Cauldron Subsidence and Fluidization: Mechanisms of Intrusion of the Coastal Batholith of Peru into Its Own Volcanic Ejecta

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ABSTRACT

The Coastal Batholith of Peru shows how diorite, tonalite, granodiorite, and granite magmas rose through their last few kilometers by a process of magmatic stoping by their fluidized upper surface. The magmas successively displaced both older, more basic plutons and their own volcanic debris downward and came to rest within 3 km of the Earth's surface after loosing volatiles by eruptions through fissures and calderas. There was a continuous association between volcanic eruptions and plutonic intrusions from at least 100 to 30 m.y. ago in a narrow belt parallel with the continental margin.

The batholith is 50 km wide, more than 1,100 km long, and probably 15 km or less thick. It has steep walls and an extensively preserved flat roof exposed in mountainous desert with relief of 4,500 m. It consists of plutons and sheets which were intruded in five distinct episodes into the same tabular belt by repeated cauldron subsidence. Each subsidence was preceded by the formation of small shear zones which were fractured and fluidized, and accompanied by the rise of corrosive, turbulent gas-liquid-solid mixtures. Individual plutons form relatively thin tabular bodies with flat roofs and floors and steep walls which pass downward into ring dikes and upward into ring dikes and calderas. *Key words: structural geology, igneous rocks, batholiths, volcanism.*

INTRODUCTION

The Coastal Batholith of Peru is one of the largest and best exposed of a chain of Mesozoic and Tertiary batholiths which occur along the western margin of the American continent. It forms an almost continuous outcrop 1,100 km long and 50 km wide on the western flank of the Andes between latitudes 8° and 16° south (Fig. 1). The 80-km-long section of it which lies between latitudes 10° and 10° 30′ south was mapped on the scale of 1:50,000 during 12 months spent in the field in 1968–1970. The shapes of the intrusions and the structure of their country rocks can be clearly observed here in mountainous desert with

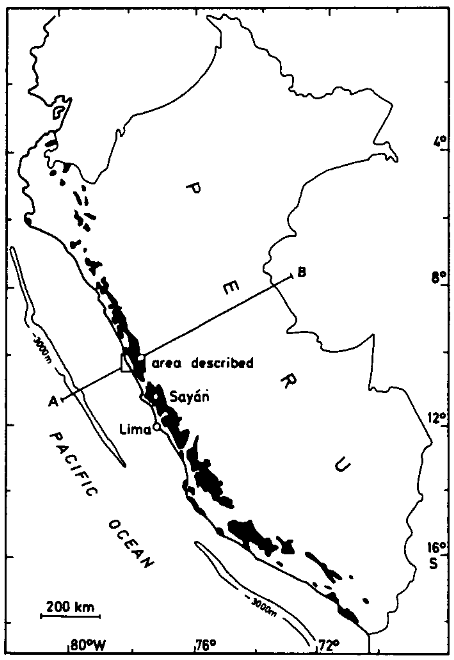

Figure 1. Map showing the extent of the Coastal Batholith of Peru (after Bellido and others, 1972) and locations of the area described and of section A–B of Figure 12.

relief of more than 4,500 m. This paper describes the structure of the batholith and evidence of the mechanism of its intrusion.

Earlier descriptions of other parts of the Coastal Batholith were made by Jenks (1948), Cossío (1964), Cossío and Jaén (1967), and Stewart (in Garcia, 1968). Part of the batholith lying immediately south of this area was described by Cobbing and Pitcher (1972) and Cobbing (1973a). These studies showed the batholith to consist of a number of plutons of which tonalite, granodiorite, and adamellite far exceed basic rocks and granite in total volume. The earliest intrusions are more basic than younger ones and local basic to acid differentiation sequences occur within some composite plutons. K-Ar minimum ages, mostly of biotite and hornblende obtained from a wide area of the Coastal Batholith, range from about 100 to 10 m.y. (Stewart and others, 1974).

Between latitudes 10° and 10° 30′ south, the batholith lies parallel with the coastline, 10 to 60 km inland, and has subvertical walls and a flat roof. It was emplaced between Late Albian and Eocene time (about 100 to 50 m.y. ago) into two groups of volcanic rocks which were erupted from the rising batholith.

Structures and features relating to intrusive mechanisms are described together, drawing on examples from different units of the batholith because the structure and intrusion mechanism of most plutons are broadly similar. A more complete account of the batholith, the volcanic rocks, and the regional geology is in press (Myers, in press). Plutonic rock names follow the

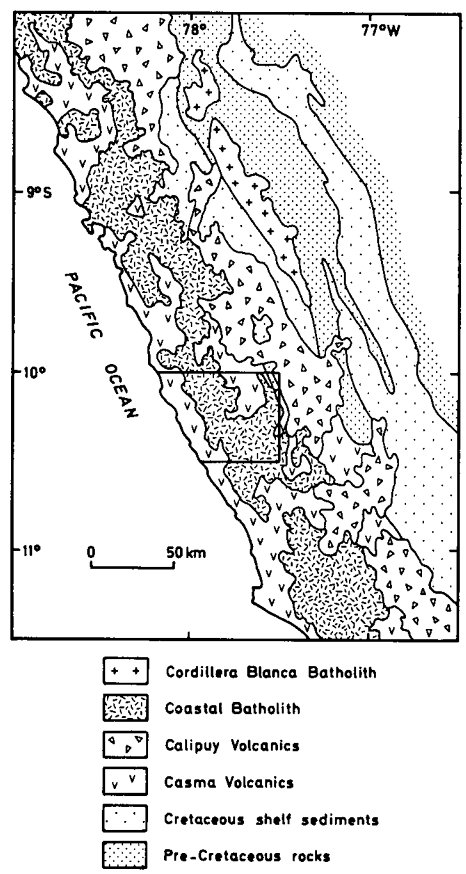

Figure 2. Part of northern Peru showing the close association of the Casma and Calipuy Groups of volcanic rocks with the Coastal Batholith (after Cobbing, 1973b); the area described is outlined.

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definitions recommended by the International Union of Geological Sciences (Streckeisen, 1973). The term "host rock" is used to include any rock into which a pluton, dike, or sheet was intruded, whereas the term "country rock" is restricted to nonplutonic rocks, mostly volcanic, into which the batholith was emplaced.

VOLCANIC COUNTRY ROCKS

The Coastal Batholith was intruded into the Casma Group of volcanic rocks which are chiefly marine and Middle to Upper Albian, and the Calipuy Group of terrestrial volcanic rocks which unconformably overlie them and are Late Cretaceous to early Tertiary in age (Fig. 2).

Casma Group

The Casma Group is a sequence of andesite lava and pyroclastic flows, andesite pillow lava, tuff, dikes, and sills, with smaller amounts of dacitic pyroclastic flows, chert, and volcaniclastic sediments. The sequence extends for at least 500 km along the coastal region of northern Peru and inland to just beyond the eastern margin of the Coastal Batholith (Fig. 2). In the area described here, it comprises six formations with a total thickness of about 6.5 km, although the actual thickness in any one place is probably in the order of 3 to 4 km. The stratigraphic sequence is summarized in the legend of Figure 3 and described in detail in Myers (1974, and in press). Fossils indicate that most of the lower part of the volcanic sequence is late Middle Albian in age. In the northeast corner of the area, the Casma Group conformably overlies a thick sequence of shale and siltstone of probable Hauterivian to Middle Albian age (Huayllapampa Group).

Regional Deformation and Metamorphism of the Casma Group

The Casma Group was folded into large, upright, open folds with axes slightly oblique to the walls of the batholith (Fig. 3). It was metamorphosed into greenschist facies during this ductile deformation before uplift, erosion, and eruption of the Calipuy Group of volcanic rocks. The Casma Group was most strongly deformed in the Canoas syncline and the Tapacocha fold belt (Fig. 3), which almost coincide in location with the future western and eastern walls of the batholith. The northwestern part of the Canoas syncline is an open fold with little associated metamorphism. The fold is tighter toward the southeast and passes structurally downward into a complex synclinorium of isoclinal folds associated with amphibolite facies metamorphism. Biotite forms a prominent schistosity, hornblende crystals are elongate parallel with fold axes, and cordierite contains spiral inclusion trails of opaque minerals. The Tapacocha fold belt is an anticlinorium of isoclinal folds associated with greenschist facies metamorphism.

