



## PALEOMAGNETISM AND GEOCHEMISTRY FROM UPPER CRETACEOUS BASALTS OF PATAGONIA

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### Abstract

A paleomagnetic study on nine sites from lavas at the Upper Cretaceous Tres Picos Prieto locality (43° 50'S and 70°3'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 intraplate and subduction-related magmatism, with the latter having a more important contribution in the younger lavas. Overall, we interpret these rocks to be transitional basalts in a supra-subduction environment.

The Late Cretaceous to Cenozoic Patagonian Plateau Basaltic Province crop out from eastern Patagonia to the cordillera, and their genesis has been associated to different tectonic processes, even for spatially separated rocks of the same age. Since the development of the magmatic province is contemporary with the stage of fast westward drift of South America, we proposed that magma generation and upwelling due to rapidly shearing asthenosphere could have induced circulatory flow associated to asperities in the lithosphere-asthenosphere interface (shear-driven upwelling, Conrad et al., 2010). This geodynamic process should be evaluated as a possible contributing mechanism when exploring the genesis of most of these transitional magmas.

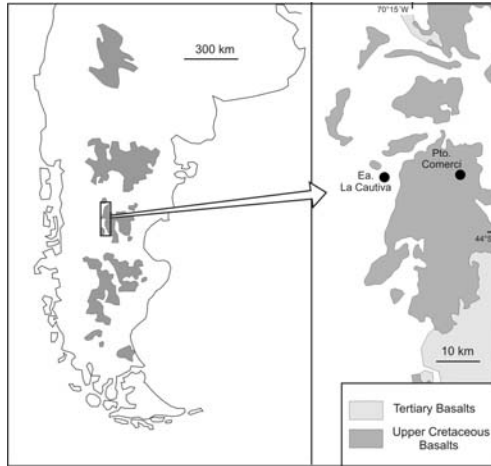
### Resumen

Se realizó un estudio paleomagnético en nueve sitios pertenecientes a las lavas del Cretácico Superior de la localidad de Tres Picos Prieto (43° 50'S y 70° 3'O), las cuales son parte de los Basaltos de Plateau de Patagonia. El estudio reveló que la columna de alrededor de 300 m de basaltos se acumuló durante tres episodios volcánicos discretos (temporalmente espaciados). La química de esas lavas muestra características compatibles tanto con magmatismo de intraplaca como de subducción. La componente de subducción se vuelve más importante hacia el techo de la secuencia. Las rocas de la Formación Tres Picos Prieto se consideran como basaltos transicionales en un ambiente de supra-subducción.

La Provincia Magmática Basáltica Cretácico Tardío a Cenozoica de Patagonia aflora desde el oriente hasta la cordillera de los Andes, y su génesis ha sido asociada a diferentes procesos tectónicos, aún para rocas de la misma edad que se encuentran en localidades diferentes. Como el desarrollo de este magmatismo es contemporáneo con la etapa de deriva rápida de la Placa Sudamericana hacia el oeste, se propone que el mecanismo de generación y ascenso de magmas debido a la cizalla rápida de la astenósfera podría haber inducido un flujo de magmas debido a las asperezas preexistentes en el límite litósfera-astenósfera. Este mecanismo se denomina “shear-driven upwelling” (Conrad et al., 2010), y se sugiere que la contribución de este proceso geodinámico debe ser tenida en cuenta cuando se evalúa la génesis de la mayoría de estos magmas de características transicionales.



## Introduction



**Figure 1:** Map of southern South America and main outcrops of Patagonian Plateau Basalts showing the studied region.

Patagonia has been the locus of widespread flood basaltic volcanism since the Late Cretaceous, which is characteristic in the landscape of the region. Several models have been proposed for their origin (i.e. Ramos and Kay 1992, Gorrington et al. 1997, Muñoz et al. 2000, Parada et al. 2001, Espinoza et al. 2005, Kay et al. 2007, Bruni et al. 2008).

This work reports the results of a paleomagnetic, petrographic and geochemical study that was carried out in the Tres Picos Prieto Formation (Franchi and Page 1980) which is a pyroclastic and lavic association that constitutes one of the main Cretaceous localities of the mafic igneous province. 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. The chemistry of the studied lavas shows signatures of both intraplate and subduction environments.

## Paleomagnetism

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	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	785
3PH	7/9	36.5	-57.6	5.4	195
3PI	6/7	315.6	-38.5	3.3	205

**Table 1:** Paleomagnetic results. n/N denotes number of samples used in statistics/number of samples collected; Dec., Inc. are declination and inclination of paleomagnetic vector in geographical coordinates;  $\alpha_{95}$  is cone of 95% confidence level around mean direction; k is the fisherian precision parameter.

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 paleomagnetic study was performed in a section located in the Puesto Comerci area (Fig. 1) and comprises a ~320 meters thick column composed of at least five basaltic flows (sites 3PA to 3PF, Table 1). 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. Differences between successive measurements from magnetic and solar compasses were noticed in the upper basalt from the top of the hill (site 3PG), because of its strong remanent magnetization.

