Journal of South American Earth Sciences, Vol. 1, No. 2, pp. 169–177, 1988
Printed in Great Britain

0895-9811/88 $3.00 + 0.00
Pergamon Press plc

New K-Ar age determinations of intrusive rocks from the Cordillera Occidental and Altiplano of central Peru: Identification of magmatic pulses and episodes of mineralization

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(*Received for publication July 1987*)

Abstract—The post-Albian evolution of the Andes of central Peru is characterized by igneous activity, both effusive and intrusive, and by at least six distinct episodes of compressional tectonics. New K-Ar age determinations have been made of intrusive rocks from the Cajatambo-Oyón-Cerro de Pasco area. In conjunction with already published information, these new data permit a better estimate of the ages and the lateral extent of successive Cenozoic magmatic arcs. Metallogenetic implications of the 26.3-29.3 Ma age of mineralized Milpo-Atacocha intrusions are also discussed.

Resumen—La evolución post-Albiana de los Andes del Perú central está caracterizada por actividad ígnea, tanto efusiva como intrusiva, y por lo menos seis episodios de tectónica compresional. Se efectuaron nuevas determinaciones de edades K-Ar de rocas intrusivas del area de Cajatambo-Oyón-Cerro de Pasco. Estos nuevos datos, en conjunción con información anteriormente publicada, permiten una mejor estimación de la edades y extensión lateral de los sucesivos arcos magmáticos cenozoicos. Iqualmente se discuten las implicancias metalogenéticas de la edad de 26.3-29.3 Ma de las mineralizaciones de las intrusiones Milpo-Atacocha.

INTRODUCTION

THE POST-ALBIAN evolution of the Andes of central Peru is characterized by igneous activity, both effusive and intrusive, and by at least six distinct episodes of compressional tectonics (Mégard, 1978; Noble *et al.*, 1979a; Mégard *et al.*, 1984).

Although Late Cretaceous and early Cenozoic magmatic activity in the Coastal Batholith seems to be only of the calk-alkaline, I-type (Pitcher *et al.*, 1985) (Fig. 1), the magmatic arc broadened and migrated eastward during late Eocene times and, in the Cordillera Occidental, Altiplano, and Cordillera Oriental, late Eocene-Pliocene magmatic activity is represented by a complex set of volcanics (Eocene-Miocene Calipuy Group, Pliocene ignimbrites) and intrusive stocks (the Eastern stocks of Cobbing *et al.*, 1981). Numerous Pb-Zn-Ag-Cu vein and skarn deposits are associated with this magmatic activity, defining the polymetallic province of the central segment of the Peruvian Andes (Soler, 1986; Soler *et al.*, 1986).

Numerous radiochronologic data, obtained mostly by the K-Ar method, have been already published for the volcanics (Farrar and Noble, 1976; Noble *et al.*, 1979a, 1979b; Cobbing *et al.*, 1981; McKee and Noble, 1982; Mégard *et al.*, 1984), some unmineralized stocks (Stewart *et al.*, 1974; Cobbing *et al.*, 1981; Mukasa, 1984; Beckinsale *et al.*, 1985), and a great number of mineralized intrusives (see section on implications for references), but there are still no age determinations for numerous intrusive stocks, either mineralized or unmineralized, previously mapped in this area by Cobbing (1973), Mégard (1978), and Romani (1982 and unpublished data), or more recently identified by Soler (unpublished data).

As geological field relationships rarely provide a good estimate of the age of the Eastern stocks and as precise knowledge of age and lateral extent of magmatic activity is of critical importance for an understanding of the petrographical and geochemical features of these stocks and their relations to global tectonics and metallogeny, new radiochronologic data are still very necessary. We partly fill this gap here by presenting new K-Ar age determinations of intrusive rocks from the Cajatambo-Oyón-Cerro de Pasco area (Figs. 1 and 2).