Calipuy Group

The Calipuy Group is a sequence of terrestrial andesite, dacite and rhyolite, lava, and pyroclastic flows which extends for at least 600 km along the western cordillera of northern Peru (Fig. 2). The rocks were first described in detail by Cossío (1964) and Cossío and Jaén (1967) and are extensively intruded by the Coastal Batholith. In the northeast part of the area described, they overlie the Tapacocha fold belt with marked unconformity (Fig. 3) and their average thickness is in the order of 2 km. The rocks are probably Late Cretaceous to early Tertiary in age, and they formed the land surface during intrusion of most of the batholith.

COASTAL BATHOLITH

The batholith is a heterogeneous mass of coarse-grained igneous rocks which was intruded as numerous plutons and sheets. Each pluton is a distinct mappable intrusive body with steep walls and a flat roof. Many plutons are composed of identical rock types, and each major mappable rock type is called a magma unit. This unit is the fundamental division of the batholith and is analogous to the lithostratigraphic term "formation." In the same way, a "complex" (or super-unit of Cobbing and Pitcher, 1972) is a group of related units, and a "subunit" is a division of a unit, analogous to the lithostratigraphic terms "group" and "member."

The main components of the batholith are listed in Table 1 in order of age, based on crosscutting relations, and are described in detail elsewhere (Myers, in press).

Dikes of microdiorite were intruded between and during the emplacement of all the complexes. In the Sayán area (Fig. 1), the dikes intruded between the Santa Rosa and Puscao – San Jeronimo Complexes give K-Ar whole-rock ages of 72 to 68 m.y. A fifth group of plutons at Sayán, younger than the Puscao — San Jeronimo Complexes, give K-Ar mineral ages of ~30 m.y. (P. A. Wilson, 1974, personal commun.).

Major Structures

The batholith has steep walls, subparallel with the coast and continental margin, and a flat roof. The roof is extensively preserved in the northeastern part of the area (Fig. 3).

Individual plutons have similar flat roofs and steep outward-dipping or vertical walls (Figs. 4, 5, and 6). The plutons generally form rectangular bodies with long sides parallel to the batholith and short sides normal to it [for example, the Huampi Piruroc granodiorite (Fig. 4); the Contaderas, Llagumpe, and Maria Cristina plutons of the Puscao unit, and northernmost San Jeronimo pluton (Fig. 5)]. The transition from steep walls to flat roof generally occurs within a vertical distance of 50 m (Fig. 4, localities B and D). This relationship is most clearly seen on a large scale in the dome-shaped outcrops of the Puca Jirca and Chasquitambo plutons of the Puscao unit. The Puca Jirca pluton forms a subcircular dome-shaped outcrop, 5 km in diameter, through which a valley cuts a section 700 m deep (Fig. 5). At the highest levels exposed, the contacts dip outward at 5°; whereas in the valley floor, they dip at 30° to 40° outward. The Chasquitambo pluton crops out over an area of 300 sq km between altitudes of 400 and 2,400 m (Fig. 5). At the highest topographic levels, its contact dips at less than 10° outward; at the lowest levels exposed, its contact dips steeply outward.

Some plutons form ring dikes, the largest of which are the Anta and Corcovado dikes, each 1 km thick and in rings up to 20 km in diameter (Fig. 5). The walls of the

TABLE 1. COMPONENTS OF THE BATHOLITH

Puscao-San Jeromino complex ~70-50 m.y. (I)	San Jeronimo unit	Granite porphyry dikes Aplite sheets Syenogranite plutons
	Puscao unit	Aplite sheets Monzogranite (adamellite) plutons Baranda granodiorite sheets
Santa Rosa complex ~95-70 m.y. (I)	Huampi Piruroc granodiorite unit Corralillo tonalite unit Huaricanga tonalite unit Puca Punta mylonite sheets	
Paccho complex ~95-90 m.y. (F)	diorite and tonalite units	
Patap complex ~100-95 m.y. (F)	gabbro and diorite units	

Note: The isotopic ages are from recent unpublished work of P. A. Wilson (I) and are K-Ar minimum ages of separated biotite, feldspar, and hornblende from samples collected over a wide area of the batholith, including the region described here, or guesses (F) based on these ages and fossil evidence (Myers, 1974).

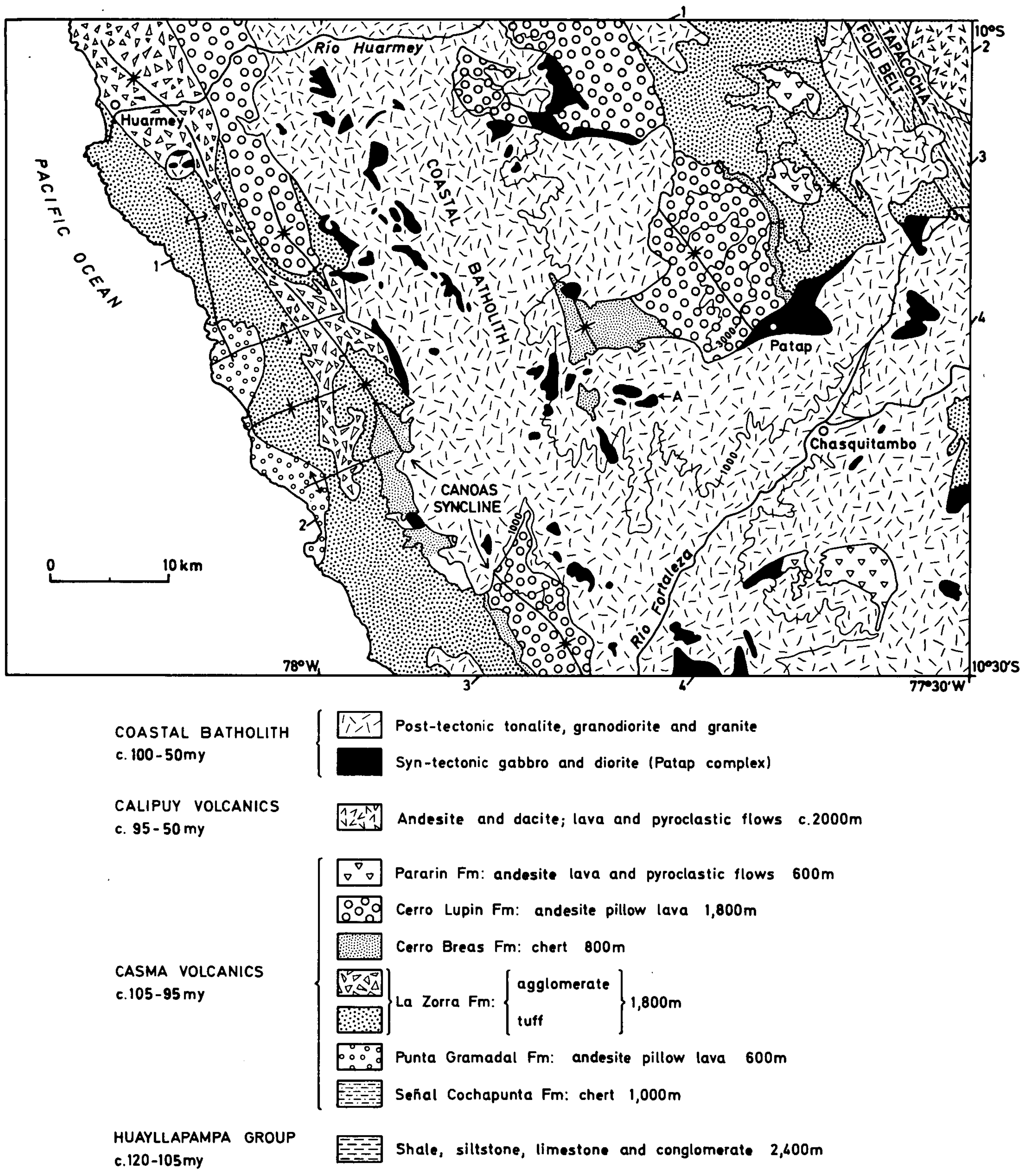

Figure 3. Map of the stratigraphy and structure of the volcanic country rocks and syntectonic and posttectonic intrusions of the batholith, with locations of sections 1–4 of Figure 6. Approximate ages after fossil evidence and unpublished age determinations by P. A. Wilson.

