POTASSIUM-ARGON AGE STUDIES IN PERU WITH PARTICULAR REFERENCE TO THE CHRONOLOGY OF EMPLACEMENT OF THE COASTAL BATHOLITH

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November 1975.

FOR TRISHA

ABSTRACT

This research was initiated in order to study the chronology of emplacement of the Coastal batholith of Central Peru particularly to find out if the batholith had evolved by a continuous or an episodic process of intrusive activity.

Some 135 new K.Ar age determinations on mineral separates from igneous rocks of the western Cordillera of Central Peru are presented and produce a broad spectrum of ages between 98 and 3 m.y.

It seems that the Coastal batholith has evolved over a period of 70 m.y., though this general picture is complicated by the profound thermal effect of the younger more acidic intrusions on the argon retention of the older tonalitic units. Nevertheless it is shown that the pattern of ages from the Coastal batholith defines three groups;

1) 98 - 85 m.y.
2) 75 - 56 m.y.
3) 35 - 30 m.y.

These are interpreted as being indicative of an episodic process of magma emplacement and are separated by periods of apparent intrusive quiescence. Reservations, however, are introduced when more than one transect of the batholith rocks is considered.

In addition reconnaissance age determinations on satellitic plutons to the east of the Coastal batholith define two younger plutonic events, of Miocene and upper Miocene-Pliocene age. This younger intrusive activity mainly corresponds to the Cordillera Blanca batholith and a southerly extension of this body is likely on the basis of the age of the granitoid stocks near Churin. It will be suggested that this apparent episodicity of magma emplacement is controlled by the complexities

which are involved in the ascent of the magmas through the crust and does not necessarily reflect an episodic process of magma generation.

For the sake of completeness age determinations on the associated Tertiary volcanic rocks are included, and these illustrate the considerable overlap between plutonic and volcanic activity which exists in the western Cordillera. It seems that the volcanic rocks were vented from the site of the Coastal batholith for over 40 m.y. and in post-Oligocene times the volcanic centres migrated to the east with the final eruption of a series of ignimbrites of Pliocene age.

This body of age determinations helps place more precise limits on the age of the Andean folding. A relationship between deformation and major culminations of plutonic activity is proposed and these are equated with similar events in the Chilean Andes.

Finally reconnaissance age determinations from the San Nicholas batholith of the Coastal Cordillera of southern Peru are included. They show this body to be of Ordovician-Silurian in age, and the significance of this finding is discussed in connection with the age of the Marcona iron ores.

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PREAMBLE

Scope of the Project and general layout of the Thesis

A research project related to the Coastal Batholith of Peru was initiated by Professor W.S. Pitcher at the University of Liverpool in 1966, at the same time a programme of technical aid to Peru, by the Overseas Division of the Institute of Geological Sciences, was also launched. The main theme of the projects involved regional mapping of the Western Cordillera in Central Peru, between Lima and Chimbote. Both teams worked in close co-operation with the Servicio de Geologia del Peru.

Progress was such that completion of the mapping north of Lima resulted in an expansion of the area to Nazca in Southern Peru, so that by 1977 a segment of the Western Cordillera over 800 kms in length should be mapped on a scale of 1 : 100,000.

In addition to the regional mapping certain aspects of the geology necessitated more detailed study; topics such as the stratigraphy of the Cretaceous country rocks and nature of the Coastal Batholith particularly its mode of emplacement, geochemistry, mineralisation and petrography have all formed the themes of more specialised projects.

The author joined the project in 1972, with the tenureship of a N.E.R.C. grant, to study the chronology of emplacement of the Coastal Batholith the foundations of which had already been established by members of the I.G.S. team (Stewart, Evernden and Snelling, 1972).

The author spent two field seasons in Peru the remainder of the time being divided between Liverpool University and the Isotope Geology Unit of the I.G.S. (London) where the analytical work was carried out.

In this thesis the author summarises the pre-existing work, both in a regional and then a more specific context, as a framework for the present study. The method of approach is discussed at some length in the second part of the thesis and the analytical procedures which were used are summarised in the appendices. The latter and main part of the thesis concerns the presentation and interpretation of the results. In the final section the author examines their significance in the light of similar studies in other Circum-Pacific environments.

PART ONE

THE GEOLOGICAL SETTING

1. THE REGIONAL GEOLOGY OF PERU

The Tectonic Setting

The Peruvian Andes consist of two subparallel, north-westerly trending fold belts, the outcrop patterns of which are reflected in the topographic division of the Andes into a Western and Eastern Cordillera

The Eastern Cordillera comprises of a Palaeozoic fold belt which is divisible into a greenschist belt lying north of Huancayo and of pre-Ordovician age. South of Huancayo the schist belt is replaced by an assemblage of black shales and quartzites of Ordovician-Devonian age (Cobbing 1972, 1974). The Palaeozoic fold belt is separated from the Western Cordillera by a large graben which is infilled with Tertiary molasse forming a broad intermontane plateau termed the Altiplano. North of Abancay the two Cordilleras converge and the Altiplano is eliminated as a structural unit (see Fig.1).

The Western Cordillera is the site of the present study and is constructed of a younger fold belt of Mesozoic-Tertiary age. This fold belt is characterised by two elongate N.W. trending belts, an eastern area of folded clastic sediments and carbonates which pass westwards into a thick succession of marine volcanites.

The two fold belts are bounded to the east by epicontinental sediments which unconformably overlie the Brazilian shield (Wilson 1964,1967). The Palaeozoic fold belt is separated from these thin platform sequences by the Sub-Andean fault

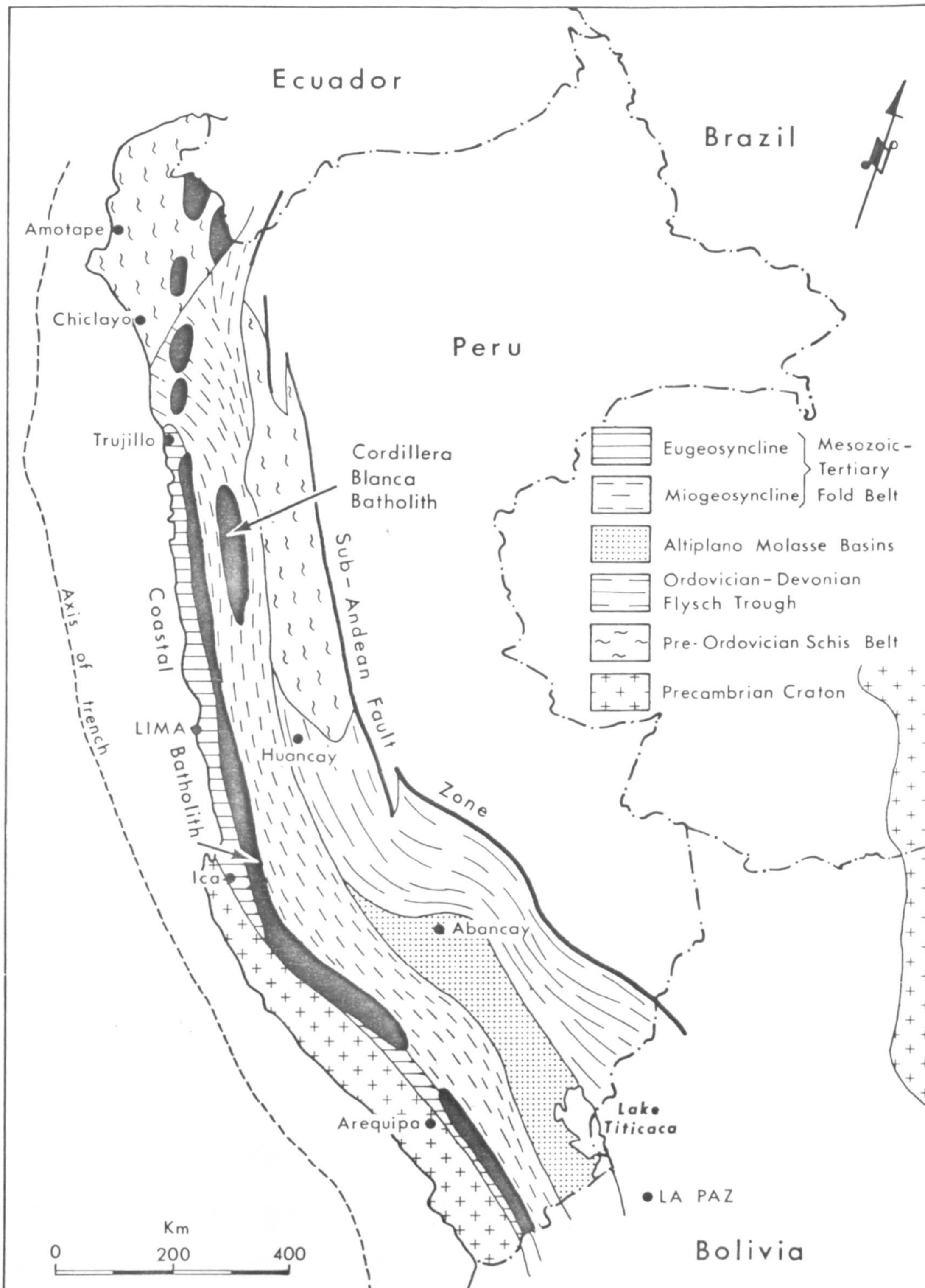


Fig.1. The main tectonic elements of the Peruvian Andes, after Cobbing (1974).

zone which is believed to be the oldest recognisable feature to follow the Andean trend. It was initially formed during the late Pre-Cambrian, or Lower Palaeozoic, and reactivated in the Pliocene (Martinez et.al. 1971, Cobbing 1974).

With the exception of the Paracas Peninsula of Southern Peru the Mesozoic-Tertiary fold belt has the Pacific Ocean as its western boundary. To the west of the Coastal Cordillera of Southern Peru the fold belt is flanked by ancient rocks of the Arequipa Massif. This massif consists of granite-gneisses and migmatites which are cut by coarse potassic granites and pegmatites. Associated with the gneisses are amphibolites; the total assemblage indicates a high amphibolite-granulite facies metamorphism (Cobbing and Pitcher, 1972b). All the recognisable structures in these rocks strike approximately east-west, normal to the general Andean trend. The gneisses and associated rocks have been referred to as Pre-Cambrian in age (Steinmann 1930, Jenks 1956) and recent radiometric age determinations by Stewart and Snelling (1972,1974) and Cobbing and Snelling (in press) confirm this.

The outcrop of the Pre-Cambrian rocks terminates north of Ica, although it is now generally accepted that they continue north and occupy a large proportion of the 200 km wide continental shelf as far north of the Ecuador border (Cobbing 1972,1974, Cobbing and Pitcher 1972b). In conclusion it seems the Andean Mobile Belt occupies an intra-Cratonic environment and is presumably underlain by sialic crust (Cobbing, 1974).

Brief Outline of the Geological History of Peru

The Pre-Cambrian rocks of the Paracas Peninsula are the oldest rocks so far recognised in Peru. The oldest fossiliferous strata recognised to date are of Ordovician age and rest with marked unconformity on the basement. They consist of shales deposited during a period of marine sedimentation which commenced in the mid-Ordovician and continued, albeit intermittently, until the Upper Devonian (Newell and Tafur, 1943). Towards the close of the Devonian the lower Palaeozoic sediments were uplifted, folded and subjected to a low grade regional metamorphism.

Marine sedimentation continued in the Carboniferous with the deposition of limestones and shales resting with angular unconformity on the folded lower Palaeozoic strata. Widespread emergence, with folding and faulting followed by uplift and erosion, marked the Hercynian Orogeny in Peru (Megard et.al. 1971). Continental clastic sediments, with interbedded volcanics, were deposited on the peneplained surface of the Carboniferous rocks during the Permian. There is no evidence of sedimentation or deformation between the late Permian and Triassic periods in Peru.

The Mesozoic history of Peru began with a major marine transgression marking the onset of the 'Andean geotectonic cycle' of Bellido (1969); this still continues to the present day.
Large elongate sedimentary troughs, with intermediate positive areas, formed parallel to the present day coastline and were the sites of deposition during the Jurassic and Cretaceous. A widespread regression of the sea began towards the close of the Cretaceous and most of western Peru was emergent at this time (Wilson, 1963); this regression marked one of the early features of the Andean orogeny.

The principal features of the Andean Orogeny involved the folding of the Mesozoic sediments along axes parallel to the present Andes and slightly oblique to the Hercynian trend. This was followed by the emplacement of the Coastal Batholith which partly overlapped with the eruption of a thick sequence of terrestrial andesitic lavas and tuffs (Cobbing and Pitcher, 1972a).
In the mid-late Tertiary the whole of western Peru was then subjected to intensive erosion resulting in its complete peneplanation and formation of the Puna erosion surface (McLaughlin, 1924). The final and still persistant stage was the uplift of the Puna erosion surface to altitudes of 4,500m which is thought to have commenced in the Pliocene (Bellido, 1969). Thick volumes of rhyolitic volcanics (ignimbrites) are associated with these late epeirogenic movements.

The Batholiths of Peru and their Environments of Emplacement

Both volcanic and plutonic activity have been widespread in the Cordilleras of the Peruvian Andes, this thesis however is concerned solely with the Western Cordillera to which further discussion will be confined. In western Peru three immense intrusions of Batholithic proportions are present, they are from west to east and in order of decreasing age, the San Nicholas Batholith, the Coastal Batholith and the Cordillera Blanca Batholith (Fig.2). Their distinctive features are outlined by the author later in the thesis and have formed the theme of a recent review by Pitcher (1974).

The San Nicholas Batholith

The San Nicholas Batholith is the name given to a series of isolated intrusions which occupy the Coastal Cordillera of Southern Peru. The batholith extends for over 140 kms along the coast and has an average

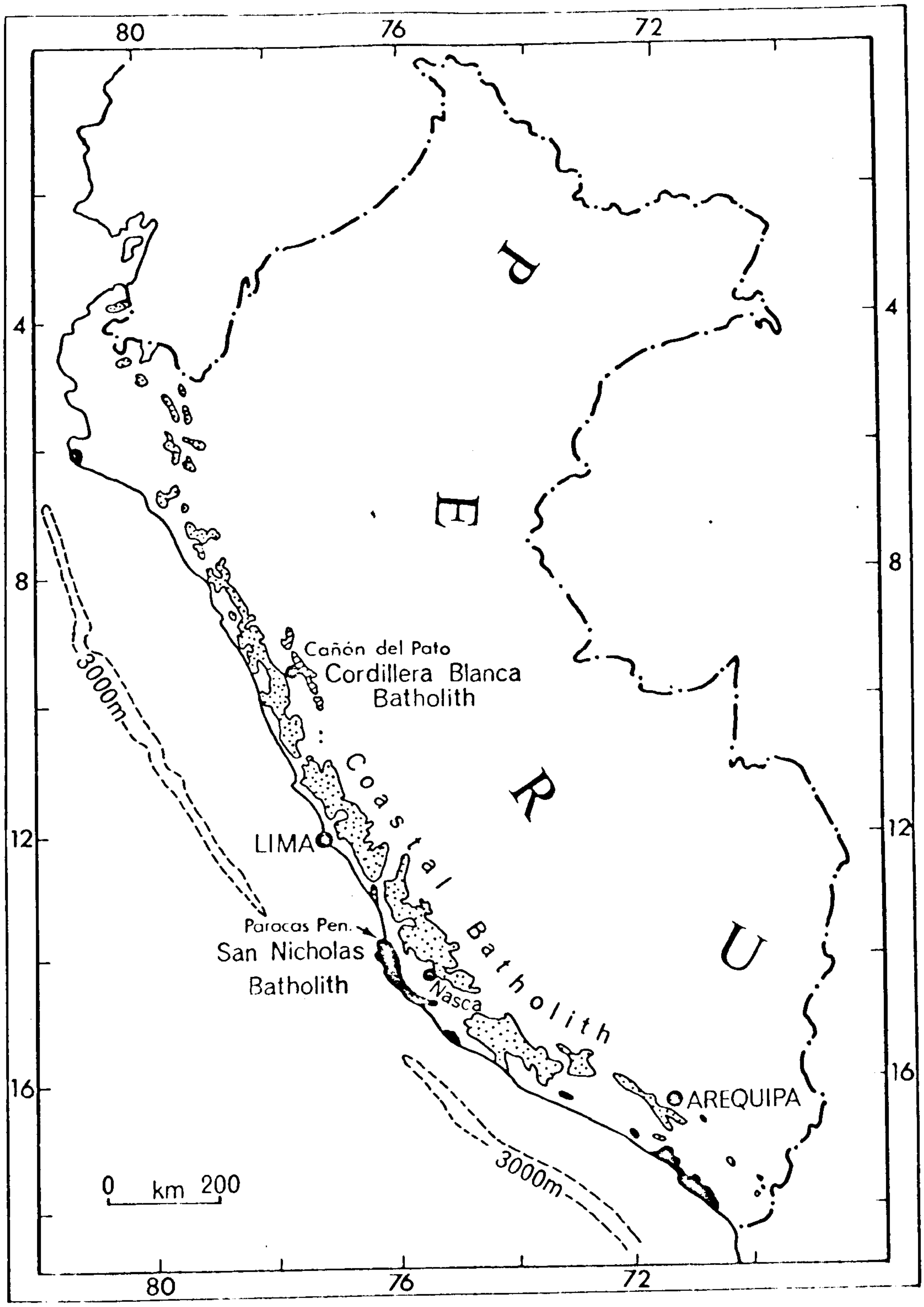


Fig.2. Outline map of Peru showing the positions of the three batholiths in relation to the Peru-Chile trench.

width of 25 kms. It is emplaced into the Pre-Cambrian rocks of the Arequipa Massif and locally into sediments of the Marcona Formation which are believed to be Upper Palaeozoic in age. The batholith has been referred to as Jurassic in age.

The Coastal Batholith

The Coastal batholith of Peru comprises of a series of related intrusions which form one sector of the continuous string of plutonic rocks which parallel the western coast of South American from Venezuela to Tierra del Fuego.

In Peru the batholith is emplaced within the western volcanoclastic geosynclinal sediments of the Mesozoic-Tertiary fold belt, this relationship continues over a distance of 720 kms between Ica and Trujillo (see Fig.1).

North of Trujillo the batholith intrudes the eastern thin shelf sequences of the fold belt (miogeosyncline). North at the Huamcabamba deflection, where the Andean trend changes from NW to NE, the batholith is emplaced within schists and phyllites of Palaeozoic age. Similarly in south-central Peru the batholith is locally emplaced within the Arequipa massif before continuing southward within a eugeosynclinal environment around Arequipa.

In conclusion, it is apparent that the Coastal Batholith is following some pre-determined structure which has localised its emplacement with little regard to the surface geology; the association of the batholith with the Mesozoic geosyncline is partly accidental (Pitcher 1972, Cobbing 1974).

The Cordillera Blanca Batholith

This, the youngest of the three batholiths, outcrops to the east of the Coastal batholith (Fig.2) and occupies the highest region of the Peruvian Andes with peaks rising upwards of 7,000m. The batholith has an average width of 12-15 kms and an overall length of 200 kms and is therefore comparable in size to the San Nicholas batholith. Unlike the Coastal batholith, the Cordillera Blanca batholith is emplaced into the miogeosynclinal sediments of the Mesozoic-Tertiary fold belt.

2. THE GEOLOGY OF THE AREA OF STUDY

The main area of study is shown in Fig.3 and has been the focal point of detailed mapping projects by members of the Liverpool team and the I.G.S. (London). As a result of this continuing mapping programme, the following quarter-degree sheets have been published and form the basis for the present research;

Huacho-Haural	(No. 23ij)	Cobbing, Pitcher and Garayer (1972)
Ambar-Barranca	(No. 22hI)	Cobbing and Garayer (1972)
Canta	(No. 23j)	Cobbing and Garayer (1971)
Oyon	(No. 22j)	Cobbing and Garayer (1971)

Location and Access

The main area is encompassed by the aforementioned six quadrangles which cover an area of 15,000 sq. kms. The area, which is outlined in Fig.3, is bounded to the west by the Pacific Ocean and to the east by the high Andean peaks of the Cordillera Negra and the Puna erosion surface which has an average height of 3,500m.

The western part of the area is dominated by the coastal desert, an area of relatively low relief characterised by absence of rainfall and devoid of vegetation. Irrigation contributes locally to land use although cultivation is generally confined to the east-west river valleys where water is more plentiful. Further inland there is a noticeable topographic change marked by an increase in relief,here many peaks attain heights of 5,000m and form the high Sierra of the eastern margin. A thin covering of soil,and the semi-arid environment, permits the growth of shrubs and cacti and the region supports a scanty population.

The area, studied in detail, is situated approximately 80 kms north of Lima and is reached by the Pan-American highway which runs from Chile to Ecuador along coastal Peru. Wide E-W trending river

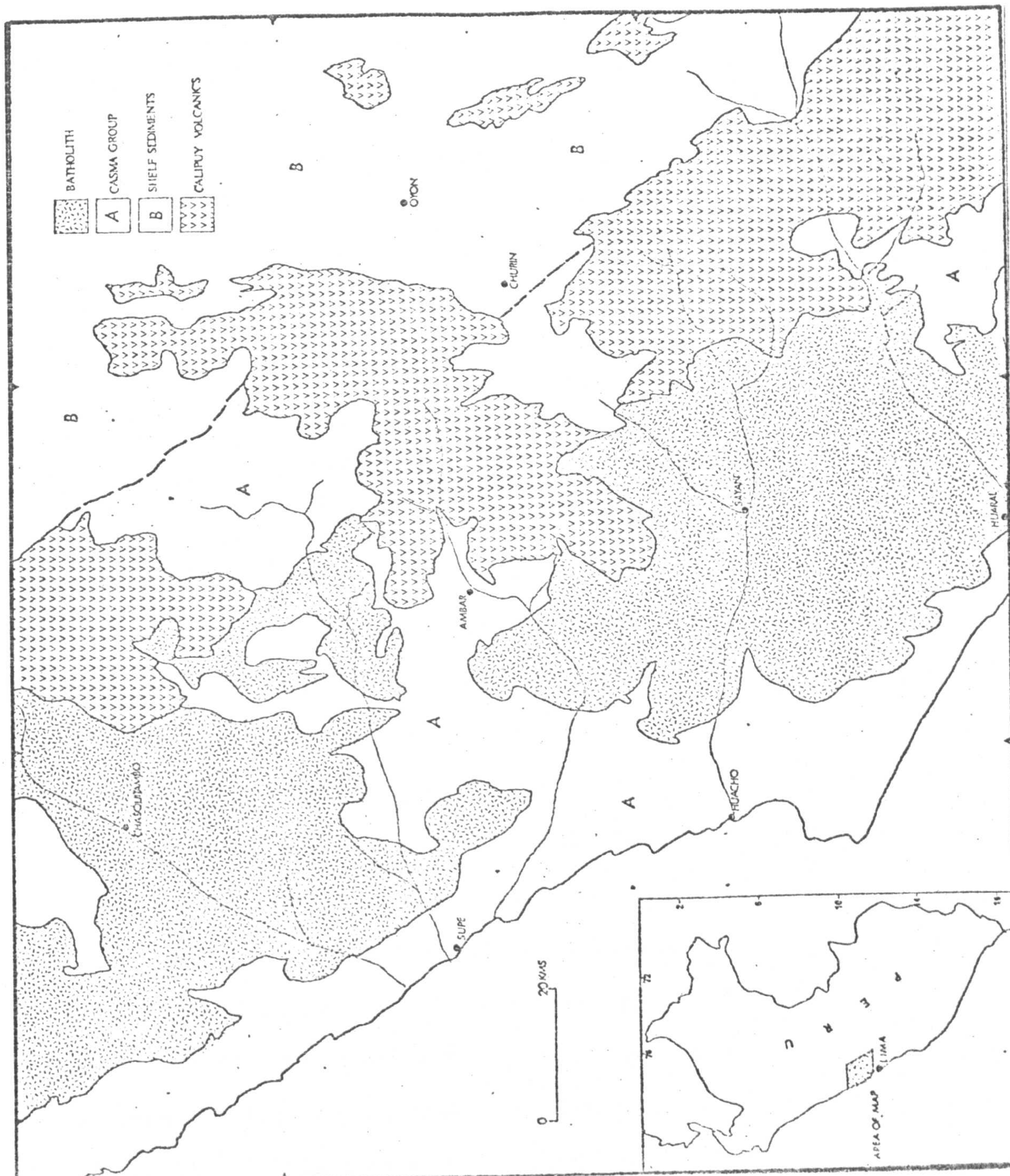


Fig. 3 Map showing the location of the main area of study together with the generalised geology

valleys afford access to the interior, these occur at regular intervals of 30km and are from south to north, the Rio's Chancay, Huaura, Supe, Pativilca and Fortaleza (Fig.3). The roads along these valleys may be metalled for the first few kilometers then pass into dust-tracks. The towns of Sayan, Huaral, Supe and Chasquitambo provided useful bases for access and accommodation, additional work in other areas involved camping.

The geology of the area can be broadly divided into two units, firstly the Batholith itself and secondly the Cretaceous and Tertiary country rocks into which it is emplaced, the outcrop patterns are generalised in Fig.3. Before describing the geology in more detail the author proposes to summarise the Cretaceous Palaeogeography of Peru to enable the reader to have a clear picture of the environment in which the country rocks were deposited.

The Cretaceous Palaeogeography of Central Peru

The present day understanding of the Cretaceous Palaeogeography of Peru can be attributed to the detailed stratigraphic studies of J.J. Wilson (1963). During the Cretaceous western Peru was dominated by two elongate troughs which were separated by a positive area of Palaeozoic rocks termed the Marañon Geanticline (Benavides, 1956). The sediments in the area of study were deposited in the most westerly trough (See Fig.4). In this West Peruvian trough there was a strong contrast in the types of facies which were deposited, Cobbing (1973) has recognised three divisions from west to east; 1) The Coastal Province, 2) Basin Province of the Cretaceous and 3) The Block Province of the Cretaceous, the latter two zones are overlain by the 'Province of the Sierra Volcanics'.

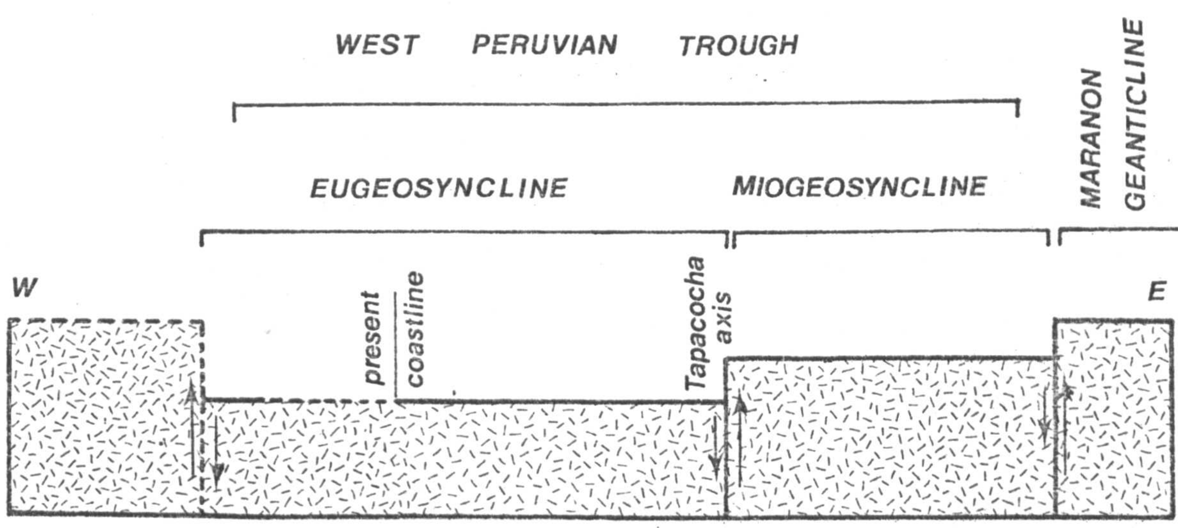


Fig.4 Diagrammatic section across the western Andes showing the position of the fault-bounded troughs, in which the Cretaceous sediments were deposited.

(Pre-Cretaceous rocks are stippled) after Myers (1974)

These provinces reflect the division of the trough into a western eugeosynclinal, dominantly volcanic facies and an eastern miogeosynclinal, marginal shelf region; these are crudely reflected in the geographic division of the study area into a coastal desert and Andean region.

In these environments both marine and terrestrial conditions prevailed, marine incursions from the west swept onto the geanticline which was the main source of clastic material. The sharp transition from the eastern shelf to the western basinal facies led to the suggestion of control by a deep fault (Wilson, 1963 Cobbing, 1973), this hypothesis has recently been more fully demonstrated by Myers (1974). Correlation of the western and eastern facies have presented major difficulties mainly due to the scarcity of fossils in the basinal rocks, moreover the emplacement of the Coastal batholith and effusion of the Sierra volcanics have obscured the facies transition.

The Geology of the Coastal Province

A thick sequence of dominantly marine volcanoclastic sediments constitute the western and much of the eastern envelope of the batholith and have been correlated with the Casma formation of Cossio (1964), (Wilson, 1963), and recently been elevated to the status of Casma group by Myers (1974).

The Casma group outcrops along the coastal desert region forming a continuous belt between Lima and Chimbote and has an average outcrop width of 25 kms. For the most part they consist of well-stratified volcanic sediments with interbedded thin flows of massive andesite. Thick pillow lavas associated with pillow-lava breccias also characterise the sequence; these together with thin infrequent fossiliferous horizons indicate deposition in a subaqueous marine environment. Their total thickness is probably greater than 5,000m, Child (pers. comm) describes a 5 km section in the Department of Ancash where a mixed facies of marine volcanoclastic sediments together with pillow lavas pass upwards into a series of sandstones and conglomerates. Child (pers. comm) has also recognised a similar sequence in the Huaura valley indicating a general uniformity of facies along the trough. In total three major episodes of volcanic activity have been recognised (Child, pers. comm);

1) Submarine extrusion of lavas interspersed by periods of volcanic quiescence marked by deposition of tuffs through the medium of turbidity currents.

2) Normal marine sedimentation interrupted by deposition of pyroclastic debris from submarine eruptions.

3) A sequence of shallow marine and subaerial sediments.

The general scarcity of fossils within the dominantly volcanic Casma group has presented difficulties with respect to their age and correlation. Cossio (1964) originally grouped the Casma in the Upper Jurassic to Lower Cretaceous due to their lithological similarity to the Punta Piedra formation near Lima (see Rivera, 1951). The rather scant fauna discovered in the Casma group in the area of study shows they are Albian in age (Wilson,1963 Myers, 1974).

The Andean Province

Myers (1974) has shown the transition from the Casma Group to the relatively thinner platform deposits further east, to be fault controlled and related to vertical oscillatory movements of strips of basement bounded by shear belts. In the Huarmey region the facies change takes place abruptly along the Tapacocha axis, a basement shear zone on which greater subsidence occurred to the west (fig.4).

The stratigraphy of the shelf deposits have been described in detail by Wilson (1963) and Cobbing (1973), and Myers (1974) has

FORMATION	LITHOLOGY	THICKNESS	AGE
CELEDIN	thinly bedded shales and limestones with evaporites and red beds at the top	250m	Coniacian-Santonian
JUMASHA	medium-bedded limestones and dolomites deposited in shallow seas.	400m	Turonian?
PARIATAMBO	thinly bedded shale, limestone and dolomite, chert bands towards the top of the sequence, facies change showing shallowing of sea to the east.	100-200m	Albian
CHULEC	marls, limestones and calcareous sandstones.	200m	L. Albian
PARIAHUANCA	medium bedded limestones and calcareous sandstones	200m	L. Albian
FARRAT	protoquartzites and orthoquartzites	80m	
CARHUAZ	thin medium bedded sandstones, silts and shales.	1150m	Aptian
SANTA	cross bedded sandstones and shales and oolitic limestones	50m	Late-Valanginian
CHIMU	metaquartzites.	500-700m	
OYON	subgraywackes, thinly bedded shales with coal at base.	100m	Valanginian or Berriasian

Table 1. Summary of Cretaceous stratigraphy of the Andean Province of Central Peru, adapted from Wilson (1963).

correlated them with the Casma Group. The distinctive lithologies of these shelf sequences have permitted accurate reconstructions of a depositional environment which is characterised by fluctuations in sea level.

Ten formations have been recognised by Wilson (1963) having a total thickness of 4,000m and ranging from Valanginian to Santonian (Cretaceous) in age. The four lowest formations equate with the Goyllarisquiga Group of Benavides (1956). The main successions recognised by Wilson (1963) and Cobbing (1973) are briefly summarised in Table 1.

Structure of the Cretaceous Rocks

The Cretaceous sediments were folded along axes parallel to the Andean trend towards the close of the Cretaceous period (Steinmann, 1929). The resulting deformation produced a sharp contrast in the style of folding between the Casma Group and the shelf facies of the Sierra; these are summarised below.

In the field the Casma Group demonstrate rather straightforward structures with the beds striking parallel to the Andes and dipping uniformly to the west; the only evidence of folding is a mild warping. These observations influenced Cobbing (1973) to refer to the coastal zone as the 'Province of Structural Tranquility'. Myers (1974, 1975) has observed a more complex situation in the Huarmey region where he noted two phases of folding within the Casma Group, one Andean parallel and the later one at a high angle to the Andean trend. The former, or Andean folding, is characterised by folds having sub-horizontal fold axes with synclines tighter than the more open anticlines. Metamorphism accompanies the deformation only in the tighter synclines and even then is controlled dominantly by the lithology. The Andean normal folds are described by Myers as open folds with vertical axial surfaces and fold axes plunging gently to the north-east.

The broad expanses of gently dipping beds described by Cobbing (1973) were also recognised further north by Myers (1974) who interpreted them as representing the hinge zones of major anticlines. Even in these zones which appear to be relatively undeformed, strain calculations on ammonites have shown the rocks are shortened by up to 17-23% (Myers 1974, 1975).

In contrast the Cretaceous rocks of the Andean region responded to the deformation as a single structural unit by decollement along the base of the Oyon formation (Wilson 1963, Cobbing 1973). The resulting folds have long fold axes which are continuous for up to 100 kms parallel to the Andes, yet the anticlines and synclines often have their limbs sheared out where thrusts are associated with over-turned folds. The fold axes are usually horizontal or slightly undulating.

The Province of the Sierra Volcanics

A thick sequence of terrestrial volcanics rest unconformably on the folded Cretaceous sediments and form part of the eastern envelope of the Coastal Batholith (See Fig.3). They were originally termed the Calipuy Volcanics by Cossio (1964) who recognised them in northern Peru, this name has since been adopted by subsequent workers in central Peru. (Wilson 1967, Cobbing and Pitcher 1972a).

In the main, they are composed of purple andesitic lavas, although coarse pyroclastics and bedded tuffs also contribute significantly. Basalts, dacites and rhyolites are also present but in lesser amounts.

Estimates of their thickness vary considerably for, due to their extensive erosion, only minimum thicknesses can be calculated. The greatest thickness so far reported is 3,700m in the Oyon area (Cobbing, 1973). The Calipuy formation is thought to be genetically related to the Coastal Batholith (Cobbing and Pitcher, 1972a.). Some plutons intrude the volcanics while others are overlain unconformably (Cobbing, E.J., pers. comm). Unfortunately there are no fossils recorded to evaluate their age and the stratigraphic evidence is rather limited; nevertheless it is generally accepted they are of lower Tertiary age for they rest with unconformity on the Casapalca formation of upper Cretaceous age (Wilson 1963, 1967).

The Coastal Batholith

In the region of study the characteristic features of the Coastal Batholith have been described by Cobbing and Pitcher (1972 a) who describe a series of composite plutons emplaced at a high level in the crust. As shown in Fig.3, the batholith is almost entirely emplaced within volcanics of the Casma Group and Calipuy formation. It has a NW-SE trend and an average outcrop width of 50 kms. Cobbing and Pitcher (1972) portray the batholith as a series of time-separated consanguineous intrusions many of which are distinct and exhibit sharp intrusive contacts, while others show transitional features. A general calc-alkaline trend has been recognised (McCourt, W. pers. comm) showing an increase of acidity with time; thus early gabbros and diorites are cut by tonalites which in turn form the host rocks to younger granodiorites and monzogranites. The relative volumes of rock types produced corresponds to those reported by Larsen (1948) for the southern California batholith where rocks of intermediate composition predominate over acid and basic 'varieties i.e.,

	Gabbro-diorite %	Tonalite %	Monzogranite %	Granite %
Peru	15.9	57.9	25.6	0.6
California	14	50	34	2.5

A regular arrangement of the rock types prevails, diorites and gabbros flank the batholith to the west and long lenticular strips of tonalite bodies occur internally. A bilateral symmetry is introduced by the intrusion of younger monzogranite plutons along the axial part of the batholith.

As a result of the regional mapping programme a relative chronology of intrusive activity has been established which is based on contact relationships (Plate 1). On this basis some seven major 'rhythms' of the main basic-acid differentiation sequence have been recognised (Fig. 5). In addition to the major basic-acid differentiation a series of micro-rhythms are present, these are particularly well displayed in the large tonalite bodies which have their own marginal diorites and monzogranitic variants which display strong textural and compositional affinities to their 'parent tonalite'.
Cobbing and Pitcher (1972 a) attributed these variations to a secondary in situ differentiation at a high level in the crust, this auxilliary variation is superimposed on the products of the primary differentiation which occurs deeper in the crust. This hypothesis gains support from the recent geochemical studies of Taylor (1973) and McCourt (pers. comm). After establishing the chronological order of emplacement for the Huaura valley section, Cobbing and Pitcher extended their studies to adjacent areas, where, using criteria such as petrography and structural similarities, they recognised the recurrence of the same units along

PLATE.1 The Santa Rosa tonalite (background) cut by a dyke swarm which in turn is cut by the younger La mina pluton (foreground), Cerro Santa Maria Rio Huaura.

PLATE.2 The Purmacana tonalite cutting the Albian Casma group on the western margin of the batholith, Rio Fortaleza.

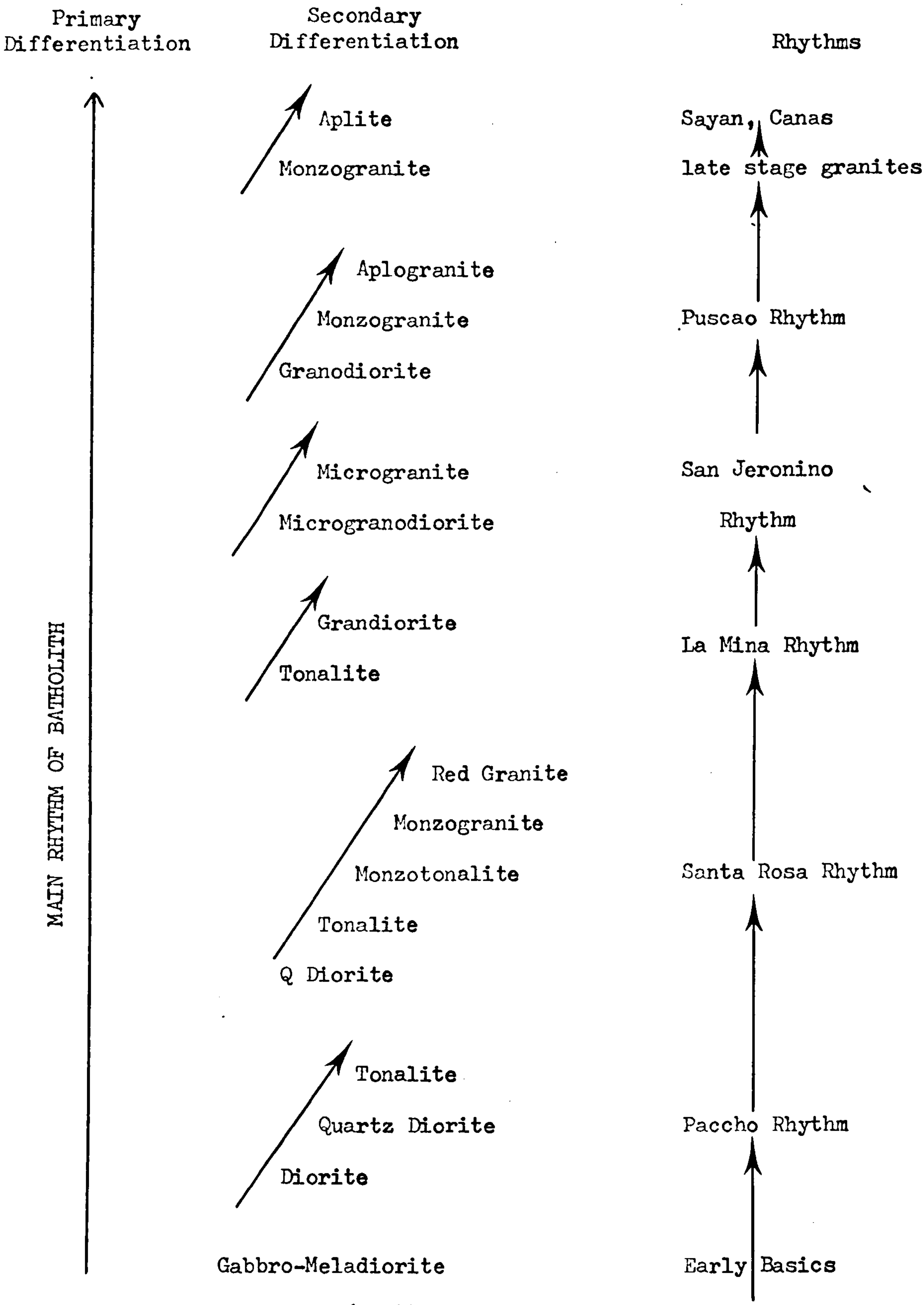


Fig.5 Diagram by Pitcher (1974) illustrating the chronological order of emplacement and rhythmic nature of the various intrusives.

a considerable length of the batholith, they state;
'each specific rock type can occur in several quite separate bodies yet still show the same time relationship to adjacent intrusions; the time of emplacement is apparently a function of magma type alone and has little to do with the particular structural relationships of the individual intrusions.'

Indeed the same rock types were recognised by Bussell (1975) in the Chimbote area, 250 kms north of the Huaura valley, where they demonstrate an identical order of emplacement a show the same petrographic characteristics to those plutons of the Huaura section. The main features of these various components of the batholith are described in a later section of this thesis.

The plutons are normally homogeneous in that internal fabrics are generally weak or absent, suggesting a passive structural situation during emplacement. Everywhere the intrusions flagrantly cross cut the country rocks (Plate 2) although as a result of the complex intrusion history of the batholith many of the younger plutons have the earlier components as their host rocks. Regional uplift of the roof rock, coupled with cauldron subsidence and fluidisation, have played important roles in the emplacement of the batholith. The attitudes of the contacts are usually controlled by fractures in the host rocks (Bussell, in press). The ascending magmas fluidised their upper surfaces and stoped off large blocks of country rock which are often preserved either as roof pendants or as septa, screens between adjacent intrusions. The mechanisms of emplacement of the batholith are discussed more fully by Myers (1975 and in press) and Bussell (1975 and in press).

The thermal effects of the batholith on its country rocks are not very obvious in the field, metamorphism is often unnoticeable particularly when adjacent plutons form the host rocks. Metamorphism is more obvious in the sedimentary envelope where it is marked by a slight recrystallisation extending a few metres, or in the case of early tonalites, hundred of metres into the country rock. Certain lithologies are more sensitive to the heating effects induced by pluton emplacement, Myers (1974) has described a distinct contact aureole to one of the tonalite units in the Huarmay area. Atherton and Brenchley (1972) have studied the aureole of the batholith in some detail and describe metamorphic assemblages which resulted from a rapid short lived heating of relatively cold country rocks. This limited contact aureole also provides evidence of a high level of emplacement which, as will be discussed later, is significant in the interpretation of the radiometric age data.

3. THE AGE OF THE COASTAL BATHOLITH

There are two main methods of approach for calculating the age of a pluton, firstly a relative age can often be ascertained by examining the stratigraphic evidence, secondly, by the more direct approach of radiometric dating of the pluton in question. Radiometric dating methods have improved over the last two decades and are now applied universally to a variety of geological problems. Nevertheless, radiometric dating is still subject to a plethora of complexities, for this reason it should where possible, be supported by an indication of the relative age based on field mapping.

An accurate assessment of the age of emplacement of a pluton is only possible using stratigraphic methods if the pluton is bracketed by two dateable horizons, preceding and post-dating the intrusion respectively. This situation is even more complex when considering multiple intrusion on a batholithic scale, here both the youngest and oldest intrusive events require defining in order to calculate the time involved in the emplacement of the whole batholith.

The youngest dateable strata intruded by the batholith are the Albian Casma group (plate 2), furthermore the aureole of the batholith is superimposed on the metamorphic fabrics produced by the Andean folding (Myers, 1975b and in press).

According to the time scale of Harland and others (1964) the Albian ranges from 106-100 m.y. this therefore reflects the maximum possible age for the batholith: for a more accurate estimate of a maximum age the age of the Andean folding would have to be known more precisely.

It is not possible to assign a minimum age to the batholith because it is not overlain by any fossiliferous strata, therefore a discussion of this problem is allied to the uncertainty in age of the Calipuy volcanics.

The Coastal batholith extensively intrudes the Calipuy volcanics(Cossio and Jaen 1967, Cobbing and Pitcher 1972a) which are of post-Santonian and probably lower Tertiary age. Over the western part of the batholith erosion has removed the Calipuy volcanics so they cannot be seen overstepping onto the recognisably older units of the batholith. Cobbing and Pitcher (1972a) and Cobbing (1973) record an early tonalite complex intruding the Calipuy volcanics which implies the batholith, or a greater part of the batholith, is of Tertiary age.

The following section is designed to examine the stratigraphic evidence for the age of the batholith and to summarise the existing published radiometric age data.

Stratigraphic Evidence for the Age of the Coastal Batholith

Observations by Jenks (1956) of the Coastal batholith cutting Turonian and Lower Cretaceous strata, and being unconformably overlain by Tertiary beds led him to assign a late Mesozoic age to the batholith. The increasing knowledge of Andean stratigraphy now enables a more accurate estimate for the age of the batholith.

The earliest tonalitic members of the batholith cut the Albian Casma group which are the youngest rocks recognised on the western margin. Furthermore the tectonic fabric produced by the deformation of the Casma group is cut by and overprinted by the contact aureole of

the batholith (Myers 1974, 1975b). At present there is some doubt concerning the age of the early gabbroic rocks in the Haural area, their complicated textures suggests they are coeval with the folding of the Casma group (Regan 1975, Bussell 1975).
Fellow workers in Peru have observed the Calipuy volcanics resting unconformably on one of the early tonalite complexes (Taylor, W.P. pers.comm.). Thus the stratigraphic evidence is somewhat ambiguous and it is impossible to come to any definite conclusion concerning the minimum age of the batholith. The preliminary conclusions on the age of the batholith are tabulated below:

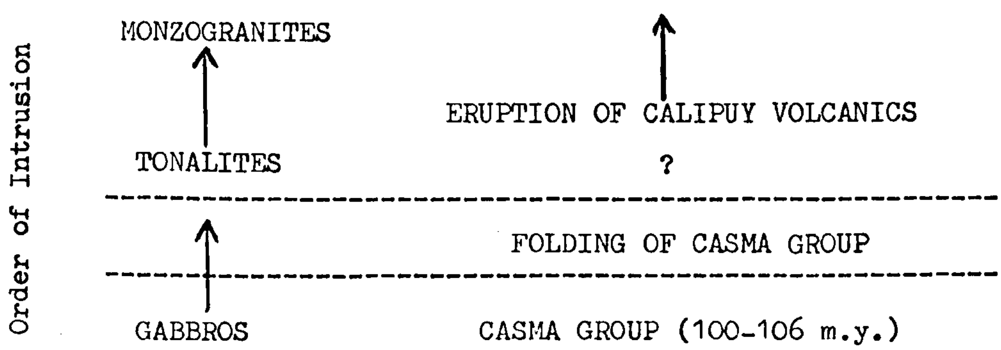


Table 2. Summary of stratigraphic evidence for the age of the Coastal batholith.