METHODS

All ages reported here were obtained by the conventional K-Ar method. The potassium content of the various samples was obtained by X-ray fluorescence for $K_2O > 1\%$ weight, or by atomic absorption for either $K_20 < 1\%$ or small samples. Argon content was determined by isotope dilution using ^{38}Ar in a 6 cm-radius mass spectrometer where the spike was calibrated by comparison with the Gl-O standard (Odin, 1982). The mean value of this standard mea-

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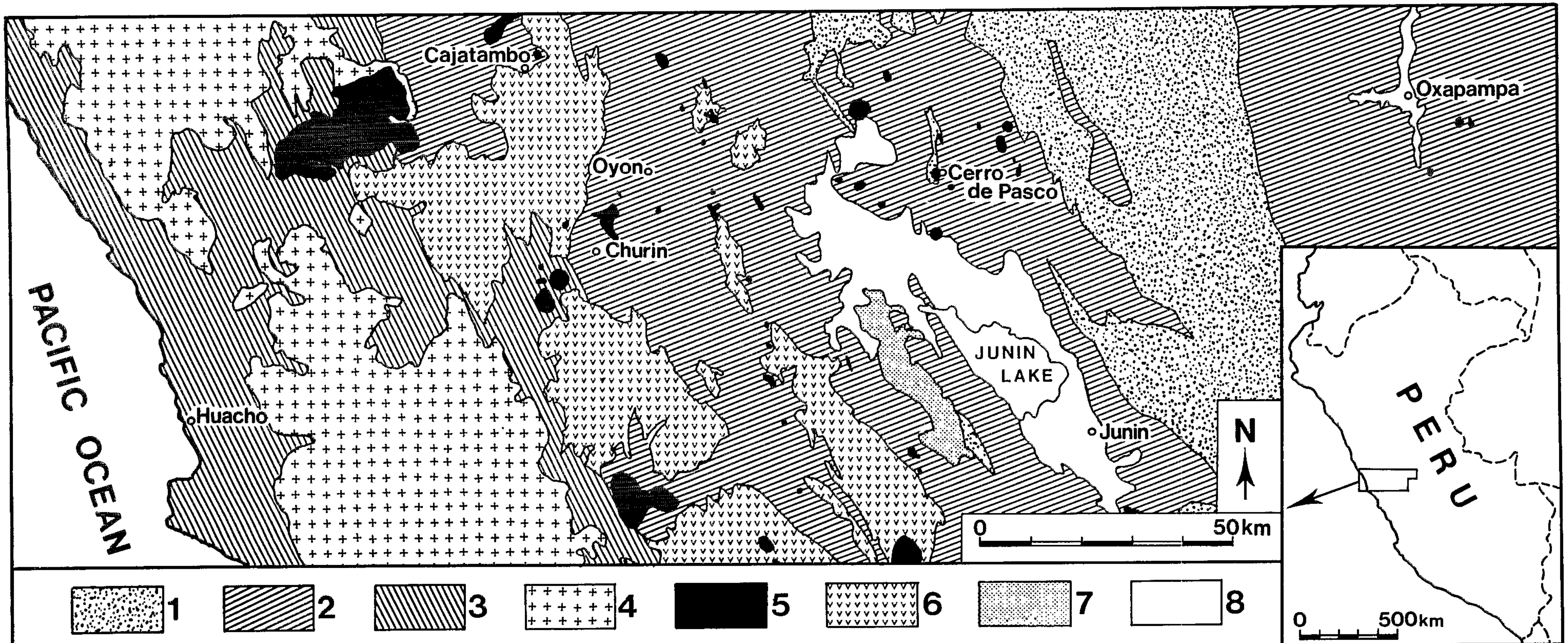

Fig. 1. Schematic geologic map of the study area: 1, Precambrian to upper Paleozoic; 2, Upper Permian to Upper Cretaceous sedimentary series; 3, Albian Casma volcanic group; 4, Coastal Batholith; 5, Eastern stocks; 6, Calipuy volcanics; 7, Pliocene Bosque de Piedra ignimbrites; 8, Quaternary deposits.

