Reconnaissance geochronology of the crystalline basement rocks of the Coastal Cordillera of southern Peru

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ABSTRACT

Granulite-facies gneiss of the Arequipa massif extensively developed along the Coastal Cordillera of southern Peru gives a whole-rock isochron age of 1,811 ± 39 m.y. ($\lambda\ ^{87}Rb = 1.47 \times 10^{-11} yr^{-1}$) and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7086 ± 0.0009. Migmatitic granite within the gneiss is probably of late Precambrian or early Paleozoic age. Mineral ages, both K-Ar and Rb-Sr, from the gneisses and granites are disturbed. Potassium feldspar from the gneiss appears to have been reset by the migmatitization event, whereas mica and potassium feldspar from the migmatitic granite appear to reflect established tectonic-thermal events of Late Devonian and Late Triassic time.

In both metamorphic grade and age pattern, these rocks are similar to those of the Trans-Amazonian nucleus of the Guianas, Brazil, Uruguay, and the Buenos Aires province of Argentina. We suggest that the Arequipa massif has always been an integral part of the Trans-Amazonian nucleus and that the Andean belt is ensialic, at least in Peru. The manner in which the structural trends in the Arequipa massif strike into the Pacific Ocean leads to speculation concerning the evolution of the Pacific. Simple rifting, tectonic erosion, and major transcurrent faulting are considered as possible mechanisms to explain the truncation.

INTRODUCTION AND GEOLOGICAL BACKGROUND

The Coastal Cordillera of southern Peru has long been known to consist of metamorphic rocks that lie to the west of the main Andean foldbelt (Douglas, 1920). In the past the rocks have been considered to be of possible early Paleozoic age (Jenks, 1948; James, 1971). Recently, however, late Precambrian K-Ar ages were recorded from metamorphic country rocks of the Arequipa batholith (Stewart and others, 1974), some 70 km inland. On the basis of these determinations, Martinez and others (1972) assigned the metamorphic rocks to the Baikalian orogenic cycle (500 to 600 m.y. ago); we will show this assignment to be premature. This area of metamorphic rocks has been given various names in the past: Lomas Complex (Hayt, 1960, unpub. rept.), Paracas Gneiss (Cobbing, 1972), and Arequipa massif (Cobbing and Pitcher, 1972a) — the name we propose to retain.

The relationship of these metamorphic rocks to the Andean foldbelt with its cordilleran batholiths is problematical and stimulated a brief geological reconnaissance in September 1971, when material for isotopic dating was collected between Mollendo and Marcona (Fig. 1).

This reconnaissance showed the metamorphic belt to be composite. Between Mollendo and the Rio Ocoña, the dominant rocks are homogenous grey gneiss with a poorly defined but pervasive banding. The rocks contain sillimanite, hypersthene, garnet, biotite, plagioclase, quartz, and a little microcline — mineral assemblages characteristic of the granulite metamorphic facies. They are cut by numerous thin pegmatite veins that are grossly parallel to the metamorphic banding but are transgressive in detail. These pegmatite stringers are almost ubiquitous. Coarser pegmatites of larger size occur sporadically. The gneisses and granitic pegmatites are in turn cut by unmetamorphosed dolerites (Douglas, 1920). The gneissose foliation trends approximately northeast-southwest and is at right angles to the normal Andean trend.

From the mouth of the Rio Ocoña to Atico, the complex consists of well-differentiated supracrustal schists ranging in composition from pelite to quartzite and containing extensive amphibolite bodies. They too are cut by pegmatites, which, however, are neither as abundant nor as pervasive as in the gneiss and are typically well-defined veins about 25 cm thick. The schists contain staurolite, garnet, muscovite, biotite, plagioclase, and quartz; they were metamorphosed in the amphibolite facies but have since been extensively retrograded. Both minor folds and schistosity trend northeast-southwest in the same sense as those in the gneiss, but the relationship between the schists and the gneiss has not yet been established. It is, however, tentatively supposed that the schists were deposited and metamorphosed as a cover upon the gneissic basement and that the amphibolite-facies metamorphism is a younger event than the granulite metamorphism of the gneiss.