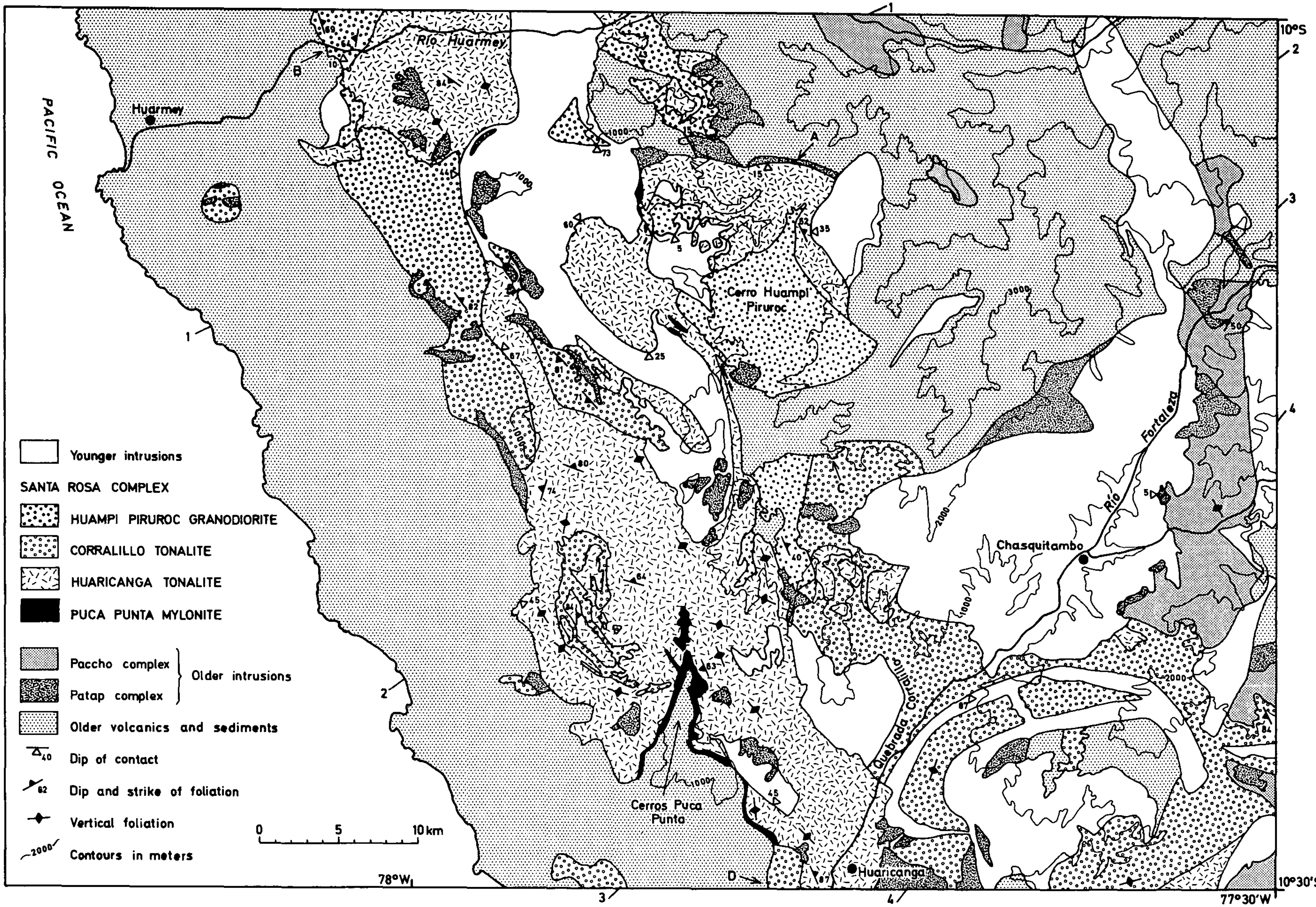

Figure 4. Map of the Santa Rosa complex and older rocks, with location of sections 1–4 of Figure 6.

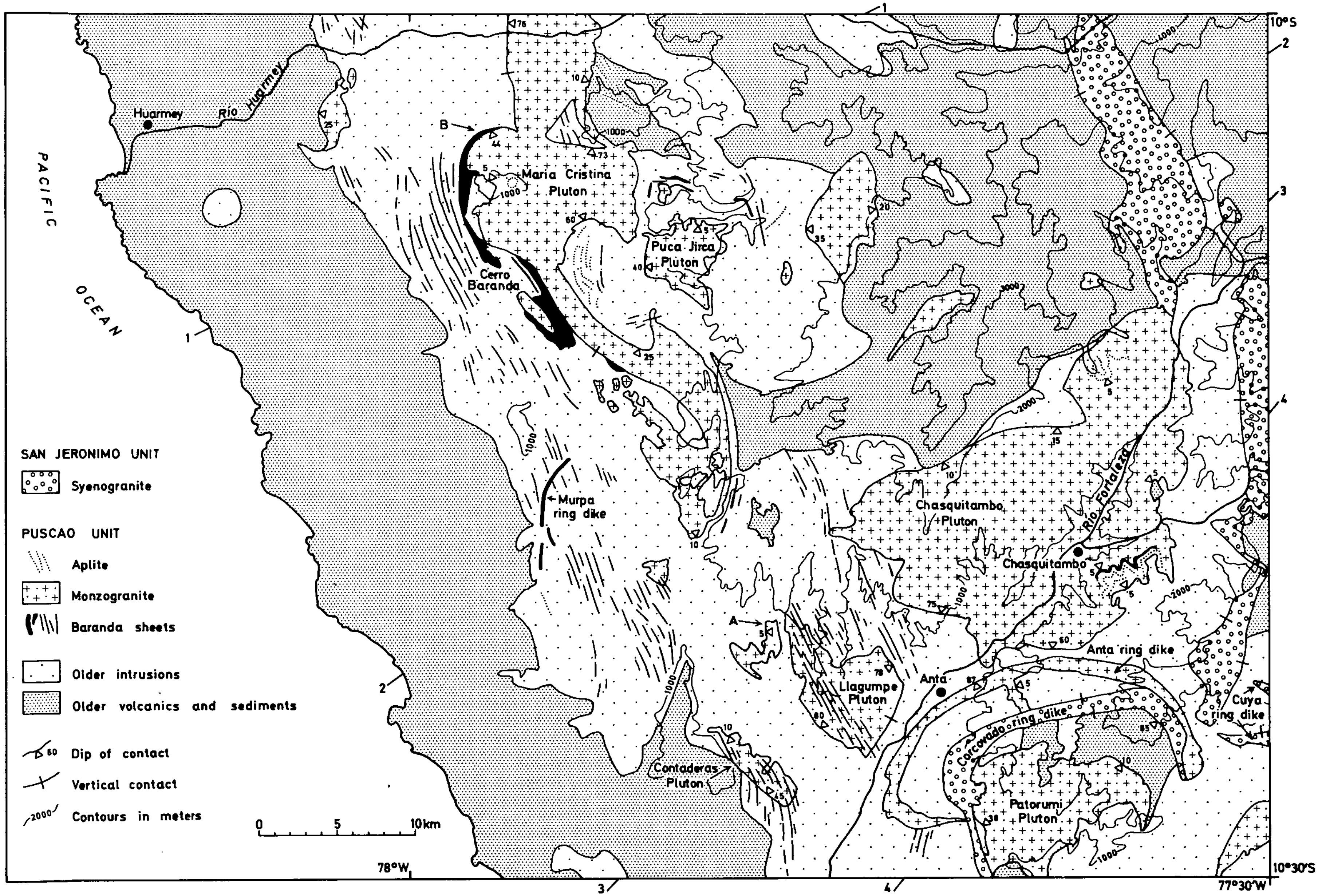

Figure 5. Map of the Puscao and San Jeronimo units, with location of sections 1–4 of Figure 6.

