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Implications of the time-dependent evolution of Pb- and Sr-isotopic compositions of Cretaceous and Cenozoic granitoids from the coastal region and the lower Pacific slope of the Andes of central Peru

Pierre Soler
ORSTOM UR 1H, 213 rue Lafayette, 75010, Paris, France, Laboratoire de Géochimie Comparée et Systématique, Université Paris VI, 4 place Jussieu, 75005 Paris, France, and Groupe des Sciences de la Terre, Lab. Pierre Sue, CEA-CNRS, C.E.N. de Saclay, 91191 GIF/Yvette, France
Nelly Rotach-Toulhoat
Commissariat à l'Energie Atomique, IRDI/DERDCA/DCAEA/SEA/SEAIN, Bat. 637, C.E.N. de Saclay, 91191 GIF/Yvette, France

ABSTRACT

Pb- and Sr-isotopic data for subduction-related Late Cretaceous and Cenozoic granitoids of the coastal region and lowermost Pacific slope of the Western Cordillera of central Peru suggest that these granitoids are derived from an undepleted mantle source (OIB–type or enriched sub-continental). A depleted MORB–type mantle did not have a major role in the genesis of the magmas.

The mantle source appears to have changed slightly with time. The data suggest that the asthenospheric wedge was isotopically heterogeneous during the early stages of Coastal batholith emplacement. During this time, the subduction slab geometry changed from steeply to moderately dipping, and the stress regime in the overriding plate changed from extensional to compressional. Subduction-related mantle convection caused a progressive homogenization of the asthenospheric wedge between 100 and 80 Ma. Since then, the isotopic composition of the mantle component has not varied significantly. Those parts of the metasomatized asthenosphere that did not melt (or where trapped magmas did not escape upward) did not participate significantly in the convective cells and were dragged along the slab to greater depth.

Evidence for participation of a radiogenic crustal component in the evolution of these Peruvian granitoids is always present. Significant crustal contamination or assimilation cannot be ruled out, since the isotopic contrast between lower- and upper-crustal rocks and mantle-derived magmas is generally low, but contamination by highly radiogenic, in situ, upper-crustal rocks appears to be sporadic in time and space. The radiogenic crustal component is shown to be mainly a component recycled by subduction. We assume that it corresponds to fluids derived from the subducting slab and associated subducted sediments. This crustal component appears to have changed with time. The variations of Pb- and Sr-isotopic compositions are consistent with a two-stage model:

(1) During the early stages of Coastal batholith emplacement (100 to 90 Ma) the crustal component was mainly derived from tectonic erosion of the Lower Cretaceous accretionary prism. The sediments in the accretionary prism were derived from the

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Brazilian Shield and had highly radiogenic Pb- and Sr-isotopic compositions similar to modern sediments of the Barbados ridge.

(2) After 84 Ma, the crustal component was Pacific oceanic sediments (and a slab component) with Pb- and Sr-isotopic compositions like those of modern Pacific sediments.

These results suggest that participation of recycled oceanic sediments in the genesis of Andean calc-alkaline magmas is the rule, although in many cases the evidence is obscured by interaction of mantle-derived magmas with the continental crust.

INTRODUCTION

The problem of crust/mantle recycling and magma genesis and evolution at a convergence zone is generally addressed through geochemical and isotopic studies of relatively young magmatic rocks (e.g., Harmon and others, 1984; Hickey and others, 1986; Hildreth and Moorbath, 1988; for the Andes). Little attention has been paid to geochemical evolution and isotopic patterns of subduction-related magmatic rocks over a long period in a single well-known locality. This latter approach can provide important constraints on genetic models of subduction-related magmas, as it allows use of time-dependent dynamics as an explanatory factor (e.g., Kay and others, 1987). For continental-margin magmatism (e.g., the Andes), such an approach may permit discrimination between recycled crustal components (oceanic sediments or tectonically eroded continental rocks) and in situ continental crust (assimilation and/or contamination en route to the surface).

The coastal region and the lower Pacific slope of the Western Cordillera of central Peru are ideal locations to examine evolution of plutonic rocks over time. In this area (Fig. 1), mantle-derived, I-type, medium- to high-K calc-alkaline granitoids, ranging from Albian to latest Oligocene in age, are exposed (Cobbing and others, 1981; Pitcher and others, 1985; Soler and Bonhomme, this volume). These granitoids can be grouped into a volumetrically dominant Coastal batholith (102 to 59 Ma) and subordinate post-batholithic plutonic events (54 to 30 Ma) (see Soler and Bonhomme, 1988, and this volume).

The most important host rocks of these granitoids are the Albian-age Casma volcanic group (Myers, 1974, 1980; Webb, 1976; Guevara, 1980). These Casma volcanics have tholeiitic and calc-alkaline arc and back-arc affinities (Atherton and others, 1985) and were extruded in an aborted marginal basin with a drastically thinned crust (Atherton and others, 1983; Aguirre and Offler, 1985). Less important host rocks are Lower Cretaceous siliciclastic sediments, derived from the Brazilian Shield and uppermost Jurassic/lowest Cretaceous back-arc volcanic and volcano-sedimentary rocks (e.g., Mégard, 1978). The Precambrian and lower Paleozoic basement of the Paracas geoanticline (Cobbing and others, 1981) does not crop out in this area but could be present at depth.

The Nazca oceanic plate (previously Farallon) has been subducting continuously beneath South America at least since Late Jurassic time. Coastal batholith emplacement began immediately after closure of the Casma basin during the upper Albian compressive "Mochica" tectonic event, marking the onset of the Andean orogeny in Peru (Mégard, 1984; Pitcher and others, 1985). This change from a dominantly extensional to a dominantly compressive regime appears to correlate with a change from a steep to moderately dipping slab (Soler and Bonhomme, this volume).

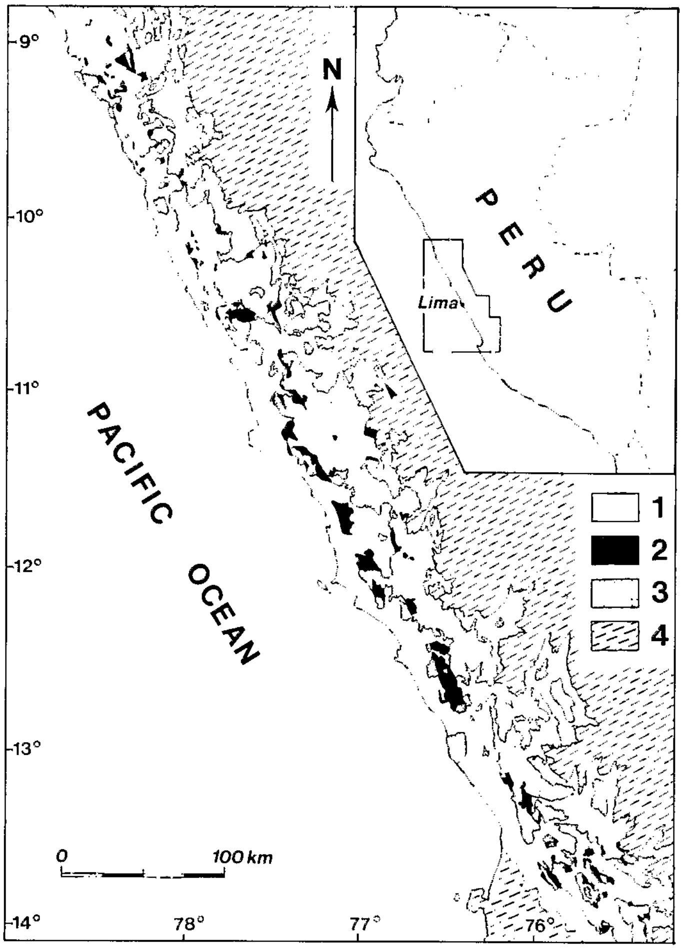


Figure 1. Geological sketch of the study area based on map of Pitcher and others (1985). 1. Casma volcanism + Early Cretaceous volcanic, volcano-clastic, and silico-clastic rocks of the coastal area; 2. Patap super-unit (mainly gabbros and meladiorites); 3. granitoids (Lima segment of the Coastal batholith + eastern stocks emplaced within a Casma envelope). The arrow indicates the location of the Paccho Tingo and Churin West tonalitic stocks; 4. other rocks.