<u>Published Radiometric Age Data from Peru</u>

A series of radiometric age determinations form a valuable contribution to the reconaissance geology of an area but it is only in the last decade that such studies have been employed in Peru. Unfortunately not all the results have been published but those available have been compiled for discussion in the following section.

The earliest recorded age determinations from Peru are by the k/Ar method on plutons of the Coastal batholith which are genetically associated with the copper mineralisation at Michiquillay, in northern Peru, and Toquepala near the Chilean border (Laughlin et.al, 1968). The aim of this dating programme was to attempt to recognise a time-space congruency between magmatism and copper mineralisation, this had already been demonstrated in the Basin and Range Provinces of the U.S.A. (Mauger et.al, 1965 and Damon et.al 1966). Laughlin and his co-workers reported three k.Ar ages from these two widely spaced localities; a diorite associated with the Toquepala deposit yielded an age of 59 m.y. on a biotite concentrate. The mineralisation of Michiquillay was dated more directly using mica separated from the sulphide deposit which gave a result (21 m.y.) markedly discordant with the associated granodiorite stock (46 m.y.) from which a hornblende separate was dated. They attributed this disparity between the age of emplacement of the stock and the mineralisation to be due to slow cooling of the pluton. On the basis of this extremely limited data Laughlin et.al. proposed the likelihood of a mid-Tertiary metallogenetic epoch in Peru, in support of the lead isotope work of Kulp and others (1957).

Additional results from the Coastal batholith by Giletti and Day (1968), on biotites separated from rocks of granodioritic composition, also gave Tertiary ages (65 and 33 m.y.). The authors, although suggesting an Eocene or Palaeocene time of emplacement for the batholith, did not discount the possibility of a Cretaceous emplacement age when the duration of cooling of an intrusion is considered with respect to the temperature of closure of mica lattices to argon diffusion.

By far the most comprehensive review of age determinations from Peruvian intrusive rocks is by Stewart, Evernden and Snelling (1972, 1974). These authors present over sixty reconnaissance age determinations using the k.Ar method which are supported by a few Rb-Sr determinations on micas and potassium-feldspars.

Twenty six k.Ar mineral ages from rocks of the Coastal batholith are presented by Stewart et.al. and are evenly distributed between 102 m.y. and 13 m.y. with a general decrease in age in a northeasterly direction across the batholith. Since all the results are by the k.Ar method Stewart and others (1974) specify that the apparent younging may not necessarily imply a migration of intrusive activity across the batholith.

The maximum age recorded corresponds to a monzogranite pluton, which outcrops on the western margin of the batholith immediately inland from Lima, from which an age of 102±1 m.y. was obtained based on the weighted mean of concordant k.Ar and Rb.Sr age determinations. This is the first direct evidence of a Cretaceous age for part of the batholith and is of great significance when considering the age of the Casma volcanics which it intrudes. A total of five samples yielded concordant ages from cogenetic biotite-hornblende pairs (76,65,43,26 and 13 m.y.) which were interpreted as crystallisation ages by Stewart and others (1974). The significance of dating cogenetic mineral pairs are discussed at some length in a later section.

The youngest age reported (13 m.y.) is from a small satellitic stock which outcrops approximately 30 kms to the east of the main batholith outcrop, in the area examined in this thesis.

Stewart et.al. also describe K.Ar age determinations from southern Peru around Arequipa, where the batholith intrudes the Paracas gneiss. Dates from the batholith in this area fall into two groups one at 77 m.y. and the other at 55 m.y. Preliminary age determinations from the Cordillera Blanca batholith range from 9.7 to 2.7 m.y. However, supporting Rb.Sr age determinations presented by Stewart et.al. tentatively implies this batholith may be partly Lower Miocene in age.
Two peralkaline stocks from Pucallpa in eastern Peru have also yielded Pliocene K.Ar ages on biotite separates (Stewart 1971).

Probably the greatest significance of these preliminary results from the Coastal batholith is the considerable span of time suggested for its emplacement (80 m.y.). This period could possibly be extended to 100 m.y. if the emplacement of the Cordillera Blanca batholith is also taken into consideration.

In the following section the author describes the main aims of the present research in the light of the geological setting.

4. AIMS OF THE RESEARCH

The fundamental aim of this thesis is to study the chronology of emplacement of the Coastal Batholith by radiometric dating of samples collected from the constituent plutons.

The reconnaissance age determinations of the batholith which have been summarised in the preceding section implies that a period of 80 m.y. could be involved in its emplacement. Nevertheless, additional data is required to determine the nature of this emplacement, particularly whether it has involved a continuous process or intrusion of a more episodic nature as reported in other Circum-Pacific batholiths by Evernden and Kistler (1971) and Lanphere and Reed (1973).

The author has attempted to resolve this problem by carrying out a detailed radiometric dating programme in the well documented segment of the batholith between the Rio Chancay and Rio Fortaleza. In this region careful sampling of mapped plutons ought to permit a more meaningful interpretation of the radiometric age data. Furthermore, because of the excellent geological control it could be possible to examine the limitations of the dating technique which is employed.

Geochronology may prove to be a useful tool for defining the duration of the major 'macro-rhythms' recognised in the differentiation sequence of the batholith. It was also hoped that the time-relationships of the associated secondary rhythms would also be resolvable.

As a subsidiary to these main themes the author decided to expand the area of study to incorporate the following problems.

Firstly, to determine reconnaissance 'ages' from the San Nicholas batholith and secondly, to add new data from the Cordillera Blanca batholith. These should allow a further examination of the hypothesis of eastward migration of intrusive activity from the leading edge of a plate. Co-workers in Chile (Farrar et. al. 1970) have proposed an eastward shift of intrusive activity away from the trench and this is rather tentatively supported by the geographical distribution of K.Ar ages reported by Stewart, Evernden and Snelling (1974).

Problems of a more specific nature, associated with the Coastal batholith, which could be resolved by the application of radiometric dating are :-

1) Examination of the time relations between the batholith and its volcanic envelope.
2) A comparison of the timing and duration of activity of the four centred acid complexes which occupy a medial position in the batholith, in the study area.
3) To date the seemingly identical magma types which occur in separate plutons, of the same 'relative age', over a considerable length of the batholith.
4) To determine the age of the main dyke swarm which is believed to be synplutonic with some intrusions.

Many of these aims necessitated visits to collect samples from key localities outside the main area of study.

Sampling of the Plutons

The main purpose of the two field seasons was to collect representative samples from the major units of the Coastal batholith. The fieldwork was centred on traverses along the four main river valleys (See Fig.3) which permit access to the well documented part of the batholith. Here the excellent three-dimensional exposures made possible a carefully controlled sampling programme. Where possible, road cuttings, and screes formed by earthquake action, were used to provide fresh samples. Samples of approximately 1-2 kgs. in weight were routinely collected, this amount proved to be adequate for mineral separation with sufficient sample remaining for reference purposes. In the previous section it was shown that the early tonalitic units of the batholith are by far more voluminous than the relatively small, younger monzogranite plutons, for this reason it proved necessary to consider this factor in the sampling. Thus, samples of the large tonalite bodies were collected from various localities throughout their outcrop in order to understand and mitigate the reheating effects of any younger plutons. All components of the main basic-acid differentiation (See Fig.5) were sampled in such a way as to carefully avoid the influence of younger plutons (see next section).

This careful geological control of the sampling used in the Coastal batholith contrasts with the reconnaissance sampling adopted for the Cordillera Blanca and San Nicholas batholiths, where freshness of the rock formed the main criterion for sampling.

PART TWO

THE POTASSIUM-ARGON METHOD AND ITS APPLICATION TO THE DATING OF PLUTONIC ROCKS - SOME PRELIMINARY FINDINGS

1. THE POTASSIUM-ARGON METHOD

Introduction - Choice of the method

The last few decades has seen remarkable progress in geochronology particularly its application to an infinitely wider range of geological problems. Much of this progress is largely due to the refinement of analytical techniques, especially mass spectrometry and ultra-high vacuum technology.
At the present time four dating methods are in routine use, these are; 1) the U-Pb method, 2) the Rb-Sr method, 3) the K-Ar method and 4) the Ar-Ar method.

The K-Ar method has been used successfully for the dating of batholiths in Circum-Pacific North America, the previous dating projects on Peruvian granitoids have also yielded satisfactory results by this method. The principle advantages of the K-Ar method for a project of this type can be summarised:

1) It can be applied to most potassium-bearing silicate minerals.
2) It is suitable for dating very young rocks; cases have been reported of potassium rich minerals yielding reproducible ages as young as 10,000 years b.p. (Dalyrymple, 1968).
3) The resolution of the method enables single geological events to be distinguished to within 5 m.y. for rocks of Mesozoic and Tertiary age.
4) The method is relatively cheap and very rapid which is important when large numbers of age determinations are required.

Naturally the method has its limitations, for example, it is common for the 'clock' to read incorrect geological time particularly when the system has been thermally or physically disturbed. Fortunately this limitation is partly advantageous because it proves to be valuable for deciphering the thermal history of an area.

In recent years the Rb-Sr whole rock method has moved into the forefront for dating the age of emplacement of plutonic rocks (see review by Faure and Powell, 1972). However, the reliability of this method is more limited for rocks of Tertiary age, furthermore, the selection of suitable material is critical. The low Rb/Sr ratios which are characteristic of Peruvian granitoids (Snelling and Stewart, 1972 W. McCourt, pers.comm.) render this method to be impractical for the aims of the present research.

All the new age determinations presented in this thesis are by the K-Ar method, the method and the problems associated with the interpretation of K.Ar ages of intrusive rocks, form the theme of the following section. It is hoped this will provide the reader who is not familiar with K-Ar dating a broader insight into the many factors which have to be considered before K-Ar age determinations can be meaningfully interpreted.

The analytical procedures which were adopted, are outlined in Appendix 2.

(a) THE POTASSIUM-ARGON AGE EQUATION

The K-Ar method is based on the decay of potassium to argon by electon capture accompanied by gamma ray emission.

The method is extremely well documented and the reader is referred to the monographs of Schaeffer and Zahringer (1966) and Dalrymple and Lanphere (1970) which trace its historical development and modern applications.

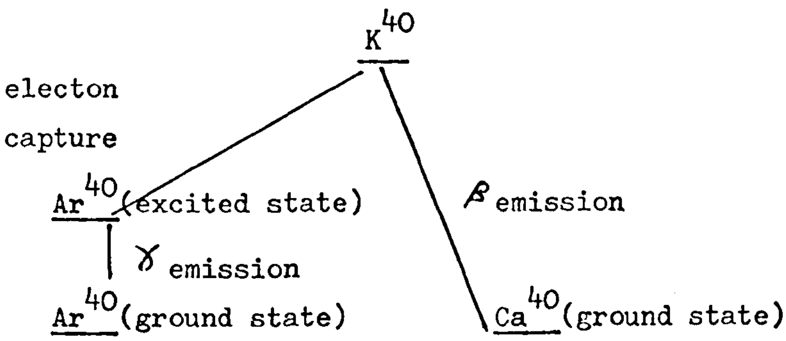
Naturally occurring potassium consists of three isotopes with the following atomic abundances (Nier, 1950):

K^{39} 93.08 atom %

K^{40} 0.0119 atom %

K^{41} 6.91 atom %

K^{40} is the unstable isotope and exhibits a branching mode of decay to Ar^{40} and Ca^{40};



This branching decay loads to two possible methods of dating, firstly, using the Ca^{40} daughter product and secondly the Ar^{40} product. Several attempts have been made to utilise the former but have not met with much success. The reason for this is that of the six naturally occurring isotopes of calcium Ca^{40} is by far the most abundant making it difficult, if not impossible, to accurately measure the small radiogenic increment which is swamped by the ^{40}Ca included at the time of formation.

When a radioactive isotope undergoes decay the rate of decay is proportional to the number, N, of nuclei present at any time t., i.e.

$$\frac{-dN}{dt} = \lambda N$$

where λ is the decay constant (the probability that an atom will decay in unit time). Intergrating this expression to obtain N gives:

$$N = No e^{-\lambda t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where No is the original number of nuclei present.

This equation is not very useful for calculating ages because No cannot be determined without knowing t and vice-versa. However, in a simple decay system each parent atom gives rise to one daughter atom, D, so that at any time:

$$No = N + D \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

Providing that the numbers of these atoms are only changed by radio-active decay, i.e. none are lost or gained by any other means, substituting equation (2) into equation (1) gives:

$$D = N\,(e^{\lambda t} - 1)$$

solving this for t gives;

$$t = \frac{1}{\lambda} \ln\left(\frac{D}{N} + 1\right)$$ the general age equation.

The dual decay scheme of K^{40} slightly modifies the general age equation to;

$$t = \frac{1}{\lambda e + \lambda \beta} \log_e \left[\frac{Ar^{40}}{K^{40}} \left(\frac{\lambda e + \lambda \beta}{\lambda e} \right) + 1 \right] \ldots\ldots\ldots\ldots (3)$$

Where λ_β and λe are the decay constants for β emission and electron capture respectively.

The decay constants generally used are those recommended by Smith (1964);

$$\lambda_\beta = 4.72 \times 10^{-10} \text{ year}^{-1}$$

$$\lambda e = 0.584 \times 10^{-10} \text{ year}^{-1}$$

The half life of K^{40} is given by the expression

$$T_{\frac{1}{2}} = \frac{\ln 2}{\lambda} = \frac{0.6931}{\lambda} = 1.31 \times 10^{9} \text{ years}$$

In order for the potassium-argon age equation to give a reliable estimate of the age of the rock, or mineral, the system must have remained closed to the diffusion of parent or daughter isotope since its time of formation.

2) GEOLOGICAL ERRORS IN POTASSIUM-ARGON DATING

The errors quoted after each k.Ar age determination (see Appendix 3) only provide a measure of the experimental precision and ideally ought to be accompanied by some data stating the criteria used in defining these parameters. Far too often in geological literature 'apparent' K.Ar ages are quoted as being 'absolute' even though many geological parameters have to be considered before the true significance of the age can be assessed.

In the following section the author examines the main geological factors which can influence the K.Ar clock and cause it to read 'incorrect' time. One of the most fundamental problems in this context involves a consideration of the diffusion behaviour of both potassium and argon in rocks and minerals. If any loss or gain of parent or daughter isotope has occurred the resulting age may provide misleading information concerning the age of the sample. For this reason it is necessary for the geologist to assess the significance of each individual result in the light of both field and petrographic evidence. Miller and Fitch (1964) have summarised the main factors which may lead to anomalous ages;

1) Low, due to a later geological event producing argon loss.
2) Low, due to argon loss related to poor retentivity of the rock or mineral.
3) High, due to anomalous initial potassium isotope ratio or due to argon-40 capture.

Discrepantly High Ages

The two main factors which generally contribute to ages that seem too high are, the loss of potassium-40 or the presence of extraneous argon.

i) Potassium Loss

Any migration of potassium in minerals would probably lead to a disruption of the crystal lattice which would be identifiable by a thorough petrographic examination, a case in point is the alteration of biotite to chlorite. According to Engals and Ingamells (1970) in order for a biotite to be pure it must contain over 7% K_2O, any lower value can usually be attributed to chlorite content. Kulp and Engels (1963) were able to remove up to 80% of the original potassium from a biotite without any significant change in the apparent age, they concluded that potassium loss was a layer by layer process which is paralleled by a loss of the associated argon.

Evernden and Kistler (1970) examined the effect of chlorite content on biotite books separated from the Cathedral Peak granite of the Sierra Nevada batholith. Their findings also showed a high degree of tolerance before any radical change of the apparent age was noticed. Unlike the case documented by Kulp and Engals, Evernden and Kistler (1970) noted a slight increase of age with decrease of potassium content which they cited as direct evidence that many argon atoms are forced into non-potassium lattice sites by recoil effects, at the time of disintegration of the K^{40}.

Whatever the cause of these features it suffices to say that a reasonably high degree of chemical alteration can be tolerated, at least in the micas, before the age is noticeably affected. This is certainly borne out by the data presented later in this thesis. However, where other minerals lie in this respect is still uncertain, although Zartman (1964) has shown that weathered hornblendes also give reliable ages. The main criterion for avoiding anomolous results which could arise from loss of potassium, is to select reasonably fresh material for dating.

ii) Extraneous Argon

One of the most fundamental assumptions in K,Ar dating is that all the argon in the sample has been produced by in situ decay of K^{40}, or is present as an atmospheric contaminant. The proportion of atmospheric contaminant can easily be evaluated (see Appendix 2), all the remaining argon-40 is interpreted as being radiogenic and the age is calculated on this basis. However, several workers have reported anomalously old ages from minerals, which have been attributed to the presence of extraneous argon (see Dalyrymple and Lanphere 1969 p.121). Damon (1968) has outlined the difference between excess $Ar.^{40}$, which is argon incorporated into minerals by processes other than radioactive decay, and inherited argon, which is caused by contamination by older material.

The major source of inherited radiogenic argon is the incorporation of older, contaminating material in the samples. This may be in the form of xenoliths or material inadvertantly introduced in the laboratory during sample preparation. Xenoliths in plutonic rocks are relatively unimportant, they present more of a problem in volcanic rocks where the rapid cooling has not allowed sufficient time for the degassing of the argon in the xenoliths (see Dalyrymple 1964 and Sharp, 1968). On the whole inherited argon is relatively unimportant and can be eliminated by careful sample preparation, for example, xenoliths are avoided during sampling and laboratories and equipment are cleaned thoroughly prior to use.

Excess argon on the other hand presents more of a problem. Very little is known of the mechanism by which argon enters, or is entrapped

by the mineral. Damon and Kulp (1958) have suggested the argon diffuses into or is occluded by the mineral during its formation.
Many of the examples of excess argon recorded apply to rocks of deep-seated origin where high confining pressures inhibit the release of residual gases. The partial pressure of argon in the magma must play an important role in this context. This is verified by the general absence of excess argon from most extrusive igneous rocks, where outgassing during cooling presumably liberates any excess argon.

A reliable method of determining whether a sample contains excess argon is to calculate its apparent age, assuming that all the argon present is radiogenic (and atmospheric), and to compare this with other dates from coexisting rocks and minerals and the available stratigraphic evidence. Excess argon is particularly noticeable in potassium poor minerals where it may contribute significantly to the total amount of argon-40 measured. Conversely, its effect on potassium rich minerals is less obvious due to the greater concentration of radiogenic component. Thus if two cogenetic minerals of differing K contents yield concordant ages this probably discounts the possibility of excess argon. However, this does not necessarily imply that discordancy is a sole function of the presence of excess argon (see next section).

Recently the introduction of K.Ar isochron methods have proved to be useful for examining the initial argon contents of co-magmatic suites of rocks and minerals (Hayatsu and Carmichael, 1970).

Excess Argon at a high level in the crust

It is important to evaluate the possibility of occurrence of excess argon for each geological environment in which K.Ar studies are undertaken. In the case of the high level environment of the Coastal batholith excess

PLATE.3 The Sayan monzogranite pluton in contact with a roof pendant of andesite on Cerro Yeta Negra east of the village of Sayan,

argon seems improbable, especially when the main mechanism of intrusion involves gas-coring processes which would effectively lead to outgassing of the ascending magmas.

Only one example of excess argon has been discovered in this study and arises from a situation where the residual gases became confined and crystallised in the roof zone of a monzogranite pluton.

The pluton in question is the Sayan monzogranite which is in contact with a roof pendant of horizontally bedded andesitic volcanics on Cerro Yeta Negra, 8kms east of the village of Sayan (see Plate 3). Here a 2 metre diameter vug was observed adjacent to the roof; pegmatitic quartz occurs in the centre of the cavity and is surrounded by a peripheral development of orthoclase feldspar. Both minerals were dated and the results are tabulated below, the presence of excess argon in the quartz is obvious.

Sample A19	k%	% Ar atmos	Ar^{40} rdg x 10^{-6} scc/gm	Age m.y.
Quartz	0.007	80.2	0.54889	1,345 + 38
Orthoclase	9.616	59.9	16.3009	42 + 1

Table 3. Excess argon in quartz from the Sayan monzogranite.

Quartz has an extremely low potassium content and being late in the crystallisation sequence ought to be a good indicator of excess argon. The potassium value of the quartz was obtained using flame photometry; although there is some doubt concerning the reliability of the method for such low concentrations (i.e. $<$ 1% k) it is felt that the method is adequate for showing the presence of excess argon.

The argon is thought to be concentrated in fluid inclusions within the quartz which are visible even in hand specimen, A phenomenon which has also been described by Rama and others (1965). Evernden and Kistler (1970) have dated quartz from five granitoids in the Sierra Nevada batholith, their results were in agreement with, or younger than co-existing mica which proved the absence of excess argon.

It seems reasonable to assume that the quartz and feldspar in the vug crystallised under the same partial pressure of argon, consequently, the feldspar ought to contain an increment of excess argon. Unfortunately the true age of the Sayan pluton is open to some debate and is discussed at length later in the thesis. A biotite - orthoclase pair, separated from the main monzogranite facies some 300 metres below the vug, yielded a concordant age of 31 m.y. (sample A50). On the assumption that this represents the emplacement age of the Sayan pluton then the pegmatitic orthoclase contains approximately 3.8×10^{-6} scc/gm of excess Ar^{40}, compared with a concentration of 5.84×10^{-7} scc/gm in the quartz. This lower concentration in the quartz is probably due to the incomplete fusion of the sample during the analysis.

All other evidence precludes the occurrence of excess argon in the Coastal and Cordillera Blanca batholiths, which is in accordance with a high level of emplacement and correspondingly low confining pressures on residual gases. The total body of evidence can be summarised;

1) The stratigraphic evidence provides a valuable check of any grossly anomalous ages.

2) The observed chronological order for intrusion of the plutons is, on the whole, supported by the radiometric age data.

3) Cogenetic mineral pairs of differing K contents are in reasonable

agreement, when diffusional loss of argon is taken into account.

4) Age data from co-magmatic suites of samples do not give positive intercepts on the conventional Ar^{40} vs K^{40} isochron.

Factors which result in Discrepantly Low Ages

Following the decay of K^{40} the radiogenic argon is trapped mechanically in the mineral (in the K lattice site) and diffusion may occur, resulting in a departure from an 'ideal closed system'. This preferential loss of argon leads to ages which are anomolously low.

Dalyrymple and Lanphere (1969) have listed several factors which contribute to the loss of argon from minerals in geological environments.

1) The inability of a mineral to retain argon at normal temperatures and pressures.
2) The complete or partial melting of a rock to form a new igneous body, with total loss of already generated argon.
3) Metamorphism.
4) Weathering and alteration which can cause complete argon loss by diffusion, although more commonly some is retained.
5) The crystallisation of soluable salts by ground water action.
6) Prolonged reheating at temperatures of a few hundred degrees.

Samples which have undergone metamorphism, weathering, alteration or physical damage can usually be identified fairly easily and where possible are avoided for K.Ar dating. Conversely, very low grade metamorphism and reheating, due to the emplacement of a younger intrusion or due to depth of burial, are often difficult if not impossible to recognise because they may not induce any visible mineralogical or textural changes in the rock. This is especially true for the Coastal batholith of Peru where contact metamorphism, although recognisable in the sedimentary envelope, is not obvious when older plutons form the host rocks. Thus the reheating effects induced by younger plutons form the main criterion for discrepantly low ages from minerals in batholithic environments; where a prolonged multiple-intrusion history can produce a broad spectrum of apparently meaningless ages.

Before taking this discussion any further, it is important to understand the time when the K.Ar clock is actually set for a plutonic rock. This occurs somewhere between the time of solidification and the time at which the temperature is low enough to prevent any significant diffusion of argon (see Fig.6); this temperature is frequently referred to as the blocking or closure temperature. If the pluton in question is then reheated by the intrusion of a nearby, younger pluton then the measured age could fall anywhere between the age of the two plutons (see Fig.7).

A careful consideration of the argon retention properties of the different minerals is therefore critical in the interpretation of the age patterns.

A lot of research has been directed towards the assessment of the argon retention properties of minerals. There are two approaches to this problem; firstly, by experimental diffusion studies carried out in the laboratory, and secondly by studying minerals which have lost argon in natural environments.

i) Laboratory Studies of Argon Diffusion

It was initially hoped that experimental argon diffusion studies would result in a classification of minerals based on their ability to retain argon. Unfortunately this approach relies on a mathematical model which relies on a number of fundamental assumptions concerning the nature of the diffusing environment. For example, it is normally

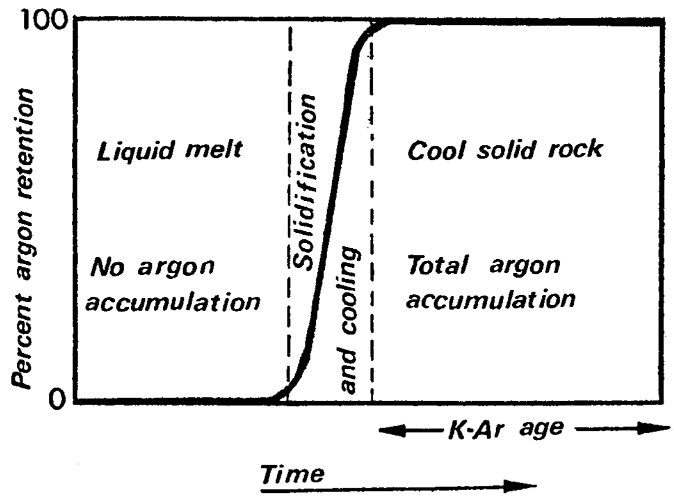


FIG.6 ARGON ACCUMULATION IN AN IGNEOUS ROCK
After Dalyrmple and Lanphere (1969)

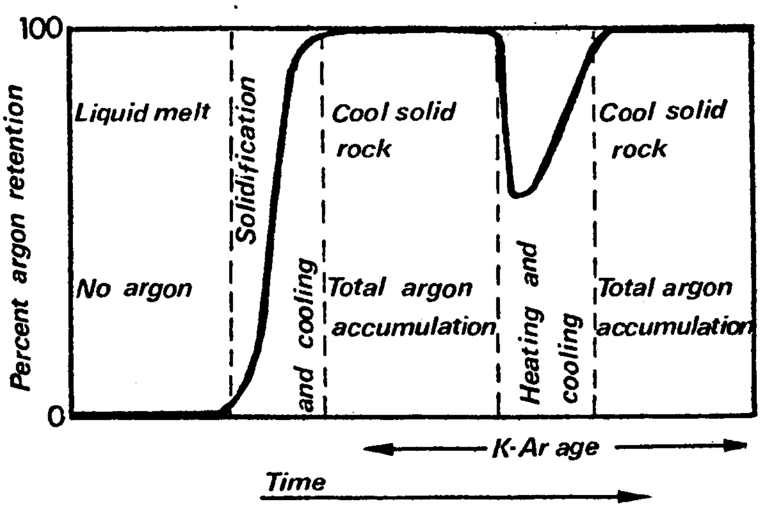


FIG.7 ACCUMULATION OF ARGON IN AN IGNEOUS ROCK
SUBJECTED TO A SUPERIMOSED HEATING EVENT

assumed that diffusion is independant of everything except temperature, though this probably varies with such factors as pressure and the nature of the medium. Evernden and others (1960) have shown that argon diffusing from glauconite, when heated under vacuum, was significantly greater than when heated in the presence of water vapour.

Another major error is introduced in the method of heating which is adopted, usually the mineral has to be raised to temperatures in excess of 300°C to liberate a measurable quantity of argon. The results are then plotted graphically and extrapolated back by several orders of magnitude to correspond to the lower temperature ranges. Mussett (1970) has pointed out that high temperature diffusion may be due to movements and defects in the crystal lattice which could account for the large variation of diffusion coefficients from similar mineral species.

The main uncertainty in the experimental approach to argon diffusion lies in the disparity between the artificial environment of the laboratory and the natural diffusing environment of minerals in their host rocks. Nevertheless, despite these uncertainties the relative argon retentivities of minerals, derived experimentally, seem to correspond fairly well with examples found in favourable natural environments.

In the writer's opinion, careful sampling can often eliminate, or at least restrict, the possibility of reheating of plutons to the very high temperatures at which most diffusion models are applicable. What is perhaps more critical for the present study is an appraisal of the diffusion behaviour of argon in minerals which have been heated, and maintained at moderate temperatures ($<$ 200°C) for considerable periods of time. Such would be the case if a pluton crystallised beneath a thick blanket of country rocks or if prolonged reheating by younger intrusions occurred. It is therefore more beneficial to refer to natural environments because these conditions cannot be entirely satisfied in the laboratory. Fortunately many geological examples have been cited which help elucidate the argon retention properties of minerals, some of which are described in the following section.

Finally, for further details concerning the models and methods used in the experimental approach to argon diffusion, the reader is referred to the reviews by Fechtig and Kalbitzer (1966), Moorbath (1967) and the general critique by Mussett (1970).

ii) Argon diffusion in Natural Environments

Hart (1964) examined the thermal effects of a Tertiary quartz-monzonite stock on the K.Ar clocks of minerals separated from Pre-Cambrian high-grade gneisses, schists and amphibolites, into which the stock was emplaced.

The only mineralogical change caused by the intrusion was the inversion of microcline to orthoclase near the contact. Conversely the thermal effect of the pluton could be detected by low K.Ar ages on fine-grained biotite over 7 kms from the contact. From this study Hart (1964) established a sequence for the order of retentivity of radiogenic isotopes applicable to the Rb-Sr as well as the K.Ar dating method (see Fig.8), this can be summarised;

Hornblende K.Ar > Feldspar Rb-Sr > Muscovite Rb-Sr > Muscovite K.Ar > Biotite Rb-Sr. > Biotite Rb-Sr > Biotite K.Ar > Feldspar K.Ar

Hart also included a quantitative interpretation of his results and computed the blocking temperature of Hornblende (the temperature at which argon diffusion effectively stops) to be about 450° - 500°,

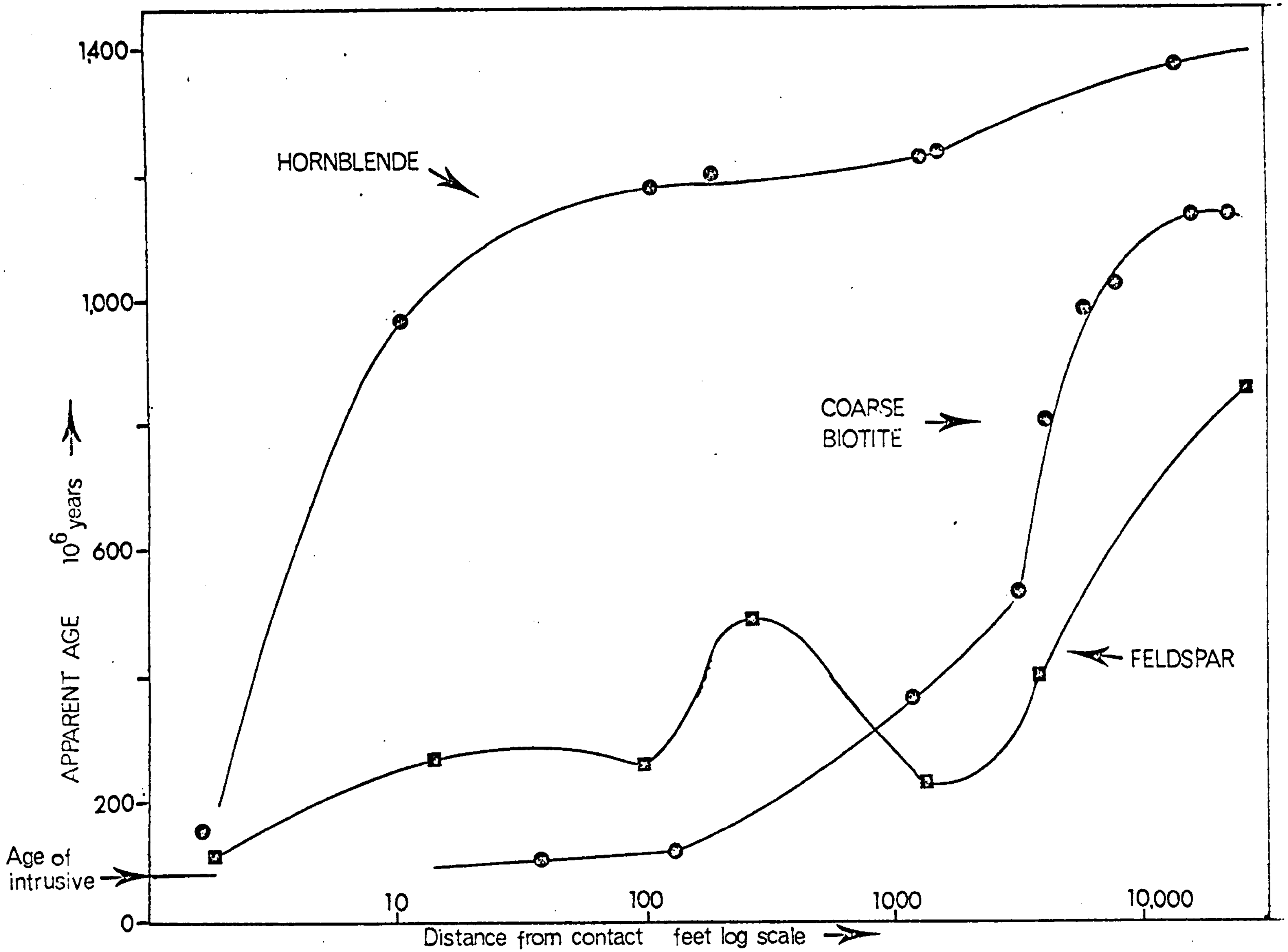


FIG.8 Changes in ages of minerals from Pre-Cambrian schists and gneisses as a function of distance from an intrusive contact, after Hart (1964).

alternatively biotite, having a lower retentivity, begins to close at 430°C and is completely closed at 230°C. These conclusions have also been supplimented by similar studies (Aldrich et.al. 1965 , Kistler et.al. 1965 and Hanson and Gast 1967).

This work has resulted in a clearer understanding of the genetic significance of K.Ar ages. For example, it is now generally accepted that concordant ages obtained from cogenetic minerals of differing argon retentivities indicates rapid cooling between the temperature ranges encompassed by their blocking temperatures. Evernden and Kistler (1970) accepted Hart's work and interpreted concordant K.Ar ages on biotite-hornblende pairs to be the result of rapid cooling between 600°-200°C which corresponds to the age of emplacement of the pluton.

Unfortunately the thesis of Hart (1964) only considered an example of rapid heating followed by relatively rapid cooling because the Eldora stock was emplaced to within 1km of the surface. It is quite probable that a slower regional cooling (i.e. emplacement at greater depth) may have a significant effect on the blocking temperatures of minerals. Hanson and Gast (1967) have outlined the difference between argon loss caused by slow cooling (i.e. pluton emplacement) and the intrusion of a dyke where very high temperatures are required to cause argon loss from the country rocks.

Hurley and others (1962) have shown depth of burial to be an important consideration in the closure of minerals to argon diffusion. They reported Pliocene K.Ar ages from micas which were formed during a Jurassic metamorphic episode. Hurley and his co-workers attributed the younger ages to burial of the schists at a depth of 3kms for over 100 m.y., the younger ages dating the uplift, by faulting, to a temperature

Depth in Kilometers	Ambient Temperature Centigrade	Never Uplifted	Long Delayed Uplift followed by Rapid Uplift	Slow Uplift & Erosion	Immediate Rapid Uplift & Erosion
4	230°	Concord	Concord	Concord	Concord
8	250°	Discord	Discord	Discord	Concord
12		No age recorded	Concord	Discord	Concord
14					

Table 4. Chart showing relation of depth of emplacement and rate of uplift and erosion to hornblende-biotite discordance. The geothermal gradient is assumed to be 50°C/km. Rapid erosion means 1 km/million years or more. After Krummenacher et.al. (1975).

at which the radiogenic argon is effectively retained. More recently evidence presented by Suggate (1963) infers a much greater depth of burial in the order of 15kms and Mussett (1970) calculated the temperature of the schists at this depth to be 400°-500°C.

Krummenacher and others (1975) utilised the data of Hart and using a geothermal gradient of 50°C/km and a denudation rate of 1.km per m.y. derived a series of cooling models for a pluton showing the dependancy of hornblende-biotite concordance on the depth of emplacement (Table 4). According to their model the K.Ar ages on biotite-hornblende pairs ought to be concordant, and this concordancy should correspond to the age of emplacement and crystallisation, for plutons emplaced at a high level in the crust i.e. less than 4kms.
It is therefore important to assess the depth of emplacement of a batholith in quantitative terms before attaching any significance to the K.Ar ages. The author has already made frequent reference to the high level emplacement of the Coastal batholith in the introductory part of this thesis, in the following section some of the evidence for assessing the depth of emplacement is summarised.

The Depth of Emplacement of the Coastal Batholith

Atherton and Brenchley (1972) examined the contact aureole of the Coastal batholith in some detail and on the basis of the spatial and textural patterns of the metamorphic mineral assemblages concluded that the aureole was heated rapidly and cooled quickly so the metamorphic minerals did not have time to equilibriate. With regard to PT conditions during thermal metamorphism the total mineral assemblage indicated a maximum temperature of 530°-600°C was attained at 1-2kbs pressure (hornblende-hornfels facies).

Myers (in press) arrived at a similar conclusion to Atherton and Brenchley and on stratigraphic grounds estimated the batholith to have crystallised within 2-3kms of the surface.

Under these emplacement conditions the K.Ar ages of cogenetic hornblende-biotite pairs ought to be concordant and this should reflect the age of emplacement and crystallisation. Furthermore individual ages on minerals of low argon retentivity (i.e. biotite, feldspar) should also approximate the age of emplacement providing the system concerned has remained undisturbed since its emplacement.

3. PRESENTATION OF DATA

Over 134 new k.Ar age determinations have been completed and are compiled for discussion in the remaining part of this thesis. A complete list of the age determinations can be found in Appendix III and brief petrographic descriptions and details of the sample localities are presented in Appendix IV. For convenience the author discusses the results in the order of their relative chronology, adopting the terminology used by Cobbing and Pitcher (1972a). The text is supplimented by diagrams which show the sample localities, and tables of the results, of all the separate units of the batholith. Reference is frequently made to the 'Geological Society Phanerozoic time-scale' (Harland and others, 1964), the relevant parts of which are summarised in table 5.

For the purpose of this thesis a critical value test is used as an objective criterion for comparing the precision of mineral ages. Reed and Lanphere (1974), in a similar study adopted the F test outlined by McIntyre (1963), to distinguish between concordant and discordant mineral pairs. The same test is adopted by the author in this thesis.
For co-existing mineral pairs to be discordant they must differ by more than the critical value, at the 95% confidence limit, where:

$$CV = 1.96 \left(\frac{\sigma}{n} + \frac{\sigma_2}{n_2} \right) \frac{1}{2}$$

Where σ = standard deviation of the 'age'

n = number of determinations

When cogenetic mineral pairs are concordant, within the limits defined by the F test, a preferred age is calculated from the weighted mean of the individual mineral ages. This C.V. test is also used to resolve any age differences between the separate intrusive phases of the batholith. For the minerals dated in the present study σ is commonly between 2 and 3%. For rocks of 100 million years old, this means that the apparent age difference must be greater than 5.4 - 8.3 m.y. respectively, before it is possible to detect any real difference between the mineral ages.

K-Ar Isochrons

When a number of age determinations are obtained from a co-magmatic suite of samples, if sufficient data is available, they can be plotted on an isochron diagram. The two types of k.Ar isochron in common use are:

(a) The Ar^{40} vs K^{40} isochron

(b) The Ar^{40}/Ar^{36} vs K^{40}/Ar^{36} isochron

The former is a plot of radiogenic argon content against K^{40} or K%. In the ideal case all the points should plot on a straight line passing through the origin. The age is proportional to the slope of the line which dates the closure of the system to argon diffusion, this may or may not approximate the time of emplacement of the pluton in question. The isochron is represented by the equation

$$\left(Ar_m^{40} - Ar_A^{40}\right) = \frac{\lambda_e}{\lambda} K^{40}\left(e^{\lambda t} - 1\right) + Ar_0^{40}$$

where $\left(Ar_m^{40} - Ar_A^{40}\right)$ = Ar^{40} radiogenic

Ar_o^{40} = initial Ar^{40}

According to Harper (1970) if the points fall on a line and give a positive intercept then all the samples contain equal proportions of

extraneous argon. Conversely, if the slope has a negative intercept this approximates to the amount of diffusional loss of radiogenic daughter isotope. Moreover, if the points from a co-magmatic suite having differing K contents do not define an isochron then the basic assumptions are not valid for that particular set of samples.
The slope and validity of the isochron is computed and assessed by linear regression treatment adopting the method outlined by Brooks et.al. (1972). The Ar^{40} vs K^{40} isochron is used widely throughout this thesis mainly as a means of observing more clearly the behaviour of the radiogenic argon in a suite of samples.
If a suite of samples define an isochron, then the isochron age represents a weighted mean of the individual samples, and may be used as a mean age of the pluton concerned.

The second type of isochron, the Ar^{40}/Ar^{36} vs K^{40}/Ar^{36} isochron, is based on the conventional Rb-Sr isochron and permits a variation in the initial Ar^{40}/Ar^{36} ratio. The isochron equation as defined by Shafquillah and Damon (1974) is:

$$Ar_m^{40}/Ar_m^{36} = K_m^{40} \; \frac{\lambda_e}{\lambda} \left(e^{\lambda t} - 1\right) / \; Ar_m^{36} + Ar_A^{40} \; / \; Ar_m^{36}$$

$$+ \; Ar_E^{40} \; / \; Ar_m^{36} \; - \; Ar_r^{40} / \; Ar_m^{36}$$

In the ideal case, in the absence of excess argon and when no diffusion has occurred, the intercept approximates 295.5 the atmospheric Ar^{40}/Ar^{36}. The isochron has been used extensively to indicate the presence of extraneous argon, resulting in high initial argon ratios (i.e.$>$295.5) by McDougall et.al. (1969), Hayatsu and Carmichael (1970), and Roddick and Farrar (1971). More recently Shafquillah and Damon (1974) devised a number of computer models from which they concluded that the isochron should be used with extreme caution and is only valid when the samples under consideration have the same non-radiogenic Ar isotopic composition. Due to the uncertainties attached to the application of the isochron it is not used by the author in this thesis.

CAINOZOIC	Age of base (m.y.)
QUATERNARY	
Pleistocene	1.5 - 2
TERTIARY	
PLIOCENE	c.7
MIOCENE	
Upper	c.12
Middle	c.18 - 19
Lower	26
OLIGOCENE	
Upper	
Middle	31 - 32
Lower	37 - 38
EOCENE	
Upper	c.45
Middle	c.49
Lower	53 - 54
PALAEOCENE	
Upper	58.5
Lower	65
MESOZOIC	
CRETACEOUS	
UPPER	
Maestrichtian	70
Campanian	76
Santonian	82
Coniacian	88
Turonian	94
Cenomanian	100
LOWER	
Albian	106
Aptian	112

Table 5

Part of the 'Geological Society Phanerozoic time-scale 1964. (Quart.J. geol. Soc.Lond. 120s, 260-2).

4. POTASSIUM ARGON AGE AS A FUNCTION OF MINERAL TYPE

Introduction

In the preceding section it was shown that each particular mineral type has a specific temperature range which governs its closure to argon diffusion. This is why the dating of mineral separates provide more information about the thermal history of a sample than the dating of whole rocks, where the resulting age may fall anywhere between the two extremes represented by the most and least retentive minerals in the sample.

Therefore, for the purpose of this thesis minerals were separated for dating, the standard separation techniques which were employed, are summarised in Appendix 2.

Of the common rock-forming minerals biotite is the most useful for K.Ar dating and is ubiquitous in the granitic rocks studied in this thesis. Hornblende, although having a higher argon retentivity than biotite, has not been widely used throughout this thesis because hornblende only occurs as an important mineral phase in the earlier tonalitic units of the batholith. Feldspars comprise the only remaining minerals with appreciable potassium content. Unfortunately very little is known of the suitability of plutonic feldspars for K.Ar dating which is why the author has included a few age determinations on both potassium and plagioclase feldspars in the present study.

THE SUITABILITY OF FELDSPARS FOR K.Ar DATING OF GRANITIC ROCKS

For a long time all feldspars were dismissed as unsuitable for K.Ar dating because of their poor argon retention. However, the research of Evernden and James (1964) showed this early rejection of feldspars to be far too universal for they obtained satisfactory results from nearly all volcanic feldspars of Phanerozoic age.

At present the almost universal acceptance of volcanic feldspars is not paralleled by their low temperature counterparts which seem to consistently yield ages between 5% and 40% lower than the corresponding micas (Folinsbee et.al. 1957, Carr and Kulp 1957, Sardarov 1957 and Zartman 1964) (See Fig. 9).

One of the main factors contributing to the differences in argon retention between volcanic and plutonic feldspars is the inhomogeneous nature of plutonic feldspars; they are frequently recrystallised and often exhibit exsolution phenomena. Despite this more workers are now beginning to include age determinations on feldspars from plutonic rocks (see Evernden and Kistler 1970, and Krummenacher et.al. 1975). Even though very few interpretations or petrographic details accompany these accounts it seems that plutonic feldspars, at least in younger rocks ($<$ 100 m.y.), give ages which are in good agreement with co-existing micas.

Feldspars, from plutonic rocks, are now routinely separated at the I.G.S. (London) and the steady accumulation of data is resulting in a better understanding of their use as geochronometers. Some 26 feldspars from the Coastal batholith have been analysed by the author and the results confirm their reliability for dating rocks of Tertiary age. Where possible the feldspars were dated with cogenetic biotite to act as an internal comparison.

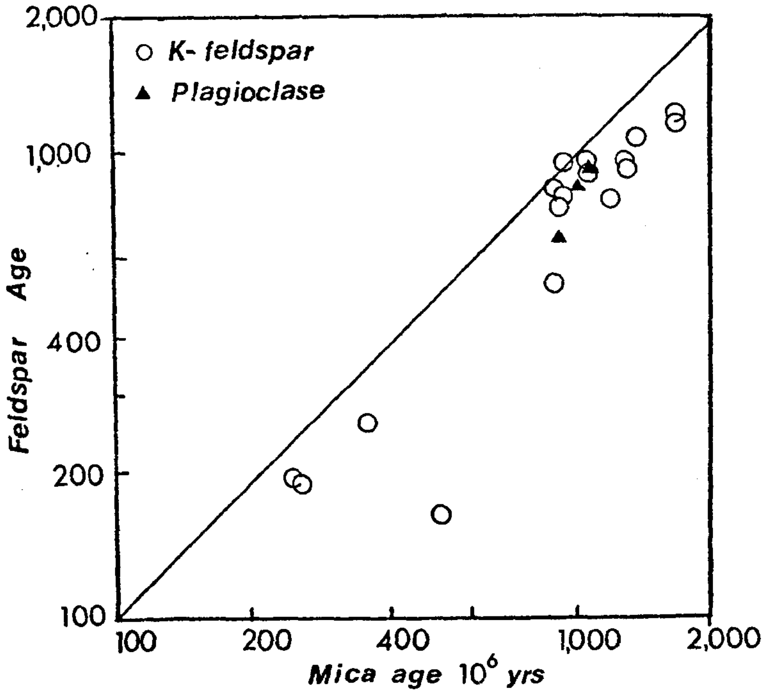


FIG.9 Comparison of potassium-argon ages from coexisting mica and low-temperature feldspars, after Dalrymple and Lanphere (1969).

