Geological Society of America Bulletin

Zircon U-Pb ages of super-units in the Coastal batholith, Peru: Implications for magmatic and tectonic processes

SAMUEL B. MUKASA

Geological Society of America Bulletin 1986;97;241-254
doi: 10.1130/0016-7606(1986)97<241:ZUAOSI>2.0.CO;2

Notes

Zircon U-Pb ages of super-units in the Coastal batholith, Peru: Implications for magmatic and tectonic processes

SAMUEL B. MUKASA* *Department of Geological Sciences, University of California, Santa Barbara, California 93106*

ABSTRACT

Zircon U-Pb ages on 50 plutonic samples from super-units in the Lima, Arequipa, and Toquepala segments of the Peruvian Coastal batholith range from 188 to 37 m.y., revealing previously unrecognized Jurassic elements. The Jurassic plutons represent a distinct, time-defined, continental arc separated from the Cretaceous arc by a quiescent period of 50 m.y.

Only 4 of the 50 samples have discordant zircons, and these are all from the Arequipa and Toquepala segments. This regionally limited discordance, interpreted to be due to inherited radiogenic Pb from the Precambrian basement, suggests that there are fundamental differences in the nature of the crust beneath the Lima and the Arequipa/Toquepala segments.

On a grand scale, magmatism in the Coastal batholith generally evolved through time from mafic to siliceous melts, but zircon U-Pb ages show that the occurrence of small bodies of old siliceous and young mafic rocks was also important. Close age association between all rock types raises the possibility that mantle-derived mafic magmas provided the heat that produced siliceous magmas in either the underplated wedge of the subduction complex or the lower crust throughout the period of batholith emplacement.

In general, age results confirm that super-units have short time spans. For the Santa Rosa, Paccho, and Linga "super-units," however, mapping generalizations were made in the absence of thorough isotopic age and trace-element data. Remapping of these "super-units" with supporting geochemical and geochronological studies will be required before the emplacement history of the batholith is fully understood.

Dated plutons in the "Paccho super-unit" yield ages between 64.0 and 39.0 m.y. They are thus considerably younger than has been previously recognized and cannot belong to one super-unit. Their young ages also verify the eastward migration of the locus of magmatism through time. A migration rate of 1.3 mm/yr, computed for the rocks along latitude 11°08.1′S on the basis of the ~105-m.y.-old Patap super-unit and a 61-m.y.-old pluton in the "Paccho super-unit," suggests that the geometry of the Andean subduction zone in Peru was very stable during batholith emplacement.

INTRODUCTION

The Coastal batholith crops out almost continuously along the length of the Western Cordillera of Peru (Fig. 1). As large as it may seem, 1,600 km long and 65 km wide, it is only part of an unbroken belt of Mesozoic to Cenozoic plutonic rocks along the western continental margin of South America from Venezuela to Tierra del Fuego (Cobbing and Pitcher, 1972). The batholith is well exposed because of the arid desert conditions, and field mapping in the area by previous workers is far advanced. High relief in a few cases, however, has prevented determination of some intrusive relationships.

Field mapping in the Coastal batholith and its host rocks by Cobbing and Pitcher (1972), Taylor (1973), Myers (1974, 1975a, 1975b), Bussell (1975), Regan (1976), and Cobbing and others (1981) provided the framework on which to base geochronology. These field studies established the tectonic setting of the batholith, determined genetic associations among its plutons, and noted their intrusive relationships.

This study was designed (1) to determine the general emplacement history of the Coastal batholith and associated principal dike swarm on the basis of zircon U-Pb geochronology; (2) to assess time relationships and possible genetic links between some mafic and siliceous plutons which crop out close together; (3) to compare zircon U-Pb with K-Ar ages on plutons for cooling histories, and, in so doing, to test the episodic emplacement hypothesis made implicit by K-Ar data (Wilson, 1975); and (4) to test the super-unit concept, which implies the emplacement of a particular group of plutons approximately together within a limited time and space frame.

TECTONIC SETTING

The Coastal batholith is similar in many respects to other circum-Pacific batholiths, particularly in its geometry and composite nature (Cobbing and Pitcher, 1972; Bateman and Clark, 1974; Armstrong and others, 1977; Bateman, 1981). One major difference, however, is that the Coastal batholith has maintained its integrity, unlike batholiths of western North America; the latter are partly dismembered, and their precise relationships with the plate margin have been obscured by tectonic disruptions and accretions (Atwater, 1970; Schweickert and Cowan, 1975; Schweickert, 1976; Jones and oth-

*Present address: Department of Geology, 1112 Turlington Hall, University of Florida, Gainesville, Florida 32611.

Additional material for this article (two appendices) may be secured free of charge by requesting Supplementary Data 86-04 from the GSA Documents Secretary.

Geological Society of America Bulletin, v. 97, p. 241–254, 11 figs., 2 tables, February 1986.

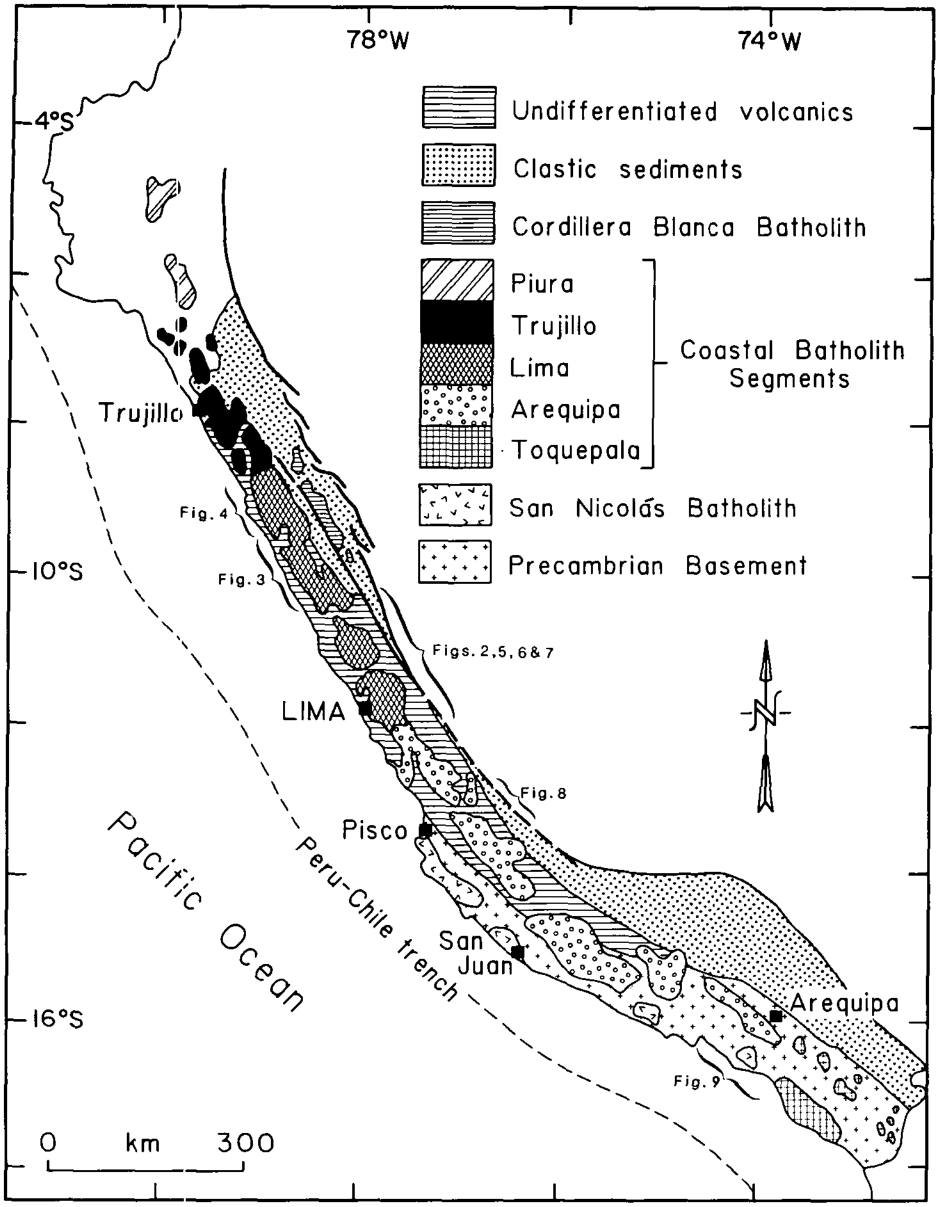

Figure 1. The five compositional segments in the Peruvian Coastal batholith, and the locations for Figures 2–9 (geology after Cobbing, 1976).

ers, 1977, 1978; Saleeby, 1977, 1981). There is clear evidence that subduction of oceanic lithosphere has been largely normal to the Peruvian continental margin, at least since the beginning of batholithic emplacement in middle Mesozoic time (Herron, 1972). Consequently, no major latitudinal translations have occurred. Even the relatively isolated coastal Precambrian belt of southern Peru, the Arequipa massif, suspected of being an allochthonous terrane (see, for example, Nur and Ben-Avraham, 1982), has not moved, at least since Devonian (Knight and others, 1984) or Silurian (Mukasa, 1986b) time.

The Coastal batholith consists of more than 1,000 individual plutons, the narrow east-west dimensions of which were probably controlled by a deep-seated lineament or weak zone (Pitcher and Bussell, 1977). Such a structure may be attributed to rifting, which was widespread in South America as the Gondwana supercontinent fragmented in early to middle Mesozoic time (Dalziel, 1985). In northern and central Peru, the batholith invaded a deep, elongate, marginal basin filled with volcanic flows and well-stratified marine and volcaniclastic sequences nearly 9,000 m thick (Atherton and others, 1983). The marginal basin was shallow in the south, and from ~14°S latitude to the border of Chile, the batholith intruded mainly Precambrian basement (Fig. 1). The basement rocks include schists, amphibolites, and migmatitic granulite-facies gneisses—some as old as ~2.0 b.y. (Dalmayrac and others, 1977, 1980; Cobbing and others, 1977b; Shackleton and others, 1979).

The Coastal batholith was emplaced in the epizone. A high level of emplacement is reflected by the presence of ring dikes and granophyric plutons. Volcaniclastic country rocks of the Casma Group, furthermore, have retained their sedimentary fabrics; their burial metamorphism has produced only zeolites, prehnite, and pumpellyite (Pitcher, 1978). Pressure estimates of 1–2 kbar were obtained from calc-silicate assemblages in the country rocks (Atherton and Brenchley, 1972). Estimates of 2–3 kbar were obtained from fluid-inclusion equilibration pressures in quartz from the plutonic rocks (Agar, 1978).

SUPER-UNITS AND SEGMENTS IN THE COASTAL BATHOLITH

Concerted mapping efforts in the Coastal batholith led to the recognition of several suites of genetically related plutons (for example, Cobbing and Pitcher, 1972; Cobbing and others, 1977a). Each suite was identified according to field criteria such as rock types, modal variations, textures and fabrics, relative intrusive relationships, content and character of any xenoliths, and relationships with the few distinct generations of dike swarms. More recently, most of these groupings were confirmed by major- and trace-element studies (Atherton and others, 1979; McCourt, 1981). For the Coastal batholith, these suites have been termed "super-units" (Cobbing and others, 1977a); the term has been adopted in this paper for consistency.

Assemblages of super-units occur together over large areas. They die out, however, in both directions along the northwest-southeast trend of the batholith and are succeeded by other assemblages, which gives the batholith a segmented character. Five compositionally distinct segments (Piura, Trujillo, Lima, Arequipa, and Toquepala in Fig. 1) have been recognized (Cobbing and others, 1977a; Cobbing and Pitcher, 1983), but only the Lima and Arequipa segments have been studied in detail. Work reported here focuses on the two best-studied segments and deals with the Toquepala segment only in reconnaissance. Descriptions of super-units in the three segments are summarized in Table 1.

