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Relation of magmatic activity to plate dynamics in central Peru from Late Cretaceous to present

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ABSTRACT

A detailed synthesis of the chronology and spatial distribution of magmatic activity along a transect of the Andes of central Peru (around 11°S latitude) and some new K-Ar radiochronological data are presented. This huge data set is compared with independent geophysical data and reconstructions dealing with the interaction dynamics between the oceanic Nazca plate (previously Farallon) and the South American continent.

The data strongly suggest that magmatic activity has been discontinuous. All periods of high convergence rate (>10 cm/yr) between Nazca (Farallon) and South American plates are characterized by important magmatic activity. In contrast, the intervals of magmatic quiescence or low magmatic activity are systematically associated with low convergence rate. Two main exceptions to these rules are: (1) The last period of Coastal Batholith emplacement, between 75 and 59 Ma, seems to be associated with a lower convergence rate (5 to 7 cm/yr) and a very weak compressive deformation. (2) Magmatic activity is absent in central Peru during the last 3 m.y. in a context of high convergence rate. This has been interpreted as a consequence of the lack of an asthenospheric wedge above an abnormally flat slab. The change from a "normal" slab dip (≈30°) to the "flat" slab is associated with the subduction of the Nazca ridge and not with a rejuvenation of the slab.

The formation of the Copara-Casma (Aptian-Albian) aborted marginal volcanic basin appears to be contemporaneous with the rifting of the South Atlantic Ocean, an extensional tectonic regime and a steeply dipping slab. The beginning of emplacement of the Coastal Batholith (Albian to Paleocene) is synchronous with the onset of active spreading in the Atlantic Ocean, the change to a compressive regime along the Andean margin, and a decrease of slab dip. Channeling of magmas through deep-seated lithospheric structures along the axis of the Casma basin may have played a role during the emplacement of the Coastal Batholith. From Albian to Mio-Pliocene times, the eastward migration of the trenchward magmatic front did not exceed 50 km. The main change in the geometry of the magmatic belt is its rapid broadening, from a narrow (≈40 km) to a wide (>150 km) belt in the early and mid-Eocene. This change is contemporaneous with the main period of compressive deformation and corresponds to a decrease in the dip of the slab. It is not associated with a rejuvenation of the slab nor with a higher trenchward motion of the overriding plate. Rather, it appears to be related to an increase in the rate

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of convergence and to a change from a very oblique to a nearly normal convergence with respect to the continental margin.

Tectonic erosion at the trench cannot be invoked at least for the last 40 m.y. but probably occurred during the first episodes of emplacement of the Coastal Batholith. No conclusion may be drawn for the period between ca. 75 to ca. 45 Ma.

INTRODUCTION

The central Andes of Peru and Chile are commonly regarded as the archetype of an ensialic orogenic belt associated with the subduction of an oceanic plate beneath a continental margin. Magmatic activity, mainly of calc-alkaline affinity, has long been recognized as one of the most characteristic features of this belt. This chapter is concerned with the chronology and spatial distribution of magmatic activity during Andean orogenesis in central Peru. Our synthesis is centered on a W-E transect near 11°S (Huacho-Oxapampa transect), but most of the published dates between Chimbote (≈9°S) and Ica (≈14°S) (Fig. 1) have been taken into account. Beyond this descriptive aspect, based on the data from the literature and some new field and radiochronological data, our purpose is to attempt a global interpretation of the space and time distributions of magmatic activity in relation to the interaction patterns between the Nazca (Farallon) oceanic plate and South America, and with tectonics.

Numerous radiochronological data from the orogenic volcanic and plutonic rocks of the Andes of central Peru are available. Since sampling is discrete and non-uniform in space, there may be some statistical bias in the evaluation of the time and space distribution of magmatic activity. For the Late Cretaceous to Paleocene granitoids of the coastal region (Coastal Batholith), the number of age determinations (about 150) seems somewhat low in comparison with the number of individual plutons (about 1,500) constituting the batholith. However, nearly half of the Coastal Batholith dates are from the transect studied here (valleys of the Rio Seco and the Rio Huaura). Our recent sampling for K-Ar dating (Soler and Bonhomme, 1987, 1988a, b, and this work) has been designed to complement the numerous existing data for the Western Cordillera and the High Plateaus, but represents only a reconnaissance survey for the Eastern Cordillera. In the Western Cordillera and the High Plateaus a great number of stocks have been dated along the studied transect. Moreover, in many cases, geochemical and field similarities with dated stocks allow age assignments for undated stocks (Soler, in preparation). Obviously, some dates need to be more precise and new dates are necessary, particularly in the Eastern Cordillera. These limitations, notwithstanding the number and spatial distributions of dated samples on a regional scale permits a descriptive synthesis of the evolution of high-level magmatism in this area. Future age determinations will probably alter the present synthesis, but these alterations should be minor.

Important advances have also been made in recent years in plate dynamics reconstructions, particularly for the Cenozoic. A comparison of these two completely independent data sets is necessary.

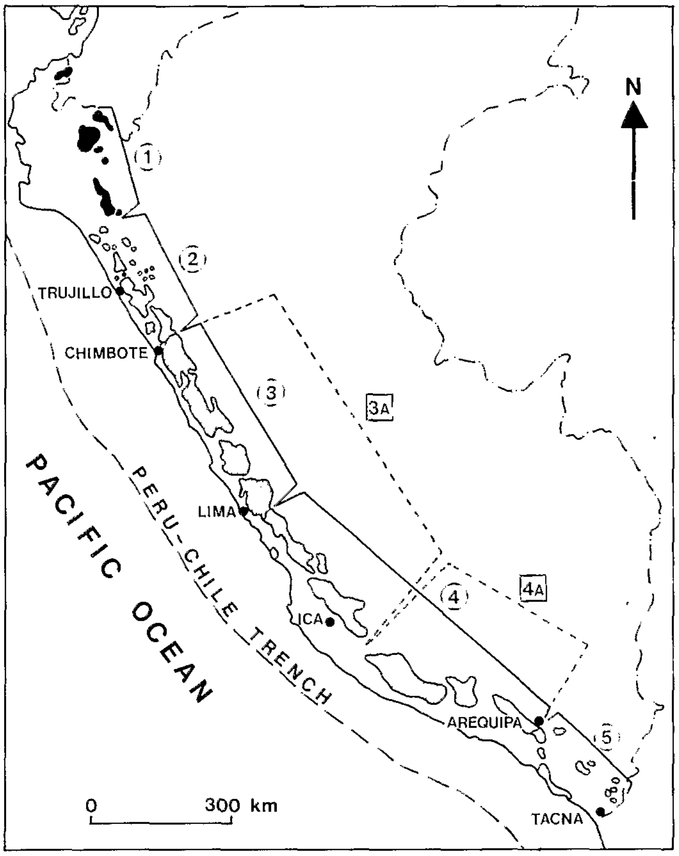

Figure 1. The segmented Coastal Batholith of Peru. 1 = Piura segment; 2 = Trujillo segment; 3 = Lima segment; 4 = Arequipa segment; 5 = Toquepala segment (from Pitcher and others, 1985). Alternative segmentation from Soler (in preparation): 3A = Lima segment (s.l.); 4A = Arequipa segment (s.s.).

CHRONOLOGY AND SPATIAL DISTRIBUTION OF MAGMATISM

During the last 110 m.y., three main periods of magmatic activity can be recognized in the central Peruvian Andes. The first period is pre-orogenic and comprises the Aptian to Albian Copara-Casma volcanism of the coastal area and minor volcanism at the eastern edge of the High Plateaus. The second period is the late Albian to late Paleocene emplacement of the Coastal Batholith. The third is the early Eocene to Pliocene emplacement of a thick volcanic series east of the Coastal Batholith and the numerous, often subvolcanic stocks, which partly intrude but mainly occur in a wide area east of the Coastal Batholith. These three main periods will be considered in relation to tectonic events that have been described and dated in the Andes of central Peru since the pioneering work of Steinman (1929).

The Copara-Casma volcanism

After a period of magmatic quiescence during most of the Neocomian (Osterman and others,1983; Soler, in preparation), volcanic activity resumed in central Peru during the late Aptian or the early Albian with the Copara Formation (Osterman and others, 1983; Cardozo, 1983; Wauschkuhn and Ohnsmann, 1984; Injoque, 1985), which is known only in a restricted area of the coastal region south of Lima. This formation consists of basalts and basaltic andesites of calc-alkaline affinity (Wauschkuhn and Ohnsmann, 1984; Injoque, 1985), related to caldera-type volcanic centers (Cardozo, 1983) and associated volcaniclastic and sedimentary rocks.

The Copara Formation is a precursor of the Albian Casma Group. The Casma Group, which is known all along the central Peruvian coastal region (Myers, 1974, 1980; Webb, 1976; Guevara, 1980; Atherton and others, 1983, 1985a), is locally in excess of 8,000 m thick and is mainly composed of basalt flows (often in pillow lavas) and associated volcaniclastic rocks and subordinated sedimentary rocks, which are often cut by basaltic dikes and sills. This volcanic suite displays tholeiitic and calc-alkaline arc and back-arc characteristics (Atherton and others, 1985a). On the basis of previous geophysical (Jones, 1981; Couch and others, 1981) and petrographic data (Aguirre and others, 1978), Aguirre and Offler (1985) consider the Casma basin as an ensialic marginal basin of aborted type, associated with important crustal thinning and a very high geothermal gradient.

Most of the Casma volcanism is marine and pre-dates the Mochica episode of compressive deformation ($\pm$105 m.y.), the first orogenic event in central Peru (Mégard, 1984; Pitcher and others, 1985). Minor terrestrial Casma volcanism postdates this tectonic event and occurs as late as Cenomanian or Campanian time (Webb, 1976; Offler and others, 1980). This terrestrial volcanism is contemporaneous with the first three periods of the Coastal Batholith (see below). The gabbros and meladiorites of the Patap superunit appear genetically linked with the Casma volcanism (Regan, 1985; Soler, in preparation) and are mainly pre- and syntectonic.

In the Cordillera, a few occurrences of basalts contemporaneous with the Copara and Casma volcanics are known along the limit between the High Plateaus and the Eastern Cordillera (Mégard, 1978; Soler, in preparation). These are typical intracontinental, rift-associated alkali basalts and do not show any chemical influence of the subduction process (Soler, in preparation).

