Crustal segmentation and the isotopic significance of the Abancay Deflection: Northern Central Andes (9-20°S)

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ABSTRACT

The Abancay Deflection (13°S) is a continental trench-normal structure that marks the northern limit of the central volcanic zone in Peru, the northern limit of exposed Precambrian basement, and the continental extension of the oceanic Nazca Ridge. In order to assess the potential influence of this structure on magma compositions emplaced across it, strontium and neodymium isotope data on the Mio-Pliocene Cordillera Blanca batholith north of the Abancay Deflection (9-11°S) are compared with volcanic rocks of similar age and composition from the Central Andes of southern Peru and northern Chile (16-20°S). The Cordillera Blanca magmas show no evidence of contamination by mature continental basement, in spite of having been intruded through continental crust in excess of 50 km thick. In contrast, Central Andean volcanic rocks of similar age, intruded through crust of similar thickness have elevated initial strontium isotope ratios (Sr_i) and negative ϵ_{Nd} values consistent with contamination by crustal or lithospheric material. The authors consider these contrasting variations in isotopic composition relate to differences in the composition of the continental crust along strike in this sector of the Andean chain, with old Arequipa-type basement dominating in the south, while farther north, the lower to mid crust is made up mostly of young, mantle-derived basaltic material. The boundary between them (the Abancay Deflection) thus, represents a deep and possibly long-lived feature separating crustal segments of different composition north and south of 13°S.

Key words: Segmentation, Peru, Cordillera Blanca, Abancay Deflection.

RESUMEN

Segmentación cortical y significado isotópico de la Deflección de Abancay: Andes centrales del norte (9-20°S). La Deflección de Abancay (13°S) es una estructura continental normal a la fosa que marca el límite norte de la zona volcánica central del Perú, el límite norte de los afloramientos de basamento precámbrico, y se ubica en la extensión hacia el continente de la dorsal oceánica de Nazca. Para evaluar la potencial influencia de esta estructura en la composición de los magmas emplazados al norte y al sur de ella, se comparan los datos de isótopos de neodimio y de estroncio del batolito mio-plioceno de la Cordillera Blanca (9-11°S) con los de rocas volcánicas de similar edad y composición de los Andes centrales del Perú meridional y de Chile septentrional (16-20°S). Los magmas de la Cordillera Blanca no muestran evidencias de contaminación por corteza continental madura, pese a que han intruido a través de una corteza continental de más de 50 km de espesor. En cambio, las rocas volcánicas contemporáneas de los Andes Centrales, intruidas a través de corteza de espesor similar, tienen elevadas razones de Sr_i y valores negativos de ϵ_{Nd}, consistentes con contaminación por material cortical o litosférico. Los autores consideran que estas variaciones contrastantes se relacionan a diferencias a lo largo del rumbo en la composición de la corteza continental en este sector de los Andes. Un basamento antiguo, de tipo Arequipa, predominaría en el sur, mientras que más al norte la corteza media

a inferior estaría constituida por material basáltico joven derivado del manto. El límite entre ellos, la Deflección de Abancay representa, por lo tanto, un rasgo profundo y probablemente de larga duración que separa segmentos corticales de diferente composición al norte y al sur de los 13°S.

Palabras claves: Segmentación, Perú, Cordillera Blanca, Deflección de Abancay.

INTRODUCTION

Crustal (and lithospheric) segmentation is a major feature of the Andean chain; its most obvious expression being the division into three volcanically active zones, separated by regions of inactivity. The western margin of northern-central Peru (*ca.* 6-10°S) is currently an area of inactivity separating the northern and central volcanic zones (Thorpe, 1984).

Two main styles of segmentation, trench parallel and trench normal, are found in the Peruvian cordillera. Examples of trench-parallel segmentation in the broadest sense are exemplified by the structures and sedimentary and magmatic rocks located within the West Peruvian Trough. Here, long lived tectonic lineaments (such as the Tapacocha axis and the 200 km long Cordillera Blanca fault) have exerted a fundamental control on both basin formation and granitoid emplacement since the Mesozoic at least (Cobbing *et al.*, 1981; Petford and Atherton, 1995).

