TRACING A MAJOR CRUSTAL DOMAIN BOUNDARY BASED ON THE GEOCHEMISTRY OF MINOR VOLCANIC CENTRES IN SOUTHERN PERU

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INTRODUCTION

Geochemical studies of Tertiary to Recent magmatism in the Central Volcanic Zone have mainly focused on large stratovolcanoes. This is because mafic minor volcanic centres and related flows that formed during a single eruption are relatively rare and occur in locally clusters (e.g. Andagua and Huambo fields in S. Peru, Delacour et al., 2007; Negrillar field in N. Chile, Deruelle 1982) or in the back arc region (Davidson and de Silva, 1992). These studies showed that the "monogenetic" lavas are high-K calc-alkaline and their major, trace, and rare elements, as well as Sr-, Nd- and Pb- isotopes data display a range comparable to those of the Central Volcanic Zone composite volcanoes (Delacour et al., 2007).
It has been argued that the eruptive products of these minor centres bypass the large magma chamber systems below Andean stratovolcanoes and thus may represent magmas that were derived from a deeper level in the crust (Davidson and de Silva, 1992; Ruprecht and Wörner, 2007). This study represents a continuation of our work to understand the regional variation in erupted magma composition in the Central Andes (Mamani et al., 2008; Wörner et al., 1992). Here we concentrate on the northern boundary of the Arequipa Pb-domain (Mamani et al., 2008) in the Colca and Cotahuasi valley regions.

DISTRIBUTION OF MINOR VOLCANIC CENTRES

Minor centres of late Pleistocene to Historical age (< 1 Ma, Kaneoka and Guevara, 1984; Delacour et al., 2007) are found in southern Peru in the Andahua, Huambo, Llauce, Caylloma fields and outcrops in Auquihuato, Iquipi and Yura area (Fig. 1). We also include lavas of Llauce valley in the Ocoña Cañon, which have Pliocene ages (2.27 ± 0.05 Ma, Thouret et al., 2007; 2.261 ± 0.046 Ma, Schildgen et al., 2007).
Cinder and scoria cones of the younger fields are all well preserved and cones have a typical height of 200-300 m and are 500-650 m across. Apparently most of the cones lie on valley floors. However, this may be an artifact and result from preferential accumulation into the valleys and enhanced erosion by glaciers at high altitudes. Some lava flow associated with the cones extents as far as 4 to 8 km and thick lavas cover the floor of Andahua and Llauce valleys and act as natural dams. Within the Llauce valley lava dams are associated to large outburst-floods. Thinner lava dams cover the Huambo valley, Auquihuato and Sibayo area (Fig. 1).
Petrographic types are basaltic andesites, andesites and dacites (Fig. 2). The most mafic sample is from Nicholson centre with SiO_2 52.3%. Plagioclase is the prominent mineral phase and clinopyroxene and Fe-Ti oxides are present in all lavas. Where Plagioclase is less abundant, olivine and clinopyroxene occur higher but in equal proportion. Hornblende and orthopyroxene appear in andesites and biotite phenocrysts are found only in dacites (Delacour et al., 2007).
According to the Pb-isotope domain map of Mamani et al. (2008), the Iquipi, Huambo and Yura centres occur within the Arequipa domain whereas the Llauce lavas, Auquihuato, Andahua and Caylloma centres occur within the northern Cordillera domain.

ISOTOPIC COMPOSITION

A striking characteristic of the minor centres in this region is their systematic variation Sr-, Nd-, Pb-isotopic data (Table 1) with an abrupt change (within 60 km) in isotopic compositions between

Arequipa and northern Cordillera domain (Fig. 1). The eNd values (-2.5 to -4.5), $^{87}Sr/^{86}Sr$ ratios (0.7055 to 0.7065) and $^{206}Pb/^{204}Pb$ ratios (18.56 to 18.78) of minor volcanic centres within the northern Cordillera domain encompass the entire range recorded from the large stratovolcaneos in this domain

