# Structural control of batholithic emplacement in Peru: a review

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SUMMARY

In the Andes, major lineaments controlled sedimentation, vulcanicity, batholithic intrusions and mineralisation throughout the Mesozoic and Cenozoic. These lineaments represent major fault lines in an ancient crystalline basement. The magmas of the Coastal Batholith were emplaced along one such lineament and the emplacement of the individual plutons was closely controlled by transcurrent faults and by smaller scale joint patterns. Such structures were continuously exploited throughout the long emplacement history of the batholith. Exceptionally, plutons were forcefully emplaced along early lineaments and lifted roof blocks along shear zones coincident with pre-existing faults. More generally subsidence of large fracture-bound crustal blocks provided the space for the emplacement of magma in bell-jar and cauldron-subsidence structures while stoping along the regular, closely spaced joints resulted in a rectilinear pattern of contacts at outcrop scale.

One of the most impressive features of the Mesozoic-Cenozoic batholiths of Peru is the control of their mode of emplacement by previously established structural elements, both on a regional and local scale. In common with all other major geological features the Cordillera Blanca and Coastal batholiths are aligned parallel to the continental margin and the adjacent trench (Fig. 1). In particular,

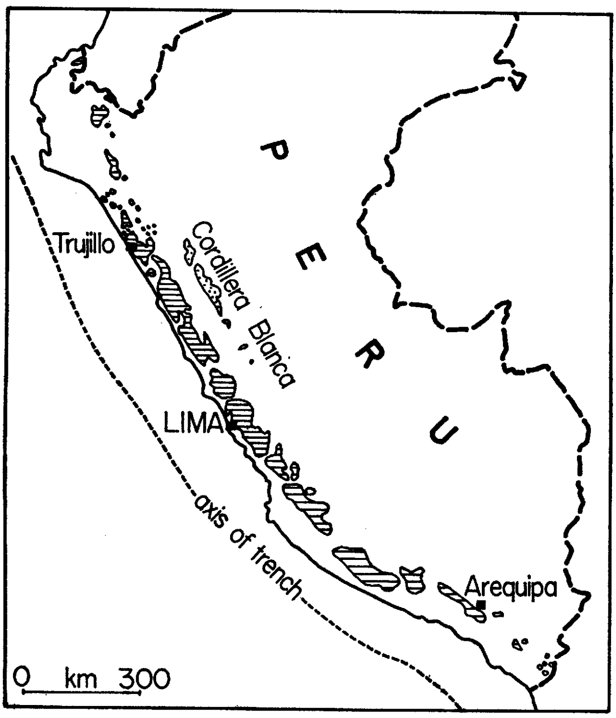


Fig. 1. Locations of the Cordillera Blanca Batholith (stipple), the Coastal Batholith and its extensions as isolated plutons (lined), in relation to the coast of Peru and the Peru-Chile trench.

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the axis of the Coastal Batholith, and the line of individual plutons which extend from either end, lie between 180–200 km from the axis of the existing trench over the whole of the 2000 km long outcrop from Ecuador to Chile.

This remarkably constant trend is the ultimate expression of the lineamental control of every aspect of the Phanerozoic history of Peru (Cobbing 1972, 1974), a control which found early manifestation in the Devonian when the long-lasting regime of encratonic, epeiric basins of sedimentation was first established. Such basins have always been linear, of Andean trend and controlled by block-faulting tectonics (Newell *et al.* 1953), a structural theme which became amplified during the Mesozoic and Cenozoic when ribbon-like belts of subsidence were separated from stable crustal blocks by steep, active faults running parallel to the ancient continental margin (Wilson 1963, Myers 1974). It is the general thesis of Myers (1975*b*) that such vertical movements were the response to a resurgence of activity on deep-seated fractures in the ancient crystalline basement which everywhere underlies the Peruvian Andes (Cobbing & Pitcher 1972*b*).