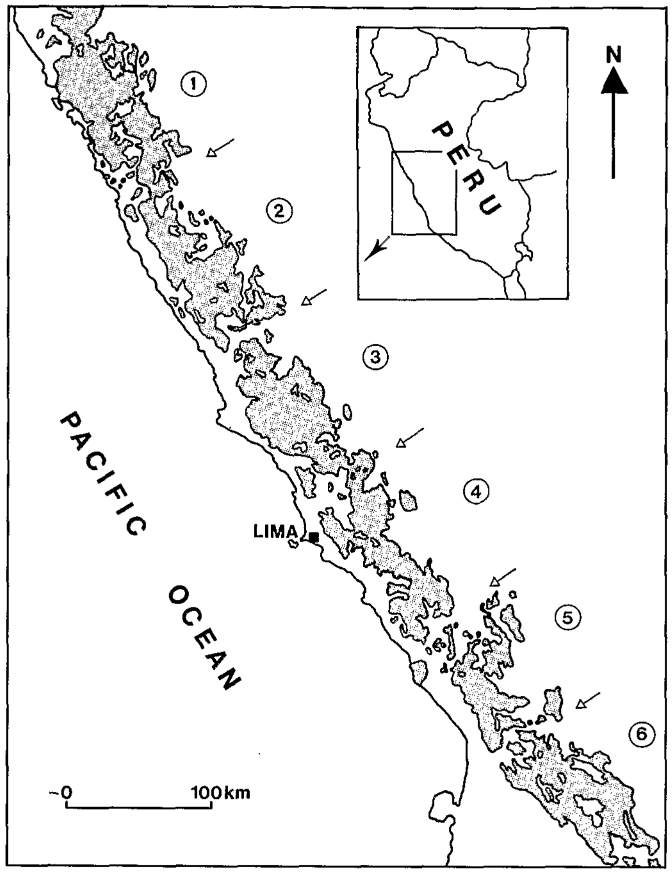

Figure 2. Main plutonic complexes in the Lima segment s.l. of the Coastal Batholith (from Bussell and Pitcher, 1985): 1 = Casma; 2 = Fortaleza; 3 = Huaura; 4 = Chosica; 5 = Cañete; 6 = Ica.

The Coastal Batholith

The Coastal Batholith, which constitutes the most intensively outcropping plutonic suite in Peru (Figs. 1 and 2), is a complex set of I-type, medium- to high-K granitoids that have been described in great detail by W. S. Pitcher, C. J. Cobbing, and co-workers (see Cobbing and others, 1981, and Pitcher and others, 1985, and references therein). In central Peru the Coastal Batholith mostly intrudes rocks of the Casma Group.

The onset of the emplacement of the Coastal Batholith postdates the Mochica phase of compressive tectonics and the associated syntectonic Patap gabbros.

Numerous age determinations are available for the Coastal Batholith. They have been obtained through K-Ar (Stewart and others, 1974; Wilson, 1975; Cobbing and others, 1981; Moore, 1984), whole-rock Rb-Sr (Stewart and others, 1974; Beckinsale and others, 1985) and zircon U-Pb (Mukasa, 1984, 1986) methods. U-Pb and K-Ar ages are generally in very good agreement, except in the easternmost part of the Coastal Batholith where K-Ar ages appear to have been reset by Oligo-Miocene tectonothermal effects (Mukasa, 1986; Soler, 1987; see below). Uncertainties in

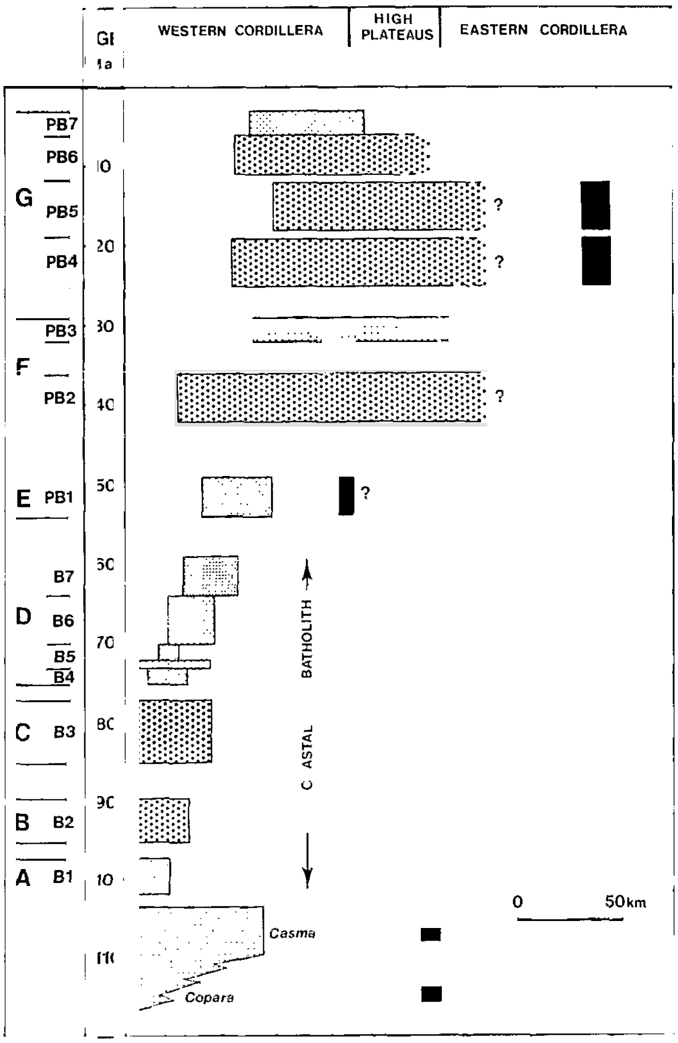

Figure 3. Chronology and spatial distribution of magmatic rocks in the central Peruvian Andes (see localities in Fig. 4): Dots = calc-alkaline orogenic plutonics and volcanics (density of points is nearly proportional to volumetric importance); black = alkali rocks.

Rb-Sr ages are generally high, probably due to Sr-isotopic heterogeneity of the magmas (Soler and Rotach-Toulhoat, this volume).

The units and superunits in the Coastal Batholith are defined from field observations and petrography (Pitcher, 1978, 1985; Cobbing and others, 1977, 1981). Radiochronological data suggest that the batholith was emplaced in a series of magmatic episodes between the late Albian and late Paleocene. In the Lima segment (s.l., Fig. 2), seven episodes of emplacement (B1 to B7 in Fig. 3 and Table 1) can be distinguished. These episodes can be grouped into four periods (A through D, Table 1) of more or less continuous magmatic activity, separated by intervals of apparent magmatic quiescence. However, the number of age determinations is small in comparison with the number of individual plutons, and future age determinations may alter the present synthesis as the works of Wilson (1975), Mukasa (1984), Moore (1984), and Beckinsale and others (1985) altered the models of Pitcher (1978) and Cobbing and others (1977).

One remarkable feature of the Coastal Batholith is the stability of the position of the plutonic belt for more than 40 m.y. (102 to 59 Ma) (see Pitcher and others, 1985), resulting in the whole batholith being less than 60 km in width (average is about 45 km). Nevertheless, in detail, the distribution of the successive superunits or units, at least in the Lima region (where field and radiochronological data are comparatively complete), suggests that the plutonic belt migrated eastward with time, as noted by Mukasa (1984, 1986). Actually, two periods can be distinguished (Fig. 3):

(1) From 102 to 78 Ma (periods A through C in Table 1), the belt broadened from about 15 to 35 km. During this time, the inner magmatic front (IMF; plutons nearest the Peru-Chile trench) was almost stable or very slowly migrated eastward (<0.2 km/m.y.) while the outer magmatic front (OMF; plutons nearest the Brazilian shield) did migrate eastward more rapidly (about 0.8 km/m.y.).

(2) From 75 to 59 Ma (period D of Table 1), after a westward jump of both the IMF and OMF, the magmatic belt broadened less than during the first period. The velocities of eastward migration of IMF and OMF are estimated at about 0.8 and 1 km/m.y., respectively.

Most of the Coastal Batholith emplacement took place during a period of weak compressive tectonic activity, mainly characterized by dextral wrench faults and planar deformation of the plutons mostly in the first period of emplacement (Bussell, 1983; Bussell and Pitcher, 1985). No thrust faults like those described by Vicente and others (1979) in the Arequipa region of southern Peru are known in the coastal region of central Peru.

Post-batholith plutonism and volcanism

Late Cretaceous and Paleocene magmatic activity was restricted to the coastal region and to the lower Pacific slope of the Western Cordillera, while Eocene and post-Eocene times are characterized by a wide magmatic belt.

In central Peru, intrusive stocks of these ages are known all across the Andes, from the lower Pacific slope of the Western Cordillera, where they intrude the Coastal Batholith or its Casma host rock, to the Amazonian slope of the Eastern Cordillera (Fig. 4). The petrology and geochemistry of these stocks will be discussed elsewhere (Soler, in preparation). Most of these intrusive rocks are of middle- to high-K calc-alkaline affinity, except for a few alkaline stocks and dikes in the upper part of the Western Cordillera, near Oyon (Romani, 1982) and in Raura (Fig. 4; Table 3), and various stocks of syenite and nephelinic syenite, identified in the Oxapampa area of the Amazonian slope of the Eastern Cordillera (Fig. 4; Table 3).

