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The anatomy of a batholith

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CONTENTS

SUMMARY: The Mesozoic-Cenozoic Coastal Batholith of Peru is a multiple intrusion of gabbro, tonalite and granite occupying the core of the Western Cordillera over a length of 1600 km. Its structure and composition are described within the context of an intracratonic Andean zone in which vertical movements were dominant. The emplacement was controlled by growth-fractures on all scales and the magmas were channelled to high levels in the crust along a single mega-lineament, to be intruded finally as hundreds of separate plutons. Discussions follow on the space problem, on the assembly (episodic or continuous) of this immense body during 70 Ma, on the extent to which the magmas of the associated volcanic piles were vented to the surface via the subvolcanic ring-complexes, and on the physical nature of the magmas. The rocks of the batholith can be assigned to distinct plutonic units, consanguineous sequences of which form super-units. The outcrop of these along the batholith reveals a compositional segmentation which may correspond with structural and metallogenic segmentation of the Andes as a whole. Further, the super-units represent temporally distinct rhythms of magma generation and differentiation, one following the other, and with increasing overall acidity and decreasing volume. The way in which each separate melt was produced, particularly the triggering role of the gabbros, is discussed in the light of a rather 'uncomfortable' model of subduction beneath progressively thickening continental crust.

1. Preamble

During the last 200 Ma the upwelling of enormous volumes of magma along the active plate margins of the southeastern Pacific has been so long-standing and complex a phenomenon that it requires comprehensive investigation. Studies embrace the generation and provenance of the magmas, how these rose into the crust, how they were guided by existing structures or produced new structures, how they replaced the crustal material and over what intervals of time they were generated and intruded. Of particular interest is the relationship of the plutonic and volcanic rocks in space and time for the granitoid rocks of the central Andes have intruded their cogenetic volcanics and have formed the roots of marginal continental volcanic 'arcs' (cf. Hamilton & Myers 1967, Hamilton 1969, Dickinson 1970).

The great batholiths of the Western Cordillera of Peru (Pitcher 1974) provide fine examples of this plutonic phase of circum-Pacific Mesozoic-Cenozoic magmatism. The deep dissection, consequent on recent rapid uplift (Myers 1976), and the arid climate conspire to produce rock deserts and high snowy sierras where the bed rock is bare of cover. Thus an objective, three-dimensional view can be obtained of the two immense intrusions which core the Andean Ranges, the Coastal (100–30 Ma) and Cordillera Blanca (13–5 Ma) batholiths (Fig. 1). It is with the former that this Address is concerned, collating the results of a decade of study by workers mainly drawn from the University of Liverpool and the Institute of Geological Sciences. Details are available in a memoir (Pitcher *in* Cobbing *et al.* in press), in shorter communications (Stewart *in* Garcia 1968, Cobbing & Pitcher 1972*a*, Cobbing 1973, Cobbing *et al.* 1972, Knox 1974, Myers 1975 and in press, Bussell *et al.* 1976, Pitcher & Bussell 1977) and earlier works (e.g. Bearth 1938, Jenks & Harris 1953, Boit 1957, 1964).

It is important to realise the scale of these phenomena. The Coastal Batholith proper is 1600 km long and up to 65 km across while lines of isolated plutons extend this plutonic lineament into Chile and Ecuador to a distance of some 2400 km (Fig. 1). The lineament is parallel to the present oceanic trench and is largely independent of the surface geology.

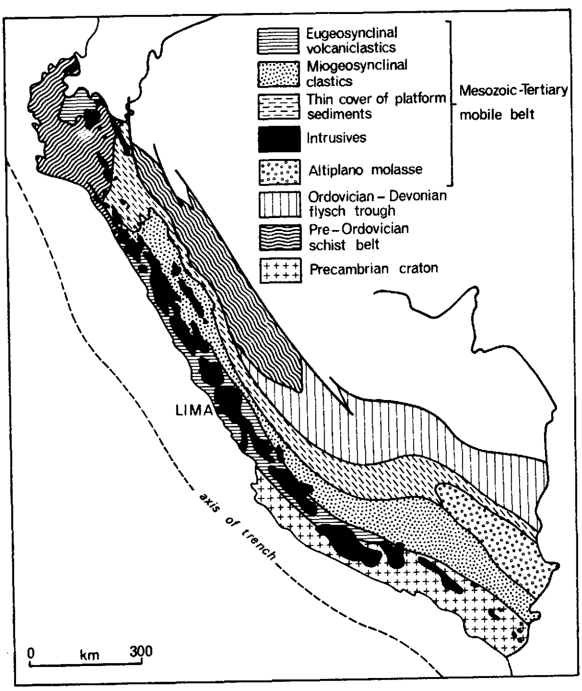
The structure and overall petrological character of the hundreds of plutons which constitute this multiple batholith remain unchanged throughout this great distance and it seems that the magmas everywhere rose to and froze at the same high, subvolcanic level in the crust. Further, despite dissection revealing the plutonic rocks over vertical distances as great as 4000 m, no obvious change with level, either in magma type, reaction with country rock or mode of emplacement is detectable.

2. Regional structural setting

In the Central Andes, the Mesozoic and Cenozoic sedimentary troughs and the associated plutono-volcanic 'arcs' were constructed upon continental crust (Cobbing & Pitcher 1972*b*, Audebaud *et al.* 1973, Cobbing 1976). Further, the Andean mobile belt was essentially an epicrustal phenomenon (cf. Clark *et al.* 1977), the structural pattern resulting from the rejuvenation of old fractures in the crystalline basement (cf. Gansser 1973).

As proof of this the ancient rocks of the Guiana-Brazilian craton appear on the Pacific flank of the Andes (Cobbing *et al.* 1977*a*) and even within faulted inliers in the Western Cordillera of southern Peru (Stewart *in* Garcia 1968) where these old rocks are caught up in the Coastal Batholith itself. They consist of silicic gneisses, which record a granulite-facies metamorphism at about 1900 Ma (Cobbing *et al.* 1977*a*, Ries 1977), overlain by a supracrustal group of metagraywackes and amphibolites and intruded by granites of Lower Palaeozoic age. Much of the 50–70 km thick continental crust beneath the Peruvian Andes (James 1971*a*) must consist of such a crystalline basement (Mégard 1968, Cobbing & Pitcher 1972*b*), through which the magmas of the Coastal

FIG. 1. The geological setting of the Mesozoic-Cenozoic Batholiths in the Andes of Peru (*after* Cobbing 1976). North of Lima the outcrop of the Cordillera Blanca Batholith is shown lying to the east of the Coastal Batholith.



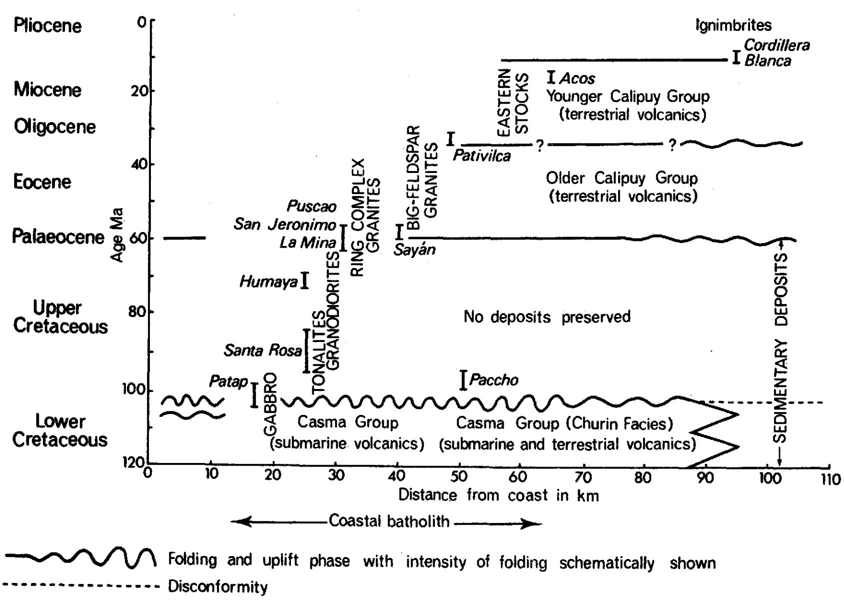
Batholith welled up. To what extent were the crustal rocks involved in the genesis of these magmas?

From the Devonian onwards (Newell *et al.* 1953) the craton played a purely passive tectonic role and the depositional environment has been one of en-cratonic, epeiric troughs elongated in an Andean trend established long before the Mesozoic (Wilson 1963, Myers 1975*b*, Cobbing 1976). Ribbon-like belts of subsidence were separated from upstanding horsts by growth-faults running parallel to the ancient continental margin—high angle structures thought to be the surface expression of deep-seated flaws in the ancient basement. As a result of the independent movement of the fault blocks these parallel troughs show different internal stratigraphic histories and contrasted sedimentary facies. Frequent periods of uplift ensured that great thickness of sediments never accumulated in any of them (cf. Clark *et al.* 1976), even though stratal thicknesses within certain stages, e.g. the Albian, were exceptional and mark very rapid rates of deposition.

At the margins of these fault-bounded troughs rapid changes of facies are the rule. Especially pertinent to the present study is the dramatic facies contrast in the mid-Cretaceous of the Western Cordillera of northern Peru (Wilson 1963, Myers 1974, Cobbing 1976), between the 7000 m flysch-like sequence of volcaniclastics and pillow-lavas in a western, eugeosyncline and the 5000 m well differentiated sequence of clastic sediments in an eastern, miogeosyncline. As shown in Fig. 1 the batholith is largely emplaced in rocks of the former facies, represented by the Casma Group, the greatest volume of intrusive rocks coinciding with the outcrop of the eugeosynclinal trough. Nevertheless batholithic rocks continue to the north and south of the present outcrop and beyond the original limits of this sedimentary trough, holding the same line but with reduced volume. Since the batholith is not restricted to the trough it would seem that the most important single control is structural (Pitcher & Bussell 1977) and that where both the batholith and trough-fill developed their maximum volume it was the common structural factor which separately favoured vulcanicity, sedimentation and plutonism (Cobbing 1976).

That no great geosynclinal thickness of sediments was ever built up in a single Andean trough (cf. Clark *et al.* 1976) seems to deny the simple blanketing hypothesis which attributes magma generation at depth to increasing geothermal gradients. Indeed one of the conclusions of this present work, is that over 70 Ma the magmas forming the batholith consistently rose to near to the same shallow level in the crust: the roof was never thick. That the cover of major granitoid complexes remained thin over long periods of time may be because, like salt-domes, they represent a continuous positive element in crustal structure (cf. Bott 1956, Pitcher & Berger 1972, p. 357). Such a view is supported by the fact that the history of emplacement of the Coastal Batholith spans at least one period of uplift and erosion (Fig. 2), with the latest and most silicic of the magmas being intruded up through a Palaeocene peneplain into an overlying pile of terrestrial volcanics of Lower Tertiary age, known collectively as the Calipuy Group.

FIG. 2. Diagram showing the time-relationship between plutonism, volcanism and tectonic history in the Western Cordillera of north Central Peru.



The dominant structural pattern of the Central Andes is of upright concentric folds, often lacking a penetrative cleavage, and steep, often reversed, faults. This is a situation in accord with a regime of vertical-uplift tectonics. The tightness of the folds depends both on the overall competence of the rocks and their proximity to restricted linear axial belts of much stronger deformation (Audebaud *et al.* 1973, Myers 1974), belts which may well have resulted from posthumous movement on deep-reaching growth-faults in the underlying basement. Also consonant with the epicrustal environment is the widespread preservation of original textures and sedimentary fabrics in clastic and pyroclastic rocks, and it is only under the microscope that the effects of burial metamorphism are detected in the form of various zeolites together with prehnite and pumpellyite (Offler *et al.* unpublished manuscript).

Crustal shortening was not important (for discussion see Mégard 1967, Rutland 1971, Audebaud *et al.* 1973, Cobbing 1976, Clark *et al.* 1976) and the general evidence for vertical displacement tectonics is so strong that it is unlikely that sufficient shortening to account for the doubling of crustal thickness could have taken place during the last 100 Ma. Such progressive thickening is indicated by the history of episodic uplift (e.g. Petersen 1958, Mortimer 1973) which elevated the basement over 10 km since the Upper Cretaceous (Cobbing *et al.* in press). Since thickening was coeval with the intrusion of the magmas of the Coastal Batholith it will be important to discuss its cause.

