GEOLOGICAL JOURNAL, VOL. 25, 351–358 (1990)

Sr–Nd Isotope Compositions of Cenozoic Granitoids along a Traverse of the Central Peruvian Andes

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Sr–Nd isotopic compositions of late Eocene to Pliocene intrusive rocks from a traverse (≈11° lat. S) of the central Peruvian Andes are presented. The data set suggests that the calc-alkaline magmatism is mainly the end-product of the evolution at deep crustal levels of magmas derived from a slightly depleted, but not MORB-type, subcontinental mantle, which have assimilated crustal material and have mixed with new batches of primary magma. Assimilation of crustal material increased eastwards and with time. The evolution of Sr–Nd isotope compositions in time and space along the traverse reflect both the lateral heterogeneities in the subcontinental mantle, the lower crust composition, and the progressive tectonic thickening of the crust during the Cenozoic. No granulitic basement akin to the early Proterozoic south Peruvian Arequipa massif has participated in the genesis of the central Peruvian calc-alkaline and alkaline magmas.

KEY WORDS Andes Calc-alkaline magmatism Cenozoic Crustal assimilation Isotopic geochemistry Subduction

1. INTRODUCTION

Central Peru is characterized by a major Neogene uplift followed by subsequent erosion of the Andean mountain belt and the absence of active or recent volcanism. It is an especially favourable area for the study of Cenozoic intrusive magmatism across the Andes. To better constrain the petrological models for the genesis of the calc-alkaline and alkaline magmatism, Sr–Nd isotope compositions of nearly twenty late Eocene to Pliocene plutons, stocks, and dykes from the Huacho–Oxampampa traverse (≈11° lat. S) across the central Peruvian Andes have been determined (Figure 1). We present here the isotopic data and the most important conclusions and hypotheses that it permits us to draw. A more complete discussion including petrographical, geochemical, and Pb-isotope data will be presented elsewhere.

2. GEOLOGICAL SETTING

The study area may be divided into four belts parallel to the Andean range and the Peru–Chile trench (Figure 1):

1. The coastal region and the lower Pacific slope of the Western Cordillera which comprises: (1) The dominantly volcanic, Albian to early Cenomanian Casma Group (Atherton *et al.* 1983, 1985a; Atherton and Webb 1989), which is regarded as the tholeiitic and calc-alkaline volcanic fill of a marginal basin of aborted type (i.e. without true oceanic crust but with drastically thinned continental crust). The basement of the Casma Group does not crop out in the study area, but southwards, near Lima, it is made up of early Cretaceous volcanics (Puente Piedra Fm.—Atherton *et al.* 1985a) and Neo-

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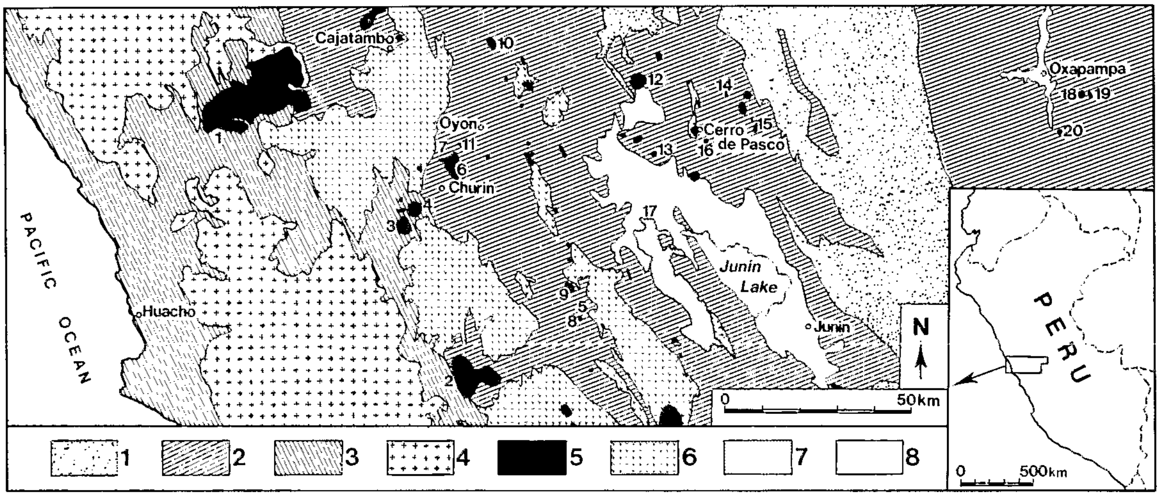