GEOCHRONOLOGY: PREVIOUS STUDIES

The most systematic attempt to unravel the emplacement history of the Coastal batholith

TABLE 1. GENERALIZED EVOLUTIONARY PATH AND BRIEF DESCRIPTIONS OF SUPER-UNITS IN THE LIMA, AREQUIPA, AND TOQUEPALA SEGMENTS OF THE PERUVIAN COASTAL BATHOLITH

Super-unit	Compositional trend	Field and petrographic characteristics	References
		Lima Segment	
Pativilca	Aplogranite Monzogranite	Large, steep-walled and flat-roofed pluton emplaced in two pulses; porphyritic with perthitic orthoclase megacrysts; plagioclase (An_{30}–An_5); large quartz; biotite is the mafic mineral	McCourt (1981); Pitcher (1985)
Paccho	Tonalite Quartz diorite Diorite	Multiple intrusion with many pulses; mafic minerals commonly altered; clinopyroxene resorbed and mantled by hornblende; plagioclase (An_{62}–An_{40} with An_{82}–An_{80} cores and An_{20} rims); quartz and microperthite occur interstitially	McCourt (1981); Pitcher (1985)
Cañas-Sayán	Aplogranite Monzogranite	Cañas pluton is circular; Sayán pluton is arcuate; Cañas is coarse-grained, with perthitic orthoclase mantled by sodic plagioclase; resorbed bipyramidal quartz; weakly zoned plagioclase (An_{35}–An_{18}); Sayán is porphyritic, with perthitic orthoclase megacrysts (~2.5 cm); plagioclase (An_{30}–An_{20}); hornblende and biotite in both plutons	Taylor (1973); McCourt (1981); Pitcher (1985)
Puscao	Aplogranite Monzogranite Granodiorite	Large, bell-jar plutons and ring dikes; vertically zoned; coarse grained, with complexly zoned plagioclase (An_{50}–An_{15}); interstitial perthitic orthoclase; quartz; hornblende, some cored by clinopyroxene; scattered biotite flakes	McCourt (1981); Pitcher (1985)
San Jerónimo	Syenogranite Monzogranite Granodiorite	Primarily in ring dikes; porphyritic granophyre with bipyramidal quartz and plagioclase phenocrysts (An_{40}–An_{10})	Bussell and others (1976); McCourt (1981)
La Mina	Granodiorite Tonalite	Zoned, multi-pulse, circular plutons; medium grained, with zoned plagioclase (An_{82}–An_{15}); hornblende and biotite both present; interstitial quartz and K-feldspar	Bussell and others (1976); McCourt (1981)
Humaya	Granite Granodiorite	Elongate and steep-walled plutons; coarse grained, with euhedral "books" of biotite; well-formed hornblende prisms; euhedral plagioclase (cores are An_{48} and rims are An_{24}–An_{13}); quartz and K-feldspar	Cobbing and others (1981); Pitcher (1985)
"Santa Rosa"	Leucogranite Monzogranite Granodiorite Tonalite Quartz diorite	Massive, multi-pulse, steep-walled, and very complex plutons; the common tonalite is coarse grained, with euhedral, zoned plagioclase (An_{65}–An_{13}); hornblende and biotite in mafic clots; quartz and K-feldspar interstitial; quartz diorites with augite and hypersthene	Cobbing and others (1981); McCourt (1981); Pitcher (1985)
Jecuan	Monzogranite Granodiorite Tonalite	Small, steep-walled plutons; mafic minerals ubiquitously altered; euhedral plagioclase; quartz; euhedral K-feldspar	Cobbing and others (1981); Pitcher (1985)
Patap	Diorite Gabbro	Complex, multi-pulse, metasomatized, and hybridized plutons; primary mineral assemblages have olivine, orthopyroxene, clinopyroxene, hornblende, and calcic plagioclase	Myers (1975b); Regan (1976); Cobbing and others (1981)
		Arequipa Segment	
Linga (Arequipa)	Monzogranite Monzonite Monzodiorite Monzogabbro	Elongate, steep-walled, flat-roofed plutons; finer grained than most super-units in the Lima segment; anhedral to subhedral pink K-feldspar; anhedral quartz; subhedral to euhedral plagioclase; biotite and hornblende present	Le Bel (1979); Cobbing and Pitcher (1983); Pitcher (1985)
Tiabaya	Monzogranite Granodiorite Tonalite Diorite	Elongate, steep-walled, flat-roofed, and predominantly granodioritic plutons; coarse and medium grained; euhedral plagioclase (An_{42}–An_{24}); acicular hornblende; euhedral biotite; interstitial quartz and microperthite	Moore (1979, 1984); Pitcher (1985)
Incahuasi	Monzotonalite Tonalite Dioite	Large, elongate, steep-walled, flat-roofed, and moderately well-foliated plutons; coarse to medium grained; euhedral plagioclase (An_{55}–An_{25}); hornblende and biotite present; interstitial quartz and K-feldspar	Moore (1979, 1984); Pitcher (1985)
Pampahuasi	Tonalite Diorite	Two magmatic pulses in elongate, steep-walled plutons; coarse-grained euhedral plagioclase (An_{56}–An_{30}); hornblende with poikilitic biotite; interstitial quartz and K-feldspar	Moore (1979, 1984); Pitcher (1985)
Linga (Ica)	Monzogranite Monzonite Monzodiorite	Elongate, steep-walled, flat-topped, multi-pulse plutons; medium to coarse grained; euhedral plagioclase (An_{55}–An_{45}); prismatic clinopyroxene; interstitial quartz and microperthite; euhedral K-feldspar in differentiated variants	Agar (1978); Pitcher (1985)
		Toquepala Segment	
Yarabamba	Granodiorite Monzonite Monzodiorite	Large, elongate, steep-walled, flat-topped plutons; medium to coarse grained; plagioclase crystals in matrix of quartz and pink or gray K-feldspar; euhedral biotite and hornblende	Garcia (1968); Le Bel (1979); Pitcher (1985)
Ilo	Tonalite Diorite	Large, linear, and foliated plutons; anhedral plagioclase, quartz, and K-feldspar; euhedral hornblende mantled by biotite	Pitcher (1985)
Punta Coles	Monzotonalite Tonalite Diorite Gabbro	Irregular remnants of foliated plutons with a very high color index; calcic plagioclase; hornblende; intensely fractured and chloritized	Pitcher (1985)

Note: The youngest super-unit is at the top and the oldest at the bottom for each segment.

quantitatively was that of Wilson (1975). He performed 124 K-Ar age determinations, mostly on cogenetic minerals from plutons in the Lima segment. Previously, Stewart and others (1974) had tabulated and evaluated the few existing age data on the batholith. Subsequently, McBride (1977), Moore (1979, 1984), and Le Bel (1979) contributed K-Ar and Rb-Sr age data on plutons in the Arequipa and Toquepala segments.

The above studies led to the following general conclusions. (1) Magmatic activity in the Lima segment began ~105 m.y. ago and ceased 35 m.y. ago, a duration of 70 m.y. (Stewart and others, 1974; Wilson, 1975). (2) The emplacement of plutons in the Lima segment of the batholith was episodic. Wilson (1975) defined three intrusive episodes separated by periods of relative quiescence: 105–85 m.y. ago, the period of gabbroic, meladioritic, and tonalitic pluton emplacement; 75–56 m.y. ago, that of granodioritic plutons; and 39–35 m.y. ago, that of many of the granites and monzogranites. (3) Magmatic activity in the Arequipa and Toquepala segments began 155 m.y. ago and ended 80 m.y. ago (McBride, 1977; Moore, 1979, 1984; Le Bel, 1979).

More recently, units with K-Ar ages of 190 m.y. have been identified in the Toquepala segment (E. J. Cobbing, 1984, written commun.). These include the gabbroic and dioritic plutons near Ilo which now comprise the newly designated Punta Coles super-unit.

Conflicting geochronologic data have been published on the Linga super-unit. Le Bel (1979) produced a 20-point Rb-Sr isochron with an age of 68 ± 3 m.y. on a suite from the Arequipa region. Beckinsale and others (1985) generated a 96 ± 3-m.y. isochron on a suite of rocks from the Ica region. This second isochron agrees with the K-Ar date of 97 m.y. B.P. obtained earlier by Moore (1979) on the same rocks. It has been argued that the 68 ± 3-m.y. Rb-Sr isochron of Le Bel (1979) on rocks from the Arequipa region reflects resetting by the copper-porphyry systems of Cerro Verde and Santa Rosa. On the other hand, the 96 ± 3-m.y. isochron by Beckinsale and others (1985) on similar rocks in the Pisco-Ica region has been considered a "good age" on pristine Linga material.

Unfortunately, the multiplicity of intrusions, spanning tens of millions of years, has severely complicated interpretation of the K-Ar and Rb-Sr data in many instances. For the K-Ar system in particular, older intrusions were apparently partially and unpredictably degassed by successively younger ones. Consequently, cogenetic phases now yield very different ages that are outside the error limits of their respective argon-retention or argon-blocking temperatures. The likelihood of plutons incorporating argon from previous systems is high, particularly in the Arequipa and Toquepala segments. The Ilo and Punta Coles super-units in the Toquepala segment, for example, clearly cut through 2.0-b.y.-old granulites which are rich in potassium feldspar and thus also in radiogenic argon. These complications necessitated the choosing of "preferred" ages in the K-Ar studies reviewed—an exercise that is unavoidably subjective.

Zircon U-Pb ages presented in this report help greatly in resolving these problems and uncertainties. The high temperature stability of zircon enables the mineral to withstand thermal disturbances (for example, multiple intrusions and associated hydrothermal circulation) more successfully than the phases used in the K-Ar and Rb-Sr methods of dating.

TABLE 2. COMPARISON OF U-Pb AND K-Ar AGES FOR THE PERUVIAN COASTAL BATHOLITH

Super-unit	Lithologies	Ages m.y. K/Ar	Ages m.y. U/Pb
Lima Segment			
Pativilca	Monzogranite-aplogranite	33	37
Santa Eulalia (unit)	Granodiorite	60†	59
Paccho	Diorite-tonalite	. .	39–64
Cañas	Monzogranite-aplogranite	61	65
Puscao	Granodiorite-monzogranite	61	65–6[illegible]
Sayán	Monzogranite-aplogranite	61	68
San Jerónimo	Granodiorite-monzogranite	62	68
La Mina	Tonalite-granodiorite	66	71
Humaya	Granodiorite-granite	73	73
"Santa Rosa"	Diorite-monzogranite	75–90	50–9[illegible]
Jecuan	Tonalite-monzogranite	102	101
Patap	Gabbro-diorite	>102	>102
Arequipa Segment			
Cerro Verde (unit)	Monzonite	58	61
Linga (Arequipa)	Monzogabbro-monzogranite	68§	67–71
Tiabaya	Diorite-monzogranite	81	78–86
Incahuasi	Diorite-monzotonalite	83	. .
Pampahuasi	Diorite-tonalite	97	94
Linga (Ica)	Monzodiorite-monzogranite	97	101
Patap	Gabbro-diorite	>102	>102
Toquepala Segment			
Yarabamba	Monzodiorite-granodiorite	59	62–6[illegible]
Ilo	Diorite-tonalite	94–155	. .
Punta Coles	Gabbro-monzotonalite	190	184–188

Note: All K-Ar ages are from work by Stewart and others (1974), Wilson (1975), McBride (1977), Moore (1979, 1984), and Estrada (unpub. data).
†Rb-Sr data by Beckinsale and others (1985).
§Rb-Sr data by Le Bel (1979).

ANALYTICAL METHODS

Zircon-separation and column-chemistry procedures used for this study are similar to those used by Krogh (1973) and Chen and Moore (1982) and are therefore not described here.

All uranium concentrations and ~75% of all lead-isotopic compositions and concentrations were measured on a computer-operated, 35-cm-radius, 90°-sector, single-focusing, solid-source AVCO mass spectrometer. The remaining 25% of all lead-isotopic compositions and concentrations were measured on a fully automated, Finnigan MAT Model 261, thermal-ionization, multicollector mass spectrometer equipped with eight fixed Faraday cups and one secondary electron multiplier that permitted simultaneous collection of the four Pb isotopes.

Ages are precise to within ±1% (2 σ) because of the high $^{206}Pb/^{204}Pb$ ratios (indicating that almost all of the Pb in the zircon is radiogenic) and because the mean standard deviations on Pb ratios except $^{206}Pb/^{204}Pb$ are <0.15% and those on U and Pb concentrations are <0.25% (see Chen and Moore, 1982, for calculation details).

Nonradiogenic corrections are based on the Pb-isotope compositions of feldspars recovered from the same samples. The feldspar data, with ranges of $^{206}Pb/^{204}Pb$: 17.580–20.803 and $^{207}Pb/^{204}Pb$: 15.555–15.709 have precisions of 0.08% for $^{204}Pb/^{206}Pb$ and 0.04% (or better) for $^{207}Pb/^{206}Pb$ and $^{208}Pb/^{206}Pb$ (Mukasa, 1986a). The young age of many units in the batholith makes nonradiogenic Pb corrections significant in a few cases, but generally $^{206}Pb/^{204}Pb$ ratios exceed 1,000. Measured blanks consistently range between 0.3 and 0.5 ng, but as indicated Pb blanks based on ^{204}Pb abundances in the zircon analyses are in one case as high as 15 ng, some of the zircons contain inclusions and other impurities whose Pb-isotopic signatures are identical with or similar to the common Pb as determined from cogenetic feldspars. Use of common-Pb ratios for nonradiogenic-Pb corrections in zircons is therefore justified.

RESULTS

The analytical data and calculated ages are tabulated in Appendix 1.[1] The U-Pb ages are also shown in Figures 2–11 and summarized in Table 2.