Regional studies show that since Triassic times, the Andean history of Peru and northern Chile has been characterized by distinct episodes each involving an interplay of uplift, erosion and volcanicity. There was also an overall change in conditions, earlier marine erosion, sedimentation and submarine volcanicity giving way, at the end of the Cretaceous, to subaerial peneplanation and terrestrial volcanicity. Clark *et al.* (*op. cit.*) hold that the plutonic events form an essential term in these rhythms, the main phase of granitoid intrusion, according to Aguirre *et al.* (1974), tending to follow a short-lived phase of compression, thus:—

No compression (possible extension)	plutonic intrusion and acid volcanicity
Compression of short duration	
No compression (possible extension)	intermediate volcanicity peneplanation uplift

The outline of geological events revealed in Fig. 2 can be tentatively fitted into such a scheme and so provide a reference framework for a general discussion of the emplacement and assembly of the Coastal Batholith.

3. Setting of the batholith in terms of plate tectonics

This is not the place to argue the application of the plate tectonic model to the Central Andes but it is important to note the absence of high-pressure metamorphic rocks, ophiolite-bearing sutures, extensive belts of under-thrusting, and accretionary oceanic trench deposits (Cobbing & Pitcher 1972*b*). A volcanic arc there may have been but it was never separated from the continental margin by an actively spreading, back-arc marginal ocean basin as is suggested for the Andes of southern Chile (Dalziel *et al.* 1975).

Nevertheless, a Benioff seismic zone exists at present beneath the central Andes, and the evidence of andesitic vulcanism since the Permo-Trias supports its past existence. Furthermore, there was an easterly migration with time of the plutonic volcanic arc in northern Chile (Farrar 1970, McNutt *et al.* 1975, Clark *et al.* 1973, 1976), a migration which can be identified in Peru (Fig. 2 and Stewart *et al.* 1974, James 1971*b*), though with the important reservation that there was a still-stand in one lineament for 70 Ma. There is also an easterly increase in the K_2O/SiO_2 ratio in the igneous rocks of southern Peru (James 1973). All this evidence supports the subduction model of James (1971*b*) and implies the continuous consumption of the Nazca Oceanic Plate, some 5000 km of which are supposed to have been thrust beneath South America since the Cretaceous (Larson & Pitman 1972).

Despite the view that steep faults can be related to a shallowly dipping subduction zone such a model of overriding continental crust seems inconsistent with the occurrence of oscillatory vertical movements in an otherwise passive continental plate, which suffered only brief, episodic, interludes of compression. Was the Americas Plate simply too thick and rigid to respond (James *op. cit.*, Sillitoe 1974, 1976) and how else are we to explain substantial thickening? Clearly Gansser (1973, p. 34) was right to recommend caution in using the Andes as a model for theoretical discussion on the interaction of oceanic and continental crust, and I agree with Ellenberger (1976) in his insistence that current plate-tectonic theses do not provide a proper causal model for epeirogeny.

Two specific points are relevant to this and further discussions. The first is that the present Benioff zone varies in inclination along the length of the Andes (Stauder 1975, Mégard & Phillip 1976, Barazangi & Isacks 1976), corresponding to a structural and metallogenetic segmentation (Sillitoe 1976), and this we might expect to see reflected in the character of the igneous rocks. Secondly, there is evidence for the westerly derivation of clastic sediments in the Upper Palaeozoic (Isaacson 1975), perhaps even in the Mesozoic (Wilson 1963, Webb 1976), which suggests that continental crust formerly extended farther west. How much farther west, and to what mechanism we might appeal for its disappearance, are hypothetical (cf. Miller 1970, Helwig 1973), but the possibility exists that continental crust was tectonically eroded and dragged beneath the Andes. Such a structural underplating might well explain not only the thickening of the crust but provide a source of supply for the intermediate and silicic magmas. However, it is only fair to point out that James (1971*b*, 1973) argues for the static positioning of the Benioff zone on the basis of a single progressive change in the K_2O/SiO_2 ratio regardless of age, whilst Brown (1977) considers the thickening to be simply a consequence of so much subduction and partial remelting of oceanic crust.

Having set the scene I turn to a discussion of the intrusive rocks which make up this compositionally and structurally multiple batholith of the Western Cordilleras, the nature of the magmas they represent, how they were emplaced and their reaction with the volcanic pile which in the main formed their host.

4. A multiple and composite batholith

(*A*) *Units and super-units*

The Coastal Batholith, in common with other cordilleran batholiths, is structurally composed of a vast number of individual intrusions, dykes, sills and plutons, assembled into major plutonic complexes. Compositionally there are two contrasted rock groups, the gabbros and the granitoids, the latter involving the entire gamut of possible lithologies in oversaturated rocks.

For rock description I have accepted, with reservations, the recommendations of Streckeisen (1967, 1976), but there is much more to the recognition of granitoid types than simple considerations of mode. Equally important are the textural parameters, *viz.* general grain size and relative grain size and shape, the systematic measurement of which has rarely been attempted (*see, however,* Roddick 1965).

In the regional mapping of the Coastal Batholith the simple visual recognition of all these features shows that the components group naturally into a relatively small number of *units*, each with specific characteristics, and that each unit can be recognized as the constituent rock of numerous separated plutons (Cobbing & Pitcher 1972*a*, Cobbing 1973, Cobbing *et al.* 1977*b*). This is again a commonplace finding in batholiths (e.g. South California, Larsen 1948; Sierra Nevada, Bateman & Dodge 1970).

To be assigned to a particular unit, rocks from within the same linear batholith should have the same relative age based on clear cross-cutting contact relationships. In addition they should show the same modal variation to a similar degree, the same texture and fabric, similar xenolith content and character, and the same relationship to the associated dyke swarms. Confirmation should be sought from aspects of the geochemistry and from geochronological studies. Usually such a unit occurs in close temporal and spatial association with a small number of related units, together forming a consanguineous rock suite which I prefer to refer to, hierarchically, as a ***super-unit***.

On this basis of division the gabbros and seven granitoid super-units have been shown to compose the major part of the 400 km stretch of the Coastal Batholith outcropping between Lima and Chimbote (Fig. 3), the relative chronology being established by cross-cutting relationships between the constituent intrusions. There are, in order of decreasing age, three early super-units designated: (1) oldest—Patap (gabbro), Paccho (diorite-tonalite), Santa Rosa (quartz diorite-tonalite-granodiorite-monzogranite) and the separate unit of Humaya; (2) an essentially coeval trio of granitoid super-units, La Mina (tonalite-granodiorite), San Jerónimo (monzogranite-syenogranite) and Puscao (granodiorite-monzogranite); (3) youngest—the Sayán-Pativilca super-unit (big-feldspar monzogranite) Cobbing & Pitcher 1972*a*, Myers 1975*a*, Pitcher *in* Cobbing *et al.* in press). It is particularly important to note that a swarm of basic to intermediate dykes is temporally and spatially associated with each super-unit.

These super-units are variously represented but commonly two, sometimes three, form the bulk of outcrops in any one section across the batholith. Overall, the area of outcrop of the super-units, particularly the extent along the axis of the batholith, decreases with decreasing age of the super-unit (Fig. 3).

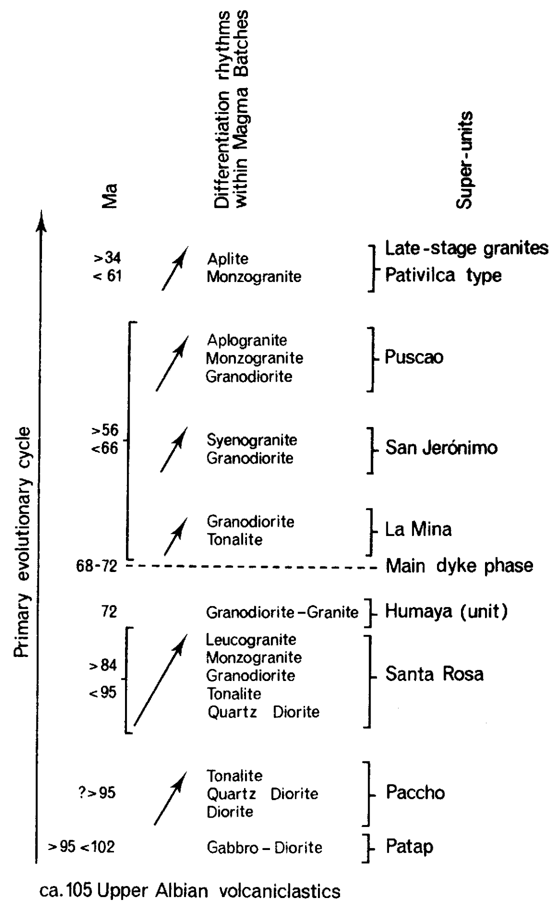
Each super-unit involves a basic-to-acid rhythm (Pitcher 1974) and the relative chronology established above shows that the Coastal Batholith is made up of rocks showing a number of such rhythmic sequences (Fig. 4) just as has been found in the Sierra Nevada (Bateman & Dodge 1970). Throughout these rhythms, in Peru, the silicic element becomes progressively more important with time, so identifying an overall major rhythm which, starting with wholly basic rocks, the gabbros, evolved through increasingly acidic granitoids to the big-feldspar granites.

(*B*) *A segmented batholith*

The recognition of super-units leads directly to the finding that specific assemblages of them characterise different *segments* of the Coastal Batholith (Cobbing *et al.* 1977*b*). There are three such segments (Fig. 5)

FIG. 4. Relative and absolute chronology of the super-units of the Lima segment of the Coastal Batholith. Radiometric determinations after Wilson (1975).

Arrows indicate sense of evolution of magmas. Relative position of the La Mina and San Jerónimo super-units is in doubt.



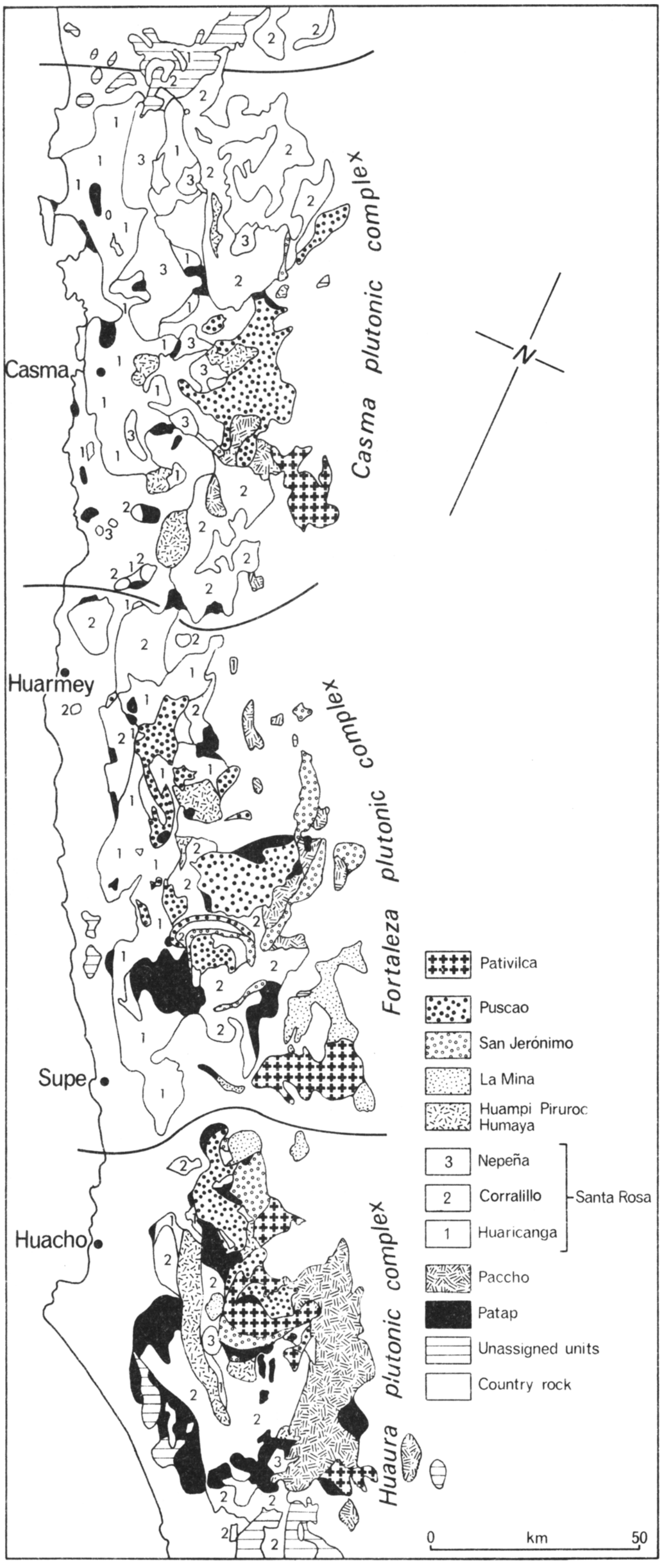


FIG. 3.