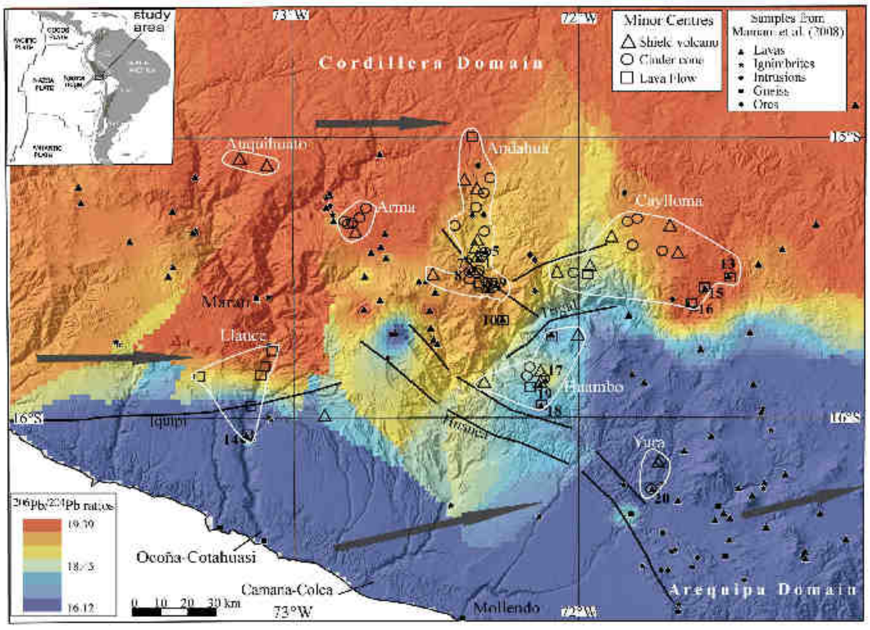

Fig. 1. Present-day $^{206}Pb/^{204}Pb$ ratios map and location of the minor volcanic centres and related lava flows. Thick black lines are the main faults in the study area. Gray arrows are the directions of plate convergence vector according to Norabuena et al. (1998).

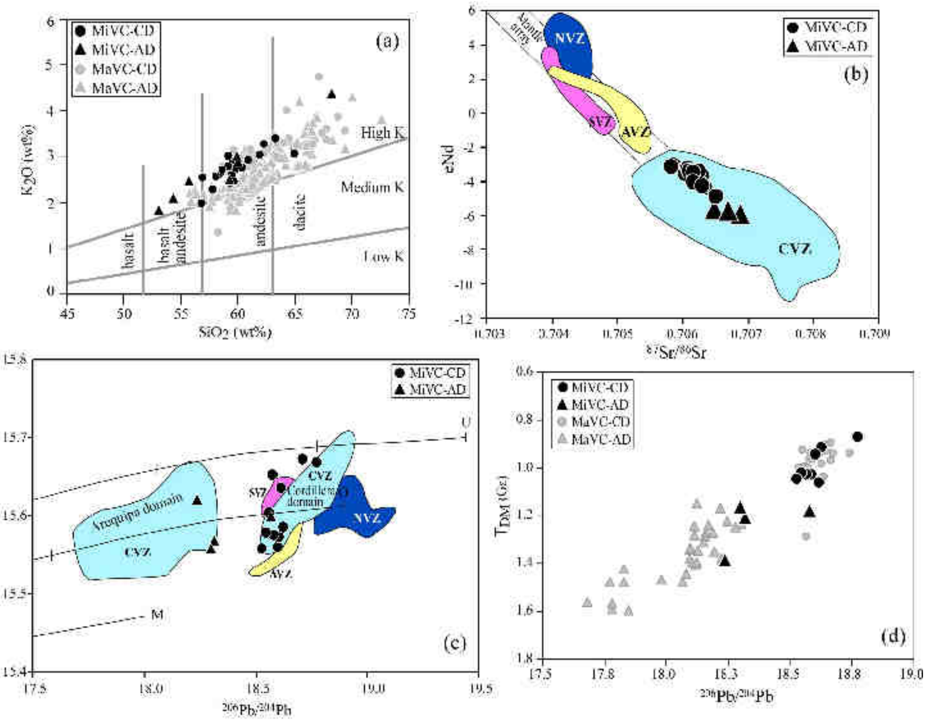

Fig.2. a) Classification of calc-alkaline series (Le Maitre, 1989). b) Plot of eNd values versus 87Sr/86Sr ratios showing the isotope range for the minor volcanic centres of the Cordillera and Arequipa domains. c) Pb isotope composition of the minor volcanic centres. The upper crust (U), orogen (O) and mantle (M) evolution curves are from Zartman and Doe (1981). d) Diagram of TDM