Between Atico and Marcona, exposure is very poor, but gneisses appear again that are heavily feldspathized by large plates of pink microcline, which may be related to the pegmatites observed in both the gneisses and the schists seen farther south. Pink granitic gneisses on the coast south of Marcona are cut by mafic dikes that are themselves metamorphosed (W. S. Pitcher, 1974, personal commun.).

Two areas of granite were noted during the reconnaissance. A distinctive red granite occurs in the neighborhood of Camana and is very similar in appearance to many of the pegmatites that cut the

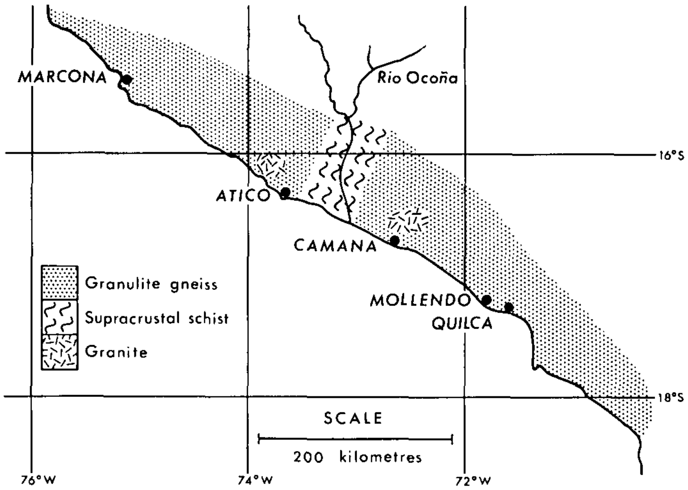

Figure 1. Locality map of Coastal Cordillera of southern Peru.

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country rocks. Immediately north of Atico a gray muscovite granite is present. Contact relationships of this granite are obscure, but it appears to cut pink migmatite gneisses, which are themselves transgressive toward the amphibolite-facies schists found to the southeast.

It is evident that the granite-migmatite history is likely to be complex. Nevertheless, for the purposes of this investigation we have considered all the migmatites, together with the two granites of Atico and Camana, to represent part of a single plutonic event that probably affected both the granulite-facies gneisses and the supracrustal schists. This will henceforward be referred to as the migmatitization event.

The reconnaissance indicated that three events had affected the rocks of the complex: (1) the granulite metamorphism giving rise to a large area of undifferentiated gneiss, (2) deposition of a sedimentary assemblage and its subsequent metamorphism under conditions of the amphibolite facies, and (3) the migmatitization event that probably affected both the gneiss and the schists, and which may have been contemporaneous with the aforementioned amphibolite-facies metamorphic event. As a working hypothesis we suggest that event 2 succeeded event 1. However, that this is only a gross simplification of the geologic history of this complex is indicated by the occurrence of mafic dikes that postdate a migmatitization event but have also been metamorphosed.

GEOCHRONOLOGY

Analytical Methods

Rubidium and strontium concentrations (Table 1) were determined by x-ray fluorescence using the methods described by Norrish and Chappell (1967). Strontium concentrations and the $^{87}Sr/^{86}Sr$ ratio were determined by isotope dilution analysis using a ^{84}Sr-enriched spike. The analyses were made with a Varian MAT CH4 mass spectrometer with automatic on-line data acquisition. A Hewlett Packard 9800B programmable calculator was used to step the magnet current, read the digital voltmeter, and calculate and print out the appropriate isotopic ratios. Six measurements on the Eimer and Amend strontium during the course of this investigation gave $^{87}Sr/^{86}Sr = 0.7081 \pm 0.0001(5)$ (one standard error of the mean).