Figure 1. Schematic geological map of the study area (after Mégard 1978, Cobbing *et al.* 1981, and Soler, unpublished mapping) including the localities of new Sr Nd isotope data (corresponding names and rock-types are given in the table)
1 — Precambrian to late Palaeozoic; 2 — Late Permian to late Cretaceous sedimentary series; 3 — Albian and early Cenomanian Casma volcanic group, 4 — Coastal Batholith; 5 — Eastern Stocks (late Eocene to Pliocene); 6 — Calipuy volcanics (Eocene to Miocene), 7 Pliocene Bosque de Piedra ignimbrites; 8 — Quaternary deposits (Junin basin)

comian–Aptian siliciclastic and carbonated platform sedimentary series (Mégard 1978). (2) The calc-alkaline Coastal Batholith (Pitcher *et al.* 1985 and references therein) which was emplaced mostly within the Casma volcanics during mid-Albian to earliest Palaeocene times (Cobbing *et al.* 1981; Beckinsale *et al.* 1985; Mukasa 1986).

2. The Western Cordillera and the High Plateaus which are made up of folded and thrusted siliciclastic and carbonated platform sedimentary series of late Triassic to late Cretaceous age, late Cretaceous–Cenozoic continental detritics, and early Eocene to Pliocene calc-alkaline volcanics (Calipuy Group and Pliocene ignimbrites—Cobbing *et al.* 1981; Atherton *et al.* 1985b).
3. The eastern and highest part of the Eastern Cordillera which comprises late Proterozoic and early Palaeozoic metamorphic and magmatic rocks, late Palaeozoic to mid-Triassic non-metamorphic epicontinental and continental sedimentary and volcanic rocks, and late Permian—early Triassic granitoids (see Mégard 1978; Dalmayrac *et al.* 1980, and Soler and Bonhomme, 1987, and references therein). No early Proterozoic granulitic basement akin to the Arequipa massif of coastal Southern Peru (Cobbing *et al* 1977; Dalmayrac *et al.* 1977) is known in the eastern Cordillera of Central Peru (Dalmayrac *et al.* 1980). The Proterozoic Palaeozoic basement, which locally crops out within the high Plateaus (e.g. Mégard, 1978), is inferred to underlie the whole Andean belt from the trench to the Brazilian shield.
4. The Amazonian slope of the Eastern Cordillera and the sub-Andean lowlands, made up of Phanerozoic epicontinental and continental sedimentary series deposited in lateral continuity with the series cropping out in the Western Cordillera and the High Plateaus at least until mid-Oligocene times.

Andean mountain building is the result of compressional tectonic episodes initiated during Albian times and whose effects migrated discontinuously eastwards with time (e.g. Mégard 1984, 1987; Sébrier *et al.* 1988; Sébrier and Soler 1990). At present the crustal thickness reaches 55–60 km below the highest part of the Western Cordillera decreasing both eastwards and westwards (James 1971).

Following the Eocene episodes of compressional deformation (Incaic event—Mégard 1984, 1987), the magmatic arc, represented by the Coastal Batholith, broadened (Cobbing *et al.* 1981; Soler 1987; Soler and Bonhomme 1988) and a great number of late Eocene to Pliocene mid- to high-K calc-alkaline magmatic rocks (the 'Eastern Stocks' of Cobbing *et al.* 1981) were emplaced in the eastern part of the Casma group and up to the eastern edge of the high Plateaus, and sporadically within the western part of the

Eastern Cordillera. Orogenic alkaline magmatic rocks were mainly emplaced during Miocene times along the Amazonian slope of the Eastern Cordillera (Soler 1989; Soler and Bonhomme 1990). Magmatic activity ceased in Central Peru during Pliocene times (3–4 Ma—Soler and Bonhomme 1988), which may relate to the beginning of shallow subduction of the buoyant Nazca ridge.