In contrast, trench-normal features are less well understood, both as individual structures and in the degree of control they exert on the intrusive and extrusive rock types that cross them. Two major transverse (across-arc) structures, the Huancabamba and Abancay Deflections, were identified in Peru (Fig. 1). The Huancabamba Deflection, located near the boarder with Ecuador marks an abrupt change in direction of Andean structures, from the northwest in Peru to the northeast in Ecuador (Thornburg and Kulm, 1981). The Abancay Deflection is the better studied of the two, and appears to represent a major geochemical and geophysical break along strike of the western Cordillera of the Andes (Cobbing *et al.*, 1981; Atherton and Aguirre, 1992). More recently Petford *et al.* (1993) and Petford and Atherton (1994) have speculated that the Abancay Deflection may represent an important boundary separating regions (segments) to the north and south that have undergone radically different modes of crustal thickening during the Miocene. Both deflections are currently associated with major offshore tectonic features; the Carnegie Ridge-Huancabamba Deflection in the north, and the Nazca Ridge-Abancay Deflection to the south (Fig. 1). Although outside the scope of this present contribution, it is worth noting that both deflections also mark important changes in style of mineralisation.

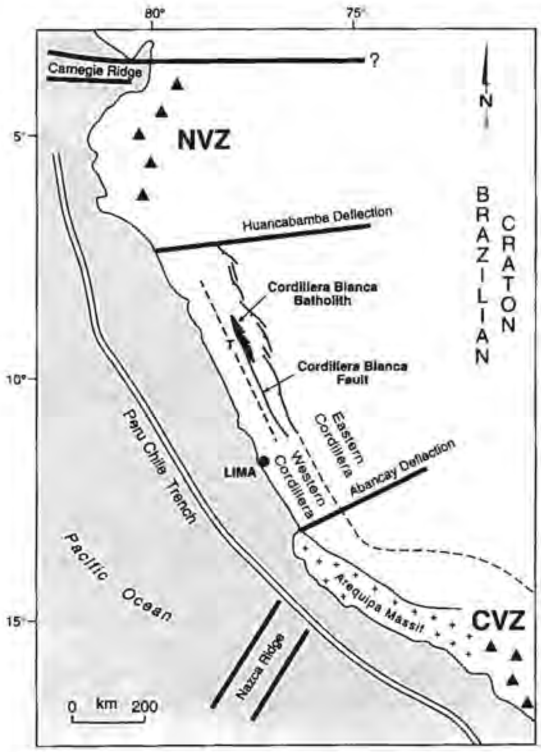

FIG. 1. Sketch map of Peru showing the major morphological features of the continental margin and offshore structures, and the location of the Huancabamba and Abancay arc-normal Deflections. Also shown are the currently active northern and central volcanic zones (NVZ and CVZ), the position of the Late Miocene Cordillera Blanca batholith and exposed regions of the Precambrian Arequipa massif. T= Tapacocha axis.

In this paper, the authors compare the isotopic compositions of plutonic and volcanic rocks of similar age intruded along strike of the Western Cordillera of the Andes between latitudes 9-20°S which cross the Abancay Deflection at 13°S. The authors show how the Abancay Deflection marks a compositional boundary between crustal segments to the north and south, and from geophysical data show how these compositional differences can be attributed to differences in the composition rather than simply to the thickness of the underlying continental crust. The authors further speculate that the Abancay Deflection may also divide regions of the Andean crust that have undergone different styles of thickening during the Miocene.

GEOLOGICAL SETTING (9-11°S)

The Late Miocene-Pliocene Cordillera Blanca batholith and associated acid volcanic rocks are the youngest magmatic rocks in northwest Peru, and represent the final stage in the Andean cycle (200-0 Ma) in this region. The batholith is situated in the high western Cordillera of Peru between 9° and 11°S (Fig. 1), where it forms a mountain range with a mean elevation of over 4,000 m. The batholith is a linear body over 120 km in length lying parallel with the main Andean trend in Peru, composed mostly of high silica (70-73 wt%) leucogranodiorite, with a subordinate marginal facies of older quartz diorite and tonalite. The batholith intrudes a basinal sequence of Jurassic shales, with both magma ascent and emplacement strongly controlled by periods of extension along the NNW/SSE trending Cordillera Blanca fault system, a long lived trench-parallel crustal lineament (Cobbing *et al.*, 1981). Radiometric dating from the batholith ranges from *ca.* 13.7 to 2.7 Ma, with combined Pb and ^{40}Ar-^{39}Ar ages from the central region of the intrusion giving an emplacement age here of about 6.0 Ma (Petford and Atherton, 1992).