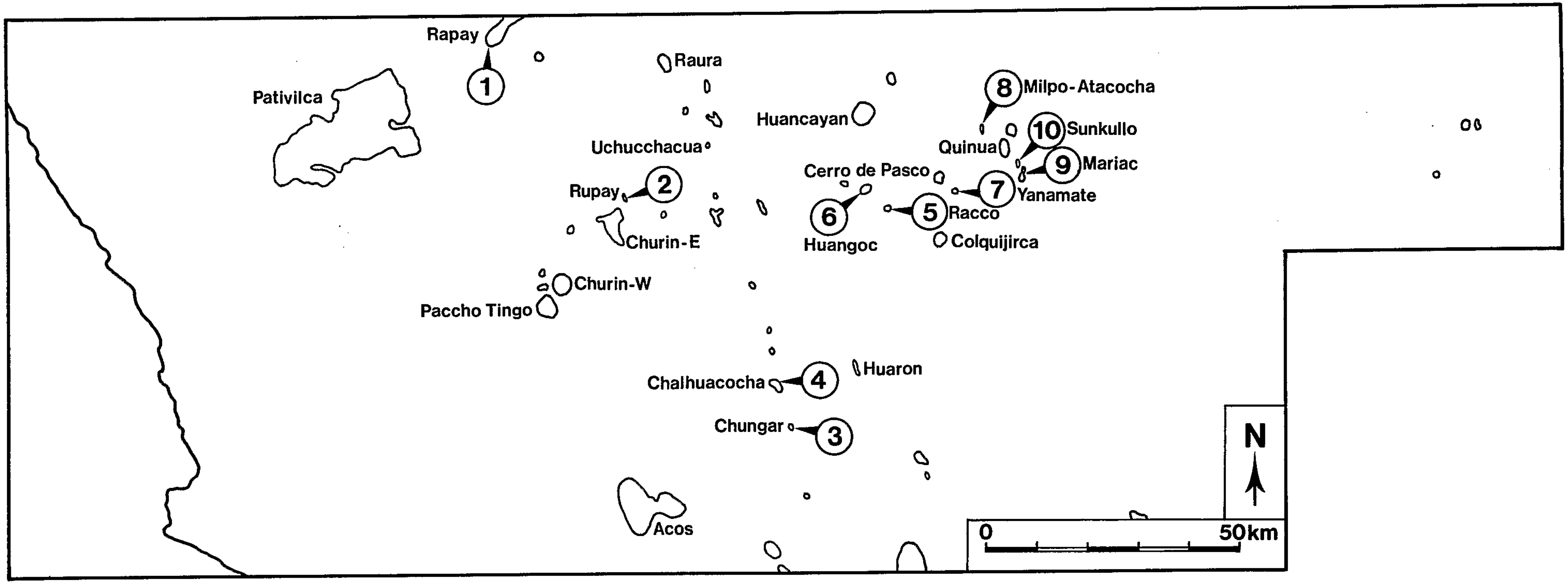

Fig. 2. Localities of previous and new data for the Eastern stocks. Numbers for sampling localities refer to Table 1.

sured in Grenoble is 24.92 nl/g as compared to the international value of 24.82 nl/g. All calculations used the constants recommended by Steiger and Jäger (1977).

Most of the samples were analyzed using various mineral fractions plus whole rock. There is poor agreement among the different results, *i.e.*, plagioclase and K-feldspar yielded systematically younger ages than did biotite, which can be explained by both types of feldspars having a low blocking temperature for radiogenic argon. As the difference is systematic, it is likely that samples were affected by young tectonothermal events. Consequently, only biotite and some whole-rock ages have been considered in the geologic interpretation. The youngest sample, the Rupay rhyolitic dike, behaved in a fashion similar to the Chijini ignimbrite of the La Paz Basin in Bolivia (Lavenu *et al.*, 1988); therefore, only the age of the K-feldspar from this sample have been taken into account. The results of these studies are given in Table 1.

RESULTS AND COMPARISON WITH PREVIOUS DATA ON THE REGION

The oldest ages obtained in this study are those from two stocks in the Atliplano west of Cerro de Pasco: the Huangoc quartz rhyodacitic stock and the Racco dacitic stock, with whole rock ages of, respectively, 38.5 and 35.5 Ma (late Eocene). The general plagioclase partial re-set in this zone implies that the actual ages of these intrusions are probably somewhat older.