Of the zircon U-Pb ages reported from the Coastal batholith, which range between 188 and 37 m.y., 92% are concordant within estimated analytical errors. Appendix 1 lists $^{207}Pb/^{206}Pb$ ages for the sake of completion, but, owing to their large inherent uncertainty in the age range under consideration, their usefulness is limited, and they are not discussed in the text. (A line from the origin through the data point to the concordia curve, giving the $^{207}Pb/^{206}Pb$ age, is

[1] Appendices 1 and 2 are available free of charge by requesting Supplementary Data 86-04 from the GSA Documents Secretary.

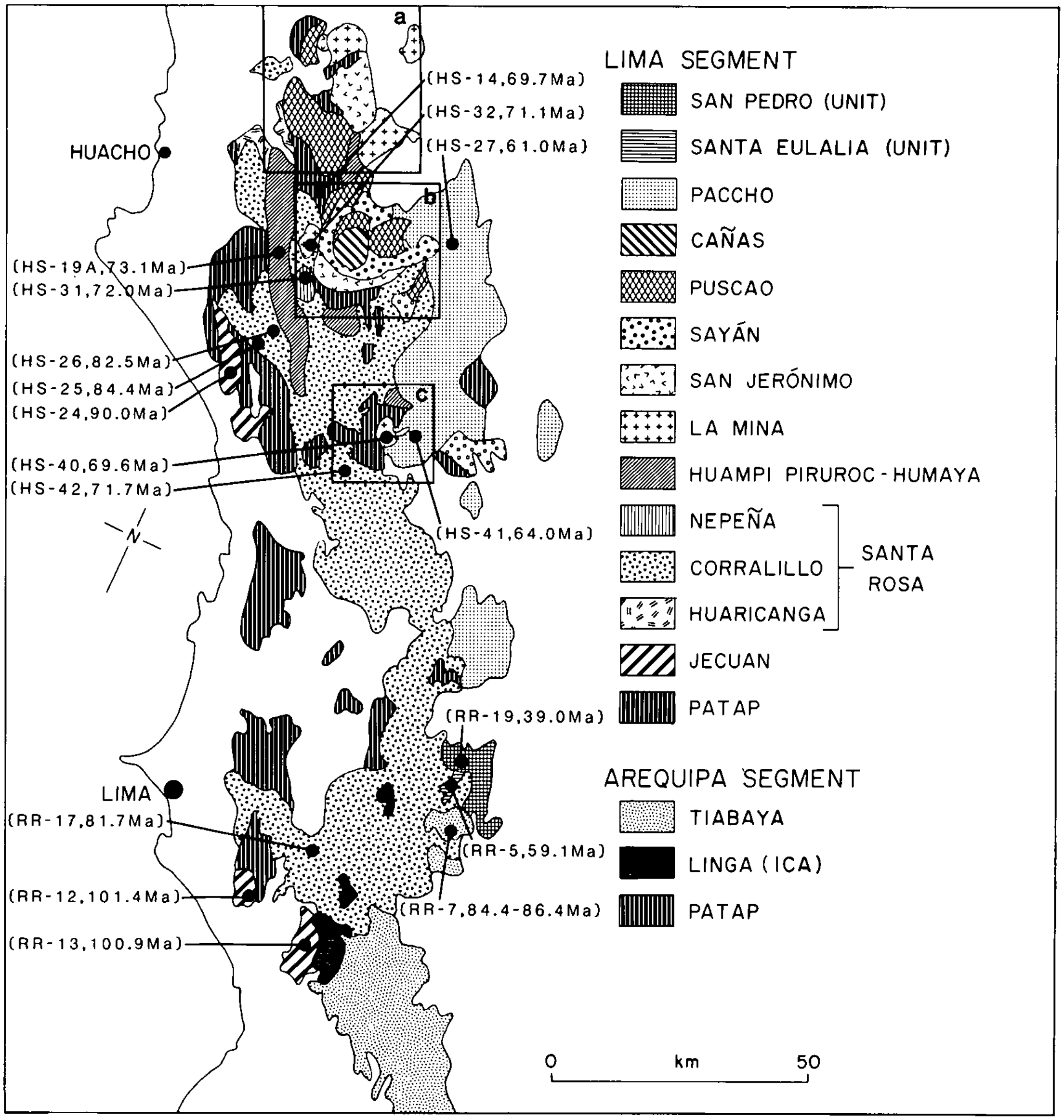

Figure 2. Huaura-Chillon plutonic complex, its sample locations and zircon U-Pb ages. The 69.7-m.y.-old diorite (HS-14) is included with Patap in this map. Boxes a, b, and c are the locations of Figures 6, 5, and 7, respectively (geology after Cobbing and others, 1981).

not resolvable from the concordia curve itself in young zircons.) Moreover, agreement between $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ is not necessarily indicative of concordance for zircons in this age range, for which the concordia curve is nearly linear. The complete lack of an inherited Precambrian component in all but 8% of the zircon samples, however, and age agreement between various size fractions with different magnetic properties and U content strongly suggest concordance. The small amount of radiation damage experienced by these young zircons relative to Precambrian zircons reported in other studies (for example, studies summarized in Gebauer and Grunenfelder, 1979) favors Pb retention. Supporting evidence for concordance is also provided by the agreement of zircon ages on four plutons emplaced within a very short time period (<5 m.y.) in the Huaura ring complex with the ages of the observed intrusive sequence.

DISCUSSION OF RESULTS

For simplicity and clarity, the zircon U-Pb ages for each segment of the batholith are discussed separately and in order from oldest to youngest in each segment.

Lima Segment

Ages were determined on all super-units in the Lima segment except Patap gabbros. Determinations are presented on samples collected between 50- and 1,850-m elevations along transverse river valleys, which provide the only relatively easy and practical access across the Andes. These river valleys within the Lima segment are, from north to south, Rio Fortaleza, Rio Pativilca, Rio Supe, Rio Huaura, Rio Seco, Rio Chancay, Rio Rimac, and Rio Lurin. Two additional samples were acquired from the Casma plutonic complex, ~75 km north of the Rio Fortaleza. All sample locations for the segment are shown in Figures 2–7.

Patap and Jecuan Super-Units. The oldest plutons dated so far in the Lima segment are the Atocongo monzogranite (sample RR-12) in the Rio Lurin valley and another pluton nearby in Quebrada Pucará (RR-13), just southeast of Lima (Fig. 2). Their emplacement ages are 101.4 m.y. and 100.9 m.y., respectively. These plutons have been correlated with others of similar characteristics; together, they constitute the Jecuan super-unit (Cobbing and Pitcher, 1983). The Lachay monzogranite (HS-24 in Fig. 2) was included in this correlation. Zircon U-Pb crystallization ages for this pluton, however, are concordant at 90.0 m.y., making it ~11 m.y. younger than the other two dated plutons in the super-unit. It is therefore suggested that the Lachay monzogranite does not belong to the Jecuan super-unit.

No zircon U-Pb ages were obtained on the Patap super-unit, but the age of its constituent gabbros can be bracketed with the 101.4-m.y. age of the Atocongo monzogranite by which it is cut and the middle Albian age of the ammonites (Wilson, 1963) found in the volcaniclastics and turbiditic sedimentary rocks which the gabbros intrude. Accordingly, the age of the Patap super-unit is estimated to be between ~106 and 101.4 m.y. old.

Santa Rosa Super-Unit. The Santa Rosa super-unit provides the best rock suite to test the super-unit concept because of its great areal extent and wide compositional range. The impetus for this part of the study comes from the report of Cobbing and Pitcher (1972) that identical magmas were emplaced in separate plutons at the same relative time over large areas of the batholith.

For 11 zircon samples collected throughout the Santa Rosa super-unit, age data group as follows: the Purmacana pluton (sample HS-39), mapped as "Huaricanga-type" Santa Rosa by Cobbing and others (1981) yields concordant zircon U-Pb ages at 91.0 m.y. (Fig. 3). The dioritic border facies (HS-25) of the Pampa Ihuanco pluton, 70 km to the south, categorized as "Corralillo-type" Santa Rosa (Fig. 2), is dated at 84.4 m.y. Tonalite, the core phase and most voluminous rock of this pluton, has a zircon age of 82.5 m.y. (sample HS-26). The dioritic border facies grades into the tonalitic main body of this pluton, which suggests that differentiation took place. As ages in this report have a maximum analytical error of ±1% (2 σ), it is probable that differentiation of the Pampa Ihuanco pluton took 3.5 m.y., at most. A virtually identical age of 81.7 m.y. comes from a "Corralillo-type" pluton (sample RR-17 in Fig. 2) which crops out 104 km south of the Pampa Ihuanco samples and 25 km east-southeast of Lima.

Emplacement of the above-mentioned plutons of the Santa Rosa super-unit was followed, 9 to 10 m.y. later, by that of the "Nepeña-type" Santa Rosa pluton of the Rio Huaura valley (Fig. 2) (sample HS-31) with a zircon age of 72.0 m.y. This intrusive activity at 72 Ma resumed with magmas so similar to those formed during 91–81 Ma that they were assigned to the same super-unit. Atherton and others (1979) and McCourt (1981), however, give trace-element evidence suggesting petrogenetic differences between the two magma batches. The age differences presented here support this.

Other "Santa Rosa–type" plutons greatly extended the age span of this super-unit toward younger ages: A dark variety of Santa Rosa tonalite in the Rio Chancay valley (HS-42 in Fig. 2), mapped as "Corralillo-type" (Cobbing and others, 1981), has zircon U-Pb ages of 71.7 m.y., 10 m.y. younger than more representative plutons. Sample HS-44 (Fig. 3) has an age of 70.6 m.y., 20 m.y. younger than the supposedly correlative Purmacana pluton unit a few kilometres to the south. The Chimbote pluton (sample HS-45 in Fig. 4) is dated at 70.6 m.y.—also 20 m.y. younger than the age of plutons with which it has been correlated. The Cerro Muerto pluton, (sample HS-38 in Fig. 3), with an age of 64.0 m.y., may be another entity that is not a part of "Corralillo-type" Santa Rosa as presently mapped (Cobbing and others, 1981). With respective ages of 59.1 m.y. and 49.7 m.y., the Santa Eulalia pluton (RR-5 in Fig. 2) and the Cerro Aislado pluton (HS-46 in Fig. 4) should be treated as quite different units that represent very young magmatic events and that happen to have a Santa Rosa–like field appearance.

In summary, zircon U-Pb ages of plutons constituting the bulk of what has been mapped as the Santa Rosa super-unit fall into three prin-

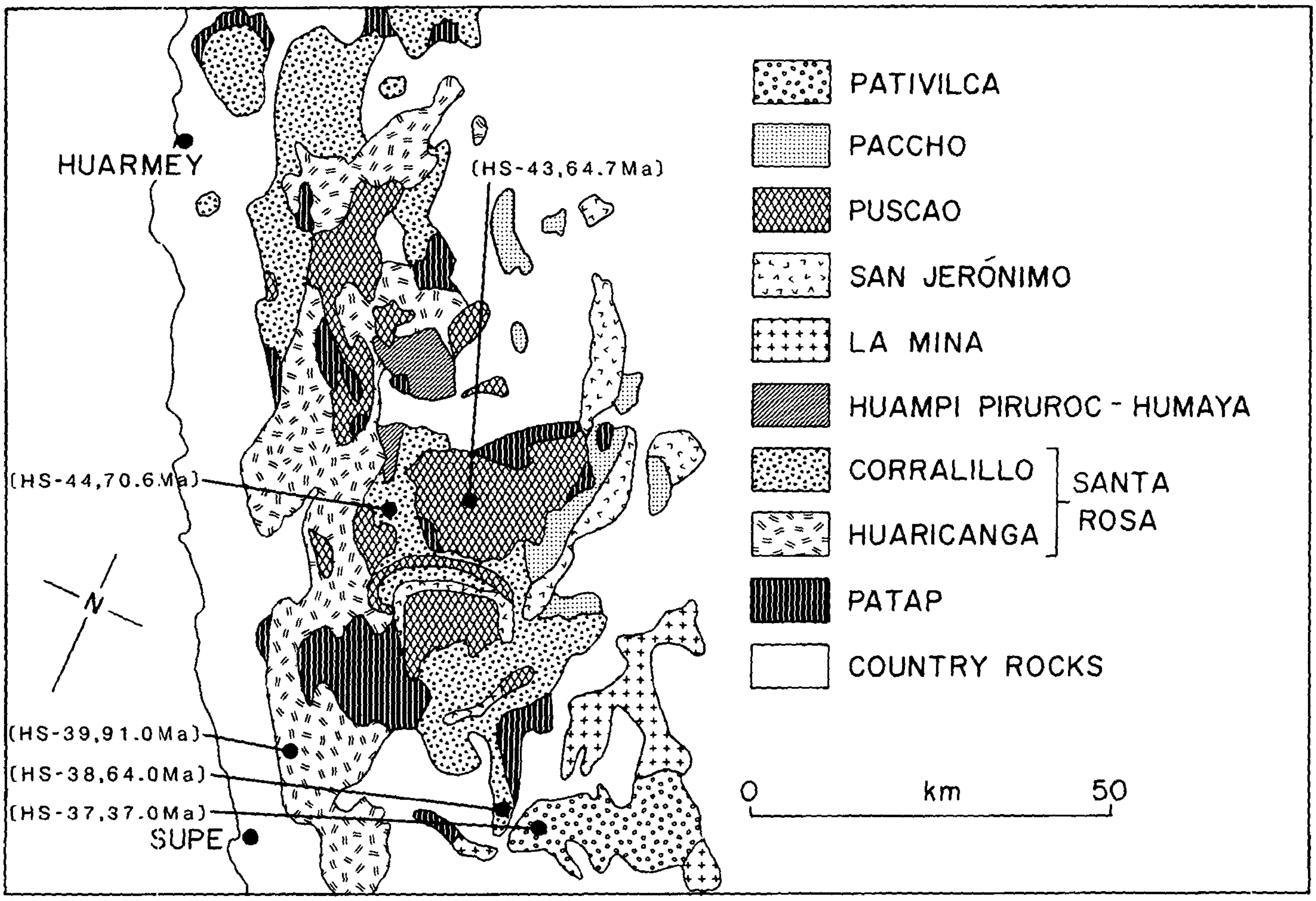

Figure 3. Sample locations and zircon U-Pb ages for the Fortaleza plutonic complex (geology after Cobbing and others, 1981).