Outline geological map showing the form of the greater part of the Lima segment of the Coastal Batholith and the distribution of the major super-units.

designated: Arequipa (900 km in length with four super-units), Lima (400 km, with seven super-units) and Trujillo (200 km, with an as yet unknown number of super-units).

Such a plutonic segmentation correlates approximately with the structural segmentation, the super-unit assemblages changing across certain fundamental cross-Andean structural lineaments. A possible explanation of this is suggested by the fact that between the Lima and Arequipa segments there is, at the present time, a marked difference in inclination of the descending Nazca plate (Barazangi & Isacks 1976), so much so as to indicate that an asthenospheric wedge exists between the crust and the more steeply dipping subduction zone in southern Peru.

If such a difference in the configuration of the crust and upper mantle had existed in Cretaceous and Tertiary times it might well account for the contrast in the plutonic assemblages and the mineralisation (cf. Carr *et al.* 1973, Sillitoe 1974).

(*C*) *A long history of episodic emplacement*

Whilst the relative age of emplacement of the plutons of such a multiple batholith are easily established in the field the determination of real age by radiometric methods is bedevilled, particularly in the case of the K-Ar method, by effects of reheating and may even be further complicated, especially in the Andes, by the regional cooling resulting from rapid uplift. However, reheating and uplift-cooling ought to be detectable by discordancy according to the models of Krumenacker *et al.* (1975). In the event a detailed study by Wilson (1975), building upon a regional survey by Stewart *et al.* (1974), has provided a chronological framework (Fig. 4) on which to base this study of batholithic emplacement.

Within the Lima segment of the Coastal Batholith, the oldest age recorded, 102 Ma, is that of a granite pluton younger than the gabbros (for details see Stewart *et al. op. cit.*), and the latter just post-date the folding in fossiliferous strata of Albian age (*c.* 105 Ma). It follows that sedimentation, burial metamorphism, folding and the initiation of batholith emplacement followed one another very closely as is commonly the case in the Andes.

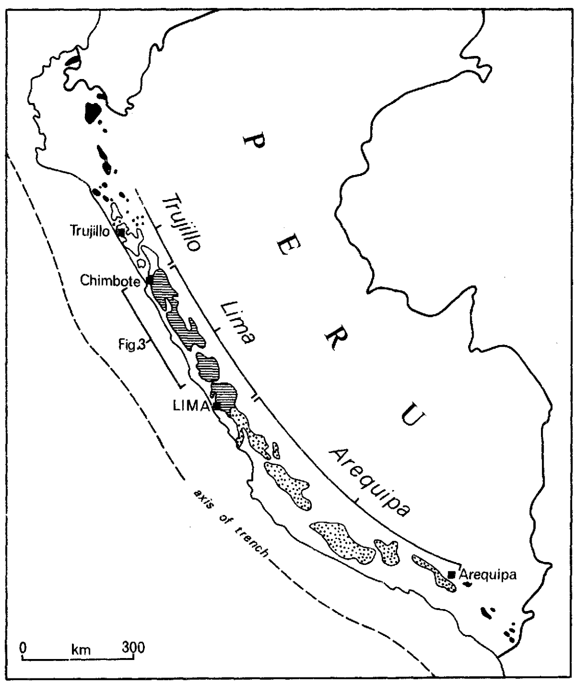
In summary the work of Wilson provides good evidence for the plutons of the Lima segment being assembled in the one plutonic lineament, over a 70 Ma period with radiometric events at *c.* 93, 73, 62 and 34 Ma relating to the main intrusion phases. Many interesting if not disturbing features are, however, revealed by the details. One of these is the recognition of a possible diachronism between units within the same super-unit when traced along the length of a segment, implying different arrival times, in the upper crust, of batches of magma generated at one particular time at depth.

As for the possibility of real episodicity in cordilleran plutonism, such as has been established in other circum-Pacific batholiths (cf. Kistler *et al.* 1971, Lanphere & Read 1973), the range of results obtained by Wilson on individual intrusions in just one transect makes this a speculation in Peru (*see* Stewart *et al. op. cit.*). Even if, as seems likely, separate episodes of plutonic activity can be established in one segment, these may not represent regional episodes. Indeed it would be remarkable if such episodicity were found to hold throughout the entire length of the Coastal Batholith and throughout the three separate segments.

(*D*) *Times of intrusion and cooling*

If it is difficult to substantiate episodicity it is even more difficult to estimate the times involved in the filling of a cauldron and its subsequent cooling. In a previous discussion (Pitcher 1975) I came to the conclusion that several millions of years were involved in

FIG. 5. The Coastal Batholith showing the three compositional segments of Trujillo (blank), Lima (lined) and Arequipa (stippled). The isolated plutons which continue the plutonic lineament are shown in black.



the cooling and crystallisation. The relevant data are lacking but answers could be obtained in Peru by utilising all the radiometric methods, including fission-track dating, in a detailed attack on selected plutons.

Wilson's (*op. cit.*) results indicate, albeit tantalisingly, the time scales which might eventually be established. As an example, within the compass of a single plutonic complex, that of the Huaura, a crudely zoned tonalitic pluton of Santa Rosa type is cut by a seemingly one-event dyke swarm (Cobbing & Pitcher 1972*a*), members of which react synplutonically with a leucocratic variant of this pluton. A pluton of La Mina type intrudes the Santa Rosa rocks and transects the majority of the dykes, though a few cross the contacts to die out into the core of this later pluton. In the field these events are readily interpretable as consecutive and overlapping, yet the relevant radiometric dates are 90 Ma for the oldest parts of the earlier pluton, 72 Ma for the dykes and 65 Ma for the later pluton. Is it possible that these events were so longstanding that a single super-unit would take 18 Ma to be assembled, and a single pluton 7 Ma to crystallize?

On the other hand Wilson's data indicate a close grouping of the ages of the silicic intrusions of the young ring-complexes; the extremes are only 5 Ma apart and, within the accuracy of the method, it seems that the volcanic calderas representing this episode of silicic volcanic activity were relatively shortlived.

I envisage each of the separate pulses of the late-stage granites filling the cauldron relatively rapidly. The magma, near to crystalization and isolated in the crust, would have little heat to spare for the recrystallization of the country rocks. On the other hand the filling of a great multi-pulse and multi-surge tonalitic pluton might have the same longevity as its crystallization. This raises the problem that the very long periods of time involved seem inconsistent with the subdued nature of the aureoles, the negligible reaction between magma pulses, and the obtaining of a sensible range of ages by K-Ar methods. Perhaps, however, this might have something to do with the whole system being relatively dry, and so inhibiting the transfer of heat, metamorphic reactions and recrystallization (cf. Fyfe & Brown, 1972, p. 275).

(*E*) *Thermal effects of short duration*

To some extent the contact effects are related to the size of the intrusion and basicity of the magma. However, even taking into account the refractory nature of the volcanic lithologies, it is evident, as noted above, that the thermal effects are subdued and metasomatism almost entirely lacking. The details are provided elsewhere (Bearth 1938, Atherton & Brenchley 1972, Myers 1975*a*, and Pitcher *in* Cobbing *et al.* in press) with the general finding that these fine-grained contact rocks only show a patchy alteration, the new thermal assemblages containing large numbers of small crystals of the new phases. Taken together with the presence of anisotropism, twinning and tabular growth cavities in the crystals of garnet, this suggests that the aureole was so rapidly heated and had so short a time at maximum temperature that the rocks had little time to equilibriate.

Atherton & Brenchley's (*op. cit.*) conclusions regarding P-T conditions during metamorphism closely follow those of Kerrick (1970) dealing with a similar example of contact metamorphism in the Sierra Nevada. From the nature of certain calc-silicate assemblages, temperatures of the order of 550°–600°C at 1–2 Kb were deduced, in general accord with an estimated thickness of 4–8 km for the roof of the batholith at any one time.

This is a further indication of shallow-seated emplacement and I think that we have to accept the indications of the short duration of heating which is not obviously consonant with the long-standing nature of the plutonic processes suggested by Wilson's results (Wilson 1975).

5. Structural control of emplacement

(*A*) *The form of the plutons and the structural control of their contacts*

The petrographic units and super-units of the batholith are disposed in many separate intrusions. Of those of mappable scale, mainly plutons representing single pulses of magmas, there are about 230 in the Lima segment alone and it is likely that the total for the whole batholith exceeds 800.

As far as it is possible to define a single pulse of magma in the field—from an overall homogeneity and lack of internal contacts—the average area of outcrop for the true granites is of the order of 70 km^2 (corresponding to a pluton diameter of 9.4 km). The zoned tonalite-plutons have much larger areas, hundreds of km^2, but even these have been built up by individual magma pulses, perhaps two to three times greater in volume than those of granitic composition. Such a measurement for the granites is of the same order as reported by Gastil *et al.* (1971, 1975) for plutons from Baja California and the Sierra Nevada and is near an average pluton size mentioned by Fyfe (1971, 1973). Perhaps this size reflects the maximum area of the roof of country rock which can remain unsupported over a granite magma. On the assumption that the granites, being relatively more water-rich than the tonalites, would be less viscous than the latter, we might expect their magmas to support a lesser area of roof material.

The early intrusions, largely of gabbro and tonalite, have the form of great lens-like plutons strung out along the batholithic lineament and these are pierced by groups of smaller plutons and ring-dykes which are more equidimensional (Fig. 3). With few exceptions the individual plutons have steep walls and flat roofs

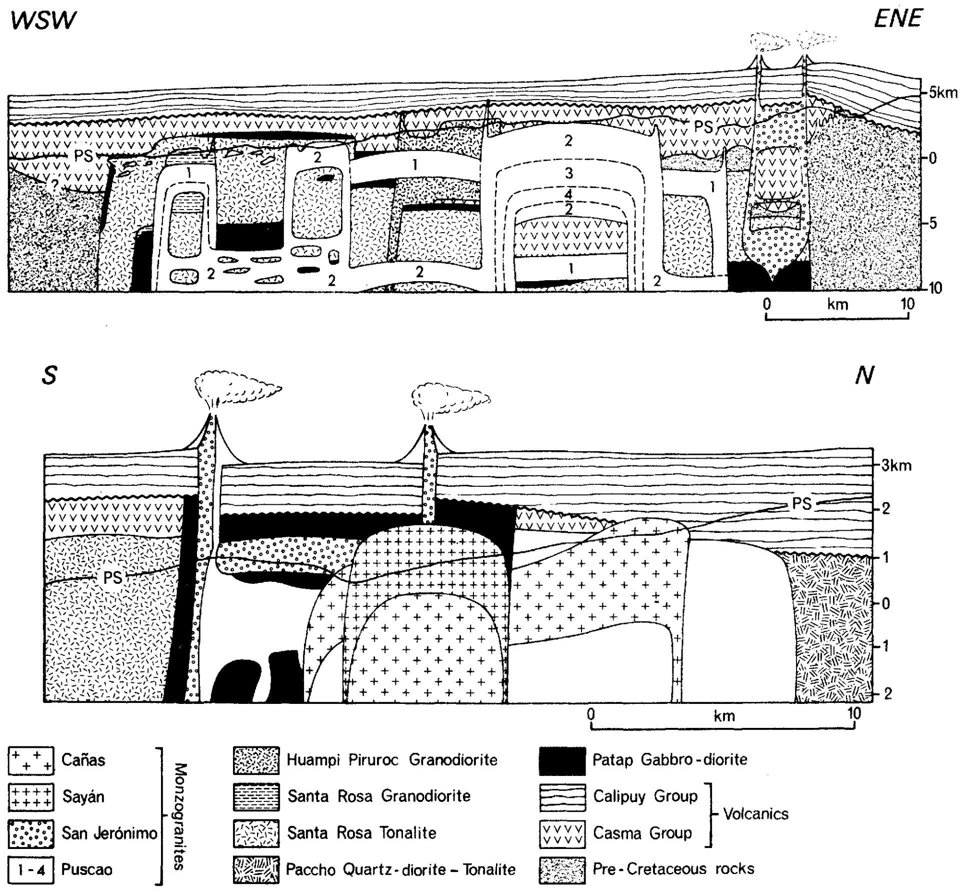
(Myers 1975*a*, Child 1976) often planar over long distances so that the overall form is rectangular or crudely polygonal. The turnover from roof to wall is accomplished over short distances and the general form of the plutons is that of a rectangular box or flat-topped bell-jar. Such plutons can pass upwards or downwards into vertically walled, polygonal ring-dykes. All these features, even rectangular plutons, are found in high-level cauldrons in many regions (e.g. Queensland, Hills 1959, Branch 1967).