The tectonic and magmatic features of this region are considered to reflect the interaction between the subducting oceanic Farallon plate until late Oligocene time, the Nazca plate thereafter with the western margin of the South American continent (Mégard 1987; Soler and Bonhomme 1990; Sébrier and Soler 1990) since at least earliest Cretaceous times (Dalmayrac *et al.* 1980; Jaillard *et al.* 1990).

2. Sr- AND Nd-ISOTOPIC DATA

2a. Analytical methods and data

Spiking and dissolution of the samples, Rb, Sr, and LREE separations were performed on carefully washed, finely crushed whole-rocks following the procedures described by Turpin *et al.* (1988). Sr- and Nd-isotopic analyses were performed at the CEA (C.E.N. de Saclay) on a VG Micromass 54–38 simple collector, double focusing mass spectrometer in fully automatic mode. The data set is given in Table 1. The whole data set is available on request from the senior author.

Table 1. Sr–Nd isotope data

Intrusion	No.*	Rock type†	Age (Ma)	nbr. of samples	$^{87}Sr/^{86}Sr$ (initial) min.	$^{87}Sr/^{86}Sr$ (initial) max.	$^{143}Nd/^{144}Nd$ (initial) max.	$^{143}Nd/^{144}Nd$ (initial) min.
A—WESTERN CORDILLERA								
Pativilca	1	Gr	37	4	0·70399	0·70418	0·512684	0·512662
Pativilca (1)	–	–	–	11	0·70413	0·70443	–	–
Acos	2	Gr	37	4	0·70400	0·70479	0·512650	0·512553
Paccho Tingo	3	To–Gd	31	4	0·70420	0·70443	0·512620	0·512552
West Churin	4	To–Gd	31	4	0·70426	0·70453	0·512613	0·512582
Chungar (dike)	5	And	40	1	0·70541		0·512717	
East Churin	6	To–Gd	14	8	0·70486	0·70520	0·512605	0·512466
Mallay	7	Gd	14	1	0·70559		0·512572	
Chungar	8	Gr	13·4	2	0·70500	0·70501	0·512630	0·512521
Chalhuacocha	9	Gd	11	1	0·70503		0·512602	
Raura	10	To–Gd	10	3	0·70501	0·70527	0·512637	0·512588
Cordillera Blanca (1)	–	Gd–Gr	10	13	0·70487	0·70540	–	–
Rupay	11	G	3	1	0·70690		0·512395	
B—HIGH PLATEAUS AND EASTERN CORDILLERA								
Huancayan	12	Gd	37	1	0·70465		0·512720	
Racco	13	Di	37	1	0·70425		0·512692	
Atacocha-Mariac	14–15	Di–Gd	31·4	3	0·70639	0·70651	0·512408	0·512390
Sacsacancha (2)		Gb–Gd	36	1	0·70422		0·512752	
Yanamate	16	Gr	15	1	0·70566		0·512481	
Bosque de Piedra	17	Rh–Ign.	5	2	0·70623	0·70626	0·512473	0·512445
Oxapampa area	18–20	Sy	13–21	3	0·70387	0·70403	0·512749	0·512519

* The numbers refer to the localities on Figure 1.

† Rock types: Gb — Gabbro, Di — Diorite, And. — Andesite, To — Tonalite, Gd — Granodiorite, Gr — Granite, Rh–Ign — Rhyolitic ignimbrites, Sy — Syenite.

(1) Data of Beckinsale *et al.* (1985) assuming ages of 37 Ma for the Pativilca pluton, and of 10 Ma for the Cordillera Blanca batholith, located to the North of the studied traverse.

(2) The Sacsacancha batholith (high-K gabbro to quartz-monzonite) is located to the South of the studied traverse in the western part of the Eastern Cordillera (Mégard 1978). It provided a K-Ar age of 36 Ma (Soler and Bonhomme 1989).

Normalizing ratios: $^{86}Sr/^{88}Sr = 0{\cdot}1194$ and $^{146}Nd/^{144}Nd = 0{\cdot}7219$. Typical 2σ errors are less than 0·00005 for Sr-isotopic ratios and less than 0·00002 for Nd-isotopic ratios.