cipal groups, indicating that the super-unit was not assembled with magmas from a single melting cell. The earliest plutons in the super-unit, such as Purmacana, were emplaced at 91.0 Ma. After quiescence of 6 to 7 m.y., the bulk of the Santa Rosa super-unit ("Corralillo-type" tonalites) was emplaced between 84.4 and 81.7 Ma. A period of virtually no magmatism that lasted 9 to 10 m.y. followed. Between 72.0 Ma and 70.6 Ma, plutons, including those of the Nepeña-type tonalites, intruded and crystallized. The relationship between the Cerro Muerto (64.0-m.y.), Santa Eulalia (59.1-m.y.), and Cerro Aislado (49.7-m.y.) plutons and the three rock groups constituting the rest of the Santa Rosa super-unit is obscure; their ages and sizes are so uncharacteristic of the three principal rock groups in the super-unit that treating them as separate units is warranted.

Humaya Super-Unit. At its type locality in Hacienda Humaya (HS-19 in Fig. 2), the Humaya granodiorite is lithologically distinct, with large, prominent books of biotite, commonly up to 1 cm across, and potassium feldspar veining. Zircons from the veins are distinct morphologically, have more advanced radiation damage, and have 12 times more uranium than the granodiorite host. Three zircon fractions from the unveined parts of sample HS-19A yield concordant ages that average 73.1 m.y. In contrast, a single zircon fraction from the feldspar veins (HS-19B) shows slight discordance, with $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 66.8 m.y. and 70.1 m.y., respectively.

Plutons of the Humaya super-unit are the youngest cut by the Santa Rosa dike swarm. A zircon age of 73.1 m.y. on one of the Humaya super-unit plutons therefore provides an upper limit to the age of the dikes.

La Mina Super-Unit. Plutons of the La Mina super-unit are the first manifestation of a drastic change in magmatic style: very large plutons with a spectrum of rock types give way to fairly small, more or less equidimensional plutons with limited compositional ranges. The La Mina super-unit contains the earliest centered complexes. Its best exposed plutons occur in the centered ring complexes of Huaura (Figs. 2 and 5) and Quebrada Paros (Figs. 2 and 6). The San Miguel pluton of the Huaura centered ring complex is crudely zoned; tonalite forms the border facies, and granodiorite, the core. Zircon sample HS-32 (Fig. 5) from the tonalite gives concordant crystallization ages of 71.1 m.y.

The La Mina age sample was collected in the tonalite border facies to provide a crystallization age for the super-unit and to constrain the lower age limit of the Santa Rosa dike swarm. Most members of this dike swarm are truncated at the outer contact of the San Miguel pluton, and others penetrate only a short distance into the marginal facies. These relationships accurately bracket the age of the dike swarm between 73.1 and 71.1 m.y. They also support the whole-rock K-Ar ages of Wilson (1975) for the dikes, which averaged 73.4 ± 1.9 m.y. They do not support his hornblende ages of 68.5 and 59.6 m.y. for the same dikes, however.

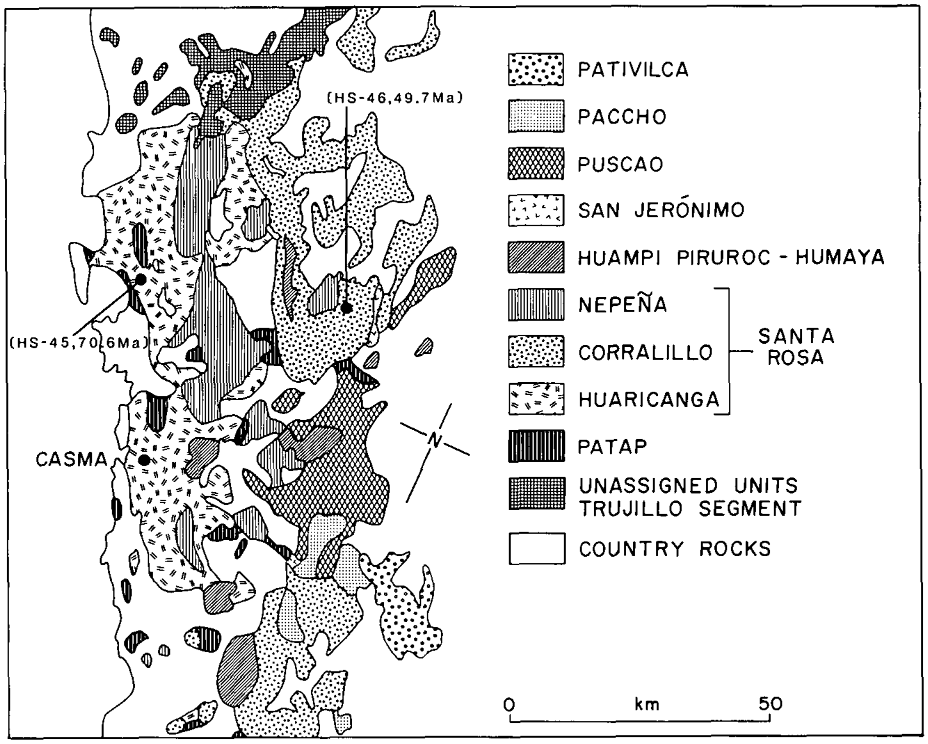

Figure 4. "Santa Rosa super-unit" zircon U-Pb ages in the Casma plutonic complex (geology after Cobbing and others, 1981).

San Jerónimo Super-Unit. Intrusive relationships between super-units of the centered ring complexes in the Lima segment show that these plutons are very close in age. For example, back-veining and composite dike relationships have been noted between some super-units (Cobbing and others, 1981). The same authors have determined that, for the Huaura centered ring complex, the San Jerónimo super-unit is oldest, followed, in order of decreasing age, by the Sayán, Puscao, and Cañas plutons. Zircon data corroborate these intrusive relationships.

Two San Jerónimo super-unit plutons have been dated, the granophyric facies of the super-unit in the Huaura ring complex (sample HS-34 in Fig. 5) and the granophyre in the ring complex of Quebrada Paros (sample HS-36 in Fig. 6). Zircon ages for the two samples are internally concordant at 67.6 m.y. and 68.7 m.y., respectively. On the basis of a maximum analytical error of ±1% (2 σ) on all ages, these plutons, separated by 35 km, were emplaced more or less contemporaneously.

Puscao Super-Unit. Plutons of the Puscao super-unit occur in three of the four ring complexes and are the largest. This super-unit comprises the Puscao facies of coarse monzogranite and the Tumaray facies of layered, granophyric aplogranites (Cobbing and Pitcher, 1972). Several large Puscao plutons without ring-complex associations are also present in the Lima segment. To determine the time span of plutons constituting the extensive Puscao facies, three samples were collected and analyzed. Sample HS-29 (Fig. 5) has concordant U-Pb ages of 66.2 m.y., and HS-35 (Fig. 6) yields a crystallization age of 66.6 m.y., suggesting contemporaneous emplacement of these two plutons. A third sample (HS-43 in Fig. 3) is dated at 64.7 m.y., only slightly younger than the other two.

Three separate plutons of the Puscao super-unit, distributed over 100 km and previously shown to be genetically related on the basis of major- and trace-element analyses (Atherton and others, 1979; McCourt, 1981), thus are approximately the same age. It is likely that they rose simultaneously from a common magmatic reservoir. Nearly identical plutons crop out sporadically for 170 km to the north of sample HS-43. If these are also the same age, the melting cell from which the Puscao super-unit was derived must have been immense.

Cañas-Sayán Super-Unit. The Cañas-Sayán super-unit crops out only in the Huaura ring complex (Fig. 5). It consists of two large plutons in the center of the complex and three small bodies of Sayán monzogranite on the southern fringes. The circular, aphyric Cañas pluton is similar in composition to the arcuate, monzogranitic, orthoclase-phyric Sayán pluton.

Two samples (HS-12 and HS-28 in Fig. 5) from the Sayán monzogranite, analyzed, in part, to determine the reproducibility of ages within a

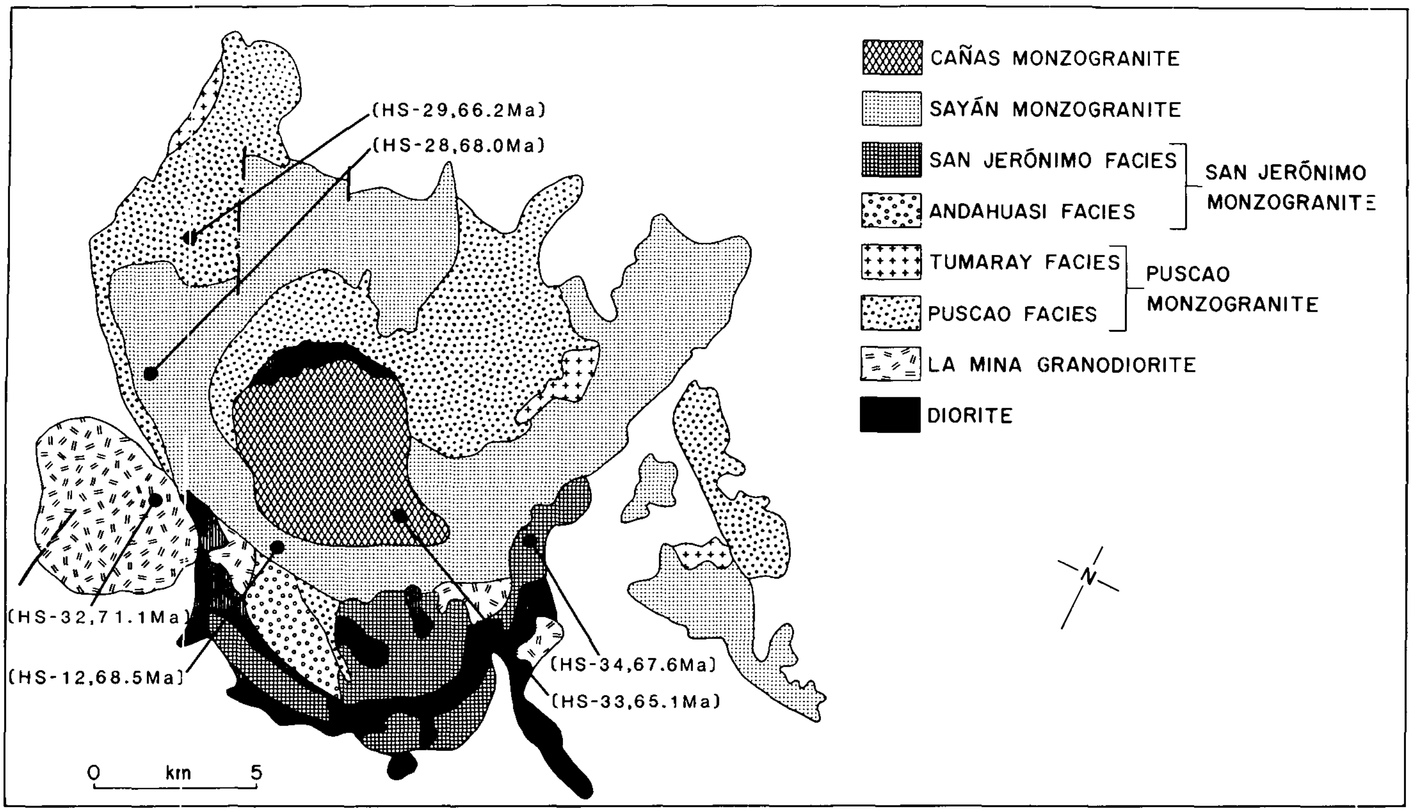

Figure 5. Huaura centered-ring complex and zircon U-Pb ages of its super-units (geology after Cobbing and Pitcher, 1972).