In Peru there is rarely any mechanical disturbance of the external structure or of chemical interaction with the host. The contacts are flagrantly cross-cutting and the plutons so obviously cut out of the crust (Fig. 6 and Fig. 9) that the emplacement can only have been accomplished by the breaking away and foundering of blocks of the crust—a conclusion long ago reached by Reginald Daly (1912) in his classic study of similar batholiths along the 49th Parallel.

Most pluton contacts, even internal ones, are knife-sharp and even devoid of contact effects such as changes of grain size or the development of hanging-wall pegmatites. Their form was controlled by pre-existing structures, such as faults and joints (Knox 1974, Child 1976, Bussell 1976), and stoping along such a regular fracture pattern has resulted in rectilinear, indented contacts and polygonal-shaped plutons, a common feature of high level plutons (cf. Pitcher 1952, Branch *op. cit.*).

The fracture system in the envelope of the Coastal Batholith has a very simple geometry related to the axis of the latter. Established before emplacement began it was maintained in constant orientation throughout the life of the batholith, being continuously reactivated and redeveloped in successive intrusions (Bussell *op. cit.*). On the evidence that even internal contacts of plutons are so controlled it seems that joint-like fractures (with the same orientation)

FIG. 6. Schematic sections across the Coastal Batholith. Top-along the northern flank of the Fortaleza valley. Bottom-along the southern flank of the Huaura valley; the former after Myers (1975*a*), the latter after Bussell *et al.* (1976). PS-present erosion surface.



were developed very soon after congelation in plutons of all ages. There is in fact plenty of support from the literature for the early initiation of such fractures (e.g. Firman 1959, Pitcher & Berger 1972) and the phenomena of synplutonic dykes strongly supports this view.

This structural control extends to the dykes (Myers, in press), the regional swarm trending along the axis of the batholith presumably as a result of this being perpendicular to the direction of lowest principal stress during periods of tension when magma surged upwards. Local controls, *viz.* the regional trend curving into a centred complex and local concentrations of dykes either encircling or radially disposed about single plutons, conform to the stress-trajectory patterns theoretically derived by Odé (1957) and Roberts (1970) on the basis of a varying degree of interaction between local and regional stress fields.

The whole picture is one of a long established, regionally effective regime of brittle fracture, operating at a high level in the crust. This is so simply related to the regional fold-trend and the axis of the batholith that it conforms to a simple structural model of Andean-normal compression interacting with an updoming due both to the upsurge of magma and the consequent thermal expansion.

(*B*) *The plutonic lineament*

The clear spatial delimitation of the magmas of the Lima segment within one fault block, together with the presence of narrow axial zones of deformation coeval with the plutonic event, the predominance of Andean-trending linear contacts, and the likelihood that the symmetrical location and even spacing of the ring-complexes reflects the point-focusing of magma at the intersection of Andean-normal and oblique faults, all indicate a fundamental structural control which has already been discussed in some detail (Pitcher 1972, Pitcher & Bussell 1977).

The ultimate expression of this is the nature of the plutonic lineament itself which is continuous over 2400 km. Not only does it cross undeviated the boundaries between the crustal segments (p. 160) but its plutons extend so far outside the present Mesozoic cover as to be emplaced in the ancient basement itself (Fig. 1). We have seen how major growth-faults continuously controlled sedimentation and structure in the Andes over long periods, even before batholithic emplacement, so that it is not surprising to find that in northern Peru, and over some hundreds of kilometres, the eastern boundary of the batholith coincides with the marked change of sedimentary facies within the mid-Cretaceous country rocks.

I believe that this plutonic lineament resulted from the magmas using such major resurgent faults as conduits, and the way in which these magmas have been continuously tapped along one line over 70 Ma suggests particularly deep penetrating structures, with the faults passing down into ductile shear belts (cf. Watterson 1975).

(*C*) *Intrusion mechanisms*

There are impressive examples of stoping (Cobbing & Pitcher 1972*a*, Knox 1974, Pitcher *in* Cobbing *et al.* in press). Great apophyses emanating from the tops and flanks of plutons can be seen frozen in the process of prising off great slabs of the walls and roofs. Disrupted slabs of spalled-off roof showered down (Cobbing & Pitcher 1972*a*, pl. III). There are 'floors' of such xenoliths in several of the Puscao-type plutons. However, viewing the batholith as a whole, such examples are relatively rare and there are many plutons with clean, xenolith-free contact zones, creating the strong impression that piecemeal stoping was only a subordinate process.

On the other hand there are sufficient examples of roofed plutons to confirm the bell-jar shape for the majority, and the subsidence of central blocks is directly observable in the Huaura and Fortaleza ring-complexes, being of the order of 2000 m and 1500 m respectively. Particularly notable is the clear evidence that this general pattern applies throughout the length of the batholith and to plutons of all ages. Cauldron-subsidence is clearly the dominant process and it is relevant to note that Roberts (1970) in his theoretical treatment of the intrusion of magma into brittle rocks predicted that the tensile fractures necessary to isolate the central blocks would only be produced at very high levels in the crust.

The passively emplaced plutonic rocks predictably lack strong fabrics, indeed many of the late granites are structurally isotropic. However, there are some exceptions where certain early tonalite plutons exhibit schistose envelopes and marginal foliations with flattened xenoliths, both attributable to deformation during emplacement. For one of these, the Cauthay Grande Pluton in the Casma plutonic complex (Fig. 3), Bussell (1975) has presented a model of *in situ* expansion, along a deformation zone, of a blister of magma which shouldered aside the wall rocks in just the same way as that described by Nelson & Sylvester (1971) for the Birch Creek pluton of California.

In Peru the narrow deformation zone containing the Cauthay Grande plutonic blister is characterized by blastomylonitic schists bearing sillimanite. Such zones are common in association with the batholith (Bussell *op. cit.*, Myers in press), representing ductile shear zones even at so high a level in the crust. I like to refer to these as 'hot-faults', and possibly we are seeing here, in the squeezing-in of magma along such zones, a hint of the kind of structure we might expect to find associated with plutons at greater depths in the Andes.

Yet another mechanism by which space was cleared for the emplacement of magma is entrainment in gas streams, as strongly advocated by Myers (1975*a*). There are many good examples of intrusive breccias especially in association with ring-dykes (p. 174), and in some contact zones there is so close an association of fractures, microbreccias and highly xenolithic and xenocrystic microgranite sheets—the *Baranda sheets* (Myers 1975*a*)—that it seems very likely that streams of gas, on penetrating the fault breccias, entrained the fragments, causing them to be abraded, fretted and mixed chaotically. Fluidized systems such as these are probably associated with gas-coring and it may be that the conduits up which magmas were emplaced were widened and cleared by such a mechanism. Gas-charged magmas would easily force their way along cracks opened in the country rock by thermally induced stresses, thus facilitating stoping. Indeed Myers provides a graphic account of the centralized block of older rocks within a cauldron subsiding into a fluidized rim of magma 'as if in a quicksand' and being corroded by flow of the fluidized system around it (*op. cit.* p. 1218). Such a model may well apply to certain Puscao-type plutons but is not, in my opinion, the general mechanism.

Finally, there is the possibility of some part of the space being created by opening or lifting of the crust on a regional scale. However, mapping of the remnants of the roof, sometimes as a continuous bridge across the axis of the batholith, conclusively proves that horizontal opening has not occurred. It is not so easy to prove or disprove updoming but I believe that domes of very broad amplitude were produced above each plutonic complex (Fig. 9, p. 175, Fig. 6, bottom, p. 165) by the uprise of magma, a possibility indicated by Taylor's (1976) identification of local doming around the northern component of the Huaura ring-complex. Such updoming is likely to have been compensated for by erosion at the surface (Pitcher 1972) and to have led to the collapse of the roofs over ascending plutons.

6. The composition of of the batholith

Viewed as a whole it is obvious (Table 1) that, like other circum-Pacific batholiths, the Coastal Batholith is far from being granitic in composition, the predominant rock types being gabbro, tonalite and granodiorite. If allowance is made for areas of gabbro intersected and removed by later intrusions, the proportion of the former rises significantly, leading to the important conclusion that the gabbroic magmas, the immediate precursors of the granitoids, were of considerable volume, and so emphasising the importance of mafic rocks in the evolution of batholiths, as pointed out long ago by Benson (1927). Geophysical data is lacking but I would expect that a considerable positive anomaly will be shown to exist along the axis of the Coastal Batholith, representing a progressive increase in the proportion of basic rocks with depth (cf. Sierra Nevada Batholith, Bateman & Eaton 1967, Oliver 1977).

There is such a contrast between the gabbros and granitoids, not least in their exhibiting fundamentally different geochemical trends (p. 173), that they may be expected to have had different origins and to have played different roles in the assembly of the batholith.

(*A*) *The gabbro precursor*

(*i*) *Cumulates and non-cumulates.* Bodies of gabbro exist on all scales, from sills and plugs to very considerable plutons hundreds of km^2 in area. Their former outcrop can often be reconstructed to show that the larger bodies were elongate, the smaller occurring in lines; also that together they formed a belt of basic intrusions sited exactly on the line of the granitoid batholith of which they were the precursor.

The considerable gabbro pluton of Huaral, 60 × 30 km, provides an example of the range of rock types and the petrogenetic processes involved. The detailed studies by Regan (1976) show that a series of consecutive but overlapping events record, first, cumulate-type crystallization from a magma, presumably at depth, followed, during and immediately after intrusion of the resulting crystal mushes to the present level, by recrystallization whilst still hot and undergoing deformation, and finally by amphibolitization associated with late-stage explosive brecciation and penetration by water-rich volatiles. The primary mineral assemblages, dominated by plagioclase and pyroxenes, exhibit simple igneous textures, an expected order of crystallization, adcumulus growth of plagioclase and intercumulus growth of hornblende. There are good examples of igneous lamination, primary rhythmic layering and crescumulate orbicular structures (Myers in press,

TABLE 1: *Representative proportions of rock types (% area) in the Coastal Batholith*

<table>
<tr><th></th><th>Gabbro</th><th>Tonalite</th><th>Granodiorite</th><th>Monzogranite</th><th>Syenogranite</th></tr>
<tr><td>Southern Peru, Arequipa (Jenks & Harris 1953)</td><td>7.0</td><td>55.0</td><td colspan="2">34.0</td><td>4.0</td></tr>
<tr><td>Central Peru, Sayán (Cobbing & Pitcher 1972a)</td><td>15.9</td><td colspan="2">57.9</td><td>25.6</td><td>0.6</td></tr>
<tr><td>Northern Peru, Casma (Child 1976)</td><td>11.5</td><td>46.3</td><td>20.0</td><td>20.2</td><td>2.0</td></tr>
</table>

Kobe 1973), all evidence of a cumulate-type crystallization in magma chambers, of high-alumina tholeiitic magma.

However, such textures have been extensively modified by coeval deformation leading to mineral assemblages and crystalloblastic textures akin to those of true pyroxene granulites, including the production of $S>L$ mineral alignments, and a deformation banding resulting from the infilling of early shear zones by intercumulus residual liquids (cf. Miller 1938, Lipmann 1963, Berger 1971). Zones of particularly intense deformation are represented by blastomylonites especially in the marginal, contact zone. That such a wholesale re-equilibration can occur without retrogression within the pyroxene-plagioclase assemblage suggests the maintenance of conditions of relatively high temperature and low P_{H_2O}, even to the stage of emplacement of the magmas to the present level.