TABLE 1. Sr- AND Pb-ISOTOPIC DATA FOR THE PACCHO TINGO AND WEST CHURIN STOCKS (31 MA)

Sample number	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Sr_i (31 Ma)	Pb	U	Th	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Paccho Tingo											
HU01	81.5	457	0.52	0.70468	0.70440	18.6	3.3	9.3	18.77	15.62	38.60
HU38	98.6	451	0.43	0.70460	0.70439	11.1	3.2	7.6	18.76	15.65	38.68
HU42	102.8	348	0.86	0.70462	0.70420	11.1	3.2	7.6	18.71	15.60	38.47
HU44	255	119	1.35	0.70502	0.70443	15.2	11.5	34.9	18.44	15.34	38.12
West Churin											
HU65	89.2	400	0.65	0.70474	0.70446	7.5	4.5	11.1	18.65	15.64	38.60
HU69	62.4	460	0.39	0.70470	0.70453	9.7	2.9	9.5	18.71	15.60	38.48
HU70	63.5	432	0.47	0.70465	0.70446	8.7	3.2	7.0	18.71	15.60	38.53
HU71	136	107	3.65	0.70574	0.70414	3.8	7.8	34.6	18.80	15.61	38.50

Pb- and Sr-isotope analyses were performed on finely crushed whole rocks following the Saclay laboratory techniques described by Turpin and others (1988) on a single collector, double focusing V.G. Micromass 54-38 spectrometer.

Standard values:

NBS 987: $^{87}Sr/^{86}Sr = 0.710245$ (current value) using the normalizing ratio $^{86}Sr/^{88}Sr = 0.1194$.

NBS 981: $^{206}Pb/^{204}Pb = 16.902 \pm 0.014$ and $^{206}Pb/^{207}Pb = 15.433 \pm 0.017$ (on 10 runs).

External reproductibility on standards are 5 10^{-5} for $^{87}Sr/^{86}Sr$ on NBS 987. 0.5 percent uncertainty is assumed on Rb/Sr from duplicate whole-rock processing.

Uncertainties regarding Pb-isotopic ratios are quoted in Figure 2.

Between the Late Cretaceous and the Oligocene, no drastic changes occurred in the geometry of the subduction zone. Main changes concern the direction and the rate of convergence; a progressive change of slab dip from ±45° (Coastal batholith) to ±30° (post-batholith plutonism) is supposed to have occurred during the Eocene (see Soler and Bonhomme, this volume). The most important change during this period was the progressive thickening of the continental crust due to tectonic shortening and magmatic addition.

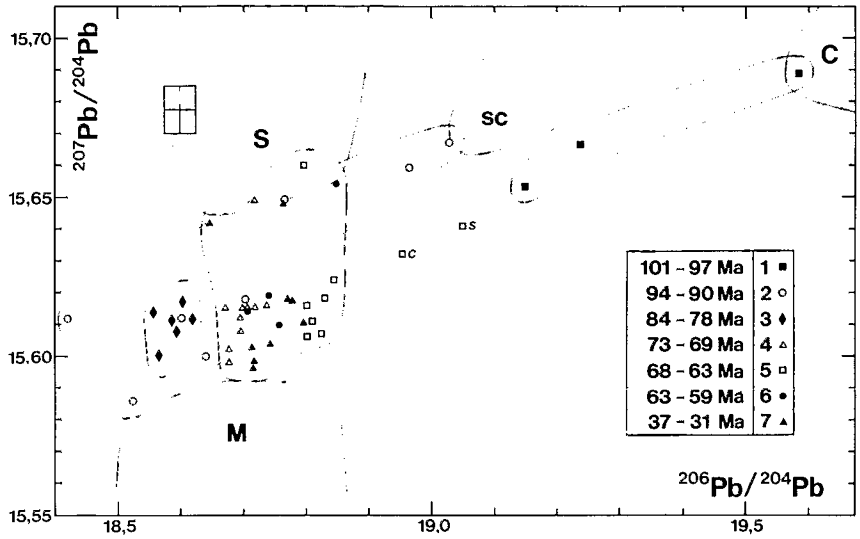
In this chapter, Sr-isotopic data on most of the Coastal batholith units from Beckinsale and others (1985), Pb-isotopic data on the Coastal batholith and some post-batholithic granitoids from Mukasa (1984, 1986a), and new Sr- and Pb- isotopic data on Oligocene granitoids from the Rio Huaura valley (Table 1; Fig. 1) will be discussed in relation to changes in the subduction regime and oceanic and continental crustal components in the magmas. Those new data and Nd-isotopic data will be discussed in more detail in a forthcoming paper. The data set has some limitations as the Pb- and Sr-isotopic data are not always on the same samples.

Pb-ISOTOPIC COMPOSITIONS

The Pb-isotopic data (notation: Pb6 = $^{206}Pb/^{204}Pb$; Pb7 = $^{207}Pb/^{204}Pb$; Pb8 = $^{208}Pb/^{204}Pb$) are plotted in Figure 2 with the granitoids divided into seven age ranges. Sample RR5 (Santa Eulalia granodiorite) from Mukasa has been omitted because of its surprisingly radiogenic Pb values (Pb6 = 20.803; Pb7 = 15.709; Pb8 = 41.177) compared to samples from the Atocongo granite (RR13 and RR12). This sample is more radiogenic than any other Andean, Cretaceous to Quaternary, magmatic rocks for which Pb-isotopic data have been published and is quite extreme compared to the most radiogenic upper-crustal rocks. This unique data is not used in the discussion, and its validity needs to be confirmed.

The data set shown in Figure 2 is extremely heterogeneous (18.42 <Pb6 19.58–15.55 < Pb7 <15.69–38.40 <Pb8 <39.23). Samples from intrusions of the same age and even within the same intrusion show a large range of values. In the Pb7–Pb6 and Pb8–Pb7 diagrams, the data define several more or less linear trends that do not have any age significance. Instead, these trends appear to be coarse mixing lines between a moderately radiogenic mantle end-member and an end-member with a more radiogenic Pb7 composition than mantle-derived OIB (considering its Pb6 composition; Fig. 3). This second end-member is either in situ continental crust, or a subduction-recycled crustal component, or a mixing of both.

The Pb content of the mantle is very low (in the range 400 to 50 ppb; Zartman and Doe, 1981). The Pb content of oceanic sediments is extremely variable, depending on the mix of sediments involved (Church, 1973). A realistic mean may be 20 to 25 ppm (Chow and Patterson, 1962; Church, 1973; Zartman and Doe, 1981; White and Dupré, 1986) for subducted sediments and continental crust. The Pb content of MORB is in the range 0.5 to 1 ppm (Tatsumoto, 1978) and may be lowered by sea-water alteration. Because Pb content in sea water is very low (±0,002 ppb), sea-water alteration does not modify the Pb-isotopic compositions of MORB and oceanic sediments. Since



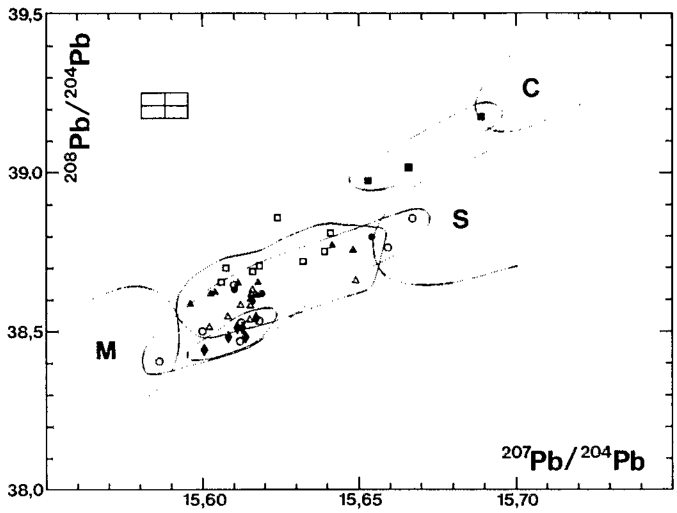


Figure 2. $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$–$^{207}Pb/^{204}Pb$ diagrams for some of the granitoids of the coastal region and the lower Pacific slope of the Western Cordillera of central Peru. Pb-isotopic data from Mukasa (1986a) except for Paccho Tingo and Churin West (Table 1), U-Pb ages from Mukasa (1986a). Age ranges as follows: 1. Atocongo (101 Ma) and Linga–Ica (97 Ma); 2. Lachay (90.0 Ma), Pampahuasi 1 (93.3 to 94.1 Ma) and Santa Rosa–Huaricanga (91.0 Ma); 3. Santa Rosa–Coralillo (81.7 to 84.4 Ma) and Tiabaya–Ica (78.3 Ma); 4. Humaya (73.1 Ma), La Mina (71.1 Ma), and Santa Rosa (70.6 to 72.0 Ma); 5. Lumbre (69.6 Ma), Andahuasi (69.7 Ma), San Jerónimo (67.6 to 68.7 Ma), Puscao (66.2 to 66.6 Ma) and Sayan (68.0 to 68.5 Ma). Field relations indicate that the Sayan granite postdates the Puscao unit. The K-Ar (Cobbing and others, 1981) and Rb-Sr (Beckinsale and others, 1985) ages at 62 ± 2 Ma are probably better; 6. Paccho super-unit (64 to 59 Ma); 7. Pativilca (37 Ma), Paccho Tingo (31 Ma) and West Churin (31 Ma). K-Ar ages from Cobbing and others (1981). See Soler (1987) for a discussion of these ages.