Contemporaneous volcanic series have been mapped in the upper part and the intermediate Pacific slope of the Western Cordillera, and in the High Plateaus (references in Table 2; see

TABLE 1. INDIVIDUAL EPISODES AND MAIN PERIODS OF EMPLACEMENT OF THE COASTAL BATHOLITH IN CENTRAL PERU

Main Periods	Episodes	Unit or Superunit (N to S for each episode)	Rock Type†	Preferred Age (Ma)	References*
A	B1	Purmacana u.	To.	100	2
		Atocongo u.	Gr.	101	1, 3
		Linga–Pisco s.u.	Tn. Gd.	101	3
		(+Quilmana u.)	Gr.		
		Linga–Ica s.u.	Tn. Gd.	97	4
B	B2	Purmacana u. (Supe)	Tn.	91	3
		Santa Rosa Huaricanga s.u.	Di. Gd.	94-90	2
		Lachay u.	Di.	90	3
		Chincha u.	Gd. Mzgr.	94	1
		Pampahuasi I s.u.	Tn. Gd.	94	3, 4, 6
C	B3	Santa Rosa Coralillo s.u.	Di. Gd.	82	2, 3
		Tiabaya s.u.	Tn. Gd.	80.5	3, 4
		Pampahuasi II s.u.	Di. Gd.	84	4, 6
		Incahuasi s.u.	Tn. Gd.	82	4, 5
D	B4	Humaya u.	Gd. Gr.	73	2, 3
	B5	Santa Rosa Nepeña s.u.	Tn. Gd.	71	3
		La Mina s.u.	Gd	71	2, 3
		Main Dyke swarm	And.	73-71	3
	B6	*Rio Huaura ring complex*			
		San Jeronimo s.u.	Gd.-Gr.	69-67	3
		Puscao s.u.	Gd.-Gr.	66	3
		Sayan u.	Mzgr.	63	2
		Cañas u.	Mzgr.	63	2
		Rio Chancay ring complex			
		Lumbre u.	Mzgr.	66	2, 3
		Tiabaya–Mala s.u. (partly)	Tn. Gd.	66	5
		Huaytara u.	Gd.	67	1
	B7	Paccho s.u.	Di. Tn.	64-59	3

*1 = Stewart and others, 1974; 2 = Cobbing and others, 1981; 3 = Mukasa, 1984, 1986; 4 = Moore, 1984; 5 = Beckinsale and others, 1985; 6 = Soler, in preparation.

†Abbreviations: Gb. = gabbro; Di. = diorite; Tn. = tonalite; Gd. = granodiorite; Qmz. = quartz-monzonite; Gr = granite; Mzgr. = monzogranite; Bst. = basalt; And = andesite; Da. = dacite; Rh. = rhyolite.

Atherton and others, 1985b, for a discussion of the petrogenesis of these volcanics).

With the exception of a few zircon U-Pb and Rb-Sr dates (quoted in Table 2), the ages of the volcanic and plutonic rocks of this third period have been obtained through K-Ar dating. Some caution is necessary in using these data, since tectonothermal events and/or hydrothermal alterations may have affected the K-Ar systems. Soler (1987) demonstrated the existence of a regional metamorphic event of early Miocene age, which induced a more or less complete resetting of the K-Ar system of plagioclase and biotite in the intrusive stocks, from the easternmost part of the Coastal Batholith to the upper part of the Western Cordillera. In the more superficial volcanic series, such resetting is less likely to occur. However, partial resetting of K-Ar plagioclase ages has been noted in the volcanics of the Western Cordillera (Noble and others, 1979b; Soler and Bonhomme, unpublished data). Moreover, hydrothermal activity is common in the study area both in volcanic and plutonic rocks, particularly in association with base-metal occurrences and ore deposits. When there is no petrographic evidence of hydrothermal alteration, the K-Ar ages

TABLE 2. INDIVIDUAL EPISODES AND MAIN PERIODS OF EMPLACEMENT OF THE POST-BATHOLITH PLUTONIC AND VOLCANIC ROCKS

Main Periods	Episodes	Intrusion (W to E for each episode)	Rock Type†	Preferred Age (Ma)	References*
E	PB1	Pariacoto (Casma)	Gr.	49	5
		Cerro Aislado (Moro)	Tn.	50	3
		Huaytara (Pisco)	Gr.	54?	1
		Calipuy (Tapa¡cocha)	And.	54?	2
		Alkali rocks:			
		Uchucchacua banakite		?	12
		Raura syenite		50?	this study
F	PB2	San Pedro (Santa Eulalia)	Tn.	39	3
		Pativilca	Gr.	37	2, 3, 5
		Acos?	Gr	37?	2, 8
		Racco	Di.	>35	7
		Huangoc	Gd.	38.5	7
		Huancayan	Gd.	>33	2
		Volcanics	Bst. And. Da.	42-35	9, 10, 11
		Llaupi	Gr.	40	28
		Sacsacancha batholith	Gb. Tn.	37-34	this study
	PB3	Paccho Tingo	Tn. Gd.	31	2, 8
		Churin West	Tn.-Gd.	31	2
		Acos?	Gr.	31	6, 8
		Uchucchacua	Gd.	>25	12, 13
		Chungar dykes	And.	>25	13
		Calipuy volcanics	And. Da.	±30	9, 10, 11
		Milpo-Atacocha	Gd. Qmz.	31-30	7, 13
		Quinua-Mariac	Gd. Qmz.	31-30	2, 7, 13
G	PB4	Catahuasi	Tn. Gr.	24	5
		Surco	Di. Gd.	21	3
		Volcanics	And. Da.	25-20	9, 14–17
		Alkali rocks:			
		Oxapampa area syenites		21-19	this study
	PB5	Churin East	Gd.	14	1, 2
		Chungar	Gr.	13.5	7, 13
		Huaron	Qmz.	16-15	29
		Volcanics	Bst, And. Da.	18-14	2, 9, 14–16
		Cerro de Pasco	Qmz.	15-14	18
		Yanamate	Gd.	15	7, 13
		Alkali rocks:			
		Oxapampa area syenite	Sy.	14-13	this study
	PB6	Rapay	Gd. Gr.	7	7
		Cordillera Blanca	Gd. Gr.	12-9	1-3, 5, 19, 20
		Raura	Tn. Gd.	10-8	12
		Anamaray	Di.	9.5	12
		Chalhuacocha	Gd.	10	7, 13
		Morococha	Di. Qmz.	8	21
		Yauricocha	Tn. Qmz.	7	20
		Antamina	Gd.	10	22
		Colquijirca	Qmz.	12-10	23
		Volcanics	And. Da. Rh.	12-7	11, 12, 15, 24

TABLE 2. INDIVIDUAL EPISODES AND MAIN PERIODS OF EMPLACEMENT OF THE POST-BATHOLITH PLUTONIC AND VOLCANIC ROCKS (continued)

Main Periods	Episodes	Intrusion (W to E for each episode)	Rock Type†	Preferred Age (Ma)	References*
G (continued)	PB7	Rimac dykes	Rh.	6-5	25
		Rupay dyke	Rh.	3	7
		Domes and flows:			
		Huachocolpa	Da.	4.5-3	26
		Ayacucho	Da. Rh.	5-4	24
		Ignimbrites:			
		Huayllay	Rh.	6-5	1, 2, 14
		Fortaleza	Rh.	6-5	2, 14
		Yungay	Rh.	6-4.5	2, 14, 27

*1 to 6 (as in Table 1. The ages from Mukasa, 1984, 1986 (3) are zircon U-Pb ages); 7 = Soler and Bonhomme, 1988a; 8 = Soler, 1987; 9 = Noble and others, 1974; 10 = Noble and others, 1979b; 11 = McKee and Noble, 1982; 12 = Romani, 1982; 13 = Soler and Bonhomme, 1988b; 14 = Farrar and Noble, 1976; 15 = Bellon and Lefèvre, 1977; 16 = Lefèvre, 1979; 17 = Noble and others, 1979a; 18 = Silberman and Noble, 1977; 19 = Landis and Rye, 1974; 20 = Giletti and Day, 1968; 21 = Eyzaquirre and others, 1975; 22 = McKee and others, 1979; 23 = Vidal and others, 1984; 24 = Mégard and others, 1984; 25 = Mégard and others, 1985; 26 = McKee and others, 1975; 27 = Bonnot, 1984; 28 = Metal Mining Agency of Japan, 1976; 29 = Thouvenin, 1984.
†Abbreviations as in Table 1.

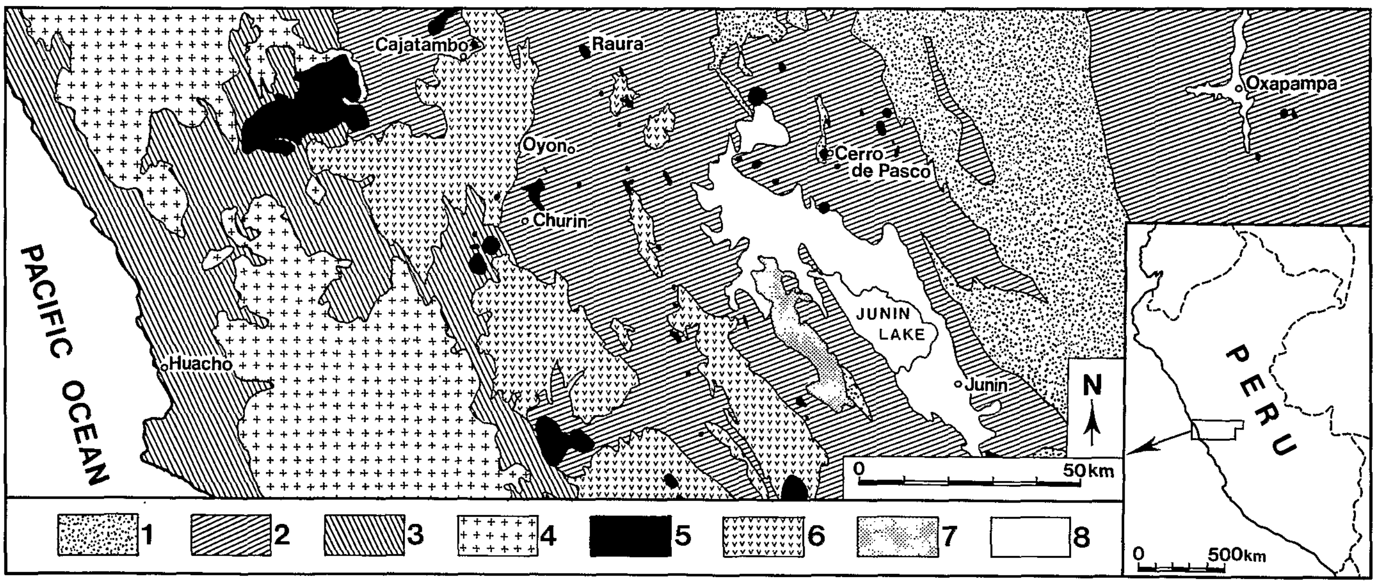

Figure 4. Geologic sketch of the Huacho–Oxapampa transect. 1 = Precambrian to late Paleozoic; 2 = Late Permian to Late Cretaceous sedimentary series; 3 = Casma volcanic group; 4 = Coastal Batholith; 5 = Eocene to Miocene eastern stocks; 6 = Calipuy volcanics; 7 = Pliocene ignimbrites (Bosque de Piedra); 8 = Quaternary deposits.