The remarkably abrupt change of facies within the mid-Cretaceous geosyncline of the western cordillera, dividing it into a westerly eugeosyncline and an easterly miogeosyncline, may be cited as an example of the influence of one of these master fractures. This line of division has been referred to as the Tapacocha Axis (Myers 1974) and it cannot be fortuitous that it neatly coincides with the eastern margin of the Coastal Batholith throughout much of its outcrop north of Lima (Fig. 2). Subsequent reversal of movement on the same steep faults which had previously

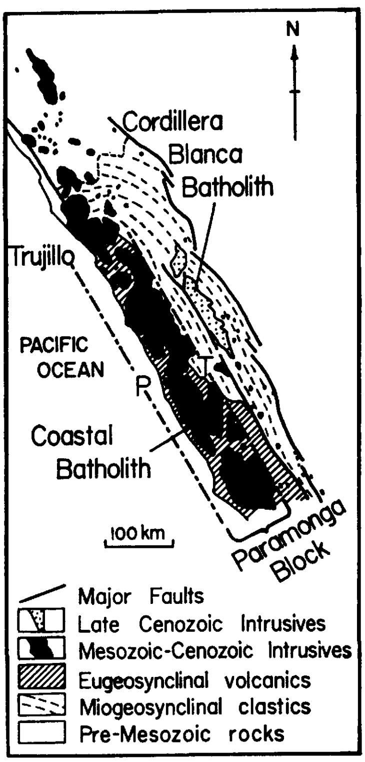


FIG. 2.
Relation of the Coastal Batholith and Cordillera Blanca Batholith to the lithology and structure in the Mesozoic rocks of northwestern Peru. Map simplified after Cobbing (1973*b*).
T—Tapacocha Axis.
P—presumed boundary of Paramonga Block against Paracas Block: both according to Myers (1975*b*).

delineated the sedimentary basins is considered by Myers (1974) to have resulted in certain linear zones of tight folds, zones which continued to isolate distinct fault blocks throughout the Cretaceous. That such faults do reach down into the ancient basement is illustrated by the appearance of upfaulted inliers of old rocks, within the Mesozoic outcrop of the Arequipa area of southern Peru, which are in line with the batholith and intruded by it (Stewart *et al.* 1974).

The clear spatial delimitation of the Lima segment of the Coastal Batholith within one such block (Fig. 2), that of Paramonga (Myers 1975*a*), is a measure of the degree of structural control on the siting and emplacement of the constituent plutons of this composite intrusion (Pitcher 1972, Cobbing & Pitcher 1972*a*), a control which also extends to the coeval volcanics. Within this Paramonga block, narrow Andean-trending zones of intense deformation, associated with a greenschist metamorphism, are also thought to have resulted as a response to resurgent movement on lesser fractures in the ancient basement. These provide a local control of the siting and delimitation of plutons, not necessarily passively, as Child (1976) considers that movement on such lines occurred during the period of batholithic emplacement.

In the northern part of Peru the batholith continues northwestwards along a single Andean trend (Fig. 1) as a broad 80 km wide zone of isolated plutons. It crosses a local structural swing in the Mesozoic strata (Fig. 2) and then passes out of the Mesozoic outcrop altogether, traversing northward through Permian and older strata, even into the Precambrian of Ecuador. It is this ultimate disregard for upper crustal composition and structure which so strongly suggests a fundamental locational control by some deep seated structure. This is here envisaged as a fault complex in the ancient basement, possibly representing the upward expression of a ductile shear zone in the deeper crust.

It is possible (Shackleton *in* discussion) that the batholith is aligned as the result of a constant relationship of magma generation to an evenly, easterly-dipping subduction zone, and that the associated faults simply represent a response to rising magma. However, major structural lines had for so long controlled sedimentation and structure in the Andes prior to batholith emplacement that we think that pre-existing fractures were utilised by the magmas, though it seems certain that resurgence of fault movement occurred during their upwelling. It is suggested that the way in which magma has been continuously tapped along one line over so long a period as 70 Ma (Stewart *et al.* 1974, Bussell *et al.* 1976) indicates the existence of a particularly deep-penetrating structure which, on intersecting a Cretaceous Benioff zone, formed a *locus* for magma generation and ascent. Only in the mid-Tertiary did the zone of magma penetration sidestep eastwards into a similar deep structure along the present line of the Cordillera Blanca.

There are other linear batholiths in the Andes. In southern Chile the emplacement of Andean plutonic rocks dates from the late Jurassic, with younger intrusions being superimposed on older ones in a single, linear batholith complex similar to that in Peru, but here over an even longer period of 140 Ma (Halpern 1973). Clearly the *locus* of emplacement does not always migrate eastwards in the step-like systematic manner postulated by Farrar *et al.* (1970) in the Andes of northern Chile; more usually it becomes fixed along a specific structural line.