ages versus Pb-isotopes of minor and mayor volcanic centres of the Cordillera and Arequipa domains. Figures (a) and (b) are compared to the North Volcanic Zone (NVZ, Bourdon et al., 2002), South Volcanic Zone (SVZ, Kay et al., 2005) and Austral Volcanic Zone (AVZ, Stern and Killian 1996). Minor volcanic centres (MiVC), Major volcanic centres (MaVC), Cordillera domain (CD), Arequipa domain (AD).

Table 1. Isotope analyses Sr.-,Nd-, Pb- on bulk rocks of minor volcanic centres and related lava flows. Samples with star are from Delacour et al. (2007).

Sample	Location	Lon (X)	Lat (Y)	SiO2	$^{87}Sr/^{86}Sr$	2σ	$^{143}Nd/^{144}Nd$	2σ
Cordillera domain								
1_AND-99-04	Puca Mauras	-72.333	-15.431	60.4	0.70632	0.00001	0.51244	0.000005
2_AND-99-01	Puca Mauras	-72.333	-15.431	62.4	0.70637	0.00001	0.51242	0.000006
3_AND-99-10	Puca Mauras	-72.348	-15.433	61.4	0.70633	0.00001	0.51242	0.000006
4_AND-99-08	Puca Mauras	-72.345	-15.431	67.3	0.70654	0.00001	0.51238	0.000005
5_AND-99-06	Andagua	-72.332	-15.413	55.7	0.70589	0.00001	0.51249	0.000004
6_AND-99-15	Andagua	-72.348	-15.433	64.3	0.70628	0.00001	0.51243	0.000004
7_AND-99-17*	Andagua	-72.416	-15.481	59	0.70608	0.00001	0.51247	0.000005
8_AND-99-18*	Tischo	-72.382	-15.481	58.1	0.70606	0.00001	0.51246	0.000004
9_AND-99-20*	Ninamama	-72.282	-15.548	57.6	0.70611	0.00001	0.51247	0.000005
10_AND 99-22*	Chilcayoc	-72.314	-15.548	57.9	0.70612	0.00001	0.51246	0.000005
11_AND 99-27*	Chilcayoc	-72.265	-15.645	56.5	0.70619	0.00001	0.51246	0.000004
12_AND 99-24	Aldagua old	-72.283	-15.589	58.5	0.70627	0.00002	0.51246	0.000004
13_BAR-02-10	Sibayo	-71.478	-15.506	57.9				
14_OCO-03-01	Llauce valley	-73.169	-16.084	57.1				
15_BAR-01-61	Chivay	-71.616	-15.595	59.1	0.70619	0.00001	0.51243	0.000004
16_BAR-01-62	Chivay	-71.598	-15.606	58.6	0.70586	0.00001	0.51249	0.000007
Arequipa domain								
17_HUAM-99-03*	Marbas Chico	-72.117	-15.867	59	0.70623	0.00001	0.51231	0.000005
18_HUAM-99-05*	Huambo valley	-72.131	-15.958	55	0.70694	0.00001	0.51232	0.000005
19_HUAM-99-04*	Huambo valley	-72.133	-15.883	53.7	0.70671	0.00001	0.51234	0.000005
20_NIC-01-22	Nicholson	-71.730	-16.260	52.3	0.70647	0.00001	0.51234	0.000006