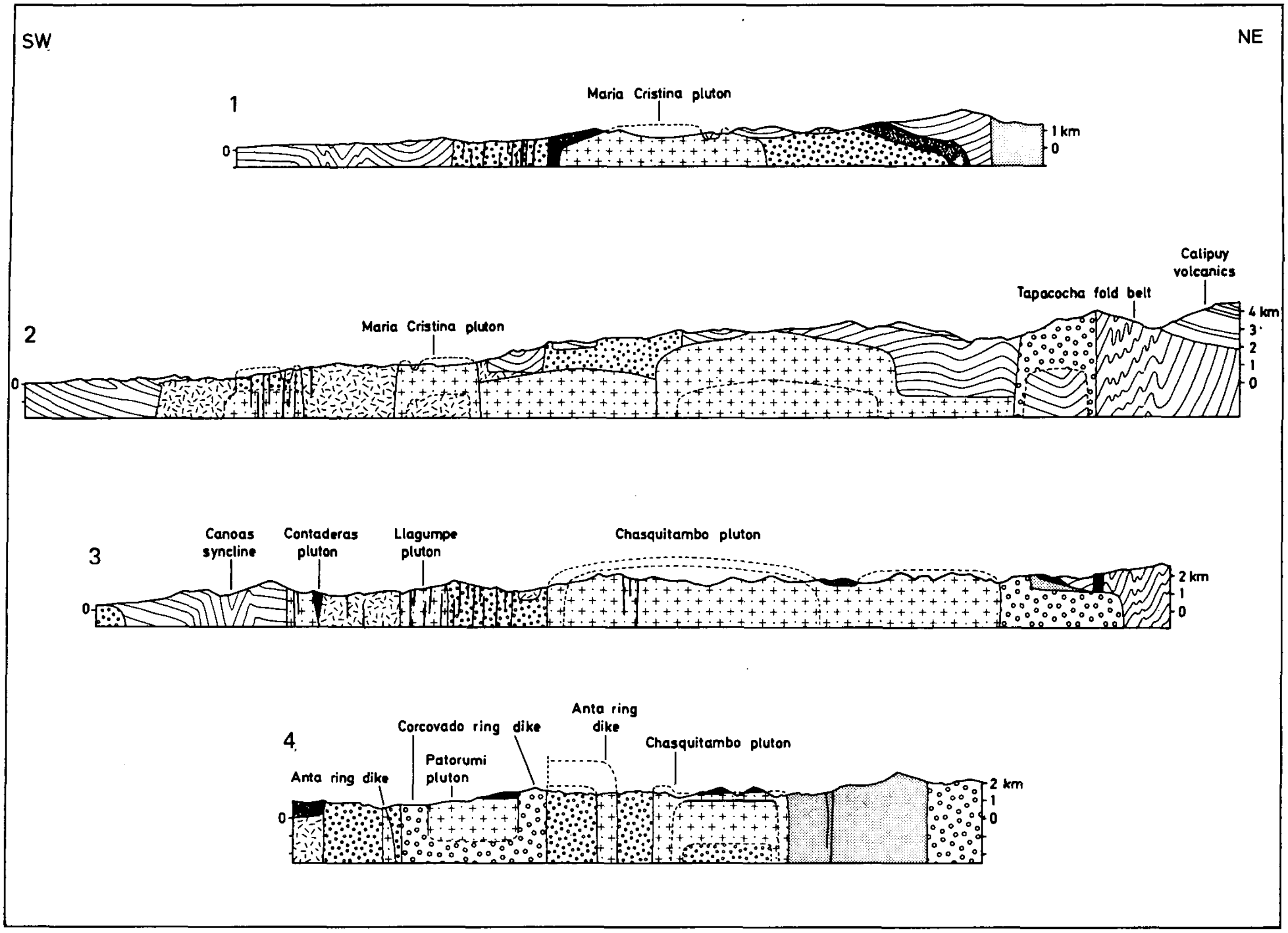

Figure 6. Sections across the batholith ornamented as on Figures 4 and 5, where their locations are also marked. The structure of the country rocks is indicated by lines representing bedding. Black lines within the batholith indicate Baranda sheets; Puca Punta mylonites are not shown. Horizontal and vertical scales are equal.

ring dikes are generally vertical, but east of the village of Anta (Fig. 5), the inner contact of the Anta dike curves gently over an apparently foundered block of Corralillo tonalite which is cut off by the younger Corcovado ring dike of the San Jeronimo unit (Fig. 6, sect. 4). Within the Corcovado ring dike, rocks of the Casma Group lie on top of the flat roof of the Patorumi pluton (Fig. 5). The stratigraphy of these volcanics (Pararin Formation, Fig. 3) indicates that relative to neighboring volcanic rocks, they have subsided a vertical distance of more than 1,500 m within the Corcovado ring dike. The Patorumi pluton and Anta ring dike are almost identical Puscao rock types, and their close spatial association on either side of the Corcovado ring dike suggests that they were originally part of one intrusive body. These outcrops both enable the thickness of a major pluton to be measured (here in the order of 2 km) and indicate that a tabular pluton passes downward into a ring dike.

Pluton Contacts

Most pluton contacts are sharp, and in many places contact effects by which to interpret the emplacement order of contiguous plutons are absent or ambiguous. Ambiguous contact features include thin pegmatite veins along the contact and a slight reduction of the grain size of both pluton and host rock.

Stoping and spalling occurred at some contacts. Figure 7 shows a typical example from the roof contact of the Corralillo tonalite (Fig. 4, locality C). At the contact, angular blocks of country rock were broken off by stoping and spalling (Fig. 7a). Within the next 200 m downward within the pluton, the angular fragments are progressively smaller, more rounded, and dispersed, as their distance from the contact increases (Figs. 7b and 7c). In the same distance, fragments of both andesite volcanic rocks and Patap diorite were recrystallized to form medium-grained, uniform xenoliths of identical appearance with diorite composition and appinitic texture.

Internal Structures

Plutons are generally homogeneous and contain rounded dioritic xenoliths less than 15 cm long, which are uniform in size and distribution. In some places the xenoliths can be seen to be derived by brittle fracturing and mechanical corrosion from volcanic country rocks and Patap diorite (Fig. 7).

In other places, the xenoliths formed from microdiorite sheets which broke up after intrusion into unconsolidated plutons. The latter situation is well displayed in the roof zone of the Puca Jirca granite pluton (Fig. 5), where various stages and kinds of breakup of the sheets are preserved (Fig. 8). Flat-lying trains of pillowlike bodies and angular fragments of porphyritic microdiorite are abundant as far as 200 m from the roof, in both the pluton and in the Huaricanga tonalite host. The microdiorite

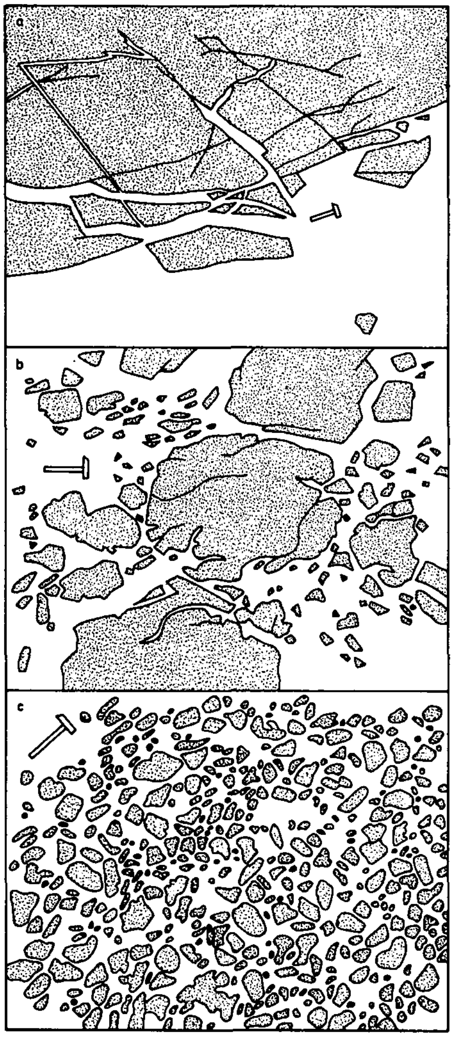

Figure 7. Stoping, spalling, and progressive rounding and breakdown in the size of andesite volcanics (stippled) in the Corralillo tonalite (white). Locality C, Figure 4; a. at the contact, b. 100 m below the contact, c. 200 m below the contact.

pillows partly resemble basaltic pillow lava erupted into water, and dolerite pillows in granophyre described by Blake and others (1965). The pillows have fine-grained margins and globular boundaries (Figs. 8b and 8c) and in different places are veined by both the Huaricanga tonalite and the Puca Jirca pluton. They enclose angular fragments of the Huaricanga tonalite but none of the Puca Jirca pluton. Some of the pillows were deformed before consolidation (Fig. 8c) and some crystallized with patchy metamorphic textures. Immediately beyond this contact zone of trains of microdiorite pillows and fragments, thin and irregular but continuous sheets of microdiorite occur in the Huaricanga tonalite. These features suggest that the trains of pillows and fragments were derived from microdiorite sheets which were intruded into the roof zone of the Puca Jirca pluton and into its locally heat-softened envelope soon after the emplacement of the pluton.