Particularly thorough-going post-consolidation changes are represented by a widespread amphibolitization in the solid state. This is concomitant with recrystallization which leads in advanced stages to the original lithologies being totally converted to a heterogeneous meladiorite exhibiting a multiplicity of disequilibrium relationships. Closely associated with this process is net-veining by a leuco-granite, implying that it was brecciation which permitted the penetration of the substantial volumes of the volatiles responsible for the overall metasomatism. Such features, particularly the progressive replacement of pyroxene to form poikiloblastic hornblende, are common to hornblende gabbros elsewhere in the batholith and are, indeed, characteristic of the appinitic suite of rocks the world over (cf. Pitcher & Berger 1972, Bowes & Wright 1960, Joplin 1959).

Not all the gabbros represent cumulates and associated fractionates. Many minor intrusions and individual pulses in the major plutons exhibit textures characteristic of simple, one-stage cotectic crystallization. What does seem to be characteristic of the suite as a whole is the ubiquitous occurrence of hornblende.

(*ii*) *The role of hornblende: the source of the volatile phase.* The presence of hornblende in Cordilleran gabbros is so common a feature that it is worthy of special note (Regan *op. cit.*, Mullan & Bussell 1977). Hornblende can appear at all stages in the evolution of the gabbros of the Peruvian Coastal Batholith; *viz.* occasionally very early as a cumulus phase, more commonly as a late intercumulus phase, abundantly as a product of a late-stage autometasomatism, a sequence which may have simply resulted from the build up of P_{H_2O} during crystallization.

There is, however, some indication that the metasomatism results from the introduction of water from external sources. Thus, according to Regan (*op. cit.*), the finding that amphibolitization post-dated the deformation recorded in the Huaural gabbro suggests that it was a late, post-consolidation event, and so is unlikely to be due to water concentrated by the normal crystallization process.

At first sight obvious sources of such volatiles are the tonalites which followed closely upon the intrusion of the gabbros, but these were probably undersaturated in water and moreover, there is no simple spatial or temporal relationship of amphibolitization, either in space or time, to tonalite-gabbro contacts. Possibly the source lies in the country rocks, the gabbros absorbing water during their final emplacement into the volcanic cover rocks.

(*iii*) *Gabbro emplacement.* In nearly all the numerous occurrences of gabbro associated with the Coastal Batholith some degree of deformation at elevated temperatures is evident, particularly in the contact zones. This usually pre-dates amphibolitization of the larger bodies. This is consistent with the finding that the period of intrusion of such basic rocks overlapped with the mid-Cretaceous compressional event (p. 163) and suggests that they may have been emplaced by squeezing of magma upwards. Whilst many gabbro intrusions are clearly post-tectonic—there are even cross-cutting plugs and traces of flat-topped and steep-sided plutons—examples exist of folded sills and deformed plutons like that of Huaral. Taking into account the relatively subdued metamorphic effects of the gabbros I am tempted to further suggest that whilst some, presumably the non-cumulates, were intruded as relatively mobile magmas, others, presumably the cumulates, were largely solid mushes when emplaced, sliding to final rest by intergranular movements which become progressively more concentrated along discrete dislocation zones as the plutons cooled.

(*B*) *The granitoids: a quartz diorite—tonalite batholith*

The granitoid components of the Lima segment of the Coastal Batholith, comprise in order of decreasing age, two predominantly tonalitic super-units, a less widespread group of three granitic super-units and certain scattered big-feldspar granites. These are assembled into the four great plutonic complexes of Chancay, Huaura, Fortaleza and Casma (Fig. 3).

(*i*) *The diorites and tonalites.* Whilst separate intrusions of quartz diorite form a small yet essential element in the construction of these complexes, such rocks more generally constitute the marginal phases of the great tonalite-granodiorite plutons. Of the latter the most generally basic are those of the Paccho super-unit, the main outcrop of which occupies the eastern part of the Huaura plutonic complex. The variation within this super-unit is from quartz diorite to a mafic tonalite and in these rocks pyroxene always accompanies the hornblende and biotite.

Much more widespread, forming the main batholith builder, are the rocks of the Santa Rosa super-unit. In their variation about a central type of biotite-hornblende tonalite, they provide a prime example of the chemical consanguinity and textural kinship characterizing a super-unit as defined above. Whilst such variations can be gradational it is more usual for the different modal-textural types, here defined as units, to be separated by mappable contacts and the relative order of intrusion is invariably quartz diorite, mafic tonalite, felsic tonalite and granodiorite, monzogranite and syenogranite. There is sometimes a crude zonation, an approach to the form of a zoned pluton, but with increasing silicic composition the contacts between the units become better defined, often with marginal variations. The latest of these may even break out from the zonal pattern, crossing the earlier established contacts as independent intrusions; the Nepeña unit provides an important example of this. Thus it seems that the more advanced the fractionation the more mobile and transgressive is the magma, a finding consistent with an expected increase in water fugacity with fractionation.

The nature of the mutual contacts, whether rapidly gradational, interbanded and schlieren-like, or sharp and discordant, must reflect differences not only in rheological conditions but in the length of the interval between the separate injections of magma. Clearly some contacts indicate distinct, time-separated magma *pulses* (cf. Harry & Richey 1963) in which the magma displaces already solidified material, whilst others simply represent internal *surges* within a single congealing pluton (cf. Cobbing & Pitcher 1972*a*, p. 425). Most of the internal contacts within the tonalitic super-units seem to represent upward surges within the same magma chambers, whilst the late Humaya-type plutons with their stoped contacts and contrasted chemistry (W. McCourt *pers. com.*) represent distinct pulses of new material from depth.

The overall similarity of the tonalitic rocks between each of the four plutonic complexes of the Lima segment is notable. Nevertheless, there are slight differences between the separate occurrences suggesting that rocks within each plutonic complex, though assigned to the same super-unit, may have been emplaced at slightly different stages in their magmatic evolution.

All these rocks have certainly resulted from the crystallization of magmas. The comparative simplicity of the textures, the widespread uniformity of grain size and the fact that the reaction relationships between the mineral phases conforms to theoretical expectations, argues for a simple liquid-crystal relationship (G. Mason *pers. com.*).

Certain features of the plagioclase do, however, provide evidence for rapid changes in physical conditions such as might arise from rapid changes in level within a magma chamber, *viz.* plagioclase cores of An_{80} are corroded and overgrown by rims of An_{55} or less (in the diorites), and corrosion surfaces correlatable between adjacent crystals of intermediate plagioclase (in the tonalites). It seems likely that most of the magmas contained suspended crystals at the time of final emplacement.

Of the mafic minerals suffice to note that pyroxene appears early in the crystallization sequence but is generally converted to amphibole in parallel with the independent growth of the latter and of biotite, all in accord with increasing water content—the result of advancing fractionation.

Also, as would be expected, the orthoclase and quartz crystallize interstitially becoming enveloping and poikilitic in the more silicic rocks where the former may react with the earlier plagioclase. Despite this latter feature there is an overall lack of late-stage, solid-state reactions between the mineral phases presumably because, with the exception of some intra-pluton contact situations, re-equilibration under conditions of slow cooling (in the presence of water) or burial metamorphism never occurred. This is consistent with the finding that the tonalitic plutons, though not always the cognate monzogranite plutons, lack pegmatitic marginal phases, late-stage dykes and veins, and metasomatic aureoles. Evidently the magmas were undersaturated in terms of water until the latest stages in evolution of any particular super-unit (see p. 176).

This classical explanation of the texture is fully confirmed by Dunin–Borkowski (1970) in his detailed study of the single Acari pluton within the Arequipa segment in which he comments on the paucity of volatiles. In describing cored plagioclases Borkowski identifies an early stage of fracturing of the crystals which is perhaps a consequence of a rapid change of pressure during an early stage of the upward surging of magma.

(ii) The granites of the cryptically layered plutons, the rectilinear plutons and ring-complexes. Throughout the Lima segment a major dyke swarm intervenes between the plutons of the Santa Rosa super-unit and a somewhat less extensive group of largely granitic plutons composed from the three highly characteristic super-units of Puscao, San Jerónimo and La Mina (Fig. 3). These super-units are so nearly related in time (Fig. 4) and space that they might be taken to form a simple association of units but for the fact that they can each occur independently and show significant differences in petrology and geochemistry; evidently they represent separate generations, separate *batches*, of magma.

The most important in terms of outcrop area is the coarse, biotite-hornblende granodiorite—monzogranite of *Puscao* which forms a particularly good example of a batholithic super-unit, maintaining all its special features and variations in each of the elongate, cut-out plutons which stretch for 270 km along the axis of the batholith. Most of these represent cryptically layered bodies showing continuous transitional sequences of rocks varying with height; internal contacts are lacking and the magmas were clearly differentiated *in situ*. Other plutons, some of ring-dyke form, are distinctly multiple, exhibiting internal vertical contacts between contrasted rock-types. It is very easy to show in the field that the latter, the multi-pulse plutons, evolved by the drawing-up of magma from underlying differentiating magma chambers, represented by the layered plutons, the magma, as we shall see, being displaced upwards around descending central blocks during the operation of cauldron subsidence.

The type pluton of Puscao-Tumaray (Cobbing & Pitcher 1972*a*, Cobbing 1973), a component of the Huaura plutonic complex (Fig. 3), is a fine example of the gradational change of facies with height, and the layer-cake structure picked out by the drusy aplogranite sheets of the roof zone is particularly striking. It has been studied by Taylor (1976) utilizing regression surface analysis techniques to establish that the magma underwent a simple *in situ* differentiation, the preferred model for which involves the settling out of plagioclase laths which were soon entrapped in crystallizing quartz and K-feldspar, the pluton crystallizing from the base upward. On to floors of such crystal mushes spalled-off fragments of the roof volcanics are thought to have settled forming the extensive layers of xenoliths which characterize such Puscao plutons. In one locality, the Quebrada Quintay, this hypothesis of simple settling is confirmed by the inclusion of large blocks of an earlier granite member in a xenolithic Puscao host, the smaller, flat-lying xenoliths being depressed beneath the blocks as if, with glacial analogy, these represented 'drop stones'. What is truly remarkable is to find this accumulative xenolithic facies, though now with the platy xenoliths lying vertical, injected into ring-dykes within the structurally overlying ring-complexes. This confirms the reality of the displacement mechanism advanced above (see p. 166) but introduces the intriguing problem of mobilizing the bottom accumulate, the crystal mush enclosing the xenoliths.

Rather less extensive in outcrop, stretching some 200 km along the axis of the Lima segment are rocks belonging to the *San Jerónimo* super-unit, a central type of which is a medium- to fine-grained monzogranite to syenogranite characterized by its granophyric texture and bipyramidal quartz. It is more texturally but less modally diverse than the other super-units and within its intrusions the textural differences across contacts enable surges and pulses to be identified.

There are some irregular, cut-out plutons of considerable size but more characteristically this rock type forms wide dyke-like intrusions, some linear some arcuate. Of the former the Carapon pluton within the Fortaleza plutonic complex (Myers in press) is sufficiently deeply dissected, to 2800 m, to reveal a gradual downward increase in grain size and concomitant decrease in phenocrysts, features which suggest that there was a rapid degassing of the higher levels during crystallization. This hypothesis is substantiated by a study of another of the broad dykes, that of Iglesia Irca (Bussell & McCourt 1977), in the Casma complex. Over a height of 750 m there is a similar change of grain size, the loss of volatiles from the higher levels being demonstrated by the association of vesicular tuffisite sheets and explosion breccias, whilst their retention at lower levels is suggested by the presence of normal granitic textures in the rock.

This association of hypabyssal rocks, intrusive breccias and ring-dykes indicates that, of all the components of the batholith, the rocks of San Jerónimo are most likely to have had volcanic equivalents, implying that the plutons and ring-dykes represent, respectively, the magma chambers and the conduits from which magma was fed to calderas at the surface.

The Puscao and San Jerónimo magmas clearly carried sufficient volatiles to provide a gaseous phase during crystallization. It is likely that they may have become, transiently, fluidized systems (cf. Reynolds 1954), the early formed crystals being fractured and corroded during transport in turbulent gas streams.

It would be interesting to know the isotopic composition of the water in these volatiles because in other situations (e.g. Southern Nevada, Lipman & Friedman 1975) isotopic studies suggest major interactions between meteoric ground water and batholith-sized bodies of silicic magma prior to the eruption of ash-flows from caldera complexes. In the field, however, there is not much evidence for its abstraction from the host-rocks, which were largely igneous anyway, or for the 'heat engine-like' systems envisaged by Taylor (1977) in other examples of granite plutons.