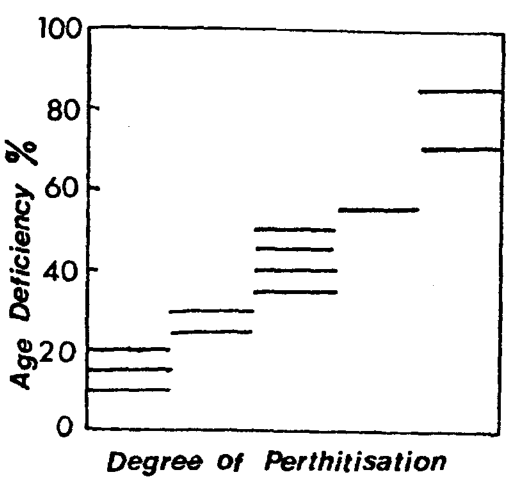


FIG.10 Potassium-argon age deficiency in microline as a function of relative degree of perthitisation, after Sardarov (1957).

i) Potassium Feldspars

Of the sixteen potassium feldspar concentrates which were analysed eleven produced ages which were sensibly concordant with their cogenetic biotite (see Table 6). This implies that under ideal conditions K feldspar has broadly similar argon retention properties to biotite. These findings contrast with the results of other workers who report K feldspar ages to be 15% - 85% lower than the corresponding mica age (see Fechtig and Kalbitzer, 1966 and Smith 1974).

It is widely believed that argon diffusion in K feldspars is enhanced by structural changes which accompany exsolution, this has been exemplified by Sardarov (1957) who has shown an inverse relationship between perthite content and argon retention in microcline (see Fig.10).

Evernden and Kistler (1970) dated six carefully selected K feldspars from granitic rocks of the Sierra Nevada batholith and from their results inferred a relationship between argon retention and the structure of the potassic phase of the feldspars. Four of their feldspar samples were unaltered and gave ages concordant with co-existing biotite, conversely, markedly discordant ages were given by two samples which had been converted to microcline.

In order to quantify the extent of microcline development, in the K feldspars dated in this study, the x-ray diffraction procedures outlined by Goldsmith and Laves (1954) were adopted. The degree of microcline development is defined as the obliquity (or triclinicity) Δ where,

$$\Delta = 12.5 \ (d\ (131) - d\ (1\bar{3}1)\ )$$

a) Concordant

Sample	Biotite age	K feldspar age
A115	64.4	61.9
A22	62.4	60.8
A135	61.9	57.9
A137	61.3	61.9
A153	59.6	62.4
A136	56.5	54.9
A82	34.8	33.4
A50	31.0	32.3
A80	30.6	28.9
A95	64.9	68.1
A97	65.3	64.9

b) Discordant

A41	72.0	66.5
A148	66.0	59.7
A27	64.9	39.9
A123	59.4	55.1
A144	45.0	50.1

Table 6. K.Ar age determinations from cogenetic biotite - K feldspar pairs.

The maximum separation of the two peaks in triclinic microcline is about 0.08Å which corresponds to a Δ value of 1.00. The obliquity decreases with increasing disorder until it reaches a value of 0.00 for a perfect monoclinic symmetry. In a study of the granites of N. Thailand, D. Tiggin (pers. comm) has observed a correlation between the degree of triclinicity (Δ) of K feldspars and their ability to retain argon.

In the present study six K feldspar samples were powdered and analysed by x-ray diffraction, there appeared to be no obvious correlation between Δ and the observed age deficiency :

Sample	Δ (obliquity)	Age deficiency c.f. co-existing biotite %
A80	0.00	5.7
A135	0.00	6.7
A137	0.00	1.0
A148	0.00	10.0
A41	0.79	7.9
A27	0.00	47.7

Table 7. The relationship between triclinicity and argon retention in K feldspars.

These results show that most of the K feldspars correspond to orthoclase, a finding which is also confirmed optically. Sample A41 is from a microgranite dyke and forms the only exception for the high Δ value of 0.79 indicates a high triclinicity. The observation that all these analysed feldspars contain noticeable amounts of perthite suggests that the observed triclinicity is a function of microcline content of the orthoclase and bears little relationship to the exsolved sodic phase (c.f. Ragland 1969). Microcline is generally uncommon in young postkinematic granites where orthoclase usually predominates, although Marmo (1958) has cited examples of primary microcline growing in fractures which cut true orthoclase granites.

The relative proportions of perthite in the 16 orthoclase samples was assessed optically in an attempt to see if a correlation exists between argon retention and perthite content (c.f. Sardarov, 1957). Whilst the author appreciates the errors in using a visual estimate for the perthite content, the method has proved to be quite adequate for the present requirements. As shown in Fig.11, there does not appear to be any relationship between the degree of perthitisation and the discordancy of the biotite - K feldspar pairs.

Sample A50 has the most well developed perthite forming beads which occupy upwards of 20% by volume of the mineral. Samples A135 and A153 are from hypabyssal intrusions and only have a poorly developed microperthite. The remaining samples display intermediate levels of perthite development, the perthite usually forming discrete threads and strings which are dispersed throughout the orthoclase.

Sample A27 has the highest age deficiency yet only has an 'average' perthite content (see Fig.11). In this case the discordancy could perhaps be attributed to the anhedral nature of the feldspar, it has diffuse crystal outlines and tends to play a late interstitial role. This contrasts to the other K feldspar samples which were dated, these were extremely fresh and had good euhedral crystal outlines.

In conclusion there does not appear to be any correlation between argon retention and perthite content for these Tertiary orthoclase perthites. Perhaps the main controlling factor in this context is the

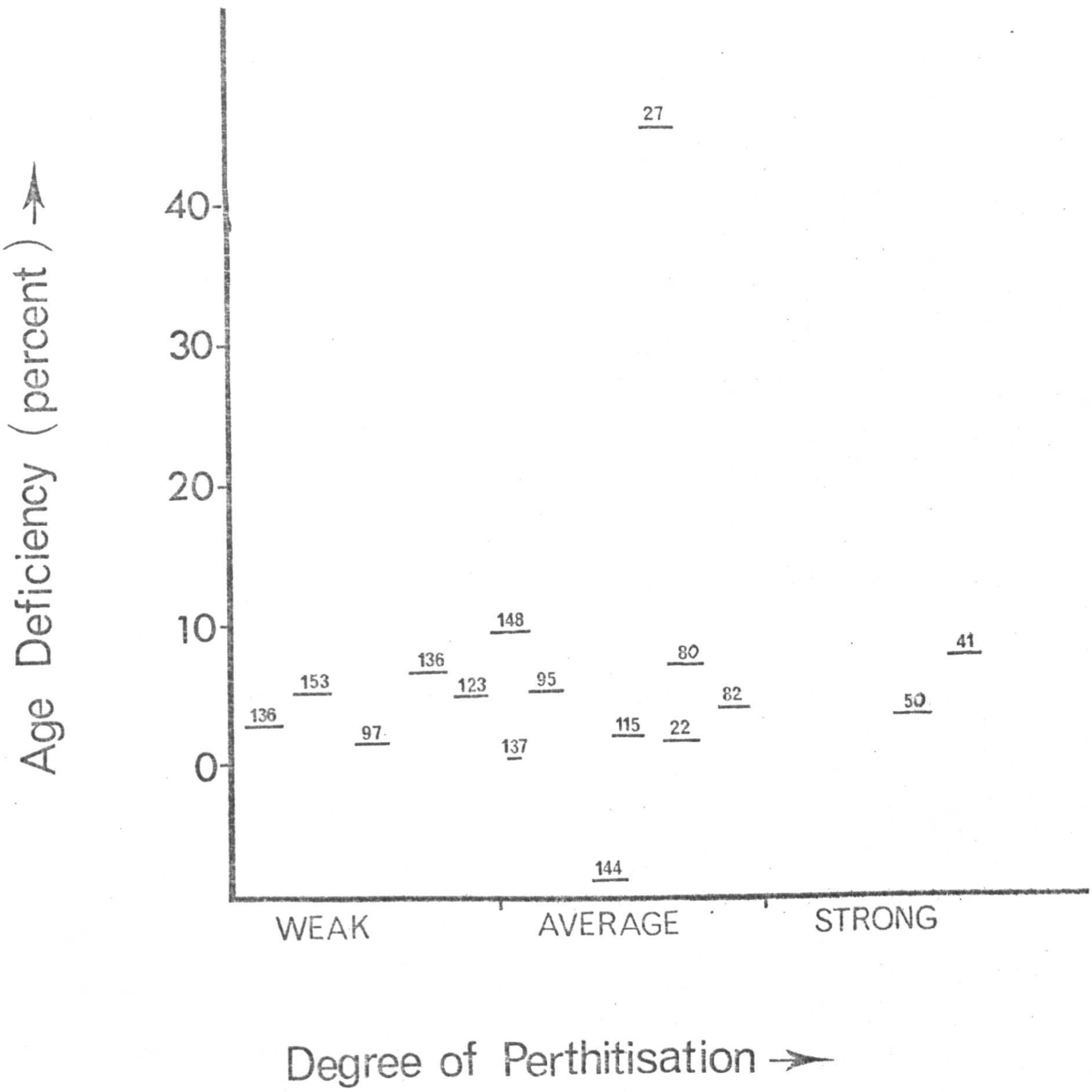


Fig. 11. Diagram showing that age deficiency in orthoclase is independent of the relative degree of perthitisation, the numbers refer to the samples described in the text.

dependancy of diffusion on time, i.e. insufficient time has lapsed for the argon to be lost in detectable amounts. This assumption partly contradicts the findings of Sardarov (1957) who stated that no correlation exists between age deficiency (% loss compared with biotite) and time. Sardarov showed that 2,000 m.y. old microclines had the same age deficiency as microclines of Upper Palaeozoic age.

In the writer's opinion the degree of microclinisation could be the primary cause of poor argon retention in K feldspars. This is tentatively suggested by the data from the Sierra Nevada batholith (Evernden and Kistler, 1970) and from Thailand (Tiggins, D. pers. comm). On the basis of the present study, the perthite content appears to play a more significant role in controlling the argon retention of microcline than it does for orthoclase, where argon retention appears to be independant of perthite content.

Summing up, the geochronologist has to assess both the degree of microclinisation and the perthite content of K feldspars before they can be used satisfactorily as geochronometers. In the particular case of orthoclase perthites of Tertiary age, the argon retention may be as high as that of biotite regardless of the perthite content.

ii) Plagioclase Feldspars

Very little is known of the reliability of low temperature plagioclase feldspars as geochronometers; their low potassium contents ($< 1\%$) and the difficulties involved in their separation have rather limited their use in K.Ar dating.

In the present study only ten plagioclase feldspars were dated and were separated from rocks ranging in composition from gabbro to monzogranite. These different rock types were chosen to try and see if a relationship exists between the chemistry and the ability of the feldspar to retain argon. Evernden and Kistler (1970) have already indicated that there is an apparent correlation between the thickness of twin lamellae and argon retention in plagioclase. The higher retentivity being associated with the broader twin lamellae.

A problem arose in the separation of the plagioclase from the more silicic rocks, where the physical properties of the plagioclase frequently overlapped with those of quartz and K feldspar. The only way of resolving this problem is by hand picking, this is inpractical in view of the large quantity of sample which is needed (3-5 grams). For this reason quartz is present as a minor contaminant in samples A123 and A134.

Either biotite or hornblende were separated from the same rock as the plagioclase to act as a control; the results are listed in Tables 8 and 9.

Of the nine cogenetic biotite plagioclase pairs, six were concordant within the limits of their critical value (Fig.12). Two of the samples, which produced discordant results, had plagioclase giving an older age than the corresponding biotite (samples A126 and A123).

a) Concordant

Sample	Biotite age	Plagioclase age
A67	89.9	87.8
A106	62.5	60.2
A122	55.2	59.3
A143	35.0	35.7
A119	18.7	17.4
A34	12.9	12.4

b) Discordant

A126	85.3	94.2
A123	59.4	74.7
A134	70.7	62.8

Table 8. K.Ar age determinations from cogenetic biotite - plagioclase pairs.

a) Concordant

Sample	Hornblende age	Plagioclase age
A143	34.3	35.7
A126	98.0	94.2

b) Discordant

A01	73.2	90.1
A122	90.3	59.3

Table 9. K.Ar age determinations from cogenetic hornblende - plagioclase pairs.

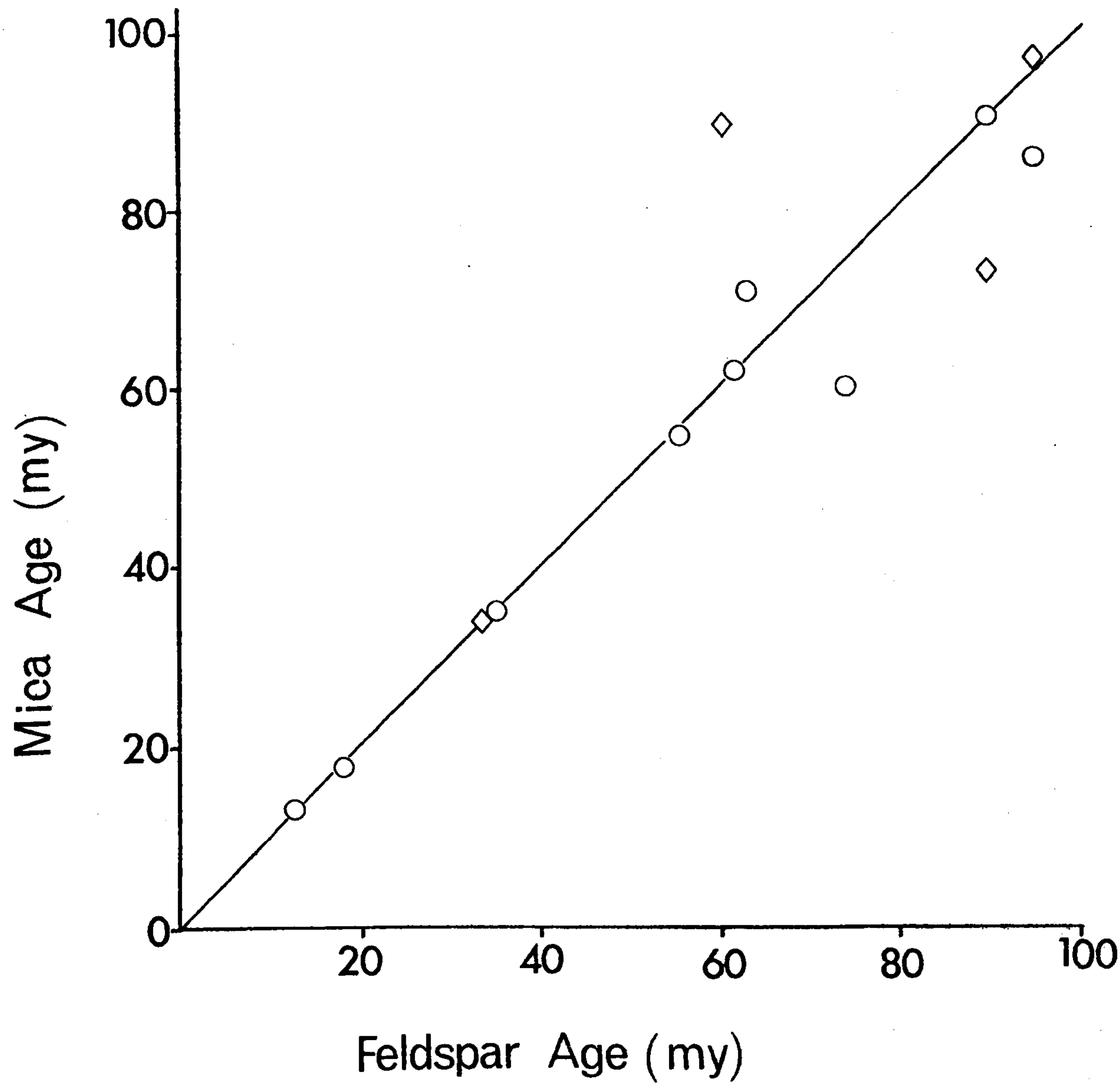


Fig 12 Comparison of K-Ar ages from co-existing plagioclase and biotite (○) and hornblende and plagioclase (◇). The solid line represents results which are in perfect agreement.

The six samples which yielded concordant ages, with their cogenetic mica, had an intermediate plagioclase composition (An_{50-30}), were fresh, unzoned, and showed well defined twin lamellae of intermediate thickness. Of the three discordant samples, A134 showed a strong albitisation of the plagioclase and had extremely narrow twin lamellae. The plagioclase from sample A126 is extremely fresh and has broad twin lamellae and is more calcic in composition (An_{60}) than the other samples. The discordancy displayed by sample A123 contradicts the trends which seem to be emerging, i.e. good argon retention in unaltered plagioclase; here the plagioclase is slightly altered and has thin twin lamellae yet has still retained more argon than its co-existing biotite.

In addition to biotite-plagioclase pairs, age determinations were also carried out on four hornblende-plagioclase pairs, the results of which are listed in table 9.

The concordancy of the plagioclase-hornblende, in sample A126, implies that the plagioclase is not only more retentive than biotite (85.3 m.y.) but may be as retentive as hornblende under certain conditions.

The two discordant plagioclase-hornblende pairs merit separate explanations because in the case of sample A01 (Hornblende gabbro) the plagioclase is demonstrably older than its co-existing hornblende. This is because the hornblende has been generated during a late-stage uralitisation which accounts for its extremely fibrous texture. Therefore the plagioclase (An_{65}) is likely to give a more reliable approximation of the age of intrusion. The plagioclase of sample A122 has thin to intermediate twinning thickness and is extensively sausseritised, furthermore it has very irregular crystal outlines due to its digestion by large poikilitic plates of orthoclase. Thus, it seems that these secondary processes have a radical effect on the argon retention properties of plagioclase feldspars.

Summary

The correlation of plagioclase characteristics with apparent age does not seem to follow any obvious pattern. The observation that these plagioclase mineral ages are either in agreement with, or older than co-existing biotite, indicates their ability to retain argon is equal to, or surpasses that of biotite.

The basic requirement seems to be a fresh crystal phase, lacking any regeneration, and an intermediate to coarse twinning thickness. These are exactly the same criteria, reported by Evernden and James (1964), required for the dating of volcanic feldspars.

Although the data, presented by the author, on hornblende-plagioclase pairs is rather sparse, it strongly suggests that fresh unaltered plagioclase of intermediate to high anorthite content, and coarse-intermediate twinning thickness, may be as resistant to argon diffusion as hornblende.

K.Ar AGE DETERMINATIONS ON COGENETIC BIOTITE-HORNBLENDE PAIRS

It is now widely accepted that concordant ages from cogenetic hornblende-biotite pairs approximates to the time of emplacement of the pluton in question. These conclusions are largely based on the research of Evernden and Kistler (1970) who utilised the blocking temperatures for hornblende and biotite, which were cited by Hart(1964).

Henry (1972), in a study of the granites of Mexico, placed more emphasis on individual hornblende ages by accepting them as emplacement ages irrespective of whether the cogenetic biotite is grossly discordant. However, under certain circumstances the argon retentivity of hornblende may be reduced significantly. Thus, O'Nions and other (1969) have suggested that the argon retention of hornblende may be influenced by chemical composition. Their studies on calcic-amphiboles showed the retentivity decreased with increasing iron content, to the extent where the resulting age may only be as reliable as that of a medium-grained biotite. Therefore, in some cases, concordant biotite-hornblende pairs may only provide an indication of the time at which the pluton cooled over a narrow temperature range.

Of the fifteen cogenetic hornblende-biotite pairs dated in this study only four were concordant, using the criterion outlined in the previous section, and are listed in table 10 in order of their determined age. They are interpreted by the writer as representing intrusive events though not necessarily of the pluton from which the samples were collected. Samples A149 and A8 correspond to tonalite and diorite from the Santa Rosa Super-unit, they have been so totally outgassed that their ages correlate with the emplacement of the nearby Humaya pluton. Samples A145 and A143 are granodiorites which were collected from the Coastal batholith near Chimbote, north of the main study area, these are interpreted as emplacement ages.

Stewart and others (1974) have also reported six concordant hornblende-biotite pairs from the Coastal batholith, which they interpreted as representing intrusive events. Two of these concordant pairs were also in agreement with Rb-Sr age determinations.

The remaining eleven hornblende-biotite pairs, which are presented in this thesis, show varying degrees of discordancy, with hornblende producing the older age in most cases. One of the major difficulties in the interpretation of this age pattern resides in the problem of distinguishing between discordancy due to 'reheating' and discordancy produced by 'slow cooling' (related to depth of intrusion). All the available evidence implies that the discordant age patterns, which are characteristic of the Coastal batholith, are related to post-formational heating of the early members of the batholith by the later more acid plutons. This interpretation conforms to the models of Krummenacher and others (1975) for plutons emplaced at a high level in the crust, where a concordant age pattern ought to be expected.

Sample	Biotite age (m.y.)	Hornblende age (m.y.)
(a) Concordant		
A149	70.6	74-6
A8	70.3	73.9
A145	43.6	43.2
A143	35.0	34.3
(b) Discordant		
A12	92.5	84.0
A122	55.2	90.3
A10	74.0	68.2
A18	61.9	69.8
A61	52.0	62.0
A5	32.8	59.4
A129	31.4	38.8
A77	23.4	33.0
A33	18.8	30.9
380 *	9.9	16.0
386 *	9.1	11.1

Table 10.

K.Ar age determinations on cogenetic hornblende-biotite pairs.

(* denotes sample from Cordillera Blanca batholith)

PART THREE

POTASSIUM-ARGON AGE DETERMINATIONS FROM THE COASTAL AND CORDILLERA BLANCA BATHOLITHS AND THEIR INTERPRETATION

1. THE CHRONOLOGY OF EMPLACEMENT OF THE EARLY UNITS OF THE COASTAL BATHOLITH

Introduction

In the introductory part of this thesis it was shown that rocks of intermediate composition form the greater proportion, by volume, of the batholith. A majority of these intermediate rocks are tonalites which, along with subordinate volumes of gabbro and diorite, were intruded during the early emplacement history of the batholith. Detailed mapping in the study area has resulted in the recognition of three major rhythms which incorporate these units (Cobbing and Pitcher, 1972). In order of decreasing age the rhythms, or Super-units, are;

1) Patap Super-unit - includes gabbro and diorite
2) Paccho Super-unit - diorite - quartz diorite - tonalite
3) Santa Rosa Super-unit - diorite - tonalite - monzogranite

In the following section the writer describes the emplacement chronology and geological characteristics of these three Super-units. It is advantageous to describe the Santa Rosa Super-unit first in order to gain a better understanding of its influence on the age patterns of the two older complexes.

(a) THE SANTA ROSA SUPER-UNIT

The Santa Rosa Super-unit consists of a complex of several members, or units, which range in composition from diorite to granite yet bear an overall tonalitic affinity. The complex constitutes the western half of the batholith from north of the Rio Huaura and continues south some eighty kilometres to the Rio Chancay (Fig.13), and has a maximum outcrop width of forty kilometres.

It has been possible to establish a relative chronology for the components of the Santa Rosa complex, based on its tendency to evolve in a more acid direction with time. For example the main tonalitic facies may be intruded by its own acid-variant, as with the case of the Humaya monzogranite pluton, or may itself intrude an earlier dioritic facies. Many gradational contacts are also present between the different facies variants. This has led to the suggestion that the complex forms a consanguineous group which represents a secondary differentiation of the main basic-acid batholith trend (see Fig.5).

All members of the Super-unit are contained within one single continuous body which cuts and metamorphoses volcanics of the Casma group (see Plate 2). The relationship of the Santa Rosa Super-unit to the other units of the batholith is summarised below.

EARLIER	LATER
Paccho Super-unit Patap Super-unit	Centred Acid Complexes La Mina tonalite Lachay monzogranite Main dyke swarm

Table 11. The relationship of the Santa Rosa Super-unit to the other members of the batholith (after Cobbing and Pitcher, 1972).

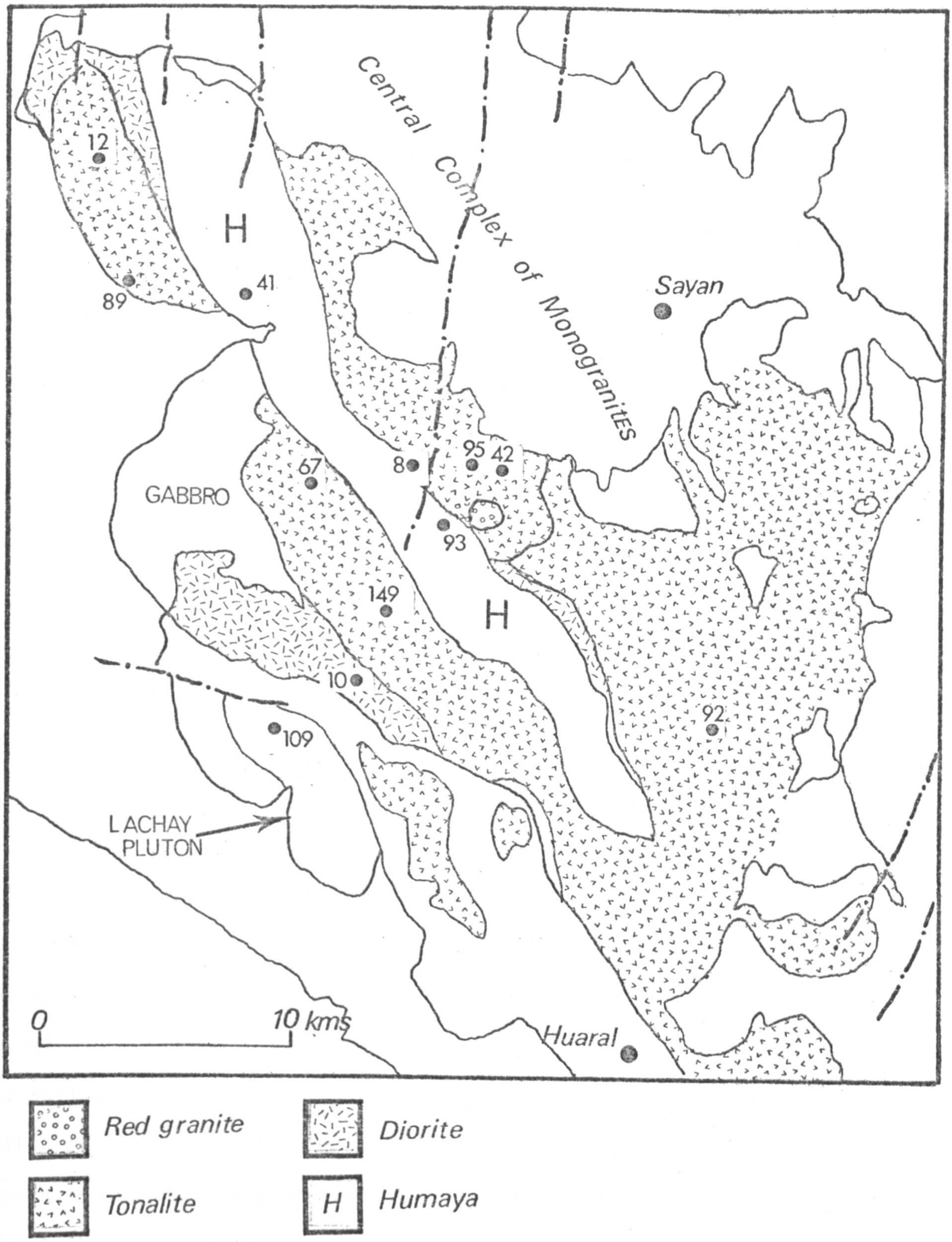


FIG. 13 Geological map of the Santa Rosa Super-unit between the Rio Huaura and Rio Chancay after Cobbing and Pitcher (1972a). The sample localities are referred t.o in the text.

For ease of discussion the writer will now describe the Santa Rosa complex in terms of its major components which are, i), the main tonalite ii), the marginal diorites iii), the Humaya monzogranite.

i) The Santa Rosa tonalite

Tonalite forms the most widespread lithology of the Santa Rosa Super-unit and usually occurs as a fresh leucocratic medium-grained rock with prismatic hornblende crystals and large flakes of biotite. Many of the internal variations seen within the tonalite are due to the increase in proportion of one of these two mafic components over the other. This is particularly well displayed in Quebrada La Capilla where a marked increase of hornblende is paralleled by a noticeable reduction of biotite.

Plagioclase and quartz are usually equidimensional, the plagioclase commonly consisting of well-twinned euhedral laths of about An_{40} composition which are sometimes mantled by a poorly twinned later generation. Quartz is ubiquitous and manifests itself as granular aggregates occupying the interstices between the plagioclase laths. Occasionally the quartz poikilitically encloses or replaces previously existing minerals, although this effect is often restricted to the plagioclase. Orthoclase is normally present and depending on the proportion may impose another variation on the tonalite, often being significant enough to form rocks of granodioritic or monzogranitic composition.

These mineralogical variations may be gradational or may form sharp contacts between two essentially similar rock types. Cobbing and Pitcher (1972) suggested these variations to be formed by magmatic surges within material which is a local, high-level differentiate of the main tonalite.

Five samples of the Santa Rosa tonalite proper were collected for dating from various localities throughout the study area. The sample localities are shown in Fig.13 and the results are tabulated below.

Sample No.	Mineral	K%	Vol Rdg Ar^{40} $\times 10^{-6}$ scc/gm	Age
A12	B	4.88	18.495	92.6 ± 1.4
	H	0.39	1.3534	84.2 ± 2
A67	B	5.44	20.0004	90 ± 1.7
	P	0.59	2.0917	88 ± 2.0
A89	B	6.17	22.09	88 ± 2.0
A149	B	7.49	21.535	71 ± 1.3
	H	0.43	1.3065	75 ± 1.8
A92	H	0.62	1.6138	65 ± 1.8

Table 12. K.Ar Age determinations from the Santa Rosa tonalite.

A total of eight mineral ages contribute to an apparent spread between 93 and 65 m.y., though this spectrum of results does not necessarily imply that a period of 28 m.y. has been involved in the emplacement of the tonalite.

Samples A89 and A12 were collected approximately 5 kms apart in the main tonalite outcrop north of the Rio Huaura. The two biotite ages are concordant and the author feels there is sufficient justification for combining these values to give a preferred age of 91.7 ± 1 m.y. The younger age of the cogenetic hornblende of sample A12 (84 m.y.) is not fully understood because hornblende, having a higher argon retentivity, should be either concordant with, or older than its co-existing biotite. In thin section the hornblende appears fresh and euhedral, and there is no visible petrographic peculiarity which could account for this young apparent age. Replicate analyses are obviously required in this case.

In view of the post-kinematic relationship of the Santa Rosa tonalite to the Albian Casma Group (106 - 100 m.y.), the 91 m.y. age must sensibly approximate to the time of emplacement of the tonalite. Furthermore the cooling of the tonalite, to the biotite blocking temperature, must have closely followed its emplacement and is probably well within the limits of the experimental error.

An age of 89.5 m.y. was obtained from a concordant biotite - plagioclase pair (sample A67) which was collected from the tonalite outcrop immediately to the south of the Rio Huaura. This result provides further evidence of the usefulness of plagioclase for K.Ar dating (see previous section).

The remaining samples of Santa Rosa tonalite give conflicting ages. A granodiorite variant samples in the Quebrada Tambera (sample A149) yielded an age of 73 $\pm$ 1 m.y. on a concordant biotite - hornblende pair; such concordancy is frequently cited as evidence of emplacement. Stewart et.al. (1974) have also presented K.Ar age determinations from a granodiorite in this area, and their value of 76 $\pm$ 3 m.y., for a concordant biotite - hornblende pair, is in general agrement with the value obtained by the writer.

On the basis of fieldwork,there is insufficient evidence to suggest this granodiorite belongs to a separate phase of intrusion, and a more positive approach is to attribute these 'young' ages to a complete loss of already accumulated radiogenic argon by the reheating effects induced by a younger intrusion. This assumption is based on geological evidence for, 1 km to the east, the Santa Rosa 'tonalite' is intruded by the youngest member of the Santa Rosa Super-unit, the Humaya monzogranite, the age of which is discussed later in the thesis.

Only one age determination was obtained from the expansive outcrop of Santa Rosa tonalite to the south of Sayan. An age of 65 m.y. was obtained from a hornblende separated from a quartz monzonite (sample A92). Lithologically this sample is similar to the aforementioned tonalite samples, except for the greater proportion of hornblende, absence of biotite and increase in the proportion of potash feldspar.

At least on the basis of lithology the sample ought to be of the same order of age as the 91 m.y. Santa Rosa tonalite. Unfortunately there is insufficient supplementary data for the writer to arrive at any definite conclusions concerning the significance of this result; there are two alternatives;

1) An emplacement age indicating that the Santa Rosa tonalite and its variants were intruded over a considerable period of time.

2) A hybrid age caused by partial or complete outgassing of the already generated argon.

The writer favours the latter explanation mainly because the sample outcrops along strike with the Huaura and Chancay Centred Acid Complexes, and the 65 m.y. age corresponds to the oldest members of these complexes. This problem can be further elaborated by referring to the age determinations from a more distinct variant of the Santa Rosa tonalite which outcrops in the proximity of Hacienda Santa Rosa.

ii) The Pampa Lhuanco Monzogranite

Around Hacienda Santa Rosa (ref. 482,585) the typical biotite-hornblende tonalite grades into a biotite monzogranite. This monzogranite body is circular in outline, having a diameter of approximately eight kilometres, although much of its outcrop is obscured by the recent alluvial deposits of the broad Pampa Lhuanco. To the west the body is intruded by the Humaya monzogranite and its northern outcrop is bounded by the younger plutons of the Huaura Centred Complex.

The relationship between the main Santa Rosa tonalite and the monzogranite has been outlined by Cobbing and Pitcher (1972) and Cobbing (1973). A gradational contact is present in the north whereas its southern extremity is marked by a sharp vertical contact against the tonalite. Cobbing and Pitcher interpret the monzogranite as Santa Rosa tonalite which has been altered by the passage of potash rich solutions, which converted the tonalite to monzogranite by metasomatic processes (c.f. Vance, 1961). This resulted in a gradational composition change which is manifested by a concentric zoning from mafic margins to a relatively leucocratic potash rich interior. The central zone is marked by a 1 km diameter circular potassic stock, termed the Red Granite, which has a vertical contact against the monzogranite. Cobbing (1973) attributes the sharp contacts seen on Cerro Ferreros, between Red Granite and monzogranite, as due to a remobilisation phenomenon related to the potash metasomatism.

Lithologically the monzogranite is an equiganular medium grained rock differing from the main tonalite in its lower colour index absence of hornblende and increase of orthoclase. The orthoclase is perthitic and forms large ramifying plates enclosing pre-existing minerals. Conversely, the Red Granite is practically devoid of mafics except for a few random flakes of biotite. Perthitic orthoclase is abundant and forms granophyric intergrowths with quartz.

The monzogranite is best exposed on the south slopes of Cerro San Martin whilst elsewhere outcrops are confined to low rounded hills rising above the Pampa. Extensive weathering along joints often renders the rock unsuitable for collection. Similarly the Red Granite is extremely weathered, orthoclase is the only mineral present which is suitable for dating, however the intimate granophyric intergrowths make it impossible to separate in a sufficiently pure state.

Sample No.	Mineral	K%	Vol Rdg Ar^{40} x 10^{-5} scc/gm	Age
A42	B	6.9	1.9193	68.4 ± 1.3
A95	K	8.66	2.3978	68.5 ± 1.5

Table 13. Age determinations from the Santa Rosa monzogranite of Pampa Lhuanco.

Two samples from the northern outcrop on Cerro San Martin gave concordant ages of 68 m.y. (see Table 13) on a biotite and an orthoclase separate. This concordancy implies the biotite and orthoclase have endured similar thermal histories.

On geological grounds these ages are too young to indicate either the original emplacement of the tonalite, or the K metasomatism. Recent geochemical studies by W. McCourt (pers. comm) indicate the potash metasomatism occurred much later than originally envisaged by Cobbing (1973). That the monzogranite is cut by the Humaya pluton, which has given reliable ages of 73 m.y. (see later), implies that this 'metasomatic event' occurred pre-73 m.y. For this reason the writer interprets the 68m.y. age obtained from the monzogranite as reflecting partial argon loss from the samples by a later thermal event. Thus, both samples were collected only two kilometres south of the Huaura Centred Complex. This conclusion lends a degree of support to the author's explanation for the ambiguously 'young' age of the tonalite further west (sample A92).

iii) The Humaya Monzogranite - general features and chronology.

Reference has already been made to the Humaya pluton which is recognised as the youngest member of the Santa Rosa Super-unit. The pluton outcrops as two large bodies of high relief (Fig.13) which are separated by the broad E-W trending Rio Huaura valley. When connected, the two outcrops form a large rectangular body extending for some fifty kilometres in length and with an average width of five kilometres, thus forming one of the largest single plutons of the batholith.

Its outcrop is largely confined to the Santa Rosa tonalite, although locally it intrudes the Santa Rosa diorite and the monzogranite of Pampa Lhuanco. At its northern extremity it cuts out of the Santa Rosa Super-unit and is locally emplaced within the Casma volcanics.

The 'Humaya' is petrographically distinct from the other units of the Santa Rosa complex; vertical intrusive contacts are typical, but Cobbing and Pitcher (1972) have also described a gradational contact which forms one criterion for their classification of the Humaya as a '<u>late magmatic pulse</u>' of the Santa Rosa Super-unit.

Lithologically the Humaya is a creamy-white leucocratic rock characterised by the development of large prominent books of biotite, frequently 0.5 - 1 cm across and often extensively chloritised. Hornblende, when present, is subordinate and usually occurs in dark mafic clusters. Plagioclase laths of about An_{40} in composition are well twinned and commonly mantled by more acid plagioclase. Orthoclase is present in varying proportions (15-35%) and occurs as perthite poikilitically enclosing and often replacing plagioclase. Quartz is plentiful forming aggregates of large granular crystals. Compositionally the Humaya pluton is a granodiorite with tendency towards monzogranite, thus representing an acid variant of the Santa Rosa tonalite.

Only three age determinations have been calculated for the Humaya pluton. A biotite separated from the characteristic 'big book' facies, from the southern outcrop near Hacienda Santa Rosa (sample A93), gave an age of 74 m.y. The two remaining ages (Table 14) correspond to a large aplo-granite dyke (Sample A41) which intrudes weathered Humaya monzogranite, west of Hacienda Humaya. Biotite separated from the dyke gave an age of 72 m.y. in agreement with sample A93. The reason for the younger age produced by the co-existing orthoclase has been discussed at length in the previous section.

Sample No.	Mineral	K%	Vol rdg Ar^{40} x 10^{-5} scc/gm	Age
A41	B	5.15	1.51006	72 $\pm$ 1
	K	9.77	2.6386	66.5 $\pm$ 1.6
A93	B	7.75	2.3434	74.1 $\pm$ 1.7

Table 14. K.Ar Age determinations from the Humaya pluton.

The writer interprets the two biotite ages as representing the emplacement of the Humaya pluton at 72.5 $\pm$ 1.3 m.y. It is clear that the observed uniformity of the mica ages over such a wide area precludes the possibility of any localised disturbances. Nowhere is the Humaya pluton cut by younger intrusions, except by the main dyke swarm, which was carefully avoided during sampling and probably only imposed very limited thermal effects on its host rocks (c.f. Westcott, 1966).

An important observation which supports this emplacement hypothesis is the widespread effect of the Humaya pluton on its host rocks, for example, it has been suggested that the Santa Rosa 'granodiorite' of Quebrada Tambera responded by the total outgassing of both its hornblende and biotite. The emplacement of the Humaya pluton also influenced the age patterns of the dioritic members of the Santa Rosa Super-unit, and will now be discussed.

iv) Age determinations on the Santa Rosa Diorites
- additional evidence for the Humaya intrusive event.

Diorites also contribute significantly to the Santa Rosa Super-unit and occur in two general associations. Firstly, as early differentiates usually marginal to the main tonalite, and secondly as contaminated tonalite marking a basified transitional zone where the main tonalite intrudes the early gabbros of the Patap Super-unit (see Cobbing, 1973).

Lithologically the diorites bear a strong textural resemblance to the Santa Rosa tonalite; prismatic green hornblende crystals are abundant and occur within plagioclase laths of intermediate composition. The presence of pyroxene has been noted by some workers

(Cobbing, 1973) yet was absent in the samples examined by the author. Biotite is usually present either as single crystals or large poikilitic plates which enclose the pre-existing minerals. At one locality along the Rio Chico (ref. 459 456) the author noted poikilitic biotite growing across a fabric of aligned hornblende prisms.

Everywhere the diorites represent an early phase in the history of the Santa Rosa Super-unit which accounts for their preservation as screens and remnants within the younger units of the complex. For this reason the argon clocks in the various mineral phases, of the diorites, have probably been re-set to coincide with the age of the intruding material. This factor was considered by the writer during sampling and such rocks were collected with the primary aim of providing additional age data on the Santa Rosa tonalite.

The two diorite samples which were dated both gave ages which are coeval with the intrusion of the Humaya pluton. The calculated results are tabulated below.

Sample No.	Mineral	K%	Vol rdg Ar^{40} x 10^{-5} scc/gm	Age
A8	H	0.48	1.9015	70 ± 1
"	B	6.65	0.1455	74 ± 1.4
A10	B	7.70	2.3309	74 ± 1.4
"	H	0.78	0.21723	68 ± 1.3

Table 15. K.Ar Age determinations of the Santa Rosa diorites

Sample A8 was collected from a narrow diorite screen which outcrops between the Humaya pluton and the Santa Rosa tonalite on Cerro La Caida (ref. 470.600); at this locality (Fig.13) large dykes of Humaya granodiorite can be seen cutting the diorite. Compared with this, the 'resetting' of Sample A10 is more complicated in that this diorite was sampled equidistant between the Humaya body and the Lachay monzogranite. The Lachay pluton yielded a biotite age which broadly corresponds to the Humaya 'event' (sample A109, 75 m.y.). Whether or not this age represents the age of emplacement of the Lachay monzogranite is uncertain, Cobbing, Pitcher and Garayer (1971) have mapped the Santa Rosa tonalite intruding the Lachay body, which implies it is > 90 m.y. in age.

Thus, the regional resetting of hornblende and biotite clocks to 73 m.y., which the author has ascribed to the emplacement of the Humaya pluton, appears to be extremely irregular. For example, sample A67 was collected only 1 km from the Humaya pluton yet the biotite retained all its already accumulated radiogenic argon (90 m.y.).

Before attempting to summarise the chronology of the Santa Rosa Super-unit the writer, following Cobbing and Pitcher (1972), proposes to integrate the main dyke swarm with the final stage in the evolution of the Super-unit. The reasons for incorporating the dykes is that they display certain features which suggest they were partly coeval with certain members of the Super-unit.

v) The Age of Emplacement of the Santa Rosa Dyke Swarm - synplutonic dykes

A marked feature of the Santa Rosa Super-unit is the extensive swarm of dykes which were emplaced during the closing stages of its evolution when the already consolidated rocks were subjected to a period of tensile stress. Myers (in press) has recognised five separate dyke swarms, in the Huarmey area, which were emplaced at different times throughout the emplacement history of the batholith. Of these the Santa Rosa suite is by far the most intensive. The same

PLATE.4 The Santa Rosa dyke swarm emplaced into the Santa Rosa tonalite at Cerro Cenicero (320.750) north of the Rio Huaura.

PLATE.5 Deformed dykes in the Quebrada El Carmen (440.753), the figure at the right of the picture gives an idea of the scale.

dyke swarm has also been observed in the Casma region by Child (1972) and as far north as Chimbote by Bussell (1975).

The dykes are related in their aerial extent to the outcrop pattern of the Santa Rosa Super-unit, the various members of which comprise their host rocks (Plate 4). They trend in a north-westerly direction and are commonly 1-5 metres in width, and often 7-8 kms in length, and generally have sharp vertical contacts with their host rocks. Compositionally they have an overall andesitic affinity, many being porphyritic with phenocrysts of green hornblende or andesine laths. Others display fine grained aphyric textures.

An interesting point concerning their chronology is that they clearly pre-date the younger monzogranite plutons of the Centred Complexes thus providing a natural time marker between the two major intrusive phases of the batholith. This relationship extends out of the study area as far north as Chimbote (Bussell, 1975).

Not all the dykes were emplaced at the same period of time, cross cutting relationships and compositional variations imply several phases of dyke injection were superimposed upon each other to produce the main swarm. Myers (in press) has recognised two main groups in the Haurmey area syn and post Santa Rosa tonalite in age. Further complexities are introduced in several areas where the dykes show certain structures which demonstrate a coeval relationship between dyke intrusion and cooling of the host rock. Many of these features are particularly well developed inland from Casma (Dept. of Ancash), here Child (1972) has described examples which reflect every possible degree of interation between dyke and cooling host rock. The formation of these features involve processes such as disruption and back-veining which lead to the eventual break up and partial assimilation of the dyke into a series of xenolith trains. Such phenomena have been interpreted as the bodily injection of the dyke into a cooling host rock, which is rigid enough to fracture and permit emplacement, yet is sufficiently plastic to flow and deform the dyke. Cobbing and Pitcher (1972) and Child (1972) have referred to these dykes as synplutonic, adopting the terminology used in the Coast Range batholith of British Columbia (see Roddick and Armstrong, 1959). Microtonalite dykes which show a synplutonic relationship with their host rocks have been described in the main Donegal Granite by Pitcher and Read (1960).

In the Huaura area these 'synplutonic' dykes are common, notably in the upper reaches of the Quebrada El Carmen (ref. 440.753) where a steep sided canyon cuts through the Santa Rosa tonalite exposing an excellent section through the dyke swarm (Plate 5). Folding, 'boudinage' and mechanical fragmentation accompany invasion of the dyke by the host tonalite and contribute to a complex pattern of dyke-host rock interaction. On a recent visit to the area these relationships were seen to intensify towards a younger acid intrusion, indicating a process of remobilisation to be the main influencing factor.