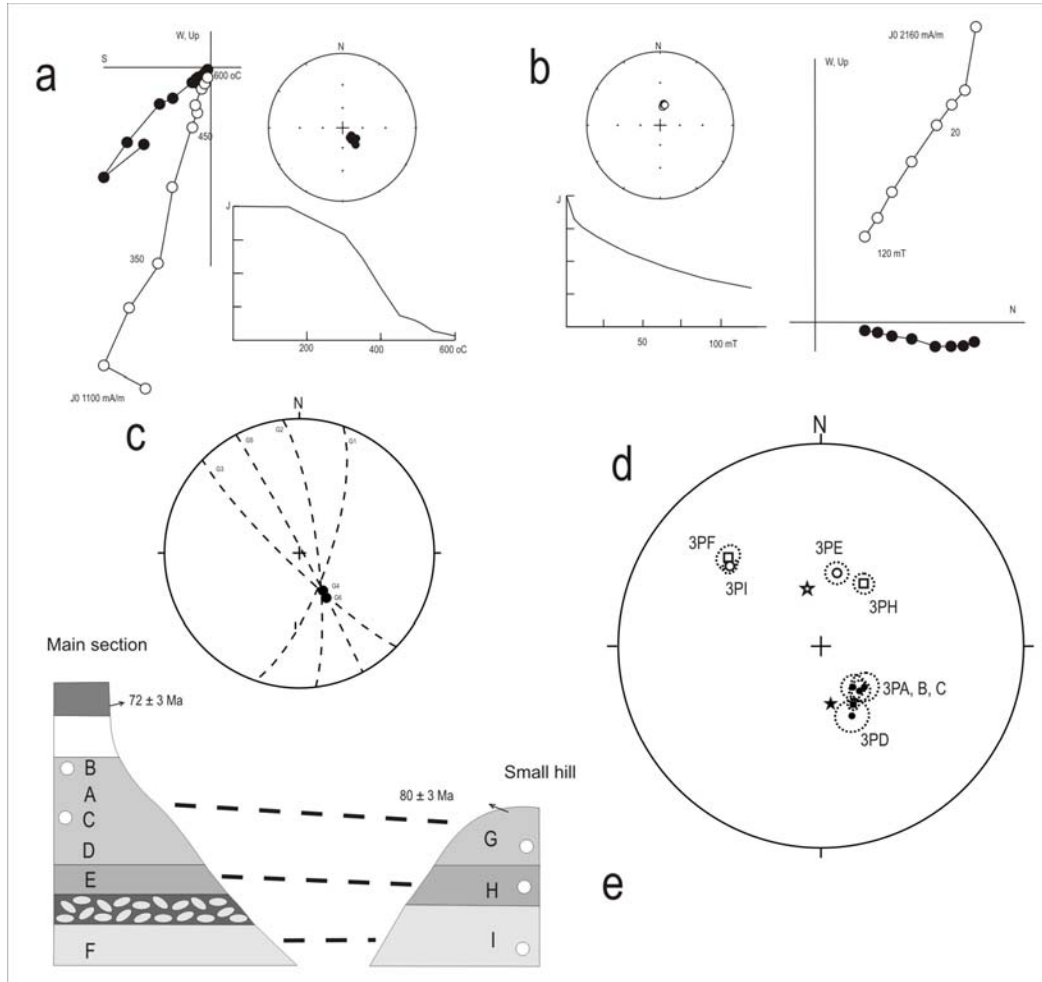
At Puesto Comerci the Tres Picos Prieto Formation dips very gently ( $\sim 2^\circ$ ) towards the southeast. Whole-rock K/Ar ages of  $80 \pm 3$  Ma for the upper lava flow in the hill and of  $72 \pm 3$  Ma for a basaltic flow overlying the ignimbrite in the main section have been previously determined by Di Tomasso (1978) and by Franchi and Page (1980).

In samples from all but one (3PG) of the studied sites both stepwise thermal and alternating field (AF) demagnetization isolated 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



the mean direction for site 3PG (Fig. 2c). The observed remanence directions are listed in Table 1 and shown in Figure 2d.

Overall, the results allow to identify three main volcanic events (Fig. 2d) which accumulated a pile of circa 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).



**Figure 2:** Paleomagnetic behaviour of samples when subjected to thermal (a) and alternating field (b) 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.

The K-Ar age of one basalt from site 3PG ( $80 \pm 3$  Ma) and its reversed polarity point out that the upper basalts in the complete correlated section cooled during chron C33r (from 83 to 79.1 Ma; Cande and Kent, 1995). This constrains the time of the eruption of the lower basalts (showing normal polarity) to be during the Cretaceous superchron of normal polarity, which covers the entire Aptian to Santonian time span. The



age from site 3PG (80 Ma) indicates that a period of at least 3 m.y. of tectonic and volcanic quiescence existed between the intermediate and the younger eruptive episodes.