The Oligocene calc-alkaline rocks (Pativilca pluton, Acos, West Churin, and Paccho Tingo stocks) intruding the Casma volcanics and/or the Coastal Batholith constitute a homogeneous group (the 'Coast group') characterized by low initial $^{87}Sr/^{86}Sr$ ratios ($Sr_i = 0{\cdot}7040$–$0{\cdot}7045$) and high initial ^{143}Nd–^{144}Nd ratios ($Nd_i = 0{\cdot}51255$–$0{\cdot}51268$) close to Bulk Earth Sr–Nd isotope ratios. The Sr-isotopic ratios of this group are in the same range as those of most of the granitoids of the Lima segment of the Coastal Batholith (Beckinsale *et al.* 1985). Eastwards, contemporaneous intrusions (Huancayan and Racco stocks) of the high part of the Western Cordillera and the western part of the High Plateaus, show similar Sr_i but higher Nd_i (0·51270–0·51275), whereas Oligocene high-K calc-alkaline intrusions (Milpo–Atacocha and Mariac–Quinua stocks) of the eastern part of the High Plateaus display much higher Sr_i ($\approx 0{\cdot}7065$) and lower Nd ($\approx 0{\cdot}51240$). Southeastwards, the Sacsacancha batholith displays Sr–Nd isotope ratios (Sr_i = 0·70422; Nd_i = 0·512752) close to those of the Racco and Huancayan stocks.

The Miocene calc-alkaline intrusives (East Churin pluton, Mallay, Raura, Chungar, and Chalhuacocha stocks) of the high part of the Western Cordillera have Sr_i in the range 0·7049–0·7053, and Nd_i in the range 0·51250–0·51264. The Sr isotope data of Beckinsale *et al.* (1985) for the Cordillera Blanca batholith fall within the same ranges. Eastwards, contemporaneous calc-alkaline intrusives (Yanamate stock) of the High Plateaus tend to have higher Sr_i and lower Nd_i. Pliocene felsic calc-alkaline dikes (Rupay) and ignimbrites (Bosque de Piedra) of the high part of the Western Cordillera and the western part of the High Plateaus show higher Sr_i (0·7062–0·7069) and lower Nd_i (0·51240–0·51247).

The Miocene syenitic stocks of the Amazonian slope of the Eastern Cordillera (Oxapampa area) have Sr–Nd isotope ratios (between Sr_i = 0·7039–Nd_i = 0·51275 and Sr_i = 0·7045–Nd_i = 0·51252) near to those of the Oligocene 'Coast group'.

2b. *Interpretation of the isotopic data*

Whatever their petrochemical composition might be (diorite to granite), contemporaneous intrusions emplaced in similar country-rocks show very similar Sr–Nd isotopic compositions. When the data set is sufficient (e.g. Pativilca and East Churin plutons, Acos, Paccho Tingo, and West Churin stocks, Cordillera Blanca batholith), slight Sr–Nd isotopic heterogeneities are apparent for individual plutons and stocks, but no correlation is observed between the isotopic ratios and the degree of differentiation of the magmas. These heterogeneities are therefore primary, i.e. due to a heterogeneity of the source or to mixing of sources at deep crustal levels, rather than acquired through some AFC process (e.g. De Paolo 1981) during low-pressure differentiation (with plagioclase as a dominant fractionating phase). For the Oligocene Atacocha–Mariac stocks and the Pliocene intrusive (Rupay dike) and volcanic (Bosque de Piedra ignimbrites) rocks, for which the few analysed samples correspond to the same stage of differentiation, more data are necessary to definitely confirm this point.

In the Nd_i *vs.* Sr_i diagram (Figure 2) the Oligocene 'Coast group' define an elongated cluster and the Oligo-Mio-Pliocene intrusions of the high part of the Western Cordillera and the High Plateaus (the 'Cordillera group') as a whole define a broad hyperbolic correlation shifted to higher Sr_i with respect to the former group. Within the latter group, a clear increase of Sr_i and a decrease of Nd_i with time is noticed for a single area, this being particularly clear for the highest part of the Western Cordillera and the western part of the High Plateaus (Figure 3). An evolution to higher Sr_i and Nd_i from West to East along the studied traverse is also observed for contemporaneous calc-alkaline intrusions, the intrusions of the Eastern Cordillera (Sacsacancha, Oxapampa area) displaying conversely rather low Sr_i and high Nd_i (Figures 2 and 3). The Sr–Nd isotope data for the Miocene alkaline stocks of the Oxapampa area define a conspicuous hyperbolic trend (Figure 2).