CRUSTAL STRUCTURE NORTH-SOUTH OF THE ABANCAY DEFLECTION (13°S)

Several geophysical traverses made along and across the Peruvian Cordillera (James, 1971; Kono *et al.*, 1989; Fukao *et al.*, 1989) including the detailed results from the Nazca Plate Project (Geological Society of America, Memoir 154, 1981) make it possible to constrain to some degree the changes in crustal thickness and mean crustal density across the Abancay Deflection from 9° to 20°S. These results are given in figure 2, where crustal thickness (depth to the Moho) and the weighted mean (three-layer) crustal density are shown in relation to the position at 13°S of the Abancay Deflection. While the Abancay Deflection corresponds broadly with an increase in crustal thickness from *ca.* 55 to greater than 60 km, this is matched by a corresponding decrease in mean crustal density, from about 3 to 2,8 g/cm³ (Table 1), implying a change in composition of the crust at or close to this boundary. When compared to surface geology, it is seen that the surface expression of the Abancay Deflection corresponds almost exactly with the most northerly exposure of the Proterozioc Arequipa Massif (Fig. 1). This enigmatic basement, comprising high-grade granulite facies rocks, extends southwards from Paracas (Central Peru) to the Chilean boarder and was considered by Cobbing *et al.* (1981) to be an integral part of the Brazilian craton. While stratigraphic evidence shows the Massif has remained in its present position since the Late Precambrian (Forsythe *et al.*, 1992), new tectonic reconstructions of the Pacific margin of Gondwana suggest that the Arequipa Massif may be part of the Grenvillian (Labrador-Scotland-Greenland promontory) province of Laurentia (Dalziel, 1992, 1994). This interpretation is supported by new U-Pb zircon ages, which give Grenvillian ages (*ca.* 1.0 Ga) for these rocks (Wasteneys *et al.*, 1995).

As discussed in the following sections, the presence of old basement material south of the Abancay Deflection has exerted a fundamental control on both the subsequent structural development of the central Andean Cordillera (Cobbing *et al.*, 1981; Dewey and Lamb, 1992), and the isotopic compositions of Miocene-Recent rocks emplaced and extruded through it.

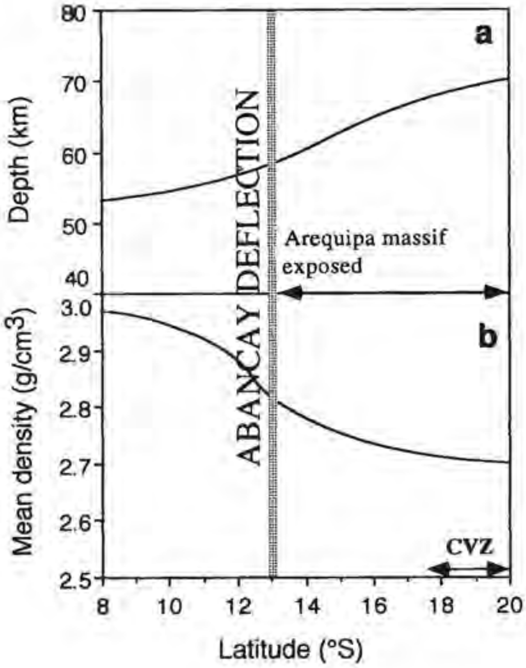

FIG. 2. a- variation in crustal thickness with latitude along strike of the Andean Cordillera (8-20°S). (Data from James, 1971; Couch *et al.*, 1981); b- variation in mean (weighted) crustal density along strike of the Andean Cordillera, assuming a three layered crust. Density decreases from north to south, with lower densities south of the Abancay Deflection due to the presence of Arequipa-type basement at depth. (Data from James, 1971; Couch *et al.*, 1981; Schmitz, 1994).