In Peru the magmas which rose along the early established zones of weakness were, in their final stages of ascent, passively emplaced to within the comparatively shallow depth of 5 km of the earth's surface (Atherton & Brenchley 1972), even to intrude into the base of contemporary calderas (Bussell *et al.* 1976) and into their own volcanic ejecta (Myers 1975*a*). At such shallow depths bell-jar plutons were emplaced by cauldron subsidence aided by fluidisation processes (Cobbing & Pitcher 1972*a*, Pitcher 1974, Myers 1975*a*). The boundaries of the sinking blocks were closely controlled by the pre-existing fracture pattern in the host rocks (Cobbing 1973*a*, Bussell 1976), a control which is evident on all scales.

On the map scale the early intrusions have the form of great lens-like plutons strung out along the batholithic lineament. These are pierced by groups of smaller plutons and ring dykes which, though more equidimensional, are crudely rectangular or polygonal in shape of outcrop (Knox 1974, Myers 1975*a*, Child 1976), with linear contacts trending parallel to regional fracture patterns and often utilising the same structure several times. One important element of the fracture pattern, the northeast to southwest dextral wrench faults, can be shown to have been in continuous activity throughout batholithic emplacement, although with an intensity varying with the overall competency of the sedimentary and volcanic country rocks (Bussell 1975). Such faults not only formed one of the structural elements delineating the trends of the contacts themselves but had a more fundamental role. This is shown by the development, within the Lima segment of the batholith, of a regularly spaced series of four ring complexes (Cobbing & Pitcher 1972*a*, Bussell *et al.* 1976), in a region of particularly well developed wrench faults. It seems that the intersection of these oblique wrench

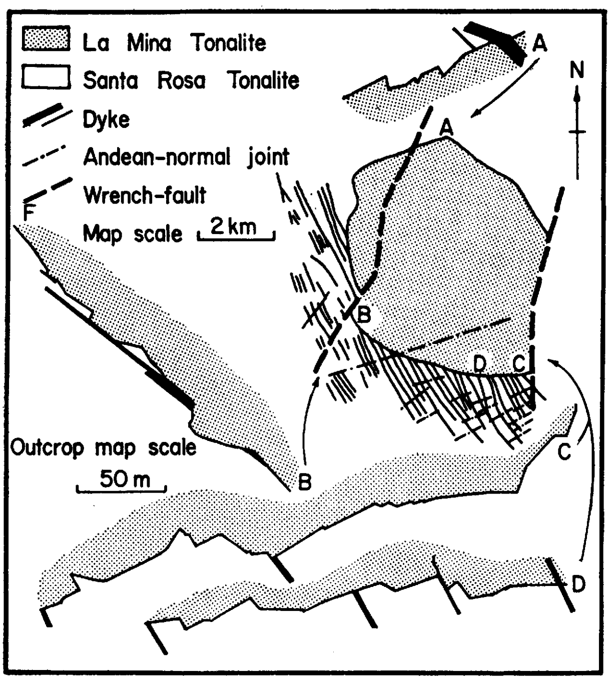


FIG. 3.
Outline map of the San Miguel Pluton in the valley of the Rio Huaura shows rectilinear outline of contacts on map and outcrop scale, particularly relationship between trends of the contacts, joints and dykes (after Bussell 1976).

faults with the deep Andean-trending lineament picked out by the batholith, resulted in the point-focussing of magma at depth while providing admirable sites for cauldron subsidence of rectangular blocks of crust at higher levels.

In conjunction with this fault control there is another control on a finer scale resulting from the stoping away of blocks along a regular fracture pattern coincident with earlier formed joints (Bussell 1976) some of which are themselves genetically connected with the wrench faulting. This results in a rectilinear contact pattern in detail (Fig. 3); further, the occurrence of stoped-off angular blocks is commonplace. Within the plutons residual aplitic liquids and synplutonic dykes were emplaced along the very same fracture trends which had controlled the emplacement of the pluton, thus emphasising the resurgent propagation of these small scale fracture patterns.

A very considerable measure of structural control clearly operated during emplacement. Further, the preferred directions of fracture were maintained throughout the very long history of emplacement, being continually reactivated and redeveloped under a stress system of constant orientation. The regional character of this fracture system, extending far beyond the confines of any one pluton, make it unlikely that the fractures were a direct consequence of strains set up during the emplacement of single plutons. Rather it seems that the pattern of wrenches and lesser fractures is the result of the interplay of a regional compressive regime, involving wrench-fault tectonics, with one of vertical uplift along the batholith axis. Of course, as mentioned above, this uplift is likely to have been in response to the generation and rise of magmas at much deeper levels.