There is no evidence of the origin of most xenoliths, but because of their general uniformity and the evidence described above, they are considered to have been derived for the most part from either host rocks or dikes intruded from depth. There is no field evidence that any xenoliths were transported by the magma from great depth below the batholith.

Many plutons possess a foliation weakly defined by disclike dioritic xenoliths and the long axes of hornblende and plagioclase. The foliation formed during magmatic crystallization under stress, and it is generally subvertical and nearly parallel with the length of the batholith. It is locally more strongly marked at pluton contacts, parallel with the contacts.

Some plutons are composite with older (darker) and younger (lighter) subunits. The large-scale relationship between such subunits is best displayed in the Chasquitambo pluton where a younger subunit occurs as a dome within a shell of an older subunit (Fig. 5; Fig. 6, sects. 2 and 3). In some places, the contact between them is sharp and the younger subunit encloses angular fragments of the older subunit; but in other places, the contact is gradational. Dioritic xenoliths are more abundant in the older subunit and can be seen in various stages of digestion which locally contaminated the monzogranite and converted it to granodiorite.

Baranda Sheets

Sheets of gray granodiorite to quartz-rich granodiorite were precursors of the emplacement of Puscao monzogranite plutons. Their fabric and grain size range from medium-grained, isotropic to fine-grained, planar to protoclastic mylonite. The sheets are named after Cerro Baranda where they are well exposed (Fig. 5); most are dikes, but they are collectively referred to as "sheets" because some occur with flat-lying attitudes. They are generally 5 to 10 m thick, but some are as much as 500 m thick. In profile section, many form irregular networks (Fig. 9), and a few form irregular pipes a few meters in diameter. They are characterized by the diversity of their size, internal structure, and xenoliths on both regional and local scales; they are of great importance in understanding the process of cauldron subsidence discussed below.

Baranda sheets are generally abundant as far as 2 km outside the walls of a Puscao pluton, parallel with the walls and along the contacts, such as on the western side of the Maria Cristina pluton (Fig. 5; Fig. 6, sect. 1). They also occur with flat-lying attitudes up to 2 km above the flat roofs of Puscao plutons. Southeast of the town of Chasquitambo, a thick flat-lying sheet occurs between the two subunits of the Chasquitambo pluton (Fig. 5; Fig. 6, sect. 4). The sheet cuts the older, darker subunit above and is itself cut by the younger, lighter subunit below. It appears to have occupied the initial fracture which became the roof fracture of the younger subunit. South of the village of Anta (Fig. 5), the wedge-shaped end of the Anta ring dike consists of Baranda granodiorite; it grades westward, as the dike thickens, into normal Puscao monzogranite which makes up the main part of the dike.

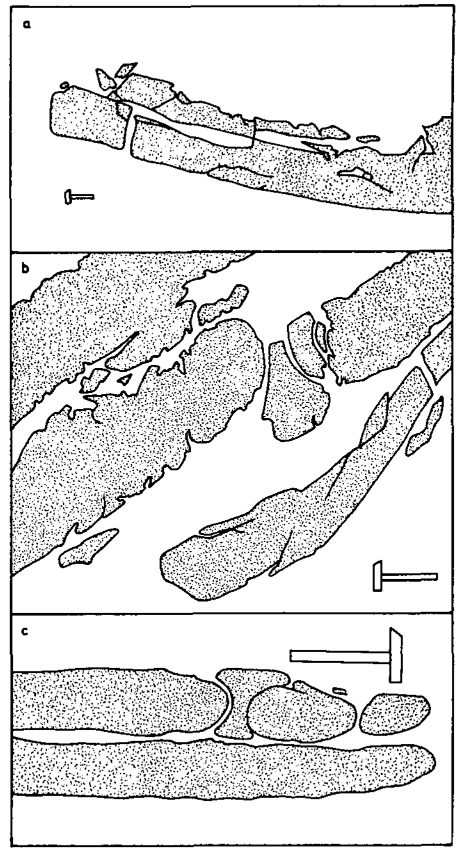

Figure 8. Disrupted, flat-lying microdiorite sheets (stippled) in the roof zone of the Puca Jirca pluton (white) (Fig. 5). a. Disruption after consolidation of a sheet, b. disruption both before and after consolidation of a sheet, c. pillows formed by disruption before consolidation of a sheet.

Contact Metamorphism

The contact metamorphism produced by the Huaricanga tonalite is typical of most units of the batholith. Intense recrystallization of the country rock is limited to within 50 m from the contact, but major recrystallization can be seen for as much as 300 m from its walls and 1,000 m above its roof. Beyond these distances, contact metamorphism is not easy to distinguish in the field from prebatholith low-grade regional

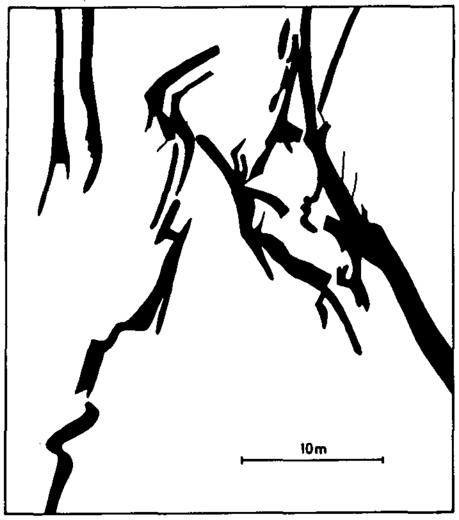

Figure 9. Profile section of subvertical Baranda sheets in the Contaderas pluton (Fig. 5).

metamorphism. Wollastonite, brucite, monticellite, diopside, and garnet are restricted to the inner part of the aureole; tremolite, epidote, and hornblende are most commonly seen in the outer part. Close to the contact, patches with scapolite, calcite, and wollastonite crystals up to 30 cm long occur and indicate high fluid mobility in this part of the aureole. The size and mineral sequence of the aureole is similar to that of plutons in the Sierra Nevada Batholith described by Kerrick (1970). Stratigraphic evidence which indicates that the roof of the Coastal Batholith was 2 to 3 km thick suggests a total pressure in the aureole of 1 kb. Mineral assemblages indicate metamorphism in the hornblende-hornfels facies with temperatures of 550° to 650°C (Turner, 1968).

DISCUSSION AND CONCLUSIONS

Major Structures

Both the whole batholith and individual plutons have flat roofs and steep walls. The shapes and spatial association of the Anta ring dike and Patorumi pluton suggest that plutons are tabular and pass downward into ring dikes (Fig. 6, sect. 4). Irregular veins of Puscao monzogranite are abundant to the east of the small Murpa partial ring dike of Baranda granodiorite (Fig. 5) and are similar to offshoots above the roofs of major Puscao plutons elsewhere. These relations suggest that the Murpa dike lies above the walls of a major Puscao pluton. Together, these outcrops suggest that ring dikes are both the upward and downward extension of the walls of Puscao plutons, and that the upward extensions are composed of Baranda granodiorite, whereas the downward extensions are of monzogranite. The Corcovado ring dike, which is similar in internal structure to a Puscao Baranda sheet, probably reached the surface and formed a caldera which contributed ignimbrite to the Calipuy Group.

It can be seen from the maps (Figs. 3, 4, and 5) and sections (Fig. 6) that both the whole batholith and its individual plutons were emplaced without any significant lateral or upward vertical distortion of their host rocks. Therefore, the plutons were neither emplaced by dilation nor by lifting their roof — they replaced the rocks which previously occupied their sites by exchange downward. A chemical, metasomatic replacement is unlikely because of the homogeneity of enormous plutons with sharp contacts, their high level in the crust, and the narrowness of their metamorphic aureoles. The associations between ring dikes, tabular plutons, and calderas and the lack of distortion of the country rocks suggest that the plutons were emplaced mainly by a mechanical replacement of the type first described by Clough and others (1909) as cauldron subsidence. This is illustrated by Figure 10, which is a simplified extension of section 2 of Figure 6 to a depth of 10 km and to the early Tertiary land surface contemporary with the last stages of the batholith's emplacement. When the magmas came close to the surface, explosive ejection of fragmented host rocks with magmatic gas and liquid through calderas and fissures provided additional space for the rising plutons.