Pb(crust)/Pb (mantle) is very high, any magma that includes even a small proportion of crustal material will have a Pb-isotopic composition strongly displaced toward crustal values.

Crustal component

As a first approximation, the Pb-isotopic composition of the crustal end-member of a given age range is close to that of the most radiogenic sample. However, considering the analytical uncertainties and the roughness of the mixing trends, only a preferred compositional field for the crustal end-member for each age range can really be defined (Fig. 2). Notwithstanding such an ample definition of the Pb-isotopic composition of the successive crustal end-members, it appears that the Pb-isotopic composition of the crustal component has changed in a very sensitive manner through time (components C, sc, and S in Figs. 2 and 3). The crustal end-member is very radiogenic (C: Pb6 $>$19.6; 15.68 $<$Pb7 $<$15.72; PB8 $>$39.15) for the oldest plutons (about 100 Ma), then becomes less radiogenic for intrusions emplaced at 90 to 94 Ma (sc:Pb6 ≈ 19.1; Pb7 ≈ 15.68; PB8 ≈ 38.90), and is least radiogenic for those emplaced between 84 Ma and the Oligocene (S:18.6 $<$Pb6 $<$18.9; Pb7 $>$15.65; 38.65 $<$PB8 $<$38.95). This variation is not linked with differences in the nature and chemistry of the host rocks of the various plutons as they all intrude either the Casma volcanics or uppermost Jurassic and Lower Cretaceous detrital and volcaniclastic rocks. Moreover, the evolution of the crustal end-member is not consistent with any lead growth curve (e.g., Cumming and Richards, 1975). Therefore, this crustal end-member has changed between the first episode of emplacement of the Coastal batholith and the following episodes.

If the crustal components (C, sc, and S) are only in situ continental crust, the evolution C–sc–C with time must be the result of mixing between the original upper continental crust (C) and mantle-derived magmas. Since most of the granitoids have lower Pb7 than the C component, additions of mantle-derived magmas should significantly lower the mean Pb7 of the upper continental crust. The nearly constant Pb7 composition of C, sc, and S is not consistent with this hypothesis.

Therefore, at least one of the crustal end-members must be oceanic sediments that have been recycled through subduction. As the compositional field for S (84 to 31 Ma) largely overlaps that of present-day Pacific sediments (Reynolds and Dasch, 1971; Sinha and Hart, 1971; Church, 1976; Meijer, 1976; Unruh and Tatsumoto, 1976; Sun, 1980; Dasch, 1981; Barreiro, 1983; see Fig. 3), our preferred hypothesis is that S represents oceanic sediments carried down by the slab. The estimated Pb-isotopic composition of S is particularly close to that of present-day Pacific sediments as given by Sinha and Hart (1971).

Although the only discernible crustal component for granitoids emplaced between 84 and 31 Ma is recycled oceanic sediments, this does not imply that there has not been any interaction between mantle-derived magmas and preexisting crustal rocks. In the study area, the lower crust appears principally to be high-density mantle-derived material (Couch and others, 1981; Jones, 1981) that is probably ultramafic and mafic cumulates from the Casma and Patap magmatism, and the upper crust is composed of volcanic and volcani-clastic rocks with lesser amounts of detrital rocks derived from the continental shield. As the isotopic contrast between these crustal rocks and the mantle-derived magmas is very low, this type of mixing is difficult to detect.

Marine geological and geophysical studies (Couch and others, 1981; Kulm and others, 1981; Jones, 1981) suggest that modern accretion of oceanic sediments is not significant along the Andean margin and that most oceanic sediments in this region are actually subducted (Scholl and others, 1977; Kulm and others, 1981; Hilde, 1983). ^{10}Be studies of recent volcanic rocks from southern Peru and northern Chile (Tera and others, 1986; Morris and others, 1987) have shown that subducted sediments are involved in the genesis of calc-alkaline arc magmas in these regions. As a subduction geometry similar to the present-day geometry in southern Peru has prevailed in central Peru from the Upper Cretaceous to the Oligocene (see above), subduction of oceanic sediments may be inferred throughout this period. These conclusions are concordant with the interpretation of the Pb-isotopic data from the central Peruvian plutons and suggest that mixing of recycled oceanic sediments in Andean calc-alkaline magmas is the rule. In many cases, detection of this mixing is difficult because of further interaction between mantle-derived magmas and the continental crust.

In the central Peruvian granitoids, the C crustal end-member could be a mixture of recycled continental and oceanic sediments, and the S crustal end-member oceanic sediments. The sc crustal member would then be a mixture of C and S. In accordance with this, crustal component C is more radiogenic than present-day Pacific sediments, but is very close to present-day detrital sediments on the Barbados ridge, carried from the Guyana Shield to the Caribbean Sea by the Orinoco River (White and others, 1985; White and Dupré, 1986).

The highly radiogenic C end-member could then result, at least in part, from erosion of an accretionary prism that contained a large component of shield-derived detritus. Voluminous clastic sedimentation, the absence of a volcanic arc barrier, and an extensional regime with loose coupling between the slab and the overriding plate all favor the presence of such an accretionary prism in the Lower Cretaceous. The first stages of Coastal batholith emplacement are thought to correspond with a change from an extensional to a compressive tectonic regime and from a steeply dipping to a moderately dipping, more tightly coupled slab. This change in tectonic style and slab dip would favor erosion of the preexisting accretionary prism at the trench at the time that the C component is dominant in the isotopic signature. Subsequently, the supply of shield-derived debris to the trench appears to have been low from the Aptian to the Oligocene (e.g., Ménard, 1978), leading to a transition from a C- to an S-type sedimentary component. Once the accretionary prism had been eroded, the subducted sediments would be essentially Pacific oceanic sediments (i.e., S component).

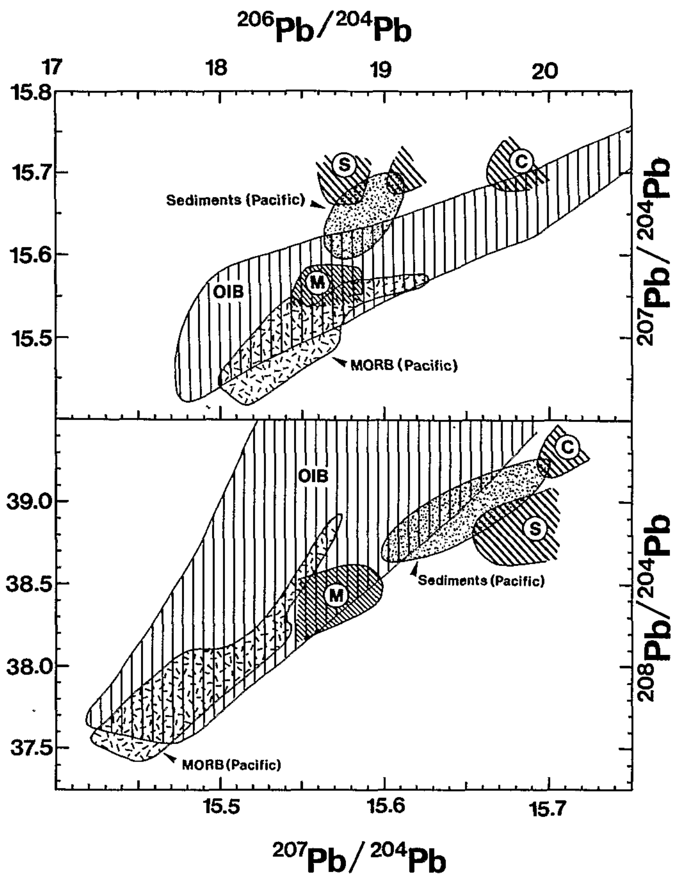


Figure 3. $^{207}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$–$^{206}Pb/^{204}Pb$ diagrams indicating the possible mantle and crustal end-members for the plutons of the coastal region and the lower Pacific slope of the Western Cordillera of central Peru. Fields for MORB and Pacific oceanic sediments as discussed in the text. Field for OIB from Sun (1980).

The C component can also, at least partially, represent the preexisting continental crust, as its Pb-isotopic composition is consistent with that of local Upper Jurassic to Lower Cretaceous shield-derived sediments, as inferred from their similarity to the modern Barbados ridge samples. The effect of such an in situ crustal component upon Pb-isotopic compositions through contamination and/or assimilation could be sporadic in both time and space. Such crustal effects are possible in age range 5 (68 to 63 Ma) for a sample of the Sayan monzogranite and the sample of the Cañas monzogranite, which have higher Pb6 and Pb7 than other Rio Huaura ring complex granitoids. In age range 2 (94 to 90 Ma), at least 2 samples of the Lachay granite that define the sc end-member have relatively high Pb6. Data for age range 1 (101 to 97 Ma) are insufficient to say whether this trend represents a mixing line or is the result of sporadic crustal contamination. However, since these age range 1 granitoids have the highest Pb6 and Pb7 and were emplaced in the thinnest continental crust, systematic crustal contamination seems unlikely, as younger units that were intruded in thicker crust show only sporadic and limited crustal contamination.