It is possible that the plutonic contacts and dyke fissures could have been produced contemporaneously with intrusion, perhaps by a process of hydraulic fracturing, the preferred directions still being developed under the influence of the unchanging regional stress regime. However, it is very common to find that the magmas utilised *existing* lines of weakness such as established faults, contacts between demonstrably earlier plutons and their host rocks, and the fissures occupied by dykes (Fig. 3). Further, the authors contend that early fractures akin to joints were produced early in the consolidation history of plutons simply as a response to regional strain, structures which added an additional measure of control. If so, this utilisation of joints by intrusions may eventually provide some indication of the depths to which this kind of fracture may be propagated.

There are some rare exceptions to this pattern of passive emplacement in Peru where certain early tonalite plutons were deformed during emplacement along pre-existing envelope faults. For these, Bussell (1975) has presented a model of *in situ* expansion, along a fault plane, of blisters of magma which shoulder aside the wall rocks in a manner similar to that described by Nelson & Sylvester (1971) for the Birch Creek pluton of California. In one example the wall rocks were downfolded along one contact and uplifted along another when a pluton was intruded along a high-temperature shear zone characterised by sillimanite-bearing rocks.

Possibly we are seeing here a hint of the deeper structure of the Peruvian intrusives, because in cordilleran batholiths elsewhere there is some indication (Gastil *et al.* 1975) that, in deeper seated environments, the constituent plutons may be diapiric. Perhaps, at lower levels of the crust and in a more ductile environment, they were being squeezed up along fault planes before mushrooming out at higher levels and losing their diapiric character.

Thus a survey of the structural setting of the Coastal Batholith of Peru reveals a high degree of structural control by resurgent fractures on all scales. The deep-seated dislocations into which the magmas were evidently collected and funnelled over long periods afford an example of the anisotropy revealed when the crust is considered regionally as distinct from globally.

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# Discussion

Professor R. M. SHACKLETON commented that a central feature of the authors' interpretation is that the Peruvian Batholith owes its linearity to the presence of a deep-fault or basement lineament, up which the magmas rose. While it is clear that at the present level of erosion the granites are associated with, and are often limited by, important faults, it seems that these faults are probably the effect and not the cause of the linear distribution of the granites. The thickening of the crust under the Andes and the recent rapid uplift must be attributed to large accessions of material from the mantle, since crustal shortening during Mesozoic and Tertiary times was clearly trivial and could not account for the thickening. Additions from the mantle are to be expected as a result of melting from a downgoing slab. A linear array of plutonic intrusions parallel to a trench is a general feature of subduction zones and is surely the result of melting at a critical depth rather than ascent along deep faults for which there is no seismic evidence. Uplift pressures exerted by the rising magma would cause faulting in the upper crust, although closer to the surface such pressures would not be in evidence. The fact that granites of different ages form separate linear arrays is further evidence against deep fault control since different faults would be needed to explain each array. The trench-arc gap is normally sharply defined. Therefore, the trench-side limit of plutons or volcanoes is itself sharply defined and parallel to the trench.

THE AUTHORS agreed with Professor Shackleton that uprise of the magmas may well have led to fracturing and fault movement in the cover. However, the thesis that the plutons had utilised deep-reaching crustal structures during their intrusion was based not only on the linear character of the batholith but on the general geological environment of the latter, a point which may not have been sufficiently emphasized in the short spoken contribution. Vertical movements had dominated sedimentation and tectonic processes in the Andean belt since Devonian times and in the Mesozoic, in particular, the history was one of encratonic geosynclines with sharply marked facies boundaries representing resurgent movement on deep faults. It was along such long standing structures that it was envisaged the plutons made their way upwards.

They did so during 70 Ma, over which span of time only a small west-east shift is recorded, and it would seem remarkable if an arc-trench gap could persist, unchanged in width, for so long a time if the ascending magmas were not channelled along some deep reaching structure. That, otherwise, magma could be generated along so exact a line simply as a response to depth is incomprehensible especially as, at present, the Benioff zone, in so far as it exists at all under Peru, is reported to be markedly uneven in its inclination.