The lack of distortion of the envelope, particularly the lack of vertical compression of the roof rocks and the absence of rimsynclines, indicates that the plutons were not emplaced as diapirs at this level. Ramberg (1970) found that there is a great difference in the structures produced in centrifuge model experiments according to the viscosity contrast between the components simulating magma and host rocks. If there is a low viscosity contrast between magma and host rocks, then the magma rises

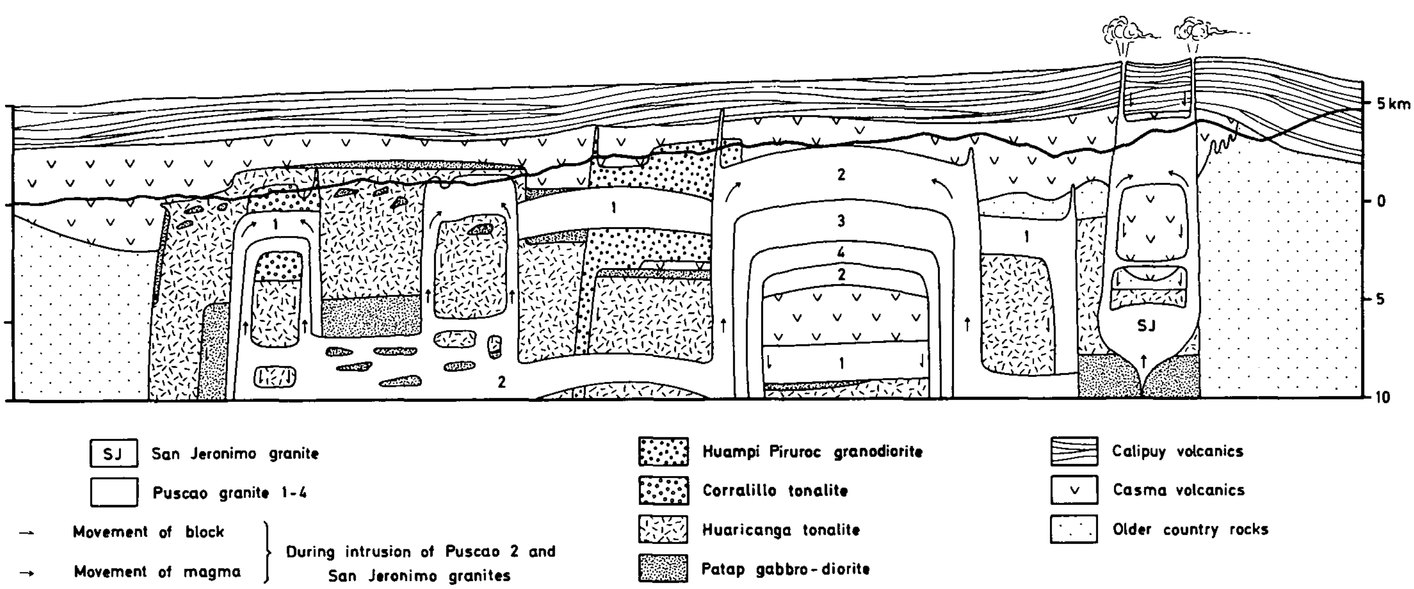

Figure 10. Simplified section showing the major structure of the batholith, which is made up of numerous plutons emplaced by repeated cauldron subsidence into their own volcanic ejecta. An extension of section 2 of Figure 6, showing the probable situation that existed during the last major episode of intrusion, ~50 m.y. ago. The present topography is shown by the thick irregular line. The thickness of Calipuy volcanics is a minimum thickness; it was probably 2 to 4 km. The batholith probably extends for about 5 km or less below the base of the section. Only two phases of Puscao granite were seen, and Puscao intrusions 3 and 4 are conjectured to emphasize the nested appearance of repeated cauldron subsidence at one place. Horizontal and vertical scales are equal.

diapirically, independent of the structure of the host rocks. If there is a high viscosity contrast with viscosity of the magma much less than that of the host, then the magma is too weak to push the host rock aside, but its high fluidity enables it to move rapidly along zones of weakness. The latter case is associated with collapse of the more rigid overburden and with stoping. The following discussion shows that the Puscao plutons and those of Santa Rosa and San Jeronimo are clearly examples of this second case in which the upper surface of the magmas possessed high fluidity.

Intrusion Mechanisms

Minor structures which provide information about the intrusive mechanisms of plutons are generally very small. They are most clearly seen around the Puscao granite plutons which are emplaced mainly into older leucocratic, homogeneous plutonic rocks of

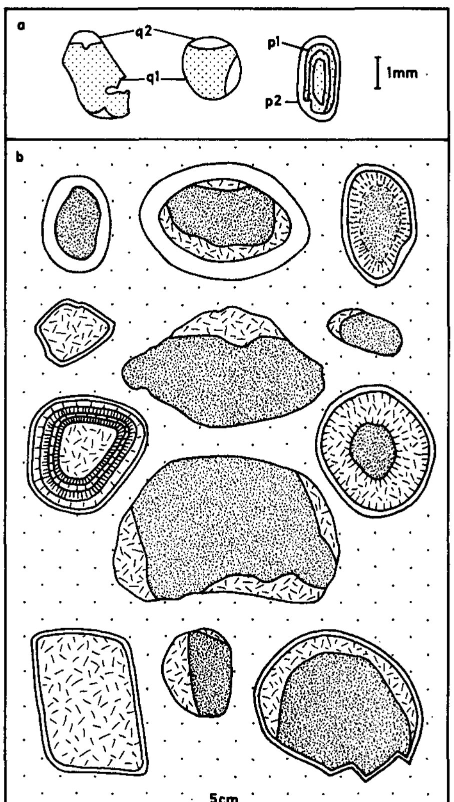

Figure 11. Inclusions in Baranda sheets: a. corroded phenocrysts of quartz (q1) and plagioclase (p1) with rounded secondary overgrowths of quartz (q2) and plagioclase (p2); b. mechanically rounded xenoliths of older microdiorite (dense stipple) xenoliths in Huaricanga tonalite (irregular dashes) in a Baranda sheet (open stipple). Some xenoliths are rimmed by quartz and plagioclase (white) and are internally partly recrystallized with segregation of felsic and mafic shells with radial fabric.

the batholith. The shapes of the Puscao plutons are also the best exposed by the present erosion level, and this enables the relationship between the small emplacement structures and the overall structure of plutons to be clearly observed.

The structures which preceded the emplacement of a major Puscao pluton by cauldron subsidence occur in the same order everywhere, although the complete sequence is not everywhere preserved. The complete sequence is summarized below in the order in which structures developed.

1. Small shear zones less than 1 cm wide and 10 cm long developed in irregular networks within distinct planar belts up to 2 km from the future margin of a pluton. The belts are subparallel with the future margin of a pluton; they are flat-lying above its roof and subvertical outside its walls. The shear zones were fractured. They now contain microbreccias with angular fragments of both schistose centers and less-deformed margins of the shear zones and undeformed host rock in a matrix of banded ultramylonite. Additional fractures and shear zones developed in irregular networks and joined many of the earlier shear zone belts together.

2. Baranda granodiorite sheets developed within 2 km of the future margins of a main pluton, both within and adjacent to the belts of shear zones and microbreccias, parallel with them. Some wider microbreccia zones pass gradationally into the Baranda sheets, whereas many other similar zones are cut by younger Baranda sheets. Angular fragments of host rocks were stoped from the walls of the sheets and were mechanically rounded. In some places, the Baranda sheets developed a flow banding which was deformed before the sheets consolidated; in other places, the adjacent softened host rocks were deformed and recrystallized and became banded gneisses.

3. A major pluton was emplaced by mass exchange with a rectangular segment of its host rocks which subsided within a framework of Baranda sheets. The pluton cut and stoped fragments from its immediately contiguous Baranda sheets.

4. In some plutons, a first major intrusion was followed by the emplacement of a second, more homogeneous and more felsic subunit within a carapace of the first subunit, preceded by a repetition of events 1 to 3. In some cases, sheets of microdiorite were intruded into both a pluton and its immediate envelope and broke up into trains of pillows.

5. Flat-lying sheets of granophyre were emplaced in the uppermost parts of some plutons during further subsidence before the pluton was stabilized.

The initial shear zones are similar to structures commonly seen in homogeneous rocks subjected to heterogeneous strain states. They are the product of heterogeneous simple shear and represent the localization of high strain states where deformation took place by ductile flow. Their distribution indicates that high strain concentrations were localized in narrow zones with either subvertical or horizontal attitudes, were parallel with and less than 2 km from the future margins of a pluton, and they defined a framework of either cylinders or rectangles.