TABLE 1. Rb-Sr DATA FOR BASEMENT ROCKS FROM SOUTHERN PERU

Sample no.*	Material analyzed	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
626	Whole rock	131	194	2.005	0.7629
627	Whole rock	72	97	2.205	0.7690
628	Whole rock	41	212	0.603	0.7249
629	Whole rock	142	130	3.223	0.7943
629	Potassium feldspar	367	426	2.541	0.7864
630	Whole rock	19	219	0.298	0.7163
631	Whole rock	152	305	1.484	0.7182
631	Potassium feldspar	258	369	2.060	0.7212
631	Biotite	591	25	62.30	0.9195
632	Whole rock	71	57	3.653	0.7728
634	Whole rock	115	363	0.962	0.7196
634	Potassium feldspar	254	373	1.995	0.7227
634	Biotite	484	56	24.70	0.8385
635	Whole rock	67	716	0.313	0.7094
635	Muscovite	290	125	6.580	0.7445
637	Whole rock	204	153	3.910	0.8202
637	Potassium feldspar	391	211	5.430	0.8354

* Sample 626, pyroxene gneiss banded with thin veins of pink feldspar, Quilca, lat 17°S, long 73°W; 627, pyroxene granulite gneiss, banded with thin veins of pink feldspar, Quilca, lat 17°S, long 73°W; 628, garnet sillimanite gneiss, roadside quarry between Mollendo and La Joya; 629, biotite gneiss veined by red feldspar, locality as for 628; 630, biotite-gneiss, 5 km south of Mollendo, lat 17°S, long 72°W; 631, red granite, 7 km west of Camana; 632, biotite schist, north of Rio Ocoña, lat 16°S, long 74°W; 634, feldspathized gneiss, probably related to red granite type as exemplified by 632, lat 16°20'S, long 74°W; 635, muscovite granite, 15 km north of Atico, lat 16°S long 14°W; 637, feldspathized gneiss, Marcona, lat 15°30'S, long 75°30'W.

The Rb-Sr data were regressed according to the recommendations of Brooks and others (1972). Estimates of the precision of both parameters — that is, $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ — were based on replicate measurements. Thus, duplicate determinations of the Rb/Sr ratio on 12 samples gave a pooled standard error of the mean of each pair of determinations of ±0.006. The actual Rb/Sr ratios ranged from 0.18 to 1.7. Duplicate determinations of the $^{87}Sr/^{86}Sr$ ratio on 16 samples gave a pooled standard error of the mean of each pair of ±0.00056. The overall range of $^{87}Sr/^{86}Sr$ ratios was from 0.7094 to 0.92, but with the exception of biotite sample 631 ($^{87}Sr/^{86}Sr = 0.92$) all the $^{87}Sr/^{86}Sr$ ratios fell in the range of 0.709 to 0.830. In view of the reconnaissance nature of the field investigation, we have adopted precision values of ±2 percent and ±0.1 percent on the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios, respectively, in all regression calculations. Ages were calculated assuming a decay constant $\lambda = 1.47 \times 10^{-11} yr^{-1}$.

Argon was determined by isotope dilution using an ^{38}Ar spike. Samples were fused in a bakeable metal and glass vacuum system, and the appropriate isotopic ratios were measured in an AEI MS10 mass spectrometer operated in the static mode. Potassium was determined by flame photometry, using lithium as an internal standard. Uncertainties assigned to the K-Ar apparent ages take into account errors in the isotopic ratio measurements, the spike volume, the effects of contaminating atmospheric argon, and errors in potassium determinations based on replicate analyses. Replicate argon and potassium analyses on a wide range of samples indicate that the experimental uncertainty on the $^{40}Ar/^{40}K$ ratio is generally better than ±2 percent.

Results

The Rb-Sr data are given in Table 1 and plotted in Figures 2 and 3. Samples 626 to 630 from the Mollendo-Quilca region are all characterized by granulite-facies metamorphism and show a good linear relationship. They yield an isochron of 1,811 ± 39 m.y., initial $^{87}Sr/^{86}Sr = 0.7086 \pm 0.0009$, and MSWD (mean square of weighted deviates) = 0.33. We consider that this age reflects an important event in the geologic history of these rocks; most probably it is the granulite-facies metamorphism itself.