Similar ages have been determined for the San Pedro pluton (39 Ma, U-Pb; Mukasa and Tilton, 1985) located within the Coastal Batholith in the valley of the Río Santa Eulalia; the Pativilca granite (37 Ma: K-Ar, Wilson, 1975; Rb-Sr, Beckinsale *et al.*, 1985; U-Pb, Mukasa and Tilton, 1985) located on the eastern margin of the Coastal Batholith in the valley of the Río Pativilca; the Huancayan quartz rhyodacitic stock (32.9 Ma on plagioclase; Cobbing *et al.*, 1981) in the Altiplano; and a granite (40 Ma, K-Ar;

Table 1. Analytical data

Sample Name and Location	Fraction Analyzed	K_2O	$^{40}Ar_{rad}/^{40}Ar_{tot}$ (%)	$^{40}Ar_{rad}$ (nl/g)	Age (Ma)
Rapay intrusion:					
77°02'44"W, 10°25'27"S	WR	3.22	73.3	0.665	6.39 ± 0.31
	Bio	8.61	68.2	1.909	6.86 ± 0.24
	KF	14.07	83.0	2.50	5.51 ± 0.09
Rupay rhyolitic dike:					
76°48'47"W, 10°41'25"S	WR	3.59	56.5	0.397	3.43 ± 0.19
	Bio	8.97	49.5	0.993	3.43 ± 0.18
	KF	12.03	73.0	1.155	2.97 ± 0.11
Chungar granite:					
76°32'05"W, 11°07'15"S	(CU31) Bio	7.65	78.1	3.29	13.3 ± 0.3
	(CU56) Bio	7.78	76.5	3.40	13.5 ± 0.3
	(CU57) Bio	8.91	81.7	3.87	13.4 ± 0.3
Chalhuacocha granodiorite:					
76°33'25"W, 11°03'00"S	Bio	8.20	71.1	2.67	10.05 ± 0.31
Racco dacitic stock:					
76°22'42"W, 10°46'34"S	WR	2.40	86.4	2.75	35.2 ± 0.1
Huangoc quartz monzonite:					
76°21'14"W, 10°40'05"S	WR	2.63	76.7	3.13	38.5 ± 1.0
Yanamate quartz monzonite:					
76°14'02"W, 10°42'23"S	WR	3.74	76.9	1.844	15.2 ± 0.4
	Pl	1.20	53.2	0.509	13.1 ± 1.1
Milpo-Atacocha intrusions:					
76°14'20"W, 10°34'40"S	(MI15) WR	4.03	82.4	3.65	27.8 ± 0.6
	(AT33) WR	3.66	76.9	3.49	29.3 ± 0.5
	(AT47) WR	2.98	87.0	2.60	26.3 ± 0.4
	(AT47) Pl	0.71	62.3	0.599	25.9 ± 1.5
Mariac quartz monzonite:					
76°07'58"W, 10°40'44"S	Bio	8.59	92.4	8.62	31.1 ± 0.4
	Pl	0.75	62.3	0.586	24.1 ± 1.9
Sunkullo quartz monzonite:					
76°08'26"W, 10°39'21"S	Bio	8.59	92.4	8.62	30.9 ± 0.5
	Pl	0.73	79.8	0.579	24.4 ± 0.9

WR, whole rock; Bio, biotite; KF, K-feldspar; Pl, plagioclase

Metal Mining Agency of Japan, 1976) located west of Llaupi in the Cordillera Oriental.

A second group, somewhat younger (±30 Ma), is formed by the rhyodacitic stocks of Mariac and Sunkullo, located northeast of Cerro de Pasco on the eastern limit of the Altiplano, and the quartz rhyodacitic stocks of the Milpo-Atacocha district north of Cerro de Pasco. Similar ages have already been determined for the Churín-West and Paccho Tingo quartz-dioritic to granodioritic stocks (30.2 Ma; Cobbing *et al.*, 1981) located east of the Coastal Batholith in the valley of the Río Huaura; the Huancayan rhyodacitic stock (32.9 Ma; Cobbing *et al.*, 1981) located 20 km northwest of Cerro de Pasco; the Quinua rhyodacitic stock (29.5 Ma; Cobbing *et al.*, 1981) located 12 km northeast of Cerro de Pasco; and various dioritic and monzonitic stocks and dikes located near Oxapampa on the eastern flank of the Cordillera Oriental (27 Ma; Metal Mining Agency of Japan, 1976).