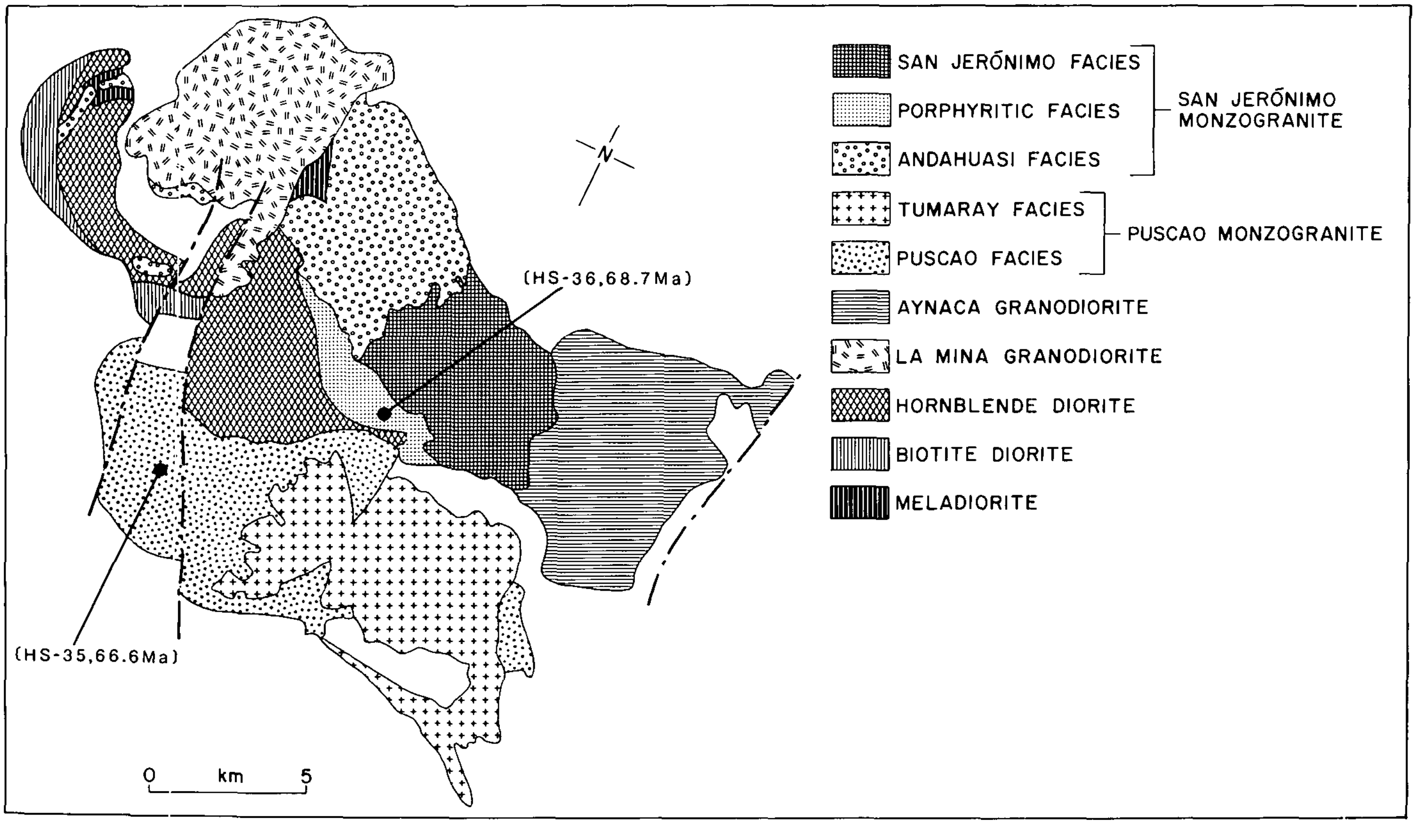

Figure 6. Rudimentary ring complex of Quebrada Paros and zircon U-Pb ages of its Puscao and San Jerónimo super-units (geology after Cobbing and Pitcher, 1972).

pluton, gave concordant ages of 68.5 and 68.0 m.y., respectively. These ages are in good agreement and are not distinguishable from ages of the San Jerónimo super-unit.

A single zircon sample from the Cañas pluton (HS-33 in Fig. 5) yields an age of 65.1 m.y., agreeing with field observations that it is the youngest intrusion in the Huaura ring complex.

"Paccho Super-Unit." Prior to this work, the "Paccho super-unit" was considered to be older than the oldest plutons in the Santa Rosa super-unit (~95 m.y. old). This "super-unit" consists of inaccessible, soil-covered, and poorly studied dioritic and tonalitic rocks, which have been grouped together because they could not be separated by use of aerial photographs (Cobbing and others, 1981). Three samples (HS-27, HS-41, and RR-19 in Fig. 5) were collected from the "super-unit" in plutons of different characters. HS-27 from the Rio Huaura valley gives a concordant age of 61.0 m.y. HS-41 and RR-19 are also concordant with ages of 64.0 and 39.0 m.y., respectively. Rocks in this "super-unit" thus are considserably younger than previously believed, and they were emplaced over such a long period of time that they are probably not the product of a single melting cell. Association of these rocks on maps continues only because thorough field observations and geochemical information are still lacking.

Pativilca Super-Unit. Various authors (for example, Cobbing and others, 1981, Fig. 32, p. 43) have treated the Pativilca pluton, represented here by sample HS-37 (Fig. 3), as consanguineous with the Cañas-Sayán super-unit on the basis of their similar petrologic and geochemical characteristics (McCourt, 1978, 1981). The Pativilca monzogranite, however, has concordant zircon ages of 37.0 m.y., 28 to 31 m.y. younger than units in the Cañas-Sayán super-unit. This age difference warrants treating the Pativilca monzogranite as a separate super-unit.

Younger Diorites and the Lumbre Monzogranite. The Lima segment has several small plutons, some dated and others not dated, that cannot be assigned to a particular super-unit. One such pluton, a biotite-rich diorite (HS-14 in Fig. 2), previously was thought to be a member of the Patap super-unit, but it yields concordant zircon ages of 69.7 m.y. Another is the Lumbre pluton, a monzogranite in the Chancay ring complex (HS-40 in Fig. 7) that yields concordant crystallization ages of 69.6 m.y.

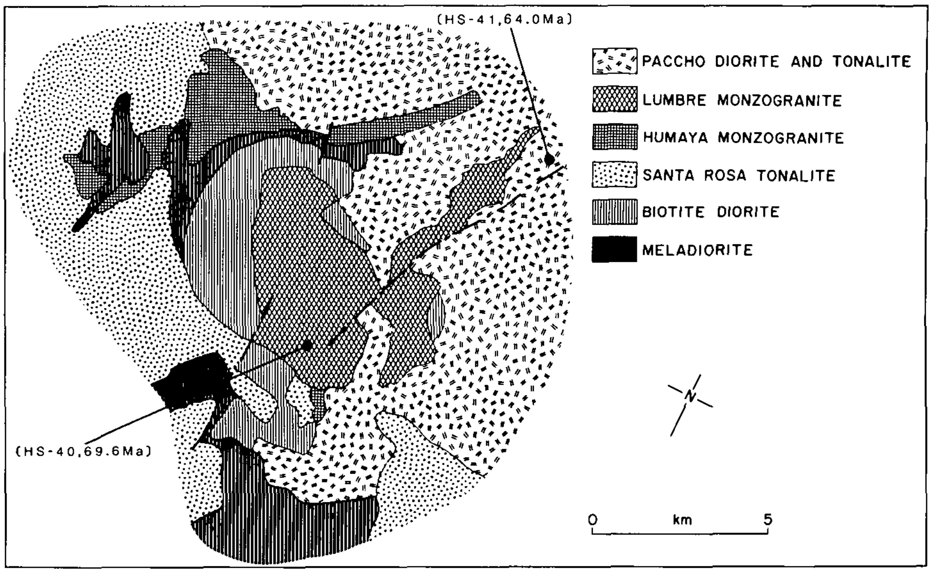

Figure 7. The rudimentary Chancay ring complex and zircon U-Pb ages for the Lumbre monzogranite and Paccho diorite-tonalite (geology after Cobbing and Pitcher, 1972).

Arequipa Segment

The Arequipa segment has been studied much less thoroughly than the adjoining Lima segment. Results discussed below, which at a later date need to be supplemented with additional data, were obtained from samples collected along the Rio Rimac east of Lima; Rio Pisco, 200 km south of Lima; and in the Arequipa plutonic complex at the southernmost end of the segment, 900 km from Lima.

Gabbros. Patap-like gabbros occur as widely dispersed, small plutons in much of the Arequipa segment. No attempt was made here to date them directly. In the Rio Pisco valley (Fig. 8), however, the age of some of the gabbroic plutons can be bracketed by the middle Albian volcaniclastics of the Casma Group, which they intrude, and by the 101.4-m.y. concordant zircon crystallization ages of the oldest granitoids, which cut the gabbros. The gabbros are thus of late Albian age (<105 m.y. but >101 m.y.).

Linga Super-Unit. Plutons with high-K_2O compositions for a given SiO_2 value, which share other features such as texture, differentiation trends, and axial position along the entire length of the Arequipa segment, were mapped by Cobbing (unpub. maps) as the Linga super-unit. A sample collected from the Linga monzonite of the Rio Pisco valley (RP-19 in Fig. 8) gives concordant crystallization ages averaging 101.4 m.y. One each from the Linga monzonite-monzodiorite and monzotonalite of the Arequipa plutonic complex (CV-23 and CV-25 in Fig. 9) give ages of 70.5 m.y. and 66.6 m.y., respectively.

As it now appears that high-K_2O magmas were produced at various times in the Arequipa segment, these plutons should no longer be regarded as a single super-unit, according to the definition of Cobbing and others (1977a). These "Linga-type" magmas are related only in being derived from a similar source and evolving by processes that concentrate components in nearly identical proportions. I have thus divided the high-K_2O plutons into two super-units on the basis of age and adopted the names "Linga (Pisco-Ica)" (101.4 m.y.) and "Linga (Arequipa)" (66.6–70.5 m.y.).

Pampahuasi Super-Unit. Two zircon samples (RP-12 and RP-18 in Fig. 8) were collected from the diorites of the Pampahuasi super-unit to determine its crystallization age and to evaluate reproducibility within a single pluton. Besides recording internally concordant U-Pb ages averaging 94.1 and 93.3 m.y., respectively, samples RP-12 and RP-18 are externally concordant with respect to one another on the basis of a maximum analytical error of ±1% (2σ). An age of 93.7 ± 1.4 m.y. is adopted for the Pampahuasi super-unit.

Tiabaya Super-Unit. Because of their widespread occurrence and great volume throughout the Arequipa segment, plutons of the Tiabaya super-unit were sampled for dating in three widely separated areas: (1) one sample (RR-7) from the Rio Rimac, due east of Lima; (2) two (RP-16 and RP-17) from the Rio Pisco, 200 km farther south; and (3) two (CV-8 and CV-29) from the Arequipa plutonic complex, at the southern end of the segment. The sample locations are shown in Figures 2, 8, and 9.

The five samples range from tonalite to monzogranite. Three give concordant zircon ages, and two are discordant. Coarse and fine zircon fractions from tonalite sample RR-7 (Fig. 2) give internally concordant ages of 86.4 and 84.4 m.y. As the two ages do not quite overlap when a maximum analytical error of ±1% is taken into consideration, however, a slight discordance of <1% is inferred. Along the Rio Pisco traverse (Fig. 8), the Tiabaya super-unit is represented by granodioritic and monzogranitic plutons. Granodiorite sample RP-16 gives an age of 78.3 m.y., whereas monzogranite sample RP-17 exhibits age patterns that are discordant and difficult to interpret.