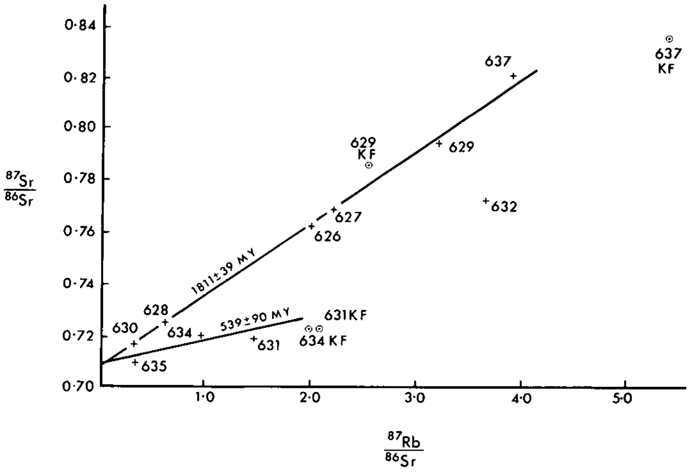

Figure 2. Isochron diagrams of whole-rock and potassium feldspar data from metamorphic and related rocks of Arequipa massif. Crosses = whole rock, KF = potassium feldspar, $\lambda = 1.47 \times 10^{-11} yr^{-1}$.

The remaining samples are from more scattered localities to the northwest. Sample 637 is from the Marcona region. It is an amphibolite-facies gneiss, and its relationships to both the amphibolite-facies schists and the granulite-facies gneiss farther southeast are completely unknown. The Rb-Sr data give a point that is colinear with the plots of the granulite-facies rock and a model age (assuming an initial ^{87}Sr/^{86}Sr ratio of 0.7086) of 1,914 ± 44 m.y. It could be argued that this gneiss is coeval and cogenetic with the granulite-facies gneiss to the southeast. However, in view of the distance separating the two areas, the lack of continuous exposure, and the difference in metamorphic grade, it would be geologically unwise to stress this correlation until the metamorphic and structural history of the whole region is better understood.

Samples 631, 634, and 635 represent the more granitic elements cutting both the supracrustal schist complex and the granulite gneisses. The Rb-Sr data plot on the isochron diagram in a crude linear fashion and give a best fit line of 539 ± 90 m.y., with an intercept of 0.7084 ± 0.0013. A high MSWD of 16 indicates that the scatter of points about the regression line is far greater than that which could be attributed to experimental error alone. Thus, these rocks may have experienced gains or losses of rubidium and (or) strontium or may not even be contemporaneous and consanguineous. In either case the calculated age must be viewed with considerable caution. Certainly, biotites from samples 631 and 634 both show evidence of radiogenic strontium loss, while potassium feldspar from sample 631 and biotite from sample 634 have also lost radiogenic argon (see below). We note, however, that micas from two gneisses from near Cerro Verde about 75 km inland give K-Ar ages of about 650 m.y. (Stewart and others, 1974) and we make the very tentative suggestion that these ages, together with the whole-rock Rb-Sr age of 539 ± 90 m.y. are manifestations of a late Precambrian–Early Cambrian event that could possibly be correlated with the migmatite event discussed above.

Sample 632 is a staurolite schist, a representative of the sedimentary component of the supracrustal metamorphic-plutonic rocks, and on the isochron diagram it plots well above the 539-m.y. line but falls below the 1,811-m.y. isochron. By assuming a minimum terrestrial ^{87}Sr/^{86}Sr ratio of about 0.700, a maximum date can be calculated for the formation of this metamorphosed pelite of about 1,340 m.y. ago. The true date of sedimentation could, of course, be significantly younger than this, depending on the amount of inherent radiogenic strontium incorporated in the pelite at the time of deposition. However, a maximum age of 1,340 m.y. is consistent with the view that members of this metamorphic group were originally deposited upon a basement composed of the 1,811-m.y.-old granulite-facies rocks.