TABLE 1. RANGE IN ESTIMATED CRUSTAL THICKNESS AND DENSITY AND ISOTOPIC COMPOSITIONS OF MIOCENE-RECENT IGNEOUS ROCKS INTRUDED AND ERUPTED ACROSS THE ABANCAY DEFLECTION (13°S), ALONG STRIKE OF THE WESTERN CORDILLERA OF THE ANDES BETWEEN *CA.* 9° AND 20°S.

Crustal depth (km)	Mean crustal density (g/cm^3)	$^{87}Sr/^{86}Sr$	ϵ_{Nd}	$^{206}Pb/^{204}Pb$
North of Abancay Deflection (9-13°S)				
53-60	2.97-2.80	0.7045-0.7065	4.0 to -4.7	18.70-18.80
South of Abancay Deflection (13-20°S)				
60-70	2.80-2.70	0.7055-0.7120	-1.7 to-12	17.85-18.75

Data from Barreiro, 1984; Couch *et al.*, 1981; Davidson *et al.*, 1990; Davidson *et al.*, 1991; James, 1971; Kono *et al.*, 1989; Mukasa and Tilton, 1984; Petford *et al.*, (in press); Soler and Rotach-Toulhoat, 1990; Wörner *et al.*, 1992.

ISOTOPIC COMPOSITION OF THE CORDILLERA BLANCA BATHOLITH ROCKS

The Cordillera Blanca batholith lies directly above the thickened continental root of the Andes of Peru, which in this sector reaches depths greater than 50 km (James, 1971; Fig. 2a). Thus, the magmas of the batholith were intruded through overthickened continental crust similar to Miocene-Recent volcanic rocks from the central volcanic zone of southern Peru and northern Chile, whose enriched isotopic compositions are considered the result of extensive contamination of mantle-derived magmas by continental crust (James, 1982; Hildreth and Moorbath, 1988; Davidson *et al.*, 1990).

Figure 3 shows the range in ϵ_{Nd} values and $^{87}Sr/^{86}Sr$ for the Cordillera Blanca batholith and intermediate to acid volcanic rocks of similar age from the Central Andes (16-20°S), south of the Abancay Deflection. A summary of the data is given in table 2. The full data set will be published elsewhere.

The Nd and Sr isotopic compositions of the batholith rocks show relatively little scatter despite their large range in SiO_2 (54-72 wt%), with average ϵ_{Nd} values close to bulk earth (-0.8) and $^{87}Sr/^{86}Sr$ ranging from 0.7047 to 0.7057. A similar range in isotopic composition is reported by Soler and Rotach-Toulhoat (1990) for Miocene plutonic rocks of the western Cordillera at *ca.* 11°S. Note that the high silica Cordillera Blanca rocks are less enriched isotopically than the majority of the most primitive basaltic andesite 'baseline' compositions from the central volcanic zone (Davidson *et al.*, 1991), despite the continental crust being of broadly similar thickness in both regions.