Sample	$^{206}Pb/^{204}Pb$	2σ	$^{207}Pb/^{204}Pb$	2σ	$^{208}Pb/^{204}Pb$	2σ	eNd	TDM
Cordillera domain								
1_AND-99-04							-3.8	1.0
2_AND-99-01	18.568	0.0008	15.602	0.0007	38.626	0.0019	-4.4	1.0
3_AND-99-10	18.551	0.0007	15.577	0.0006	38.549	0.0019	-4.3	1.0
4_AND-99-08	18.530	0.0007	15.559	0.0007	38.461	0.0018	-5.0	1.1
5_AND-99-06							-2.9	0.9
6_AND-99-15							-4.1	1.1
7_AND-99-17*							-3.2	0.9
8_AND-99-18*	18.629	0.0007	15.583	0.0006	38.621	0.0018	-3.6	0.9
9_AND-99-20*	18.604	0.0012	15.558	0.0010	38.520	0.0027	-3.2	0.9
10_AND 99-22*	18.607	0.0007	15.571	0.0006	38.561	0.0018	-3.4	0.9
11_AND 99-27*	18.586	0.0007	15.573	0.0012	38.523	0.0016	-3.5	1.0
12_AND 99-24							-3.4	1.0
13_BAR-02-10	18.716	0.0014	15.670	0.0013	38.865	0.0038		
14_OCO-03-01	18.578	0.0021	15.650	0.0019	38.757	0.0056		
15_BAR-01-61	18.619	0.0014	15.633	0.0012	38.723	0.0029	-4.0	1.1
16_BAR-01-62	18.777	0.0021	15.667	0.0020	38.931	0.0060	-2.9	0.9
Arequipa domain								
17_HUAM-99-03*	18.576	0.0008	15.601	0.0008	38.643	0.0022	-6.4	1.2
18_HUAM-99-05*	18.315	0.0012	15.568	0.0011	38.545	0.0034	-6.3	1.2
19_HUAM-99-04*	18.298	0.0008	15.558	0.0007	38.489	0.0018	-5.9	1.2
20_NIC-01-22	18.235	0.0020	15.620	0.0018	38.740	0.0045	-5.8	1.4

(e.g. Sara Sara, Coropuna, Solimana and Antapuna volcanoes). Only dacite sample from Puca Mauras centre have $^{206}Pb/^{204}Pb$ ratios (18.53 to 18.57) like lavas from Arequipa domain and eNd values around -5 that plot between both domains (Fig. 2b).

Equally, eNd values (-5 to -6.3), $^{87}Sr/^{86}Sr$ ratios (0.7065 to 0.707) and $^{206}Pb/^{204}Pb$ ratios (18.23 to 18.58) of minor volcanic centres in the Arequipa domain cover most of the same range observed in stratovolcanoes to the S of the domain boundary in southern Peru (e.g. Sabancaya, Chachani, Misti, Ubinas, Huaynaputina, Yucamane, Tutupaca, Ticsani volcanoes). An andesite sample from Marbas Chico has $^{206}Pb/^{204}Pb$ ratios of 18.58 like lavas from the northern Cordillera domain (i.e. basaltic andesite of Llauce valley). This implies that the the isotopic signatures are really different between minor centres and large stratovolcanoes within a given region, but *both* change their geochemical character when crossing the boundary between crustal domains.

CRUSTAL CONTAMINATION OF MINOR VOLCANIC CENTRES

The amount of crustal contamination in typical andesite is 16% according to EC-AFC modeling (Chang, 2007). However, the composition of the assimilated crustal component is variable in the two distinct domains (Fig. 1, see Mamani et al., 2008 for a full discussion). T_{DM} ages are also different, lavas of Cordillera domain vary between 0.8 and 1.1 Ga., and contaminated magmas on the Arequipa domain have T_{DM} ages from 1.3 to 1.5 Ga (Table 1). Loewy et al. (2004) published T_{DM} ages from 1.9 to 2.3 Ga. of the Arequipa basement. Interestingly, the Nd model ages correlate nicely with the Pb-isotopic composition of contaminated magmas (Fig. 2d) and this suggests that minor volcanic centres derive their assimilated component from crust of different age and composition (Fig. 3). The fact that we highlighted above, i.e. that minor centres and large stratovolcanoes are not distinct in their isotopic character, allows to define the boundary between the domains of different assimilated crust with much better local spatial constraint because these minor centres happen to be particularly abundant in this region (Fig. 1). Therefore, we demonstrate that the domain boundary is surprisingly abrupt (within 60 km laterally for a crust that is > 60 km thick), which suggest that the boundary most likely is relatively steep. If so, the boundary probably represents a major, crustal suture between distinct crustal blocks. As the isotopic difference is very large, this implies that these blocks must have had a long (> 1Ga) distinct geochemical history. It is therefore surprising to find that this region shows a system that runs along the crustal domain boundary (Iquipi fault, Roperch et al., 2006). It has been argued also that the eruptions of minor centres were controlled by regional scale faults (Huanca, Uchupampa and Trigal faults Antayhua et al., 2001). If so, then these eruptions indeed are fed from deeper level magma storage areas, which implies that both, minor centres and large stratovolcanoes receive their crustal imprint equally at depth and that shallow crustal assimilation is not a major process in determining the isotopic composition of Central Andean magmas.