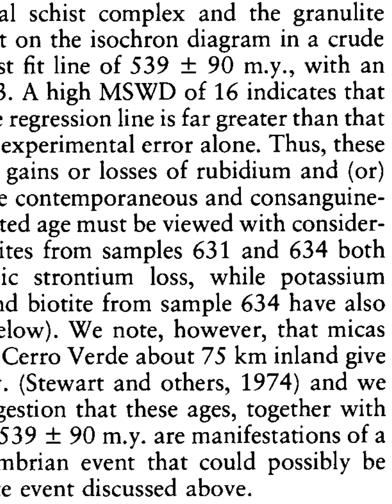

Figure 3. Main units of crystalline basement in South America. 1, Trans-Amazonian cratons unaffected by Brazilian orogenic cycle; I = Guyana Shield, ~2,000-m.y. basement overlain by virtually undisturbed sedimentary rock of Roraima Formation deposited about 1,700 m.y. ago; II = Guapore cratonic area (~2,000 m.y. old); III = São Luis cratonic area (~2,000 m.y. old). 2, Trans-Amazonian cratons reworked by Brazilian orogenic cycle; IV = São Francisco craton; V = Rio de la Plata cratonic area; VI = Arequipa massif. 3, Area of crystalline basement apparently not characterized by ~2,000-m.y. ages. P = Sierras Pampeanas massif; Brazilian orogenic cycle ages and Pennsylvanian plutonic rocks. PM = Patagonian massif; metamorphic and plutonic rocks give Pennsylvanian to Triassic ages. DM = Deseado massif; diorite plutonic rocks give early Jurassic ages. CR = Coast Range basement of Chile and Cordillera Frontal of Argentina. Schists from Coast Range basement give whole-rock isochron of 320 m.y.; K-Ar ages from Cordillera Frontal range from 250 to 400 m.y. Intrusive plutonic rocks give K-Ar ages in range 220 to 260 m.y. Compilation based on Cordani and others (1973) and Halpern (1972).

Mineral K-Ar age determinations have been made for samples of granitic rocks (Table 2). Several other relevant K-Ar determinations were discussed by Stewart and others (1974). The simplest results to interpret are the K-Ar ages from the granitic samples 631, 634, and 635. The apparent ages are 374 ± 6 m.y., 365 ± 6 m.y. and 339 ± 5 m.y., respectively, a range corresponding to Late Devonian and Early Pennsylvanian time. The concentration of K-Ar ages from three different mineral species within such a limited time range suggests a significant thermal event at about this period. Evidence of a minor Acadian orogeny in Peru has been presented by Jenks (1959, p. 241), who showed that the older Paleozoic rocks experienced low- to medium-grade regional metamorphism at this time. Jenks's views have been further amplified by Egeler and de Booy (1961) and Mégard and others (1971), who referred the folding and metamorphism to a Hercynian tectonism comprising a Late Devonian early phase and an intra-Permian late phase.

Stewart and others (1974) quoted two K-Ar mica ages of 447 and 395 m.y. from coarse potassic granites (granito rosado) that penetrate the basement gneisses in the Coastal Cordillera. It seems likely that the parent rocks are also the granitic representatives of the migmatite event, but the micas have apparently not experienced the same degree of outgassing as the minerals of the samples collected for this investigation. Potassium feldspar from granulitic facies rock sample 629 gives an appreciably younger age of 192 ± 3 m.y. (Table 2). Evidence of a thermal event at about this time in northern Chile has been presented by Farrar and others (1970), and Stewart and others (1974) recorded an age of 204 m.y. from a quartz diorite that intrudes sedimentary rocks of the Permian Mitu Group near Ocoña. The apparent age and intrusive relationships of this granite leave little doubt that it was emplaced in Late Triassic time. A staurolite schist from nearby gave concordant muscovite and biotite K-Ar ages of 210 m.y. The schist was probably a member of the supracrustal metasedimentary rocks, as described above; evidence suggests that these rocks underwent virtually complete argon outgassing in response to a Late Triassic intrusive episode. Thus, in the region under consideration it seems likely that during Phanerozoic time, partial or complete resetting of mineral K-Ar ages could have occurred in Late Devonian–Early Pennsylvanian (about 360 m.y.) and Late Triassic–Early Jurassic (about 200 m.y.) time at least. The available K-Ar age determinations are in accord with such resetting.

The Rb-Sr mineral data also show evidence of considerable disturbance. However, whereas disturbance of a K-Ar system appears

TABLE 2. K-AR AGE DATA FROM BASEMENT ROCKS OF SOUTHERN PERU

Sample no.*	Material analyzed	K (%)	Vol radiogenic ^{40}Ar (nl/g)	Age (m.y.)
631	Potassium feldspar	11.06	182.4	374 ± 6
634	Biotite	6.05	97.11	365 ± 6
635	Muscovite	8.57	126.6	339 ± 5
629	Potassium feldspar	10.67	86.41	192 ± 3

Note: K-Ar analyses by M. Brook and C. C. Rundle. Decay constants: $\lambda_\beta = 4.72 \times 10^{-10}$ yr^{-1}, $\lambda_\epsilon = 0.584 \times 10^{-10}$ yr^{-1}. Abundance ^{40}K = 0.0119 atom percent.