A third group (mid- to late Miocene) is formed by the Yanamate rhyodacitic porphyry stock (15.2 Ma) located 4 km south of Cerro de Pasco; the Chungar granite (13.4 Ma) and the Chalhuacocha granodiorite (10.0 Ma) located in the upper part of the Cordillera Occidental southwest of Cerro de Pasco; and the Rapay granodioritic-granitic lacolith (6.9 Ma) located in the Pativilca valley 10 km northwest of Cajatambo. The presence of this magmatic event has already been demonstrated in the Cordillera Occidental and the Altiplano (Churín-East stock (14.5 Ma), Cobbing *et al.*, 1981; Cordillera Blanca batholith, Cerro de Pasco stock (15.7-14.2 Ma), Silberman and Noble, 1977; Cobbing *et al.*, 1981; Colquijirca stock (13.0-11.2 Ma), Vidal *et al.*, 1984) and may be represented in the eastern flank of the Cordillera Oriental (a dioritic stock east of Oxapampa yielded a K-Ar whole rock age of 14 Ma; Metal Mining Agency of Japan, 1976).

The youngest date obtained is a Pliocene (3.0 Ma) age for the Rupay rhyolitic dike located between Churín and Oyón in the valley of the Río Huaura. This is the first evidence of intrusive magmatism of Pliocene age in this part of the Andes and indicates magmatic activity younger than ignimbrites of the Bosque de Piedra near Huallay (Fig. 1) or ignimbrites of the upper part of the valley of the Río Fortaleza (6.0 Ma; Cobbing *et al.*, 1981).

IMPLICATIONS FOR METALLOGENESIS

The new data presented here suggest that some modifications must be made with respect to the ages of metallogenic provinces in central Peru. All previous data indicate that the hydrothermal polymetallic ore deposits of the central segment of the Peruvian Andes (Soler, 1986) are associated with the mid- to late Miocene magmatic pulse. Radiochronologic data for Hualgayoc (Borredon, 1982), Pasto Bueno (Landis and Rye, 1974), Antamina (McKee *et al.*, 1979), Huaron (Thouvenin, 1984), Cerro de Pasco (Silberman and Noble, 1977), Colquijirca (Vidal *et al.*, 1984), Morococha (Eyzaguirre *et al.*, 1975), Chungar (this work), Yauricocha (Giletti and Day, 1968), Huachocolpa (McKee *et al.*, 1975), Raura (Noble, unpublished data), and Julcani (Noble and Silberman, 1984) yielded ages ranging from 15 to 7 Ma.

The late Eocene-early Oligocene magmatism of central Peru has been regarded as characterized by a lack of associated mineralization (Noble *et al.* 1984). However, data on intrusive stocks from the Milpo and Atacocha ore deposits demonstrate that magmatic rocks of this age are actually mineralized in central Peru. Furthermore, the Milpo-Atacocha district does not seem to be an isolated case — in the Altiplano, uneconomic ore occurrences are associated with the Quinua rhyodacitic stock; unpublished data (quoted by Romani, 1982) suggest the possibility of similar ages for at least part of the Uchucchacua ore deposit located on the physiographic crest of the Cordillera Occidental in the study area (Fig. 2).

On the other hand, in the central segment and in the south-central segment of the Peruvian Andes (Sillitoe, 1976; Soler *et al.*, 1986), mineralization contemporaneous with Oligocene magmatic activity is different in both nature and importance. In the south-central segment, the Andahuaylas-Yauri Batholith is characterized by the presence of numerous skarn-type Cu-Fe deposits (Santa Cruz *et al.*, 1979; Noble *et al.*, 1984), whereas in the central segment plutons include polymetallic Zn-Pb-Ag-Cu skarn and vein deposits.

AGE AND LATERAL EXTENT OF PULSES OF MAGMATIC ACTIVITY IN CENTRAL PERU DURING CENOZOIC TIMES

Additional radiochronologic data are necessary in order to define the latitudinal and longitudinal extent of the Cenozoic magmatic arcs of central Peru. Nevertheless, published data, together with our newly acquired data (Table 1), illustrate the distribution of magmatic activity during Cenozoic times in the transect studied (Fig. 3; Table 2) and are sufficient to demonstrate that this distribution cannot be interpreted in terms of a simple progressive eastward migration, at least in central Peru.