Since shield-derived detrital sediments are inferred to have formed the accretionary prism and also composed the Upper Jurassic to Lower Cretaceous sediments underlying the Casma volcanics, a dual origin for crustal component C seems to be a reasonable hypothesis. Additional Pb-isotopic data are necessary, but Sr-isotopic data presented below favor the dual hypothesis.

Mantle component

The Pb-isotopic composition of the mantle end-member is difficult to define precisely because small amounts of crustal contamination displace the Pb-isotopic values to highly radiogenic values and the composition of the crustal component varies. However, a composition field for a mantle end-member that is compatible with data in age ranges 3 to 7 can be defined (18.5 <Pb6 <18.85, Pb7 <15.60 and 38.2 <Pb8 <38.6; field M in Figs. 2 and 3). More data are needed to clearly define the mantle component for age range 1 (101 to 97 Ma). The large amount of scatter in the data makes identification of a single mantle end-member for age range 2 (94 to 90 Ma) very difficult.

The Pb-isotopic data are not clear enough to show whether the mantle end-member was a depleted MORB–type source or an undepleted OIB–type or subcontinental mantle source. However, as stated by Mukasa (1986a), the trends defined by the data never reach the Pacific MORB field (see Fig. 3; data from Church and Tatsumoto, 1975; Unruh and Tatsumoto, 1976; Tatsumoto, 1978; Sun, 1980; Dupré and others, 1981; Cohen and O'Nions, 1982; Hamelin and others, 1984; White and others, 1987), and the least radiogenic samples have Pb7 well above the Pacific MORB field or the depleted mantle modeled by Zartman and Doe (1981). These Pb-isotopic data, along with trace-element (Atherton and others, 1985b; Soler, in preparation) and Nd-Sr-isotopic (Soler and Rotach-Toulhoat, unpublished data) data are more consistent with multistage evolution of an old, long-term, enriched mantle reservoir. The data are consistent with the subducted oceanic crust participating in magma genesis through metamorphism and dehydration (the "IRS fluids" of Gill, 1981), but not as a major magma source.

When considered in more detail, the data for age ranges 3 to 7 suggest that the Pb-isotopic composition of the mantle end-member changed with time. Pb6 increases from age range 3 to 5, then decreases to intermediate values for age ranges 6 to 7. Trends are less clear for Pb8. More data are necessary to define this evolution, but this progressive change cannot be explained by normal time-dependent Pb evolution of the mantle source or by progressive mixing of mantle and oceanic sediments (S). This is particularly clear in the Pb7–Pb6 diagram (Fig. 2a), where Pb7 is nearly constant for successive mantle end-members when the crustal components have high Pb7. The causes of this progressive change are unclear, but the hypothesis of a homogeneous subcontinental mantle reservoir for the Chilean (Tilton and Barreiro, 1980; Barreiro, 1984) and Peruvian (Mukasa, 1984, 1986a) Andes needs to be reconsidered.

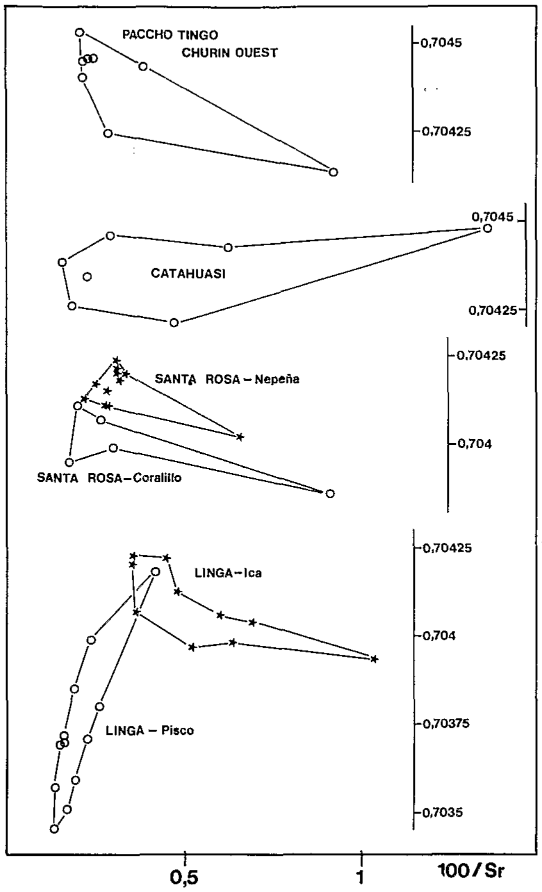
The probable geometry of the convection cells above the subducting slab (e.g., Hsui and Toksöz, 1979; Tatsumi and others, 1983) suggests that long-term convection will insure progressive homogenization of the mantle wedge. The melting region is inferred to be the asthenospheric wedge modified by metasomatic fluids derived from a slab-sediment component. Arculus and Powell (1986) have suggested that part of the produced magmas do not ascend and are trapped in the wedge. If this is the case, the fact that Pb-isotopic compositions of the mantle component do not become more radiogenic with time (in Pb7) implies that most of this modified asthenosphere is dragged to greater depths by the descending slab.

Sr-ISOTOPIC COMPOSITIONS

Initial $^{87}Sr/^{86}Sr$ ratios (Sr_i) of upper Albian to latest Oligocene granitoids in the study area vary from 0.70351 to 0.70516 (Figs. 4 and 5). These values are consistent with an OIB-like or enriched subcontinental mantle source that has been partially modified by a crustal component, as inferred above from Pb-isotopic data and from petrological and geochemical studies (Atherton and others, 1985b; Soler, in preparation).

Sr-isotopic heterogeneity of individual intrusions or units

The narrow range of $^{87}Sr/^{86}Sr$ ratios make Rb-Sr isochrons impossible to define for most of the intrusions considered here (Table 2; Beckinsale and others, 1985). Thus, the initial $^{87}Sr/^{86}Sr$ ratios have to be calculated using age data obtained by other methods (U-Pb and K-Ar). In most cases, the Sr_i calculated for the different samples from a single intrusion or unit fall in a relatively wide range. Even when the number of samples and the variation in the $^{87}Sr/^{86}Sr$ ratios are sufficient to make an isochron, those isochrons are of poor quality. For example, the Atocongo granite, which has been dated at 101 ± 1 Ma (zircon) by the U-Pb method (Mukasa, 1984, 1986b) and at 104 ± 2 Ma (biotite) by the K-Ar method (Cobbing and others, 1981) gives a



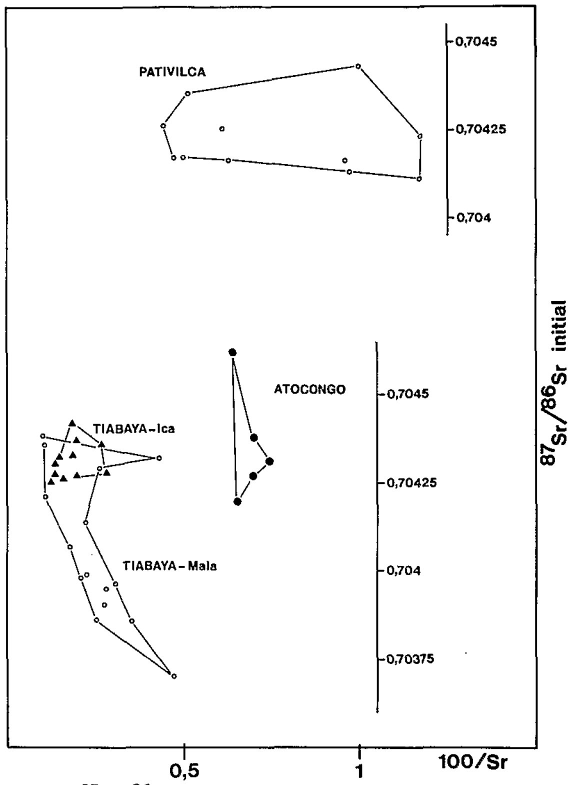


Figure 4. Initial $^{87}Sr/^{86}Sr$ ratio (Sr_I) versus 1/Sr for some granitoids of the coastal region and the lower Pacific slope of the Western Cordillera of central Peru.

Rb-Sr isochron age of 81 ± 25 Ma (MSWD = 3.40) (Beckinsale and others, 1985).