* Sample locations as in Table 1.

to involve only the partial or complete loss of the radiogenic element, disturbance of a Rb-Sr system may involve a more complex redistribution of strontium among various mineral phases present in a rock. Interpretation of such data is consequently not without ambiguity. We have used strontium isotope evolution diagrams to illustrate the analytical results obtained in this investigation. Unfortunately, the mineral and rock phases analyzed have ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr parameters such that the common intersections are based for all intents and purposes on the intersection of two lines only (equivalent to two-point isochrons). Under these circumstances, the requirements of strontium isotope homogenization cannot be adequately tested. However, three of the analyzed systems include micas that because of their high Rb/Sr ratios dominate the age calculations. In effect, it is the mica apparent age that is determined. The three granitic samples representing the migmatitization event give the following results: sample 631, age = 224 ± 5 m.y., homogenized ^{87}Sr/^{86}Sr ratio = 0.7138 ± 0.0005, MSWD = 1.1; sample 634, age = 341 ± 8 m.y., homogenized ^{87}Sr/^{86}Sr ratio = 0.7138 ± 0.0006, MSWD = 4.1; sample 635, age = 374 ± 13 m.y., homogenized ^{87}Sr/^{86}Sr ratio = 0.7077 ± 0.0007, whole-rock and muscovite age only. As we have already pointed out, these ages are for all intents and purposes mica ages; they clearly correspond well with the available K-Ar ages and amplify the indications of thermal events in Late Devonian and Late Triassic time.

The only mineral Rb-Sr data for the granulite-facies gneisses are on potassium feldspars from samples 629 and 637. K-Ar determinations indicate that the feldspar from sample 629 has suffered extreme argon loss, and the plots of the Rb-Sr data for the feldspar relative to the parent-rock isochron indicate that their Rb-Sr systems have also been disturbed. Thus, model ages, calculated assuming an initial ^{87}Sr/^{86}Sr ratio of 0.7086, give ages of 2,052 ± 45 m.y. (sample 629) and 1,570 ± 35 m.y. (sample 637). However, if strontium isotope homogenization is assumed, the combined whole-rock–potassium feldspar data give ages of 783 ± 131 m.y. and 677 ± 69 m.y. for samples 629 and 637, respectively. These results do not differ significantly from each other and could also relate to the late Precambrian thermal event postulated above.

Summary

Rb-Sr analyses of whole-rock granulite-facies gneisses from the Mollendo-Quilca region provide firm evidence of metamorphism at 1,811 ± 39 m.y. ago. The initial ^{87}Sr/^{86}Sr ratio of 0.7086 suggests a crustal history prior to the dated metamorphic event. Amphibolite-facies supracrustal rocks found to the northwest of the granulites give ambiguous results: one sample is colinear with the granulite isochron, whereas another appears to indicate a younger age. The granitic members of migmatites associated with both the granulite- and amphibolite-facies metamorphic rocks may have been emplaced in late Precambrian or Cambrian time.

Both K-Ar and Rb-Sr age determinations of minerals from the granulites and migmatites show evidence of later disturbances. The Rb-Sr data for the potassium feldspars from the granulites may have been reset in late Precambrian time, possibly in response to the migmatitization event, but a K-Ar age on one of these same feldspars also indicates outgassing in Late Triassic or Early Jurassic time. Mica from the migmatites show evidence of mid-Paleozoic and early Mesozoic disturbances. These disturbances are believed to relate to well-established Late Devonian and intra-Permian tectonism. The intra-Permian tectonism was also associated with intrusive activity.