Late Cretaceous and early Cenozoic magmatic activity appears to be represented only in the Coastal Batholith (Pitcher et al, 1985), with ages ranging from 100 to 50 Ma (Cobbing *et al.*, 1981; Beckinsale *et al.*, 1985; Mukasa, 1984). Contemporaneous igneous activity has been suggested for the Cordillera Oriental of central Peru (Mégard, 1978; Carlier *et al.*, 1982); however, recent K-Ar radiochronologic data (Soler and Bonhomme, 1987) show that intrusive bodies previously considered as Late Cretaceous in age are actually of Late Permian to Early Triassic age, which makes the previous hypothesis unconvincing.

The mid- to late Eocene (50-41 Ma) seems to have been a time of magmatic quiescence (Noble *et al.*,

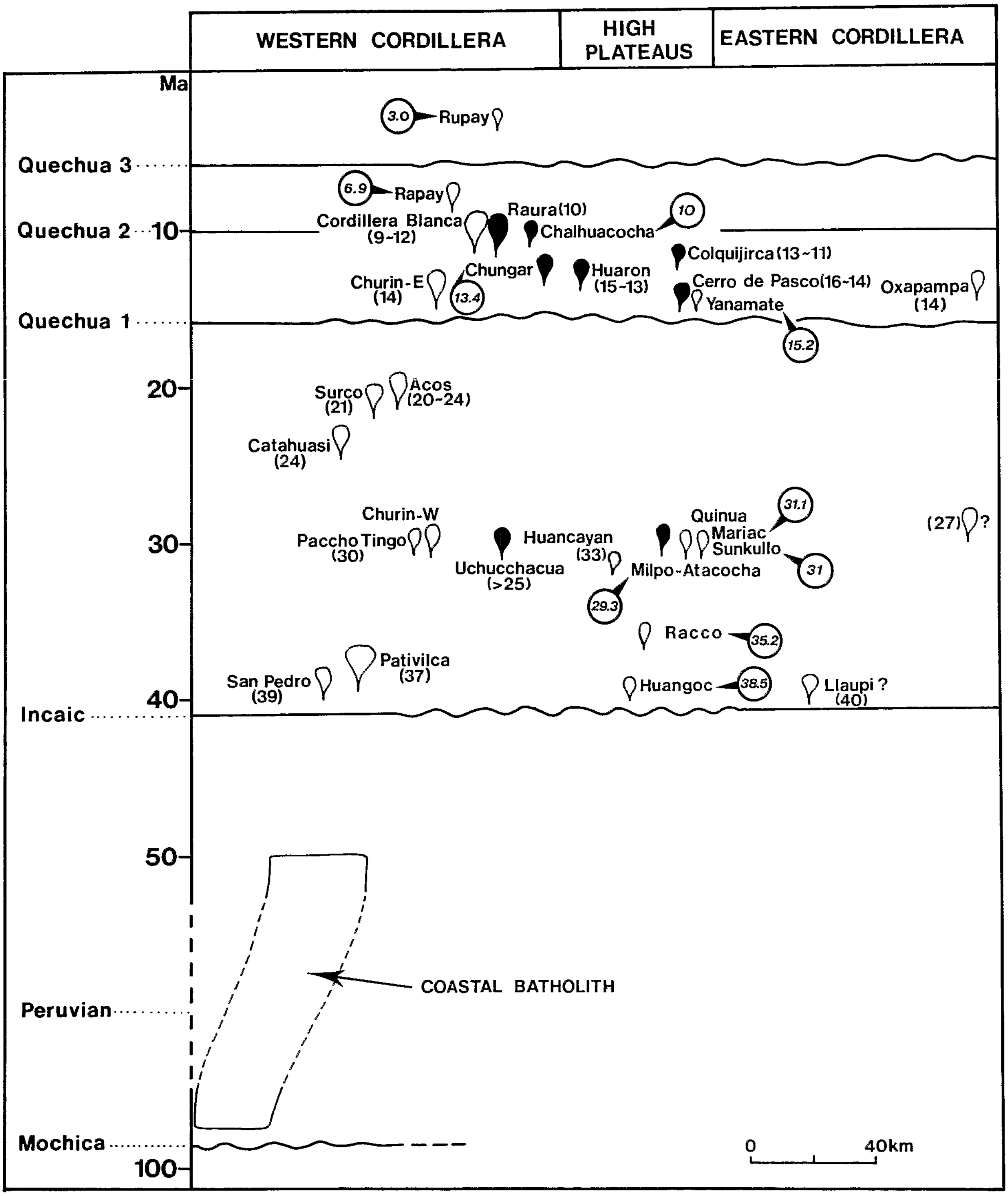

Fig. 3. Space-time distribution of intrusive rocks in central Peru. Previous data in brackets; new data in circles. Solid symbols, mineralized stocks; open symbols, unmineralized stocks.