If the pluton is comagmatic and the ages of the samples are identical, there are two reasons, not mutually exclusive, for a poor isochron. The first is that isotopic heterogeneity was acquired by mixing with another magma from a different source, by selective contamination, or by hydrothermal alteration. The second is that isotopic heterogeneity is a characteristic of the source region and different magma batches have different isotope compositions.

The problem of whether the samples from a pluton have identical ages needs to be addressed first. The Pampa Ihuanco pluton, which belongs to the "Santa Rosa–Coralillo super-unit" of the Coastal batholith (Pitcher, 1978, 1985), will be used as an example. Mukasa (1984, 1986b) found concordant U-Pb ages on zircon at 84.4 Ma for the dioritic border and at 82.5 Ma for the granodioritic central part. Following Mukasa, the precision in these ages is better than 1 percent; thus, the age difference is significant. For larger, more differentiated intrusions, somewhat greater age differences between the least and most evolved samples might be expected.

In the range of ages that we consider here (<100 Ma), the difference between calculated Sr_i using an age T or an age T–ΔT will be:

$$\Delta Sr_i = Sr_i\,(T) - Sr_i\,(T - \Delta T) = -\lambda\,\Delta T\,(^{87}Rb/^{86}Sr)_{meas}$$

A variation of only 3 m.y. for the assumed age will bring a ΔSr_i of 0.00042 for $(^{87}Rb/^{86}Sr)_{meas} = 10$.

For a number of intrusions or units (Linga-Ica, Santa Rosa–Coralillo, Santa Rosa–Nepeña, Paccho Tingo, West Churin), using a single intrusion age results in a decrease in the calculated Sr_i with the degree of differentiation. An in situ contamination process would produce an increase in Sr_i with differentiation (e.g., Briqueu and Lancelot, 1979; Taylor, 1980; De Paolo, 1981), whereas other mechanisms such as magma mixing and source region heterogeneity might not produce a systematic trend. Thus, it is possible that the low calculated Sr_i of the more evolved parts of these intrusions or units is only an artifact of the calculation, due to the different ages of the magma batches.

Differences in Sr_i in the least evolved parts within an intrusion are difficult to explain by age alone, as age differences of magma batches with only slightly different degrees of differentiation and small differences in Rb/Sr ratios have to be low. Heterogeneity in this case must be acquired during evolution of the magma by mixing, contamination, or weak hydrothermal alteration or be a characteristic of the source. In the Sr_i versus 1/Sr diagram (e.g., Briqueu and Lancelot, 1979) in Figure 4, Sr_i does

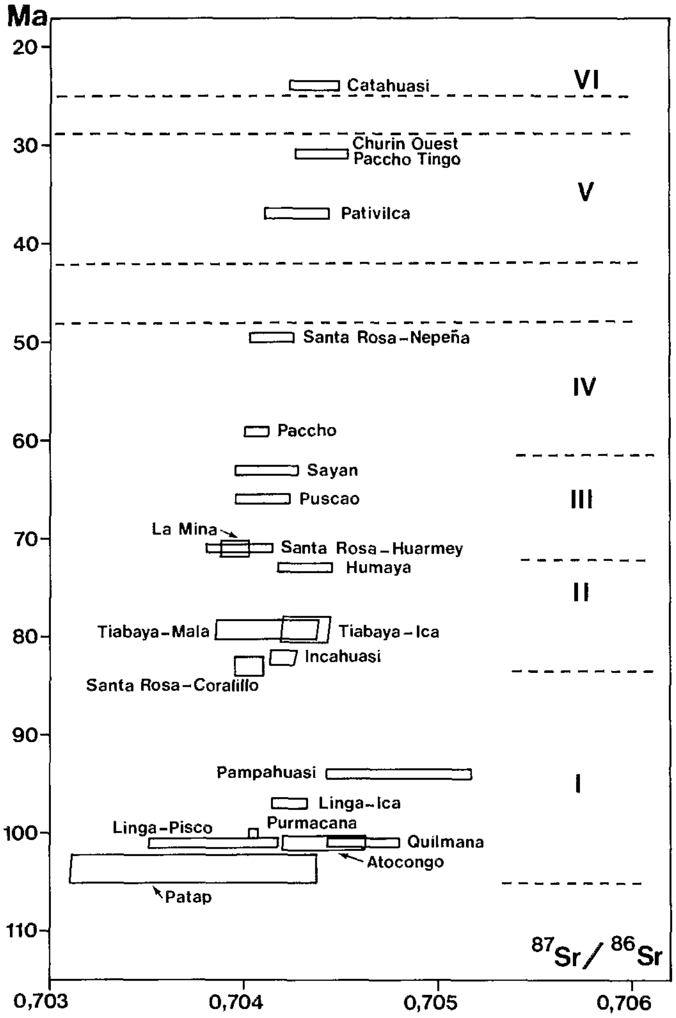


Figure 5. Initial $^{87}Sr/^{86}Sr$ ratio (Sr_i) versus time for the granitoids of the coastal region and the lower Pacific slope of the Western Cordillera of central Peru. Calculated Sr_i and references are given in Table 2.

not increase with differentiation, and the range in Sr_i for the least evolved samples covers the whole range observed in the pluton. Thus, assimilation and/or contamination processes cannot explain the Sr-isotopic heterogeneity of these granitoids. The Sr_i–1/Sr diagrams for the Linga (Pisco and Ica) and Tiabaya (Ica and Mala) units (Fig. 4) suggest that the Sr-isotopic heterogeneities may be produced by magma mixing in some cases (see Beckinsale and others, 1985). However, a slight heterogeneity of the source area is still needed to explain the observed data. This heterogeneity could be a consequence of vein-like metasomatic transformation of the mantle wedge by fluids (or melts) extracted from the slab and sediments (Gill, 1981) and of the trapping of part of these magmas in the wedge (e.g., Arculus and Powell, 1986).

Sr_i variations with time

All of the available data are plotted in a Sr_i versus time diagram in Figure 5. The diagrams show that the Sr_i varies from 0.70351 to 0.70516, that the pattern of variation is quite complex, and that no systematic increase in Sr_i occurs with time. The most extreme and greatest range of values occur within units intruded during the early stages of the Coastal batholith (period I in Fig. 5; 101 to 94 Ma). During this time the minimum Sr_i (for a given age) increases from 0.70351 at 101 Ma to 0.70442 at 94 Ma.

Between 82 and 24 Ma, the global variation of Sr_i is much smaller (0.70385 to 0.70450). This period can be divided into 5 episodes (II to VI in Fig. 5). The transition between period I to II is marked by a decrease of Sr_i (from 0.70442 to 0.70516 for the Pampahuasi unit to 0.70395 to 0.70427 for the Santa Rosa–Coralillo and Incahuasi units). The boundary between periods II and III is marked by a less abrupt drop of Sr_i (from 0.70418 to 0.70445 for the Humaya unit to 0.70391 to 0.70414 for the La Mina and Santa Rosa–Huarmey units). Periods III to VI are defined rather by episodes of magmatic quiescence, which limit them (Soler and Bonhomme, this volume), than by the evolution of the Sr_i. A limited increase of Sr_i occurs between the beginning of period III and the end of period V.

Compared with the wide range of Sr_i of modern, central Andean, volcanic rocks (0.7055 to higher than 0.710; James and others, 1974; James, 1976, 1982; Francis and others, 1977, 1980; Thorpe and others, 1979; Hawkesworth and others, 1979, 1982; Briqueu and Lancelot, 1979; Harmon and others, 1984), the 110 to 24 Ma central Peruvian magmatic rocks show a narrow range of relatively low Sr_i. The high and variable Sr_i of these modern volcanic rocks have been interpreted as a consequence of contamination and/or assimilation processes in a thick continental crust (e.g., Harmon and others, 1984). The generally lower values of the central Peruvian granitoids show that they were not as strongly modified during their ascent through the continental crust. As discussed for the Pb-isotopic data, this does not imply that there has been no interaction between the mantle-derived magmas and continental crust, as the isotopic contrast may be low in the study area.