TABLE 3. NEW K-Ar AGE DETERMINATIONS OF INTRUSIVE ROCKS FROM THE WESTERN CORDILLERA AND THE EASTERN CORDILLERA OF CENTRAL PERU*

Sample Number and Location		Analyzed Fraction†	K_2O (%)	^{40}Ar Rad. / ^{40}Ar Total (%)	^{40}Ar Rad. (nl/g)	Age (Ma. ± 2σ)
Raura syenite						
RA37	76°44'30"W	FK	8.85	58.3	3.86	13.5 ± 0.8
	10°26'15"S	H	0.096	42.9	0.133	42.5 ± 16
Oxapampa area						
Quebrada Chacu western stock						
OXO4	75°18'57"W	WR	8.37	30.5	3.48	12.8 ± 0.6
	10°37'39"S					
Quebrada Chacu eastern stock						
OXO3	75°17'55"W	WR	3.25	17.1	1.72	19.1 ± 1.0
	10°37'28"S	Pl	2.78	39.9	1.558	17.4 ± 0.6
Tambo Maria stock						
OXO9	75°21'19"W	WR	6.02	70.7	4.10	21.0 ± 1.0
	10°42'37"S					
Sacsacancha batholith						
CO13	75°48'47"W	B	8.07	56.1	9.27	35.2 ± 1.6
	11°46'05"S	H	1.89	49.4	2.202	35.8 ± 3.0
		Pl	0.498	84.9	1.217	74.2 ± 4.6
CO11	75°13'53"W	Pl ± FK	2.34	87.3	6.33	82.0 ± 3.8
	11°46'11"S					

*Analyses in the Institut Dolomieu, Université Joseph Fourier, Grenoble. Analytical techniques given in Soler and Bonhomme (1988a). Decay constants after Steiger and Jäger (1977).
†WR = whole rock; B = biotite; H = hornblende; FK = K-feldspar; Pl = plagioclase.

obtained on amphiboles are the most reliable for the plutonic rocks, while biotite and amphibole ages may be used for the volcanics (see Soler, 1987, and Soler and Bonhomme, 1988a, for a detailed discussion of these ages).

Reliable dates from the literature, our previous results (Soler and Bonhomme, 1988a, b), and the new dates presented here for the Raura syenite and some stocks of the Eastern Cordillera (Table 3) strongly suggest that during this third period, magmatic activity was not continuous. Three main periods separated by intervals of apparent magmatic quiescence may be distinguished (Periods E, F, and G in Figs. 3 and 7; Table 2).

The volumetrically minor PB1 episode (period E) postdates the Inca I compressive tectonic event (Cobbing and others, 1981; Noble and others, 1985; Marocco and others, 1987).

Period F involves two episodes of magmatic activity. The major PB2 episode immediately postdates the major compressive Inca s.s. (or Inca II) deformation (Steinman, 1929; Mégard, 1978, 1984; Noble and others, 1979b). The episode of magmatic quiescence between PB2 and PB3 magmatic pulses, whose existence is not readily demonstrated, does not correspond to any known tectonic event.

A clearly defined episode of magmatic quiescence (about 25 to 30 Ma) separates periods F and G. This episode is observed all along the central Andean margin of Peru and Chile (see for instance Tosdal and others, 1981, and Sébrier and others, 1988, for southern Peru; and Drake and others, 1982a, b, and Aguirre, 1985, for Chile). A minor episode of deformation occurs during this interval of magmatic quiescence (phase N1 of Macharé and others, 1986; Sébrier, 1987; Sébrier and others, 1988).

The latest Oligocene to Pliocene period (period G in Table 2) is characterized by more or less continuous magmatic activity. The four episodes of magmatic activity (PB4 to PB7 in Figs. 3 and 7; Table 2) are defined more by the relation to tectonic events than by radiochronological data (Fig. 5). The Quechua 1 tectonic event (about 19 Ma; Steinman, 1929; Mégard, 1978, 1984; Noble and others, 1974, 1979b; Soulas, 1977; McKee and Noble, 1982) separates episode PB4 from episode PB5. In this case there is little or no overlap between PB4 and PB5 dates. The distinction between episodes PB5 and PB6 is exclusively related to the existence of the Quechua 2 tectonic event (about 12 Ma); no age gap appears between both episodes. Finally, age determinations for episodes PB6 and PB7 largely overlap. However, since the volcanism that postdates the Quechua 3 tectonic event (about 6 Ma) corresponds exclusively to acid ignimbrites and rhyolitic dikes (references in Table 2), the distinction of a PB7 episode appears to be justified. The PB6–PB7 overlap of K-Ar ages is mainly due

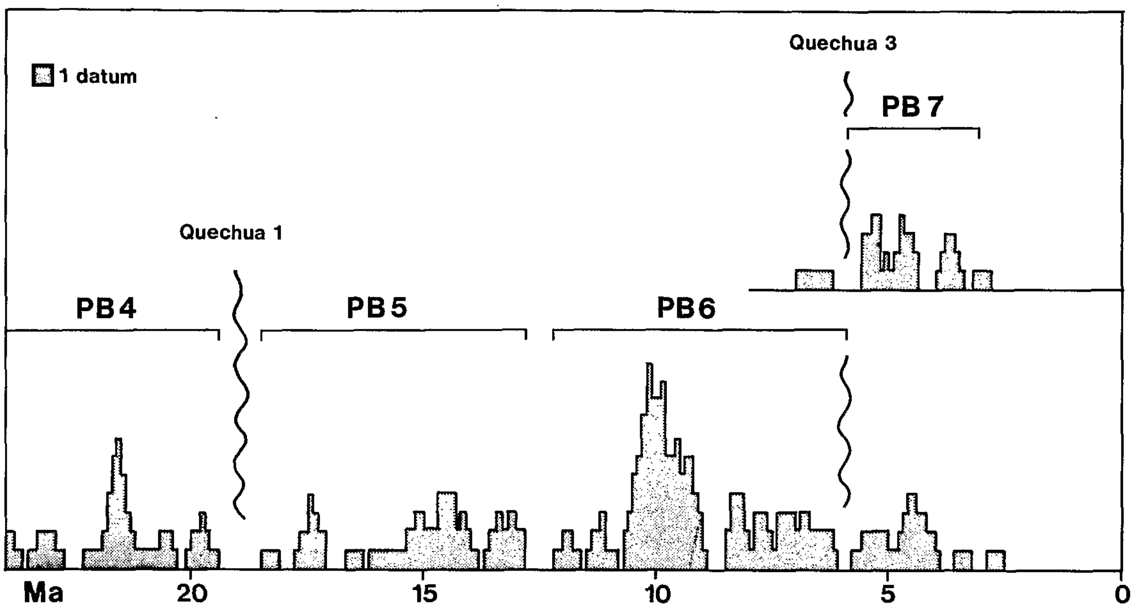

Figure 5. Histogram of radiochronological data (volcanic and plutonic rocks) for the late Oligocene, Miocene, and Pliocene in central Peru (episodes PB3 to PB7) (references in Table 2 and in text).

to resetting of the K-Ar system of the PB6 episode and to "too old" biotite K-Ar ages for some ignimbrites of the PB7 episode (Lavenu and others, 1989). Magmatic activity ceased in the studied area some 3 m.y. ago (Soler and Bonhomme, 1988a).

When considering the spatial distribution of post-batholith magmatism (Figs. 3 and 4), it appears that the IMF did not migrate during episodes PB1 and PB2 with respect to its position during the last episodes of the emplacement of the Coastal Batholith. Thereafter, the IMF migrated some 30 to 50 km eastward and remained relatively stable from episodes PB3 through PB7. In contrast, the migration of the OMF is much more important, although additional data are still necessary to determine the extent of the magmatic belt in the Eastern Cordillera (Carlier and others, 1982). With respect to the Coastal Batholith, the magmatic belt broadened from episodes PB1 (about 70 km) through PB2 (more than 150 km and probably more than 200 km wide when taking into account the tectonic shortening; Mégard, 1978, 1984; Romani, 1982). Our new data from the Sacsacancha gabbro-diorite-granodiorite batholith, located slightly south of the studied transect (Table 3; Fig. 6), show that episode PB2 reached the Eastern Cordillera, as previously suggested by an unpublished K-Ar age at 40 Ma obtained by the Metal Mining Agency of Japan (1976) on a granite near Llaupi. No magmatic activity belonging to episode PB3 is known in the Eastern Cordillera, but various subvolcanic granodioritic stocks of this episode (Quinua, Mariac, Milpo, Atacocha; Cobbing and others, 1981; Soler and Bonhomme, 1988a, b) have been described along the eastern limit of the High Plateaus. After the well-defined late Oligocene episode of magmatic quiescence, the OMF reached the Amazonian slope of the Eastern Cordillera (alkali stocks of the Oxapampa area; Fig. 4; Table 3) at least during episodes PB4 and PB5. The presence of dikes belonging to the PB5 and/or PB6 episodes in the Cerro Azul area, in the Eastern Cordillera south of the studied transect, is suggested by Mégard (1978) and Valdez (1983). In the studied area, magmatic activity of the PB7 episode is restricted to the highest part of the Western Cordillera and the western part of the High Plateaus. Southward, however, magmatic activity is known to reach the eastern limit of the High Plateaus in the Ayacucho basin (Mégard and others, 1984).

Altogether, it appears that, after a period of fast broadening between about 55 and 40 Ma, the post-batholithic magmatic belt remained stable during the last 40 m.y., until the cessation of magmatic activity in central Peru some 3 m.y. ago. In the studied area, the belt broadening appears much more important that the eastward migration of the IMF, in contrast with other portions of the central Andean margin (see Clark and others, 1976; Maksaev, 1979; Frutos, 1981; Drake and others, 1982a, b; Aguirre, 1985, for the Chilean Andes).

THE TIMING OF MAGMATIC ACTIVITY AND THE FEATURES OF THE SUBDUCTION PROCESS

The subduction of the oceanic plate (first the Farallon and later the Nazca plate) beneath the South American continent plays an essential role in the genesis of Andean magmatism, either through direct melting of the slab plus subducted sediments or through metamorphism and dehydration (e.g., the "IRS fluids" of Gill, 1981) leading to mantle metasomatism and melting of mantle and/or lower crust. This justifies looking for possible correlations between space and time distribution of magmatic activity and variations in the features of the subduction process.