As stated previously, the differences observed between the different groups of intrusions and the evolutionary patterns of each group cannot convincingly be linked to low-pressure AFC processes and must be considered as primary and/or related to the early evolution at deep crustal levels. Obviously, whatever the nature of the observed correlations might be, the differences between the 'Coast group' and the 'Cordillera group' trends, which are roughly parallel in the Sr_i versus Nd_i diagram, require differences in the isotopic composition of the source regions below the coastal area and the cordillera respectively. In fact,

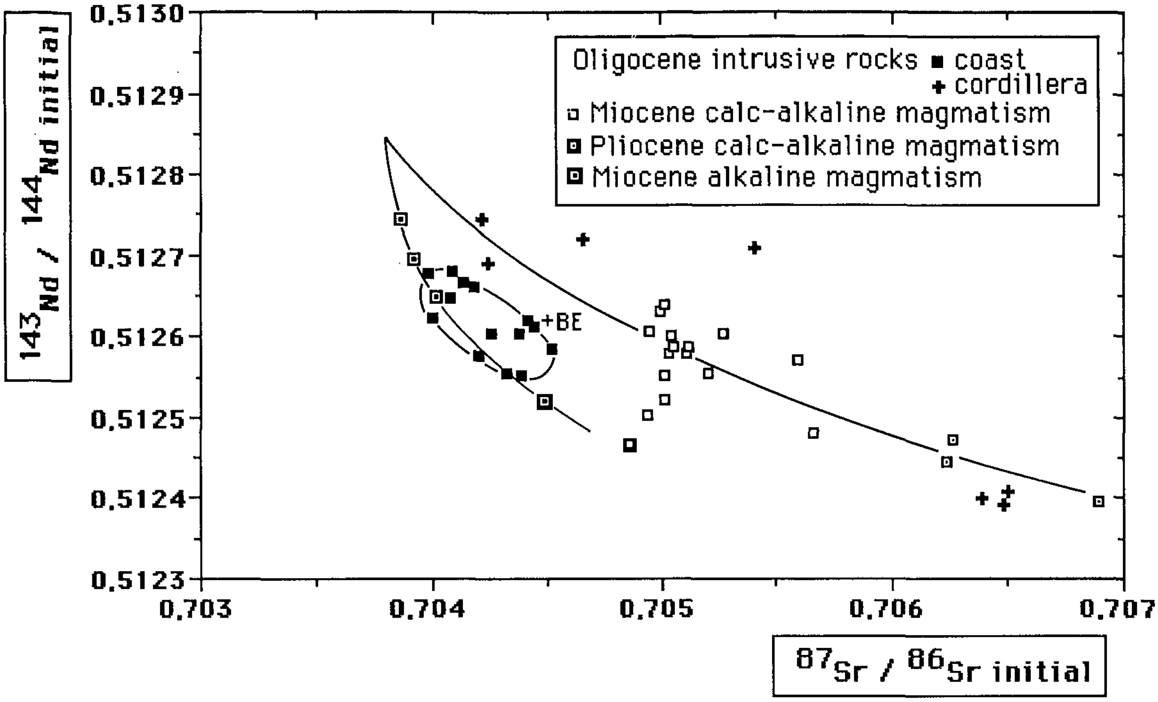

Figure 2. Diagram $^{87}Sr/^{86}Sr$ (initial) *vs.* $^{143}Nd/^{144}ND$ (initial). Within the Oligocene intrusions, those emplaced within the Casma group and/or the Coastal Batholith ('coast') and those emplaced eastwards in the Mesozoic and Cenozoic series of the Western Cordillera and the High Plateaus ('cordillera') have been distinguished. BE = Bulk Earth

the rather similar chemical compositions of both groups (Soler *et al.* in prep.) cannot be explained by any mixing or assimilation process from a single source. Conversely, the hyperbolic trends for the 'Cordillera group' and the Miocene syenites of the Oxapampa area may correspond to the evolution from a similar source. Both trends converge at about Sr_i = 0·7038; Nd_i = 0·51284. The different curves of these two hyperbolic correlations may reflect differences in composition of the primary magmas (i.e. higher Sr/Nd ratio in the alkaline magmas relative to the calc-alkaline magmas).