Plutons of period I have been emplaced in a comparatively thin crust. Their Sr-isotopic heterogeneity and high Sr_i are consistent with their highly radiogenic Pb-isotopic compositions. The Sr-isotopic data are more numerous and more representative than Pb-isotopic data. These Sr-isotopic compositions are not regarded as consequences of crustal contamination or assimilation, but are thought to be due to participation of highly radiogenic recycled sediments in the subduction zone. As suggested by the Pb-isotopic data, these sediments were mainly derived from a Lower Cretaceous accretionary prism. Norman and Landis (1983) give Sr_i as high as 0.7165 for Upper Jurassic–Lower Cretaceous shield-derived deltaic sediments in the Western Cordillera of central Peru. As with the Pb-isotopic data, these Sr_i are close to those

TABLE 2. RANGE OF INITIAL Sr-ISOTOPIC RATIOS FOR THE GRANITOIDS OF THE COASTAL BATHOLITH (LIMA SEGMENT) AND FOR SOME EASTERN STOCKS

Intrusion or unit	Assumed age (Ma)†		Sr_i* Min.	Sr_i* Max.	Number of samples
Patap (gabbros)	105-102	(1, 2, 4)	0.70307	0.70438	5
Atocongo	101	(1)	0.70420	0.70462	6
Quilmana	101	(2)	0.70442	0.70479	7
Purmacana	100	(4)	0.70404	0.70405	2
Linga-Ica	97	(3)	0.70414	0.70432	10
Linga-Pisco	101	(1)	0.70351	0.70418	12
Pampahuasi	94	(1, 3)	0.70442	0.70516	7
Incahuasi-Cañete	82	(2, 3)	0.70415	0.70426	8
Incahuasi-Ica	82	(2, 3)	0.70396	0.70436	6
Santa Rosa-Coralillo	82	(1, 4)	0.70395	0.70419	5
Tiabaya-Ica	80.5	(1, 3)	0.70421	0.70442	11
Tiabaya-San Juan	80.5	(1, 3)	0.70418	0.70441	6
Tiabaya-Mala	80.5	(1, 3)	0.70386	0.70438	15
Humaya	73	(1, 4)	0.70418	0.70445	11
La Mina	71	(1, 4)	0.70388	0.70403	6
Santa Rosa-Huarmey	71	(1)	0.70391	0.70414	7
Puscao	66	(1)	0.70380	0.70423	14
Sayan	63	(2, 4)	0.70396	0.70428	11
Santa Eulalia (Paccho)	59	(1)	0.70401	0.70412	6
Santa Rosa-Nepeña	50	(1)	0.70402	0.70424	11
Pativilca	37	(1, 2)	0.70411	0.70423	11
Paccho Tingo	31	(4, 5)	0.70420	0.70443	4
Churin West	31	(4, 5)	0.70414	0.70453	4
Catahuasi	24	(2)	0.70422	0.70448	7

*All Sr_i calculated with the data of Beckinsale and others (1985) except for West Churin and Paccho Tingo (Table 1).

†Following 1 - Mukasa (1984, 1986b); 2 - Beckinsale and others (1985); 3 - Moore (1984); 4 - Cobbing and others (1981); 5 - Soler (1987).

obtained for the modern Barbados ridge (White and others, 1985).

In periods II to VI, the Sr ratio of the recycled crustal component is more difficult to assess, as it corresponds to fluids derived from the slab and Pacific oceanic sediments. Sr-isotopic ratios of unaltered slab are in the range 0.7023 to 0.7029 (O'Nions and others, 1977; De Paolo and Wasserburg, 1979; Jahn and others, 1980; Cohen and O'Nions, 1982; White and others, 1987), but sea-water alteration results in an increase in Sr_i (Spooner, 1976; O'Nions and others, 1978; De Paolo and Wasserburg, 1979). Pacific oceanic sediments are a mixture (Dymond, 1981) of detrital sediments (Sr_i = 0.712 to 0.715; Dasch, 1969; Stern and Ito, 1983), metalliferous sediments (Sr_i = 0.708 to 0.710; O'Nions and others, 1978, Goldstein and O'Nions, 1981), and carbonates (Sr_i = sea water). Thus, 0.708 to 0.710 may be regarded as a realistic mean Sr_i for recycled crustal components in periods II to VI. This value is significantly lower than during period I and could explain the lower Sr_i in younger granitoids.

The volume of recycled material was probably greater in period I, when oceanic sediments and accretionary prism sediments were both subducted, than during the following periods, when only oceanic sediments were subducted. The greater heterogeneity of period I plutons is thus linked both to higher Sr_i and greater sediment participation. During period I, minimum Sr_i increases with time as the convective renewal of the mantle wedge was not rapid enough to erase the evidence of fluids extracted from the subducting slab and sediments. Conversely, only slight changes in minimum Sr_i occur during periods II to VI. As suggested by the Pb-isotopic studies, the asthenospheric wedge was homogenized in and after period II. Convective renewal in the wedge at this time must have been sufficient to homogenize the geochemical signature of the fluids. Minimum Sr_i (for a given age) increases slightly between period III and VI. Three non–mutually exclusive interpretations are possible: (1) The asthenospheric wedge is not completely homogenized, and metasomatized asthenosphere participates in the convective cells. The Pb-isotopic study shows this effect can be only minor. (2) A slight increase in crustal contamination and/or assimilation with time, corresponding to the progressive thickening of the continental crust. (3) An increase of Sr-isotopic ratio of the IRS fluids reflects the increase of the Sr-isotopic ratio of sea water (seen in altered

MORB and oceanic sediments) through this period (Peterman and others, 1970; Burke and others, 1982; Hess and others, 1986; Palmer and Elderfield, 1985).

CONCLUSIONS

Pb- and Sr-isotopic data for subduction-related Late Cretaceous and Cenozoic granitoids of the coastal region and lowermost Pacific slope of the Western Cordillera of central Peru suggest that these granitoids are derived from an undepleted mantle source (OIB-type or enriched sub-continental). A depleted MORB-type mantle did not have a major role in the genesis of the magmas.

The mantle source appears to have changed slightly with time. The data suggest that the asthenospheric wedge was isotopically heterogeneous during the early stages of Coastal batholith emplacement. During this time, the subduction slab geometry changed from steeply to moderately dipping, and the stress regime in the overriding plate changed from extensional to compressional. Subduction-related mantle convection caused a progressive homogenization of the asthenospheric wedge between 100 and 80 Ma. Since then, the isotopic composition of the mantle component has not varied significantly. Those parts of the metasomatized asthenosphere that did not melt (or where trapped magmas did not escape upward) did not participate significantly in the convective cells and were dragged along the slab to greater depth.

Evidence for participation of a radiogenic crustal component in the evolution of these Peruvian granitoids is always present. Significant crustal contamination or assimilation cannot be ruled out, since the isotopic contrast between lower and upper crustal rocks and mantle-derived magmas is generally low, but contamination by highly radiogenic, in situ, upper-crustal rocks appears to be sporadic in time and space. The radiogenic crustal component is shown to be mainly a component recycled by subduction. We assume that it corresponds to fluids derived from the subducting slab and associated subducted sediments. This crustal component appears to have changed with time. The variations of Pb- and Sr-isotopic compositions are consistent with a two-stage model:

(1) During the early stages of Coastal batholith emplacement (100 to 90 Ma), the crustal component was mainly derived from tectonic erosion of the Lower Cretaceous accretionary prism. The sediments in the accretionary prism were derived from the Brazilian Shield and had highly radiogenic Pb- and Sr-isotopic compositions similar to modern sediments of the Barbados ridge.

(2) After 84 Ma the crustal component was Pacific oceanic sediments (and a slab component) with Pb- and Sr-isotopic compositions like those of modern Pacific sediments.

These results suggest that participation of recycled oceanic sediments in Andean calc-alkaline magma genesis is the rule, although in many cases the evidence is obscured by interaction of mantle-derived magmas with continental crust.

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REFERENCES CITED

Aguirre, L., and Offler, R., 1985, Burial metamorphism in the Western Peruvian trough: Its relation to Andean magmatism and tectonics, *in* Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R. D., eds., Magmatism at a plate edge; The Peruvian batholith: Glasgow, Blackie, p. 59–71.

Arculus, R. J., and Powell, R., 1986, Source component mixing in the regions of arc magma generation: Journal of Geophysical Research, v. 91, p. 5913–5926.

Atherton, M. P., and Sanderson, L. M., 1985, The chemical variation and evolution of the super-units of the segmented Coastal batholith, *in* Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R. D., eds., Magmatism at a plate edge: The Peruvian batholith: Glasgow, Blackie, p. 208–227.

Atherton, M. P., Pitcher, W. S., and Warden, V., 1983, The Mesozoic marginal basin of central Peru: London, Nature, v. 305, p. 303–306.

Atherton, M. P., Warden, V., and Sanderson, L. M., 1985, The Mesozoic marginal basin of central Peru; A geochemical study of within-plate-edge volcanism, *in* Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R. D., eds., Magmatism at a plate edge: The Peruvian batholith: Glasgow, Blackie, p. 47–58.

Barreiro, B., 1983, Lead isotope composition of South Sandwich Island volcanic rocks and their bearing on magmagenesis in intra-oceanic island arcs: Geochimica et Cosmochimica Acta, v. 47, p. 817–822.

——, 1984, Lead isotopes and Andean magmatogenesis, *in* Harmon, R. S., and Barreiro, B., eds., Andean magmatism; Chemical and isotope constraints: Nantwich, Shiva Publishing Limited, p. 21–30.