The time scale used here is from Harland and others (1982)

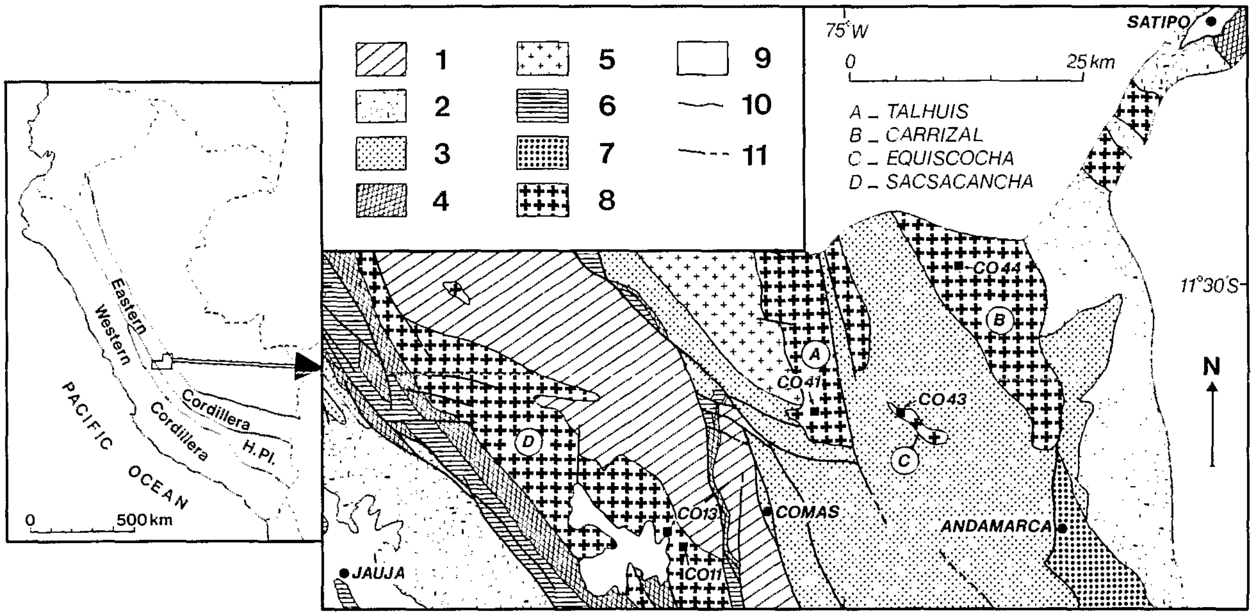

Figure 6. Localization of the Sacsacancha Batholith (from Soler and Bonhomme, 1987, modified from Mégard, 1978). 1 = Precambrian basement; 2 = early Paleozoic; 3 = late Paleozoic; 4 = Permian Mitu group; 5 = Permian granites; 6 = Mesozoic; 7 = latest Cretaceous red beds; 8 = gabbros to granites previously assumed to be of Late Cretaceous age (Mégard, 1978)—Talhuis, Carrizal, and Equiscocha yielded Permian age (Soler and Bonhomme, 1987), Sacsacancha is Eocene (this study); 9 = Quaternary deposits; 10 = normal contact; 11 = abnormal contact.

for the Cenozoic and from Kent and Gradstein (1985) for the Cretaceous.

Present-day features of the subduction process

The present-day direction of convergence of the Nazca plate with the South American continent is N78°, and the convergence rate is 10.8 cm/yr (Minster and Jordan, 1978). In central Peru, the convergence direction is nearly normal to the continental margin; the shear component (parallel to the continental margin) of subduction is sinistral and weak (<2 cm/yr).

The pole of the Nazca–South America rotation is located at 48.9°N, 86.4°E, so that no significant variation of convergence rate with latitude occurs along the Andean margin.

It is now generally accepted, since the work of Stauder (1973, 1975), Barazangi and Isacks (1976, 1979), Hasegawa and Sacks (1981), Grange and others (1984), and Bevis and Isacks (1984), that the Benioff-Wadati zone below western South America presents five well-defined segments: in three segments the slab dips at about 30° and in two segments (northern and central Peru between 3° and 13°S, this transect, and central Chile between 27° and 32°S) the slab has a "normal" dip to a depth of 100 km and then becomes subhorizontal. The change between "normal" and "flat" segments corresponds to an abrupt or more progressive twisting of the slab without tearing (Hasegawa and Sacks, 1981; Grange and others, 1984; Bevis and Isacks, 1984).

For our purposes, the most interesting feature of the present-day geometry is that the segments with active volcanism are those with "normal" (≈30°) dip; the segments without any active or Quaternary volcanism are the "flat" segments (Barazangi and Isacks, 1976, 1979; Mégard and Philip, 1976; Thorpe and others, 1982; Grange and others, 1984). This has been interpreted to be a consequence of the absence of an asthenospheric wedge between the subducting slab and the continental lithosphere.

Magnetic anomalies are poorly defined along central Peru; the estimated age of the slab at the 12°S trench is nearly 42 to 45 Ma (anomaly [18] or [20]; Herron, 1972; Handschumacher, 1976). In the same segment, north of the Mendaña fracture zone, the slab is somewhat younger (34 to 37 Ma; anomaly [13] or [12]).

Evolution from early Oligocene to present

Anomaly [13] (ca. 37 Ma) corresponds to the last major change in the South Atlantic expansion (Ladd, 1974, 1976; Chase, 1978; Sibuet and Mascle, 1978). For the interval from anomaly [13] to present, a constant pole of rotation (57.4°N, 37.5°W) for the Africa–South America pair can be assumed, as well as a mean half-rate of expansion of about 2 cm/yr in the South Atlantic (Minster and Jordan, 1978; Chase, 1978; Davis and Solomon, 1981) with variations lower than ±10 percent (Brozena, 1986).

For the interval from anomaly [7] to the present, available plate dynamics reconstructions for the southeastern Pacific (Pilger, 1981, 1983, 1984; Pardo Casas and Molnar, 1987) show that convergence patterns have not varied markedly.

Pardo Casas and Molnar (1987) suggest a mean of 11.0 ± 0.8 cm/yr for the whole period (Fig. 7), while Pilger (1983) suggests the convergence rate was 10 cm/yr from the present to anomaly [3], 12 cm/yr from anomaly [3] to [5], 11.2 cm/yr from anomaly [5] to [6], and 9.2 cm/yr from anomaly [6] to [7]. Because Pardo Casas and Molnar reanalyzed published magnetic anomaly and bathymetric data, and estimated the uncertainties in their reconstructions, their conclusions, though conservative, are preferred. In contrast, Pilger does not give a detailed estimation of the uncertainties, and we think that his conclusions are less well established, and that he overinterprets some of the data. Since constant poles and rates are assumed between two anomalies (following Pitman and Talwani, 1972), the finite-rotations method used in both of these reconstructions has the disadvantage of producing an artificial concordance between possible changes in poles or rates and the dates of the anomalies. Another disadvantage of the constant-rate assumption is that any short-lived change, even if drastic, will be smoothed and not appear in the reconstruction.

All authors agree that from anomaly [7] to the present, the convergence direction has not changed more than ±10° from the present-day direction (N78°; Minster and Jordan, 1978). Two reorganizational events occurred in the southeastern Pacific during this time. The more recent event was the extinction of the Galapagos rise at 6.5 Ma (Mammerickx and others, 1980), which corresponds in time with a minor change in Pilger's reconstruction of the interval [5] to [3] (point A in Fig. 8). The older event is the beginning of spreading of the present-day East Pacific rise (except in the Galapagos area), at about 18.5 Ma (Mammerickx and others, 1980). This event also correlates with a minor change noted by Pilger in the interval [6] to [5] (point B in Fig. 8).

These reorganizations and minor changes in direction and rate of convergence appear to be the consequences of a major reorganization of plate geometry, which occurred at ca. 25 Ma just after anomaly [7]. At that time the Farallon plate broke up into the Nazca and Cocos plates (Herron, 1972; Handschumacher, 1976; Hey, 1977; Mammerickx and others, 1980). This corresponds to an alteration of the convergence direction (from SW-NE to WSW-ENE; point C in Fig. 8) and an increase in the convergence rate (from ≈5 cm/yr to ≈10 cm/yr).

Therefore, the latest magmatic activity in central Peru (period G: PB4 to PB7) is contemporaneous with a high convergence rate (about 11 cm/yr) and an almost perpendicular convergence direction along the Peru-Chile trench. The beginning of this magmatic activity appears to be directly associated with the break-up of the Farallon plate.