1979a; Cobbing *et al.*, 1981). Subsequent to late Eocene Incaic compressional tectonics (Steinman, 1929; Mégard, 1978; Noble *et al.*, 1979a), magmatic activity spread to the east. A first pulse of magmatic activity of late Eocene-early Oligocene age (41-34 Ma) is present over the whole Cordillera Occidental and the western half of the Altiplano. In the Cordillera Occidental, this pulse is represented by intrusive rocks, such as the Pativilca and San Pedro granites located within the eastern margin of the Coastal Batholith, and by a thick sequence of volcanic rocks that mantles the post-Incaic erosional surface (Noble *et al.*, 1979a). In the Altiplano, this episode is represented by subvolcanic stocks such as Racco and Huangoc. According to the observations of the Metal Mining Agency of Japan (1976), this pulse would be represented, too, in the Cordillera Oriental by a granite located west of Llaupi. Our own data (Bonhomme and Soler, unpublished) do not confirm the eastern spread of this pulse.

Table 2. Late Eocene to Pliocene magmatic pulses in the central Peruvian Andes, and their susceptibility to mineralization.

Pulse	Age Range	Lateral Extent	Associated Mineralization
I	41-36 Ma	From inside the Coastal batholith to the western part of the Altiplano Extension in the Cordillera Oriental?	None
II	33-29 Ma	From the mid-Pacific slope of the Cordillera Occidental to the eastern margin of the Altiplano Extension in the Cordillera Oriental?	Some Pb-Zn-Ag-Cu vein and skarn deposits, mostly in the eastern part of the Altiplano (Milpo-Atacocha)
III	24-19 Ma	From the mid-Pacific slope of the Cordillera Occidental to the western part of the Altiplano	None
IV	18-7 Ma	From the mid-Pacific slope of the Cordillera Occidental to the eastern slope of the Cordillera Oriental	Numerous Pb-Zn-Ag-Cu vein and skarn deposits in the Cordillera Occidental and the Altiplano
V	6-3 Ma	From the mid-Pacific slope of the Cordillera Occidental to the western part of the Altiplano	Ag epithermal vein mineralizations and/or remobilizations (Huaron)

A second pulse, of mid-Oligocene age, is represented by volcanic rocks and intrusive stocks (Paccho Tingo, Churín-West) on the western flank of the Cordillera Occidental, by subvolcanic stocks (Huancayan, Quinua, Mariac, Sunkullo, Milpo-Atacocha) across the Altiplano, and possibly by dioritic and monzonitic stocks (Oxapampa, Villa Rica) on the eastern flank of the Cordillera Oriental. The western front of the magmatic belt corresponding with this pulse appears as slightly displaced eastward (20-30 km) with respect to the western front of the first pulse.

The available data do not permit a clear discrimination between these two first pulses; the existence of a real hiatus between them still needs to be demonstrated and they can be considered together as a single first major episode. This magmatic belt may be correlated with at least a part of the Andahuaylas-Yauri Batholith located in the south-central segment of the Peruvian Andes, the last manifestations of which have been dated at 33 Ma (Noble *et al.*, 1984).

Apparently, magmatic activity abruptly ceased at about 29 Ma, and mid- to late Oligocene time is characterized by magmatic quiescence. In southern Peru, a tectonic episode has been reported for the mid-Oligocene (Sébrier *et al.*, in press); however, the existence of this tectonic event has not been demonstrated in central Peru. The available data suggest that the lack of magmatic activity throughout mid- to late Oligocene times is general over the Peruvian Andes.