Tiabaya granodiorite samples from the Arequipa plutonic complex yield both concordant

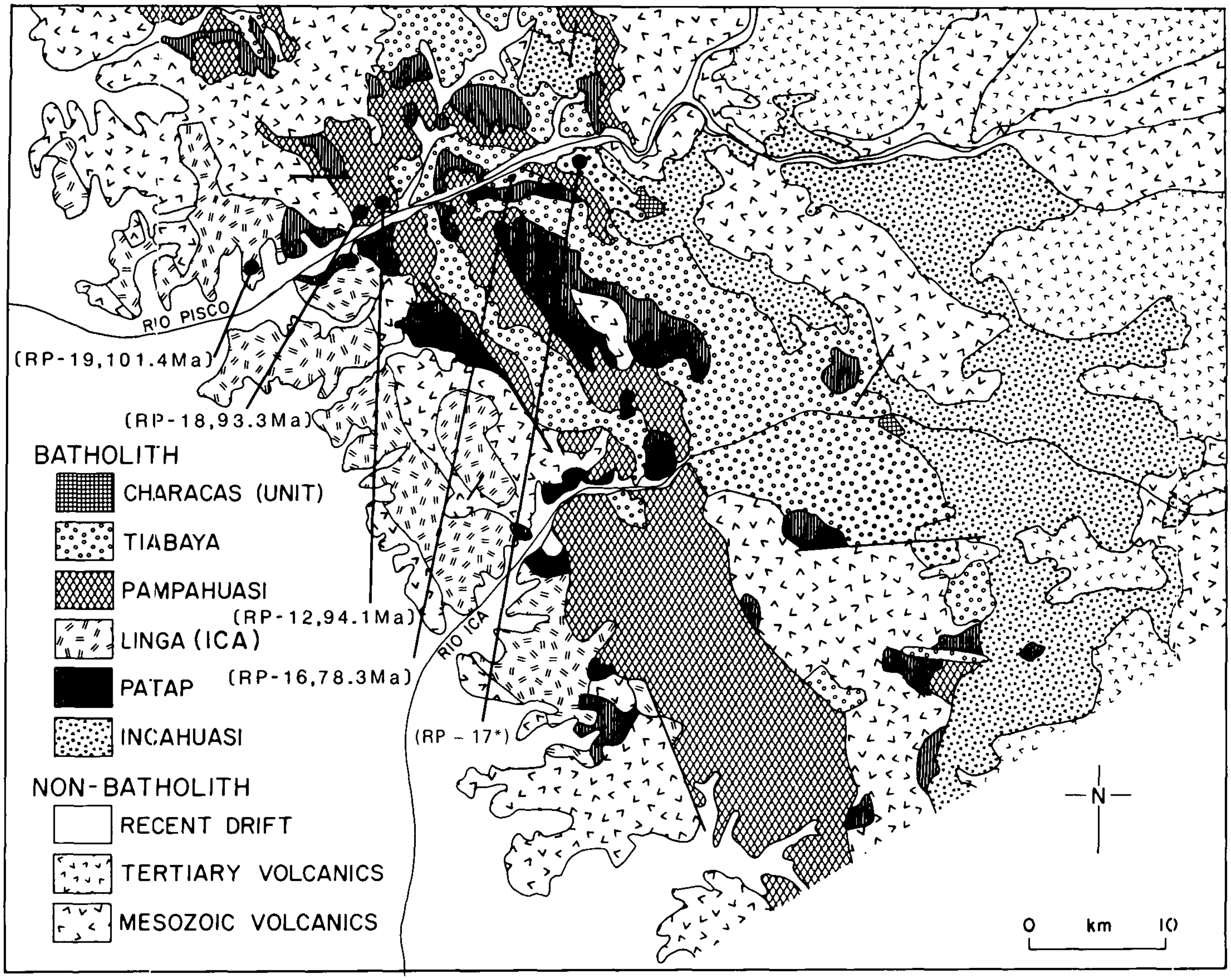

Figure 8. Geology of the Rio Pisco–Rio Ica region and zircon U-Pb ages for the Linga (Ica), Pampahuasi and Tiabaya super-units. *Sample RP-17 exhibits age patterns that are discordant and difficult to interpret (see text for discussions) (geology after Moore, 1979, 1984).

and discordant zircon populations. Sample CV-8 (Fig. 9) was collected near the contact between the pluton and the Precambrian basement rocks. As expected, it produced discordant patterns attributable to an inherited zircon component from the Precambrian gneiss. Unfortunately, the sample produced only two zircon fractions. These provide lower and upper intercepts on a concordia diagram of 78 and 1,532 m.y., respectively. The intercept ages have large errors, however, owing to the weak statistical significance of the chord. The lower intercept, nevertheless, is interpreted as being the approximate time of emplacement of the Tiabaya granodiorite in this area. The upper intercept here represents an intermediate value between the lower and upper intercepts of the chord for the Precambrian host rocks, as described below in the section on the ages of the Punta Coles super-unit.

Tiabaya granodiorite sample CV-29 was collected far from any contacts. The zircons yield concordant ages at 84.0 m.y., which is interpreted as the time of pluton crystallization.

The three Tiabaya super-unit samples with internally concordant zircons thus give ages of 86.4–84.4, 84.0, and 78.3 m.y. The sample population is still too small to pin down age relationships between the various Tiabaya plutons. The short time span indicated by the present data suggests, however, that these plutons may be consanguineous along the entire length of the Arequipa segment.

Cerro Verde Quartz Monzonite. Two zircon fractions from the Cerro Verde porphyritic quartz monzonite (sample CV-9 in Fig. 9) suggest emplacement of the pluton at 61.0 Ma. This hypabyssal intrusion and others like it perhaps provided the heat and some of the fluids for the surrounding hydrothermal alteration halo. The Cerro Verde–type, porphyry-copper deposits in the Arequipa region therefore are probably not much younger than the quartz-monzonite emplacement age.

Toquepala Segment

Geochronological work in the Toquepala segment is still very preliminary. At present, zircon data are available only on an unnamed porphyritic diorite and on the Punta Coles and Yarabamba super-units, all shown in Figure 9.

Punta Coles Super-Unit. Plutons of the Punta Coles super-unit are large bodies of diorite and monzotonalite that crop out discontinuously in the Toquepala segment. Two of these plutons have been studied in detail in the Arequipa plutonic complex (Fig. 9). They are both well foliated and are locally hydrothermally altered.

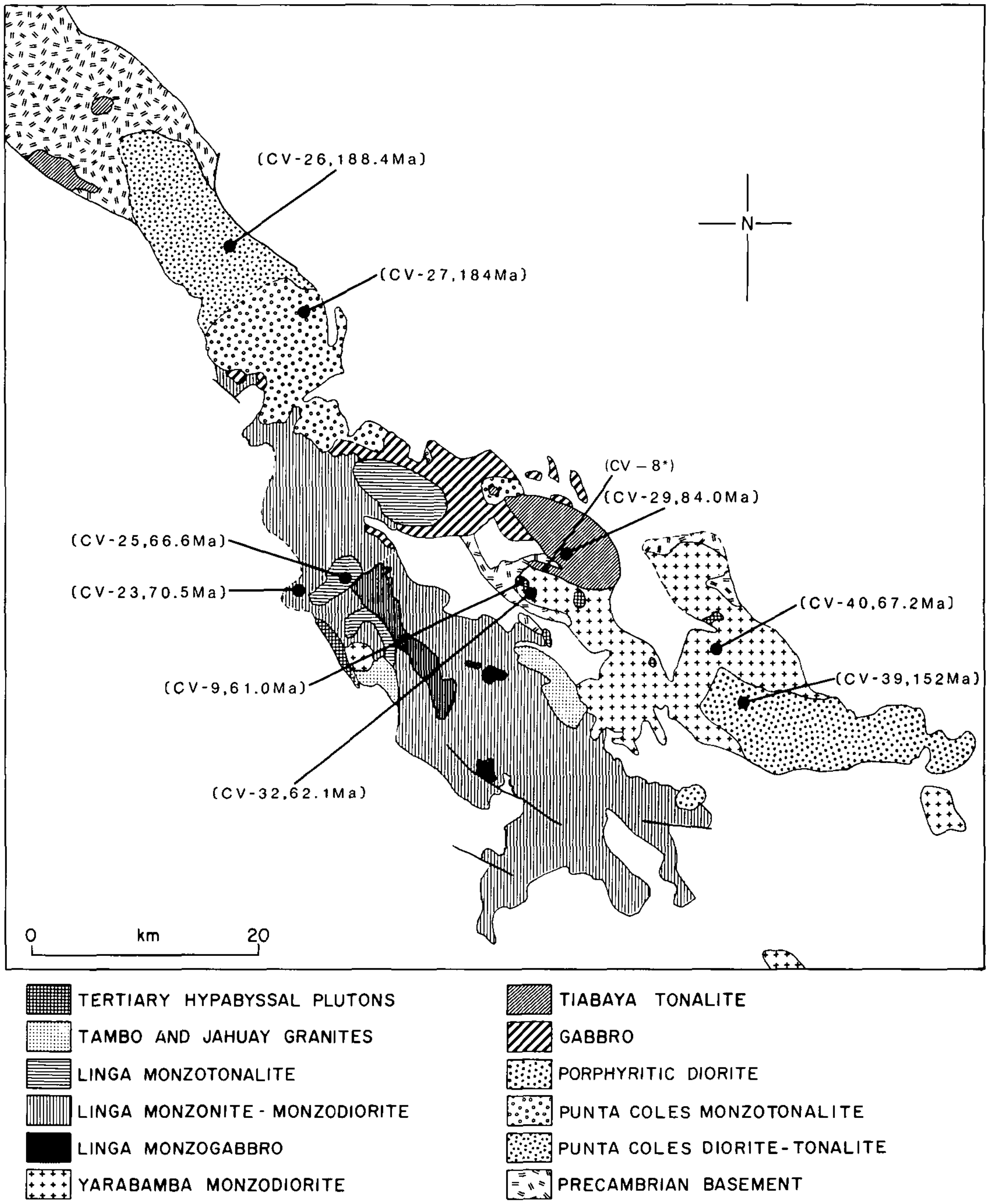

Figure 9. Arequipa plutonic complex, its sample locations and zircon U-Pb ages. This plutonic complex is the boundary region between the Arequipa and Toquepala segments. *The zircon U-Pb age of sample CV-8 has a large statistical error as discussed in detail in the text (geology after Vargas, 1970; Garcia, 1968, 1978; Cobbing, unpub. maps).

Two zircon fractions of sample CV-26 from the large Punta Coles diorite-tonalite (Fig. 9) yield concordant ages that average 188.4 m.y. The adjoining, more differentiated Punta Coles monzotonalite (sample CV-27) gives discordant ages. Four zircon fractions from the sample define a line whose lower and upper intercepts on the concordia diagram (Fig. 10) are 184 ± 1 and 1,376 ± 95 m.y., respectively. Because these two Punta Coles plutons cut and shoulder aside Jurassic sedimentary rocks of the Yura Group (Vargas, 1970) and intrude Precambrian basement gneisses, the lower intercept is interpreted as the time of crystallization. The poorly constrained upper intercept reflects an inherited basement component.

The upper intercept on the concordia diagram (Fig. 10) is not precisely known (due to the limited dispersion of data points along the discordia), but an age of 1,376 ± 95 m.y. requires one of two possible explanations: (1) The Precambrian belt of southern Peru has sections with an age of 1,376 ± 95 m.y.; (2) a second metamorphic event overprinted the ~2.0-b.y. basement granulite facies such that zircons from the basement rocks now give an ~2.0-b.y. upper intercept and a <1.38-b.y. lower intercept. In the second case, Phanerozoic intrusives which inherit zircons from the basement will develop a chord that extends from the crystallization age of the intrusion (lower intercept) to some value between the extreme ends of the chord for the Precambrian basement (upper intercept). Dalmayrac and others (1977) and Barreiro (1982) produced zircon evidence for a second metamorphic event between ~0.8 and 1.0 b.y. in the Precambrian belt of southern Peru. I prefer the second of the two possibilities because of widespread evidence for a retrograde metamorphic event.

There is some uncertainty as to why sample CV-27 shows zircon inheritance, but CV—26 does not. It could be argued, however, that the younger and more differentiated pluton, while still very reactive, interacted with the Precambrian crust longer. Alternatively, the diorite-tonalite magma was undersaturated and that of the monzotonalite saturated with respect to Zr, similar to the peraluminous granite in studies by Watson and Harrison (1983). Magmas undersaturated in Zr readily consume old inherited zircons, thus dispersing all of their radiogenic Pb; Zr-saturated magmas are incapable of totally consuming zircon, and the identity of the inherited component is therefore preserved. Zirconium concentrations of 66 ppm in sample CV-26 and 148 ppm in sample CV—27 (Mukasa, 1984) support the second view.

Several conclusions can be drawn from the Punta Coles super-unit ages. First, these plutons are Jurassic, not Cretaceous, as has been generally believed. They are part of a Jurassic continental arc that may include, as its members, the Chocolate volcanics described by James and others (1975). Second, the two dated plutons are >90 m.y. older than the Incahuasi plutons in the Pisco-Ica region, which are dated at 93 m.y. (Moore, 1979, 1984) and with which the Punta Coles plutons in the Arequipa region had been correlated (Cobbing, unpub. maps). Third, these zircon-crystallization ages contradict the stratigraphic ages for formations in the Yura Group, which Vargas (1970) listed as Callovian to Hauterivian. The two dated plutons (184–188 m.y.) intrude the oldest formations in the Yura Group, which indicates that these sedimentary rocks are no younger than Bathonian age, according to the Decade of North American Geology (DNAG) Jurassic time scale (Palmer, 1983).

Porphyritic Diorite. Zircons from the porphyritic diorite sample CV-39 were analyzed in four fractions because of their discordance. The data (Fig. 11) define an array with concordia lower and upper intercepts of 152 ± 4 and 1,697 ± 151 m.y., respectively. The diorite crystallization age is indicated by the lower intercept. The upper intercept is interpreted as being a manifestation of the polymetamorphic history of the inherited zircon component, as discussed above for the Punta Coles super-unit.