## Geochemistry

Major- and trace-element analyses were measured on five representative samples by ICP-MS at ACTLABS Ltd. (Ontario, Canada). 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. There are some chemical differences between the lowermost event (represented by site 3PI), and the other two events (sites B, C, G and H). In the TAS diagram, the lowermost event 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 modal composition; while the intermediate and upper levels are Quartz normative ( $Q = 3-7\%$ ), 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 quartz normative basaltic andesites. Notably the Hy-normative rock also has lower contents of La, Ce, Nd, Zr, Th, Rb, Ba and Sr.

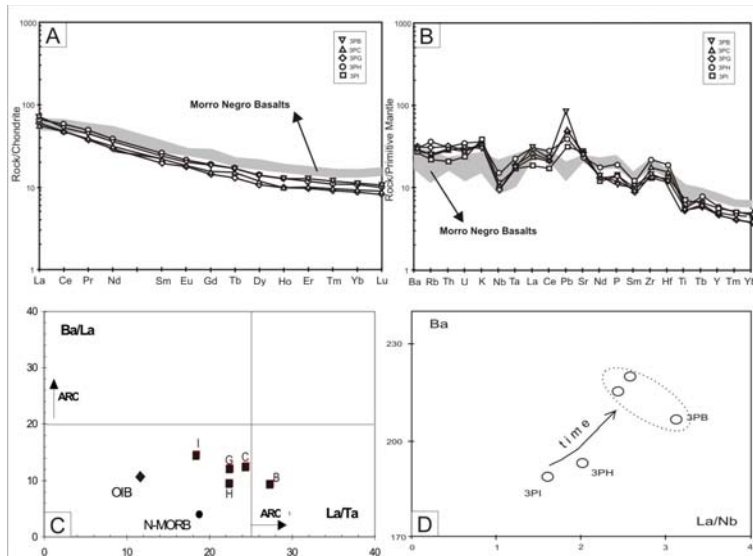


Figure 3: a) Chondrite-normalized REE diagram for Tres Picos Prieto lavas b) Normalized primitive Mantle multi-elemental diagram. Grey fields correspond to Morro Negro basalts (Demant et al. 2007) plotted for comparison. c) La/Ta vs. Ba/La diagram; lines defining arc field according to Kay et al. (2004), OIB and MORB mean values are from Sun and McDonough (1989), squares are the results from Morro Negro basalts (Demant et al., 2007). d) La/Nb vs. Ba plot pointing out the evolution trend through time. e) Y vs. Sr/Y diagram showing 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.

1 are characteristic of subduction related magmas, which is in accordance with the calcalkaline nature of the studied rocks. Patterns in the multi-elemental diagram including the positive Pb anomaly (Fig. 3b) are similar to those of type-2 basaltic samples from the Southern Volcanic Zone (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, pointing

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). In the chondrite-normalized (cn; Boynton, 1984) REE diagram (Fig. 3a), samples display a rather flat slope pattern, in congruence with low light REE/ heavy REE fractionation. The Hy-normative rocks have lower contents of LREE than the others, which is evident in the lowest La/Yb ratios (cn 3.96 from site 3PI against 6.07-6.74 from the other sites). In normalized to primordial mantle (Sun and McDonough, 1989) multi-elemental diagrams the rocks show a similar behaviour, characterized by negative Nb and Ti negative anomalies and a positive Pb peak (Fig. 3b).

## Discussion and conclusions

The low values of MgO, Cr and Ni indicate that the rocks at Puesto Comerci do not represent primitive melts. The negative Nb anomaly (Fig. 3b) and the trace element ratio  $La/Nb >$



out to an increasing subduction imprint towards the upper part of the section. This is particularly illustrated by the positive correlation of the Ba vs. La/Nb curve with lava-age (Fig. 3d).

However, Ba/La ratios  $< 20$  and Ta/La ratios  $< 25$  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  $\geq 39$  (David et al., 2000) ratios (Fig 3c), 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.

From the previous discussion, the Tres Picos Prieto basaltic lavas represent an intermediate case between subduction-related and within-plate volcanism. Some examples of this particular type of basalts in Patagonia were described in Meseta de la Muerte (Gorring et al., 1997), in Meseta de las Vizcachas and Camusú Aike (D'Orazio et al., 2004) and in Cerro Ante (Bruni et al., 2008). Kay et al. (2006) also suggested that 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, outcrops of  $81.7 \text{ Ma} \pm 1.3$  plutonic bodies  $\sim 150$  km WSW of the locality (e.g. Teta granodiorite, Rolando et al., 2002) suggest that the studied rocks correspond to a proximal back-arc area.

The main localities of Late Cretaceous Patagonian Plateau Basalts define a  $\sim 200$  km, NNE-SSW trending line with the Tres Picos Prieto occupying the northernmost position and the Morro Negro basalts (e.g. Demant et al., 2007) occupying the southernmost position. We consider unlikely that the rather coeval plateau basalts in these nearby localities could have been generated by different tectonic processes. There is not a single model that accounts for the entire magmatic province. Because the development of the magmatic province encompasses the stage of fast westward drift of South America with respect to the mantle in the 90-95 Ma (Somoza and Zaffarana 2008), we propose that shear-driven upwelling (Conrad et al., 2010) is a geodynamic process that could be taken into account as a possible contributing mechanism when analyzing the genesis of most of these backarc to intraplate lavas.

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