In the writer's opinion a clarification of the term synplutonic is necessary, especially since in older batholithic terranes any dyke intruded during the emplacement history a batholith tends to be referred to as synplutonic. For the purpose of this study any dyke emplaced during the history of the batholith shall be referred to as synbatholithic, whereas the term synplutonic will be restricted to those dykes which display morphological characteristics which imply they are of the same age as their host rocks. In the Coastal batholith detailed radiometric

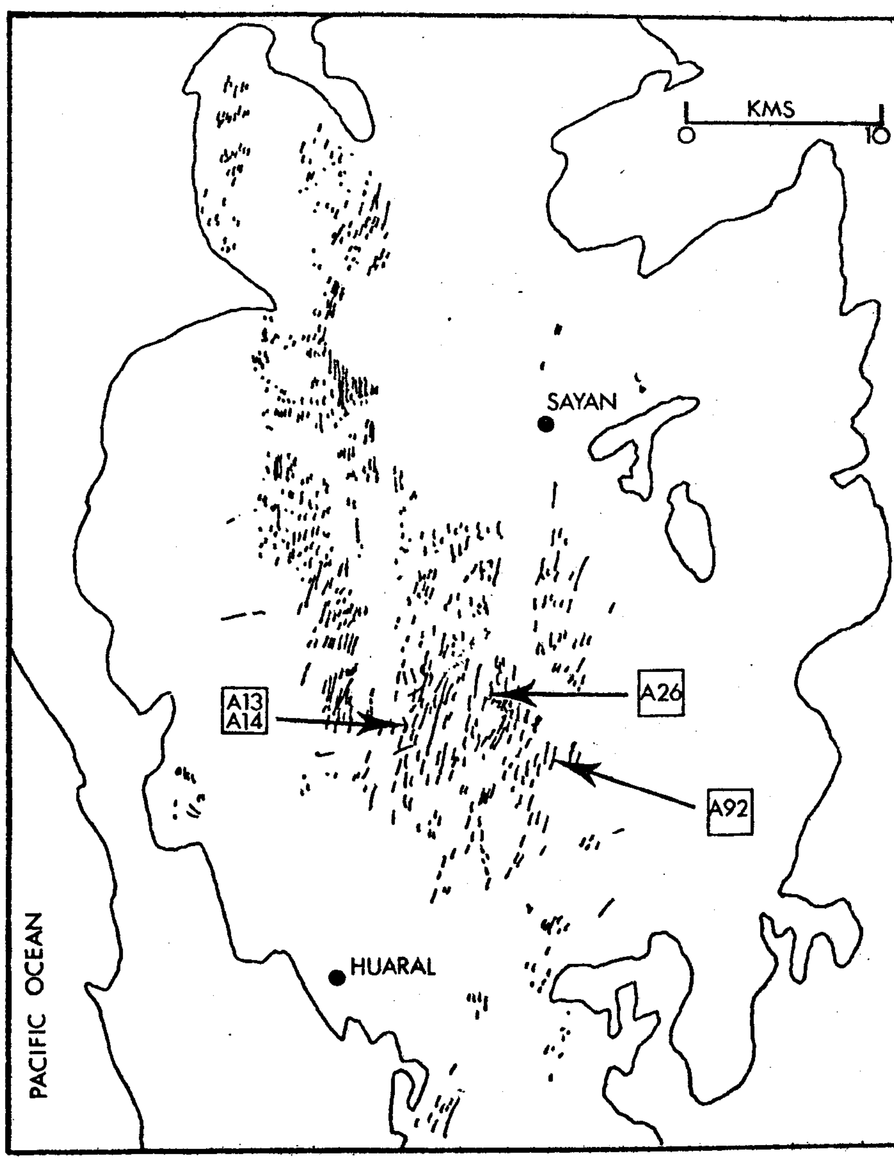


FIG. 14 The Santa Rosa dyke-swarm and it's relationship to the batholith outcrop, sample locations are indicated.

studies should be able to distinguish between true synplutonic dykes and the similar features produced by remobilisation of a normal synbatholithic dyke, as exemplified in the Quebrada El Carmen.

Four of the dykes were analysed and were collected from the low desert region around Pampa Lhuanco (Fig.14), the results are tabulated below.

Sample No.	Mineral	K%	Vol rdg Ar^{40} x 10^{-6} scc/gm	Age
A13	WR	1.202	3.5811	73.2 ± 1.9
A14	WR	3.148	10.2261	73.5 ± 1.9
A26	H	0.306	0.85341	68.5 ± 2.8
A91	H	0.516	1.2475	59.6 ± 2.4

Table 16. K.Ar Age determinations of the Santa Rosa dyke swarm.

Two of the dykes represent undeformed porphyritic microdiorites, in one case (sample A26) stubby prisms of green hornblende occur, whereas the hornblende is subordinate to phenocrystic andesine in the other (sample A91). Despite these minor textural differences both dykes have the same trend and are presumably members of the same dyke swarm. Another minor difference lies in the nature of their host rocks; sample A26 was collected from a dyke which intrudes both the Santa Rosa tonalite and Pampa Lhuanco monzogranite on Cerro Ferreros (ref. 520.568), whilst sample A91 is from a dyke which intrudes the main Santa Rosa tonalite near Quebrada La Capilla. The unusually high errors which accompany these two ages are due to a high atmospheric argon contamination.

The two remaining samples are fine-grained dykes and intrude the Humaya monzogranite on the western slopes of Cerro Perla (ref. 492.578). Here the dykes are deformed within their host monzogranite and show cross-cutting relationships to each other; a dark fine-grained microdiorite being cut by a lighter, grey dyke.

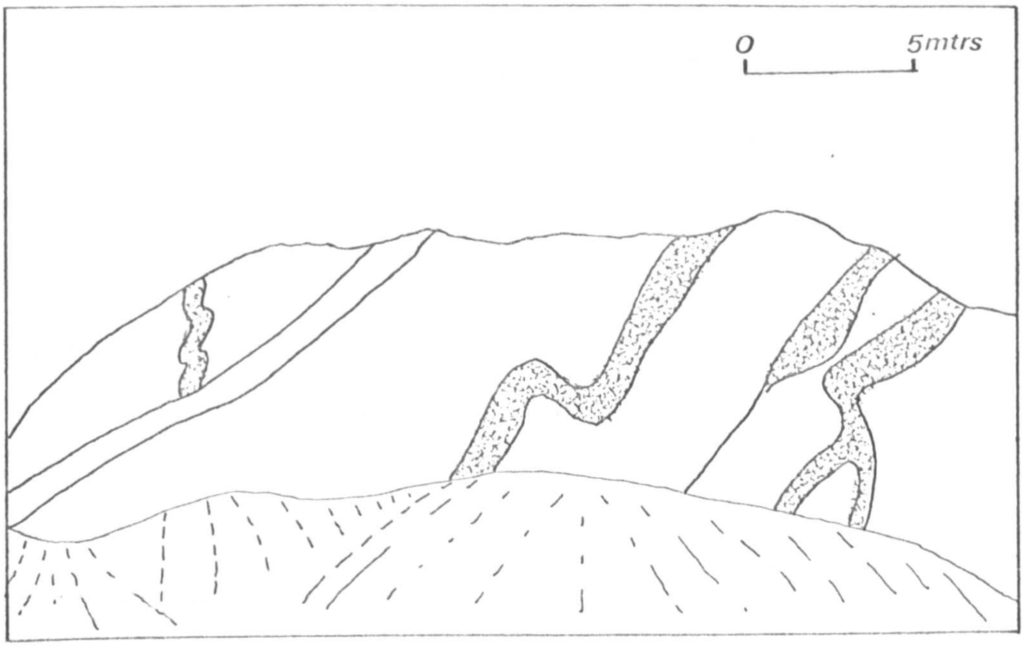


Fig. 15 The relationships of the Santa Rosa dyke swarm in the Humaya monzogranite on Cerro Perla (ref. 492.578).

Due to their fine grain size and absence of phenocrysts, mineral separation proved to be impractical so the dykes were dated using whole rock samples. In both cases the fresh holocrystalline nature of the samples implied that they would be reliable geochronometers (see review on whole rock K.Ar dating in Appendix 1). The pale grey dyke (sample A14) has a different minerology to the microdiorite, notably in its more acid plagioclase, and the presence of small subhedral flakes of biotite which contributes to its higher potassium content.

Both samples yielded ages of 73 m.y. in agreement with the age of their host rock, which was discussed in some detail in the preceding section. The age of the Humaya pluton is based on evidence taken throughout its area of outcrop and it is unlikely therefore that the dykes produced sufficient heat to cause this mobilisation locally. The work of Westcott (1966), on Tertiary dykes intruded into Moine schists, showed that dykes only had very limited effects on the argon retention of their host rocks. For this reason the writer interprets the emplacement of these two dykes as direct evidence of synplutonic dyking, with the dyke emplacement occurring during the final stages of cooling of the Humaya pluton.

In addition the ages computed for samples A13 and A14 are not significantly different from the age of the porphyritic dyke (sample A26) and belong to the same phase of intrusion, at least as defined by the resolution of the method.

vi) Summary of the Age of the Santa Rosa Super-unit

In Fig.16 the writer has plotted all the age data from the Santa Rosa Super-unit on a K^{40} vs Ar^{40} isochron. The theoretical positions of the 90 m.y. and 72 m.y. isochrons are included to help visualise the distribution of the K.Ar ages.

The data described in the previous section suggests that a period of 20 m.y. has been involved in the evolution of the Super-unit. Many of the age determinations correspond to what the author has referred to as the 'Humaya event', and only a few age determinations on mica and hornblende penetrate this 'metamorphic veil' (c.f. Armstrong, 1966) to refelct the age of the Santa Rosa tonalite. Using the available data it is impossible to arrive at any definite conclusions as to whether the tonalite and its variants were emplaced as one pulse (at 92 m.y.), or as a series of pulses over a period of 20 m.y. which culminated with the emplacement of the Humaya pluton.

The duration of the time of emplacement of the Super-unit questions the hypothesis of 'magmatic surges' envisaged by Cobbing and Pitcher (1972). If this represents a high level secondary differentiation then the process has taken <u>at least 20 m.y.</u> to complete.

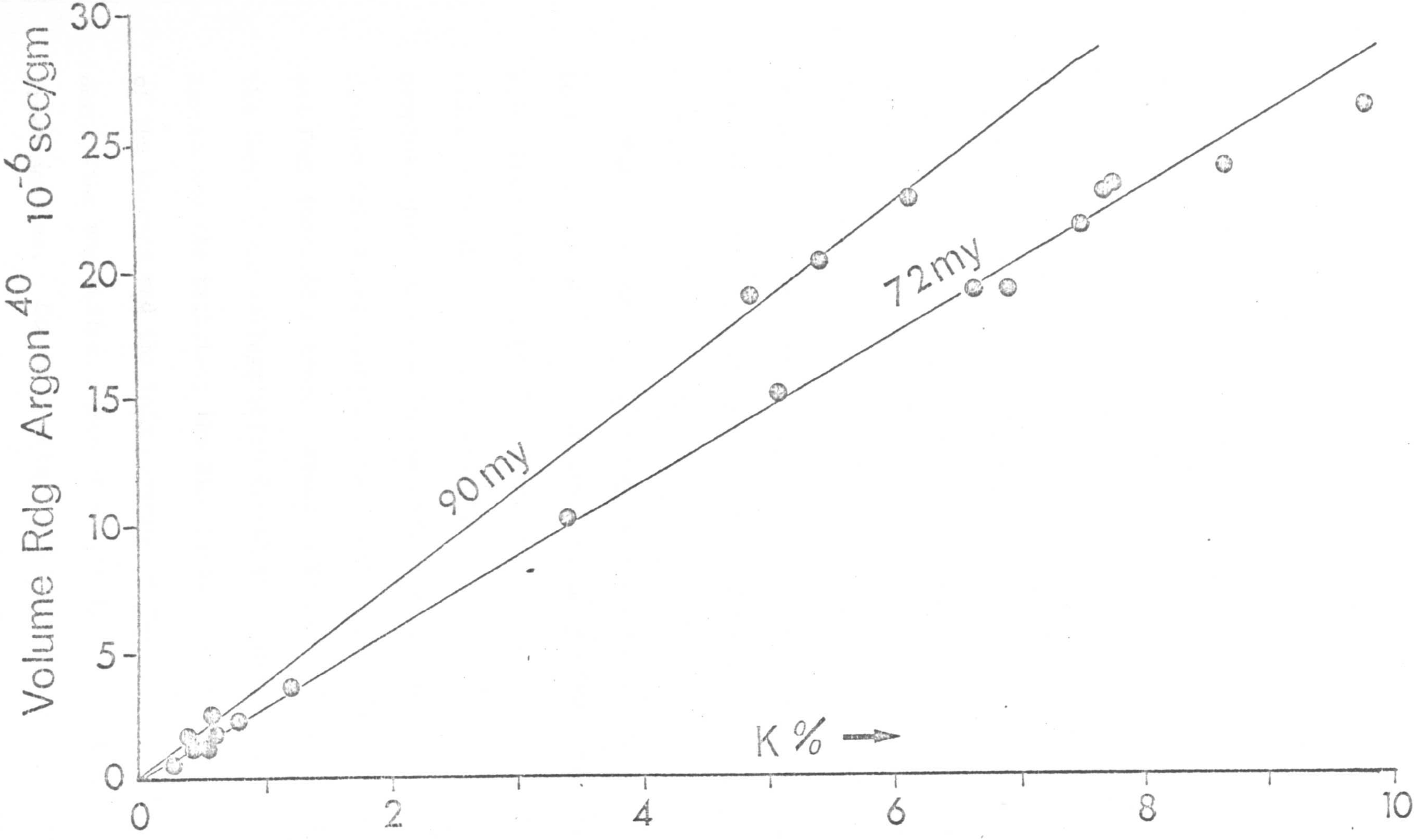


Fig.16 K-Ar age determinations from the members of the Santa Rosa Super-unit (including dykes) plotted on an isochron relative to the positions of the 90my and 72my isochrons.

(b) THE PACCHO SUPER-UNIT

The relationship between the Santa Rosa Super-unit to its eastern counterpart, the Paccho Super-unit, is generally obscured by the emplacement of the Centred Acid Complexes. Consequently the two Super-units have only been seen in contact in the almost inaccessible terrane along the eastern reaches of the Quebrada Los Leones (ref. 675-556). Here Cobbing and Pitcher (1972) and Cobbing (1973) have described a vertical contact with sufficient difference in lithology to demonstrate the older relative age of the Paccho complex. This observation is further reinforced by the available geochemical data which points to an older age for the Paccho, based on its more basic position in the differentiation sequence of the batholith (W. McCourt pers. comm).

The Paccho Super-unit occupies a similar linear distance to that of the Santa Rosa complex, extending for some seventy kilometres parallel to the Andes, and having an average outcrop width of twenty kilometres (fig.17). Unlike the Santa Rosa complex, which outcrops in low rock desert, the Paccho outcrops further inland and therefore is exposed at altitudes between one and four thousand metres. Access is therefore restricted to the large river valleys which dissect the complex, notably the Rio Huaura and its tributary the Rio Chico. The precipitous nature of the terrane and the thin covering of soil, with semi-arid shrub-like vegetation, makes it extremely difficult to collect fresh samples. Compared with the other units of the batholith the Paccho complex has not been studied in any great detail due

FIG. 17 Outcrop map of the Paccho Super-unit showing sample localities.

to these access problems, and the vegetation cover which discourages the use of aerial photographs. For this reason the following discussion is handicapped by the limited number of samples collected from the aforementioned river sections.

Almost all the Paccho complex is enclosed within one continuous body. On its eastern margin it intrudes and metamorphoses andesitic volcanics which were originally mapped as Cretaceous (Casma group?) by Bellido (1956), but have been designated Calipuy volcanics by Cobbing and Pitcher (1972). As mentioned earlier, the Paccho is intruded by the Santa Rosa tonalite making it extremely early in the evolution of the batholith; with the exception of the Patap Super-unit it is the oldest recognisable body and often forms the host rock for younger intrusions.

Composition and Petrography

The Paccho Super-unit differs from the Santa Rosa complex in its overall uniformity and in the greater preponderance of basic over acidic variants. Although quartz diorite and tonalite predominate monzonitic variants also contribute significantly. The rocks are uniformly medium grained and are devoid of any mineral alignment. An extremely high proportion of microdiorite xenoliths are universally present and frequently reach 5-10% by volume of the rock. All internal variations appear to be gradational, sharp internal contacts are generally absent although this finding is partly due to the restricted access because Taylor (pers.comm. in Cobbing and Pitcher, 1972) has reported internal contacted in the Chancay valley section.

The Paccho is frequently altered and the mafic constituents are generally thoroughly chloritised, pale green and fibrous in nature. Narrow anastamosing veins of epidote are ubiquitous and minor shear zones were observed by the writer along parts of the Rio Huaura Valley. These factors indicate that the Paccho has been subjected to a certain degree of post-formational disturbance.

Probably the most notable petrographic feature is that rocks of the Paccho complex often contain clinopyroxene as a primary mineral. This occurs either as euhedral stubby prisms with lobate outlines, or as a resorbed remnants mantled by hornblende. In many cases pyroxene is absent and blue-green euhedral hornblende forms the main mafic constituent. Biotite is usually present as large poikilitic plates. Plagioclase (An_{50-40}) consists of an interlocking meshwork of well twinned laths which are often mantled by later more acid plagioclase. Quartz is generally scarce and occurs as triangular nests between plagioclase laths, orthoclase is present in varying amounts and is usually perthitic in nature, digesting the earlier plagioclase.

One of the most noticeable internal variations of the Paccho is the sporadic increase of orthoclase which often results in a change of composition to a quartz monzodiorite or quartz monzonite. Cobbing (1973) believes this is due to the crystallisation of the Paccho Super-unit which is reinforced by the addition of K feldspar at a late stage its cooling history.

Age determinations from the Paccho Complex

The major difficulty encountered in a geochronological study of the Paccho complex is the poor geological control. Only a limited number of samples were collected from the Paccho, and of these, only a few provided material suitable for mineral separation.

The samples which were dated all yielded highly discordant ages on cogenetic biotite-hornblende pairs, with the hornblende producing the older age by up to 40%.

Sample	Mineral	K%	Vol Rdg Ar^{40} x 10^{-6} scc/gm	Age
A122	H	0.52	1.91912	90 ± 4.6
"	B	3.41	7.6249	55 ± 1.3
A61	P	0.545	1.3099	59 ± 1.8
"	B	5.5	11.592	52 ± 1.2
A5	H	0.62	1.5477	62 ± 2.1
"	B	6.95	9.1809	33 ± 0.5
A38	H	0.513	1.2368	59.4 ± 1.9
	B	1.23	2.6734	47 ± 1.2

Table 17. K.Ar ages from rocks of the Paccho Super-unit

It is obvious that more factors are at play in influencing the quantity of argon retained by the Paccho minerals than was the case with the Santa Rosa Complex.

Sample A5 illustrates the effect of a late thermal event on an already consolidated rock. In this case the hornblende age (59 m.y.) has resisted argon loss to a much greater extent than the co-existing biotite (33 m.y.), which probably corresponds in age to the younger thermal event. In this instance the Paccho was collected along the Rio Huaura, only 2.5 kms east of the Sayan monzogranite and the writer tentatively suggests this younger biotite age reflects the age of this pluton. Stewart and others (1974) obtained a comparable biotite age (32.4 m.y.) from the Paccho diorite approximately ten kilometres further east which implies this young value probably represents a more regional thermal event (see next section). The significance of the hornblende age of sample A5 is not clear, it probably represents a 'hybrid' value related to partial loss of accumulated radiogenic argon.

A similar case of argon loss has occurred in the Paccho along the Rio Chico, where a quartz monzonite produced a discordant age pattern on a biotite-hornblende pair (Sample A61). In this case the resetting of the hornblende (62 m.y.) can be attributed to the emplacement of the Huaura Centred Acid Complex. However, the younger biotite age (52 m.y.) does not appear to correspond to any thermal event which occurred at this time.

Unfortunately these age patterns do not give a realistic estimate of the age of emplacement of the Paccho Super-unit. Probably the closest approximation to an emplacement age is derived from a tonalite sampled along the Chancay valley (Sample A122). Again the individual mineral ages showed a strongly discordant age pattern, with biotite (55 m.y.) younger than co-existing plagioclase (59 m.y.) and a hornblende separate producing a much older age (90 m.y.). The sample was collected over 6 kms from the Rio Chancay Centred Complex and a similar distance from the Vilca monzogranite pluton, both demonstrably younger intrusions. The writer attributes this discordant age pattern to a prolonged reheating, with the temperature maintained above the blocking temperature of biotite but below that of hornblende.

Conclusions concerning the Age of Emplacement of the Paccho Super-unit

The limitations of the K.Ar method, notably argon loss induced by later heating events, presents special problems in the assessment of the age of emplacement of the Paccho Super-unit. Two factors come into play which are effective in producing this pattern;

1) The emplacement of younger more acidic plutons at both the western and eastern margins of the Paccho complex. These exerted localised reheating effects on the already consolidated Paccho rocks.

2) Another consideration is the original depth of emplacement of the Paccho, prior to its later uplift to form the highest terrane occupied by the batholith.

The writer feels that both of these factors have been significant in controlling the K.Ar clocks of the Paccho Complex. The latter explanation gains support from recent geochemical studies which show the complex has evolved by pyroxene controlled fractionation and was therefore probably emplaced at a greater depth, and hence a lower vapour pressure, than the Santa Rosa complex. On these grounds, it is possible that the complex as a whole was emplaced at a depth where the ambient temperature was above the biotite blocking temperature.

Finally the writer supports Cobbing and Pitcher (1972) in placing the Paccho early in the emplacement history of the batholith, though this assumption is based entirely on field, petrographic and geochemical evidence and is not reflected by the K.Ar ages. On the basis of the relationship of the Paccho to the Santa Rosa tonalite the writer places a minimum age of 90 m.y. on the complex.

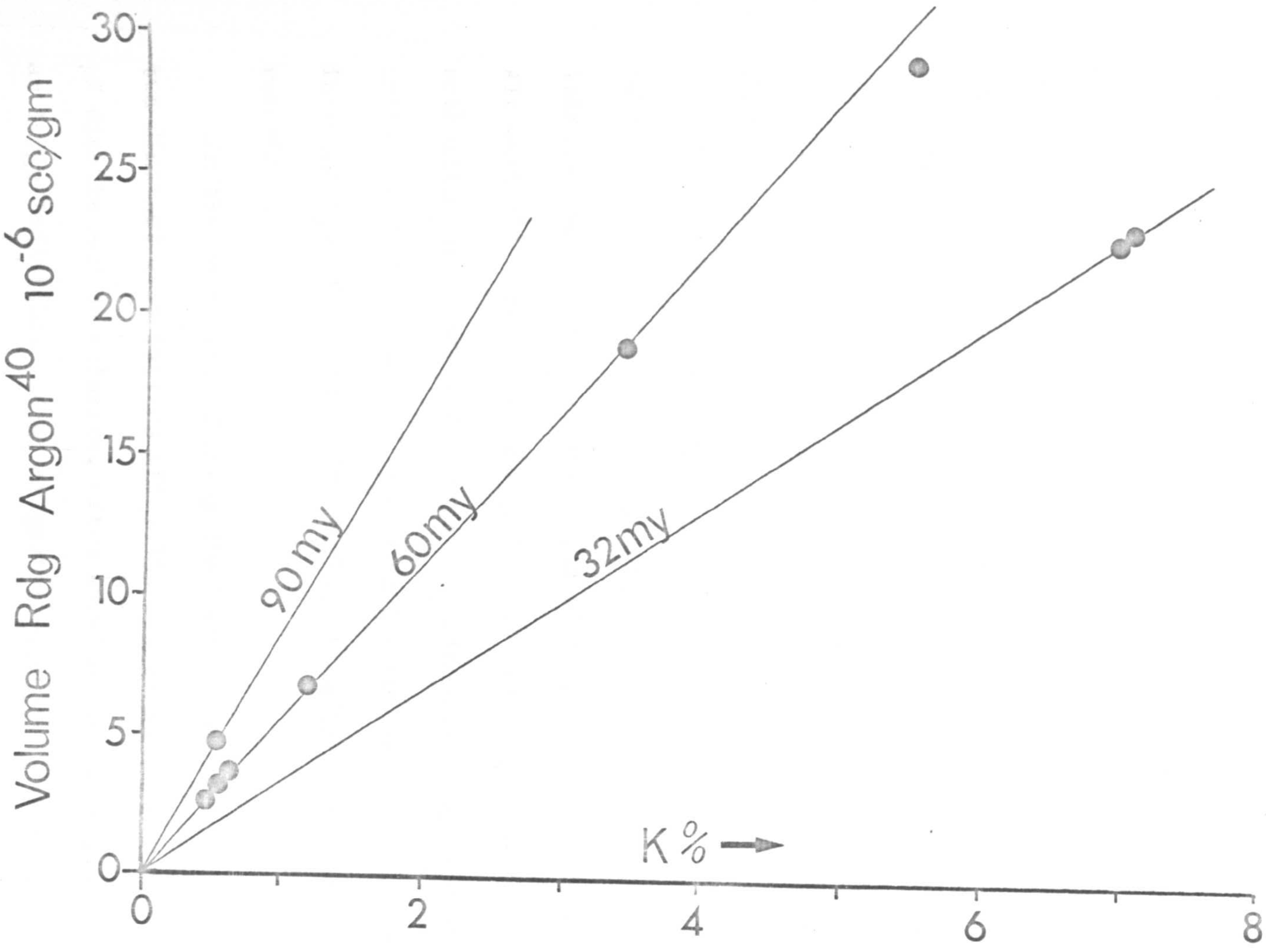


Fig. 18 The distribution of ages from the Paccho Super-unit shown on a K-Ar isochron, relative to the positions of the 90,60 and 32my. isochrons.

(c) THE PATAP SUPER-UNIT - THE GABBROS

Gabbros and diorites together constitute the basic units of the Coastal batholith and make up approximately 16% of its total area of outcrop. These basic units have recently been grouped under the general category Patap Super-unit, a subdivision which was introduced by Myers (in press) for the early basic members of the batholith in the Huarmey area. The dioritic rocks described in the previous section are purposely omitted from this classification because they have compositional and textural characteristics which illustrate their close alliance with the Santa Rosa and Paccho Super-units.

Rocks of the Patap Super-unit always form the earliest phase of intrusion of the batholith, even predating the tonalites which intrude and impose varying degrees of thermal metamorphism on them. Although they are formed early in the intrusion history of the batholith the writer has postponed a discussion of their chronology until now with the aim of providing the reader with a clear insight into the age of the tonalitic rocks, which influence their argon retention.

In the main area of study the basic rocks are preserved in two distinct associations (Fig. 19) either as scattered remnants of diorite and meladiorite, often marginal to other plutons. Or as large individual bodies of gabbro which are well developed on both the western and eastern margins of the batholith. The western or Haural Gabbro has the most extensive outcrop forming a rectangular body originally occupying an area of 45 by 15 kms, before its disruption by younger intrusions. In view of the widespread re-heating effects, caused by the younger units of the batholith, the

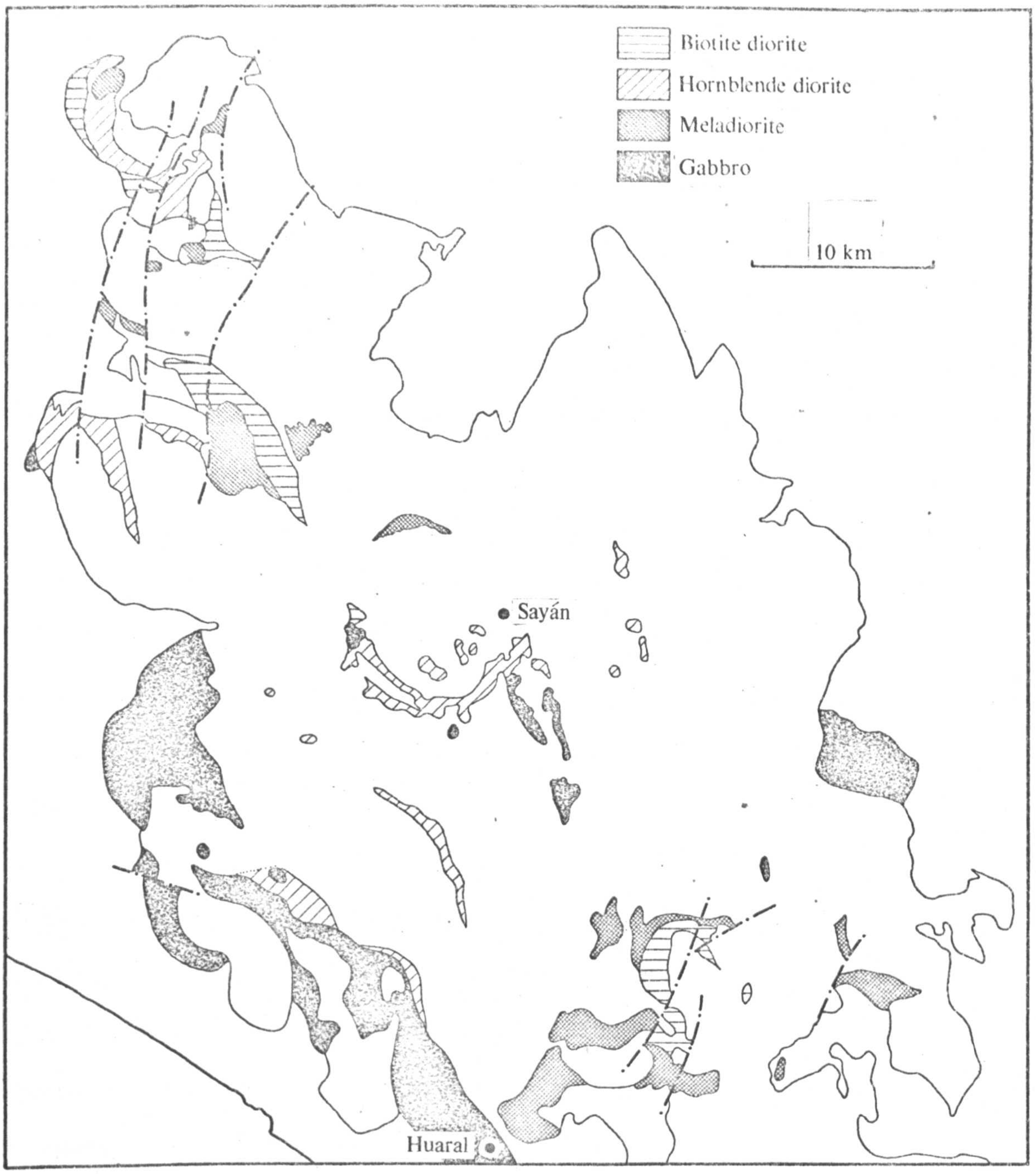


Fig. 19 Diagram showing the distribution of basic rocks (Patap Complex) in the area of study. After Cobbing and Pitcher (1972a).

Haural Gabbro is the natural choice for finding material suitable enough to give an emplacement age.

Lithologically the Haural Gabbro displays a wide range of internal variations which provide insight into an extremely complex emplacement history. Thus an original two pyroxene $\pm$ olivine gabbro, often displaying a cumulate texture, changes progressively by processes involving uralitisation and hybridisation into a meladiorite having a granulose metamorphic texture. These metamorphic changes have been interpreted as the interaction of a crystal mush with late volatile rich fluids in a tectonically controlled regime. The processes involved are of course much more complex then portrayed by the writer, and for further details the reader is referred to the major contributions by Knox (1971), Cobbing and Pitcher (1972), Cobbing (1973), Regan (1972, 1975), Bussell (1975) and Myers (1975b).

Chronology of Emplacement of the Haural Gabbro

If the ultimate stage of amphibolisation and hybridisation of the gabbro is attributed to rising volatile rich fluids representing the forerunners of the Santa Rosa tonalites, as some authors believe (Knox, 1971; Regan, 1975), then it is likely the dating of the gabbros will reflect this event.

Only one sample of the gabbro was analysed (Table 18) because of the unlikelihood of obtaining a significant result. The dated sample produced highly discordant ages on co-existing hornblende and plagioclase. The plagioclase (An_{60}), which yielded the older age (90 m.y.), was extremely fresh, euhedral and showed no indication of alteration. Conversely the hornblende which produced a younger age (73 m.y.) represents the only mafic mineral, indicating that the process of amphibolisation has gone to completion.

An important question arises from this discordant age pattern which concerns the significance of the hornblende age. It could either reflect the formation of the mineral, or conversely, resetting of the argon clock. The latter explanation is preferred by the writer since the sample was collected within the postulated zone of influence of the Humaya and Lachay monzogranites, with which the hornblende age corresponds (73 ± 3 m.y.). The greater resistance of the plagioclase to this 'event' further signifies the potential of plutonic plagioclase feldspars as geochronometers (see preceding section). In fact plagioclase provides the only primary magmatic mineral present in the gabbros which would provide a 'maximum age'. Despite this the plagioclase age is still only a reflection of the emplacement of the Santa Rosa tonalite.

Sample	Mineral	K%	Vol Rdg $^{1}Ar^{40}$ x 10^{-7} scc/gm	Age
A1	P H	0.21 0.315	7.686 9.3799	90 ± 2 73 ± 3

In summary the writer feels that a direct radiometric assessment of the age of emplacement of the gabbros is a hopeless task, especially with the restrictions of the K.Ar method. Neither is the situation improved by the characteristically low Rb/Sr ratios and zircon content of the gabbro.

A satisfactory appraisal of the age of the gabbros can be gained from knowledge of their temporal relationship to both the envelope rocks, and the Santa Rosa tonalite. This dates their emplacement in the interval 100-95 m.y. (mid-Cretaceous) which implies they are coeval with the folding of the Casma group; a conclusion which is in agreement with the structural evidence for a syntectonic emplacement (Cobbing and Pitcher 1972; Regan 1975 and Bussell, 1975).

In general the basic rocks which form the forerunners in other Cordilleran Batholiths are always reheated by younger, more acid plutons, and consequently their ages only reflect these later intrusive events. However, McDowell and Kulp (1969) have reported K.Ar ages on gabbros from the Idaho Batholith, which are considerably older than the tonalite ages. Furthermore, the oldest ages obtained from the Alaska-Aleutian batholith are by K.Ar on hornblende gabbro (Lanphere and Reed, 1973). Henry (1972) has proposed the existance of an 'intrusive epoch' for gabbroic rocks of the Sinaloa batholith (Mexico) which precedes the intrusives of intermediate composition by 30 m.y. This hiatus between gabbro emplacement and emplacement of the more acidic rocks has also been recognised on stratigraphic evidence (Mullan, 1975).

In Peru however, such a hiatus does not exist and the gabbros bear an extremely close temporal relationship with the main tonalitic units of the batholith. This relationship alone is strong enough to imply consanguinity although present geochemical studies are beginning to envisage a different source for the basic magmas (McCourt, W. pers. comm).

CONTINUATION OF THE EARLY UNITS OF THE BATHOLITH TO ADJACENT AREAS

A similar spatial association of the Patap, Paccho and Santa Rosa Super-units has been recognised in adjacent areas. Gabbros and diorites continue to occupy the western margin of the batholith, or occur as screens and remnants. Moreover the paired tonalite bodies, described in the preceding section, have their equivalents to the north and south. Thus, Cobbing (1973) has equated the Cayan tonalite of the Chancay valley with the Santa Rosa tonalite. In addition the Paccho-Santa Rosa Super-units have been correlated with the Purmacana and Cerro Muerto units of the Barranca quadrangle (Cobbing, 1973). Myers (in press) extrapolated these units further north to the Huarmey area, where he has described an eastern complex of quartz diorites which he termed 'Paccho'. These in turn are intruded by a younger group of tonalites, which occupy a more westerly position in the batholith, and are equated with the Santa Rosa Super-unit.

It seems these associations are diagnostic along a considerable length of the batholith, thus Bussell (1975) has mapped western gabbroic units and paired tonalites as far north as Chimbote. It is not yet known how far these complexes continued south of Lima for preliminary mapping around Ica shows the batholith to be markedly different in that it consists of a sheeted diorite complex for most of its outcrop width (Agar,R. pers. comm.).

This correlation of 'units' between different areas is based largely on lithological and structural similarities. One of the writers intentions was to examine the validity of this by comparing the ages of the units in different areas, however this theme proved to be rather ambitious because time did not permit the detailed sampling, and dating, which was required. Instead only a few age determinations were carried out from plutons in adjacent areas and the results combined with others reported by Stewart and others (1974).

The Purmacana diorite-tonalite complex

The Purmacana tonalite complex occupies the western margin of the batholith in the Barranca quadrangle (see Cobbing and Garayer, 1971); it is entirely emplaced within the Casma volcanics isolated remnants of which also occur as roof pendants. Contacts which show a relationship with other units of the batholith are generally scarce, however Cobbing and Pitcher (1972) have described a contact which shows the Purmacana to be intruded by the Santa Rosa tonalite.

The Purmacana complex consists of rocks ranging from diorite to monzogranite in composition, with tonalite forming the dominant lithology. Cobbing (1973) therefore proposed the Purmacana body to be of a composite nature even though it has not been mapped in any detail.

A sample of the main tonalitic facies was collected for dating and yielded an age of 95 m.y. from a concordant hornblende-plagioclase mineral pair (Sample A126, table 18). However, the co-existing biotite gave a younger age (85 m.y.) which is presumably related to a mild reheating event. The writer dismisses a slow delayed cooling as a plausible explanation for this discordancy because the occurence of roof pendants and the low grade of metamorphism (Atherton and Brenchley, 1972) point to a shallow depth of emplacement for the Purmacana body. Therefore the writer interprets

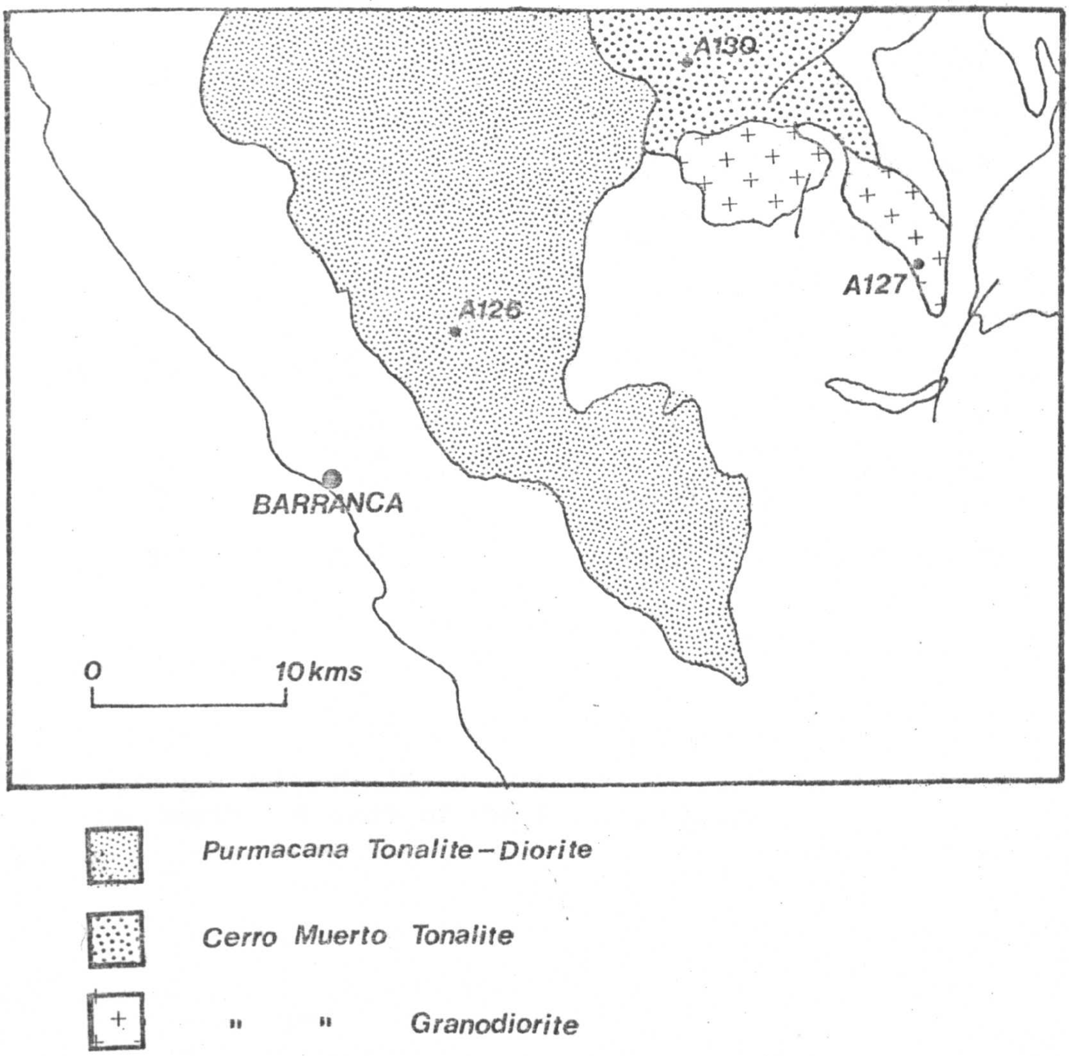


FIG.20 The Purmacana tonalite - Cerro Muerto tonalite association in the Ambar-Barranca quadrangle showing localities of the dated samples, geology after Cobbing and Garayer (1971).

Sample	Mineral	K%	Vol rdg Ar^{40} x 10^{-6} scc/gm	Age
1) Purmacana - Cerro Muerto tonalites				
A126	H	0.36	1.4538	97.9 ± 3.2
	P	0.63	2.4331	94.2 ± 2.1
	B	4.68	16.3182	85.3 ± 1.2
A127	B	5.67	14.3094	62.2 ± 1.2
A130	B	7.4	16.496	55.1 ± 1.0
2) Tonalite complexes south of the Rio Chancay				
A123	B	6.54	15.7469	59.4 ± 1.3
	R	8.66	19.3295	55.1 ± 0.9
	P	0.43	1.30554	74.7 ± 1.8
A124	K	7.36	1.8366	61.5 ± 1.08

Table 18. K.Ar age determinations on tonalitic rocks to the north and south of the Huaura valley.

the 95 m.y. age as an emplacement age for the Purmacana tonalite and on this basis correlates it with the Santa Rosa tonalite further south.

The Cerro Muerto tonalite-granodiorite

The Cerro Muerto tonalite-granodiorite complex intrudes and outcrops immediately east of the Purmacana body (Fig. 20). The complex also cuts the Casma volcanics and Cobbing and Garayer (1971) describe an intrusive relationship with the Calipuy volcanics, although this has proved to be erroneous because the lavas have recently been remapped as Casma volcanics (Cobbing, E.J. pers. comm.).

Two separate plutons have been mapped, the larger is of tonalitic composition containing biotite and hornblende in equal proportions, whilst granodiorite forms the other pluton and has a greater proportion of biotite. Cobbing (1973) was unable to establish a relative chronology of their emplacement because of the inaccessability of the contact, but assumed a younger age for the granodiorite based on the overall basic to acid trend of the batholith.

Both the tonalite and granodiorite were dated using biotite separates, the tonalite gave a younger age than the granodiorite (sample A127, 62 m.y.). In view of the paucity of information concerning the relative chronology of the Cerro Muerto complex, these results must be treated as minimum ages.

The batholith in the Pativilca valley differs from the other sections examined, in the absence of a centred acid complex and consequently tonalites extend for a greater distance across the batholith. The only indication of any younger intrusive activity is the Pativilca monzogranite pluton which outcrops 3 kms east of the Cerro Muerto granodiorite.

Due to the absence of any evidence which could account for the bulk loss of radiogenic argon from the dated samples the writer tentatively suggests that the Cerro Muerto complex, rather than being related to the Paccho Super-unit as inferred by Cobbing (1973), comprise a group of lower Tertiary tonalites. This hypothesis gains a certain amount of support from the geochemical similarity of the Cerro Muerto complex to the 'La Mina' complex (McCourt, pers. comm.), the age of which is discussed in a later part of the thesis.

Chronology of the Tonalite Complexes south of the Rio Chancay

In the south-eastern sector of the Huaral quadrangle (Fig. 21) two large tonalite plutons have been mapped which have features in common with the Paccho and Santa Rosa Super-units further north. The two complexes have been named the Paraisio and Cayan tonalites and are both cut by a narrow tongue of Santa Rosa tonalite (Cobbing, Pitcher and Garayer, 1971). A third more isolated pluton, the Pacaybamba tonalite, outcrops some ten kilometres to the east and is almost entirely emplaced within the Casma volcanics; its age relative to the Santa Rosa tonalite is not known. For detailed descriptions of these three plutons the reader is referred to the memoir which accompanies the geological map of the area (Cobbing, 1973).

Orthoclase separated from the Cayan tonalite (Sample A124) gave an anomolously young age (61 m.y.) when contrasted with the

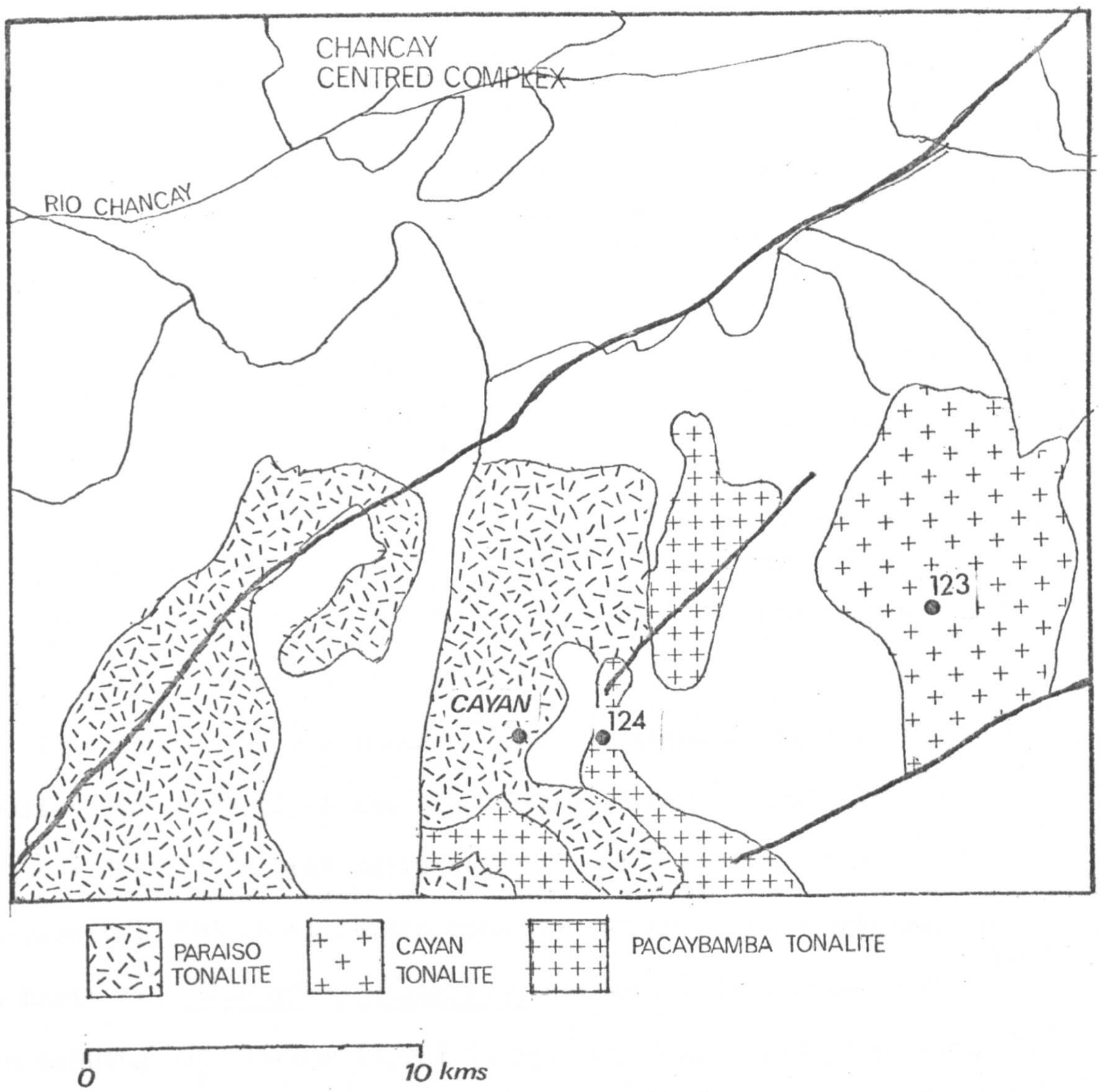


FIG.21 The Complexes of tonalites to the south of the Rio Chancay, geology after Cobbing (1973) sample localities are included and are discussed in the text.

aforementioned field evidence. Two feldspars and biotite separated from the Pacaybamba tonalite (Sample A123) produced ambiguous ages, the biotite and orthoclase were concordant (59 m.y.) yet markedly younger than the associated plagioclase (72 m.y.). In order to quantify the significance of the plagioclase age a replicate analysis is required. However, without placing too much emphasis on the individual plagioclase age, the results suggest that argon loss has occurred and at best the 59 and 61 m.y. ages date the termination of this episode of argon loss. In fact these lower Tertiary ages possibly correspond to the climax of activity of the Chancay centred acid complex, which is discussed in the following section.