An apparent conflict between the 152 ± 4-m.y. zircon age and the stratigraphic age of this porphyritic diorite cannot be resolved at present. The pluton intrudes sedimentary rocks of the Yura Group, the youngest formations of which are Early Cretaceous in age according to ammonite biostratigraphy (Vargas, 1970). As similar conflicts in the Lima segment were finally resolved in favor of isotopic data, detailed stratigraphy of the Yura Group may be in need of review.

Yarabamba Super-Unit. Internally concordant ages of 62.1 and 67.2 m.y. have been obtained on samples CV-32 and CV-40 from the Arequipa plutonic complex (Fig. 9). The textural and compositional similarities between large portions of the Yarabamba super-unit (Toquepala segment) and the Linga (Arequipa) super-unit (Arequipa segment) suggest a possible

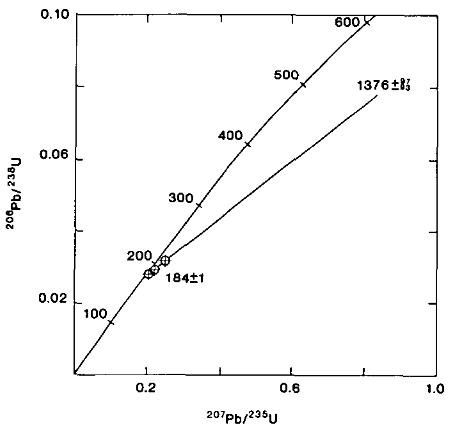

Figure 10. Concordia diagram for the Punta Coles monzotonalite (sample CV-27). The sample location is given in Figure 9. See text for interpretations.

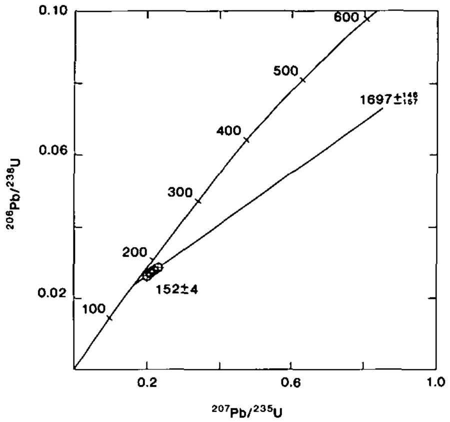

Figure 11. Concordia diagram for an unnamed porphyritic diorite in the Toquepala segment (sample CV-39). See Figure 9 for the sample location and the text for discussion.

genetic relationship between them. The remarkable similarity in emplacement ages further supports that possibility.

Comparison Between U-Pb and K-Ar Ages

Direct comparison between U-Pb and K-Ar ages cannot be made, because studies using the two isotopic systems carried out separate sampling programs, and many K-Ar ages are "preferred ages" chosen from several analyses in unavoidably subjective fashion. Most of the samples used for the two dating methods were collected along the same river valleys, however, due to the limited access to the rugged terrain in the Coastal batholith. In some areas, I attempted to obtain zircon samples from the same outcrops that Wilson (1975) sampled for his K-Ar study; this permitted a general comparison of the two dating methods.

The ages computed from the two dating methods are summarized in Table 2. The U-Pb ages, in most instances, are older than, or equal to, the K-Ar ages. K-Ar ages are seldom older than U-Pb ages. In the more common case, U-Pb ages may be as much as 8 m.y. older than corresponding K-Ar ages. In only a few cases, K-Ar ages may be up to 3 m.y. older, although this small difference may not be statistically significant. If the epizonal nature of the batholith is considered, however, the 8-m.y. age discrepancy seems better explained by radiogenic argon loss, which was triggered by either multiple intrusive activity or hydrothermal circulation. For example, K-Ar ages of the San Jerónimo and Sayán plutons in the Huaura ring complex (Fig. 5) seem to have been reset to the K-Ar age of the younger Cañas pluton. Intermediate age differences of ~4 m.y. or less, which make some zircon U-Pb and K-Ar ages statistically identical, may be the result of rapid cooling, to be expected in epizonal environments.

Chen and Moore (1982) made similar observations in comparing their zircon U-Pb ages with K-Ar ages by Kistler and others (1965), Kistler and Dodge (1966), and Evernden and Kistler (1970) for the Sierra Nevada batholith of California. U-Pb and K-Ar age differences of 5 to 15 m.y. for some Cretaceous plutons were attributed to argon loss that resulted from the emplacement of younger intrusions. The older Jurassic plutons reportedly have an even more complicated thermal history, which severely reset the K-Ar system (Chen and Moore, 1982).

Implications of U-Pb Ages for Magmatic and Tectonic Processes

Mafic and Siliceous Magma Associations. Modern studies of the Coastal batholith (for example, those of Cobbing and Pitcher, 1972; Cobbing and others, 1977a) inferred an evolutionary path that involved initiation of intrusive activity with mafic magmas which were sequentially followed by more and more siliceous melts. This is still generally true on a grand scale, but the occurrence of small bodies of young mafic and old siliceous rocks is gradually being recognized.

Mafic magmas (SiO_2 <53%) formed a fair percentage of the Santa Rosa dike swarm, 72 m.y. ago, and part of the Huaura ring complex, in intimate association with monzogranites of the 65–67-m.y.-old Puscao and 68-m.y.-old San Jerónimo super-units (Bussell, 1983). These magmas formed pillow-like structures, injection tongues, and hybrid rocks that are contemporaneous with the siliceous super-units. Young mafic rocks occur similarly in the predominantly siliceous Chancay and Quebrada Paros ring complexes (Fig. 6 and 7) and also as large, separate plutons (for example, HS-14 in Fig. 2).

The 101.3-m.y. granodiorites and monzogranites of the Jecuan super-unit (Fig. 2) are closely associated in time and space with gabbros of the Patap super-unit, which demonstrates that silica-rich magmas appeared early in the history of the Coastal batholith.

Close relationships between some mafic and siliceous rocks suggest that mantle-derived mafic magmas, through their latent heat of crystallization, may contribute to the production of siliceous melts in either underplated or lower crustal materials.

Episodic Emplacement Hypothesis. Lima segment K-Ar data by Wilson (1975) fall into three groups, at 105–85 m.y., 75–56 m.y., and 39–35 m.y., suggesting episodic emplacement of the Coastal batholith. Zircon U-Pb ages summarized in Table 2 do not support this mode of emplacement, however. Cretaceous and Tertiary magmatic activity was nearly continuous between 105 and 37 m.y. ago, although plutonic volumes varied considerably through time. Emplacement of the most voluminous plutons in both the Lima and Arequipa segments (the Santa Rosa and Tiabaya super-units) occurred between 86 and 70 Ma.

Validity of the Super-Unit Concept. Grouping of plutons into super-units, stated explicitly first by Larsen (1948) and later by Bateman and Dodge (1970) for Californian batholiths, provided the framework for mapping the Coastal batholith (Cobbing and others, 1977a). Super-units were recognized in the Coastal batholith on the basis of rock types, modal variations, textures and fabrics, relative intrusive relationships, and content and character of any xenoliths (Cobbing and others, 1977a). Moreover, it was deduced that a batch of magma in a super-unit was the product of a single melt cell or fusion event that lasted a short time.

In general, results of age studies confirm that super-units have short time spans. For example, plutons of the Puscao super-unit, shown to be genetically related on the basis of major and trace elements (Atherton and others, 1979; McCourt, 1981), are the same age in an area over 100 km long. Flaws are recognized, however, in some rock suites that had been grouped together. To cite two examples, 11 zircon ages of plutons mapped as the Santa Rosa super-unit span a wide range between 91.0 and 49.7 m.y. As it is unlikely that a single fusion event lasted 40 m.y., these similar plutons must belong to more than one super-unit. Similarly, high-K_2O rock suites in the northern and southern sections of the Arequipa segment (previously grouped under the Linga super-unit) have a 35-m.y. age difference and must belong to more than one super-unit. These results warrant re-evaluation, not of the super-unit concept, which has been shown to be geochronologically valid, but of some plutonic groupings for which generalizations have been made in the absence of thorough age and trace element data.

Stress Regimes and Magma Locus Migration. Initiation of extensive plutonism in the Cretaceous continental arc, as shown by zircon U-Pb ages of the Jecuan and Patap super-units, closely followed change in the pole of rotation for South America relative to Africa between 120 and 110 Ma (Rabinowitz and La Brecque, 1979). This change may have increased convergence rates along the Pacific margin of South America, thereby modifying stress regimes and promoting melting events, as suggested by Larson and Pitman (1972).

With the age of the Santa Rosa dike swarm constrained between 73.1 and 71.1 Ma (only 2–3 m.y.), it becomes clear also that massive fracturing and accompanied dike emplacement in continental arcs can be accomplished in a very short time.

Finally, zircon U-Pb age distribution in the Lima segment demonstrates a gradual eastward migration of the locus of magmatism through time. A migration rate of 1.3 mm/yr, calculated for the area along latitude 11°08.1′S on the basis of the ~105-m.y. Patap super-unit and the 61-m.y. Paccho pluton 55 km to the east, is only half the migration rate for plutons in the Sierra Nevada batholith (Chen and Moore, 1982). If migration rates are controlled by variations in the angle of dip of the subducted plate, then the stability of the Andean subduction zone during batholith emplacement is realized.

A pause in migration for the Coastal batholith is inferred from the close proximity of plutons that range in age from 64 to 37 m.y. Resumption of eastward migration is indicated by the Neogene emplacement of the Cordillera Blanca batholith and related stocks farther east (Fig. 1).

CONCLUSIONS

1. Intrusions in the Arequipa region with zircon U-Pb crystallization ages of 188–184 m.y., previously believed to be Cretaceous in age, represent the plutonic substructure of a Jurassic continental arc. The extent of this arc remains to be demonstrated. The Lower Jurassic Chocolate volcanics (James and others, 1975) which crop out sporadically throughout southern Peru are probably also part of this arc.

2. The first extensive plutons in the Cretaceous arc, the Patap and Jecuan super-units, with ages between 105 and 101 m.y. closely followed changes in the pole of rotation for South America relative to Africa. Their origin may therefore be related to plate rearrangements and may have accompanied increases in convergence rates along the Andean margin.

3. Zircon U-Pb ages confirm the eastward migration of the locus of magmatism in the Coastal batholith through time. The Coastal batholith migration rate of 1.3 mm/yr is only half the rate calculated for the Sierra Nevada batholith (Chen and Moore, 1982), which suggests that the geometry of the Andean subduction zone was very stable during batholith emplacement.

4. Coastal batholith age data reported here do not support the episodic emplacement hypothesis that is based on K-Ar ages (Wilson, 1975). The clustering of K-Ar ages in three groups is probably the result of resetting in some plutons to equilibrate with younger ones emplaced in close proximity.

5. The San Jerónimo and Puscao plutons in all the ring complexes were emplaced in <5 m.y. General age agreement between these widely scattered plutons shows that the ring complexes, which are vestiges of caldera-type structures (Cobbing and Pitcher, 1972), erupted material to the surface contemporaneously.

6. The super-unit concept is geochronologically valid in the Coastal batholith. For some plutonic groupings, however, particularly in the Santa Rosa, Paccho, and Linga super-units, generalizations are inevitable in the absence of thorough geochemical and age data. It is important, therefore, that this batholith, the plutonic yardstick of Andean-type margins, be remapped with supporting geochemical and geochronological studies so that its emplacement history can be better understood.

7. On a grand scale, magmatism in the Coastal batholith evolved from mafic to siliceous melts, but the occurrence of young mafic and old siliceous rocks was also important. Close age association between all rock types raises the possibility that mantle-derived mafic magmas provided the heat that produced siliceous magmas, either in the underplated wedge of the subduction complex or in the lower crust, throughout the period of batholith emplacement.

8. Only 8% of the Coastal batholith samples analyzed give discordant age patterns, and all of these came from the Arequipa and Toquepala segments; zircon ages in the Lima segment are all concordant. The discordance is in all cases attributed to an inherited zircon component from Precambrian rocks. These relationships indicate that there are fundamental differences in the nature of the crust beneath the Lima and Arequipa/Toquepala segments. Indeed, seismic data and gravity modeling by Couch and others (1981) and Jones (1981) and feldspar Pb-isotopic compositions reported by Mukasa (1986a) suggest that the Precambrian basement is thick in southern but not in central and northern Peru.

9. Where reliable and direct comparisons can be made between U-Pb and K-Ar ages, the differences are ~4 m.y. or less. They result from the

emplacement of the Coastal batholith into the epizone, where the plutons cooled quickly.

10. The porphyritic quartz monzonite that caused the hydrothermal activity and sulfide-ore formation at Cerro Verde gives concordant zircon U-Pb ages of 61.0 m.y. This is probably also the age of the porphyry-copper mineralization.