At this point for the sake of completeness and reference, the least abundant of the trio of granites should be mentioned—the uncomplicated biotite-hornblende granodiorite of *La Mina* (Fig. 3).

(*iii*) ***The big-feldspar granites; a late stage in the evolution of the batholith.*** A third group of granitoid components is represented by great irregularly shaped plutons of coarse-grained, biotite monzogranite of Pativilca type which have wholly granitic textures characterized by megacrysts, up to 3 cm, of orthoclase microperthite.

A feature of these plutons is the occurrence of flat-lying sills of aplite and pegmatite that can be observed to thicken inwards towards the centre of a particular pluton. It is as if fractures were produced in the consolidating carapace due to a central sagging (due to contraction), and into these late-stage, volatile-rich fractionates segregated. Further evidence for such a volatile phase is provided by great pegmatitic vugs in roof zones. However, only at this latest stage in the long evolutionary history of the batholith was there any real approach to the production of water-saturated magmas.

Appropriately, the differentiation process was now influenced by a volatile phase. Thus for a Cañas body (W. P. Taylor *pers. com.*) the data depict an inward zoning from the roof, floor and walls which can best be explained by crystallization *in situ* within a pluton emplaced by simple cauldron-subsidence. Crystallization from the margins sealed in the released volatile phase forcing them inwards with the result that the alkalis were also carried inwards progressively to enrich the rest-magma of the core leaving behind a more basic peripheral residue. This is an application of the hypothesis of Vance (1961).

With the emplacement of the Pativilca-type plutons the assembly of this great multiple batholith was virtually complete yet there was one final episode, the wide-spread emplacement of relatively small stocks, dykes and sills of a red syenogranite—the 'last gasp' of this long-standing plutonic event.

(iv) An order in terms of space and time. Viewed overall there might seem to be a crudely defined order in the areal distribution of the main super-units across the Lima segment (Fig. 2, p. 159). But in detail any systematic distribution in rock types can hardly be sustained, for gabbroic remnants occur across the entire outcrop as do monzogranite plutons of various affinity. Any simple picture of a west-east order in temporal or compositional terms is decisively broken by the position of the Paccho rocks (Fig. 3, p. 162). On the contrary, it is clear that the Coastal Batholith was assembled within the one narrow structural lineament over as long a period as 70 Ma.

However, to the east of the batholith proper there are scattered stocks of granitoids (e.g. Acos stock of Fig. 2) which yield ages between that of the youngest member of the Coastal Batholith (34 Ma) and that of the Cordillera Blanca Batholith (12 Ma) which outcrops even farther to the east (Fig. 1). It seems that the channelling of magmas into the one structural line ceased abruptly in the Oligocene, intrusion migrating eastwards in a 'normal' manner.

It is the decrease in the volume and lateral extent of the super-units with time which I regard as of fundamental importance in establishing a genetic model.

(v) The associated dyke-swarms: synplutonic dykes. The impressive swarm of dykes which accompanies the batholith and trends dominantly along its axis, represents fissure-filling that dilated the host rocks. The range in composition is similar to that of the most abundant plutonic rocks of the batholith and the commonest type is a porphyritic quartz microdiorite. Despite a structural and compositional homogeneity it is easily established that the swarm is made up of dykes intruded at various times, some even pre-date the gabbros or post-date the big-feldspar granites, but the crescendo of activity coincided with the waning of the Santa Rosa rhythm (Figs. 2 and 4).

Each period of dyke intrusion showed an overlap in time with the cooling history of a particular plutonic unit (Cobbing & Pitcher 1972*a*, Myers 1975*a*, Myers in press). The simplest evidence of this synplutonism is provided by dykes passing across a contact between two plutons but dying out rapidly into the interior of the younger intrusion. More important proof is provided by the disruption of dykes in a still mobile host—these are examples of synplutonic dykes as defined by Roddick & Armstrong (1959) in the Coast Mountain Batholith of British Columbia. A general explanation is that under rapidly developed strains even quasifluidal material might fracture and so permit the intrusion of new magma. In Peru dykes have been recorded which neck along their length and eventually are made up of an isolated string of pillow-like globules in the granite host (S. G. Edwards *pers. com.*). It is as if the dyke material had been injected into a still plastic medium. In other examples the dyke material has been broken up into angular xenoliths as if it had fractured in a brittle manner before being back-veined by the host. Such a difference in dyke-host relationship may have something to do with the contrast in temperature or in the rate of cooling between dyke and host material, but whatever the exact explanation the synchroneity can hardly be denied.

The dykes must be a candidate for a supply of magma to the surface independant of the plutonic magma chambers. Also important is the fact that they show that andesitic magma was immediately available *throughout* the construction of the Coastal Batholith. Further, the structural uniformity of the swarm implies a particularly long-standing stress regime.

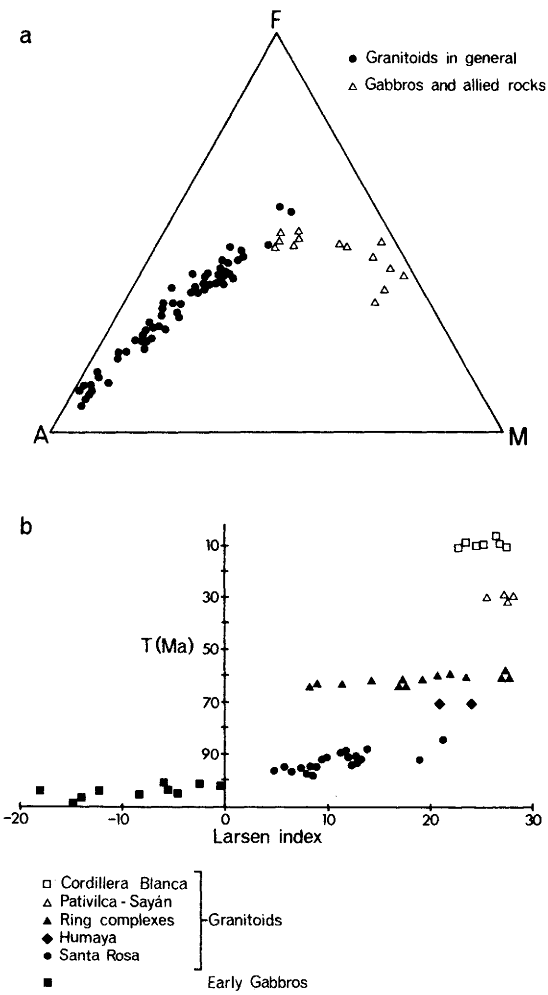
(vi) The xenolith content. At this point I am led naturally to a brief mention of the xenoliths which are ubiquitous in the plutons of the Coastal Batholith: details are provided elsewhere (Pitcher *in* Cobbing *et al.* in press). Consonant with a view that stoping is an important mechanism in the emplacement process there are many examples in contact situations of the engulfment of fragments of country- or host-rock. Within the main body of any pluton, however, the source of the xenolithic material is not so apparent because recrystallization necessarily involves a degree of convergence of rock type, particularly when so many of the possible source rocks are essentially similar in chemical composition.

There are gradational sequences illustrating the derivation from country- and host-rocks of various kind (e.g. Myers 1975*a*), and particularly good examples of the mechanism of the spalling-off of slabs of material at contacts, their splitting up and disruption and their subsequent corrosion within the magma. There are also examples, of the contribution made by syn-plutonic dykes and sheets, when their dismemberment leads to xenolithic trains of pillows or angular blocks which can recrystallize and react with their host in a way similar to true accidental xenoliths. Such a mechanism was also recognized by Tabor & Crowder (1969, p. 168) in their study of the Cloudy Pass Batholith in Oregon and may be more common than currently supposed.

However, whilst such modes of origin provide an explanation for the greater number of the enclaves, especially for those in the late granites, there remains the real possibility that a proportion of the dark patches in the tonalites, in their various states of convergence to the composition of their host, represent the residual from a remelting process at depth, as has been suggested by Piwinski (1968*a*) and Chappell & White (1974) in other granite terrains.

A final and important point is the general lack of thorough contamination associated with xenolithic concentrations, with the one possible exception of certain situations adjacent to contacts between tonalite and gabbro (Stewart 1968, Cobbing & Pitcher 1972*a*). This is well illustrated by Taylor (1976) in which he showed that the dark rocks accompanying a concentration of xenoliths in a Puscao-type pluton were not due to contamination but to normal crystal-differentiation processes, the two phenomena simply being associated as a natural consequence of accumulation at the bottom of a chamber. This lack of contamination is in accord with the mild contact-metamorphic effects and is also in agreement with a high level of intrusion.

FIG. 7 (a) AFM plot of compositions of rocks representing four super-units and the gabbros (after W. McCourt *pers. com.*).
(b) Ditto plotted as Larsen index against time determined by the K-Ar method (after P. Wilson & W. McCourt *pers. com.*).
Compositions of Cordillera Blanca granitoids are inserted for comparison.



(*vii*) *A simple calc-alkaline differentiation process.* The overall picture of the chemical variation emerges from the work of McCourt (*pers. com.* 1977), whilst the details of certain single plutons are due to Taylor (*in* Cobbing & Pitcher 1972, 1976).

When the representative analyses of all the granitoid rocks are plotted they show a general consanguinity with compositional points falling on a simple curve (Fig. 7a) defining a classic calc-alkaline trend. The same is true at any level of detail from the overall sequence of super-unit to single-pulse plutons differentiating *in situ*, and within specific examples of the latter the element variations are completely compatible with the established models of differentiation (Gribble 1969, Taylor 1976). The logical conclusion is that some simple process of crystal differentiation was responsible for the evolution of all granitoid units of the batholith, wherever and however generated, either by the settling out under gravity of the early formed crystals, the concentration of late phases due to continuing crystallization from the peripheries of a pluton, or by diffusion mechanisms.

Viewed in relation to time of emplacement the overall differentiation path is shown to be a composite result of a multiple process in which a number of time-separated differentiation systems overlap (Fig. 7b). Nevertheless, when relative volumes are taken into account, it still remains true that basic rocks decrease and silicic rocks increase in volume with time, in an overall basic-to-acid trend (Pitcher 1974).

The evolution of a single super-unit might well be explained on the basis of a single magma cell providing steadily more fractionated pulses of magma during its crystallization history. However, the sequential nature of the emplacement of the super-units, each clearly separated in time and each with its own differentiation rhythm, is not so simply explained; rather it seems that each super-unit must represent a new generation of magma, a view held by Presnall & Bateman (1973) in their interpretation of a similar situation in the Sierra Nevada, California. Thus the problem in Peru is to explain the bulk compositional change between the magma batches with time.

In their detailed account McCourt & Taylor (*in* Cobbing *et al.* in press), on the basis of Ca-Y characteristics, distinguish between super-units differentiated by hornblende-dominated fractionation, e.g. the Santa Rosa super-unit of the Huaura plutonic complex, and those differentiated by pyroxene-dominated fractionation, e.g. the Paccho super-unit. The contrast probably depends on relative differences in P_{H_2O} which, in turn, might be related to depth in the crust at the time of differentiation. Even within the same super-unit similar differences are discernible (p. 169), both during the time of its evolution and over long distances of the outcrop, and again differences in the physical parameters, especially of vapour pressure, seem likely to have been the cause.

I later comment again on the relative dryness of the magmas especially those of the early tonalites, but there must have been water to stabilize hornblende and biotite. The necessary threshold value for the water content is, however, quite low (<1 per cent according to Wyllie *et al.* 1976).

None of the data so far accumulated suggests anything but the simplest of models for the changes in composition recorded in the field. However generated, the magmas crystallized in accord with simple liquid-crystal equilibria, with the water content building up to near-saturation only at the very end of each rhythm of differentiation. Complicating processes like contamination and late-stage auto-metasomatism were unimportant at any level near to that of the present erosion surface.

Turning to the basic rocks the simple AFM diagram of Fig. 7a seems to indicate that there is a continuous and consanguineous relationship with the granitoids. In fact, a weighted sampling would show a neat calc-alkaline trend in the latter intersecting a more tightly grouped population of gabbroic rocks. If anything the compositions of the basics define a tholeiitic trend and detailed work shows a high-Al basaltic chemistry with primitive trace-element characteristics (McCourt & Taylor *op. cit.*, P. Regan *pers. com.*). This dichotomy is a commonplace of cordilleran granites and it is tempting to see the basic magmas, in their role as precursor to the granitoids, as somehow providing the triggering mechanism for the whole grand process of batholith formation.