The fracturing of the shear zones indicates a change of deformation state from ductile flow to brittle failure within the same planar zones, perhaps caused by an increase in strain rate, as the mineral assemblages do not indicate any marked change in temperature or confining pressure. A similar association of shear zones and microbreccias was described from along the main boundary fault of the Glencoe cauldron subsidence in Scotland by Clough and others (1909, p. 629). They observed of the microbreccias ("flinty crush rock") their "invariable connexion in the field with obvious signs of shearing. . . . Under the microscope . . . banded structure is often strongly pronounced, and the rocks themselves are found to be richly charged with fragments derived from the adjacent shear-zone."

The fragments of microbreccias within the fractured shear zones are both mixed up and disorientated, indicating that locally the fragments were free to move independently of each other. This suggests that streams of gas were introduced into the fractures from below and isolated the finest grained rock fragments. Progressive stages can be observed in the enlargement of the microbreccia zones by stoping. The larger breccia zones more than a centimeter thick contain both rounded as well as angular fragments, and rounded fragments are progressively more abundant in larger breccia zones, and away from the zone margins. These observations suggest that the rounded fragments are the result of mechanical abrasion of angular stoped wall fragments rather than being of primary derivation from initially curved fractures.

Wide breccia zones are rarely seen, but transitions occur between breccia zones consisting of both round and angular fragments in a matrix of ultramylonite, and Baranda sheets containing between 20 and 75 percent by volume of both rounded and angular xenoliths of host rocks (Fig. 11). True tuffisites as first described by Cloos (1941) are of only minor occurrence in the batholith, and Baranda sheets greatly outnumber breccia zones in volume.

The Baranda sheets represent the third stage in the development of the surfaces of weakness initiated by the formation of the shear zones and then developed by stoping and widening of the microbreccia-filled fractures. Sheets in which angular xenoliths occur at the margin and are followed inward by progressively more rounded xenoliths suggest that the rounding of the fragments is related to the time they were detached from their original position. A similar situation was described by Cloos (1941) in the Swabian tuffisite vents and was interpreted by Reynolds (1969) as the result of rapid flow of gas-tuff streams in the center of the vents, bringing in material which had traveled farther and had been suspended within the vents for longer than that in the marginal parts of the bodies where stoping was just beginning. In the case of the Baranda sheets, this conclusion is supported by the rare occurrence of exotic xenoliths which are invariably more rounded than xenoliths of the immediate host rock.

Some of the xenoliths are composite and consist of either Santa Rosa tonalite or Puscao monzogranite which enclose older xenoliths of diorite or tonalite (Fig. 11b). Such composite xenoliths which are spherical and in which the truncated surfaces of both rock types have been equally smoothed indicate that the rounding was caused by a mechanical process. The presence of concentric felsic and mafic shells around some spherical xenoliths indicates vigorous chemical reaction between the fragments and their matrix, but the fracturing of some concentric shells indicates the continued mechanical attrition of the xenoliths. The occurrence together, in a single part of one sheet, of diorite xenoliths with angular shape and no sign of reaction with their matrix, spherical xenoliths with concentric reaction shells, and similar spherical xenoliths with concentric shells which are partly broken and unconformably overgrown, indicates that vigorous processes of both mechanical attrition and chemical reaction were operative at the same time. The irregular mixup of both different kinds and sizes of fragments indicates that these processes were combined with the thorough mixing of the particles contained within the sheet. Similar phenomena relating to the origin of orbicular xenoliths were recently described from the Sierra Nevada Batholith of California by Moore and Lockwood (1973).

The phenocrysts in the Baranda sheets also indicate a history of both mechanical corrosion and chemical reaction, because they are both rounded and have embayments infilled by secondary growths of the same mineral, but with rounded outer margins conforming with the general curvature of the rounded outer surface of the phenocrysts (Fig. 11a). Some phenocrysts have secondary spherical overgrowths around spherical inner crystals.

These phenomena suggest that the matrix of the Baranda sheets was fluidized, a state whose importance as a geological process was first recognized by Reynolds (1954). The state of fluidization in which solid and (or) liquid particles are isolated and suspended in through-flowing gas is known from industrial experience to stimulate chemical reaction between its components as well as to thoroughly mix them and bring about mechanical attrition of the solid particles (Reynolds, 1954, 1969). At first, gas diffuses through a body or bed of fine-grained rock and (or) liquid particles but "at a particular rate of gas flow, the bed expands and the individual particles become free to move. With increase in the rate of gas flow, a bubble phase forms and travels upwards through the expanded bed in which the particles are violently agitated; the bed is now said to be fluidized" (Reynolds, 1954, p. 577).

Although in some cases the adjacent host rock of a Baranda sheet shows signs of earlier shearing or deformation during emplacement of a sheet, in many cases the host rock shows no signs of deformation. In the latter cases where Baranda sheets show strongly contorted banding, this banding is probably a flow structure. Planar banding may be the result of laminar flow, whereas contorted banding may reflect turbulent flow. The thorough mixing of fragments of different size, source, and degree of rounding, together with the occurrence of locally derived well-rounded fragments with associated turbulent structures, indicates that the fluid agent in these cases was gas and not liquid (Reynolds, 1954; Lewis and Bowerman, 1952).

The fluidized state of the uppermost part of the magmas at the time of their intrusion also explains the narrowness of their metamorphic aureoles. Experimental observations (Lewis, 1969, p. 107-108) show that in a fluidized bed, "the particle movement at walls, or any solid surface immersed in the bed, is so rapid as to produce a steep temperature gradient if the surface is heated or cooled. Consequently heat transfer to or from a surface is very rapid." The expected consequence is realized by a narrow aureole with a mineralogy which indicates rapid heating and only a short time at maximum temperature (Atherton and Brenchley, 1972).

The bounding fractures of the rising plutons appear to have been controlled by the pre-existing framework of Baranda sheets. The occurrence of Baranda sheets as partial ring dikes, together with the occurrence of larger ring dikes of monzogranite, suggests that the widening of the Baranda sheets by stoping associated with fluidization provided the conduits up which the magmas were emplaced. The central block of older rocks subsided into the fluidized rim of the magma as if in quicksand and was corroded by flow of the fluidized system around it.

VOLCANIC AND PLUTONIC HISTORY

The batholith and its associated volcanic rocks were intruded through sialic crust at least as old as late Precambrian (Stewart and others, 1974). The Precambrian gneisses are exposed to the west of the batholith along the coast of southern Peru and are overlain by lower and upper Paleozoic shale and sandstone (Bellido, 1969). Abundant volcanic rocks first occur in the Permian Mitu Group of clastic sediments, but much larger volumes of volcanic rocks were erupted in the Late Triassic, concurrently with initiation of the two great Andean troughs of Peru, and also during Jurassic time.

During Cretaceous time, the older rocks subsided in two linear belts, parallel with the continental margin, which are called the West and East Peruvian Troughs (Wilson, 1963) (Fig. 12, sect. a). The West Peruvian Trough was itself divided into western and eastern belts by the Tapacocha axis (Myers, 1974), a tectonic line which allowed the western block to sink faster than the eastern block. Submarine eruptions of andesite lava and pyroclastics and the intrusion of numerous sills (Casma Group) took place through and onto the fractured western block, while thinner shelf deposits accumulated on the eastern block. The age of ammonites interbedded with the volcanic rocks (Myers, 1974) indicates that subsidence was most rapid in the Middle and Upper Albian (~100 to 95 m.y. ago). Fragments of diorite and granodiorite in pyroclastic rocks of the Casma Group indicate that some plutons had already crystallized by this time, probably at shallow depth. The close spatial and temporal association of the Coastal Batholith and Casma Group (Figs. 2, 3, and 10) suggests that these volcanic rocks were erupted during early phases of intrusion which culminated with emplacement of the Coastal Batholith at its present level (Fig. 12).