In summary, the available radiometric evidence from the tonalite bodies south of the Rio Chancay is too inconclusive to enable a direct temporal correlation with the Paccho-Santa Rosa Super-units; this must remain open for future work. Certainly on the basis of lithological comparison the writer is in agreement with Cobbing and Pitcher (1972) in equating these tonalites with the early units of the batholith.

The problems encountered by the writer in the detailed study of the early members of the batholith in the Rio Huaura section endangers a reconnaissance correlation of ages to other areas. Nevertheless this situation is not entirely hopeless because radiometric age data reported for other sectors of the batholith show that a close temporal correlation of diorite-tonalite units exists along a considerable part of its western margin (Fig. 22). Thus, inland from Lima, the Machay diorite gave a concordant biotite-hornblende age of 89 ± 3 m.y. and the associated Ataconga monzogranite yielded a concordant biotite hornblende age of 102 ± 1 (Stewart and others, 1974). Stewart and his co-workers also describe ages from a monzogranite (92 m.y.) and a granodiorite (86 m.y.) in the batholith near Chincha, south of Lima.

Giletti and Day (1968) have reported a biotite age of 89 m.y. from a granite dyke cutting tonalite (Santa Rosa?) inland from Casma.

This apparent consistency of ages along the western margin of the batholith lends support to the hypothesis of Cobbing and Pitcher (1972) that identical magma types show the same relative chronology along the length of the batholith.

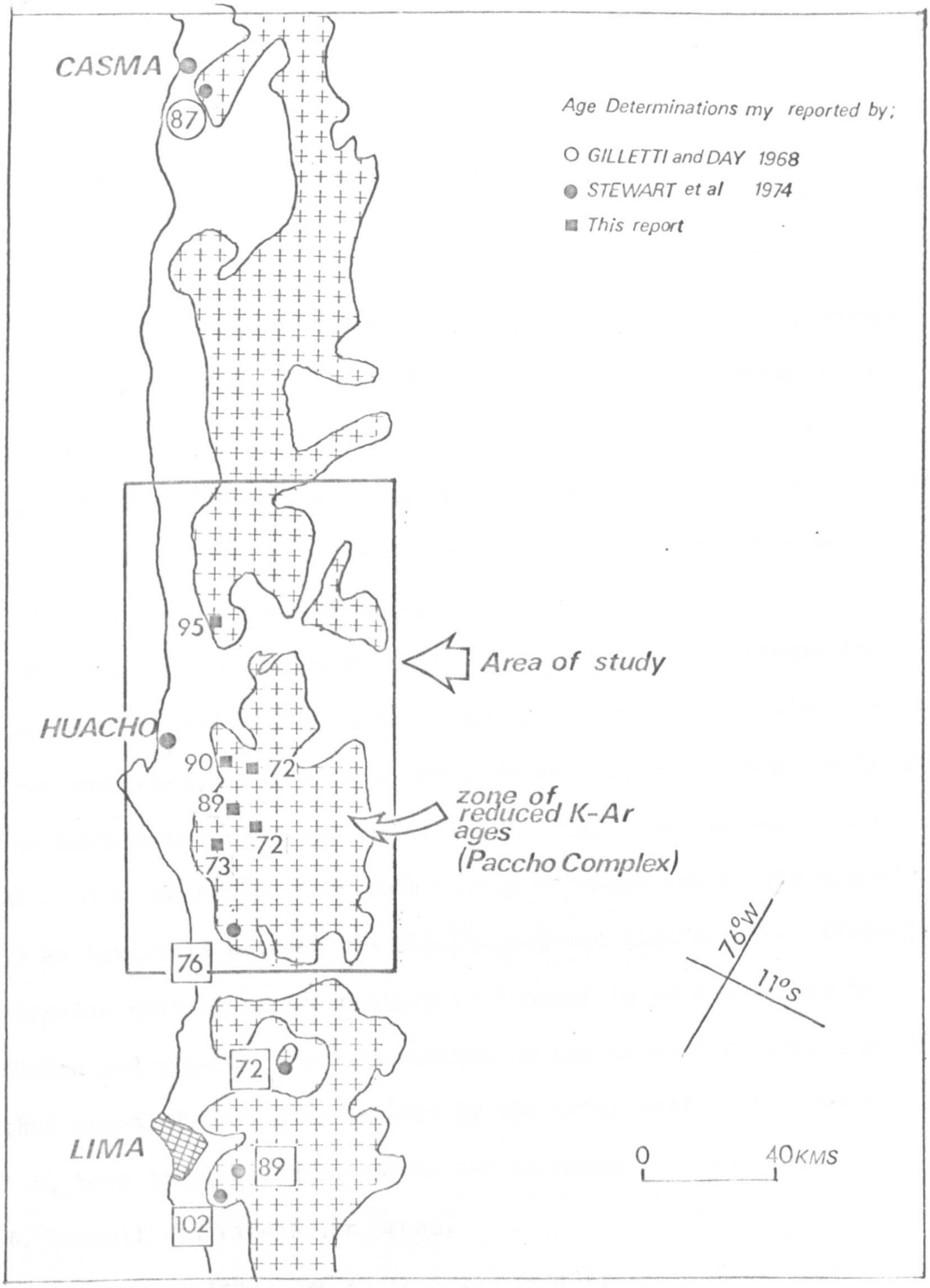


FIG.22 Correlation of ages on the early units of the Coastal batholith, to adjacent areas.

2. THE CHRONOLOGY OF EMPLACEMENT OF THE CENTRED ACID COMPLEXES AND RELATED ROCKS

Introduction

The simple bilateral symmetry displayed by the outcrop patterns of the early tonalite units is enhanced by the emplacement of more acidic granitoids along the centre of the batholith. That the Paccho and Santa Rosa Super-units form the host rocks of these younger intrusions partly explains the discordant age patterns which were described in the previous section.

The younger granitoids range in composition from granodiorite to monzogranite and have a tendency to form multiple intrusions, acid centred complexes, which outcrop at regular intervals along the length of the batholith throughout the area of study. Cobbing and Pitcher (1972 a) have described four such complexes which are evenly spaced at 35 km intervals between the Rio Chancay and Rio Fortaleza (Fig.23). The regular spacing of the centres is thought to be controlled by the thickness and physical characteristics of the crustal carapace, notably in that zones of weakness, defined by the intersection of major oblique faults, have localised the emplacement of magma at these centres (c.f. Bussell and Pitcher,in press).

All four centres have essentially similar characteristics pertaining to their mode of emplacement, association of the different rock types and relative chronology. With the exception of the Chancay centre and the early episodes of the Paros complex (Fig. 23), the Centred Complexes always post-date the Santa Rosa Super-unit and truncate the main dyke swarm. On this basis Cobbing and Pitcher (1972 a) and Cobbing (1973) have proposed a coeval relationship

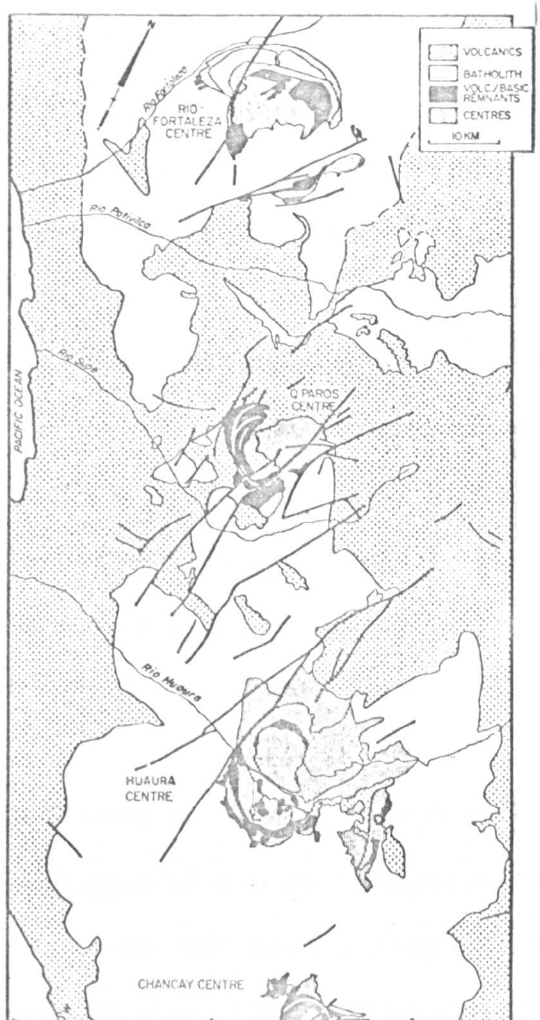


FIG.23 The Centred Complexes in the area of study, from Cobbing and Pitcher (1972) and Knox (1974).

between the three northerly complexes. The observation by these authors that members of the Santa Rosa dyke swarm intrude the Chancay centre provides insight into the long duration of activity of the complexes. Thus, both the Chancay and Paros centres contain dioritic units which have been correlated with the Patap and Santa Rosa Super-units. Further, Bussell (1975) has also correlated the dioritic remnants of the Huaura complex with these early components of the batholith.

Unfortunately the early phases of activity of the Centred Complexes are only demonstrable on the basis of lithology and structure because their disruption by the younger monzogranites will have totally re-set the K.Ar clocks. The following section is therefore restricted to the presentation of radiometric age data on the granodiorite-monzogranite suites which represent the most recent phase in the evolution of the complexes.

The writer studied the Huaura complex in some detail with the aim of comparing the results with ages of a more reconnaissance nature from the three other centres. To avoid confusion the writer has chosen to describe the salient features of each complex separately; the general findings being summarised in a concluding section.

The Huaura Complex

The Huaura complex straddles the Rio Huaura due west of the village of Sayan; it has a roughly circular outline with a mean diameter of 20 kms (Fig.24). The complex was initially mapped by Cobbing, Pitcher and Garayer (1971) and on this basis described by Cobbing and Pitcher (1972 a) and Cobbing (1973). More recently it has formed the theme of a detailed structural study by Bussell (1975).

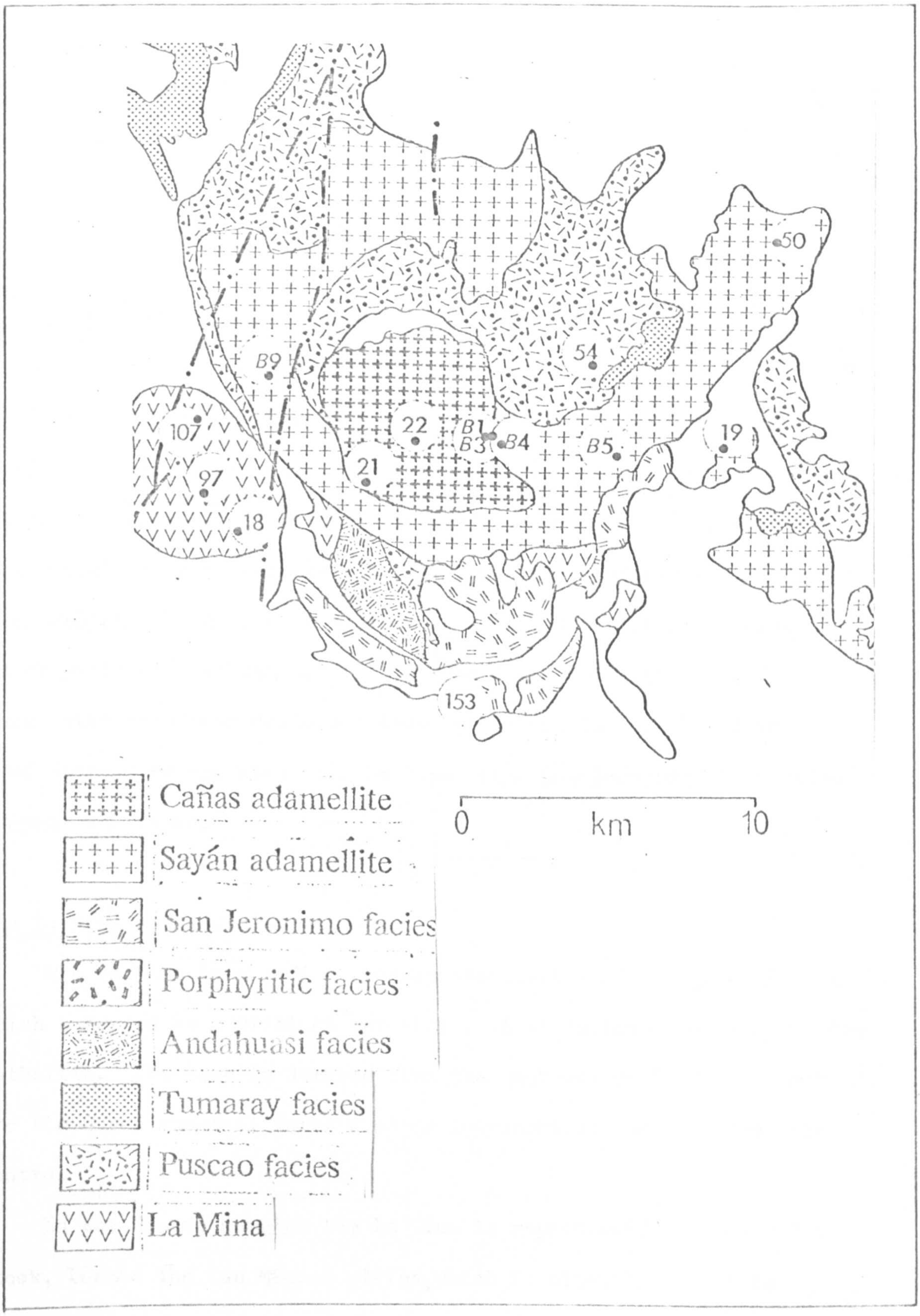


Fig.24 Generalised map of the Huaura Centred Complex, showing localities of dated samples. Geology after Cobbing and Pitcher (1972a).

The evolution of the complex can be divided into two main periods of intrusive activity;

1) Basic rocks of the Patap Super-unit intruded into the Casma volcanics and foundered into rising plutons of the Santa Rosa Super-unit (tonalites).

2) The emplacement of a series of acid bell-jar plutons and ring dykes enclosed within a remnant of the original basic centre.

The former phase of activity can only be dated relatively by correlation with the radiometric age data presented in the preceding section. The age of the second phase of activity has been dated more directly. It comprises of a centrally emplaced granite pluton which is enclosed within a multi-componental ring dyke, the northern part of which has been obscured by a complex of three monzogranite plutons forming a second slightly offset centre. Within this framework a total of five separate units have been defined : these are shown in Fig.24 and in order of decreasing age are; i). La Mina ii). San Jeronimo iii). Puscao iv). Sayan v). Canas.

i) The La Mina - the San Miguel stock

The La Mina is a medium grained biotite-hornblende granodiorite which outcrops as a distinct mappable unit at various places along the batholith. Its name is derived from the Quebrada de La Mina, north of the Rio Supe, where it forms a major component of the Quebrada Paros centre.

In the Huaura complex the La Mina is represented by a circular stock, termed the San Miguel pluton, which is slightly offset to the west of the main centre. Minor outcrops also occur as disrupted remnants within the main ring dyke. The stock has an overall diameter of 8 kms and is almost entirely emplaced within the Santa Rosa tonalite. An eastern contact with the younger Sayan monzogranite is faulted, and unexposed due to a covering of recent alluvial deposits.

Two features concerning the relationship of the San Miguel pluton to its host Santa Rosa tonalite are noteworthy;

1) The contact between the two rock types can easily be traced along the south-west slopes of Cerro Santa-Maria where a classical joint controlled contact is visible (see Bussell, in press).

2) Members of the Santa Rosa dyke swarm are truncated at this contact (Plate 1) while others penetrate as far as an internal potash rich facies.

The internal facies of the San Miguel pluton is thought to represent a primary zoning probably caused by a process such as that outlined by Vance (196). The writer's observations of the contact in the north-western part of the pluton clearly demonstrates a younger age for the inner facies. Here the contact was marked by a one metre wide melange containing schlieren of granodioritic xenoliths parallel to the contact. Elsewhere the contact appears to be more gradational (Bussell, pers comm.).

Lithologically the marginal facies comprises of a medium-grained hornblende-biotite tonalite varying locally to granodiorite. Hornblende is present as well developed prisms frequently twinned and in the form of irregular clusters which are partly replaced by biotite. Biotite also occurs as large brown plates with irregular to euhedral outlines. Plagioclase laths (An 40) form an interlocking meshwork with quartz occupying the interstices. Late altered orthoclase plates are present in varying amounts and corrode the pre-existing minerals.

In contrast, the internal facies is a distinctive creamy coloured rock having irregular patches of chloritised mafic minerals. Plagioclase is well zoned yet thoroughly sausseritised and corroded by quartz and orthoclase. The orthoclase occurs as large interstitial plates which are slightly perthitised and form the only mineral suitable for dating.

K.Ar Age determinations

Of the three samples which were dated, two were collected from the outer facies, the third corresponds to the internal facies. The results are tabulated below and the sample locations shown in Fig 24.
The discordancy displayed by the cogenetic hornblende-biotite mineral pair of Sample A18 can be attributed to the partial loss of accumulated argon from the biotite. It is unlikely that the movement associated

Sample	Mineral	K%	Vol Rdg Ar^{40} x 10^{-5} scc/gm	Age
A18	B	7.46	1.8687	62 ± 1.4
	H	0.173	0.1728	69.8 ± 1.8
A97	K	10.18	2.6838	65 ± 1.1
A107	B	6.13	1.627	65 ± 1.2

Table 19. Age determinations from the San Miguel pluton.

with the neighbouring fault (Fig. 24) was sufficient to cause this discordancy for comparable studies have shown that faulting has to be intense to produce argon loss from micas (Lee and others, 1970). Thus reheating is a more likely explanation and it is interesting to note that the biotite age (62 m.y.) corresponds to the climax of activity of the Huaura complex.
Conversely the biotite separated from a sample collected from the outer facies, further away from the Huaura centre, produced an age of 65 m.y (Sample A107). This is in agreement with a determination on orthoclase separated from the inner leucocratic facies (Sample A97). A problem now arises concerning the significance of these two ages. The resolution of the method does not permit a distinction to be made between these values and the hornblende age from Sample A18 (69.8 m.y.), even

though this may be a realistic estimate of a true emplacement age. Thus, the inner facies could be younger by as much as 4 m.y. The writer has calculated a preferred age of 66 ± 0.7 m.y. for the San Miguel stock, based on the weighted mean of the three mineral ages, which is interpreted as a minimum age of emplacement.

(ii) The San Jeronimo Unit

The San Jeronimo unit is an important component of the Huaura complex and plays a significant role in its early history. It outcrops in two broad associations; firstly south of the Rio Huaura where it forms a partly disrupted ring dyke. However its main development occurs as a number of closely related plutons which straddle the Rio Supe some 30 kms to the north. Three distinct facies of the San Jeronimo unit have been recognised by Cobbing and Pitcher (1972):

(1) San Jeronimo facies; commonly a medium grained granophyre.

(2) A porphyritic facies; composed of large cream-coloured feldspar phenocrysts in a fine-grained orange groundmass.

(3) The Andahausi facies; a fine grained monzonite with a high proportion of mafic minerals.

All three facies are easily recognisable and generally exhibit gradational contacts towards each other.

Rocks of the San Jeronimo unit are generally unsuitable for dating because of the deep level of weathering and the scarcity of mafic minerals which, when present, are always extensively altered and tend to occur as chloritised aggregates.

	Sample	Mineral	K%	Vol rdg Ar^{40} x 10^{-5} scc/gm	Age
(i)	San Jeronimo				
	A153	B	4.54	1.0969	59.5 ± 1.4
		K	10.02	2.5391	62.4 ± 1.0
	A105	B	5.65	1.5961	56.2 ± 1.0
(ii)	Puscao				
	A27	B	6.83	1.814	64.9 ± 0.7
		K	9.15	1.4722	40 ± 0.6
	A56	B	6.38	1.4767	57 ± 1.2
	A54	B	6.66	1.6617	61.7 ± 1.2
(iii)	Sayan				
	B4	B	6.72	1.6441	60.3 ± 1.0
	B5	B	6.54	1.6157	60.9 ± 1.0
	B9	B	6.97	1.7251	61.9 ± 1.0
	A50	B	6.21	0.8059	31.0 ± 0.7
	A50	K	8.94	1.1616	32.3 ± 1.2
(iv)	Canas				
	B1	B	7.23	1.7483	59.6 ± 0.9
	B3	B	7.16	1.7930	61.7 ± 1.1
	A21	B	6.91	1.8076	64.4 ± 1.6
	A22	K	9.77	2.4132	60.8 ± 1.0
		B	5.92	1.4997	62.4 ± 1.0

Table 20. K.Ar age determinations from the Puscao-San Jeronimo plutons between the Rio Huaura and Rio Supe and from the Sayan and Canas monzogranite plutons of the Huaura complex.

Only two samples were dated, one from the southern extremity of the Huaura ring dyke (Sample A153), here the characteristic granophyric intergrowth was absent and K feldspar occurred as subhedral crystals of microperthitic orthoclase. Biotite was present as isolated brown flakes with ragged outlines and only marginally chloritised. A biotite-orthoclase pair separated from this sample yielded a concordant age of 61.4 m.y.

The second age determination was calculated on a biotite separated from the Andahuasi facies (Sample A105) which outcrops along the Rio Supe, and gave a younger age of 56 m.y. In the writers opinion these results probably reflect a true difference in age between the two facies of the San Jeronimo unit.

Within the Huaura ring dyke the San Jeronimo magma shows an extremely close relationship to another more basic unit termed the Puscao, which will now be described.

(iii) The Puscao Unit

Members of the Puscao unit display a similar spatial pattern in the Huaura complex as the San Jeronimo unit. Thus rocks assigned to the Puscao unit contribute to the Huaura ring dyke. Another more voluminous association occurs north of the Rio Huaura where a large NW - SE trending pluton extends for some 40 kms between the Rio Huaura and Rio Supe and has a maximum outcrop width of 20 kms. This large body is a steep sided flat-roofed pluton which displays a wide range of compositions which are marked by a number of internal variations. Three facies have been defined (Cobbing and Pitcher 1972, Taylor 1973);

(1) Monzogranite facies ('acid Puscao')

(2) Basified xenolithic facies

(3) Tumaray facies.

The dominant facies is a biotite monzogranite, this grades locally into a hornblende granodiorite which contains abundant saucer-shaped microdiorite xenoliths. Cobbing and Pitcher (1972) initially attributed the darker facies to a basification of the monzogranite by the xenoliths. This was later proved to be fortuitous by Taylor (1973) whose detailed geochemical studies showed the darker facies to be the result of a primary zoning, and the xenolith association was therefore purely accidental.

The Tumaray facies is the name given to a distinctive facies which forms a layered pluton along the Rio Supe at Cerro Pan de Azucar. The layering is manifested by large horizontal aplite-aplogranite sheets up to 30m in thickness. They are thought to have formed by collapse within a crystallising magma chamber, mainly because feeders are absent and the flats thin dramatically towards the pluton margin.

By reference to the geological map of the area (Fig. 24) it can be seen that a narrow tongue of the Sayan monzogranite bisects the Puscao pluton, the northern part is dominated by the Tumaray facies (Rio Supe) and the southern granodioritic part is central to the Huaura ring dyke. The Puscao body from the Huaura complex yielded a biotite age of 61.7 m.y. (Sample A54). In contrast the Tumaray facies of the Rio Supe gave a correspondingly older age of 65 m.y. on a biotite separate (Sample A27). Sample A56 dates a biotite pegmatite (57 m.y.) which is associated with the aplite flats of the Tumaray facies. The reason for the younger age of the pegmatite is not fully understood and is therefore interpreted as a minimum age. Moreover the younger age of the Puscao body in the

Huaura complex (61.7 m.y.) is interpreted by the writer as a re-set age which corresponds to the final phase of activity in the evolution of the complex.

The radiometric age data from the Puscao-San Jeronimo plutons north of the Huaura complex tentatively points to an older age for the Puscao body. However, in the Huaura ring dyke which is preserved south of the Rio Huaura, there is a complex interplay of San Jeronimo-Puscao magmas which suggests they are essentially coëval. Some of the conflicting evidence, so well exposed along the Quebrada Huamillache (ref. 598644), is summarised below:

San Jeronimo younger	Puscao younger
Development of fine-grained margins against the Puscao. Veins of pink porphyritic microgranite cutting the Puscao. Flow contacts against Puscao. Rounded xenoliths and schlieren of Puscao in San Jeronimo.	Contains large rafts and xenoliths of San Jeronimo. Flow fabric against the San Jeronimo with xenoliths of San Jeronimo parallel to the contact.

Following a detailed examination of the Huaura ring dyke Bussell (1975) arrived at the same conclusion as Cobbing and Pitcher (1972) in placing the San Jeronimo magma earlier on the balance of evidence. Nevertheless Bussell has placed emphasis on their almost coeval relationship and concluded that the San Jeronimo ring was probably unconsolidated during the emplacement of the Puscao magma.

From these conclusions it is obvious that the age of 61.4 m.y. derived from the San Jeronimo ring dyke (Sample A153) also dates the Puscao ring. The writer interprets this age as the final cooling of the ring dyke to the biotite blocking temperature which, as will be shown later, followed the final stage in the evolution of the complex and does not correspond to the emplacement of the Puscao-San Jeronimo ring dykes.

(iv) The Sayan Monzogranite

The Sayan monzogranite maps out as a uniformily homogeneous yet irregular shaped pluton. It is easily recognisable in the field by the large pink phenocrysts of orthoclase perthite which are commonly 3 cms in length. The Sayan pluton forms the second youngest intrusion of the Huaura complex and flagrantly cuts the San Jeronimo and Puscao bodies along the line of the Rio Huaura. At its eastern margin it intrudes tonalites of the Paccho complex.

To the east of the village of Sayan the monzogranite is in contact with its roof of andesitic volcanics, a relationship which has already been described in connection with the occurence of excess argon in the pegmatitic roof facies (plate 3). The outer contacts of the Sayan pluton vary between vertical and steeply inclined and give the impression of a steep sided flat roofed pluton.
Lithologically the rock is composed of large orthoclase phenocrysts occupying up to 30% by volume of the rock. These form well developed euhedra with prominent carlsbad twinning, their perthite content varies considerably both in intensity and morphology. Plagioclase occurs as pale corroded remnants which are poorly zoned and often show incipient alteration of their cores. Quartz occurs as individual rounded crystals or as large rounded aggregates. Biotite constitutes the only mafic mineral and forms dark brown euhedra often showing chloritisation along cleavage traces.

K.Ar ages were calculated from four samples which were collected along an E - W traverse along the Rio Huaura. The results show there is a considerable difference in age between the western and eastern ends of the body: three biotite mineral ages from the western outcrop gave concordant ages of 61 m.y. (Samples B4, B5, B9). Conversely one sample (A50) from the eastern end of the pluton yielded an age of 31.4 m.y , based on the weighted mean of a concordant biotite-orthoclase pair. This younger value is also in agreement with a biotite age of 33 m.y reported by Stewart and others (1974).

In an attempt to clarify this disparity the data has been plotted on an Ar^{40} vs K^{40} isochron (Fig. 25) the approximate positions of the 61 m.y. and 32 m.y. isochrons are drawn to show the distribution of the data points.

The writer would like to refer once more to the discordant age pattern displayed by the Paccho complex to the east of the Sayan pluton. Biotite ages from the Paccho tonalites reflected the 'younger event' for a considerable distance from the Sayan contact. For this reason the writer suggests the disparity between the age of the western (61 m.y.) and eastern (32 m.y.) parts of the Sayan body is due to a regional disturbance which also extends into the Paccho complex. The author does not propose to speculate on what could have caused the 'resetting' of the argon clocks of the eastern part of the Sayan pluton. However, these mid-Tertiary ages reflect the age of the Pativilca monzogranite pluton which is discussed at length in the next section of the thesis.

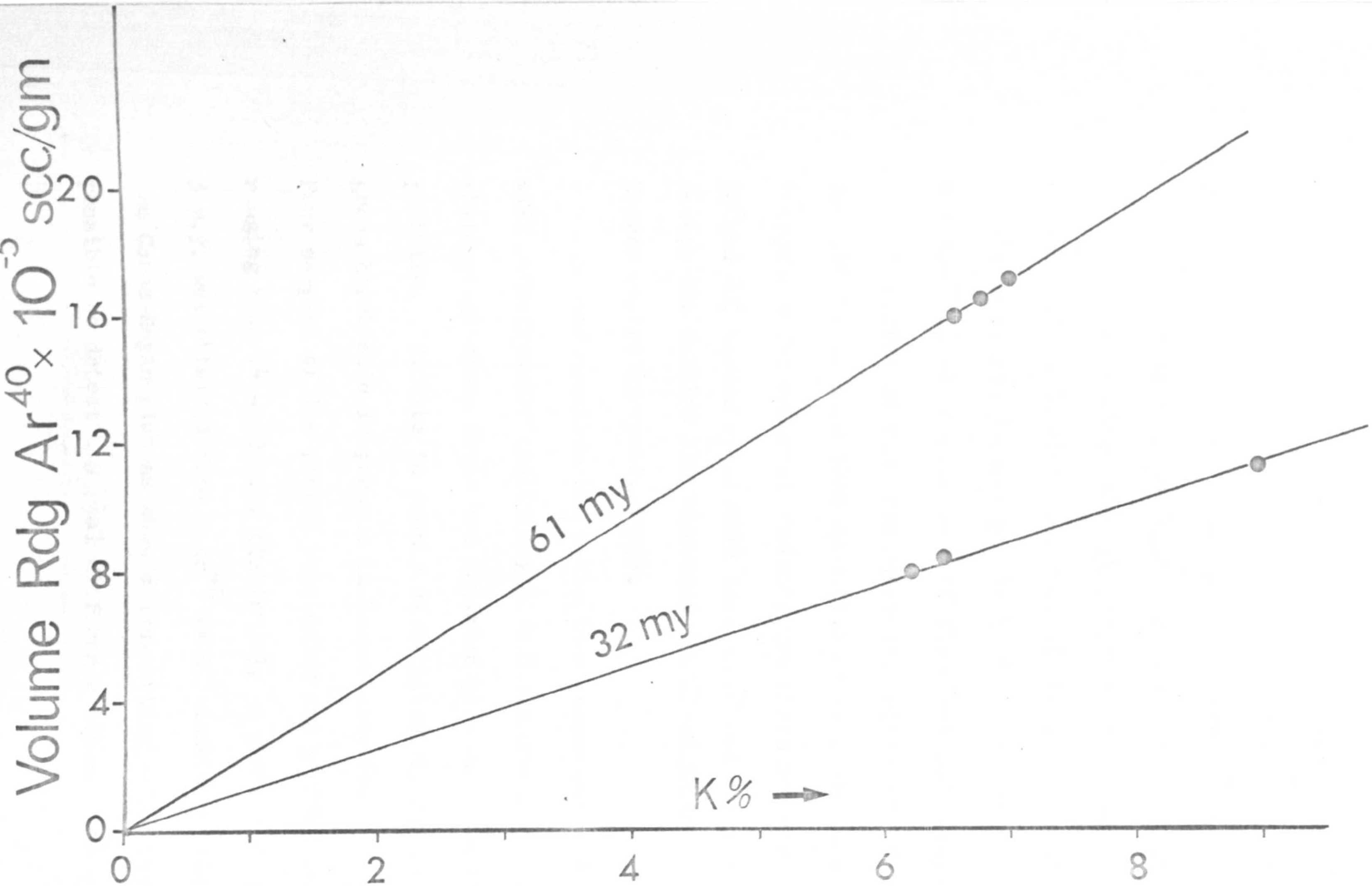


Fig.25 Age determinations from the Sayan monzogranite pluton plotted on a K-Ar isochron in order to demonstrate the difference in apparent age between the two ends of the body.

(v) The Canas monzogranite

The Canas monzogranite forms a circular 8 km diameter pluton which is emplaced in a central position in the Huaura complex and represents the final stage in its evolution.

The Canas is a uniform monzogranite and differs from the Sayan pluton in the absence of large orthoclase phenocrysts. However, it clearly intrudes the Sayan monzogranite and cuts the Puscao pluton to the north. The age relationship between the Canas and Puscao plutons is also confirmed by the attitude of the Puscao isopleths (lines joining points having the same chemistry) which are domed by the emplacement of the Canas body (Taylor, 1974).

A process of cauldron subsidence along outward dipping factures is believed to have been operative as an emplacement mechanism. Everywhere the external contacts are sharp and dip outwards between $50^{o}$and 80^{o}, narrow crescentic screens of meladiorite and gabbro occupy the margins and represent foundered parts of the early Huaura centre (Bussell, 1975).

In hand specimen the Canas is a coarse-grained monzogranite with equigranular quartz crystals dispersed within a network of white plagioclase laths and isolated pink crystals of orthoclase-perthite. Biotite is evenly distributed throughout the rock and green hornblende is present in lesser amounts.
Four samples of the pluton were dated and yielded apparent ages ranging from 64 - 59 m.y. (Table 20). A preferred age of 58 $\pm$ 3 m.y. was obtained from a Ar^{40} vs K^{40} isochron (Fig. 26). Although the Canas-Sayan plutons show cross-cutting relationships it is not possible to detect any real difference between their emplacement

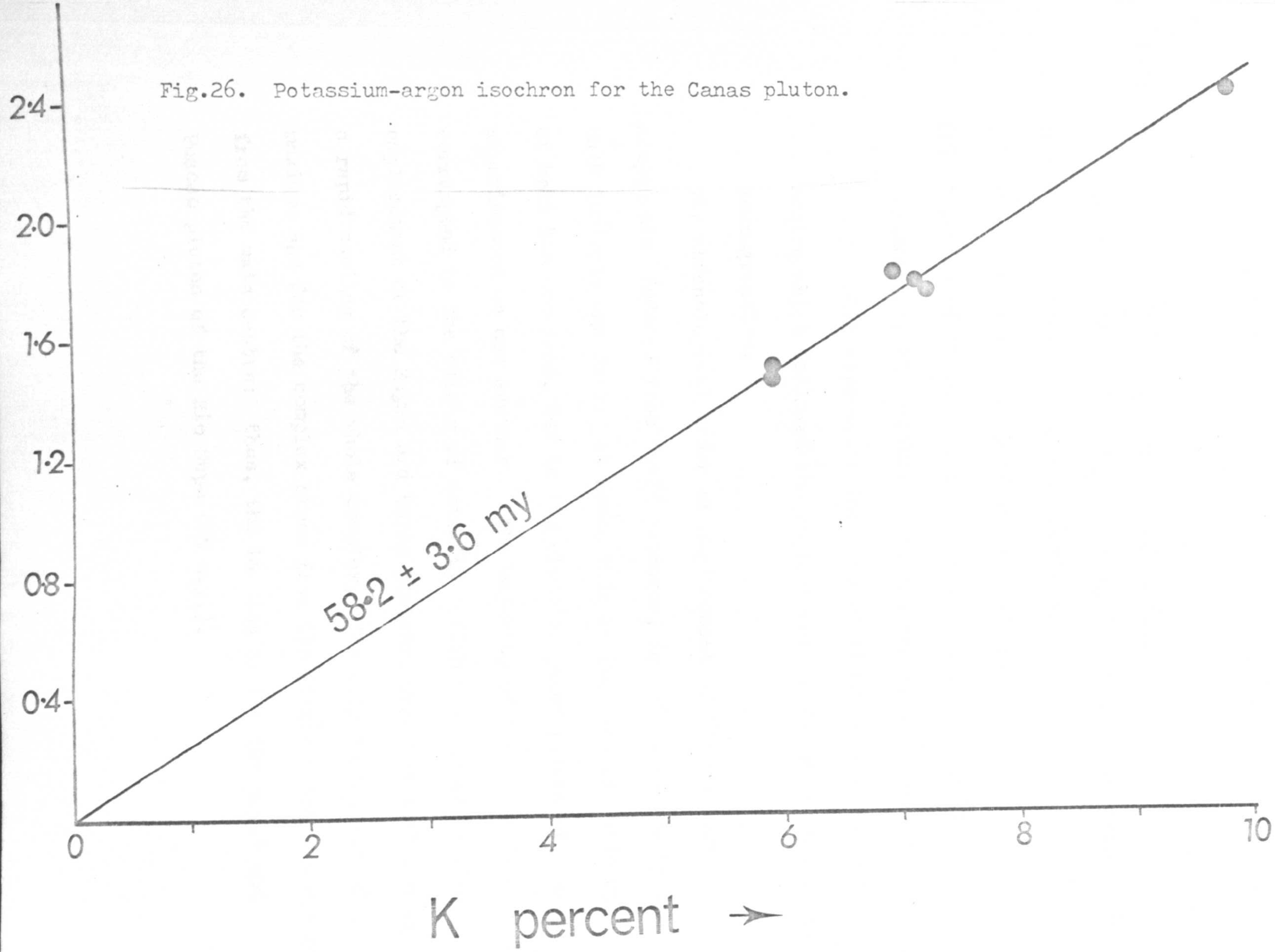


Fig.26. Potassium-argon isochron for the Canas pluton.

ages; in fact it is quite possible that the Canas stock was emplaced before the Sayan pluton cooled to the biotite blocking temperature.

In the following section the writer proposes to summarise the timing of activity of the Huaura complex on the basis of the new age determinations.

(vi) Summary of Chronology of the Huaura Complex

The principal conclusions arising from the radiometric study of the Huaura complex can be summarised;

(1) The complex is wholly of lower-Tertiary age.

(2) A period of at least 5 m.y. has been involved in its emplacement, the climax of activity occurred at 61 m.y and probably represents the time of final cooling of the centre which followed the emplacement of the Sayan and Canas monzogranites.

The chronological order of emplacement of the various components deduced from field evidence, is not reflected by the bulk isotopic age data. It seems that an incremental build up of heat has occurred, due to the closely spaced pulses of magma superimposed on one another. The majority of ages from the centre correspond to the climax of activity which was marked by the emplacement of the Sayan and Canas plutons, this was followed by a rapid cooling of the whole complex. The only indication of a maximum age for the complex stems from the stocks which are offset from the main centre: thus, the La mina pluton (66 m.y.) and Puscao pluton of the Rio Supe (65 m.y.).

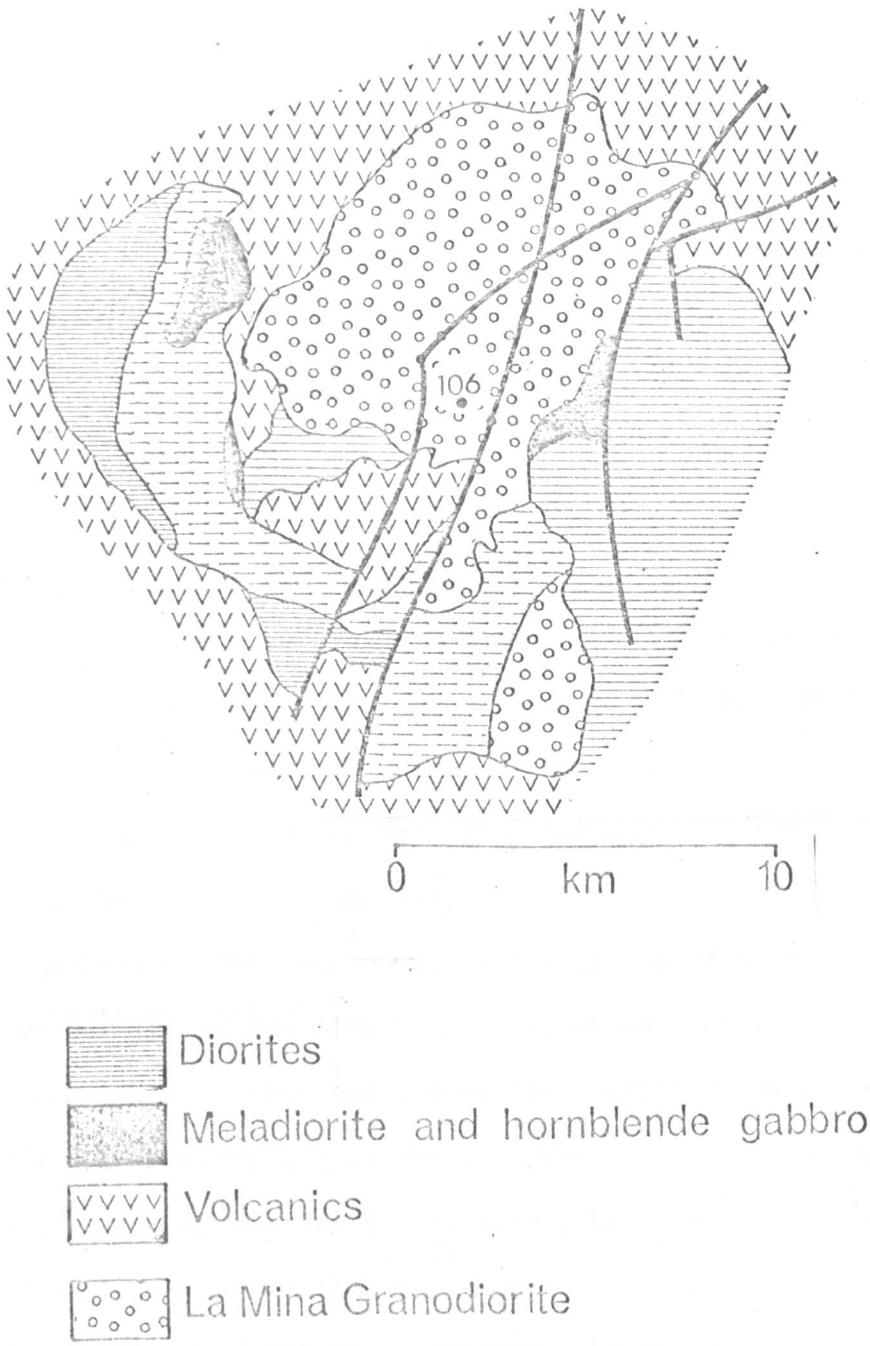


Fig.27 Generalised map of the Quebrada Paros Centre showing the central stock of La Mina granodiorite together with the sample locality, geology after Bussell et.al.(in press

Although a time scale for the evolution of the different components of the Huaura complex is not possible by K.Ar method, it is interpreted as being at least 5 m.y. This parallels the findings of Moorbath and Bell (1965), Kelly (1973) and Mitchell and Reen (1973) for the Tertiary centres of N.W. Scotland.

The Chronology of the Quebrada Paros Centred Complex

It has been shown in the preceding section that acidic plutons of San Jeronimo and Puscao type, straddle a 20 km wide belt along the centre of the batholith between the Rio Huaura and Rio Supe. This association terminates to the immediate north of the Supe in the Quebrada Paros centre (Fig. 27).

The Quebrada Paros centre was initially mapped as a rudimentary complex, consisting of two main components which were assigned to the Patap and La mina units and are entirely emplaced within the Casma volcanics (Cobbing and Pitcher, 1972a). However, a more recent examination by Pitcher (pers. comm.) has shown the centre to be much more complex in that rocks of the Puscao, San Jeronimo and La mina types are involved. Briefly, the structure is dominated by a series of arcuate intrusions; the outer ring is a biotite-hornblende diorite which is cut by a net-veined Puscao complex. A 10 km diameter granodiorite stock is emplaced centrally and represents the latest event in the evolution of the complex. In the Paros centre the San Jeronimo magma is earlier than the Puscao because it occurs as inclusions within the Puscao breccia complex; thus the relationship observed in the Huaura ring dyke appears to be consistent.

Only one sample of the central La mina stock was dated and the author considers the result satisfactory for purposes of correlation. An age of 62.7 m.y. was obtained from a concordant biotite-plagioclase pair and is sensibly coeval with the climax of activity of the Huaura complex.

Sample No.	Mineral	K%	Vol Rdg Ar^{40} x 10^{-5} scc/gm	Age
A106	B P	5.53 0.85	1.40292 0.20685	62.5 ± 1.2 60.2 ± 1.4

Table 21. K.Ar age determinations from the La mina stock of the Quebrada Paros centre.

The Chronology of the Rio Fortaleza Centred Complex

The Fortaleza complex outcrops approximately 35 kms north of the Paros centre and occupies the south-eastern part of the Hauyllapampa quadrange. The geology of this region is described in a recent memoir by Myers (in press) and the Centred complex has been studied in detail by Knox (1971, 1974).

The complex is composed of granodiorites and monzogranites which Knox has equated with the Puscao and San Jeronimo units of the Huaura region. However, the chronology of emplacement differs because the Puscao magma convincingly pre-dates the San Jeronimo magma in the Fortaleza complex. Knox has recorded two main phases of intrusive activity: the former (Puscao) is represented by bell-jar pluton, structurally divisible into the Anta ring dyke and Julquillas roof pluton. The second phase of activity relates to the San Jeronimo unit which is represented by the Corcovado ring dyke (Fig.28).

K.Ar ages were calculated for both the Puscao and San Jeronimo

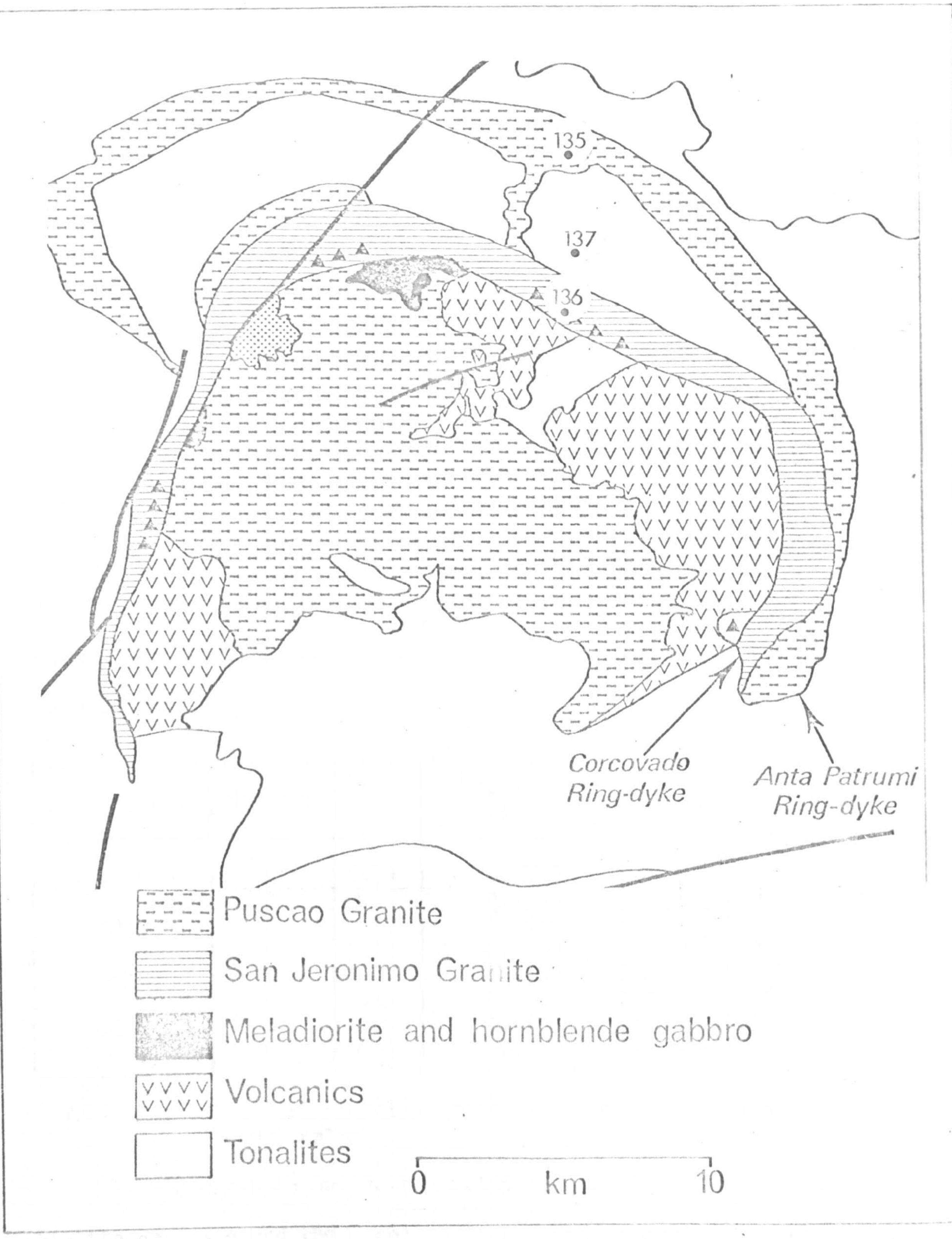


Fig.28 Map of the northern part of the Fortaleza Complex showing localities of dated samples. After Knox,(1972,1974).

units of the complex and will now be discussed.