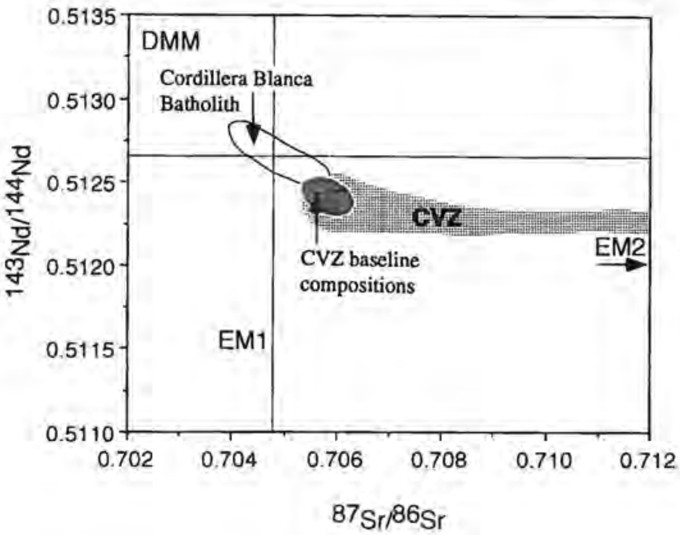

FIG. 3. Sr-Nd plot showing isotopic compositions of the Mio-Pliocene Cordillera Blanca batholith and fields defined by volcanic rocks of similar age from the Central Andes (16-20°S). The Cordillera Blanca batholith rocks have higher $^{143}Nd/^{144}Nd$ and lower $^{87}Sr/^{86}Sr$ than the most isotopically primitive Miocene-Recent volcanic rocks (CVZ baseline compositons) of the Central Andes south of the Abancay Deflection. (CVZ data from Hawkesworth *et al.*, 1982; de Silva, 1988; Davidson *et al.*, 1990).

ISOTOPIC COMPOSITIONS NORTH-SOUTH OF THE ABANCAY DEFLECTION (13°S)

The isotopic variation in Pb, Sr and Nd from latitudes 8° to 20°S are shown in figure 4(a-c) along with the position of the Abancay Deflection at 13°S. Isotopic and geophysical data used to construct the various profiles are summarised in table 2. In general, there is a marked decrease in radiogenic $^{206}Pb/^{204}Pb$ from north to south along the traverse, with a corresponding increase in initial Sr ratios and decreasing ϵ_{Nd}, south of the Abancay Deflection. The Arequipa massif gneisses are known to be low in radiogenic Pb, with $^{206}Pb/^{204}Pb$ ratios <17 (Barreiro, 1984; Mukasa and Tilton, 1984) and depleted in $^{143}Nd/^{144}Nd$ ϵ_{Nd}=-20 to -30). Thus, the observed change in isotopic compositions (Fig. 4) are consistent with geological and geophysical evidence for Arequipa basement material, north of 13°S, that would provide a suitable crustal contaminant for the CVZ magmas. In contrast, the relatively primitive isotopic compositions seen in the Cordillera Blanca rocks, which also correlate with increased crustal densities, strongly support the lack of similar basement material north of the Abancay Deflection.

TABLE 2. RANGE IN Sr AND Nd ISOTOPIC COMPOSITION OF SELECTED ROCKS FROM THE CORDILLERA BLANCA BATHOLITH.

SiO_2 (wt%)	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	ϵ_{Nd}
QUARTZ DIORITES			
54-69	Min: 0.704737±09	Min: 0.512627±09	-0.21
	Máx: 0.704926±09	Máx: 0.512646±07	0.16
	Mean: 0.704865±17	Mean: 0.512668±7	-0.06
Leucogranodiorites			
70-72	Min: 0.705248 + 08	Min: 0.512512±08	-2.46
	Máx: 0.705710 + 08	Máx: 0.512611±12	-0.53
	Mean: 0.705425 + 16	Mean: 0.512567± 3	-1.40

Whole rock isotopic compositions were determined using a VG sector multicollector mass spectrometer at the Department of Geological Sciences, University of Michigan, Ann Arbor. Metals were separated using standard ion-exchange methods. $^{87}Sr/^{86}Sr$ ratios were normalised to $^{86}Sr/^{88}Sr$=0.1194 and $^{143}Nd/^{144}Nd$ to $^{146}Nd/^{144}Nd$=0.7219. Bulk earth $^{143}Nd/^{144}Nd$=0.512638. Errors are quoted at 2σ.