Magmatic activity recommenced in the latest Oligocene (24 Ma) with a third pulse that extended into the early Miocene (24-19 Ma). This event is not documented in our new data but is mainly represented by volcanics in the Cordillera Occidental (Noble *et al.*, 1974; Farrar and Noble, 1976; Noble *et al.*, 1979a,b) and by various isolated quartz-dioritic to granitic stocks located in the western flank of the Cordillera Occidental not far from the Coastal Batholith (Catahuasi, Surco, Acos) (Steward *et al.*, 1974; Cobbing *et al.*, 1981; Mukasa, 1984). The available data suggest that the magmatic belt corresponding to this pulse did not reach the Altiplano and was narrower than earlier (first and second pulses) and subsequent (fourth pulse) magmatic belts.

A fourth pulse of mid- to late Miocene age (18-7 Ma) postdates Quechua-1 compressional tectonics (Mégard, 1978; McKee and Noble, 1982; Mégard *et al.*, 1984). This pulse is represented as volcanic rocks and numerous intrusive stocks, mainly subvolcanic, principally in the Cordillera Occidental and is also represented in the Altiplano (Cerro de Pasco, Yanamate, Colquijirca) and probably in the eastern flank of the Cordillera Oriental (east of Oxapampa). North of the study area, this pulse is represented by the Cordillera Blanca Batholith (Cobbing *et al.*, 1981; Mukasa, 1984; Beckinsale *et al.*, 1985), a southern prolongation of which may be supposed to exist beneath the subvolcanic stocks and volcanic formations of Miocene age in the study area and farther south. This fourth pulse is not interrupted by Quechua-2 compressional tectonics, and it ends with Quechua-3 tectonics at 6 Ma (Romani, 1982; Mégard *et al.*, 1984).

Finally, a fifth pulse of Pliocene magmatic activity occurs in the Cordillera Occidental and in the western part of the Altiplano. In the study area, this pulse is represented by ignimbritic deposits of the Bosque de Piedra near Huallay and by the rhyolitic dike of Rupay in the western flank of the Cordillera Occidental. No magmatic activity younger than 3 Ma is known in the study region.

There is continuity in magmatic activity throughout the Quechua tectonic episode such that the three later pulses may be grouped to constitute a second major magmatic episode. During this second episode, which lasted from 24 to 3 Ma, the eastward migration of the western limit of the magmatic belt is of the same order of magnitude (±30 km) as during the first episode. However, there is no continuity between the two major magmatic episodes; the western limit of manifestations of the third pulse (Catahuasi, Acos, Surco) lies more to the west than does the western limit of the second pulse (Paccho Tingo, Churín-West). Thus, the available data suggest the existence of a retrogressive westward migration of magmatic activity between the two major episodes.

In active margin settings such as the Andes, the presence and the position of calc-alkaline magmatic activity is generally interpreted as being related to the geometry, angle, and velocity of the subduction zone. In this context, the present lack of magmatic activity in central Peru has been interpreted as a consequence of the abnormal, shallow, subhorizontal subduction zone (Mégard and Philip, 1976).

The northern limit of the Plio-Quaternary magmatic arc, associated with normal deep angle subduction, migrates southward so that the disappearance of magmatic activity in the study area after 3 Ma may be regarded as a consequence of the rapid southward migration into this region of the abnormal subhorizontal subduction zone (Pilger, 1984).

The disappearance of magmatic activity nearly 30 Ma ago may be interpreted in the same way. However, the occurrence of a mid-Oligocene tectonic event in southern Peru, the lack of magmatic activity during mid- to late Oligocene times over the Peruvian Andes, and the retrogressive westward migration of magmatism between the two major episodes all suggest that the interruption of magmatic activity in the mid-Oligocene might have been the result of an abrupt modification in modes of subduction angle and/or velocity.

The migration of the western front of magmatic activity during each major episode may be interpreted, therefore, as the result of a progressive modification of subduction geometry, including a progressive change in angle and velocity of subduction and subcrustal erosion along the trench. In contrast, the continuity of magmatic activity through the three Quechua tectonic phases during the second major episode suggests that these tectonic events do not correspond to any major change in subduction mechanism.

Acknowledgements—Field work for this study was conducted as part of a joint Peruvian/French (INGEMMET/ORSTOM) research program dealing with the polymetallic Pb-Zn deposits of Peru. K-Ar analytical work was supported by ORSTOM (UR 606). This paper is a modification of a contribution presented at *IGCP 120: Magmatic Evolution of the Andes* (Santiago, November 1985). The authors thank Drs. W. S. Pitcher and E. J. Cobbing for their helpful reviews.

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