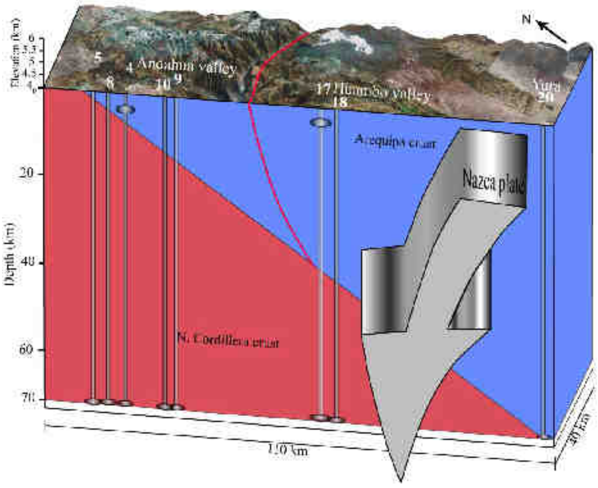

Fig. 3. Schematic cross section showing interpretation of the northern boundary of Arequipa domain. Red line is Ichupampa fault. The Numbers are the minor volcanic centre names according to the Table1.

LOWER CRUSTAL ASSIMILATION OR MANTLE SOURCE CONTAMINATION?

Lower crustal assimilation may occur in MASH or "Hot Zones" (Hildreth and Morbath, Annen et al., 2006) and there is no doubt to us that a major portion of the crustal signature in Central Andean Arc magmas derives from crustal assimilation. As the Peru-Chile trench is almost free of sediments and no accretionary prism is observed (von Huene et al., 1999; Allmendiger et al., 2005; Thornburg and Kum, 1987) the subduction of sediments into the mantle wegde source region for Central Andean magmas is not expected. However, tectonic erosion of the forearc region in northern Chile and southern Peru is a well-established process (von Huene et al., 1999; Stern, 1991ab) and has more recently been emphasized again for affecting magma genesis in the Central Andes (Kay et al., 2005) and was quantified in more detail by Clift and Hartley (2007). However, the question remains whether such tectonically eroded forearc material is actually subducted to >100 km depth into the magma generation, or whether the eroded material is quantitatively underplated below the forearc region (Clift and Hartley, 2007). New studies of O isotopes and U-Th isotopes now show that limited source contamination of 1-2% for lavas of El Misti and possibly other Central Andean volcanoes (Chang, 2007; Kiebala, 2008) in addition to lower crustal assimilation.

Our study has significant implication for this discussion. If subduction of tectonically eroded material from the forearc would be the main process controlling the isotopic composition of the erupted magmas (i.e. no or limited crustal assimilation, Stern 1991 a,b), then the isotopic composition of forearc rocks would directly project downward parallel to the plate convergence vector. In this case, Pb-isotope domain boundaries in the erupted magmas should all be parallel to the plate vector motion. This is in fact what we observe (Fig. 1). However, plate vectors have changed through time and domain boundaries have remained constant through time. This is shown by the fact that young **and** old (>30 Ma) rocks all show he same domain distribution. Thus we conclude that assimilation in the deep crust still is the main process that determines the isotopic composition of Central Andean magmas and that defines the domain boundaries. The effect of limited tectonic erosion, however, cannot be excluded.

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