The northeast extension of the Nazca ridge also arrived at the Peru-Chile trench during the interval between the present and anomaly [7]. Reconstructions by Pilger (1981, 1984) and Pilger and Handschumacher (1981), which assume that the Nazca ridge is a mirror image of the Tuamotu ridge, date the arrival of the Nazca ridge between 10 and 3 Ma. The age uncertainty is mainly due to lack of information on the geometry of the now-subducted northeastern extension of the ridge. A detailed field study on

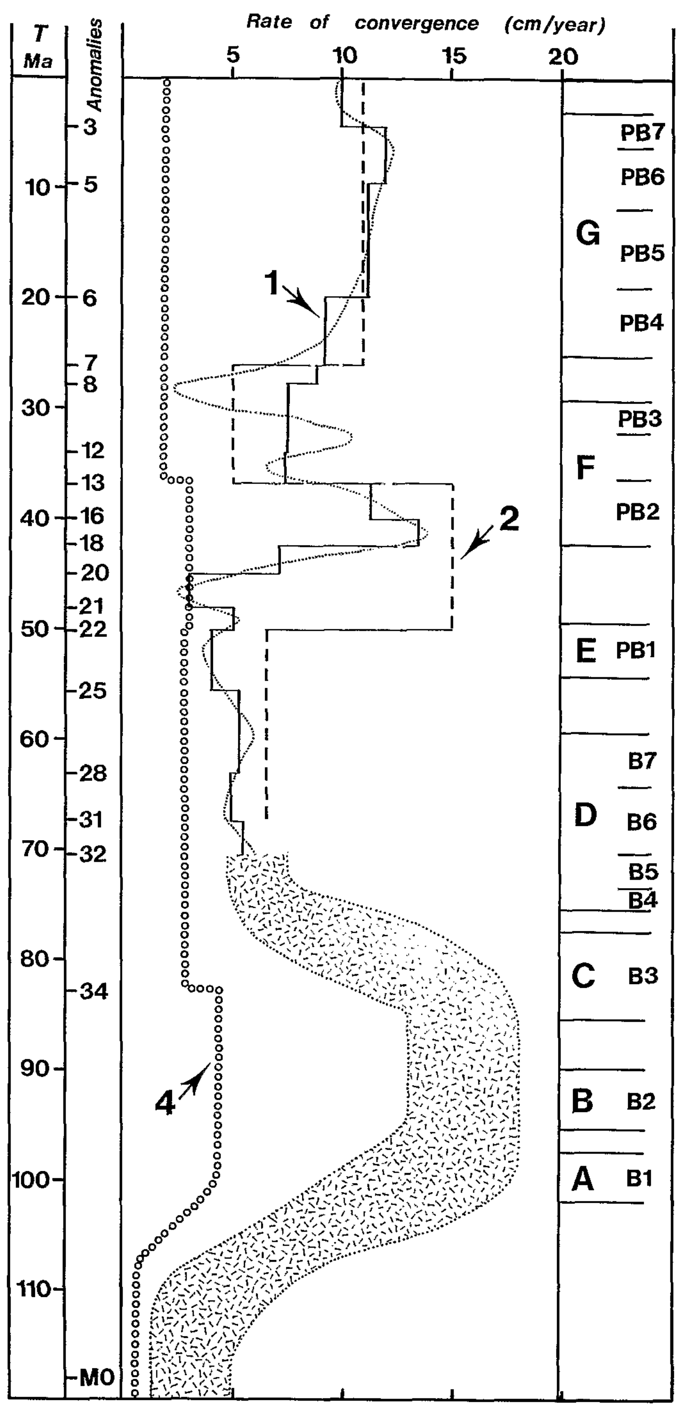

Figure 7. Convergence rate between the Nazca (previously Farallon) plate and South America. Data from 1. Pilger (1983); 2. Pardo Casas and Molnar (1987); 3. Larson and Pitman (1972). The stippled curve is our interpolation of Pilger's data, including our hypothesis about the short-lived very-low-convergence-rate period of late Oligocene time (discussion in text); 4. Half spreading rate of the South Atlantic Ocean (references in text).

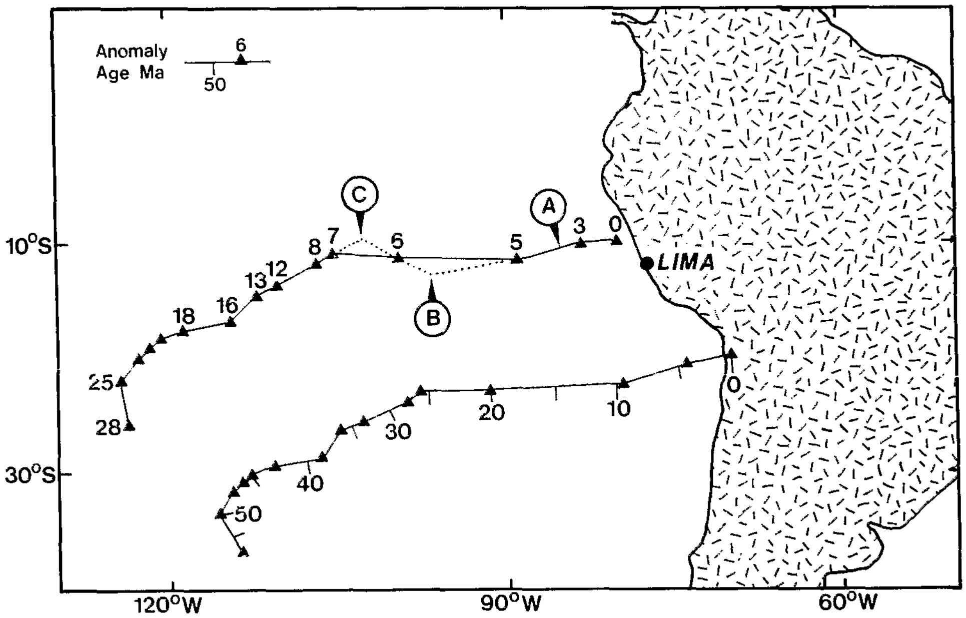

Figure 8. Reconstruction of the trajectory of two arbitrary points of the Nazca plate from early Eocene to the present (modified from Pilger, 1983). A. Definitive extinction of the Galapagos rise (6.5 Ma, following Mammerickx and others, 1980). B. Onset of the present-day East Pacific rise, excepting the Galapagos area (18.5 Ma, following Mammerickx and others, 1980). C. Break-up of the Farallon plate into Nazca and Cocos plates [about 25 Ma, following Herron (1972), Handschumacher (1976), Hey (1977), and Mammericix and others (1980)]. The dotted line is an hypothetic trajectory assuming that the changes in the convergence direction fit with the A, B, and C events and not with the dates of the anomalies (discussion in text).

coastal uplift in southcentral Peru by Macharé (1987) suggests that the NW-SE–trending portion of the Nazca ridge probably arrived at the trench at 4 Ma.

Thus, the cessation of magmatic activity in central Peru some 3 m.y. ago (end of PB7) apparently corresponds with the arrival of the Nazca ridge, as suggested by Pilger (1984). In central Peru, the subduction of the Nazca ridge results in a buoyancy effect that leads to a decrease in the dip of the subducted slab (Pilger, 1981, 1983, 1984; Cross and Pilger, 1982) and to a progressive change from "normal" (like in southern Peru today) to "flat" subduction. Therefore, we assume that magmatic activity from 25 to 3 Ma occurred above a "normal" (about 30°) dipping slab in central Peru.

For the interval from anomaly [13] to [7], Pilger (1981, 1983, 1984) gives a convergence rate of 7.5 to 8 cm/yr, while Pardo Casas and Molnar (1987) give a rate of 5.0 ± 3.0 cm/yr at 10°S (Fig. 7). The break-up of the Farallon plate at about 25 Ma appears to be a consequence of a situation in which plate-tectonic forces were not fully effective in maintaining the motion of the Farallon plate and created very high intraplate stresses (Wortel and Cloetingh, 1981, 1983). These stresses seem to have been generated by the arrival of the northern portion of the Pacific-Farallon spreading center at the Californian trench at about 30 Ma (Whitman and others, 1983). This chronology and peculiar mechanical situation suggest that the period between 30 and 25 Ma was characterized by a very low convergence rate. This short-lived episode, which does not appear in the previous reconstructions, would have been smoothed out in the longer interval ([7] to [13]) used in these reconstructions. However, its existence is consistent with Pardo Casas and Molnar's conclusions (convergence rate of 5.0 ± 3.0 cm/yr). The magmatic quiescence between about 30 and 25 Ma, which appears to be well defined all along the central Andean margin, then corresponds to a period of very low convergence.

Evolution from latest Paleocene to early Oligocene (anomaly [25] to [13] interval)

For this interval and the preceding ones (see below), plate reconstructions must be regarded with some caution, since the uncertainties increase with time (e.g., Hellinger, 1981; Pardo Casas and Molnar, 1987).

Finite-rotation reconstructions correlate anomaly [13] time with two global events. (1) In the central and south Atlantic, the Africa–South America rotation pole changes and a decrease in the half spreading rate from 3.3 to 2.0 cm/yr occurs (Ladd, 1974, 1976; Sibuet and Mascle, 1978). (2) In the southeastern Pacific, convergence rates decrease from 11 to 12 cm/yr to 7 to 8 cm/yr, according to Pilger (1981, 1983, 1984), or from 15.4 ± 5.8 cm/yr to 5.0 ± 3.0 cm/yr, according to Pardo Casas and Molnar (1987). According to Pilger, anomaly [13] also corresponds to a slight change in convergence direction. The near magmatic quiescence between episodes PB2 and PB3 corresponds with these relatively low convergence rates between [13] and [12].

For the period between anomaly [18] and [13], Pilger (1981, 1983) and Pardo Casas and Molnar (1987) agree that convergence rates were high. This period of fast convergence corresponds with the major PB2 magmatic episode (42 to 37 Ma).

In contrast, reconstructions for the interval [22] to [18] differ greatly (Fig. 7). Pilger (1981, 1983) concluded that the high convergence rates of the interval [18] to [13] began at anomaly [18] time. Pardo Casas and Molnar (1987) conclude that this high convergence rate (15.4 ± 5.8 cm/yr) began before anomaly [21] and existed through the mid–late Eocene (about 52 to 37 Ma). The reconstruction proposed by Gordon and Jurdy (1986) using hot-spot traces and hot-spot reference frames is in better agreement with Pardo Casas and Molnar. Lastly, many authors (e.g., Atwater and Ménard, 1970; Candé and others, 1982) suggest a major plate reorganization near anomaly [21] time. Therefore, we can assume that both PB1 and PB2 magmatic episodes correspond with a period of high convergence rates.

For the interval between anomaly [25] and 52 Ma, all reconstructions suggest low convergence rates (5 to 7 cm/yr; see Fig. 7). This interval nearly corresponds with an episode of apparent magmatic quiescence between the end of the emplacement of the Coastal Batholith (B7; 64 to 59 Ma) and the beginning of post-batholithic magmatic activity (PB1; 54 to 49 Ma).

Near anomaly [25] time (about 56 Ma), the Farallon–South American convergence direction changed from a nearly N-S or N15 direction (Solomon and others, 1977; Pilger, 1981, 1983, 1984; Whitman and others, 1983) to N45. This change in direction did not correspond with a change in convergence rate (4 to 5 cm/yr; Fig. 7).

