Negro also have geochemical signatures intermediate between subduction-related and within-plate magmas (Demant *et al*., 2007), since their high Zr/Hf (between 42 and 50) and their Ba/La<20 ratios (*e.g*., Fig. 5c) suggest OIB affinities according to the limits pointed out by David *et al*. (2000) and Kay *et al*. (2004), respectively, whereas their La/Ta>25 ratios are typical of arc magmatism following Kay *et al*. (2004).

## 5. On tectonomagmatic models from the Patagonian Plateau Basalts

We consider unlikely that the rather coeval plateau basalts in these nearby localities could have been generated by different tectonic processes. In the introduction we mentioned several mechanisms that have been proposed to account for the origin of Late Cretaceous to Recent Patagonian Basalts, highlighting that there is not a single model that accounts for the entire magmatic province. Below we discuss the possible application of these and other models to the genesis of Late Cretaceous and younger plateau lavas.

We have shown that the Tres Picos Prieto lavas at Puesto Comerci have some slab imprint, pointing to an origin at a supra-subduction environment. Likewise, we have shown similarities between lavas from Tres Picos Prieto and Morro Negro localities. In particular, the chemistry of the Morro Negro locality has been found similar to that of Quaternary basalts which in turn are thought to be associated to the subduction of the Chile Rise (Demant *et al*., 2007). However, invoking ridge-subduction and associated slab melting mechanism to account for the Upper Cretaceous basalts can not be supported by available information on the latest Cretaceous-Paleocene convergence in Patagonia, which points to fast (~10 cm/yr) east-southeastward subduction of the Aluk plate without evidence for the presence of an additional oceanic plate (Somoza and Ghidella, 2005), a requirement for the occurrence of subduction of a plate boundary (*e.g*., oceanic ridge). This agrees with the lack of slab melt signature in the studied rocks, as suggested by their relatively low Mg and Sr/Y ratios, which plot away from the adakitic field

(Fig. 5e). Therefore, the subduction signal in the Tres Picos Prieto basalts would be related to fluids released from the Aluk slab.

Noting the difficulties to invoke slab window models for all of the lavas, Parada *et al.* (2001) discussed the origin of the Upper Cretaceous back-arc basalts in the general terms of extensional tectonics, adding that observed compositional variations between different localities in the Aysén region can be attributed to different degree of lithospheric stretching. Construction of plateau basalts in Patagonia began soon after the first contractional episode of the Andean Cycle (*ca.* 90-95 Ma, Somoza and Zaffarana, 2008) which is represented in the region by the angular unconformity between Lower to mid-Cretaceous rocks and 70-80 Ma flatlying basalts in both the Alto Río Senguerr and the Tres Picos Prieto areas. Then, Late Cretaceous back-arc volcanism could have been related to passive magma upwelling due to either or both post-contractional lithosphere relaxation and/or renewed slab rollback leading to effective trench retreat and associated lithosphere extension. In fact, magma upwelling throughout fractures associated to lithosphere dilation-extension is a mechanism that can be invoked whatever the age of the considered rocks in this magmatic province.

Shear-driven upwelling (Conrad *et al*., 2010) is another mechanism that may be applied to the petrogenesis of any of the Late Cretaceous to Cenozoic Patagonian back-arc lavas irrespective of their rock ages. Plate motion requires shearing between the westward moving lithosphere and the asthenosphere. Tomographic studies of the astenosphere show a variety of shapes and sizes of low-velocity anomalies that presumably result from a variety of time-dependent processes. These irregularities in the lithosphere-asthenosphere plane would imply the presence of lateral viscosity heterogeneities. Analysing classic engineering problems, Conrad *et al*. (2010) concluded that rapid shearing in a lithosphere-asthenosphere zone having asperities (*i.e*., lateral viscosity heterogeneities) will induce circulatory flow within cavities, facilitating magma upwelling (Fig. 6). We do not know how the shape of the Patagonian lithosphere-asthenosphere zone is, nevertheless it could be speculated the presence of irregularities inherited from pervasive pre-Late Cretaceous extensional tectonics. Additionally, South America began to move fast to the west with respect to the underlying mantle at 90-95 Ma (Somoza and Zaffarana, 2008) and continued throughout the entire Cenozoic, matching the timing of back-arc volcanism in Patagonia. Then, the Late Cretaceous to Recent mafic volcanic province of Patagonia developed above a rapidly shearing asthenosphere, making shear-driven upwelling (Conrad *et al.*, 2010) a geodynamic process capable to contribute in the genesis of most of these back-arc to intraplate lavas.

## 6. Conclusions

Paleomagnetic results from nine sites *(i.e*., individual lavas) of the Tres Picos Prieto basalts provide only three independent records of the paleomagnetic field, illustrating the difficulties in canceling paleosecular variation to obtain true paleomagnetic poles from lavas. The results further indicate that a 300 m thick pile of Upper Cretaceous lavas was constructed by several flows erupted during three discrete (*i.e*., temporally separated) episodes of volcanism. The chemistry of the studied basalts shows signatures compatible with both subduction and intraplate related magmatism, which we interpret as representing transitional lavas in a supra-subduction environment.

The Late Cretaceous to Cenozoic Patagonian Plateau Basalts crop out from eastern Patagonia to the cordillera, and their genesis has been associated to different tectonic processes. The latter also apply for rocks of the same age cropping out in different locations. Because the development of the magmatic

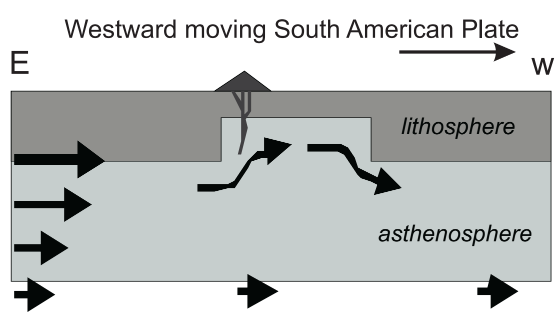



FIG. 6. Schematic draft showing the model of shear-driven upwelling, modified from Conrad *et al.* (2010) (http://www.mantleplumes.org/ShearDrivenUpwelling.html). The model involves rapid shearing in a lithosphere-asthenosphere zone having asperities (*i.e*., lateral viscosity heterogeneities) which induce circulatory flow within cavities and then facilitates magma upwelling. The sketch represents an E-W section of Patagonian lithosphere-astenosphere with the observer looking to the south.

province encompasses the stage of fast westward drift of South America, we propose that shear-driven upwelling (Conrad *et al*., 2010) is a geodynamic process to take into account as a possible contributing mechanism when analyzing the genesis of most of these backarc to intraplate lavas.

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