GEOLOGICAL CORRELATION

Despite the relatively small area of this occurrence (50,000 km^2) and the isolation from the main South American shield areas imposed by the intervening Andean belt, it is remarkable that these Precambrian rocks exhibit an age pattern similar to that seen in the shields. Thus, the largest ancient core of the continent comprising the Guyana Shield, the basement of the Amazon sedimentary basin, and the Guapore craton to the south, with a total area of about 4.5 × 10^6 km^2, is characterized by ages in the 1,800- to 2,000-m.y. range, although older components are also present. Similarly, the São Francisco craton of similar age crops out over an area of about 1 × 10^6 km^2 in eastern Brazil. Smaller ancient nuclei also characterized by ~2,000-m.y. ages constitute the São Luis craton in northeast Brazil and the Rio de la Plata cratonic area in Uruguay and the adjacent areas of Argentina (Cordani and others, 1973). We suggest that the area embracing these ancient cratonic segments be termed the Trans-Amazonian nucleus (Fig. 3).

These older cratonic areas are separated from each other by metamorphic belts characterized by late Precambrian and early Paleozoic ages in the range 450 to 650 m.y. Cordani and others (1973) assigned these belts to the Brazilian orogenic cycle; they are the Caririan belt and the Sergipe geosyncline in northeastern Brazil, the Ribeira belt along the southern Atlantic coast of Brazil, the Brazilia and Paraguay-Arguaia belts in the central part of the continent, and the Sierras Pampeanas massif of northwest Argentina. With the exception of the Sierras Pampeanas massif, these belts all occur within the Trans-Amazonian nucleus (Fig. 3).

Evidence of thermal events in late Paleozoic and early Mesozoic times possibly related to the ~360- and ~200-m.y. resettings of mineral ages in the area under consideration is widespread in Chile and Argentina. Thus, in addition to ages characteristic of the Brazilian orogenic cycle, Halpern and others (1970) and Halpern and Latorre (1973) recorded whole-rock and mineral Rb-Sr analyses from northern Argentina giving late Paleozoic and Cretaceous ages. Schists forming part of the crystalline pre-Mesozoic basement of central Chile (the Cordillera de la Costa, south of Santiago) have been dated by Rb-Sr, and the whole-rock data plot between the 320- and 255-m.y. isochrons (Munizaga and others, 1973). Slates and phyllites from the Cordillera Frontal of Argentina give whole-rock K-Ar ages of 365 to 400 m.y., whereas micas from the mica schists give 250- to 265-m.y. ages. K-Ar dates on the plutonic igneous rocks that intrude the metasedimentary basement along the coast of Chile and in the Cordillera Frontal give results of 220 to 260 m.y. K-Ar mineral and Rb-Sr whole-rock and mineral analyses have given ages in the 100- to 300-m.y. range from the Patagonian massif, and basement gneiss from the Magellan Basin has given a poorly defined Rb-Sr isochron of 306 ± 156 m.y. (Halpern, 1972, 1973).

Cobbing and Pitcher (1972a) have summarized the evidence to show that the metamorphic rocks of the Arequipa massif are overlain not only by Mesozoic volcanic and sedimentary rocks of the Andean belt but also by various sedimentary formations of Carboniferous and Permian age that are indistinguishable from representatives of the same groups in the central Andes and by Devonian and lower Paleozoic deposits. On this basis, they concluded that the Arequipa massif has occupied its present position relative to the Andean mobile belt since Devonian time and probably earlier. The new age data reported here show patterns that have such strong similarities with the ancient cratonic areas of the Guyana Shield and, more particularly, the Brazilian Shield as to suggest that the Arequipa massif has been an integral part of the evolving South American continent since middle Precambrian time. In this regard, the Arequipa massif contrasts with the Sierras Pampeanas and Patagonian massifs and the Chilean basement, which appear to lack components as old as ~2,000 m.y. However, although Precambrian ages for the Chilean basement have not yet been recorded; one of us (Cobbing) has found gneisses in the Coastal Cordillera of Chile at the latitude of Santiago that are similar to the gneisses of the Arequipa massif and whose structures are truncated in the same manner. It would be prudent to suspect the presence of ancient Precambrian elements in the Chilean Coastal Cordillera, which is structurally continuous with the Arequipa massif.