Beckinsale, R. D., Sanchez F., A. W., Brook, M., Cobbing, E. J., Taylor, W. P., and Moore, N. D., 1985, Rb-Sr whole-rock isochron and K-Ar age determinations for the Coastal batholith of Peru, *in* Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R. D., eds., Magmatism at a plate edge; The Peruvian batholith: Glasgow, Blackie, p. 177–202.

Briqueu, L., and Lancelot, J. R., 1979, Rb-Sr systematics and crustal contamination models for calc-alkaline igneous rocks: Earth and Planetary Science Letters, v. 43, p. 385–396.

Burke, W. H., Denison, R. E., Hetherington, E. A., Koepnick, R. B., Nelson, H. F., and Otto, J. B., 1982, Variation of seawater $^{87}Sr/^{86}Sr$ throughout Phanerozoic time: Geology, v. 10, p. 516–519.

Chow, T. J., and Patterson, C. C., 1962, The occurrence and significance of lead isotopes in pelagic sediments: Geochimica et Cosmochimica Acta, v. 26, p. 263–272.

Church, S. E., 1973, Limits of sediment involvement in the genesis of orogenic volcanic rocks: Contributions to Mineralogy and Petrology, v. 39, p. 17–32.

——, 1976, The Cascade Mountains revisited: A re-evaluation in light of new lead isotopic data: Earth and Planetary Science Letters, v. 29, p. 175–188.

Church, S. E., and Tatsumoto, M., 1975, Lead isotope relations in ocean ridge basalts from the Juan de Fuca–Gorda ridge area: Contributions to Mineralogy and Petrology, v. 53, p. 253–279.

Cobbing, E. J., Pitcher, W. S., Wilson, J. J., Baldock, J., Taylor, W. P., McCourt, W. J., and Snelling, N. J., 1981, The geology of the western Cordillera of northern Peru: London, Overseas Memoir 5, 143 p.

Cohen, R. S., and O'Nions, R. K., 1982, The lead, neodynium, and strontium isotopic structure of ocean ridge basalts: Journal of Petrology, v. 23, p. 299–324.

Couch, R., Whitsett, R., Huehn, B., and Briceño-Guarupe, L., 1981, Structures of the continental margin of Peru and Chile, *in* Kulm, L. D., Dymond, J., Dasch, E., and Hussong, D. M., eds., Nazca plate; Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 703–726.

Cumming, G. L., and Richards, J. R., 1975, Ore lead isotope ratios in a continuously changing earth: Earth and Planetary Science Letters, v. 28, p. 155–171.

Dasch, E. J., 1969, Strontium isotopes in weathering profiles, deep-sea sediments, and sedimentary rocks: Geochimica et Cosmochimica Acta, v. 33, p. 1521–1552.

——, 1981, Lead isotopic composition of metalliferous sediments from the Nazca plate, *in* Kulm, L. D., Dymond, J., Dasch, E., and Hussong, D. M., eds., Nazca plate; Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 199–209.

De Paolo, D. J., 1981, Trace element and isotopic effects of combined wall rock assimilation and fractional crystallization: Earth and Planetary Science Letters, v. 53, p. 189–202.

De Paolo, D. J., and Wasserburg, G. J., 1979, Petrogenetic mixing models and Nd-Sr isotopic patterns: Geochimica et Cosmochimica Acta, v. 43, p. 615–627.

Dupré, B., Lambret, B., Rousseau, D., and Allègre, C. J., 1981, Limitations on the scale of mantle heterogeneity under oceanic ridges: London, Nature, v. 294, p. 552–554.

Dymond, J. R., 1981, Geochemistry of Nazca plate surface sediments; An evaluation of hydrothermal, biogenic, detrital, and hydrogenous sources, *in* Kulm, L. D., Dymond, J., Dasch, E., and Hussong, D. M., eds., Nazca plate; Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 133–173.

Francis, P. W., Moorbath, S., and Thorpe, R. S., 1977, Strontium isotope data for recent andesites in Ecuador and North Chile: Earth and Planetary Science Letters, v. 37, p. 197–202.

Francis, P. W., Thorpe, R. S., Moorbath, S., Krezschmar, G. A., and Hammil, M., 1980, Strontium isotope evidence for crustal contamination of calc-alkaline volcanic rocks from Cerro Galan, northwest Argentina: Earth and Planetary Science Letters, v. 48, p. 257–267.

Gill, J. B., 1981, Orogenic andesites and plate tectonics: New York, Springer-Verlag, 385 p.

Goldstein, S. L., and O'Nions, R. K., 1981, Nd and Sr isotopic relationships in pelagic clays and ferromanganese deposits: London, Nature, v. 292, p. 324–327.

Guevara, C., 1980, El grupo Casma del Peru central entre Trujillo y Mala: Boletin de la Sociedad Geológica del Perú, v. 67, p. 73–83.

Hamelin, B., Dupré, B., and Allègre, C. J., 1984, Lead-strontium isotopic variations along the East Pacific Rise and the Mid-Atlantic Ridge; A comparative study: Earth and Planetary Science Letters, v. 67, p. 340–350.

Harmon, R. S., Barreiro, B., Moorbath, S., Hoefs, J., Francis, P. W., Thorpe, R. S., Déruelle, B., McHugh, J., and Viglino, J. A., 1984, Regional O-, Sr-, and Pb-isotope relationship in late Cenozoic calc-alkaline lavas from the Andean Cordillera: Journal of the Geological Society of London, v. 141, p. 803–822.

Hawkesworth, C. J., Norry, M. J., Roddick, J. C., Baker, P. E., Francis, P. W., and Thorpe, R. S., 1979, $^{143}Nd/^{144}Nd$, $^{87}Sr/^{86}Sr$, and incompatible element variations in calc-alkaline andesites and plateau lavas from South America: Earth and Planetary Science Letters, v. 42, p. 45–57.

Hawkesworth, C. J., Hammill, M., Gledhill, A. R., Van Calsteren, P., and Rogers, G., 1982, Isotope and trace element evidence for late-stage intra-crustal melting in the High Andes: Earth and Planetary Science Letters, v. 58, p. 240–254.

Hess, J., Bender, M. L., and Schilling, J.-G., 1986, Evolution of the ratio of strontium-87 to strontium-86 in seawater from Cretaceous to Present: Science, v. 231, p. 979–984.

Hickey, R. L., Frey, F. A., Gerlach, D. C., and Lopez-Escobar, L., 1986, Multiple sources for basaltic arc rocks from the Southern Volcanic Zone of the Andes (34°–41°S); Trace element and isotopic evidence for contributions from subducted oceanic crust, mantle, and continental crust: Journal of Geophysical Research, v. 91, p. 5963–5983.

Hilde, T.W.C., 1983, Sediment subduction versus accretion around the Pacific: Tectonophysics, v. 99, p. 381–397.

Hildreth, W., and Moorbath, S., 1988, Crustal contributions to arc magmatism in the Andes of central Chile: Contributions to Mineralogy and Petrology, v. 98, p. 455–489.

Hsui, A. T., and Töksöz, M. N., 1979, The evolution of the thermal structure beneath a subduction zone: Tectonophysics, v. 60, p. 43–60.

Jahn, B.-M., Bernard-Griffiths, J., Charlot, R., Cornichet, J., and Vidal, P., 1980, Nd and Sr isotopic compositions and REE abundances of Cretaceous MORB (Holes 417D and 418A, Legs 51, 52, and 53): Earth and Planetary Science Letters, v. 48, p. 171–184.

James, D. E., 1976, Andean Cenozoic volcanism; Magma genesis in the light of strontium isotopic composition and trace element geochemistry: Geological Society of America Bulletin, v. 87, p. 592–600.

——, 1982, A combined O, Sr, Nd, and Pb isotopic and trace element study of crustal contamination in central Andean lavas; 1, Local geochemical variations: Earth and Planetary Science Letters, v. 57, p. 47–62.

James, D.E., Brooks, C., and Cuyubamba, A., 1974, Strontium isotopic composition and K, Rb, Sr geochemistry of Mesozoic volcanic rocks of the central Andes: Carnegie Institution Washington Yearbook 73, p. 970–983.

Jones, P. R., 1981, Crustal structures of the Peru continental margin and adjacent Nazca plate, 9°S latitude, *in* Kulm, L. D., Dymond, J., Dasch, E., and Hussong, D. M., eds., Nazca plate; Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 423–443.

Kay Mahlburg, S., Maksaev, V., Moscoso, R., Mpodozis, C., and Nasi, C., 1987, Probing the evolving Andean lithosphere; Mid-late Tertiary magmatism in Chile (29–30°30′S) over the modern zone of subhorizontal subduction: Journal of Geophysical Research, v. 92, p. 6173–6189.

Kulm, L. D., Prince, R. A., French, W., Johnson, S., and Masias, A., 1981, Crustal structure and tectonics of the central Peru continental margin and trench *in* Kulm, L. D., Dymond, J., Dasch, E., and Hussong, D. M., eds., Nazca plate; Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 445–468.