ACKNOWLEDGMENTS

The work reported here constituted a chapter in my Ph.D. dissertation at the University of California, Santa Barbara. I am indebted to Prof. G. R. Tilton, under whose direction this work was pursued. My field studies, sample collecting, and clarity of purpose benefited from discussions with W. S. Pitcher, E. J. Cobbing, C. E. Vidal, B. Atkin, P. Harvey, and G. Flores. Critical reviews of the original manuscript by members of my dissertation committee, G. R. Tilton, C. A. Hopson, J. M. Mattinson, and W. S. Wise, and by E. J. Cobbing, W. S. Pitcher, D. Sherrod, M. Boily, and S. Swanson greatly improved this report. Funding for this project came chiefly from National Science Foundation Grants EAR80-08211 and EAR82-12931 to G. R. Tilton. Additional funding was provided by the Geological Society of America, Society of the Sigma Xi, and Standard Oil Company of California.

REFERENCES CITED

Agar, R. A., 1978, The Peruvian Coastal batholith: Its monzonitic rocks and their related mineralization [Ph.D. thesis]: Liverpool, England, University of Liverpool.

Armstrong, R. L., Taubeneck, W. H., and Hales, P. O., 1977, Rb-Sr and K-Ar geochronometry of Mesozoic granitic rocks and their Sr isotopic composition, Oregon, Washington, and Idaho: Geological Society of America Bulletin, v. 88, p. 397–411.

Atherton, M. P., and Brenchley, P. J., 1972, A preliminary study of the structure, stratigraphy and metamorphism of some contact rocks of the western Andes, near the Quebrada Venado Muerto, Peru: Journal of Geology, v. 8, p. 161–178.

Atherton, M. P., McCourt, W. J., Sanderson, L. M., and Taylor, W. P., 1979, The geochemical character of the segmented Peruvian Coastal batholith and associated volcanics, *in* Atherton, M. P., and Tarney, J., eds., Origin of granite batholiths: Geochemical evidence: Nantwich, England, Shiva Publishing, p. 45–64.

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

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513–3536.

Barreiro, B. A., 1982, Lead isotope evidence for crust-mantle interaction during magmagenesis is the South Sandwich Island arc and in the Andes of South America [Ph.D. thesis]: Santa Barbara, University of California, 172 p.

Bateman, P. C., 1981, Geological and geophysical constraints on models for the origin of the Sierra Nevada batholith, California, *in* Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 71–86.

Bateman, P. C., and Clark, L. D., 1974, Stratigraphy and structural setting of Sierra Nevada batholith, California: Pacific Geology, v. 8, p. 79–89.

Bateman, P. C., and Dodge, F.C.W., 1970, Variations of major chemical constituents across the Sierra Nevada batholith: Geological Society of America Bulletin, v. 81, p. 409–420.

Beckinsale, R. D., Sanchez-Fernandez, 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 Andes: Glasgow, Scotland, Blackie, p. 177–202.

Bussell, M. A., 1975, The structural evolution of the Coastal batholith in the provinces of Ancash and Lima, central Peru [Ph.D. thesis]: Liverpool, England, University of Liverpool, 375 p.

——— 1983, Timing of tectonic and magmatic events in the central Andes of Peru: Geological Society of London Journal, v. 140, p. 279–286.

Bussell, M. A., Pitcher, W. S., and Wilson, P. A., 1976, Ring complexes of the Peruvian Coastal batholith: A long standing subvolcanic regime: Canadian Journal of Earth Sciences, v. 13, p. 1020–1030.

Chen, J. H., and Moore, J. G., 1982, Uranium-lead isotopic ages from the Sierra Nevada batholith, California: Journal of Geophysical Research, v. 87, p. 4761–4784.

Cobbing, E. J., 1976, The geosynclinal pair at the continental margin of Peru: Tectonophysics, v. 36, p. 157–165.

Cobbing, E. J., and Pitcher, W. S., 1972, The Coastal batholith of central Peru: Geological Society of London Journal, v. 128, p. 421–460.

——— 1983, Andean plutonism in Peru and its relationship to volcanism and metallogenesis at a segmented plate edge, *in* Roddick, J. A., ed., Circum-Pacific plutonic terranes: Geological Society of America Memoir 159, p. 277–291.

Cobbing, E. J., Pitcher, W. S., and Taylor, W. P., 1977a, Segments and super-units in the Coastal batholith of Peru: Journal of Geology, v. 85, p. 625–631.

Cobbing, E. J., and Ozard, J. M., and Snelling, N. J., 1977b, Reconnaissance geochronology of the crystalline basement rocks of the Coastal Cordillera of southern Peru: Geological Society of America Bulletin, v. 88, p. 241–246.

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

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

Dalmayrac, B., Lancelot, J. R., and Leyreloup, A., 1977, Evidence of 2 b.y. granulites in the late Precambrian metamorphic basement rocks along the southern Peruvian coast: Science, v. 198, p. 49–51.

Dalmayrac, B., Laubacher, G., and Marocco, R., 1980, Caractères géneraux de l'évolution géologique des Andes péruviennes: Paris, Office de la recherche scientifique et technique outre-mer Special publication, 501 p.

Dalziel, I.W.D., 1985, Collision and cordilleran orogenesis: An Andean perspective: Geological Society of London Special Publication on collision tectonics (in press).

Evernden, J. F., and Kistler, R. W., 1970, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geological Survey Professional Paper 623, 42 p.

García, W., 1968, Geología de los cuadrángulos de Mollendo y La Joya: Servicio de Geología y Minería Boletín 19, 93 p.

——— 1978, Geología de los cuadrángulos de Puquina, Omate, Huaitire, Mazo Cruz y Pizacoma: Instituto de Geología y Minería Boletín 29, 63 p.

Gebauer, D., and Grunenfelder, M., 1979, U-Th-Pb dating of minerals, *in* Jager, E., and Hunziker, J. C., eds., Lectures in isotope geology: New York, Springer-Verlag, p. 105–131.

Herron, E. M., 1972, Sea floor spreading and Cenozoic history of the east central Pacific: Geological Society of America Bulletin, v. 83, p. 1671–1691.

James, D. E., Brooks, C., and Cuyubamba, A., 1975, Early evolution of the central Andean volcanic arc: Carnegie Institute of Washington Yearbook, v. 74, p. 247–250.

Jones, D. L., Silberling, N. J., and Hillhouse, J., 1977, Wrangellia—A displaced terrane in northern North America: Canadian Journal of Earth Science, v. 14, p. 2565–2577.

Jones, D. L., Blake, M. C., Jr., Bailey, E. H., and McLaughlin, R. J., 1978, Distribution and character of upper Mesozoic subduction complexes along the west coast of North America: Tectonophysics, v. 47, p. 207–222.

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. J., and Hussong, D. M., eds., Nazca plate: Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 423–443.

Kistler, R. W., and Dodge, F.C.W., 1966, Potassium-argon ages of coexisting minerals from pyroxene-bearing granitic rocks in the Sierra Nevada, California: Journal of Geophysical Research, v. 71, p. 2157–2161.

Kistler, R. W., Bateman, P. C., and Brannock, W. W., 1965, Isotopic ages of minerals from granitic rocks of the central Sierra Nevada and Inyo Mountains, California: Geological Society of America Bulletin, v. 76, p. 155–164.

Knight, R. J., Mortimer, N., Wilson, D., Nur, A., and Villafuerte, M. G., 1984, Paleomagnetic study of the Arequipa massif, Peru, *in* Howell, D. G., Jones, D. L., Cox, A., and Nur, A., eds., Proceedings, Circum-Pacific Terrane Conference: Stanford, California, Stanford University Publications, p. 134–135.

Krogh, T. E., 1973, A low-contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica et Cosmochimica Acta, v. 37, p. 485–494.

Larsen, E. S., 1948, Batholith and associated rocks of Corona, Elsinore and San Luis Rey Quadrangles, southern California: Geological Society of America Memoir 29, 182 p.

Larson, R. L., and Pitman, W. C., III, 1972, World-wide correlation of Mesozoic magnetic anomalies and its implications: Geological Society of America Bulletin, v. 83, p. 3645–3662.

Le Bel, L., 1979, Etudes des conditions de formation du porphyre cuprifère de Cerro Verde-Santa Rosa (Pérou méridional) pris dans son contexte plutonique [Ph.D. thesis]: Lausanne, Switzerland, University of Lausanne, 140 p.

McBride, S. L., 1977, A K-Ar study of the Cordillera Real, Bolivia, and its regional setting [Ph.D. thesis]: Kingston, Ontario, Queen's University, 230 p.

McCourt, W. J., 1978, Geochemistry of the Coastal batholith of Peru [Ph.D. thesis]: Liverpool, England, University of Liverpool, 320 p.

——— 1981, The geochemistry and petrography of the Coastal batholith of Peru, Lima Segment: Journal of the Geological Society of London, v. 138, p. 407–420.

Moore, N. D., 1979, The geology and geochronology of the Coastal batholith of southern Peru [Ph.D. thesis]: Liverpool, England, University of Liverpool.

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

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

——— 1986a, Lead isotopic compositions of the Lima and Arequipa segments in the Coastal batholith, Peru: Implications for magmagenesis: Geochimica et Cosmochimica Acta (in press).

——— 1986b, The San Nicholás batholith: Evidence for an early Paleozoic magmatic arc along the continental margin of Peru: Geological Society of London Journal (in press).

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

——— 1975a, Cauldron subsidence and fluidization: Mechanisms of intrusion of the Coastal batholith into its own ejecta: Geological Society of America Bulletin, v. 86, p. 1209–1220.

——— 1975b, Vertical crustal movements of the Andes in Peru: Nature, v. 254, p. 672–674.

Nur, A., and Ben-Avraham, Z., 1982, Oceanic plateaus, the fragmentation of continents, and mountain building: Journal of Geophysical Research, v. 87, p. 3644–3661.

Palmer, A. R., 1983, The Decade of North American Geology 1983 Geologic Time Scale: Geology, v. 11, p. 503–504.

Pitcher, W. S., 1978, The anatomy of a batholith: Geological Society of London Journal, 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 Andes: Glasgow, Scotland, Blackie, p. 93–101.

Pitcher, W. S., and Bussell, M. A., 1977, Structural control of batholithic emplacement in Peru: A review: Geological Society of London Journal, v. 133, p. 249–255.

Rabinowitz, P. D., and La Brecque, J., 1979, The Mesozoic South Atlantic Ocean and evolution of its continental margins: Journal of Geophysical Research, v. 84, p. 5973–6002.

Regan, P. F., 1976, The genesis and emplacement of mafic plutonic rocks of the coastal Andean batholith, Lima Province, Peru [Ph.D. thesis]: Liverpool, England, University of Liverpool, 237 p.

Saleeby, J. B., 1977, Fracture zone tectonics, continental margin fragmentation and emplacement of the Kings-Kaweah ophiolite belt, southwest Sierra Nevada, California, *in* Coleman, R. E., and Irwin, W. P., eds., North American ophiolites: Oregon Department of Geology and Mineral Industries Bulletin 95, p. 141–160.

——— 1981, Ocean floor accretion and volcanoplutonic arc evolution of the Mesozoic Sierra Nevada, *in* Ernst, W. G., ed., The geotectonic development of California: Englewood Cliffs, New Jersey, Prentice-Hall, p. 132–181.

Schweickert, R. A., 1976, Early Mesozoic rifting and fragmentation of the Cordilleran orogen in the western U.S.A.: Nature, v. 260, p 586–591.

Schweickert, R. A., and Cowan, D. S., 1975, Early Mesozoic tectonic evolution of the western Sierra Nevada, California: Geological Society of America Bulletin, v. 86, p. 1329–1336.

Shackleton, R. M., Ries, A. C., Coward, M. P., and Cobbold, P. R., 1979, Structure, metamorphism and geochronology of the Arequipa Massif of coastal Peru: Geological Society of London Journal, v. 136, p. 195–214.

Stewart, J. W., Evernden, J. F., and Snelling, J., 1974, Age determinations from Andean Peru: A reconnaissance study: Geological Society of America Bulletin, v. 85, p. 1107–1116.

Taylor, W. P., 1973, The geochemistry and mineralogy of the Cañas and Puscao plutons, Lima Province, Peru [Ph.D. thesis]: Liverpool, England, University of Liverpool.

Vargas, V., 1970, Geología del cuadrángulo de Arequipa: Servicio de Geología y Minería Boletín 24, 64 p.

Watson, E. B., and Harrison, T. M., 1983, Zircon saturation revisited: Temperature and composition effects in a variety of crustal magma types: Earth and Planetary Science Letters, v. 64, p. 295–304.

Wilson, J. J., 1963, Cretaceous stratigraphy of the central Andes of Peru: American Association of Petroleum Geologists, v. 47, p. 1–54.

Wilson, P. A., 1975, K-Ar age studies in Peru with special reference to the emplacement of the Coastal batholith [Ph.D. thesis]: Liverpool, England, University of Liverpool, 299 p.

Manuscript Received by the Society February 8, 1985
Revised Manuscript Received August 5, 1985
Manuscript Accepted September 9, 1985