(i) The Puscao unit

Age determinations from the Puscao unit show an apparent spread between 70 and 58 m.y which, on the surface, implies the unit was intruded over a period of 12 m.y. This inference is based on age determinations from both the Chasquitambo pluton and the Anta ring dyke.

The Chasquitambo pluton outcrops to the north-east of the Fortaleza complex and occupies an area of 300 sq. kms. It contains two distinct sub-units, the former being a tonalite which is intruded by a younger monzogranite variant.

Sample No.	Mineral	K%	Vol. Rdg Ar^{40} x 10^{-5} scc/gm	Age
A134	B	5.71	1.6438	70.7 ± 1.6
	P	0.414	0.10547	62.8 ± 1.3
A135	B	6.17	1.5511	61.9 ± 1.4
	K	9.41	2.2079	57.9 ± 0.9
A136	B	5.81	1.3303	56.5 ± 1.2
	K	9.95	2.2129	54.9 ± 0.88
A137	B	6.29	1.5654	61.3 ± 1.2
	K	9.13	2.2913	61.9 ± 1.0

Table 22. Age determinations from the Fortaleza Centred Acid Complex.

The monzogranite sub-unit yielded an age of 70.7 m.y. on a biotite separate and the associated plagioclase gave a younger value of 62.8 m.y (sample A134).

The Anta Ring Dyke outcrops as a one kilometre wide monzogranite forming an arcuate structure having an overall length of 24 kms and a radius of 10-12 kms. Its outer contact with earlier tonalites is clear and sharp and generally dips outwards at 80° - 90°. The southern part of the ring has been cut out by the intrusion of the younger Corcovado ring dyke (Fig. 28). A monzogranite forms the dominant lithology although this grades locally to a granodiorite. Both Knox (1971) and Myers (in press) have emphasised the lithological similarities between the Anta ring dyke and the Chasquitambo pluton.

Two samples from the Anta ring were analysed by the writer; sample A135 corresponds to the typical monzogranite and yielded an age of 61.9 m.y. on biotite and 58 m.y. on a co-existing orthoclase. An associated quartz-feldspar porphyry gave concordant results of 61.7 m.y from a biotite-orthoclase mineral pair (sample A137).

Thus the similarity between the Chasquitambo pluton and the Anta ring, described by Myers, is not reflected by the age determinations which suggests that a period of at least 9 m.y. is involved in the emplacement of the Puscao magma in the Fortaleza centre.

(ii) The San Jeronimo Unit

The San Jeronimo unit is represented by three plutons on the eastern side of the batholith and the Corcovado ring dyke in the Fortaleza centre. At all these localities the San Jeronimo unit clearly post-dates the Puscao plutons.

The Corcovado ring dyke (= Patirumy ring dyke of Knox 1971, 1974) has a width of between 1 and 2 kms and forms an arcuate structure some 30 kms in length. Knox (1974) has described three main facies which include granophyres, a porphyritic facies and Tuffisites. The main porphyritic facies comprises flecks of biotite and euhedra of orthoclase perthite set in a fine grained groundmass.

Both the biotite and orthoclase were separated and gave a concordant age of 55.6 m.y ; clearly demonstrating the younger age of the San Jeronimo ring dyke.

It is evident from this data that a strong temporal correlation exists between the Fortaleza and Huaura centres, although they certainly differ in so far as the same magma types are emplaced at different periods of time. K.Ar dating has permitted the recognition of two separate phases of activity in the Fortaleza centre; unlike the Huaura centre where the separate phases of intrusion were unresolvable using the K.Ar method. Perhaps the answer to this lies in the more ideal preservation of the Fortaleza centre which has not been as disrupted by younger plutons as its counterpart in the Rio Huaura.

The Age of the Chancay Centred Complex

The final and most southerly complex straddles the boundary between the Paccho and Santa Rosa Super-units along the Rio Chancay (Fig. 29). It differs from the other centres in that it is believed to be a much older structure which ceased to be active following the emplacement of the Santa Rosa Super-unit (Cobbing and Pitcher 1972a, Cobbing 1973).

The earliest members correspond to a meladiorite and younger biotite diorite, which are demonstrably older than the tonalites of the Paccho and Santa Rosa Super-units. A centrally emplaced 8 km diameter stock, termed the Lumbre monzogranite, forms the youngest component of the Chancay centre and has been classified as a late monzogranite variant of the Santa Rosa complex by Cobbing and Pitcher (1972a).

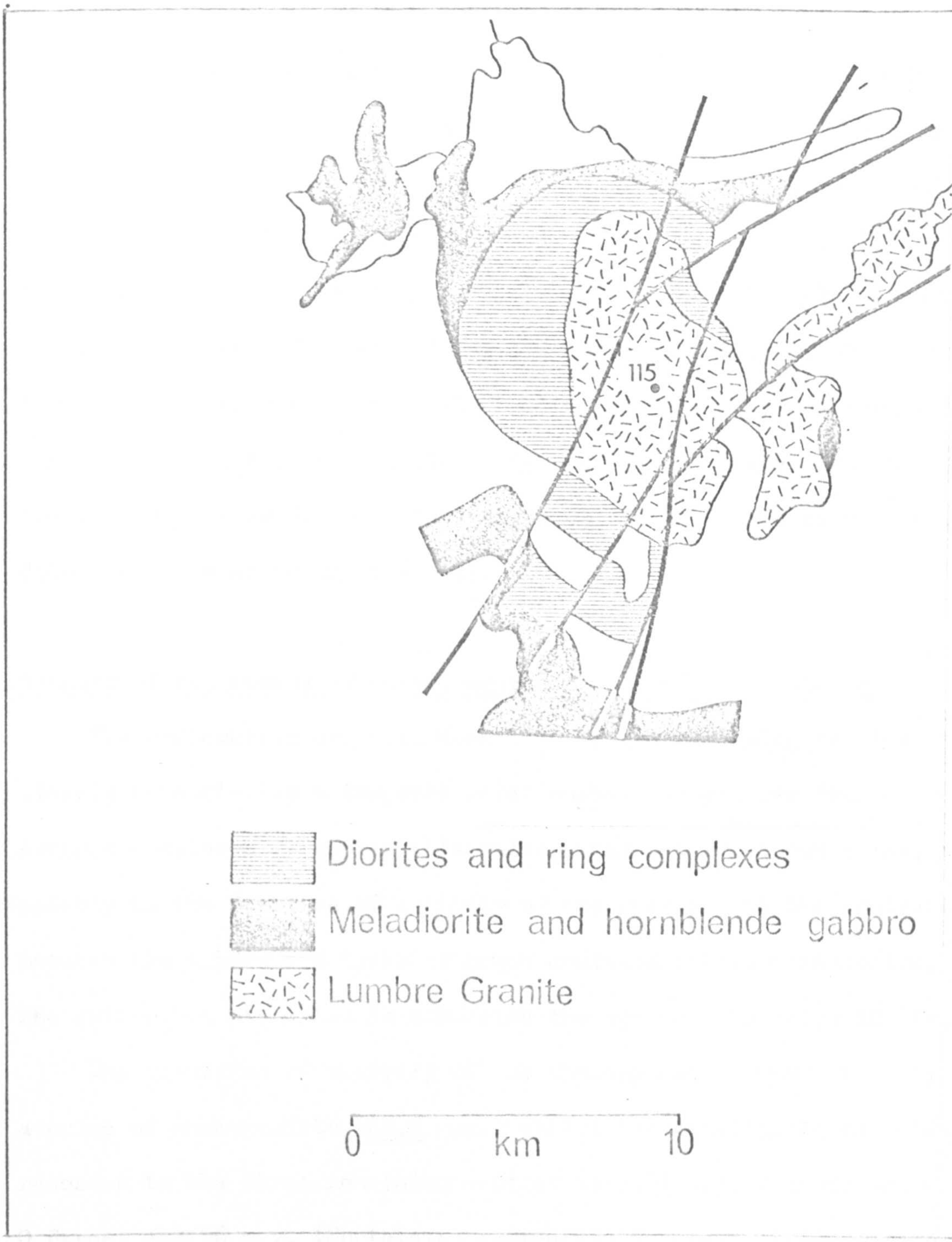


Fig.29. Generalised map of the Chancay Centred Complex showing early ring structure of diorite and gabbro and later central stock of Lumbre monzogranite. Adapted from Cobbing and Pitcher (1972a).

An age of 62.6 m.y. was calculated for the Lumbre monzogranite, based on the weighted mean of a concordant biotite-orthoclase pair (sample A115). Although this result equates the Chancay centre with the three northerly complexes it partly contradicts the pre-Santa Rosa age envisaged by Cobbing and Pitcher, which is largely based on their observation of dykes cutting the complex. However, the author has mentioned that members of the Santa Rosa dyke swarm penetrate the outer facies of the La mina pluton in the Huaura centre. Furthermore the radiometric evidence tentatively suggests that members of the dyke swarm are as young as 60 m.y.

Summary of the timing of emplacement of the Centred Complexes

The radiometric age data described in the foregoing section clearly demonstrates a temporal relationship between the four centred complexes. Despite this pattern major differences exist, notably in the duration of activity of the centres and the contrast between the timing and types of magma emplaced within each centre. The author has attempted to summarise the age relationships in Fig.30.

The cessation of activity of the Chancay centre was marked by a pulse of monzogranite (62.6 m.y.) whilst the final phase of activity recorded in the three remaining centres were 61 m.y. (Huaura and Q Paros) and 56 m.y. (Fortaleza) respectively. An individual time scale was only possible for the Fortaleza centre where a difference of 5 m.y. between the Puscao and San Jeronimo ring dykes can be argued as being representative of two separate intrusive phases. Alternatively the 61 m.y. climax of the Huaura centre gives a measure of the final cooling of the complex following the emplacement of the Canas and Sayan plutons. The available data on the Paros and

Chancay centres implies that one single pulse of magma emplacement marked their final phase of activity. In view of the fact that these late centred plutons are not intruded by younger bodies the biotite ages will approximate their age of emplacement.

Probably the most surprising feature which arises from this study concerns the relationship between magma type and time of emplacement. In the previous section the author showed the early tonalitic units to be broadly coeval throughout the mapped length of the batholith. However, in the four centred complexes the greater variety of rock types and better geological control shows that magma type tends to be independent of the time of emplacement. For example, the monzogranites of the Huaura centre were being emplaced at the same time as a granodiorite in the Paros centre. This casts a certain degree of doubt on the practice of using lithology as a criterion for correlation especially when this implies a coeval relationship. Thus the La mina unit has yielded a minimum age of 66 m.y. in the Huaura centre which contrasts with an age of 62 m.y. in the Quebrada Paros centre. A clearer case is exemplified by the relationship between the Puscao/San Jeronimo magmas, which can again be summarised;

	FORTALEZA	Q PAROS	HUAURA	CHANCAY
PUSCAO	70[1] 61	65[2]	(synchronous 61 m.y.)	-
SAN JERONIMO	56	56[3]		-

1 Chasquitambo pluton
2 Cerro Pan de Azucar } Supe
3 Andahuasi facies

Thus the coeval relationships of the two magma types in the Huaura complex contrasts with the younger age of the San Jeronimo magma in the two northerly complexes.

In conclusion the four centred complexes are spatially and temporally related and were active throughout the Palaeocene. Although minor variations are present each centre corresponded to a climax of activity at C. 62 m.y. This period of time involved in their emplacement is comparable to the span of time taken for the emplacement of the Tertiary ring complexes of N.W. Scotland (Evans 1969, Mitchell and Reen 1973). The writer has briefly mentioned the association of gabbros and diorites in the three most southerly complexes. If the hypothesis of Bussell and Pitcher (in press), linking these early units to the Patap and Santa Rosa Super-units holds, then it is conceivable that these centres have been active and have vented magmas to the surface, for as long as 40 m.y.!

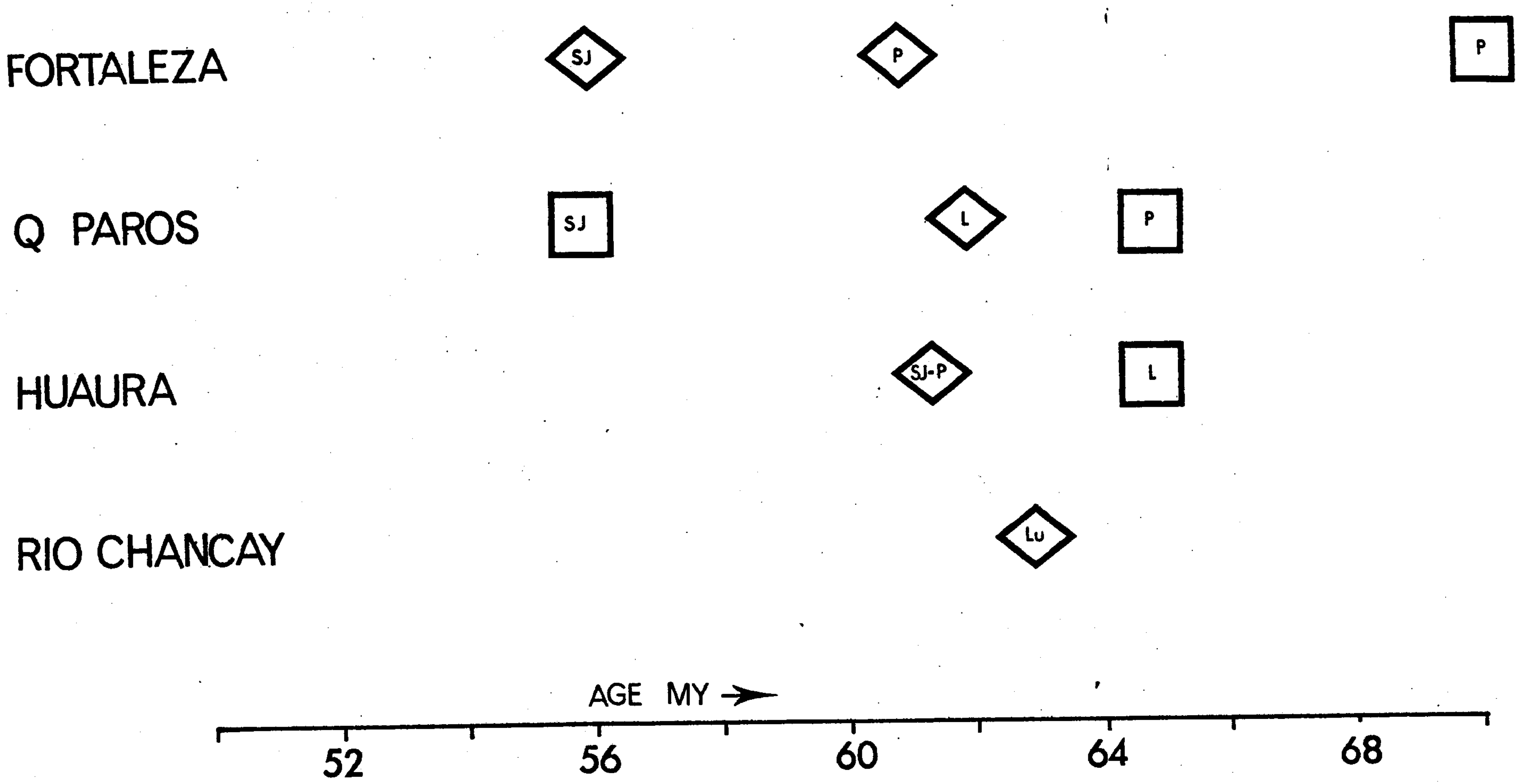


FIG.30. Chart summarising and comparing the duration of activity of the four Centred Complexes. The diamonds correspond to the ring dykes and the squares to the associated plutons, the inset denote the magma types which are emplaced ie; SJ=San Jeronimo, P=Puscao, L=La Mina and Lu=Lumbre.

3. THE PATIVILCA PLUTON - Age and general features

Age determinations from the Pativilca pluton show it to be the youngest pluton of the Coastal batholith in the area of study. However, before discussing the evidence for the age of this body the writer proposes to outline some of its main geological characteristics which emphasise its close similarity to the Sayan monzogranite.

The Pativilca pluton occupies the eastern sector of the batholith along the Rio Pativilca valley and outcrops over an area of approximately 25 kms by 15 kms, thus forming the largest single monzogranite body recognised in the batholith.
The Casma volcanics form the host rocks of the pluton and outcrop as roof at its northern and southern margins, they also occur as isolated roof pendants in the south-western margin of the pluton. Slabs of roof material are widespread throughout the higher levels of the pluton where they occur as subhorizontal xenolith trains, illustrating that the pluton was emplaced largely by a process involving piecemeal stoping. Thus the Pativilca body bears a structural resemblance to the eastern Sayan pluton which is further reinforced by their lithological similarities.

The main facies is a coarse biotite monzogranite which differs from the Sayan pluton only in the smaller size of the orthoclase phenocrysts and for this reason Cobbing (1973) has suggested that they are comparable in age. Only at two localities can the Pativilca pluton be seen to be in contact with other units of the batholith; it cuts the Lamina granodiorite at its north western margin and is faulted against the La mina to the south-east (Cobbing and Garayer, 1971).

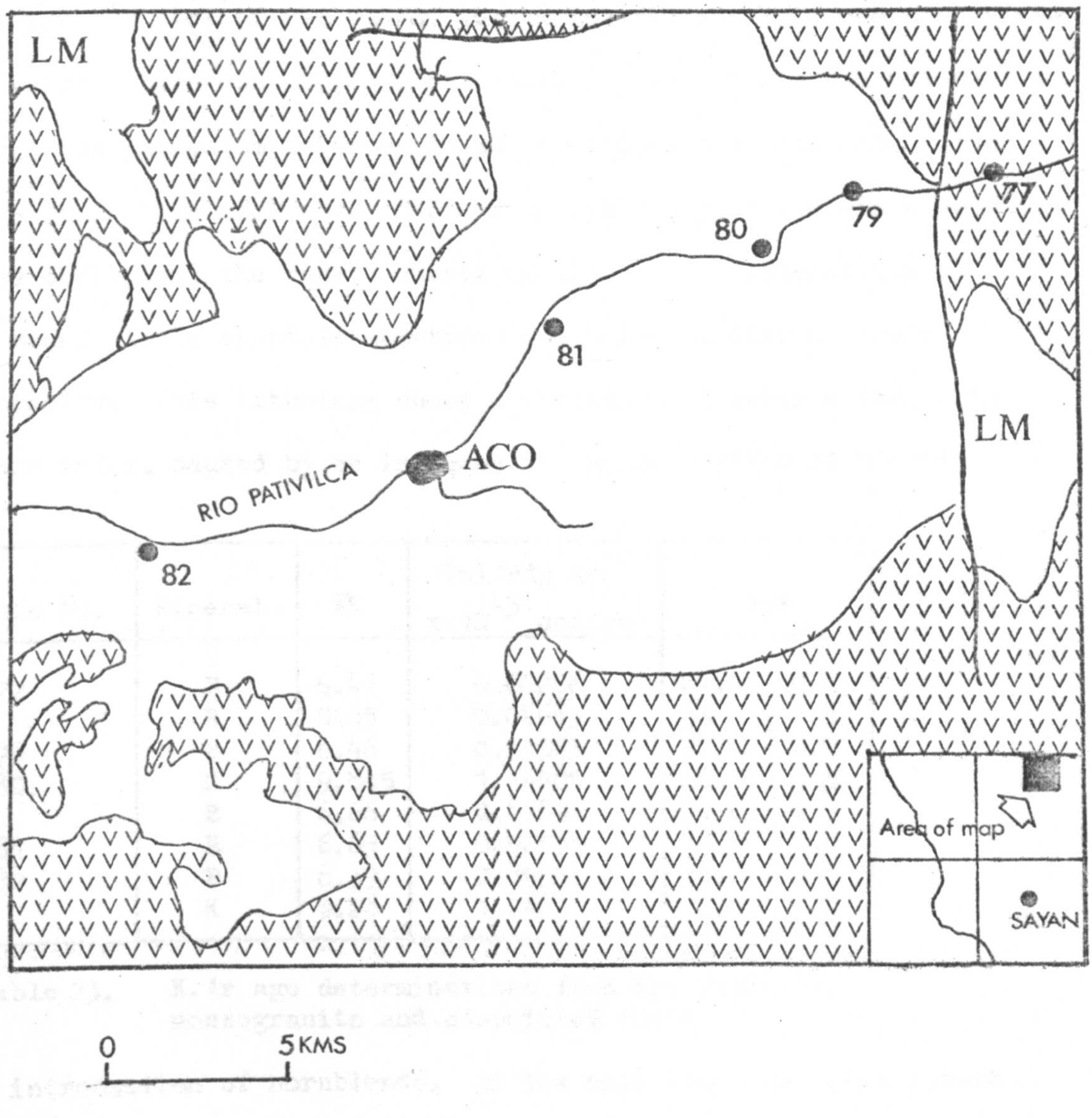


FIG.31 Map showing the outcrop of the Pativilca monzogranite it is almost entirely emplaced within volcanics of the Casma group (stippled), LM denotes La Mina granodiorite stocks. Sample localities are shown along the Rio Pativilca. Geology after Cobbing (1973).

The Pativilca body was originally described as a uniformily homogeneous monzogranite (Cobbing, 1973), yet field and petrographic observations by the author show it to have a more basic eastern component. Recently Cobbing (pers. comm) has remapped the pluton and separated a western monzogranite 'facies' from an eastern granodioritic variety.

The western part of the pluton is characteristically a coarse-grained biotite monzogranite containing phenocrysts of plagioclase and potash feldspar; the potassium feldspar is an orthoclase perthite which often attains a grain size of 2 cms. Biotite occurs as brown euhedra widely dispersed throughout the rock; quartz usually occurs interstitially forming round single crystals sometimes enclosing earlier minerals poikilitically. This lithology shows a variation, notably a change in the colour index, caused by an increase in the proportion of biotite

Sample No.	Mineral	%K	Vol rdg Ar^{40} x 10^{-5} scc/gm	Age
A77	B	6.41	0.60206	24.4 ± 0.7
	H	0.65	0.08685	33 ± 1.5
A79	B	6.46	0.71563	27.6 ± 0.7
A80	K	9.845	1.14409	28.9 ± 1.5
	B	6.66	0.8189	30.6 ± 0.7
A81	B	6.65	0.92551	34.6 ± 0.8
A82	B	6.39	0.89567	34.8 ± 0.5
	K	9.28	1.248	33.4 ± 0.5

Table 23. K.Ar age determinations from the Pativilca monzogranite and associated rocks.

and the introduction of hornblende. At the same time the large potash feldspar phenocrysts decrease in importance whilst the proportion of plagioclase increases. Together these changes result in a rock which approaches a leucocratic granodiorite in composition. Unfortunately all these variations occur over unexposed terrane and for this reason it is not yet certain whether they represent two time separated intrusive events.

A total of four samples were collected from various localities throughout the Pativilca body and incorporated the aforementioned variations. Thus, two samples correspond to the main western monzogranite and the two remaining samples were collected from the eastern margin of the Pativilca body (See Fig.31).

The two samples from the western monzogranite were collected over 10 kms apart. Their calculated ages, based on a biotite separate and a cogenetic biotite-K feldspar pair, were in agreement and gave a preferred age of 32.4 m.y. (samples A81, A82). Due to this consistancy, and in view of the fact that the pluton is thought to represent the youngest intrusive event in the area, it can be stated with some confidence that this result approximates to its time of emplacement.

In contrast the two samples which equate with the eastern body produced an ambigous age pattern which points to an extremely complex post-formational thermal history. This pattern is manifested by a progressive decrease, in an easterly direction of the K.Ar mica ages. For example, sample A80 yielded an age of 29.4 m.y based on the weighted mean of a concordant biotite-K feldspar pair, whilst approximately 2 kms further east the biotite age decreases to 27.6 m.y. (sample A79) which indicates that a true difference in age exists between the two ends of the Pativilca pluton. This difference appears to be spatially controlled because it is also reflected in age determinations from a small granodiorite stock which outcrops in the Pativilca valley 2 kms east of the fault which delineates the eastern margin of the Pativilca pluton (See Fig.31).

This stock is more basic than the Pativilca pluton and bears a close lithological similarity to the La mina granodiorite. A biotite-hornblende pair (sample A77) produced strongly discordant ages with the hornblende (33 ± 1.5 m.y.) corresponding in age to the Pativilca west pluton, whilst the biotite age is demonstrably younger (23 m.y.).

In order to visualise the age patterns which characterise this sector of the batholith the author has plotted them on an Ar^{40} vs K^{40} isochron which is shown in Fig.32. The wide scatter of data points indicates that the basic assumption of a 'closed istopic system' does not apply to this suite of samples. Unfortunately it is not clear whether the younger ages from the eastern margin of the Pativilca pluton represent a younger intrusive event. Certainly on the basis of the hornblende age of 33 ± 1.5 m.y. from the eastern granodiorite stock, it is obvious that this body was emplaced at the same time, or before, the emplacement of the Pativilca monzogranite.

Therefore in the writer's opinion the 'young' biotite ages of samples A80, A79 and A77 presumably reflect either partial outgassing of the already generated argon, or the time at which they were progressively uplifted from depths where the mica lattice remained open to argon diffusion. The latter hypothesis gains a certain degree of support from the presence of a large northerly trending fault which cuts the eastern part of the Pativilca pluton and along which this uplift may have occurred. The writer prefers the former explanation because a theory of 'deep emplacement', followed by delayed uplift, contradicts the well established thesis of a high level of emplacement.

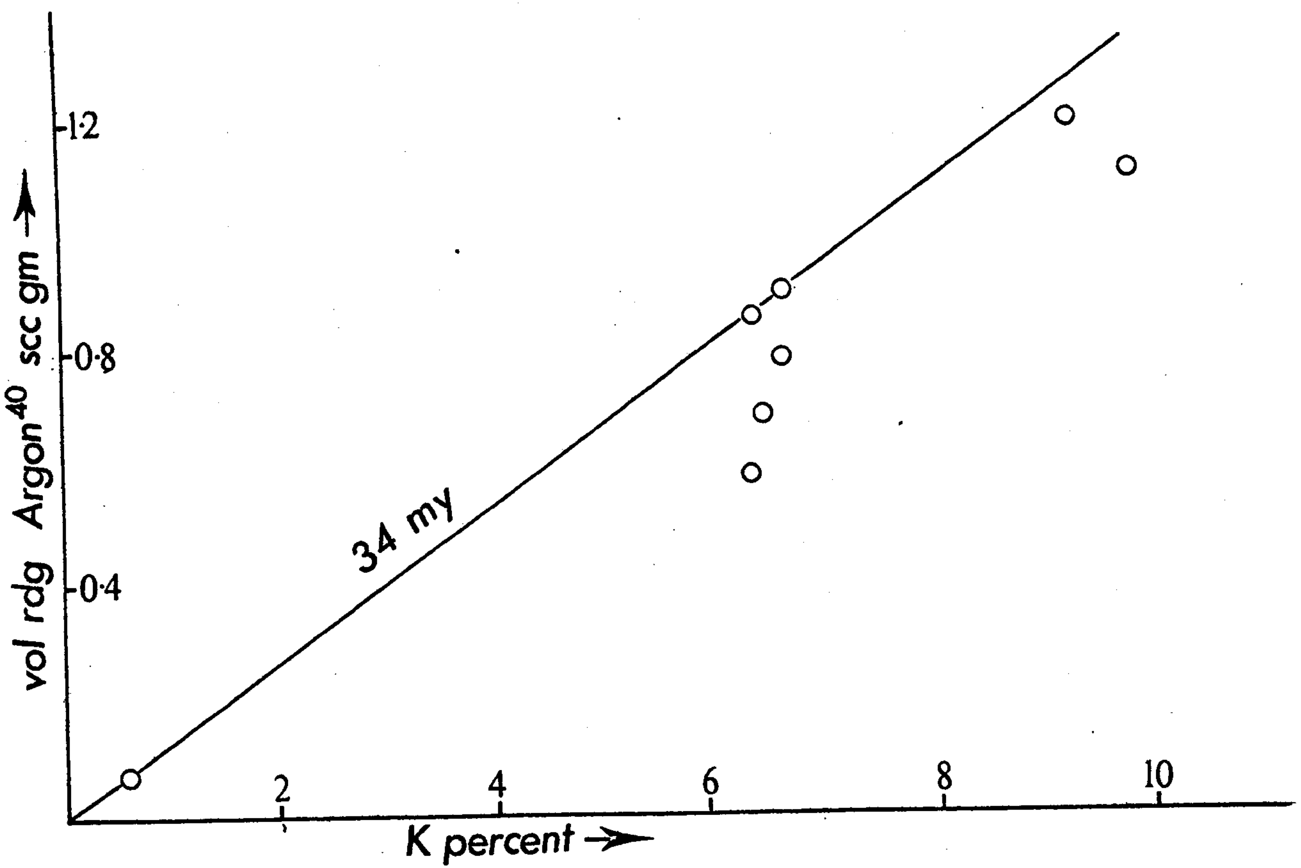


FIG.32 Age determinations from the Pativilca monzogranite, and eastern stock, shown on a K-Ar isochron.

To summarise :

1) The Pativilca monzogranite was emplaced during the Oligocene (34 m.y.) and bears an extremely close relationship to the Sayan monzogranite of the Huaura complex.

2) The decrease of apparent biotite age at the eastern end of the Pativilca pluton could equate with a separate phase of intrusive activity or reflects an outgassing 'event'.

3) The eastern granodiorite stock yielded a hornblende age which corresponds to the emplacement of the Pativilca monzogranite, conversely the younger biotite age dates the time at which the pluton cooled to the biotite blocking temperature - or reflects a later reheating event.

Finally there appears to have been a hiatus of intrusive activity in the batholith lasting C 20 m.y , between the final emplacement of the Centred Acid Complexes and the emplacement of the Pativilca monzogranite. These findings conclude the dating of the main sector of the Coastal batholith in the study area.

In the following section the writer presents supporting radiometric evidence from granitic stocks which outcrop to the east of the Coastal batholith. Ages from these stocks illustrate the regional significance of the 'resetting' of apparent biotite ages in the eastern sector of the batholith.

4. THE CHRONOLOGY OF INTRUSIONS TO THE EAST OF THE COASTAL BATHOLITH

A number of small granitic stocks are exposed in the river valleys east of the Coastal Batholith, and are separated from the batholith by volcanic country rocks. It is largely due to their spatial isolation that they are included in a separate section because in many cases they have compositional affinities with the tonalites of the Paccho Super-unit. The most easterly stocks are on strike with the Cordillera Blanca batholith and one of the primary aims of the study was to see whether they represent a southerly extension of this body.

The stocks continue as far inland as Cerro de Pasco, a distance of 180 kms from the coast, and it is interesting to note that Stewart (1971) has described peralkaline stocks of Pliocene age at Pucallpa, some 500 kms east of the present coastline. To date all these stocks would be over ambitious and instead the writer concentrated on the stocks which outcrop along the Rio Huaura and Rio Chancay (Fig.33). Ages from two rhyo-dacite plugs from Cerro de Pasco are described in the next part of this thesis.

The Tonalite Stocks of the Rio Huaura

Two small stocks outcrop along the upper reaches of the Rio Huaura around the village of Churin (Fig.33). The largest stock outcrops east of Churin at an altitude of 2,400 metres; it has an irregular outline having an overall length of 8 kms and an average width of 3 kms. It is entirely emplaced within a syncline of folded upper-cretaceous sediments which were originally deposited in the miogeosyncline.

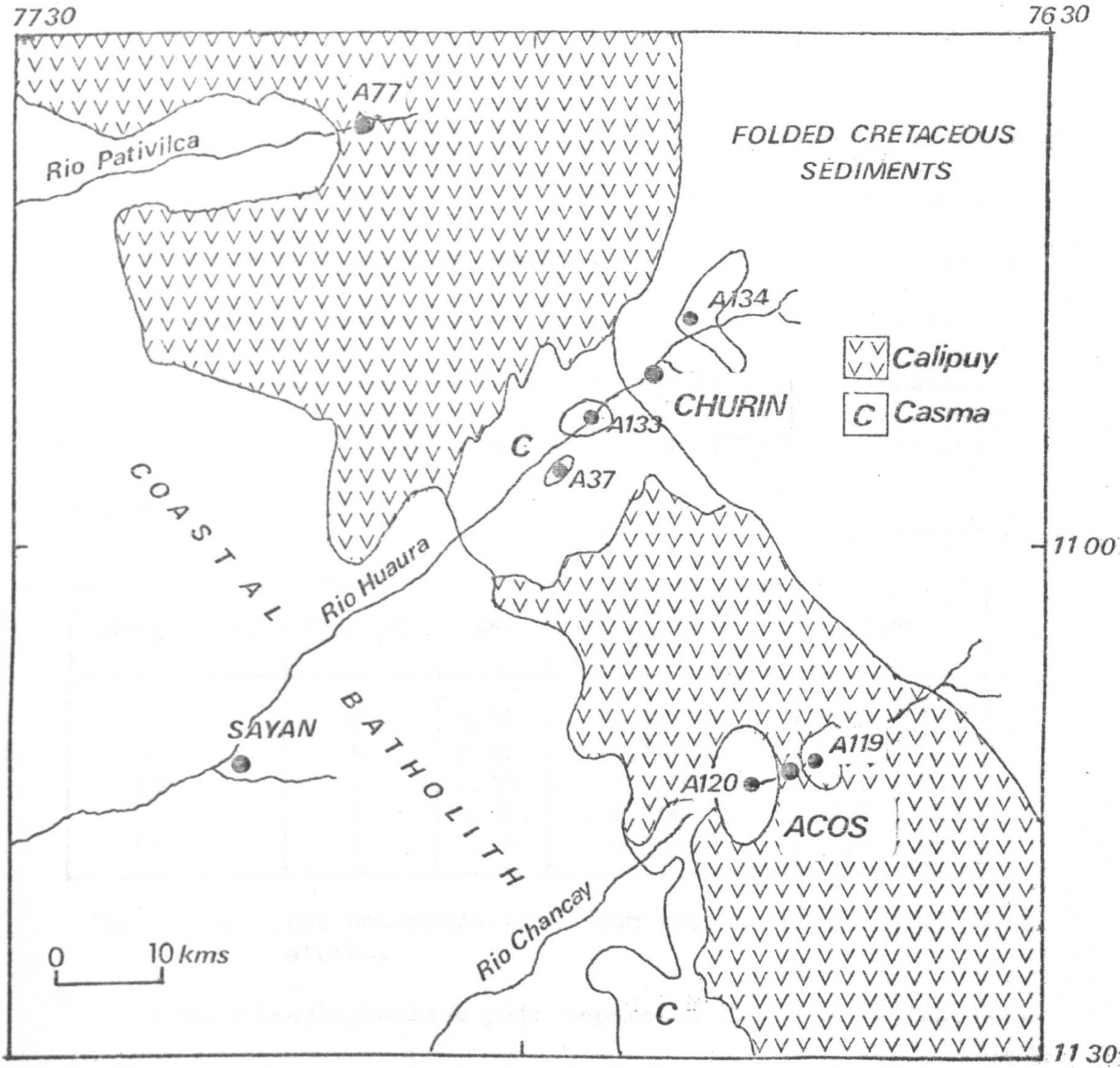


FIG.33 Diagram showing the location of the granitic stocks to the east of the Coastal batholith, sample localities are also included. Geology after Cobbing and Garayer (1971).

Conversely the smaller Churin west stocks is emplaced in folded volcanics of the Casma group. There is a strong contrast in lithology between the two stocks which implies they represent two separate intrusive events. Thus the eastern stock is coarser in grain size and more leucocratic than its western counterpart, even though they both have an overall tonalitic composition.

Sample No.	Mineral	K%	Vol Rdg Ar^{40} x 10^{-6} scc/gm	Age
A33	H	0.44	0.55107	30.9 ± 1.0
	B	7.21	5.4467	18.8 ± 0.3
A34	B	7.15	3.5271	12.4 ± 0.2
	P	0.72	0.4063	12.9 ± 0.3
A37	B	5.78	4.5847	19.8 ± 0.6

Table 24. Age determinations from the Rio Huaura granitic stocks.

A biotite-plagioclase pair separated from the Churin east stock yielded a concordant age of 12.6 m.y. (sample A34) and this result is in agreement with a hornblende age of 13 ± 1 m.y reported by Stewart and others (1974). The writer interprets this concordancy as indicating a Miocene age of emplacement.

In contrast the stock to the west of Churin yielded strongly discordant ages from a biotite-hornblende pair (sample A33) with the hornblende age (31 m.y.) older than the associated biotite (19 m.y.). A biotite separated from the smaller satellitic stock along the Quebrada Paccho (Fig. 33), also reflected the younger biotite age (sample A37). A plausible solution for this discordancy is the partial loss of argon from the stock induced by the reheating effects of the younger Churin east stock (see Fig. 33 for distances involved).

The true emplacement age of the Churin west stock cannot be evaluated using the K.Ar method but geochemical data shows its close affinity with the Paccho Super-unit (McCourt pers.comm). If this is true, then both the biotite and hornblende have lost considerable amounts of radiogenic argon. A similar age pattern has also emerged from the stocks which outcrop in the Chancay valley, these will now be discussed.

The Tonalite Stocks of the Rio Chancay

The Chancay valley cuts through two large tonalite stocks which outcrop to the west and east of the village of Acos (See Fig.33). The stocks have been termed the Acos east and Acos stocks by Cobbing (1973) and this terminology is adopted by the writer.

The Acos stock is the largest body and has a roughly oval outline measuring 12 kms by 5 kms; the smaller Acos east stock is almost circular in outline with a diameter of 5 kms. Unlike their counterparts along the Rio Huaura, the Chancay stocks are emplaced in the Calipuy volcanics; in addition the Acos stock is also emplaced within the Casma volcanics at its western margin. At present there is some doubt as to whether these country rocks really represent Calipuy volcanics or subhorizontally disposed Casma volcanics. The significance of this debate is discussed at length in the next part of this thesis.

The Acos stock outcrops only 5 kms to the east of Coastal batholith and Cobbing and others(1971) have placed it older in the intrusive history of the batholith than the Vilca monzogranite on the basis of its more basic character.

The two stocks differ compositionally, for example the Acos stock corresponds to a hornblende monzo-tonalite whilst the Acos east stock is an extremely fresh porphyritic granodiorite. This relationship is similar to that observed in the Rio Huaura where the eastern more acidic stock was shown to represent a younger intrusive episode.

Sample No.	Mineral	K%	Vol Rdg Ar^{40} x 10^{-6} scc/gm	Age
A119	B	6.67	5.0023	18.7 $\pm$ 0.5
	P	2.71	1.8961	17.4 $\pm$ 1.0
A120	B	6.05	5.7815	23.8 $\pm$ 0.6

Table 25. Age determinations from the Acos stocks

The Acos east stock gave an age of 18.4 m.y. based on the weighted mean of a concordant biotite-plagioclase pair (sample A119). Sample A120 corresponds to the Acos stock,in this case the biotite age is strongly discordant with a hornblende age of 35 $\pm$ 3 m.y. which has been reported by Stewart and others (1974).

On the basis of lithology and the discordant age pattern the writer equates the Acos stock with the Paccho Super-unit. Conversely the Acos east stock probably represents a much younger intrusion and the writer interprets the 18 m.y. age as a Miocene age of emplacement.

SUMMARY

In conclusion this sector to the east of the Coastal batholith is dominated by granitoids of two distinct types.

1) Uplifted representatives of the Paccho Super-unit which are characterised by discordant ages from biotite-hornblende pairs.

2) Younger granodioritic stocks of Miocene age which are emplaced further to the east.

The significance of the hornblende ages (31-35 m.y.) from the Acos and Churin west stocks are not entirely clear. It is obvious that they must have lost a considerable proportion of their radiogenic argon if they really represent members of the Paccho Super-unit.
In the writer's opinion these Oligocene ages are a reflection of a regional thermal event which influenced a greater part of the Paccho Super-unit at the eastern margin of the Coastal batholith. This hypothesis is partly based on the almost universal resetting of biotite clocks of the Paccho tonalites in the Rio Huaura (for example see Fig.18). The same event is also reflected in the hornblende age of the eastern stock in the Rio Pativilca, which was described in the preceding section.
The only conclusive plutonic activity which reflects this'Oligocene event' is the emplacement of the Pativilca monzogranite. To attribute this regional resetting of K.Ar clocks to a concealed monzogranite body would be pure speculation, nevertheless this assumption does gain a certain degree of support from the 33 m.y. ages obtained from the eastern Sayan monzogranite. Fig.34 represents a compilation of the ages which correspond to this 'Oligocene event', and it is referred to in the concluding part of this thesis.

The younger group of stocks to the east of the Paccho outcrop are comparable in age to the Cordillera Blanca batholith, and this forms the theme of the following section.

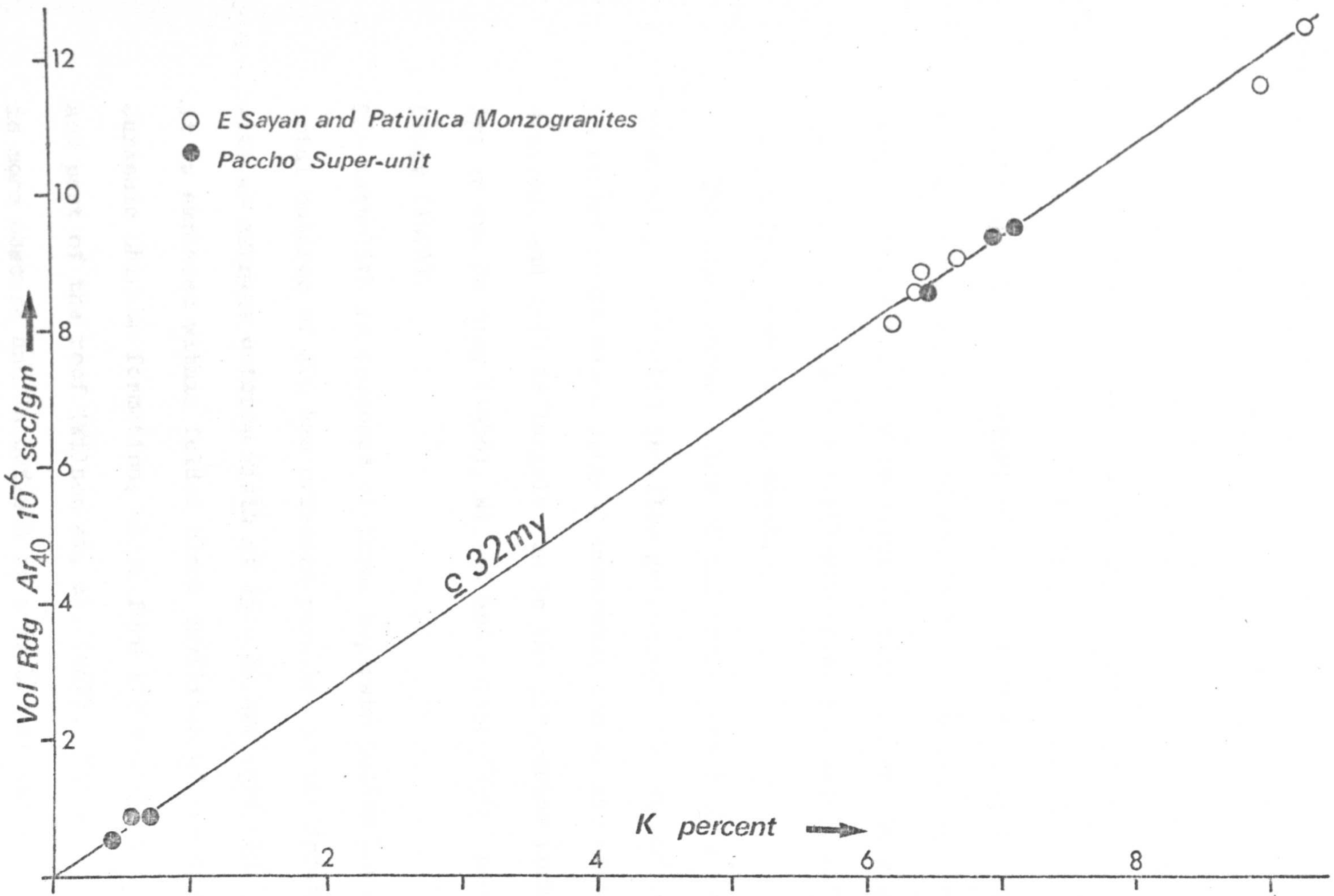


FIG.34 K-Ar isochron plot of ages from the eastern sector of the Coastal batholith which define an Oligocene 'event'. Plutonic activity is reflected by the emplacement of the Pativilca monzogranite (and E Sayan ?).The other points correspond to disturbed Paccho ages.

5. THE CORDILLERA BLANCA BATHOLITH

(a) Introduction

The general geographic features of the Cordillera Blanca batholith have already been outlined in the introductory part of this thesis. Thus, the Cordillera Blanca batholith is separated from the Coastal batholith by the Cordillera Negra and the Callejon de Hauylas. The latter being a broad NW trending fertile valley along which the Rio Santa flows in a northerly direction before cutting a westerly course to the coast.

The mountainous nature of the Cordillera Blanca range originally restricted detailed geological studies and only in recent years has a general understanding of the area evolved, and this is largely due to the pioneering work of Egeler and De Booy (1956), Wilson and others (1967) and Coney (1971).

The batholith is composed of three separate bodies having a total outcrop of 200 kms oriented parallel to the Andes, and with an average outcrop width of 15 - 20 kms (see Fig. 35). It is emplaced within folded black phyllites of the upper-Jurassic Chicama formation, which form its eastern envelope and part of the roof (Wilson et. al. 1967). The western margin is more obscure and is defined by a number of large N-W trending faults which parallel the entire length of the Cordillera Blanca range. Here ignimbrites and Quaternary alluvial deposits overlie the batholith.