Thus, the age pattern of the Arequipa massif, together with the absence of any obvious suture zone, suggests that this relatively small area of Precambrian rocks does not represent a microcontinent that fused on to the ~2,000-m.y.-old Trans-Amazonian nucleus of the South American continent. Rather, it appears to be part of that nucleus, a finding that amplifies the earlier conclusions of Mégard (1967) and Cobbing and Pitcher (1972a) — namely, that "the Mesozoic-Tertiary fold-belt is known to be contained within and underlain by sialic crust both at the present time and during that of the deposition of its constituent rocks."

The manner in which the structures of the Arequipa massif strike more or less at right angles to the existing coastline provokes questions about the location of the matching cratonic crust and, possibly, the timing of the opening of the Pacific.

We suggest three possible approaches to these problems: the first involves the rifting of the ancient Trans-Amazonian nucleus, possibly in response to the opening of the Pacific Ocean; the second involves the lateral movement of segments of the nucleus along transcurrent faults; and the third involves underthrusting of continental material beneath the Andean zone.

For the first approach, it is assumed that an ancient continent broke apart with the opening of the Pacific Ocean. Because the oldest part of the Pacific basin is at least Jurassic, the rifting must be older. Isaacson (1975) has shown that a large accumulation of Devonian sediments in Bolivia were derived from an almost exclusively western land source. The volume of sedimentary detritus suggests that more land area existed in the western South American continent than exists today. These observations thus suggest that the rifting was post-Devonian but pre-Jurassic.

Paired metamorphic belts of late Paleozoic age have been recognized in southern Chile (González-Bonorino and Aguirre, 1970); these belts have been compared with the paired metamorphic belts of similar age in Japan. The latter have been interpreted by Miyashiro (1961) as resulting from geologic activity in an oceanic trench — that is, a subduction zone. That the Chilean metamorphic belts carry the same implication indicates the existence of an ocean to the west by late Paleozoic time.

If simple rifting truncated the Precambrian structures, we suggest that the missing continental segment now forms part of eastern Asia and as such may be apparent because of its distinctive age pattern — Trans-Amazonian with an age of about 2,000 m.y. and a superimposed Brazilian orogenic cycle with ages in the 450- to 650-m.y. range.

The second approach involves lateral movement of segments of the Tran-Amazonian nucleus along transcurrent faults. Such movement would be induced by any element of oblique convergence between the oceanic plates of the Pacific and the continental South American plate. Fitch (1972) has proposed a model for such oblique convergence of plates whereby at least a fraction of slip parallel to the plate margin results in transcurrent movement on a nearly vertical fault plane located on the continental side of a zone of plate consumption. The advantage of this hypothesis is that the structures would have been merely twisted within faulted segments, which would account for their apparent truncation. It would thus not necessarily require a matching cratonic segment in another continent.

In Peru large faults more or less parallel to the present coastline are abundant and are considered to have influenced the formation and deformation of the present "geosyncline" as well as to have provided a locus for plutonism (Cobbing and Pitcher, 1972b; Cobbing, 1972). Although there is no evidence of significant transcurrent movement along any of these faults, considerable vertical movements at various times are known to have occurred.

In northern Chile, extensive strike-slip faults parallel to the north-trending coastline have been recognized (St. Amand and Allen, 1960; Allen, 1965), and farther inland the northwest-trending Chiquitos structure in the southwest of the Brazilian Shield is seen by Gansser (1973) as a rejuvenation of an old structure with sinistral movement.

The third approach, underthrusting of continental material beneath the Andean zone, was suggested by Helwig (1972) as explaining the great crustal thickness and elevation of the central Andes. However, the presence of marine Cretaceous sedimentary rocks, in some localities at elevations greater than 5 km, suggests that crustal thickness in late Mesozoic time could not have been more than about 40 km. Crustal thickening to the present 70 to 75 km must have occurred during the Cenozoic Era, but the structural evidence for this period all suggests that the region of the volcanic arc has, in the main, been one of tensional rather than compressive stresses. This would appear to eliminate the possibility of major crustal foreshortening to produce a doubling of crustal thickness (James and others, 1974).

It would seem that either simple rifting or transcurrent faulting is a viable hypothesis that could explain the truncation of the Precambrian structural trends.

The Andean orogen was probably associated with different processes at different times throughout its history, and it may have been related to distinct episodes in the evolution of the Pacific Ocean. We believe that it is in this kind of context that the Andean orogen is most likely to be understood.

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