During middle to Late Cretaceous time (~95 m.y. ago), most of the Casma Group was folded into Andes-parallel folds and was strongly deformed in two narrow belts. The most intense deformation formed the Tapacocha fold belt, marking continued activity of an older tectonic line (Tapacocha axis). This fold belt is similar to the most strongly deformed part of the Canoas syncline which passes gradationally upward into a more open structure of less deformed and less metamorphosed rocks, and therefore it is probable that these structures pass downward into zones of increasingly intense deformation and metamorphism. They may be the upward expression of major shear zones in the basement which were intermittently active throughout Cretaceous time. Similar shear zones may

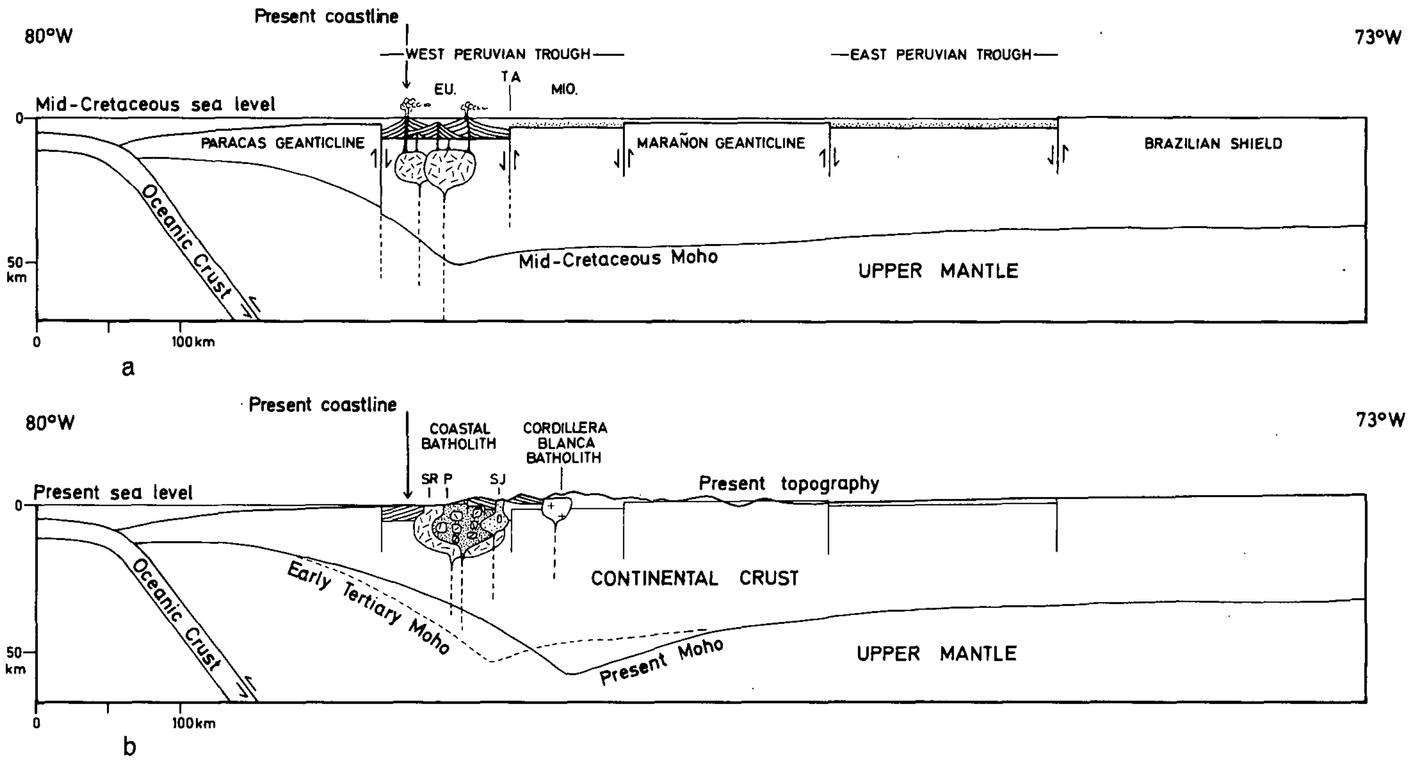

Figure 12. Sections across Peru along the line A–B on Figure 1, showing the location of the Coastal Batholith in relation to major earth structures. Section a shows the sum of Valanginian to Senonian block movements and eruption of Casma volcanics above the rising batholith. Divisions of the West Peruvian Trough are: Eu = eugeosynclinal and Mio = miogeosynclinal facies, with Tapacocha axis = TA. In section b, divisions of the 100- to 50-m.y.-old Coastal Batholith are: SR = Santa Rosa complex, P = Puscao unit, and SJ = San Jeronimo unit. The 12- to 3-m.y.-old Cordillera Blanca Batholith is also shown. Thickness of present continental and oceanic crust after James (1971), surface geology of section a after Wilson (1963) and Myers (1974), approximate ages of batholiths after P. A. Wilson (unpub. data) and Stewart and others (1974).

bound the East and West Peruvian Troughs (Fig. 12).

Large bodies of rising magma first reached the level of crust now exposed during the ductile deformation which formed the Tapacocha and Canoas structures. They crystallized both during and between pulses of deformation as hornblende diorite and gabbro of the Patap complex. Many of these rocks possess rhythmic layering, which may have formed in association with volcanoes within the Casma volcanic succession; they may have supplied heat for the greenschist and amphibolite facies metamorphism within the narrow deformation belts.

After major erosion of the folded Casma Group, perhaps associated with regional uplift caused by the rise of magmas which formed the Santa Rosa complex, renewed eruptions of andesite and dacite formed the lower part of the terrestrial Calipuy Group of volcanic rocks (~95 to 70 m.y. ago). Eruptions were associated with the emplacement of tonalite and granodiorite within the same 50-km-wide belt already outlined by the Patap complex (Fig. 10). The hiatus between the eruption of the Casma and Calipuy Groups probably corresponds with the pause between syntectonic intrusion of the Patap complex and successive emplacement of the Santa Rosa and younger plutons by cauldron subsidence. The oldest tonalite unit of the Santa Rosa complex has a minimum age of 96 m.y. (P. A. Wilson, 1974, personal commun.) which indicates that intrusion of the Paccho complex and part of the Santa Rosa complex by cauldron subsidence occurred less than 4 m.y. after the eruption of their Albian host rocks, the intrusion of the Patap complex, and the ductile deformation of these rocks. The younger granite intrusions of the Puscao – San Jeronimo complex (~70 to 50 m.y. ago) rose into the Calipuy Group to within 2 or 3 km of the surface and added to these volcanic rocks by eruptions from fissures and calderas, located mostly above the walls of rising plutons (Fig. 10).

This sector of the western Andes provides a fine example of a batholith composed of numerous plutons of a small number of magma types, each emplaced by cauldron subsidence into the same 50-km-wide belt over a span of 50 m.y. or more. It shows the flat top of a batholith about 15 km thick, emplaced into its own volcanic debris to within 2 or 3 km of the surface. There was a close association between volcanic eruptions and plutonic intrusions from at least Albian to Eocene time (~ 100 to 50 m.y. ago) (Fig. 2), although individual volcanic eruptions and cauldron subsidences were probably intermittent and rapid events. This suggests that the Casma and Calipuy Groups of volcanic rocks and the Coastal Batholith were all part of the same magmatic sequence, in which the average composition of both volcanic rocks and plutons became more silicic with time. Perhaps zone-refining of magmas, initially derived from subducted oceanic crust and mantle, became more effective as the magmas rose to the surface through an increasingly thicker, hotter, and more silicic crust. Intermittent fracturing and intrusion of microdiorite dikes indicate the continual presence or intermittent generation of intermediate magma at the depth from which the fractures were propagated, during the whole intrusive life span of the batholith.

The Coastal Batholith of Peru supports the view of Hamilton and Myers (1967) that many western American batholiths are thin and crystallized beneath covers of their own volcanic ejecta. Not all western American batholiths, however, were emplaced in the same passive way as most of the Coastal Batholith of Peru, even at the same high crustal level. Many plutons in the southern part of the Sierra Nevada Batholith are considered by Bateman and others (1963) to have been forcefully emplaced as they pushed wall and roof rocks aside and upward. The Boulder Batholith of Montana is considered by Hamilton and Myers (1974) to have been emplaced during part of a period of thrust faulting and to have spread laterally, deforming its wall rocks and carrying its volcanic roof with it. Different batholiths therefore appear to have been emplaced into a variety of near-surface tectonic environments. The emplacement history of many batholiths is indeed so long that a local tectonic environment may change during intrusion of a single batholith, such as in the Sierra Nevada of California and between the Patap and younger complexes of the Coastal Batholith of Peru. In spite of these local changes of environment, the close association in space and time of major volcanism, plutonic intrusion, and deformation over an extensive but narrow area of western Peru reflects the constant location of but a single cycle of magma generation and differentiation of great magnitude and long duration, contemporary with the widely postulated subduction of oceanic lithosphere below.

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