In both the coast and cordillera, the source region may correspond to a slightly depleted mantle modified by fluids extracted from the basalts and sediments of the subducted slab (e.g. Thorpe *et al.* 1984; Hildreth and Moorbath 1988; Rogers and Hawkesworth 1989). These mantle sources are not of MORB type but resemble rather a subcontinental mantle source (Soler and Rotach-Toulhoat 1990). The differences between the mantle sources beneath the coastal region and the cordillera is not convincingly linked to various degrees of participation of fluids (or melts) extracted from the subducted slab, since no major changes in slab dip and lithospheric age actually occurred between Oligocene and Miocene times (Soler and Bonhomme 1990). Furthermore the Oligocene magmatism beneath the Western Cordillera and the western part of the High Plateaus seems to be derived from a similar source as the Miocene and Pliocene magmatism of the same area. Thus the differences in mantle source between the 'Coast' and the 'Cordillera' may reflect differences acquired during the Albian to earliest Palaeocene, i.e. during the emplacement of the Casma volcanics and the Coastal Batholith.

Whether the evolution within each group corresponds to some crustal contamination process at deep crustal levels (e.g. Thorpe *et al.* 1984; Hildreth and Moorbath 1988) or to a change in mantle source (e.g. Rogers and Hawkesworth 1989) is not clear. A simple east–west evolution would be in favour of the progressive mobilization of old mantle lithosphere as magmatism migrates eastwards, as proposed by Rogers and Hawkesworth (1989) for the Central Chilean Andes. Along the studied traverse however (1) the main evolution appears to be the increase of Sr_i (and the correlative decrease in Nd_i) with time