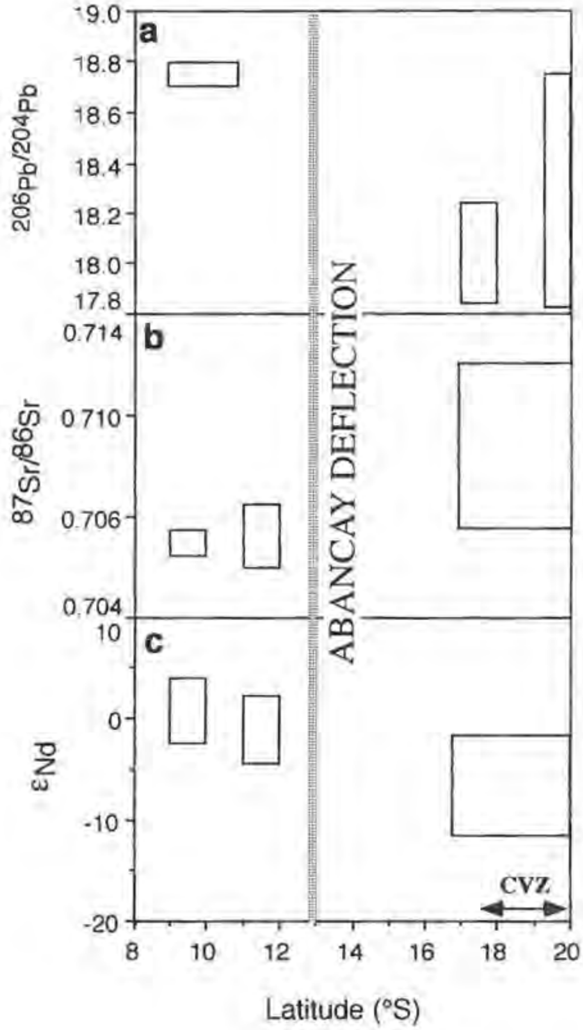

FIG. 4. Variation in isotopic composition of Miocene-recent plutonic (Cordillera Blanca batholith) and volcanic rocks between 8-20°S across the Abancay Deflection (13°S); a- decreasing $^{206}Pb/^{204}Pb$ from north to south. The northern central volcanic zone rocks (16-20°S) are characterised by low $^{206}Pb/^{204}Pb$ compositions typical of Arequipa Massif basement material; b- increasing $^{87}Sr/^{86}Sr$ and c- decreasing ϵ_{Nd} southwards across the Abancay Deflection are consistent with a change in crustal composition and age, and not simply the thickness of the continental crust in this region (cf. Fig. 2). (Data from Mukasa and Tilton, 1984; Wörner *et al.*, 1992).

DISCUSSION

SIGNIFICANCE OF THE ABANCAY DEFLECTION

It is commonly assumed that variations in the compositions of Andean magmas along strike simply reflect changes in crustal thickness, with the most crustally contaminated magmas occurring in regions of thickest crust (James, 1982; Harmon and Hoefs, 1984; Hildreth and Moorbath, 1988; Davidson *et al.*, 1990, 1991). However, the authors' results from Northern Peru suggest that the situation is more complex in that crustal thickness alone does not support *a priori* models for crustal contamination. Crustal age and composition are just as important and must also be considered. The deep keel of dense (3.0 g/cm³) material beneath Central Peru north of the Abancay Deflection (Couch *et al.*, 1981; Kono *et al.*, 1989) considered by Kono *et al.* (1989) as newly accreted basaltic underplate has recently been interpreted as the source region for the Mio-Pliocene Cordillera Blanca batholith, which has trondhjemitic affinities (Atherton and Petford, 1993). The batholith magmas were formed in a two stage process of underplating followed by rapid remelting that occurred over the time integrated emplacement history (*ca.* 12-6 Ma) of the batholith (Petford *et al.*, 1993). This model is consistent with the available isotopic data (Pb, Sr, Nd) for the batholith that require an ultimate source in enriched subcontinental mantle (Mukasa and Tilton, 1984; Atherton and Sanderson, 1987). In this model, summarised in figure 5, the crust beneath the western Cordillera north of the Abancay Deflecion was thickened magmatically during the Miocene through the accretion of mantle-derived underplate. Vertical thickening of the crust in this way is consistent with all the available geochemical and geophysical data (including high electrical resistivity and high heat flow) from the region north of 13°S.