7. Comments on the Arequipa segment: super-units and metallogenesis

The construction of the Lima segment has been detailed as an example of the batholith as a whole and indeed, in all structural aspects the plutons constituting the Trujillo and Arequipa segments conform to the established pattern: 'cut-out', high level plutons are everywhere the rule. Also, judging from the studies of Jenks & Harris (1953), Stewart (1968) and Dunin-Borkowski (1970) supplemented by much recent work (W. P. Taylor, R. Agar and N. Moore *pers. com.*), there was a similar history of magmatic evolution involving a similar abundance of rock types, with the exception that the late-stage granites are less important, the monzonitic rocks much more so. For the latter, Stewart (*op. cit.*) makes a case for the mixing of basic and acid magmas which I would not now accept.

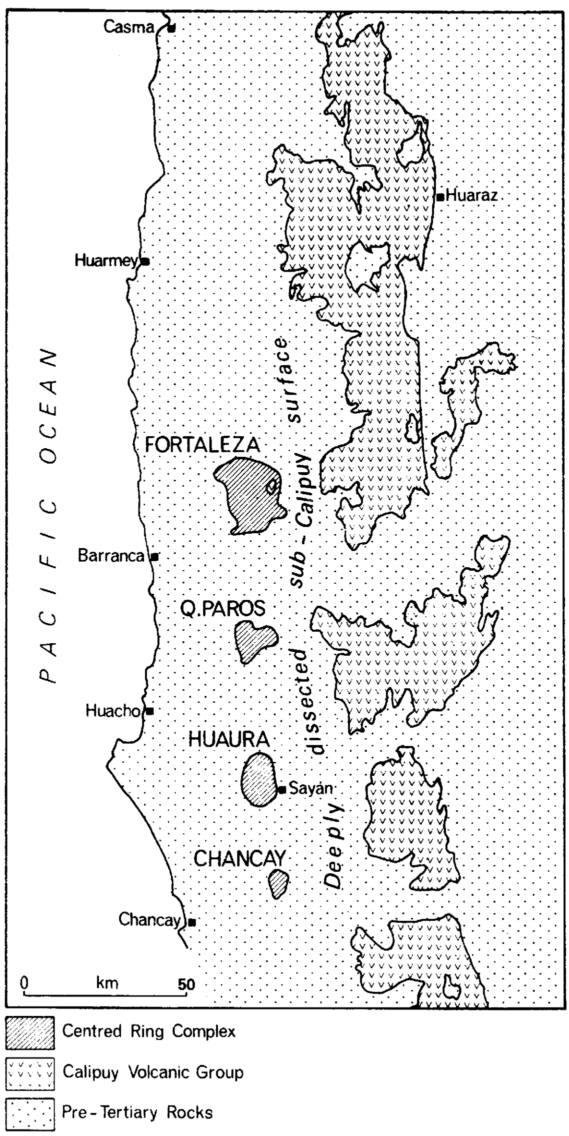
Two of the great super-units which make up much of the Arequipa segment (Jenks & Harris 1953, Stewart 1968, Cobbing *et al.* 1977*b*), those of Tiabaya (tonalite-monzogranite) and Linga (monzogabbro-quartz monzonite-monzogranite), have the notable lateral extent of 900 and 800 km, respectively, along the batholithic lineament. They seem to have been intruded over a shorter life span, not older than 77 Ma and not younger than 58 Ma, than the magmas of the Lima segment (Stewart *et al.* 1974), the absence of the big-feldspar granites corresponding to the lack of younger dates. Interestingly enough the dates obtained from the great tonalites and monzonitic units of this southern segment are coeval with those of the granites of the centred complexes in the central segment. All this seems to deny any overall pattern in the time and type of magma generation.

Between the segments there is a strong contrast in the nature and strength of the mineralization. Whereas the Lima segment is relatively weakly mineralized, the outcrop of the southern segment is covered by innumerable mines, exploiting metals in several distinctive associations, *viz.* quartz-Au, Cu-Mo, Cu-Pb-Zn (Bellido & De Montreuil 1972); further, tourmaline appears widely. It seems that specific types of mineralization are associated with separate super-units, even with specific units (Hudson 1974, Stewart *et al.* 1974, p. 197, R. Agar *pers. com.*). Most impressive is the way in which the great breccia pipes associated with the batholith in southern Peru (Stewart *op. cit.*) are the sites for major porphyry copper deposits, yet well developed breccias within the Lima segment are totally barren. It is this direct relationship between the magma types of the batholith and metallogenesis which is now the centre of attention in this research project and which must lead into studies concerned with inclusions in minerals and their isotopic composition.

8. The plutonic-volcanic Interface: the centred ring-complexes

A special feature of the Lima segment of the Coastal Batholith is the presence of sizeable ring-complexes (Fig. 8, p. 174) again suggesting a high-level crustal environment. In these the younger silicic super-units of the batholith occur as ring-dykes and nested bell-jar plutons, combining to form two centred ring-complexes of classical form and dimension, namely the Huaura (Cobbing & Pitcher 1972*a*, Bussell 1976) and the Fortaleza (Knox 1974). A third arcuate structure is that of Quebrada Paros (Cobbing 1973), notable for a half-moon shaped pluton of intrusion breccia (G. Mason *pers. com.*). Another centre, that of Chancay, is more rudimentary and this, like the Paros complex, involves basic rocks at such a relatively early date in the evolution of the batholith as to indicate that the formation of such complexes, and therefore possibly the calderas they supported, spanned some 40 Ma of batholith history (Bussell *et al.* 1976).

FIG. 8. Distribution of the centred ring-complexes in relation to the outcrop of the Lower Tertiary volcanics of the Calipuy Group and the exhumed erosion surface on which they rest.



The linear arrangement of these four centres, evenly spaced at 35 km and in a central position in the batholith, is a gross measure of the high degree of the structural control already commented upon. It seems that the intersection of oblique wrench faults with a major Andean-trending lineament resulted in the point-focusing of magma at depth while providing admirable sites for cauldron subsidence of rectangular blocks at higher levels.

As shown by the studies of Bussell *et al.* (1976) not only do these centres have the classical form of ring-complexes the world over (cf. Branch 1967) but they have all the special features of the latter, including: updoming, multiple intrusion within the ring-dykes, flinty-crush on the ring-faults, dykes crammed with fretted xenoliths showing back-veining phenomena, breccia pipes, tuffisite dykes, and hypabyssal rocks. Everywhere there is evidence of the forceful injection of gas-charged magmas, and of the operation of fluidized systems. There is no doubt that these complexes are volcano-plutonic formations in the sense of Ustiyev (1963) and representing a direct connection between the intrusives of the batholith and the volcanics of the country rocks and cover.

In the Fortaleza the connection is almost direct with a ring-dyke intruding up into ash-flows. Further the adjacent Calipuy volcanic field with its basic lava-flows and dacitic, even rhyolitic, ash-flows provides dates, *c.* 53 Ma, very near the youngest age (56 Ma), obtained from the intrusive in the Fortaleza (Fig. 2), and I believe that some of the Calipuy ash-flows were vented from the centred complexes (Fig. 8).

The early initiation of such complexes suggests that such a direct plutono-volcanic connection has persisted throughout the entire history of emplacement of the granitoids. Further a similarity in chemistry has led McCourt (*pers. com.*) to seek a direct connection between the gabbros and the basic flows in the Albian Casma Group of the envelope.

All this evidence is entirely consistent with the contention of Myers (1975, p. 1218) that 'the plutons rose into their own ejecta'. Indeed, as noted above (p. 159), they rose high enough to cut through at least one erosion surface, a finding wholly in agreement with those of Clark *et al.* (*op. cit.*) in northern Chile.

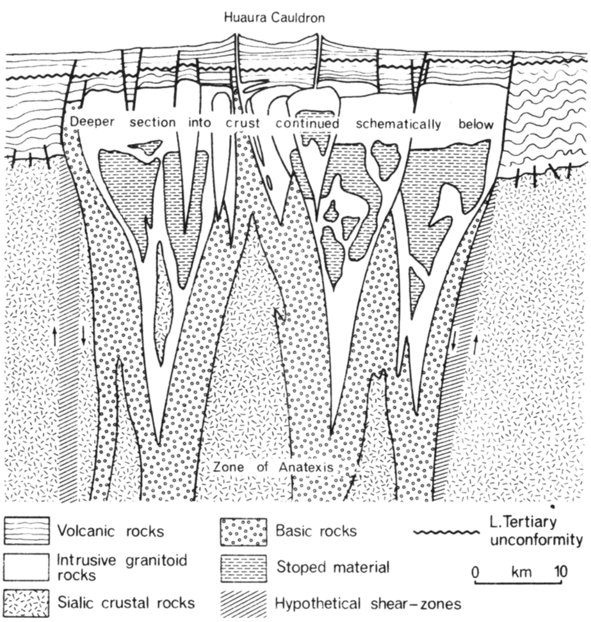
In the Arequipa segment there are some fine examples of breccia-pipes closely related in time and space (Laughlin *et al.* 1968, Stewart *op. cit.*) with the plutonic rocks of the batholith. At Cerro Verde, Cerro Negro and Toquepala, where they are the sites of important porphyry copper deposits, such pipes probably represent the remnants of extinct strato-volcanoes.

The Peruvian ring-complexes are clearly seen to be firmly rooted in assemblages of nested plutons. As noted above (p. 170) the connection between a Puscao-type pluton and ring-dykes of the same magma type in the structurally overlying Huaura ring-dyke complex is so clear that it needs no imagination to envisage a differentiating magma chamber providing the source of fractionated magma draughts. The denudation series (Jacobson *et al.* 1958)—caldera, ring-complex and nested pluton—is all but complete and supports the view that there is a genetic connection between the batholiths and volcanic fields of the Andes (Hamilton 1969).

Nevertheless, it is difficult to decide what proportion of the volcanic material was vented via the central complexes, and therefore the plutons, or via fissures represented by the dykes, or via the small stocks which punctuate the outcrop of the lava fields. I think that many of the ash-flows may have originated from the calderas represented by the complexes whilst the lava-flows were vented from fissures or neck-like stocks.

Having made this final interconnection I can now summarize the general position regarding the assembly of the Coastal Batholith by commenting on the possible source of its magmas.

FIG. 9. Schematic profile of the extension of the Coastal Batholith to depth. Illustrated, in the model sense, is the restriction of the intrusions to a crustal block limited by deep penetrating ductile shear zones, also the suspected increasing involvement of basic rocks with depth and the possible mushrooming out of the granitoid plutons in the upper crust. Such a model profile emphasizes the problem of deciding the fate of the foundering blocks.



9. A general model

From this account of the anatomy of the Coastal Batholith it can be established that magmas stoped their way high into the crust largely by cauldron-subsidence mechanisms. The way in which they broke into the relatively brittle supracrustal rocks was controlled by a system of growth-fractures which resulted from the episodic interplay of Andean-normal compression and synemplacement updoming. It was this stretching of the roof above the fluid granite bodies (cf. Bott 1956) which helped to initiate the stoping and foundering of crustal blocks.

The magmas were confined to one structural block isolated by major growth-faults rooted in the crystalline basement, faults which probably passed down into ductile shear zones. Movements on such long-standing structures had already been responsible for the establishment of the trough in which volcaniclastic country rocks had accumulated. I envisage dislocations of this kind penetrating so deeply into the crust that they tapped the generative source of the magmas, funnelling and channelling them upwards. This system remained stable, from 100 Ma until 30 Ma ago, when the plutonic line side-stepped eastward into the Cordillera Blanca lineament. Possibly with an eastward migrating generative source the channelling back into the master lineament finally became impossible.

Great composite plutons were assembled in the upper crust where the mechanism of emplacement was essentially by displacement, the intrusions bypassing and isolating great foundering blocks of crustal rock (Fig. 9). It is, however, difficult to envisage the rocks at depth responding in this brittle way and the squeezing up of the Cauthay Grande plutonic blister along a shear zone may provide a clue to what happens in the more ductile environment. I am also reminded of the situation in the Peninsula Ranges of Baja California (Gastil *et al.* 1975), and the Coast Range of British Columbia (Roddick & Hutchinson 1974), where apparently deeper levels of the erosion of batholiths reveal granitic diapirs which shoulder aside their metamorphic envelopes. Perhaps, too, at depth, the magmas in Peru were squeezed up the major shear zones finally to mushroom out laterally in the upper crust, assuming something of the form of the tabular batholith envisaged by Hamilton & Myers (1967).