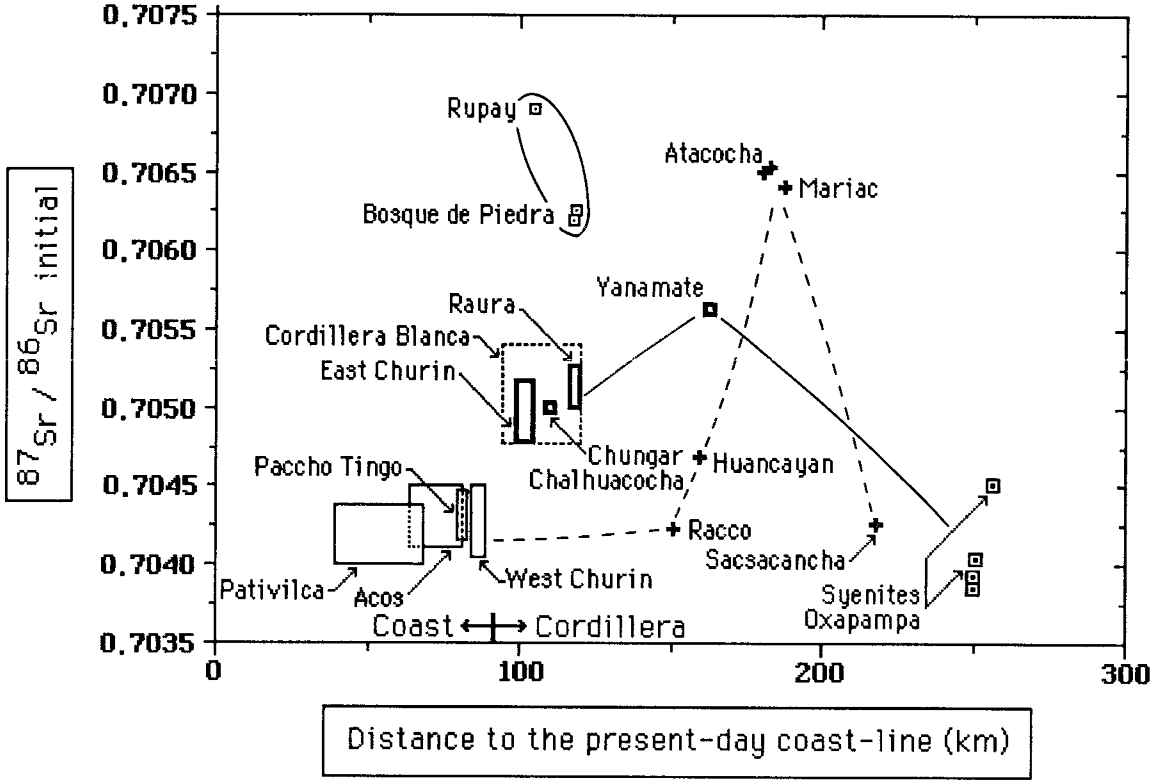

Figure 3. Diagram $^{87}Sr/^{86}Sr$ (initial) *vs.* Distance from the present coast-line for the whole data set (Cenozoic calc-alkaline and alkaline rocks of central Peru). Cenozoic tectonic shortening has not been taking into account, i.e. the distance quoted in the figure corresponds to the present-day position of the studied intrusions (Figure 1) and not with their actual position with respect to the coast-line (or the trench) when they emplaced. The dotted line ties the Oligocene stocks, the continuous line ties the Miocene stocks, and the upper group corresponds to the Pliocene dyke and ignimbrites

in a single area: (2) the highest Sr_i and the lowest Nd_i are observed above the thickest crust while the easternmost intrusions (Sacsacancha and Oxapampa area) do not have the more radiogenic Sr-isotopic compositions. Thus we favour the interpretation of the observed trends resulting from the evolution of mantle-derived magmas by assimilation of crustal material and mixing with new batches of mantle-derived magmas at deep crustal levels, *cf.* Hildreth and Moorbath (1988) for the Southern Volcanic Zone of the Andes. In the Western Cordillera, the importance of crustal assimilation appears to increase with time, which may reflect the progressive tectonic thickening of the continental crust during the Cenozoic.

The Sr–Nd isotope data clearly suggest that no granulitic basement akin to the early-Proterozoic Arequipa massif (Cobbing *et al.* 1977; Dalmayrac *et al.* 1977, 1980), characterized by very high Sr_i and very low Nd_i (e.g. Briqueu and Lancelot 1979; James 1981), participate in the genesis of the Cenozoic magmatism along the studied traverse. The crustal component appears to rather be late Proterozoic and/or Palaeozoic lower crust. As a whole, for the 'Coast group' the crustal participation appears to be less important than for the 'Cordillera group', conceivably because (1) the coastal lower crust is made up of a much greater proportion of mantle-derived material (Atherton and Webb 1989) than the continental crust underlying the cordilleran area and (2) the crust is thinner beneath the 'coast' than beneath the 'cordillera'.

3. SUMMARY AND CONCLUSIONS

For the Oligo-Mio-Pliocene magmatism of central Peru the Sr–Nd isotope data and unpublished geochemical and Pb isotope data (Soler *et al.* in preparation) allow us to propose a genetic model as follows:

1. The melting of a slightly depleted (but not MORB-like) subcontinental mantle source modified by fluids extracted from the basalts and sediments of the subducting oceanic slab; the mantle source region has similar Sr_i but lower Nd_i beneath the coastal region than beneath the cordillera. No change in the isotopic composition of the mantle source region occurred beneath the cordillera between Oligocene and Pliocene times;
2. The evolution of the magmas at deep crustal levels was through a complex process of fractional crystallization, assimilation of crustal material, and mixing with new batches of mantle-derived magmas. Crustal assimilation is less important in the coastal region, because of the more mantle-like isotopic compositions and thinner crust in this area than beneath the cordillera. Assimilation of crustal material occurred progressively during Miocene and Pliocene times and mainly below the Western Cordillera, which presumably reflects the Neogene tectonic thickening of the Andean crust.

   No granulitic basement akin to the early Proterozoic Arequipa massif participates in the genesis of the Cenozoic magmatism of central Peru. The crustal component appears to be late Proterozoic and/or Palaeozoic rocks.
3. Assimilation of crustal material during the low-pressure differentiation of the magmas, if any, appears to be a very minor process along the studied traverse. It could partly explain some very radiogenic compositions of Pliocene felsic dykes and ignimbrites.

ACKNOWLEDGEMENTS

Field work was completed as part of the INGEMMET (Peru)–ORSTOM (France) and UNI (Peru)–ORSTOM (France) joint research programs. Isotopic analyses were performed at the CEA thanks to funds provided by ORSTOM (UR1H—TOA Dept.) and the CEA (DAMN). The participation of M. Aubertin and J. Ménès in the analytical work has been greatly appreciated. This is a modified version of a contribution presented during the Granite symposium held in Liverpool in January 1990.

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