Reconnaissance age determinations by Stewart and others (1974) favour a late Miocene age of emplacement for the batholith and in the following part of this thesis the author presents new K.Ar age determinations which substantiate these preliminary findings.
Before discussing the chronology of the Cordillera Blanca granitoids the writer proposes to outline some of its main characteristics which illustrate both its dissimilarity and affinity to the Coastal batholith.

A Review of the Geology of the Cordillera Blanca Batholith

The characteristic features of the batholith have been the subject of a recent review by Pitcher (1974) who describes a composite batholith composed of a number of consanguineous plutons which differ both compositionally and in their relative ages. In the southern sector of the batholith Egeler and DeBooy (1954) have mapped three internally homogeneous plutons, these range in composition from tonalite to leucogranodiorite and display cross-cutting relationships. Egeler and DeBooy also noted the predominance of acid rocks over basic and intermediate varieties; the most voluminous rock type being a leucogranodiorite which is diagnostic by its two micas and large potash feldspar phenocrysts.

The Cordillera Blanca batholith differs geochemically from the Coastal batholith in its peraluminous, calcium-poor nature and according to Pitcher (1974) it may be classified as an 'S' type granite, adopting the criteria outlined by Chappel and White (1974). Concurrently recent geochemical studies on

the batholith show it to be related to the acid end of the Calc-alkaline differentiation sequence of the Coastal batholith (McCourt, W. pers. comm.).
Other contrasts between the two batholiths include the virtual absence of dykes and xenoliths in the Cordillera Blanca batholith and its association with lead-silver, copper, zinc and tungsten mineralisation, which is widespread through the area (c.f. Petersen, 1965).

The relationship between the batholith and its envelope is extremely complex; there is convincing evidence for a forceful, diapiric mode of emplacement. This contrasts with the processes of stoping and assimilation which has controlled the emplacement of the Coastal batholith. Also, and again in contrast, Egeler and DeBooy (1956) describe the intensive thermal effects which the Cordillera Blanca batholith imposes on the envelope rocks. As an example of this a spectacular high temperature aureole is exposed in the Canon del Pato which extends for over 2 kms into the country rocks (see Pitcher, 1974). Usually the most spectacular contact effects are confined to the immediate border zones of the plutons, and it is of interest to note that Egeler and DeBooy have recorded both metasomatism and feldspathisation of the country rocks in these border regions.

A weak mineral foliation is present within the batholith and this increases in intensity towards the margins where it parallels the schistosity in the country rocks. This feature, combined with the shouldering aside of the country rocks, places emphasis on a forcible manner of emplacement. Despite these observations Egeler and DeBooy (1956) have stated that the overall balance of evidence favours stoping as the main mechanism of emplacement.

Like the Coastal batholith, it seems the Cordillera Blanca batholith has been emplaced in a tectonically pre-destined zone. The present elevation of the batholith is due to recent uplift along the fault line which defines its western margin, and possibly accounts for its limited linear extent compared with the Coastal batholith.

The Chronology of Emplacement of the Cordillera Blanca batholith

The regional stratigraphy is somewhat inadequate for defining the age of the batholith. The youngest fossiliferous strata which are cut by the batholith are of upper Jurassic age although it also intrudes and metamorphoses the Calipuy volcanics which are of lower Tertiary age. Wilson and others (1967), and Pitcher (1974) have suggested that the batholith pre-dates the Puna erosion surface, because the latter appears to truncate the associated ore deposits. On these grounds the relative age of the batholith can be fingerprinted by two events;

(1) It post-dates the Calipuy volcanics.

(2) It pre-dates the Puna erosion surface.

A few radiometric age determinations on the Cordillera Blanca batholith have been reported in a number of recent publications, and include determinations by the K.Ar, Rb.Sr and fission track methods.

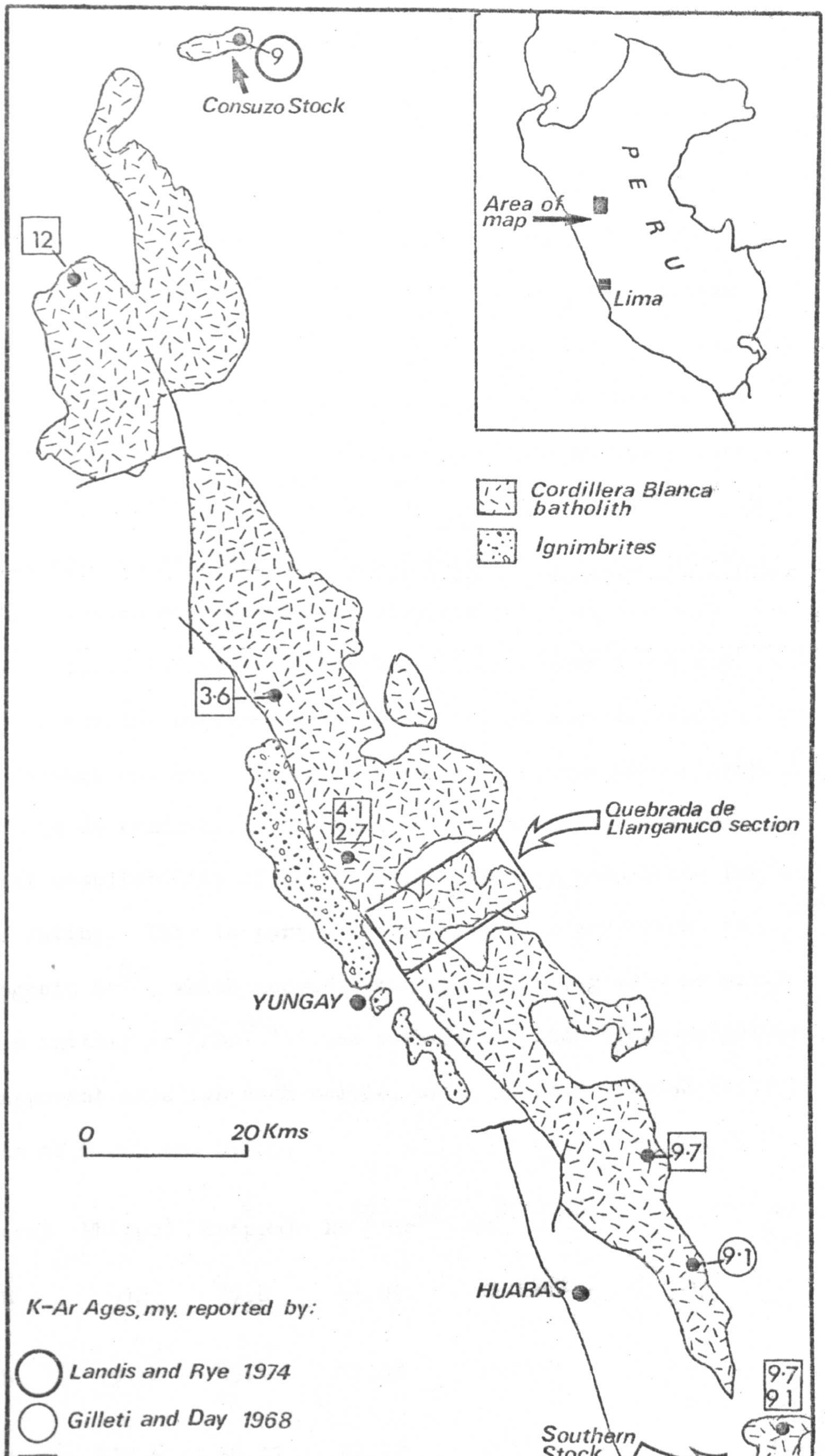


Fig. 35 Outcrop map of the Cordillera Blanca batholith showing it's relationship to the ignimbrites, the published age determinations and study areas are also included. Geology after Wilson et.al. (1967).

Stewart and others (1974) describe seven K.Ar age determinations on micas which show a spread of their apparent ages between 12 and 3 m.y. In fact their data falls into three general groups; 12 m.y., 10 - 9 m.y. and 4 - 3 m.y. A biotite age reported by Giletti and Day (1968), and a fission track date reported by Landis and Rye (1974) also fall within the 10 - 9 m.y. group. At its face value this data implies that three separate phases of plutonic activity are involved, although Stewart et.al. (1974) have attributed the younger 3 - 4 m.y. group to partial outgassing of plutons of an earlier cycle.

Stewart and his co-workers also provide some preliminary Rb-Sr age determinations on micas, although they stress the general unsuitability of the Cordillera Blanca granitoids for Rb-Sr dating. This is partly due to their low enrichment in radiogenic Sr^{87}, which accounts for the age being very sensitive to the initial Sr^{87}/Sr^{86}. The authors have therefore calculated two apparent ages for each sample, using assumed initial isotope ratios of 0.705 and 0.703.

Sample	Mineral	Rb(ppm)	Sr(ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}	Sr^{87}/Sr^{86}_{o}	Age m.y.
12	B	912	27.8	95.09	0.7188	0.705	10
						0.703	11
16	B	491.8	83.1	17.03	0.7063	0.705	5
						0.703	13
10	M	429.6	56.11	22.17	0.7113	0.705	19
						0.703	30

Table 26. Rubidium-strontium age determinations from the Cordillera Blanca batholith after Stewart et.al. (1974)

The younger age values shown in Table 26 correspond to an initial Sr^{87}/Sr^{86} value of 0.705 which is based on the average ratio obtained from plutons of the Coastal batholith. Conversely the older ages have been computed on the basis of an initial ratio of 0.703 which is the minimum acceptable value for Cordilleran granites. Despite the uncertainties involved the data is useful for it predicts a maximum possible age for samples of 11, 13 and 30 m.y , respectively.
In view of the dependance of the age on the initial strontium isotope ratio the writer now proposes to consider the true value of this figure.

It was mentioned earlier that the Cordillera Blanca batholith has certain features in common with 'S' type granites, these are characterised by initial strontium isotope ratios of 0.704 - 0.706 (Chappell and White, 1974). In fact the few ratios which have been reported for the Coastal batholith also fall within this range (Snelling and Stewart 1972; James and Brooks 1973). On these grounds it seems reasonable to assume that the lower Rb.Sr ages will give a more accurate measure of the age of the mineral because they use the higher ratio.

In the following section the author presents new K.Ar ages from two different areas of the batholith. Firstly some mica ages from a west-east traverse across the batholith centred along Quebrada Llanganuco, which is a glaciated U-shaped valley between the peaks of Nevados Hauscaran (6,768 m) and Nevados Haundoy (6,356 m). The remaining samples were provided by Dr. E.J. Cobbing and were collected from the southern extremity of the batholith east of Recuay.

The Quebrada de Llanganuco section

This sector of the batholith is dominated by a creamy-white, muscovite-bearing leucogranodiorite, and contains a weak foliation which is manifested by a preferred orientation of the micas. From the limited number of sections which were available a crudely developed cataclastic texture was discernable. Thus quartz crystals are frequently granulated and show a wavy extinction, and the micas are bent and contorted around the large potash feldspar phenocrysts.

Five samples from this area were dated, the sample localities are shown in Fig. 35 and the results are tabulated below:

Sample	Mineral	K%	Vol Rdg Ar^{40} x 10^{-6} scc/gm	Age
CB3	M	8.78	2.1600	6.15 ± 0.18
CB4	B	7.62	1.0106	3.3 ± 0.12
CB5	B	7.02	1.1483	4.1 ± 0.17
CB5	M	9.0	1.6181	4.5 ± 0.17
CB6	B	7.19	1.3038	4.5 ± 0.2
CB9	B	7.89	1.5437	4.9 ± 0.17

Table 27. K.Ar age determinations from the Quebrada de Llanganuco section.

The age determinations show an apparent spread between 6.1 and 3.3 m.y., and with the exception of sample CB3, fall within the 4 - 3 m.y. group of Stewart and others (1974). One of the samples (CB5) has yielded concordant results from a muscovite-biotite pair and since muscovite has a higher argon retention than biotite (see Hart 1965, Harper 1967, and Dewey and Pankhurst, 1970) this indicates rapid cooling between their respective closure temperatures.

Sample CB3 dates a muscovite pegmatite which yields an anomalous result (6.1 m.y.) in that it is older than its host rock (Sample CB4, 3.3 m.y.). It is necessary to point out that the age of the host leucogranodiorite is based on fine-grained biotite

biotite (<3 mm) whilst the muscovite flakes, in the pegmatite, commonly average 2 - 5 cms. This contrast in grain size may further enhance the argon retention properties of muscovite relative to biotite (c.f. Hart and others, 1968). Although a replicate analysis is required to test the validity of this older muscovite age, the author tentatively considers it to be a more reliable estimate of the age of the pluton in question.
Before attempting to discuss the significance of these ages the writer would like to describe the new K.Ar age determinations from the southern end of the batholith.

K.Ar ages from the southern sector of the Cordillera Blanca

In view of the fact that most of the ages which have been calculated for the Cordillera Blanca batholith are by the K.Ar method on micas, the author dated two hornblende bearing granodiorites which outcrop in the southern sector of the batholith. The results clearly illustrate the older age of the hornblende separates and suggests that the discordancy displayed by the cogenetic biotite is a reflection of a later post-formational event.

Sample	Mineral	K%	Vol Rdg Ar^{40} x 10^{-6} scc/gm	Age
380	B	7.51	2.96138	9.9 ± 0.2
	H	0.88	0.56537	16.0 ± 0.5
386	B	6.12	2.2353	9.0 ± 0.2
	H	0.67	0.2967	11.0 ± 0.6

Table 28. Age determinations on hornblende-biotite pairs from the Cordillera Blanca batholith

The hornblende age of 16 m.y. obtained from Sample 380 represents the oldest K.Ar age determination so far obtained from the batholith and is strongly discordant with the associated biotite. Sample 386 was collected from the same general area and its younger age of 11 ± 0.6 m.y. is only slightly discordant with the co-existing biotite. In fact the younger hornblende age and two biotite ages broadly equate with the 9 - 10 m.y. group of Stewart and others (1974).

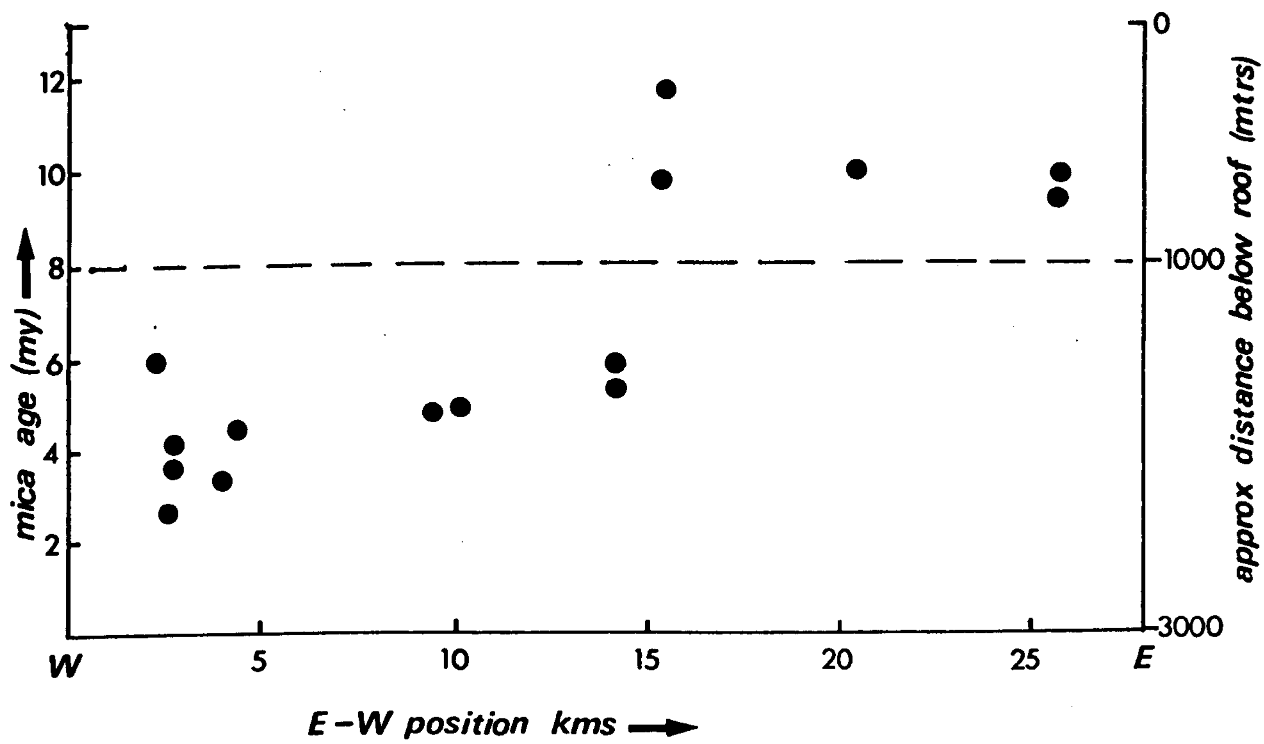


Fig. 36. Apparent mica ages from the Cordillera Blanca batholith, as a function of their E-W position and depth of emplacement.

Unfortunately the detailed field relations of Samples 380 and 386 are not knownbut on the basis of the evidence which is available the writer suggests the 11 - 9 m.y group reflects a major plutonic event. An earlier phase of intrusive activity is defined by the hornblende age of Sample 380 and this also gains some support from the Rb-Sr muscovite age which has been reported by Stewart and others (1974).

The question now arises concerning the true significance of the unusually young mica ages from the Quebrada de Llanganuco section. A possible explanation for these resides in their geographic distribution. Figure 36 represents a plot of all the mica ages against E-W position and, perhaps more significantly, their approximate depth below the roof.

On the basis of this diagram there are two possible explanations for the 4 - 3 m.y. group;

(1) An intrusive event of Pliocene age indicating that intrusive activity has migrated in an easterly direction.

(2) Slow cooling in the deeper levels of the batholith.

In order to substantiate the second hypothesis the depth of emplacement of the batholith and the average geothermal gradient of the area have to be assessed. Thus, Landis and Rye (1974) have estimated the depth of emplacement of the Consuzo stock to be in the order of 1.5 kms and Uyeda and Watanabe (1970) have shown that an extremely high geothermal gradient (40 - 60^{o} c/km) exists in the area. Providing these figures are acceptable then the ambient geothermal temperature some 2 km below the roof would approximate 210 - 140^{o}c, which is probably within the range at which micas close to argon diffusion. Providing a pluton was maintained at these temperatures for a long period of time and then uplifted on a major fault line, the resulting ages would reflect the movement of the fault. A phenomenon of this type is well illustrated in the sub-Alpine fault zone of New Zealand (Sheppard, et.al. 1975).

The author appreciates the tenuous nature of this discussion but would like to point out that the young mica ages characterise the region where uplift was at a maximum. Conversely the 11 - 9 m.y. group correspond to the higher zones of the batholith where the mica ages ought to reflect its age of emplacement. Finally the hypothesis that these younger ages represent an intrusive event gains support from the occurrence of Pliocene ignimbrites at the eastern margin of the batholith. Pitcher (1974) has tentatively proposed that a genetic relationship exists between these and the batholith (see Part 4.).

In conclusion the aforementioned age data strongly supports at least two separate periods of plutonic activity in the Cordillera Blanca batholith (Fig. 37); one of mid-upper Miocene age (16 - 19 m.y.) and a younger late Miocene early Pliocene episode (12 - 9 m.y.). Additional work is required before the true significance of the 4 - 3 m.y. group can be assessed.

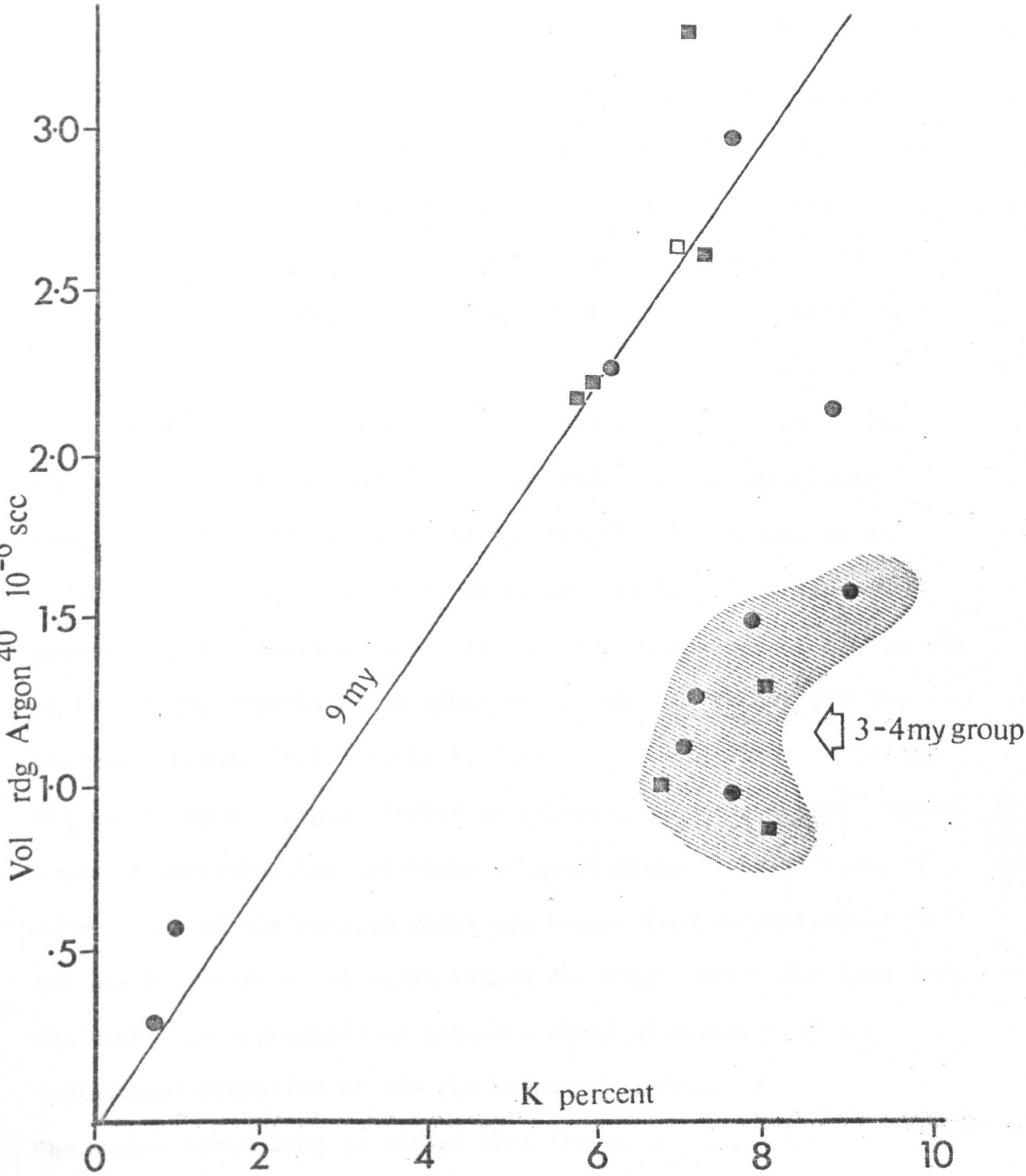


FIG. 37 Isochron plot of all age determinations from the Cordillera Blanca batholith, the position of the 9my. isochron is included as a reference point. Data sources; Stewart et.al. (1974) ■ Gilletti and Day (1968) □ , this report ● .

7. SUMMARY OF THE CHRONOLOGY OF EMPLACEMENT OF THE COASTAL AND CORDILLERA BLANCA BATHOLITHS

The preceding part of this thesis has been devoted to the presentation of radiometric data on the component plutons of the Coastal, and to a lesser extent, the Cordillera Blanca batholiths. In this section the author proposes to briefly summarise the regional patterns which have emerged from the study of these two batholiths.

A plot of mineral age versus frequency is presented in Fig. 38 and in general terms provides a good indication of the timing involved in the evolution of the two batholith complexes as is reflected by in the total body of mineral ages. The writer appreciates the dangers which are inherent in the use of histograms of this type, especially in cases where the ages do not define intrusive events (c.f. Moorbath, 1967). In this study, although the resetting of 'argon clocks' is extremely common, the geological evidence precludes the existance of meaningless 'hybrid' ages; indeed most of the samples which are re-set tend to correspond to the new intrusive event which caused the argon loss. For this reason the histogram represents an accurate means of visualising the 'pulsatory' evolution of the two batholith complexes.
The author would like to stress that the major culminations on the histogram do not have any relationship to the volume of magma emplaced but merely represent a distribution which is controlled partly by sampling, and partly by the regional extent of the heating effects of the younger intrusive episodes.

The diagram shows that intrusive activity has persisted over a period of at least 90 m.y. from the mid-Cretaceous to the Miocene-Pliocene. Moreover this activity has been episodic in nature because at least two distinct gaps occur in the histogram and these are interpreted as representing a cessation of intrusive activity.

It is possible to envisage five separate intrusive epochs on the basis of the histogram, and the different plutonic units which contribute to these epochs are summarised in Table 29. This apparent episodicity of magma emplacement is discussed more fully in the final part of the thesis.

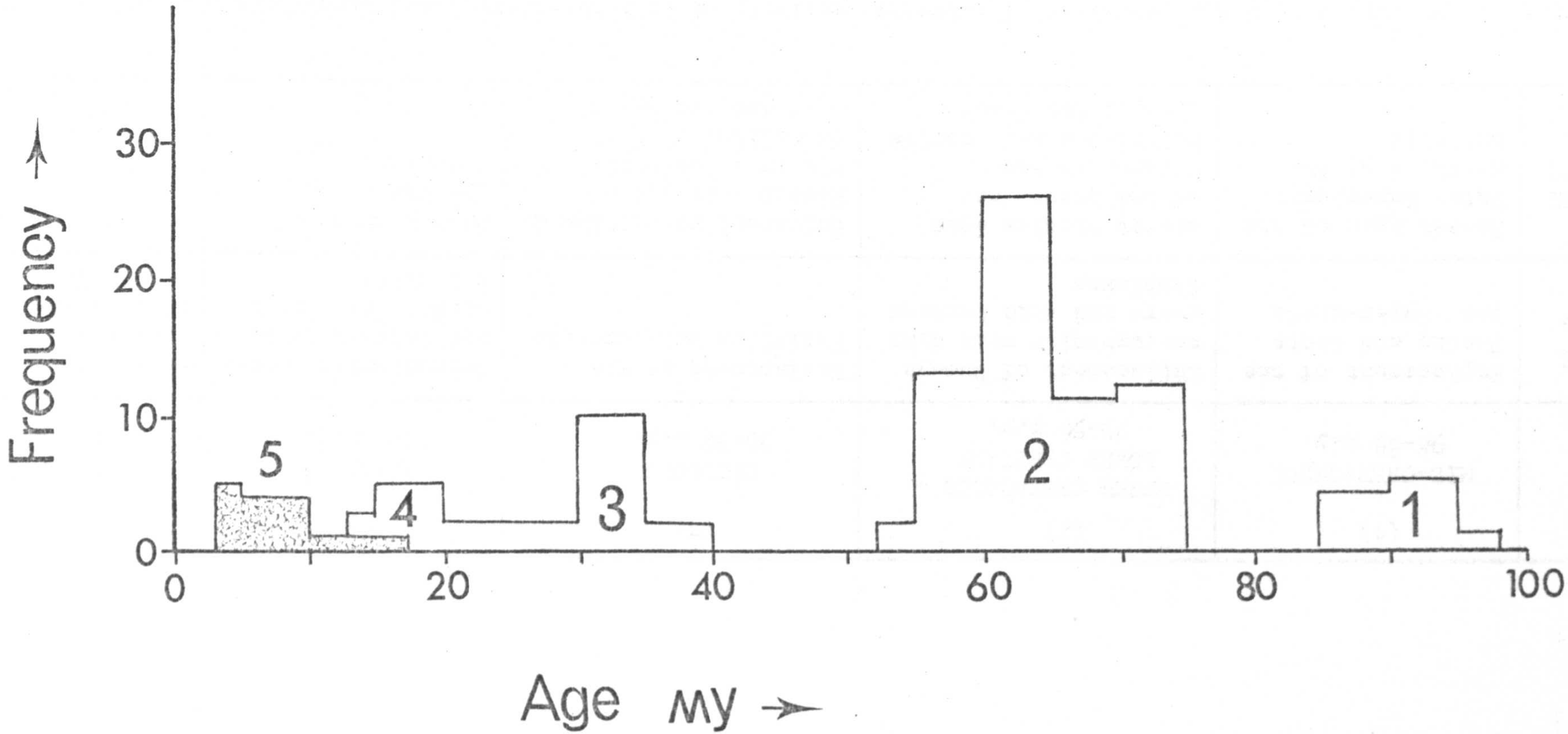


Fig.38 Histogram diagram of all Potassium-argon ages from the Coastal and Cordillera Blanca batholith (stippled), the five groups are referred to in Table 37.

GROUP	(1) MID-CRETACEOUS 98-85 m.y.	(2) UPPER CRETACEOUS - LOWER TERTIARY 75-56 m.y.	(3) OLIGOCENE 35-30 m.y.	(4) MIOCENE 19-9 m.y.	(5) PLIOCENE 4-3 m.y.
INTRUSIVE ACTIVITY	Emplacement of the Paccho and Santa Rosa Super-units	Emplacement of Humaya monzogranite main dyke swarm and Acid Centred Complexes	Emplacement of the Pativilca monzogranite	Granodiorite stocks and intrusions of Cordillera Blanca batholith	Final emplacement? uplift and cooling of Cordillera Blanca batholith
OTHER AGES WHICH CONTRIBUTE TO THE GROUP	Re-set ages of the Patap Super-unit on the W of the batholith	Re-set biotite ages of the Santa Rosa Super-unit and Hornblende and biotite ages of the Paccho	Universal re-setting of Paccho ages and of stocks to east of batholith. Also eastern Sayan?	Re-set micas of the Paccho Super-unit	-

Table 29. Chart summarising the evolution of intrusive activity of both the Coastal and Cordillera Blanca batholiths; the groups correspond to the culminations on the histogram. (see Fig.38).

PART FOUR

THE TEMPORAL RELATIONSHIP BETWEEN PLUTONIC AND VOLCANIC ACTIVITY IN THE AREA OF STUDY

Introduction

So far this thesis has been limited to the presentation and discussion of age data on intrusive rocks, although frequent reference has been made to the envelope rocks of both the Coastal and Cordillera Blanca batholiths. These country rocks are for the greater part volcanic in nature and bear a close contiguity to their intrusive counterparts. In fact Hamilton (1969) has made both volumetric and genetic comparisons between the volcanic rocks of the central Andes and the great batholiths of North America. Similarly Francis and Rundle (in press) have equated the extensive volcanic fields of northern Chile with the Coastal batholith of Peru largely on the basis of their volumetric similarity and comparative durations of igneous activity. Unfortunately the volcanic rocks in the area of study are by no means as voluminous as their counterparts in southern Peru and northern Chile, where stratovolcanoes are still active (Casertano, 1961).

In the following section some new radiometric age determinations are combined with the stratigraphic evidence in an attempt to decipher the chronology of the volcanic rocks and in particular their relationship with the intrusive rocks of the Coastal and Cordillera Blanca batholiths. It has been shown in the introductory part of this thesis that the volanic envelope rocks are divisible into three separate yet related groups:

(1) The Casma volcanics

(2) The Calipuy volcanics

(3) The Ignimbrites

The Albian age of the former group is based on reliable faunal evidence so the following section largely concerns the age of the Calipuy volcanics and the overlying ignimbrites.

1. THE AGE OF THE CALIPUY VOLCANICS

Some of the problems which are involved in assessing the age of the Calipuy volcanics have already been briefly outlined in the first part of this thesis. Their inferred lower Tertiary age is based on the observation of an unconformable relationship with red beds of the Casapalca formation (Wilson 1963, Cobbing 1973). However, Egeler (pers. comm.) has recently proved the presence of red beds of upper Cretaceous age in central Peru and such findings may cast doubt on the true age of the Casapalca formation.

Probably the most conclusive evidence for a satisfactory estimate of the age of the Calipuy volcanics is their unconformable association with folded upper Cretaceous strata to the east of the Coastal batholith. Here beds of Santonian-Coniacian age comprise the youngest members of the sequence and were folded and then eroded prior to the effusion of the Calipuy formation. On these grounds the Calipuy are less than 70 m.y. in age and possibly even younger because a long period of erosion must have followed the folding before the onset of vulcanicity (c.f. Cossio, 1964).

There are two main approaches for resolving the age of the Calipuy by radiometric dating; firstly by the dating of plutons which intrude the volcanics, and secondly the more direct approach of dating the volcanics themselves. The latter is the more idealistic because it also provides a means of quantifying both the rate and the duration of the volcanic activity. However, direct dating of the volcanics is fraught with difficulties because of their extensive hydrothermal alteration and hornfelsing by the younger plutons of the Coastal and Cordillera Blanca batholiths. These factors may substantially

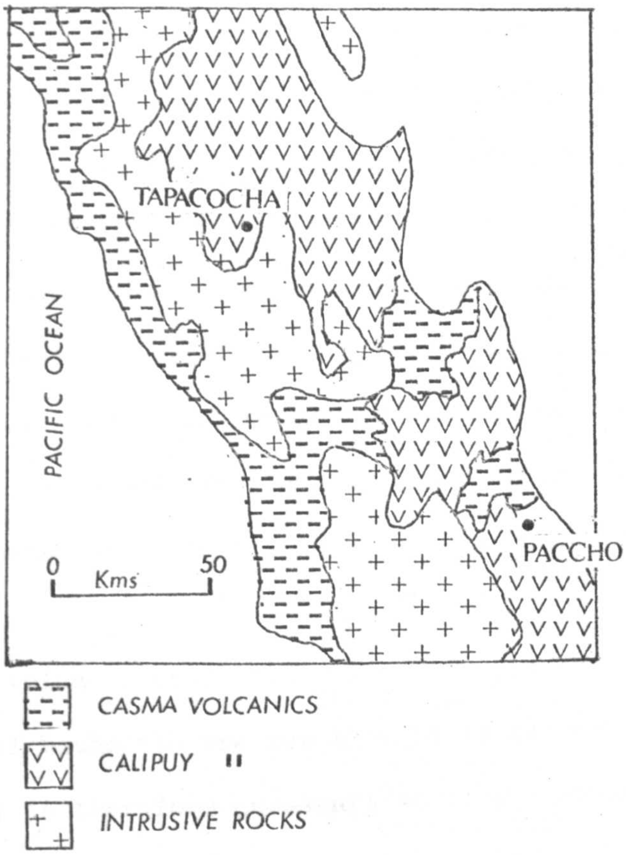


FIG.39 Part of the main area of study showing the relationship of the Casma aand Calipuy Groups of volcanic rocks with the Coastal batholith (geology after the 1;500,000 map of northern Peru, Cobbing 1973). The two localities described in the text are included.

reduce the argon retention properties of the volcanic rocks.

The Age of the Calipuy relative to dated intrusions

There have been many examples cited of plutons of the Coastal and Cordillera Blanca batholith intruding the Calipuy volcanics (Cossio 1964, Cossio and Jaen 1967, Wilson et. al. 1967, Cobbing 1973 and Myers in press). Unfortunately many of these reports may be unfounded because of the problems of distinguishing the Calipuy volcanics from the Casma volcanics especially when hornfelsing occurs because this tends to obliterate any diagnostic structures in the rocks. Thus the reports of the Calipuy being cut by members of the Paccho complex (Cobbing and Pitcher, 1972a) are open to debate especially since this contradicts their assumed post-Santonian age.

A greater part of the volcanic sequences which form the eastern envelope of the Coastal batholith are now thought to belong to the Casma group and it is therefore necessary to look further east for plutons which convincingly intrude the Calipuy volcanics.

The oldest pluton which was dated in this study and which intrudes the Calipuy volcanics corresponds to the Acos tonalite (24 m.y sample A120). Stewart and his co-workers established a minimum age of 33 m.y for the Calipuy based on the age of the Sayan monzogranite, which hornfelses a volcanic roof pendant on Cerro Yeta Negra (Plate 3). Although recently there has been some doubt as to whether this roof pendant really represents Calipuy or subhorizontally disposed Casma volcanics.

In conclusion the relative dating of the Calipuy volcanics has proved to be unsatisfactory because they are not bracketed by dated plutons. Conversely in south-central Peru the Calipuy volcanics are more ideally preserved and have been seen to rest unconformably on the early tonalitic members of the Coastal batholith.

Age determinations from the Calipuy Volcanics

The author examined the Calipuy volcanics at two well exposed localities some distance to the east of the Coastal batholith (Fig. 39). At the first locality above the village of Paccho, in the Huaura valley, the volcanics were extensively altered and were generally unsuitable for dating purposes. In

Plate 6. The Calipuy volcanics resting unconformably on folded sediments of the Hauyllapampa group, above the village of Tapacocha.

the second area above the village of Tapacocha, the Calipuy outcrops as a thick succession of dominantly pyroclastic deposits which contain thin flows of andesite and dacite which are apparently fresh and not penetrated by visible intrusions. At this locality a basal conglomerate is present and the sub-horizontal volcanics are easily distinguishable from the underlying isoclinally folded sediments of the Hauyllapampa group (see Myers, 1974). A spectacular trap topography is developed in the area due to the differential weathering of the lavas and tuffs in the volcanic pile (Plate 6).

Three samples were collected from lava flows throughout the volcanic pile and were dated using their whole rocks because their fine grain size precluded the possibility of mineral separation. Before describing the results, which are tabulated below, the writer refers the reader to the discussion in Appendix 1 concerning the suitability of volcanic rocks for K-Ar dating.

Sample	K%	Vol Rdg Ar^{40} x 10^{-7} scc/gm	Age
A71	0.386	8.2052	52.5 ± 2.3
A72	1.05	10.121	24 ± 2.2
A74	1.44	8.5655	14.9 ± 2.4

Table 30. K-Ar age determinations from the Calipuy Volcanics, Tapacocha section.

The samples were carefully selected from the base (Sample A71) to the top of a 1,000m section through the volcanic pile and at face value the results imply that a period of 38 m.y. has been required for their eruption. However before attaching any significance to these values it is important to discuss the petrography of the lavas in order to assess their reliability as argon traps.

In hand specimen all three samples are comparatively fresh fine-grained blue-grey lavas. Under the microscope they display a microporphyritic texture which is characterised by well twinned andesine phenocrysts. Phenocrystic clinopyroxene is also present yet is subordinate in amount to plagioclase and is frequently chloritised. Pseudomorphs of chalcedony and carbonate, probably after olivine, were observed in the two higher flows.

In all three samples the groundmass consists of orientated feldspar microlites and are usually aligned parallel to the long axes of the andesine phenocrysts. The major textural differences between the three flows can be summarised:

(1) the basal lava flow contains a much higher ratio of phenocrysts to groundmass, approximately 1 : 1 compared with 1 : 2 in the higher flows

(2) there is a noticeable change in the characteristics of the groundmass; individual euhedral feldspar crystals are easily discernable in the groundmass of Sample A71. The grain size of the groundmass decreases significantly in the two higher flows, thus sample A72 exhibits a pilotaxitic texture and a decrease in grain size continues further until individual grains are not visible in Sample A74.

These petrographic changes are paralleled by an increase of potassium content with decreasing age (0.4 - 1.4%). Since the mineralogy of the porphyritic phases are essentially similar this potassium must reside in the groundmass of the two higher flows which in view of their fine grain size and greater degree of alteration, will act as poor argon traps (c.f. Miller and Mussett, 1963). Sample A71 on the other hand is composed dominantly of plagioclase which has extremely good argon retention properties especially for low K values (Evernden and Evernden, 1969). The age of 53 m.y which was obtained from this sample possibly approaches the true age of this flow, although caution predicts that this should also be treated as a minimum age.

Essentially similar volumes of radiogenic argon were extracted from the three lava flows therefore the differences in their ages is purely a function of their differing potassium contents. It is likely that a much shorter period of time was involved in the eruption of this volcanic sequence than is predicted by the age determinations.

Probably the greatest significance of this data concerns the minimum age of the basal lava flow (52.5 ± 2.3 m.y.) which is not significantly different to the age of the San Jeronimo ring dyke of the Fortaleza Centred Complex (56 m.y.).

The relaticnship of the volcanics to the intrusive rocks are discussed at length later in the thesis. In the following section the writer presents age determinations from the ignimbrites which help to provide a minimum age for the Calipuy volcanics.

2. THE AGE OF THE IGNIMBRITES

GENERAL INTRODUCTION

The Calipuy volcanics are unconformably overlain by felsic ignimbrites which have a very limited aerial coverage but must have once been very widespread prior to their removal by erosion. In the area of study their present outcrop is confined to a few isolated outliers (see Fig. 40). This contrasts with the enormous volumes which have been described by Fenner (1948) around Arequipa in southern Peru.

Lithologically the ignimbrites comprise creamy dull-white friable tuffs which are composed of abundant euhedral quartz phenocrysts together with small specks of black biotite dispersed through-

Plate 7. Ignimbrite resting unconformably on the Coastal Batholith in the Rio Fortaleza valley.

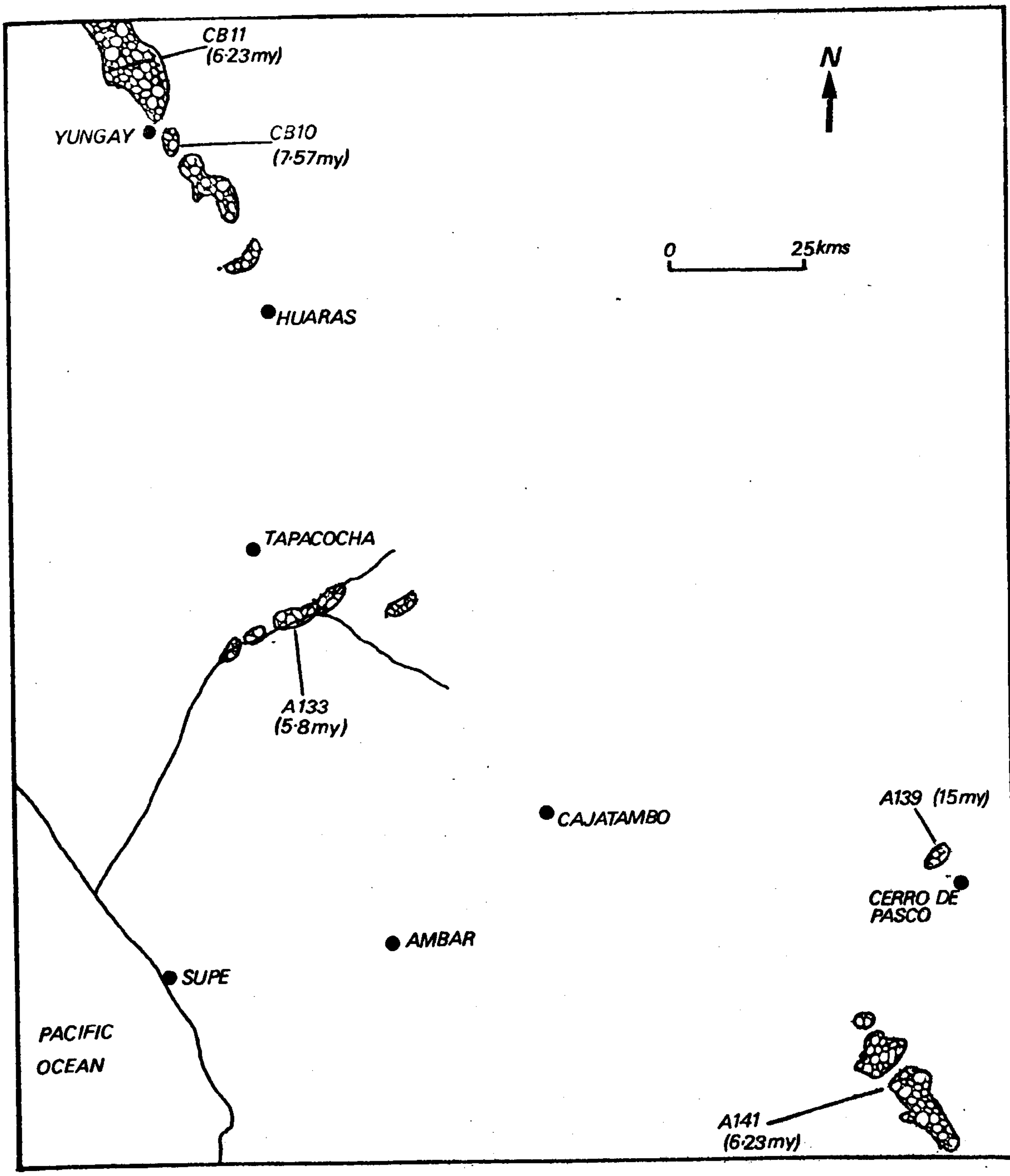


FIG.40 Map showing the distribution of Ignimbrites in the western Cordillera of central Peru, adapted from the 1:500,000 geological map of Peru. The sample localities are shown together with the results of the K-Ar ages of biotite phenocrysts.

out a feldspathic fequently altered matrix. The groundmass is normally unconsolidated and extremely friable.
Phenoclasts of sedimentary origin are ubiquitous and are commonly derived from the underlying strata. A marked columnar jointing is extremely well developed particularly in the flows which are exposed in the Rio Fortaleza valley (Plate 7.).

The biotite phenocrysts were isolated from the rocks for K.Ar dating but their low concentration in the rock necessitated the collection of extremely large samples. Care was taken during the initial stages of mineral separation to exclude any foreign material which may contribute inherited argon-40.

Since the ignimbrites represent the youngest period of igneous activity in the area it can be stated with confidence that the ages obtained represent the crystallisation of the flows.

The results which were obtained are tabulated below and with the exception of one sample (A139) their ages fall into one group of 7.6 - 5.8 m.y which together with their lithological similarities implies they represent a consanguineous group.

Sample	K%	Vol rdg Ar^{40} x 10^{-6} scc/gm	Age
A133	7.29	1.7026	5.8 ± 0.2
A141	7.35	1.8307	6.2 ± 0.2
CB10	7.3	2.2117	7.6 ± 0.2
CB11	7.65	1.9044	6.2 ± 0.2
A139	6.87	4.2205	15.0 ± 0.3

Table 31. K.Ar age determinations from biotite phenocrysts from the Ignimbrites of west-central Peru.

(i) The Pliocene group (7.6 - 5.8 m.y.)

Two of the samples (CB10, CB11) correspond to the Yungay formation of Wilson and others (1967) and were collected from the western margin of the Cordillera Blanca batholith, where they attain a maximum thickness of 150m. In this region they lie unconformably on the Calipuy volcanics and overstep onto shales of the Chicama formation. Wilson and others (1967) have also described them resting unconformably on the Cordillera Blanca batholith. Sample CB10 was collected to the east of Yungay below the entrance to the Quebrada de Llanganuco where it outcrops at an altitude of 2,800m, and CB11 was sampled at an altitude of 2200m between the villages of Caraz and Sucre in the Callejon de Hauylas. The difference in age of these two samples suggests that they represent two separate eruptions and the ambiguity in their relative stratigraphic positions can be attributed to the complex faulting which was associated with the updoming of the Cordillera Blanca batholith.

Sample A153 (5.8 m.y.) was collected from the Rio Fortaleza and dates the time at which a thick ignimbrite sheet infilled the negative topography which was formed at an early stage in the valley development. (see Plate 7)

The ignimbrite oversteps progressively from sediments to the east, onto the eroded Coastal batholith further west. A lateral change in thickness accompanies this westward overstep, for example, at Huayllapampa the ignimbrite is 750m in thickness and decreases to 100m at Chasquitambo over a distance of some 35 kms.