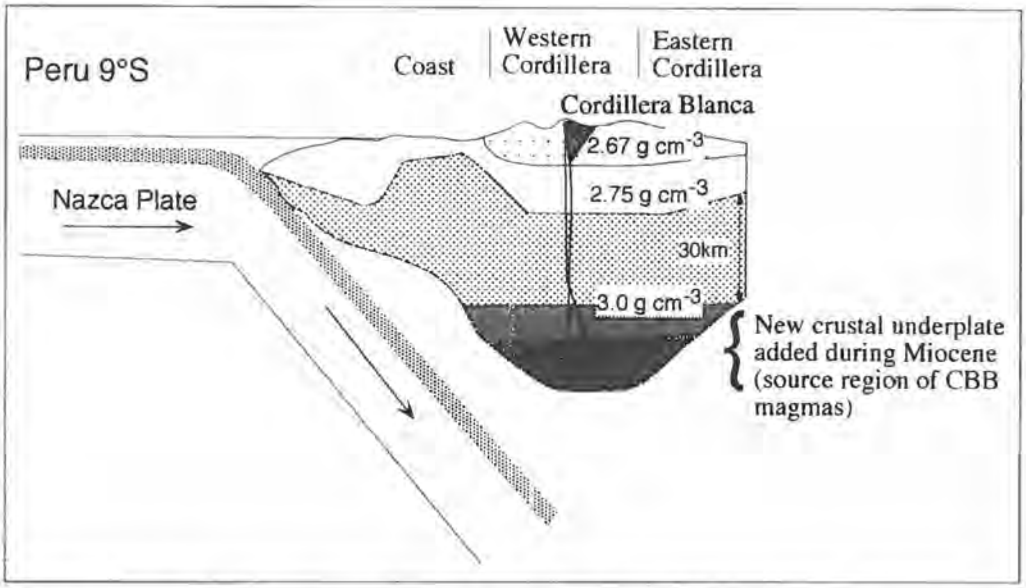

FIG. 5. Cartoon showing the development of the crust north of the Abancay Deflection at 9°S during Late Miocene times based on available geophysical data defining a three-layer crust (Couch *et al.*, 1981). Crustal thickening and uplift at 12-10 Ma coincide with the emplacement of the Cordillera Blanca batholith, whose source is newly underplated basaltic crust. Magmatic accretion, consistent with available geophysical and geochemical data, was the main thickening mechanism beneath the western Cordillera north of the Abancay Deflection.

In contrast, the enriched isotopic and trace element compositions in Miocene-recent volcanic rocks from the CVZ appear to require a substantial crustal (or enriched lithospheric) involvement. Although the presence of Arequipa basement south of the Abancay Deflection satisfies most of these requirements through a variety of assimilation-fractionation-contamination processes (Davidson *et al.*, 1991), it is interesting to speculate on possible tectonic differences between both segments that may also help explain the observed change in compositions between both segments. Recently, Miller and Harris (1989) suggested that the marked increase in Nd model ages with decreasing emplacement age of granitic intrusions in the central Andes could reflect a major period of horizontal crustal thickening and uplift at 12-10 Ma as proposed by Isacks (1988). Similar magmato-tectonic models involving large scale anatexis of tectonically thickened crust have been used to explain the elevated $^{87}Sr/^{86}Sr$ and negative ϵ_{Nd} values seen in the ignimbrites of the Altiplano-Puna volcanic zone of Central Andes (de Silva, 1988). Thus, although Miocene crustal thickening and uplift apparently occurred simultaneously in the Northern and Central Andes (Isacks, 1988; Kono *et al.*, 1989), Sr, Nd (and Pb) isotopic data from the Cordillera Blanca batholith clearly rule out an origin through anatexis of old continental crust (cf. Miller and Harris, 1989) as well as any significant contamination by similar material. If, as proposed by some authors, crustal anatexis through horizontal shortening, either as a means of producing directly highly evolved magmas, or as providing a contaminant for mantle-derived melts, was significant in the Central Andes south of the Abancay Deflection during the Miocene, why then are these effects conspicuously absent north of 13°S? One explanation may be that the Abancay Deflection separates not only crust of different composition, but also divides segments that have undergone different crustal thickening mechanisms, with horizontal shortening and associated anatexis in the Central Andes giving rise to isotopically evolved, crustally derived melts and contemporaneous magmatic underplating in the north.

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