Mégard, F., 1978, Etude géologique des Andes du Pérou Central: Paris, Mémoire ORSTOM, 310 p.

——, 1984, The Andean orogenic period and its major structures in central and northern Peru: Journal of the Geological Society of London, v. 141, p. 893–900.

Meijer, A., 1976, Pb and Sr isotopic data bearing on the origin of volcanic rocks from the Mariana island-arc system: Geological Society of America Bulletin, v. 87, p. 1358–1369.

Moore, N. D., 1984, Potassium-argon ages from the Arequipa segment of the coastal batholith of Peru and their correlation with regional tectonic events: Journal of the Geological Society of London, v. 141, p. 511–519.

Morris, J., Tera, F., Sacks, I. S., Brown, L., Klein, J., and Middleton, R., 1987, Sediment recycling at convergent margins; Constraints from the cosmogenic isotope ^{10}Be: NATO Advanced Research Workshop, Crust-mantle recycling at convergence zone, Antalya, Turkey, p. 63–71.

Mukasa, S. B., 1984, Comparative Pb isotope systematics and zircon U-Pb geochronology for the Coastal, San Nicolas, and Cordillera Blanca batholiths, Peru [Ph.D. thesis]: Santa Barbara, University of California, 362 p.

——, 1986a, Zircon U-Pb ages of super-units in the Coastal batholith, Peru; Implications for magmatic and tectonic processes: Geological Society of America Bulletin, v. 97, p. 241–254.

——, 1986b, Common Pb isotopic compositions of the Lima, Arequipa, and Toquepala segments in the Coastal batholith, Peru; Implications for magmagenesis: Geochimica et Cosmochimica Acta, v. 50, p. 771–782.

Myers, J. S., 1974, Cretaceous stratigraphy and structure, western Andes of Peru between latitudes 10°–10°30′S: American Association of Petroleum Geologists Bulletin, v. 58, p. 474–487.

——, 1980, Geología de los cuadrángulos de Huarmey y Huayllapampa: Instituto Geológico Minero y Metalúrgico, Lima, Boletin 33, 153 p. + 2 maps.

Norman, D. I., and Landis, G. P., 1983, Source of mineralizing components in hydrothermal ore fluids as evidenced by $^{87}Sr/^{86}Sr$ stable isotope data from the Pasto Bueno deposit, Peru: Economic Geology, v. 78, p. 451–465.

O'Nions, R. K., Hamilton, P. K., and Evensen, N. M., 1977, Variations in $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios in oceanic basalts: Earth and Planetary Science Letters, v. 34, p. 13–22.

O'Nions, R. K., Carter, S. R., Cohen, R. S., Evensen, N. M., and Hamilton, P. J., 1978, Pb, Nd, and Sr isotopes in oceanic ferromanganese deposits and ocean floor basalts: Nature, v. 273, p. 435–438.

Palmer, M. R., and Elderfield, H., 1985, Sr isotope composition of sea water over the past 75 Myr: London, Nature, v. 314, p. 526–528.

Peterman, Z. E., Hedge, C. E., and Tourtelot, H. A., 1970, Isotopic composition of strontium in sea water throughout Phanerozoic time: Geochimica et Cosmochimica Acta, v. 34, p. 105–120.

Pitcher, W. S., 1978, The anatomy of a batholith: President's anniversary address 1977: Journal of the Geological Society of London, v. 135, p. 157–182.

——, 1985, A multiple and composite batholith, *in* Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R. D., eds., Magmatism at a plate edge; The Peruvian batholith: Glasgow, Blackie, p. 93–101.

Pitcher, W. S., Atherton, M. P., Cobbing, E. J., and Beckinsale, R. D., eds., 1985, Magmatism at a plate edge; The Peruvian Andes: Glasgow, Blackie, 328 p.

Reynolds, P. H., and Dasch, E. J., 1971, Lead isotopes in marine manganese nodules and ore-lead growth curve: Journal of Geophysical Research, v. 76, p. 5124–5136.

Scholl, D. W., Marlow, M. S., and Cooper, A. K., 1977, Sediment subduction and offscraping at Pacific margins, *in* Talwani, M., and Pitman, W. C., eds., Island arcs, deep sea trenches, and back-arc basins: American Geophysical Union, p. 199–210.

Sinha, A. K., and Hart, S. R., 1971, A geochemical test of the subduction hypothesis for the generation of island arc magmas: Carnegie Institution of Washington Yearbook 71, p. 309–312.

Soler, P., 1987, Sur l'existence d'un épisode de métamorphisme régional d'âge Miocène inférieur dans la Cordillère Occidentale des Andes du Pérou central: Comptes Rendus de l'Académie des Sciences, Paris, v. 304, série II, p. 911–916.

Soler, P., and Bonhomme, M. G., 1988, New K-Ar ages determinations of intrusive rocks from Western Cordillera and High Plateaus of central Peru; The identification of magmatic pulses and episodes of mineralization: Journal of South American Earth Sciences, v. 1, p. 169–177.

Soler, P., 1989, Contribution à l'étude du magmatisme associé aux zones de subduction: Pétrographie, géochimie et géochimie isotopique des roches intrusives sur un transect des Andes du Pérou central; implications géodynamiques et métallogéniques [Dr. thesis]: Paris, Université Pierre et Marie Curie, (in preparation).

Spooner, E.T.C., 1976, The strontium isotopic composition of seawater and seawater-oceanic crust interaction: Earth and Planetary Science Letters, v. 31, p. 167–174.

Stern, R. J., and Ito, E., 1983, Trace elements and isotopic constraints on the source of magmas in the active volcano and Mariana Island arcs, western Pacific: Journal of Volcanology and Geothermal Research, v. 18, p. 461–482.

Sun, S. S., 1980, Lead isotope study of young volcanic rocks from mid-ocean ridges, ocean islands, and island arcs: Philosophical Transactions of the Royal Society of London, v. 297, p. 409–445.

Tatsumi, Y., Sakuyama, M., Fukuyama, H., and Kushiro, I., 1983, Generation of arc basalt magmas and thermal structure of the mantle wedge in the subduction zones: Journal of Geophysical Research, v. 88, p. 5815–5825.

Tatsumoto, M., 1978, Isotopic composition of lead in oceanic basalt and its implication to mantle evolution: Earth and Planetary Science Letters, v. 38, p. 63–87.

Taylor, H. P., Jr., 1980, The effects of assimilation of country rocks by magmas on $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ systematics in igneous rocks: Earth and Planetary Science Letters, v. 47, p. 243–254.

Tera, F., Brown, L., Morris, J., Sacks, I. S., Klein, J., and Middleton, R., 1986, Sediment incorporation in island arc magmas; Inference from ^{10}Be: Geochimica et Cosmochimica Acta, v. 50, p. 535–550.

Thorpe, R. S., Francis, P. W., and Moorbath, S., 1979, Rare earth and strontium isotope evidence concerning the petrogenesis of north Chilean ignimbrites: Earth and Planetary Science Letters, v. 42, p. 359–367.

Tilton, G. R., and Barreiro, B., 1980, Origin of lead in Andean calcalkaline lavas, southern Peru: Science, v. 210, p. 1245–1247.

Turpin, L., Velde D., and Pinte, G., 1988, Geochemical comparisons between minettes and kersantites from western European Hercynian orogen; Trace element and Pb-Sr-Nd isotope constraints on their origin: Earth and Planetary Science Letters, v. 87, p. 73–86.

Unruh D. M., and Tatsumoto, M., 1976, Lead isotope compositions and uranium, thorium, and lead concentrations in sediments and basalts from the Nazca plate, *in* Initial reports of the Deep Sea Drilling Project: Washington, D.C., U.S. Government Printing Office, v. 43, p. 431–442.

Webb, S., 1976, The volcanic envelope of the Coastal batholith in Lima and Ancash, Peru [Ph.D. thesis]: Liverpool, University of Liverpool, 176 p.

White, W. M., and Dupré, B., 1986, Sediment subduction and magma genesis in the Lesser Antilles; Isotopic and trace element constraints: Journal of Geophysical Research, v. 91, no. B6, p. 5927–5941.

White, W. M., Dupré, B., and Vidal, P., 1985, Isotope and trace element geochemistry of sediments from the Barbaros Ridge-Demerara Plain region, Atlantic Ocean: Geochimica et Cosmochimica Acta, v. 49, p. 1875–1886.

White, W. M., Hoffmann, A. W., and Puchelt, H., 1987, Isotope geochemistry of Pacific Mid-Ocean Ridge Basalt: Journal of Geophysical Research, v. 92, p. 4881–4893.

Zartman, R. E., and Doe, B. R., 1981, Plumbotectonics; The model: Tectonophysics, v. 75, p. 135–162.

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