I am not confident that this is the correct model because I suspect that the cauldron mechanism may have operated to great depths, with magma columns extending a long way down towards their source. A geophysical survey would be of the greatest value in testing these models, though it is salutary to remember that there is not much room to accommodate models involving changing modes of emplacement with depth because the width of the Coastal Batholith equals the depth of the continental crust! However, neither the displacement of magma around foundering blocks or the squeezing up of magma globules along dislocations introduces an acute space problem.

I can at least be sure that throughout the history of the batholith the magmas consistently rose to within 3–8 km of the surface, cooling and crystallizing in major plutons under thin roofs. Those magmas of granitoid compositions were motivated by buoyancy but were presumably only able to rise so high because they were relatively undersaturated with water (cf. Cann 1970). Only after absorbing water on reaching the zone of meteoric circulation did they quickly freeze to a stop.

The magmas intruded coeval volcanics. Plutons stoped up into the bases of caldera represented at shallow depth by the ring-complexes with their granophyre and tuffisite ring-dykes and their breccia pipes up which magmas were channelled to the surface. Such a volcano-plutonic association was as long lived as the granitoid batholith itself, and the axis of the latter sustained a line (arc) of major volcanoes venting magma directly from the plutons over at least 30 Ma. Even the earliest members of the batholith, the gabbros, were likely to have had volcanic equivalents.

So important were the basic dykes at specific stages in the evolution that it is just possible that they too represent fissures venting at the surface. Their materials show that relatively basic magma was available at all times during the batholith's history.

The two major plutonic components of the batholith, the early gabbros and the later granitoids, are so strongly contrasted compositionally that they probably had different origins. The basic magmas were ultimately derived from mantle sources (McCourt & Taylor, *in* Cobbing *et al.* in press). Some of the gabbros represent the cumulate fraction of such magmas crystallizing at depth, others the liquid fraction. The cumulates were squeezed upwards as crystal mushes during the late-Albian compressional event, suffering deformation thereby, and finally auto-metasomatism during the final stages of emplacement and cooling, when they might well have absorbed water from the volcaniclastic rocks of the envelope. As the precursor of the granitoid batholith the basic rocks must have played some part in triggering the process of generation of the tonalites and granites.

I would emphasize that the granitoids evolved as a result of very simple magmatic processes uncomplicated by significant contamination or even late-stage deuteric changes. *There is no room here for complex models of petrogenesis.* Dry magmas (cf. Maaløe & Wyllie 1975) of relative high viscosity became progressively more mobile as the water content naturally increased as a result of normal crystallization processes, but only in the latest stages in the evolution of the batholith did the magmas approach sufficient H_2O-saturation, possibly by absorption of water from the volcaniclastic rocks, to provide any significant volume of volatile-rich fractionates and to support explosive vulcanicity.

Plutons differentiated *in situ*, not necessarily by simple crystal settling, for layers are rare, but by inward crystallization from walls, floors and roofs of cauldrons. Possibly the cooled carapaces insulated the magma from the host rocks as a result of which contact effects were at a minimum even though the magmas remained mobile for long periods.

The simple pattern of calc-alkaline differentiation is shared by pluton, super-unit and batholith, suggesting a common process for all the granitoids, even in multipulse situations where fractionates were intermittently injected to higher levels, presumably by the displacement of magma up and around the foundering blocks in cauldron subsidences. Following Presnall (1969) I think that the rock suites, the super-units, each evolved by differentiation from single parent magmas and not by progressive remelting. Each is the product of a fresh batch of magma, e.g. seven in all in the Lima segment. Nevertheless, the progressive increase in the proportion of silicic magmas with time, coupled with decreasing total volume, argues for a fundamental relationship between these separate batches. It also suggests that such a batholithic cycle measures the duration of a natural rhythm of crustal reworking.

On the basis that the more silicic the melt the lower the PT conditions at the time of origin, it is suggested, rather simplistically, that each batch was generated at successively higher levels (cf. Brown 1973). Nevertheless, overall, the origin of such magma batches must be sought deep in the crust if only to provide sufficiently high PT conditions for the generation of water-undersaturated tonalitic melts. I am also reminded of Cann's thesis (*op. cit.*), based on the relative drynesss of magmas, that the higher a granite rises in the crust the deeper it must have been formed—and certainly the granites of the Coastal Batholith rose high, even into the bases of volcanic caldera, before being trapped by their melting curves.

The generative process itself, which cannot be separated from the problem of the origin of andesites, has been the subject of considerable discussion in the light of experimental studies (e.g. Winkler 1967, Mehnert 1968, Piwinskii 1968*b*, 1973, Brown 1973, 1977, Wyllie *et al.* 1976). Brown (1977) reviews the evidence on a quantitative basis concluding that, on balance, cordilleran granitoids contain a dominant component of recent mantle derivation, though partial melting of crustal material may well have provided a modest contribution. An important consideration is that crustal thickening in the absence of significant shortening requires underplating by light material and, according to Brown (*op. cit.*), the latter is most likely to have been derived from the mantle, providing a source of granitoids directly, or by a two-stage process.

Further, the granitoids of the Coastal Batholith have all the characteristics of I-types (Chappell & White 1974) which, it has been suggested, indicates derivation by partial melting of an igneous source. However, it is the low value of the initial $^{87}Sr/^{86}Sr$ ratios of Cordilleran intrusives which apparently indicates the mantle source (Kistler 1974, Kistler *et al.* 1971), and the average ratio of 0.7044 (W. McCourt *pers. com.*) for the Coastal Batholith is 'low' in these terms, equalling the value obtained by James *et al.* (1974) for the Cretaceous volcanics of Peru. I am not convinced, however, that deep crustal material would not have been impoverished in ^{87}Sr during its long history previous to its involvement in Mesozoic magmatism (cf. Heier 1964), or otherwise consist of material ultimately derived from the mantle. A full scale investigation of the isotopic compositions of the plutons is clearly called for.

I have little directly to contribute to this ongoing and largely geochemical debate except to provide some of the constraints to the model as indicated in the above account. Nevertheless, I remain attracted to the anatectic concept, especially as developed by Presnall & Bateman (1973) in their studies of the Sierra Nevada Batholith, whereby the granitoid magmas develop by remelting in the lower crust. I suspect that future geochemical researches in Peru will show that, whilst both mantle and crustal sources were involved, the importance of the crustal contribution increased with time. The batholith is, after all, spatially associated with a thick sialic crust and melting of sialic materials is theoretically possible (Piwinskii & Wyllie 1968, Wyllie *et al. op. cit.*). It seems from the experimental work that any such melting would only be partial in water-undersaturated conditions, providing a magma, possibly only 80 per cent liquid, with suspended crystals, chiefly of plagioclase. The calcic cores of the plagioclase in the most basic of the granitoid rocks of the batholith may represent these crystals and the dark xenolithic patches the refractory residuals.

There is no evidence in Peru of a metamorphic belt of Mesozoic age in which anatexitic granites might have been generated by purely ultrametamorphic processes. Even though such a zone of metamorphism might be hidden at depth I doubt that it could have been produced in so passive a crustal environment. However, the necessary heat could have been supplied by the basic intrusives, and it is therefore of particular interest to report that their host rocks, the nearly coeval volcanics of Albian age, reveal burial metamorphic assemblages indicative of an abnormally high thermal gradient (R. Offler *et al. pers. com.*), even at the presently exposed high level in the crust.

A thesis that the rise of such magmas triggered the remelting of deep crustal rocks to produce the great welts of tonalitic rocks, as proposed for the Peninsular Ranges Batholith (Gastil *et al.* 1974, Gastil 1975), is in accord with the established time relations in Peru. It is possible that the new melts maintained the heat plume by transferring sufficient heat upwards to remelt even higher levels in the crust, the necessary loss of energy, coupled with increased water fugacity providing an explanation of the decreasing volume and increasing acidity of the new magmas with time. But would this be feasible if the generation of the batches were separated by the long intervals of time suggested by the episodicity of the radiometric ages? Perhaps Crowder *et al.* (1973) were right in arguing for continuous magmatic activity, holding that episodicity is more apparent than real and is inherent in the K-Ar method. Here it is important to recall that the coeval dykes and volcanics show that basic magmas were always available with a capacity to introduce heat into the base of the crust.

Although the application of a conventional underthrusting mechanism involving a Benioff zone in the central Andes (James 1971*b*) is not as straightforward as the model makers would have us believe, the certainty that great volumes of magma were produced, in volcanic lines parallel to a continental edge, from the Trias onwards, requires that a subduction model be accepted as a basis for any generative model for the magmas.

The apparent time relationship between the phases of magma generation and mild compression in the edge of the continental plate (see Fig. 2, p. 159) argues for a common cause which, if both prove to be regionally episodic, might be sought in the episodic changes in the velocity of the overriding plate or sea-floor spreading. According to Noble *et al.* (1974) the timing of magmatic and tectonic events in Peru does indeed correspond well with proposed changes in plate movements in the Pacific. Also Aguirre *et al.* (1974), using the data of Charrier (1973), suggest a correlation between temporary interruptions in sea-floor spreading and compressive tectonic phases. But if, as seems likely, the pattern of episodicity differs in the separate segments of the Andes, one would then have to suppose differing patterns of spreading rate between parallel transform faults normal to, and continuing under, the continental edge.

The parallelism of the Coastal Batholith and the present continental edge might suggest (see Shackleton *in discussion of* Pitcher & Bussell 1977) that magmas were generated at a specific depth on an evenly inclined subduction zone. But the latter is not at present equally inclined and I doubt that it was ever so; indeed the difference in dip beneath the separate segments provides a possible explanation of contrasts in magmatic and metallogenic phenomena. My own view is that the arc-trench gap was not fixed for the 70 Ma of batholith history, but that the continental edge migrated eastward because of episodic tectonic erosion and subduction of sialic material beneath the

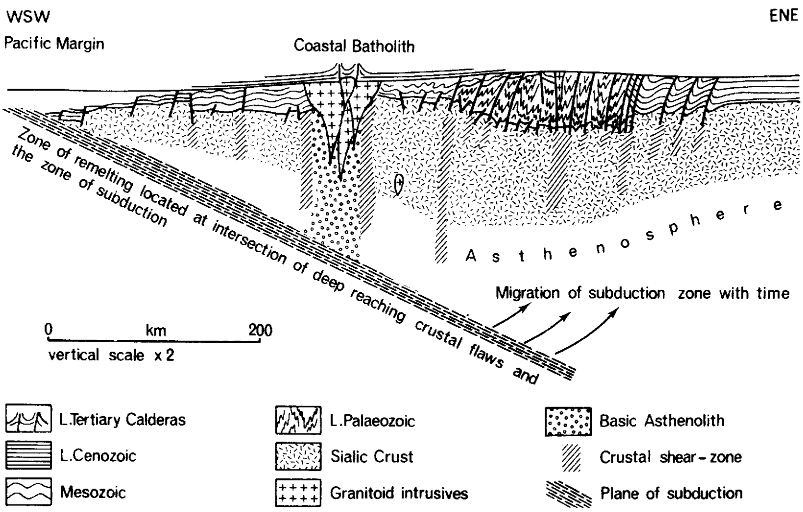


FIG. 10.

Schematic profile of the crust of Peru sometime in the Lower Tertiary. The Model again depicts the deep penetration of faults, represented by ductile shear zones, which possibly reached down into the asthenosphere to intersect with an equally hypothetical, eastward migrating and progressively shallowing zone of subduction.

continental plate. This contributed to the crustal thickening and, by remelting, to the batholithic magmas. Consequently the Benioff slip-zone would have migrated eastward, and may even have changed inclination at the same time.

It is the present thesis that basic magmas generated on the subduction zone were preferentially funnelled and channelled into a long-standing structural 'flaw' in the continental plate. Provided that the PT conditions for melting were appropriate the intersection of the two dislocation zones might have facilitated remelting by providing a channel for the release of volatiles and the rise of the heat plume (Fig. 10). There is a growing realisation of the inter-relation of deep-seated shear zones and fluid and heat transfer (Beach 1976), and even the theoretical possibility that the coalescence of melt droplets might be facilitated in shear zones. The early production of basic melts within an asthenospheric wedge and the subsequent generation of granitoid magmas with the transfer of heat upwards into the lower crust may be explained in these terms. Such a model would invoke an overall shallowing with time of the intersection of the lineaments and hence the site of the generative source, even into the lower crust itself progressively thickening by accretion.

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