Evolution during the Cretaceous and Paleocene

Prior to anomaly [25], the uncertainties in Farallon–South American plate reconstructions become even larger due to the lack of anomalies before [23] along the Andean margin (Herron, 1972), the accumulation of uncertainties from younger reconstructions, and the Cretaceous magnetic quiet zone (118 to 83 Ma, anomaly [34] to J [M0–M3]). The reconstructions by Pilger (1983, 1984), Whitman and others (1983), Jurdy and Gordon (1984), Gordon and Jurdy (1986), and Pardo Casas and Molnar (1987) all suggest a low convergence rate (Fig. 7) and a very oblique (nearly N-S) convergence direction, at least for the period between ca. 70 Ma (anomaly [32]) and 52 Ma. The period D (75 to 59 Ma) of the Coastal Batholith would correspond with this period of relatively low convergence rate.

The most important feature of the Pacific Ocean in the Cretaceous is probably its very fast spreading rate (mean half spreading rate = 14 to 18 cm/yr for the Pacific-Farallon pair, Larson and Pitman, 1972) between the Aptian and the Campanian. The Copara and Casma volcanics and the first three periods of the emplacement of the Coastal Batholith occurred during this time.

In the Neocomian, Larson and Pitman (1972) suggest a low Pacific spreading rate (about 2.5 cm/yr). During this period, Africa separated from South America (Sibuet and Mascle, 1978; Rabinowitz and LaBrecque, 1979; Sibuet and others, 1984). Opening of the South Atlantic (i.e., active spreading) began at 115 Ma at 40°S and at 105 Ma near the equator (Sibuet and others, 1984). During the preceding rifting episode, the rate of opening was about 1.5 cm/yr at 40°S and 0.8 cm/yr at the equator. The active spreading rate increased up to 4 to 5 cm/yr until anomaly [34] time, and then decreased to 3 cm/yr. The Copara-Casma marginal basin coincides with the rifting of the South Atlantic, and the Coastal Batholith is synchronous with active spreading.

The coexistence of two oceanic plates along the central Andean margin, the Farallon plate to the north and the Phoenix plate to the south, during the Cretaceous and much of the Cenozoic (Larson and Pitman, 1972; Hilde and others, 1977; Jurdy and Gordon, 1984; Gordon and Jurdy, 1986), complicates the picture. The reconstructions of Larson and Pitman (1972) at 110 Ma and of Gordon and Jurdy (1986) at 61 Ma (Fig. 9), suggest that the ridge separating these two plates was subducted at a relatively high angle to the South American margin, but that the location of this ridge migrated between the Albian and the Paleocene. The probable existence of transform faults affecting the Farallon-Phoenix boundary suggests that this migration occurred through jumps, since the transform faults were more or less parallel to the western boundary of the South American plate. On the whole, southward jumps predominate, but northward intermediate jumps cannot be excluded, depending on the geometry of the Farallon-Phoenix boundary.

Summarizing, it appears that the periods of high convergence rate (>10 cm/yr) between Nazca (Farallon) and South American plates are characterized by high magmatic activity. In contrast, the periods of magmatic quiescence or low magmatic activity seem to be systematically associated with low convergence rates. Some exceptions are:

(1) The hiatus in magmatic activity in central Peru in the last 3 m.y. has occurred despite a high convergence rate because of abnormally flat subduction.

(2) The last period of emplacement of the Coastal Batholith, between 75 and 59 Ma, seems to be related to a low convergence rate (5 to 7 cm/yr) and a very weak compressive deformation.

The short-lived and still poorly documented interruption of magmatic activity during the Miocene, which can be linked to the climax of compressive tectonics, could constitute a third minor exception.

GEOMETRY OF THE MAGMATIC BELT AND FEATURES OF THE SUBDUCTION PROCESS

The main changes that occurred in the magmatic history of Peru in the last 110 m.y. are: (1) the transition from "aborted" marginal basin volcanism to "batholithic" plutonism during Albian times; (2) the progressive change from a narrow (±40 km) magmatic belt to a wide (>150 km) magmatic belt over a short period (15 m.y.) in the early to mid-Eocene; (3) the cessation of magmatic activity in the Pliocene. Minor changes include progressive but limited migrations of the IMF and OMF during the emplacement of the Coastal Batholith and during post-batholith magmatism.

These changes have to be related to variations in the thermomechanical and geometric features of the subduction zone: the state of stress of the overriding continental crust, the dip of the subducted slab, the thermal structure of the mantle wedge, and the existence of an accretionary prism or frontal tectonic erosion of the overriding plate.

If we assume, as a first approximation, that the magmas were generated at the same depth (either in the slab or the wedge) throughout the period under consideration, changes in the arc geometry must be regarded essentially as consequences of changes in the dip of the subducted slab. The dip of the Benioff-Wadati zone depends principally on four factors (Uyeda, 1982; Cross and Pilger, 1982): the normal convergence rate (Luyendyk, 1970; Yokokura, 1981), the lithospheric age of the slab (Molnar and Atwater, 1978; England and Wortel, 1980; Wortel, 1984), the absolute motion of the subducted plate (Chase, 1978; Uyeda and Kanamori, 1979), and the subduction of buoyant portions of the subducted plate (Vogt, 1973; Vogt and others, 1976; Kelleher and McCann, 1976; Pilger, 1981, 1983, 1984; Cross and Pilger, 1982).

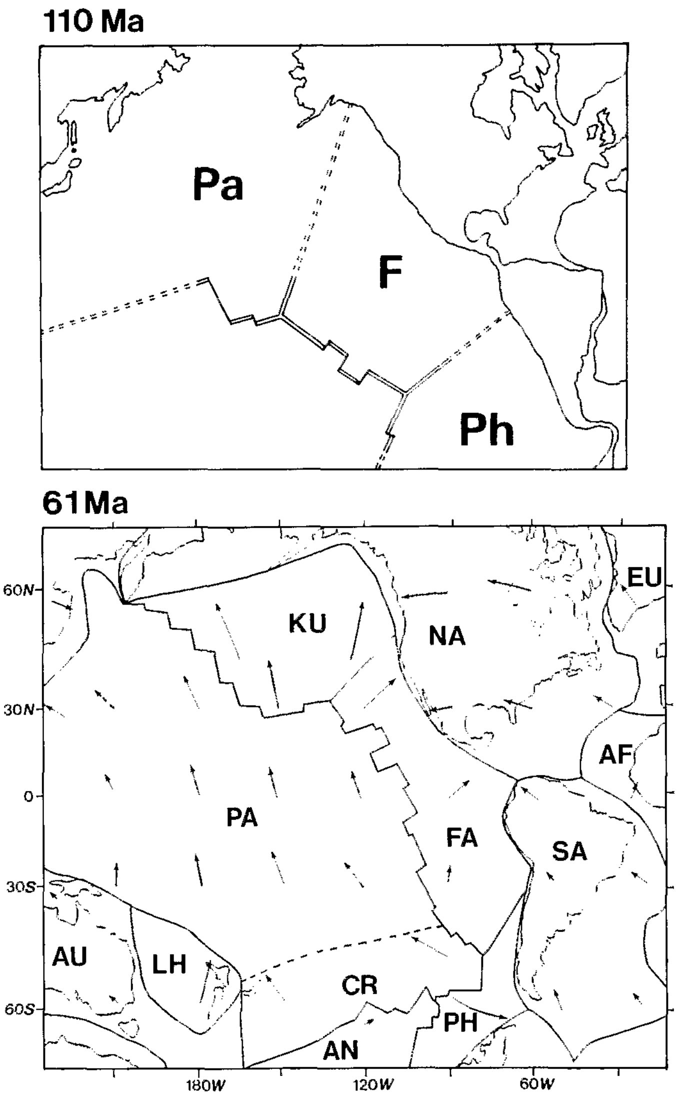

Figure 9. Reconstructions of plate geometry in the eastern Pacific at 110 Ma (from Larson and Pitman, 1972) and 61 Ma (from Gordon and Jurdy, 1986).

Lithospheric age of the slab

The Wortel and Vlaar's (1978) method allows for a step-by-step calculation of the lithospheric age of the slab on the basis of the present-day position of magnetic anomalies and available reconstructions of convergence rates and directions. With a short step (Δt), the rate and the direction may be considered as constant during every step, then:

$$\mathrm{LAS}(t+\Delta t) + \Delta t\,(1 - \sin\Omega\,.x\,(V_{c(t)}/V_{ac(\mathrm{LAS}(t))})) \qquad (1)$$

where LAS(t) is the lithospheric age of the subducted slab at the trench, Ω is the angle of the magnetic anomalies with respect to the trench, V_c is the trench normal convergence rate at time t, and V_{ac} is the half spreading rate at time LAS(t) (= the rate of creation of the crust subducting at time t).

The calculation was carried out for 1-m.y. steps (see Fig. 10), with different rates and directions of convergence within the limits of the Pilger's (1981, 1983, 1984) and Pardo Casas and Molnar's (1987) reconstructions for the Cenozoic and using either the very high spreading rate model of Larson and Pitman (1972) or a lower spreading rate for the Cretaceous.

Using these parameters, it appears that the calculated lithospheric age of the subducted slab at the trench (LAS) decreased during the last 20 m.y., as previously shown by Wortel (1984). From the late Paleocene (60 Ma) to the early Miocene (20 Ma), the age of the subducted slab increased (model 2A; Fig. 10) or remained stable (models 1 and 2B; Fig. 10), but decreased during the late Cretaceous and Paleocene (models 1, 2A, and 2B). Finally, the calculation suggests that the age of the subducted slab decreased rapidly before 80 Ma (models 1 and 2B; Fig. 10) or 100 Ma (model 2A; Fig. 10), but this can be considered only a rough indication due to the uncertainties in Early Cretaceous and Jurassic plate reconstructions. The inferred decrease in slab dip during the early to mid-Eocene is not associated with a progressive younging of the subducted slab.

Another consequence of these results is that the model proposed by Wortel and Vlaar (1978) and Wortel (1984) for changes of slab dip in central Peru is not valid. These authors proposed that the change from "normal" to "flat" dip was associated with a decrease in the lithospheric age of the slab and that the critical "transition" age is 70 Ma. We show that the litho-

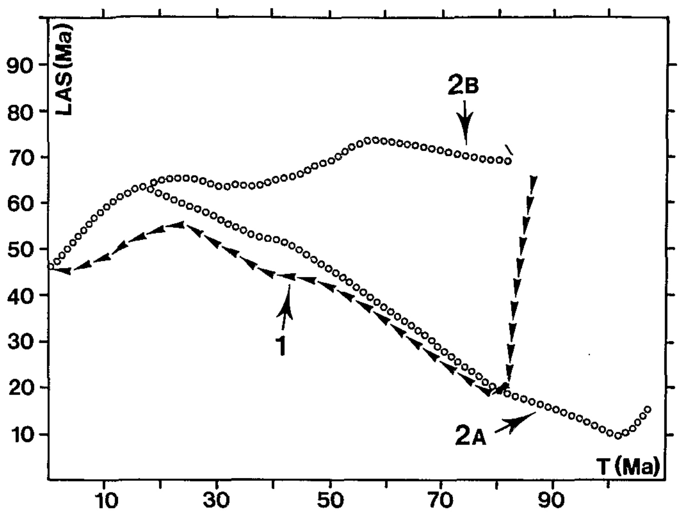

Figure 10. Lithospheric age of the subducted oceanic crust at the trench (LAS) versus time (T) at 11°S. Discussion of calculation method and results in text. Assuming: (1) reconstructions of Pardo Casas and Molnar (1987) and high convergence rate during the Cretaceous quiet period; and (2) reconstructions of Pilger (1983) and high convergence rate (A) or low convergence rate (B) during the Cretaceous quiet period.

spheric age in central Peru has been younger than 65 Ma since the Late Cretaceous. Results for the northern part of the "flat" Peruvian segment (Soler, in preparation) are even more at odds with Wortel's model. Consequently, we believe that Pilger's "Nazca ridge model" more accurately explains the present "flat" slab in central Peru.

Absolute motion of the South American plate

The change from marginal-basin volcanism (Copara-Casma volcanics) in an extensional regime to batholithic plutonism in a neutral or compressive regime is associated with the opening of the South Atlantic Ocean and is a good illustration of the concepts of Uyeda and Kanamori (1979) and Uyeda (1982).

The Copara-Casma volcanism developed above a steeply dipping slab, as confirmed by the presence of typical intracontinental alkali basalt flows (with no evidence of influence of the subduction process; Soler, in preparation), erupted during Albian times along the boundary between the High Plateaus and the Eastern Cordillera. The change to batholithic plutonism appears to be contemporaneous with the first episode of compressive deformation in the Andes of central Peru (Mochica tectonic phase of Mégard, 1984, and Pitcher and others, 1985) between 102 and 105 Ma.

The progressive and limited migrations of the IMF and OMF during Coastal Batholith emplacement may be associated with a progressive decrease in slab dip and erosion of the accretionary prism, as suggested by Soler and Rotach-Toulhoat (this volume).

Neither drastic changes in the spreading rate of the South Atlantic Ocean (Ladd, 1974, 1976; Sibuet and Mascle, 1978; Fig. 7) nor important modifications of the absolute motion of the South American plate (in a hot-spot reference frame; Jurdy and Gordon, 1984; Gordon and Jurdy, 1986) have occurred since Albian times. Moreover, the spreading rate of the South Atlantic has decreased by steps during the last 100 m.y. (Fig. 7), so that the decrease in slab dip during the early and mid-Eocene cannot be correlated with an increased rate of overriding of the upper plate.

Tectonic erosion at the trench

Tectonic erosion at the trench has been called upon in many cases to explain variations in arc geometry (Karig and Sharman, 1975; Uyeda, 1982) and has been regarded as a typical feature of "Chilean-type" subduction (Uyeda and Kanamori, 1979). In fact, no accretionary prism is known along the central Peruvian margin (Kulm and others, 1981), and it seems that the fore-arc basins have maintained their present geometry at least since the mid- or late Eocene (Thornburg and Kulm, 1981; Macharé and others, 1986; Macharé, 1987), so that tectonic erosion at the trench cannot be invoked at least for the last 40 m.y.

However, it is possible that the migration of the magmatic arc between Albian and mid-Eocene times has been partly a consequence of tectonic erosion. Isotopic data are consistent with tectonic erosion of an accretionary prism during the first episodes of emplacement of the Coastal Batholith (Soler and Rotach-Toulhoat, this volume), but no conclusion can be drawn for the period between ca. 75 and ca. 45 Ma.

Obliquity of the subduction

The drastic broadening of the magmatic belt in central Peru in the early to mid-Eocene is contemporaneous with the change in the convergence direction and increase in convergence rate, which occurred at that time.

When comparing Late Cretaceous and late Eocene or Miocene reconstructions, it appears that many of the factors that control the slab dip (convergence rate, lithospheric age of the slab, absolute motion of the upper plate) were the same during both periods. However, there is an important uncertainty in the normal convergence rate during the Late Cretaceous. Furthermore, during the Late Cretaceous, convergence was very oblique, inducing a dextral wrench faulting (Bussell, 1983) in a continental crust that was relatively thin near the coast due to extension in the Aptian-Albian. In contrast, during the late Eocene and Miocene, convergence was nearly normal to the margin, resulting in thrusting and faulting with a very minor lateral component (e.g., Mégard, 1984).

Following Bussell and Pitcher (1985), we assume that during Coastal Batholith emplacement there was a deep-seated lithospheric structural control that channeled magmas to the surface more or less along the axis of the Casma basin. Consequently, the width of the Coastal Batholith may not represent the actual width of the melt zone. In contrast, during the more recent magmatic episodes that took place in a predominantly compressive regime, no magma channeling occurred, and the width of the magmatic belt could represent the width of the melt zone. However, disappearance of the "channeling effect" is insufficient to explain the magmatic belt broadening; hence, a change in slab dip probably also occurred (Fig. 11).

CONCLUSIONS

A systematic comparison between the chronology and spatial distribution of Andean magmatism in central Peru and independent plate reconstructions showing the dynamics of the interaction between the oceanic Nazca (Farallon) plate and the South American continent has resulted in several important conclusions. The data strongly suggest that magmatic activity has been discontinuous and that periods of high convergence rates (>10 cm/yr) are characterized by voluminous magmatic activity. In contrast, intervals of magmatic quiescence or low activity are systematically associated with low convergence rates.

Two main exceptions occur.

1. In central Peru, magmatic activity has been absent during the last 3 m.y. despite high convergence rates. This is interpreted to be due to the lack of an asthenospheric wedge above an abnormally "flat" slab. The change from a "normal" (30°) to a "flat" dip is associated with the subduction of the Nazca ridge, not with subduction of progressively younger oceanic crust.

2. Between 75 and 59 Ma, the last period of emplacement of the Coastal Batholith seems to be associated with a low convergence rate (5 to 7 cm/yr) and a weak compressive deformation.

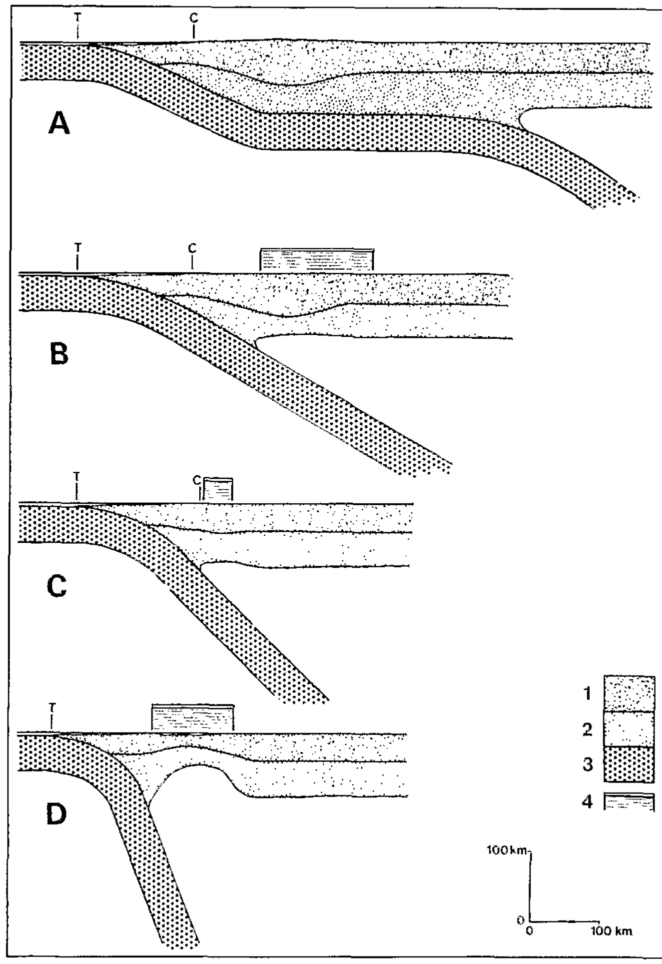

Figure 11. Subduction geometry: A = present day; B = late Eocene to early Pliocene (Eastern Stocks); C = Cenomanian to Campanian (main units of the Coastal Batholith); D = Albian (Casma volcanics). 1 = continental crust; 2 = subcontinental lithospheric mantle; 3 = oceanic lithospheric plate; 4 = magmatic belt; c = coast line; T = trench.

The type of magmatism is mainly determined by global plate dynamics. The formation of the Copara-Casma (Aptian-Albian) aborted marginal basin appears to be contemporaneous with rifting in the South Atlantic, an extensional tectonic regime and a steeply dipping slab (Fig. 11). The beginning of the emplacement of the calc-alkaline I-type Coastal Batholith (Albian to Paleocene) is synchronous with the onset of active spreading of the South Atlantic, the change to a compressive tectonic regime along the central Andean margin, and a decrease in slab dip. Channeling of magmas by deep-seated lithospheric structures along the axis of the Casma basin may have played a role during the emplacement of the Coastal Batholith. From Albian to Miocene-Pliocene times, the eastward migration of the magmatic front did not exceed 50 km. The main change in the geometry of the magmatic belt is a rapid broadening from a narrow (about 40 km) to a wide (>150 km) belt in the early and mid-Eocene. This change is contemporaneous with the main period of compressive deformation (Inca) and corresponds to a decrease in slab dip (Fig. 11), which appears to result from an increase in the convergence rate and a change from very oblique to nearly normal convergence. This change does not correlate with a decrease in age of the subducted plate or a relative increase in the rate of overriding of the upper plate. The post-Inca magmatic belt has maintained nearly the same geometry during the last 40 m.y. Miocene tectonic (Quechua) episodes produced only short and poorly characterized intervals of relative magmatic quiescence.

Tectonic erosion at the trench cannot be invoked over the last 40 m.y. but probably occurred during the first episodes of emplacement of the Coastal Batholith.

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