Myers (1974) has referred to the ignimbrite as the Rio Fortaleza formation and correlates with the Yungay formation further to the east.

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Sample A141 was collected from the extensive ignimbrite which outcrops to the west of lago Junin at an altitude of 4,200m on the Puna erosion surface (Fig.40). In this area they rest unconformably on a peneplained surface of folded limestones of the Jurassic Pucara group and form a series of hills which rise 350m above the surrounding country and display a spectacular 'bad lands' topography. The rock is poorly indurated and the biotite phenocrysts are less well developed than in the aforementioned samples. A high proportion of angular sedimentary phenoclasts are present in the lower horizons and vary in size between 1 and 20 cms. A flow fabric is often well developed around these inclusions.

The age obtained from the central part of this ignimbrite unit (6.2 m.y.) is coeval with the Yungay formation and the Fortaleza ignimbrite. It is obvious from these results that the volcanic activity which resulted in the deposition of the ignimbrites was operative over a distance of 350 kms along the Cordillera. Of course it is impossible to estimate the total volume of ignimbrite which must have been erupted over this area but it could have been comparable to that which is now exposed in southern Peru and northern Chile.

(ii) Ignimbrites of Miocene age

One sample (A139) yielded an older Miocene age thus proving the existance of an earlier period of ignimbrite eruption. Before discussing this result in any detail the author would like to describe its field occurrence for this has some bearing on the significance of the calculated Miocene age.

The sample was collected 2 kms north-east of Cerro de Pasco, which is part of the base and precious metal province of Central Peru. It differs from the Pliocene ignimbrites both in its field occurrence and lithology. Thus the rock is more indurated and contains a much higher proportion of biotite phenocrysts than the other ignimbrites. Furthermore xenoliths are more abundant and of a greater variety, being of both sedimentary and igneous origin. Angular to subrounded fragments of limestone and shale occur together with large rounded pebbles of a porphyritic quartz monzonite.

In addition to these lithological differences the Cerro de Pasco ignimbrite contrasts with the Pliocene ignimbrites in its unique occurrence in that it represents a vent infilling rather than an ash-flow deposit. It forms part of the extensive sequence of agglomerates and tuffs which are genetically related to a quartz monzonite stock which outcrops to the north-west of Cerro de Pasco (Fig.40). This sequence of steeply dipping pyroclastic rocks have been termed the Aglomerado Rumillana by Lacy and Hosmer (1956) and is referred to in many of the Mining reports, although most of these observations are based on sub-surface mapping (Ward 1961, Petersen 1965).

According to Ward (1961) the interbedded pyroclastic rocks occupy a 2.5 km diameter circular vent and are intruded by a quartz monzonite stock at depth. The stock and associated tuffs both pre-date the extensive Cu-Pb-Zn-Ag deposits which replace the limestones of the Pucara group, and these in turn are truncated by Puna erosion surface. Thus the 15 m.y. biotite age, obtained from the ignimbrite, places a maximum age on the Cerro de Pasco ore deposits and on the formation of the Puna erosion surface. In the following section the writer proposes to summarise the timing of vulcanicity in the study area on the basis of these results.

3. SUMMARY OF TIMING OF VOLCANIC ACTIVITY IN THE REGION OF STUDY

The data which has been presented in the preceding section is somewhat inadequate for precisely defining the absolute limits of the initiation and duration of vulcanicity in the study area. A maximum limit of 70 m.y. is acceptable for the base of the Calipuy volcanic on stratigraphic grounds. However, this period is probably substantially less if the time involved in the folding and peneplanation of the Cretaceous sediments in considered. On these grounds it seems reasonable to place the base of the Calipuy formation between 70 and 53 m.y. and this confirms their inferred Tertiary age.

Alternatively an accurate assessment of a minimum age for the Calipuy episode is open to debate, mainly due to the unreliability of the ages from the younger lavas at Tapacocha (Sample A72, A74). In order to help resolve this problem the author defines the Calipuy as the volcanic and pyroclastic rocks which unconformably overlie the Cretaceous sediments and which in turn are truncated by the Puna erosion surface. Admittedly this statement is probably too wide in scope but the definition immediately sets an upper limit on the Calipuy by involving the ignimbrites which show that the Puna erosion surface is probably of upper Miocene age. On this basis it is now possible to envisage a period of at least 40 m.y. for the effusion of the Calipuy extending from the Palaeocene to the Miocene period. These findings have important consequences primarily due to the considerable overlap between volcanic and intrusive activity in western Peru. Before debating the source of the volcanic rocks in any detail it is advantageous to refer to published age determinations on Cenozoic volcanic rocks from other parts of Peru.

4. PUBLISHED AGE DATA ON CENOZOIC VOLCANIC ROCKS IN PERU

A few K.Ar ages have recently been reported from volcanic rocks in southern and south-central Peru by Noble and others (1974) and McKee and others (1975). Since these published ages are significant in the light of the new data presented in this thesis they are briefly discussed in this section.

From the accounts of fellow workers in Peru the Calipuy volcanics appear to be very extensive for they occupy a considerable part of the Cordillera Negra. Throughout this area of outcrop certain major differences are noteworthy, for example the degree of deformation changes radically. Thus the subhorizontal Calipuy in the area of study contrasts with the tight isoclinal folds described in the volcancis of south-central Peru by Noble and others (1974). Differences in composition also occur for andesite and ash fall tuffs in central Peru give way to more ignimbritic tuffs further south. In the area around Pisco in south-central Peru, large sheets of ignimbrite unconformably overlie the Coastal batholith portraying a situation which must have once existed in the Rio Fortaleza.

Noble and others (1974) have reported K.Ar age determinations from samples which were collected throughout a thick succession of highly folded ash-flow tuffs around Hauncavelica (See Fig. 41). Their results define two general groups; 41-14 m.y. for a series of folded tuffs which are overlain unconformably by a sequence of undeformed silicic tuffs (10-4 m.y.). This younger group correlate with the ignimbrites which were described in the previous section.
McKee and others (1975) have also recognised this younger group to the south of Hauncavelica where they describe a series of andesites, dacites

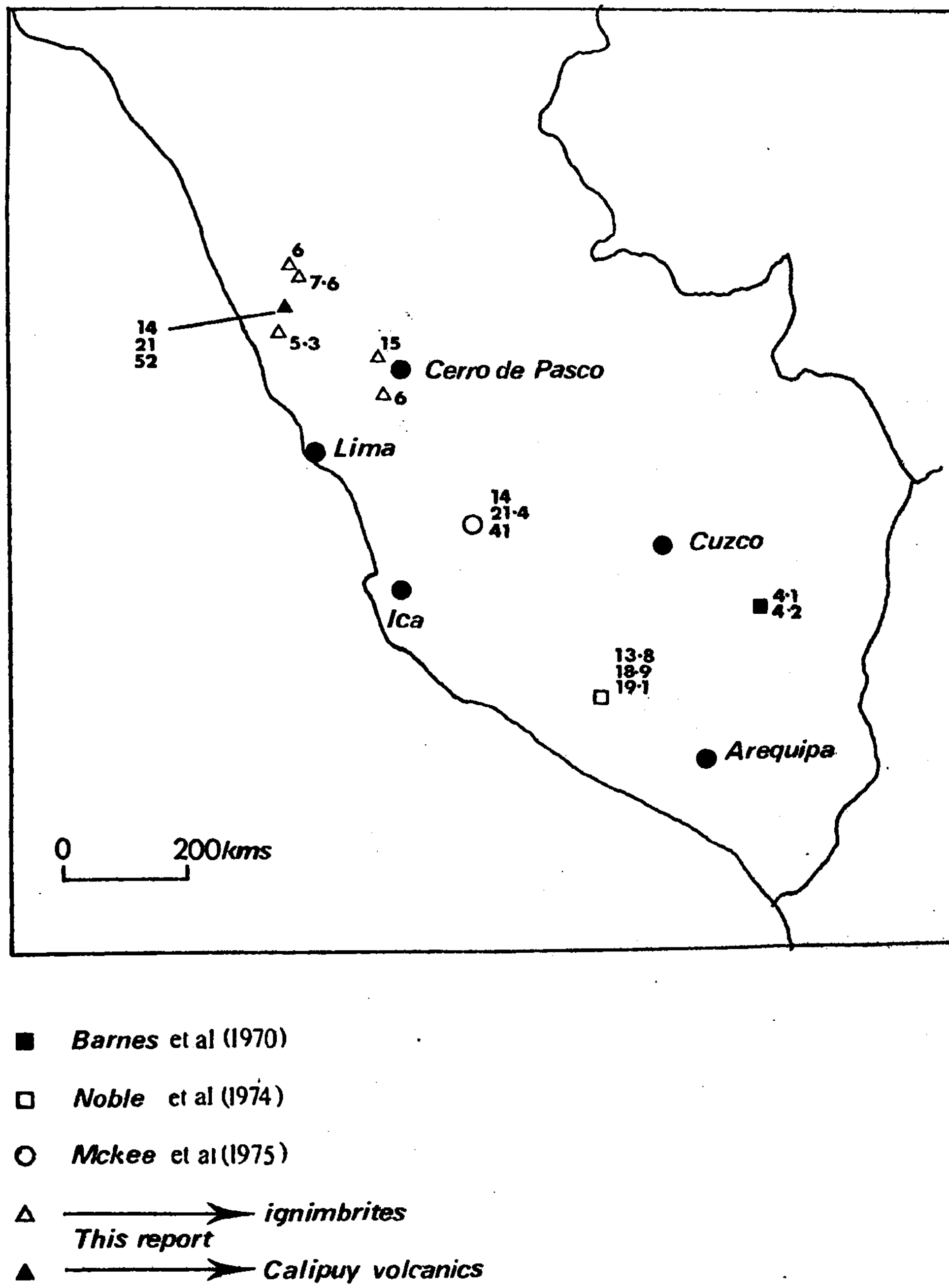

FIG.41 Part of Peru showing the areas where dating projects have been carried out on Cenozoic volcanic rocks.

and rhyodacites which form a complex network of flow, sills, dykes and composite volcanoes. These have yielded ages 10.4 - 8.2 m.y on biotite concentrates.
Two Miocene ages (18.9 - 19.1 m.y.) have been obtained from the extensive ash-flow sheets which outcrop in the Andahua Valley near Arequipa and these have been folded prior to the deposition of a younger series of ash-flows. (Farrar et.al., pers comm in Noble et. al. 1974). Pliocene ages of 4.1 and 4.2 m.y., have also been recorded from Ignimbrites near Macusani in south-east Peru (Fig. 41) by Barnes et. al. (1970) and this data is also supported by a fission track date of 4.3 m.y on an associated volcanic glass (Fleischer and Price, 1964).

All this data is plotted graphically in Fig41b and shows that the volcanic chronology established in the area of study is broadly reflected further south, even though the folding is locally more intense. Thus undeformed silic lavas and tuffs (ignimbrites) of Pliocene age everywhere rest on a peneplained surface of folded volcanic rocks. In south-central Peru the K.Ar ages have provided a clearer insight into the duration of vulcanivity throughout the Tertiary period than the limited data from the study area. Furthermore all the age determinations from southern Peru are on biotite phenocrysts which, depending on their depth of burial in the volcanic pile, give reliable crystallisation ages.

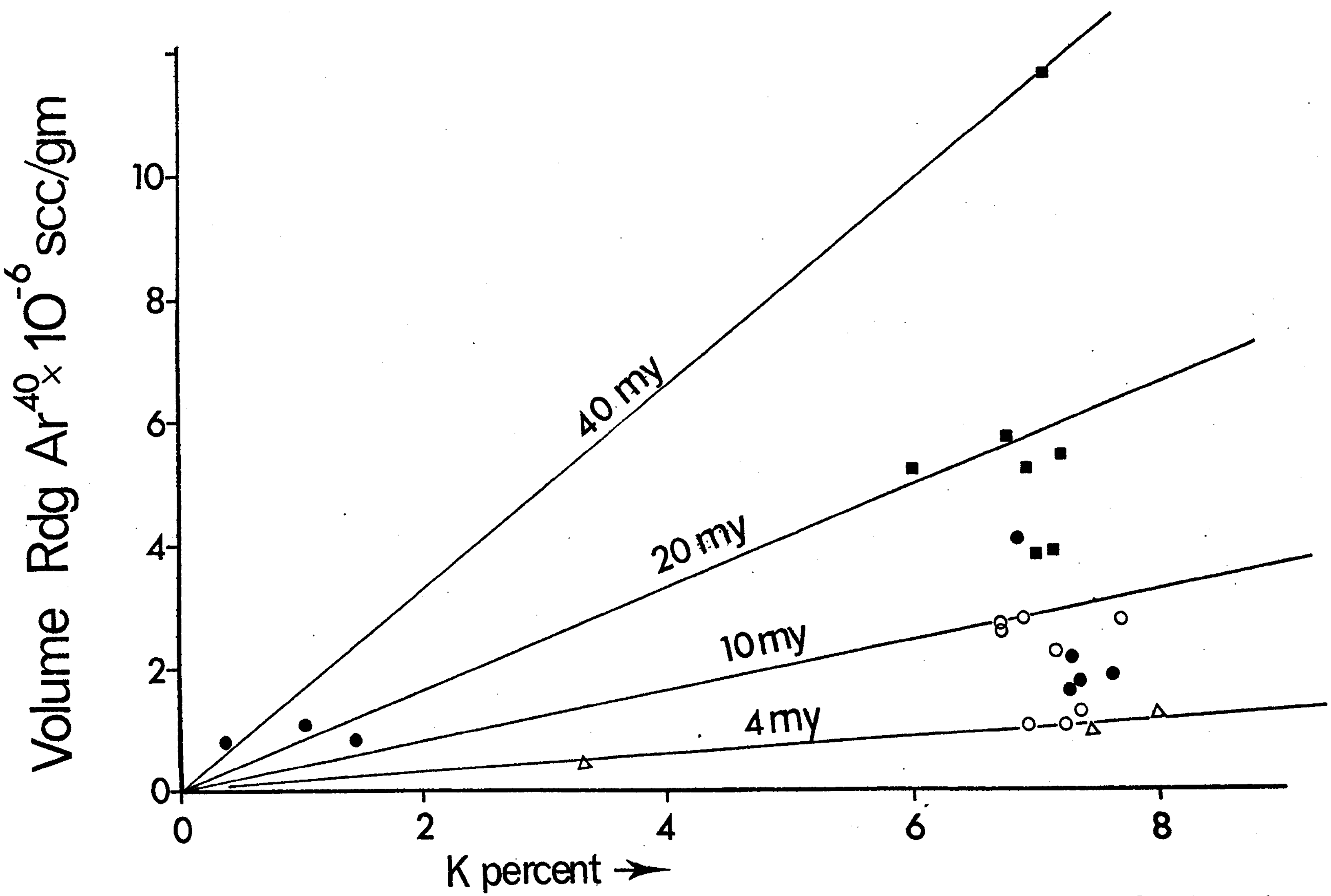

FIG.42b. Potassium-argon isochron summarising the age determinations from Cenozoic volcanic rocks in Peru. Data sources; (●) this report, (■) Noble et.al.1974, (O) McKee et.al.1975, (▷) Barnes et.al.1970.

5. TIME RELATIONS BETWEEN PLUTONIC AND ASSOCIATED VOLCANIC ROCKS IN THE AREA OF STUDY

Introduction

It is obvious from the age data presented in this thesis that there is a considerable degree of correlation between plutonic intrusions and volcanicity, both of which overlap with tectonism. Members of the Peru project envisage the Coastal batholith as having crystallised beneath a roof of its own volcanic ejecta, in accordance with the views of Hamilton and Myers (1967, 1974) who have described a similar relationship for the Boulder batholith of Montana.

The Calipuy volcanics are thought to be petrogenetically related to the Centred Acid Complexes of the Coastal batholith as the latter probably represent the root zones of large calderas which fed the volcanic pile (see Bussell and Pitcher, in press). Similarly Noble et.al. (1974) and McKee et.al. (1975) have proposed a genetic relationship between the ash fall tuffs of Hauncavelica, and the Cordillera Blanca batholith. The same origin has been suggested for the ignimbrites in the present area of study by Pitcher (1974). These relationships form the theme of the following section. However the discussion is slightly restricted because the fingerprinting of intrusive and extrusive activity is based only on the similarity of their ages and requires supporting geochemical work before a genetic relationship can be proved.

The Casma Volcanics

Myers (1975.b) and Regan (1972) have shown that the complex fabrics displayed by the basic rocks of the Patap Super-unit suggests they are synkinematic with the folding of the Albian Casma volcanics. This hypothesis also gains support from the radiometric evidence for the age of the gabbros, which was discussed by the author earlier in the thesis. These ages provide convincing evidence for a genetic relationship between the Casma volcanics and the early members of the Coastal batholith. Recently feeder pipes have been recognised within the Casma volcanics and these possibly represent the channels through which the ascending basic magma was tapped to the surface (Knox, 1972 and Myers 1975.b).

The Calipuy Volcanics

By combining both the radiometric and stratigraphic evidence it is possible to envisage a period of 40 m.y. for the eruption of the Calipuy volcanics. On this basis their effusion overlapped with that intrusive activity of the Coastal batholith which followed the emplacement of the Santa Rosa Super-unit. The most likely source of the Calipuy volcanics are the Centred Acid Complexes which appear to have been active in the Palaeocene (65 - 60 m.y.).

It has been shown that certain remnants within the Centred Complexes represent much earlier phases in their activity, and were possibly the sites of extrusion of the volcanic equivalents of the Santa Rosa Super-unit. However, extrusive equivalents of the Santa Rosa Complex have not been recognised in the area of study but were presumably represented by higher levels in the Casma volcanics which have been removed by subsequent erosion. Thus Myers (1974) has described a 600m sequence of lavas and pyroclastic rocks, including ignimbrites, in the Haurmey area. These rest unconformably on the Casma volcanics and according to Myers represent a

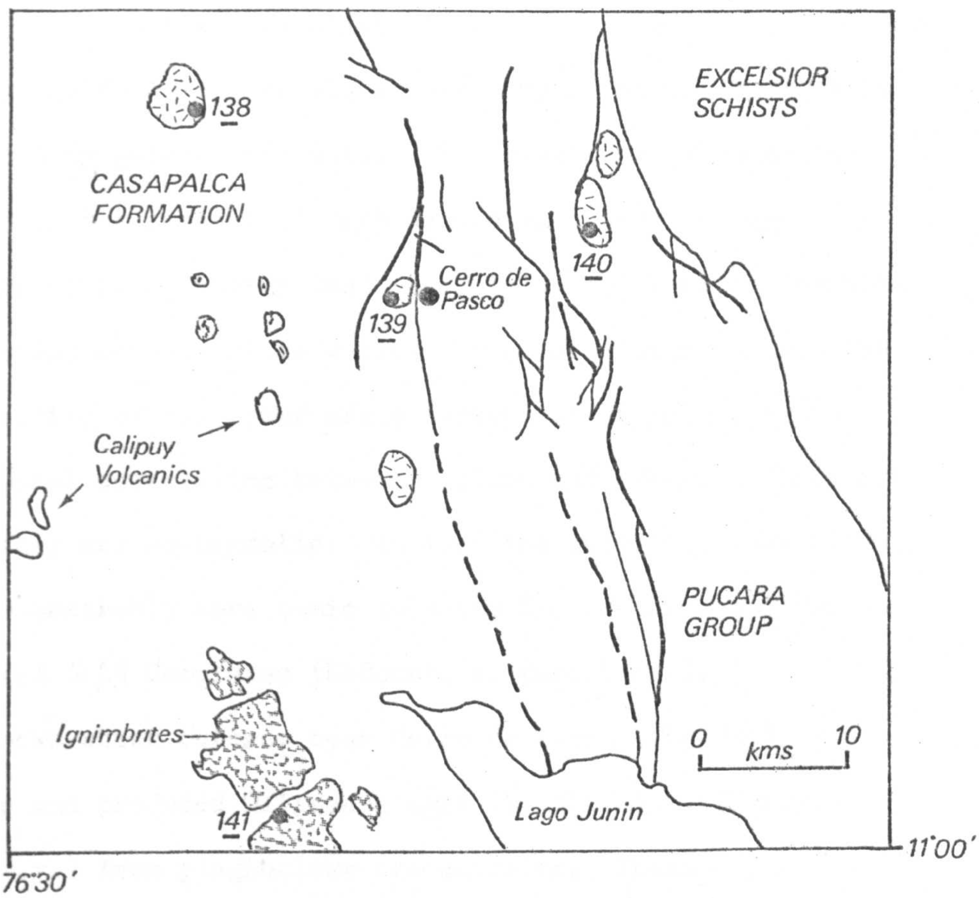

FIG. 42 a. Diagram showing the distribution of stocks of porphyritic granite around Cerro de Pasco. The stocks intrude folded sediments of the Jurassic Pucara Group and Tertiary Casapalca Formation. Geology is based on the 1;500,000 map of northern Peru.

transitional facies between the Casma and Calipuy volcanics. If this assumption is correct then it is possible that there is a complete volcanic record which spans the entire emplacement history of the Coastal batholith.

Unfortunately the genetic relationship between plutonic and volcanic activity implied by age data is possibly an oversimplification because it is as yet unsupported by geochemical data. The provenance of andesites and granites have been the subject of much debate with some workers advocating different sources, namely that andesite arises from the partial melting of a subducting oceanic plate whilst the granite magma originates from the partial melting of the lower crust (Green and Ringwood, 1966, 1967). Thus a temporal correlation between plutons and volcanics does not necessarily imply they are co-magmatic. In fact the andesitic lava flows at Tapacocha are demonstrably more basic than the San Jeronimo and Puscao magmas of the Centred Acid Complexes (McCourt, W. pers.comm.).
Two rhyo-dacite stocks which outcrop near Cerro de Pasco (Fig. 42) were dated by the writer and produced Oligocene ages (Sample A138, 32 m.y., Sample A140, 28.7 m.y.) from plagioclase concentrates. These hypabyssal intrusions furnish direct evidence of a link between plutonism and volcanic activity and may have acted as a magma source for the upper part of the Calipuy volcanic pile.

The Ignimbrites

In the area of study there is a noticeable break between the Calipuy volcanics and the overlying ignimbrites which is defined by the Puna erosion surface. The ignimbrites which were erupted onto this peneplain have yielded Pliocene ages which correlate with the younger ages obtained from the Cordillera Blanca batholith (Fig. 43).

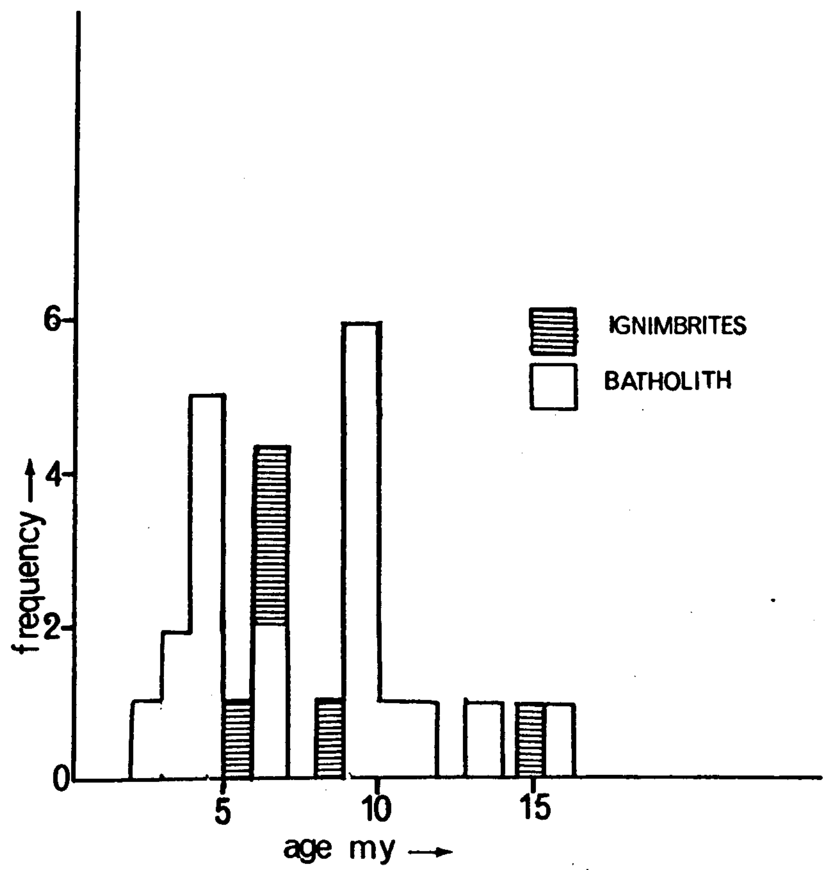

Fig. 43 Comparison betwen ignimbrite ages and those from the Cordillera Blanca Batholith.

Myers (in press) has suggested that the Fortaleza ignimbrite originated from a fissure eruption to the immediate west of the Cordillera Blanca batholith and a similar mechanism has also been envisaged by Pitcher (1974). Such a process readily explains how large volumes of ignimbrite can be erupted over vast areas.

However, there is some disagreement concerning the origin of ignimbrites and they have been cited as being products of explosive plutonism (Harriss et. al. 1970) and this seems acceptable in view of the genetic relationship between the ignimbrite and porphyritic granite described near Cerro de Pasco. Stewart and his co-workers (1974) have obtained a Pliocene age from a 'granite plug' near Lago Junin and proposed a consanguineous relationship between this and the nearby ignimbrite. From this evidence it seems that small circular stocks have also featured as important sources of magma for the ignimbrites. Many of these stocks outcrop on the Puna erosion surface and probably form a southern continuation of the

Cordillera Blanca batholith.

Table 32 represents a summation of the time relationships between vulcanicity and plutonic activity in the area of study. The age determinations provide strong evidence of a genetic link between the Coastal and Cordillera Blanca batholiths and the three suites of volcanic rocks. However the Oligocene ages of the two rhyo-dacite stocks near Cerro de Pasco tentatively suggests that the source of the higher parts of the Calipuy volcanics may have been a considerable distance to the east of the Coastal batholith.

INTRUSIVE ACTIVITY	TECTONIC ACTIVITY	EXTRUSIVE ACTIVITY
UPLIFT OF CORDILLERA BLANCA BATHOLITH		IGNIMBRITES (8-5 m.y.)
PLIOCENE INTRUSIONS ?		
	- EROSION -	(?) 10 m.y.
	MINOR FOLDING VARYING IN INTENSITY	
(ORE DEPOSITS)		VENT IGNIMBRITE (15 m.y.)
CORDILLERA BLANCA BATHOLITH (20-9? m.y.)		RHYO-DACITE STOCKS (32-28 m.y.)
STOCKS (19-13 m.y.)		CALIPUY VOLCANICS
YOUNGER MONZOGRANITE PLUTONS (32-35 m.y.)	UPLIFT ?	
CENTRED ACID COMPLEXES (68-56 m.y.)		BASAL CALIPUY LAVA FLOW (> 55 m.y.)
	- EROSION -	70 m.y.
	FOLDING OF EASTERN ENVELOPE	
SANTA ROSA SUPER-UNIT (95-72 m.y.)		(?) PARARIN FMT
PACCHO SUPER-UNIT		
	MAIN ANDEAN FOLDING	
PATAP SUPER UNIT		CASMA GROUP (107-100 m.y.)

Table 32. Summary of the time relationships of Plutonic, Volcanic and Tectonic activity in the area of study.

6. EVIDENCE FOR THE AGE OF THE ANDEAN FOLDING - ON THE BASIS OF THE ISOTOPIC AGE DETERMINATIONS

By combining the age determinations on both plutonic and volcanic rocks,with stratigraphic evidence from the area of study, it is possible to bracket the age of the principal folding of the Western Cordillera. It has been shown that the emplacement history of the Coastal and Cordillera Blanca batholiths have spanned a period of some 90 m.y. and during this time the local tectonic environment has changed. This fact is well exemplified by the syntectonic gabbros of the Coastal batholith which contrast with the post-tectonic tonalites of the Santa Rosa Complex. Comparative studies in North America (Evernden and Kistler, 1970), and Chile (Aguirre and others, 1974), have demonstrated a contemporaneity between major periods of voluminous magmatism and regional deformational events. A similar relationship is apparent on the basis of the radiometric age data which has been presented in this thesis. Thus the major 'pulses' of magmatism (see Table 29) broadly correspond to periods of compression which are recognisable in the country rocks. Therefore the three orogenic phases which were recognised by Steinmann (1929) are defined by culminations of K.Ar ages and these equate with the tectonic sequences recognised in central Chile by Aguirre et.al. (1974).

To summarise;

(1) The main Andean folding in the study area occurred in the interval 106-100 m.y. (mid-Cretaceous) this affected the Casma group and corresponds with the Subhercynian phase of central Chile, Aguirre et.al. (1974).

(2) Interval between 70 m.y. and 60 m.y. (Cretaceous-Palaeocene) marked by the folding of the eastern envelope and emplacement of Centred Complexes. This equates with the Laramic phase in Chile (Aguirre et.al. 1974).

(3) Interval between 34 m.y. and 30 m.y. (Oligocene) represents the Incaic phase of Steinmann (1929) and has also been recognised in central Chile. Represented in study area by possible large scale uplift and minor folding of Calipuy volcanics and emplacement of monzogranite plutons.

(4) Interval between 15 m.y. and 10 m.y. (Upper Miocene) corresponds to the Quechan phase of Steinmann and is represented by uplift mild warping and formation of the Puna erosion surface accompanied by emplacement of Cordillera Blanca intrusions and ignimbrite eruption.

Probably the most surprising feature of this tectonic evolution is the contrast in timing between the folding of the western and eastern envelope of the Coastal batholith. Both these compressive phases correspond to the Peruvian folding of Steinmann (1929) which correlates well with the Subhercynian and Laramic phases recognised in central Chile (Aguirre et.al. 1974).

Andean Uplift

The age of the principal uplift of the Andes to their present elevation has formed the theme of many recent studies, especially in northern Chile (Hollingworth 1964, Rutland et.al. 1965 and Mortimer 1973). Here a careful examination of the extensive erosion levels and dating of the associated ignimbrite flows have led to an absolute chronology for the evolution of the topography. Rutland and others (1965) have contended that the greater part of Andean uplift occurred during the Pliocene, and envisaged uplift rates of 0.4 k.m./m.y. Conversely, Sillitoe et. al. (1968) state that altitudes of at least 3,500 m had clearly been attained before the close of the Miocene, and any subsequent tectonic uplift was of a subordinate nature.

In the area of study the volcanic record is inadequate for defining the rate, or onset, of Andean uplift with any accuracy.

However, the Pliocene age obtained from the Fortaleza ignimbrite shows that the Andes were already an impressive and much dissected mountain range at this time (6 m.y. ago). This observation adds weight to the theory of a Miocene age of uplift which has been visualised by Sillitoe and his co-workers (1968).

Throughout this thesis the author has discussed the timing of plutonic activity in the Coastal and Cordillera Blanca batholiths and in the preceding section has attempted to relate these findings to the tectonic and volcanic evolution of the area of study. These inter-related topics are summarised and viewed in a much broader context in the final part of this thesis.

PART FIVE

RECONNAISSANCE AGE DETERMINATIONS FROM THE SAN NICHOLAS BATHOLITH AND THEIR SIGNIFICANCE

THE SAN NICHOLAS BATHOLITH

Introduction and General Geology

As outlined in the introductory part of this thesis, the San Nicholas batholith comprises a group of apparently disconnected yet related intrusions which are poorly exposed in the low desert along the Coastal Cordillera of southern Peru (Fig.2). The batholith has been examined in greatest detail around Marcona (Fig.44), mainly in connection with regional studies related to the occurrence of the important Marcona iron-ore deposits (Atchley 1956, Adrian 1958, Hoyt 1962). More recent studies by Hudson (1974) laid down the foundations of the writer's interest in the geology of the region.

In the Marcona region the batholith intrudes the Pre-Cambrian Lomas Complex and sediments of the Marcona formation. The various units of the batholith range in composition from hornblende gabbro and diorite to granodiorite, all of which are characterised by the presence of euhedral hornblende phenocrysts giving rise to an appinitic texture. Internal contacts have not been recognised so the afforementioned variations appear to be gradational, although this is possibly a reflection of the poor nature of the exposure. The major differences between the San Nicholas batholith and the Coastal and Cordillera Blanca batholiths have been outlined in a recent review by Pitcher (1974).

There is a certain degree of controversy concerning the age of the San Nicholas batholith its origin and its relationship to the iron-ore deposits. It has been referred to as Jurassic by Hoyt (1962) who has described an intrusive relationship with the Jurassic

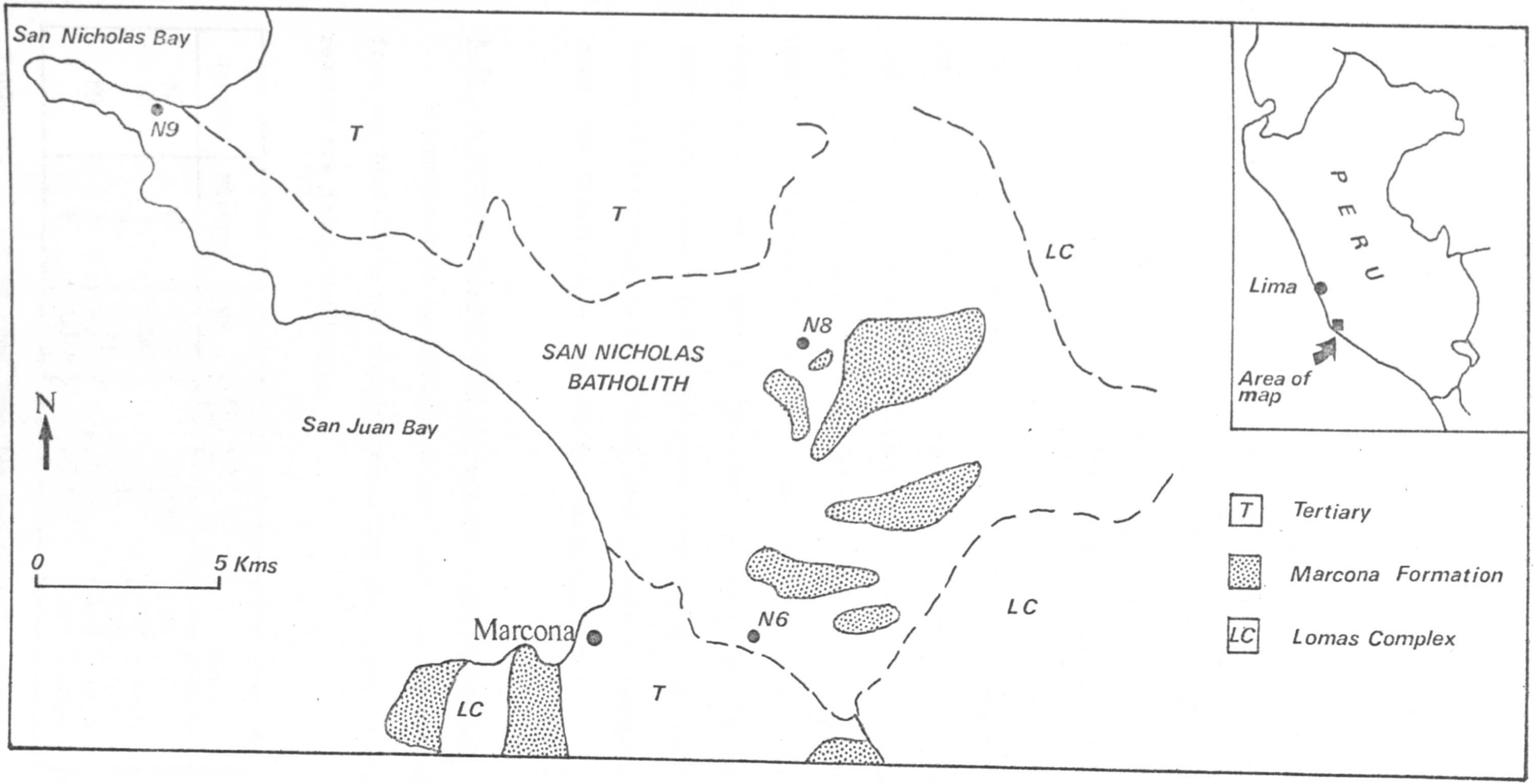

FIG.44 Diagram showing the geology of the Marcona area of south-central Peru, the localities of the dated samples are included, geology after Hudson (1974).

Cerritos formation near Marcona; and this observation is supported by a Jurassic K.Ar age reported by Bellido (1969). Hudson (1974) in his survey of the batholith found no evidence for any relationship with the Cerritos formation because the contacts were obscured by longitudinal faults. However, he suggested a possible Jurassic age for the intrusives based on lithological similarities with rocks in northern Chile.

The maximum age for the batholith is clearly related to the age of the Marcona formation these comprise a series of well-bedded hornfelsed siltstones, cherts and quartzites, with interbedded iron ores, which are cut by the batholith. The age of the Marcona formation is problematical due to the absence of fossils. They rest unconformably on the Lomas Complex and are in turn unconformably overlain by the Jurassic Cerritos formation. Hudson (1974) has correlated the Marcona formation, on the basis of lithology, with Carboniferous strata in southern Peru which have been described by Bellido and Narvaez (1970).

K.Ar age determinations from the San Nicholas batholith

Reconnaissance age determinations were carried out on three samples from the batholith, the sample localities are shown in Fig. 44 and the results are tabulated below.

Sample	Mineral	K%	Vol rdg Ar^{40} scc/gm x 10^{-5}	Age
N6	WR	0.61	.660466	254 $\pm$ 6
N8	B	4.56	8.4372	442 $\pm$ 10.4
	H	0.92	1.8083	438 $\pm$ 9.4
N9	B	3.24	6.2074	428 $\pm$ 12.2
	H	0.898	1.69136	421 $\pm$ 10.9

Table 33. K.Ar ages from the San Nicholas batholith.

Samples N8 and N9 were collected approximately 20 kms apart and represent medium-grained hornblende granodiorites which contain abundant hornblende phenocrysts which attain lengths of 2 cms. The two rocks are essentially similar and differ only in their relative proportions of quartz and orthoclase. In both cases biotite is subordinate to hornblende and occurs as brown euhedral flakes which are frequently chloritised. On the basis of these lithological similarities it is possible that they are part of the same intrusion.
Sample N9 was collected from San Nicholas Bay, from which the batholith derives its name.

Both samples N8 and N9 yielded concordant results from cogenetic hornblende-biotite pairs which the writer interprets as indicating an Ordovician-Silurian age of emplacement.
Sample N6 on the other hand corresponds to a fine-grained pyroxene diorite and yielded a whole rock age of 254 m.y. (Permian). This result is rather suspect because most of the potassium resides in late poikilitic clots of biotite and the true significance of the age is therefore uncertain and so is interpreted as a minimum value. Despite the difference between this younger result and the two which are based on cogenetic hornblende and biotite, the data is sufficient to indicate a lower Palaeozoic age for at least part of the San Nicholas batholith. These conclusions equate with the findings of Stewart and others (1974) who have described lower Palaeozoic ages (447, 441, 395 m.y.) from potassic granites which intrude the Lomas complex around Mollendo. Therefore it seems that intrusive activity is quite widespread along the Coastal Cordillera and has probably caused the lower Palaeozoic disturbance defined by the Rb-Sr isochron on the rocks of the Lomas complex (Cobbing and Snelling, in press).

Not only do these results confirm a much older age for the San Nicholas body but have additional significance in relation to the age of the Marcona formation and the associated iron-ore deposits.

The Age of the Marcona Iron-Ore deposits

The calculated lower Palaeozoic age of the San Nicholas batholith questions the assumed Carboniferous age of the Marcona formation and their associated iron ore deposits. A discussion of the origin of the strataboured ores is beyond the scope of this thesis; they form but part of the extensive magnetite-haematite deposits which are widely distributed throughout the highly deformed rocks bordering the Pacific ocean (cf. Park, 1972). The reader is referred to the work of Hudson (1974) which forms the most recent summation of the geology and origin of the Marcona ores, Hudson contends that the ores are syngenetic with the deposition of sediments of the Marcona formation.

That the San Nicholas batholith intrudes and assimilated the Marcona sediments and iron ores is beyond doubt, and Hudson has attributed the anomalously high proportion of magnetite in the batholith to this source. On these grounds the Marcona ore deposits are much older than was first envisaged and a possible late Pre-Cambrian age cannot be discounted. This is in accordance with the recent finding of a cleaved tillite at the base of the Marcona formation (Cobbing and Pitcher, pers. comm. 1974).

The problem of the occurrence of the iron-ore deposits in the Jurassic Cerritos formation originally weighted the argument of a Jurassic age for the San Nicholas batholith. It is of interest to point out that Hudson (1974) has attributed the occurrence of the disseminated ores in the Cerritos formation to be formed by the erosion of the Marcona formation, and subsequent redeposition of the ore in the Jurassic strata at the onset of the Andean Orogenic cycle.

In conclusion the main significance of these reconnaissance age studies are :

(1) The age of the San Nicholas batholith indicates that plutonic activity was widespread in the Coastal Cordillera during the lower Palaeozoic, and possibly suggests that this part of the Pacific margin has been active as a site of magma generation since the Ordovician!

(2) A pre-Silurian age of the Marcona formation is confirmed and this also implies a comparable age for the iron-ore deposits.

PART VI

CONCLUSIONS CONCERNING THE CHRONOLOGY OF EMPLACEMENT OF THE MESOZOIC-CENOZOIC BATHOLITHS OF PERU IN THE LIGHT OF OTHER CIRCUMPACIFIC STUDIES

Introduction

Since the introduction of Plate tectonic theory the association of igneous activity and tectonism at plate margins have formed the focal point of intensive geological studies. In this context the continential margin bounding the east Pacific Ocean has been cited as the prime example of interaction between oceanic and continental crust (Dickinson 1970, 1971; James 1971). Probably the most characteristic feature of this plate margin is the almost continuous string of Mesozoic-Cenozoic batholiths which parallel the coast from Tierra del Fuego and as far north as Alaska. Many of these batholiths are essentially similar with respect to their age and composition and yet show structural differences due to their post-kinematic and synkinematic nature and also to their differing levels of denudation (c.f. Pitcher 1974).

The large Phanerozoic batholiths of North America have been studied most extensively and this is clearly illustrated by the plethora of publications concerning their geochemistry and geochronology. Indeed most of the findings concerning the interpretation of K-Ar ages from plutonic rocks, adopted throughout this thesis, have arisen from such studies.

One of the most fundamental problems which has evolved from geochronological studies of Circum-Pacific batholiths concerns the disparity between continuous and episodic emplacement of granite magma. The patterns of distribution of K-Ar ages from North American batholiths favours an episodic mechanism of magma emplacement, a finding which is also supported by the data presented in this thesis (see p. 180). Some authors have taken this apparent episodicity one stage further and suggested that pluton emplacement is not only episodic but periodic implying there is a a regularity to the intrusive episodes (see Kistler et. al. 1971). Episodic pluton emplacement has now been reccgnised in most Circum-Pacific batholiths although it is generally accepted that if significantly large parts of the Cordillera are considered their individual emplacement histories tend to blur into a continuum (Gilluly 1973, Lanphere and Reed 1973 and Pitcher 1975).

In the concluding part of this thesis the author summarises the findings of co-workers in North America, with special reference to the pioneering work in the Sierra Nevada batholith. Similarly the results of radiometric dating projects in Chile are also descibed and are related in general terms to the patterns which have emerged from the present study.

1. EPISODIC OR CONTINUOUS MAGMATISM

The Sierra Nevada Batholith

The Sierra Nevada batholith of California and western Nevada consists of a composite of discrete plutons which are emplaced within the axial part of a N-NW trending synclinorium (Bateman et. al. 1963). Using stratigraphic evidence the batholith was assigned to a Jurassic or Cretaceous age (Bateman loc.cit; Bateman and Eaton 1967).

The first attempt to determine the age of the Sierra Nevada batholith by radiometric dating, was undertaken by Larsen and others (1958) who dated zircons by the Pb-alpha method. Their seven samples were collected from the eastern part of the Sierra Nevada batholith and produced ages in the range 117 - 94 m.y. Subsequent efforts concentrated on the K-Ar method and several hundred age determinations have now been completed for rocks of the Sierra Nevada and south California batholith (Kistler et. al. 1965; Kistler and Dodge 1966).

Evernden and Kistler (1970) analysed all the pre-existing age determinations and presented more analyses from which they concluded that five major epochs of magma generation and emplacement have occurred in the central Sierra Nevada. These conclusions were based on over 400 mineral ages including 48 concordant hornblende-biotite pairs, 4 zircon Pb-alpha and 4 Rb-Sr isochrons. Each of these five episodes of magma emplacement took from 10 to 15 m.y. to complete and were initiated at intervals of approximately 30 m.y. Furthermore each phase of intrusion was coeval with a period of deformation of the country rocks.

The five intrusive 'epochs' of Evernden and Kistler can be summarised:

Maximum to Minimum age m.y.	Geological Age	Intrusive epoch
79 - 90	Late Cretaceous	Cathedral Range
104 - 121	Early Cretaceous	Huntington Lake
132 - 148	Late Jurassic	Yosemite
160 - 180	Early-mid Jurassic	Inyo Mountains
195 - 210	Mid-late Triassic	Lee Vining

Lanphere and Reed (1973) have recently criticised the validity of the hypothesis of five periodical intrusive epochs, which were proposed by Evernden and Kistler for the Sierra Nevada and South California batholith. Their re-interpretation discounts both the Rb-Sr and Pb-alpha data, on account of their high analytical errors, and using the remaining K-Ar data on concordant hornblende biotite pairs recognise only two intrusive epochs for the Sierra Nevada - South California batholith;

Epoch A — represented by a continuum of concordant ages from 106 - 79 m.y. which are interpreted as an intrusive event.

Epoch B — covers the time span from 158 - 132 m.y. and incorporates the Yosemite and most of the interintrusive period preceding the Yosemite epoch.

A few K-Ar mineral ages older than 160 m.y. which were classified as 'Lee Vining' by Evernden and Kistler are not included in the two epochs of Lanphere and Reed. However comparable ages have been reported by Crowder and others (1973), from the White and Inyo mountains, which also suggest the existance of a Triassic period of intrusive activity.

Potassium-argon age studies have also been carried out in the Alaska-Aleutian range batholith and these also demonstrate the episodic nature of the plutonic activity (Gabrielse and Reesor 1964, Reed and Lanphere 1969, 1973 and Richter et. al. 1975).

Originally intrusive epochs appeared to be synchronous over large areas and led to the concept of periodic magma emplacement in the Pacific margin of North America (Dickinson 1970, Kistler et. al. 1971 and Shaw et. al. 1971). However as more radiometric age data accumulated these preliminary conclusions became modified and co-workers in North America now favour episodicity as a relatively local phenomenon generally recognisable only in individual batholiths. Thus when large areas of the Western American Cordilleras are considered, the 'intrusive epochs' tend to fade and magma emplacement appears as a rather continuous process (c.f. Gilluly 1973).

In the following section the writer reviews the age determinations which are available from South America, most of which correspond to detailed studies on Chilean granitoids.

K.Ar age determinations from plutonic rocks of Chile

Until relatively recent time (around 1960) the Chilean granitoids were considered to be of a general Cretaceous - Tertiary age based on cross-cutting relations with fossiliferous Neocomian strata. However the discovery of marine Triassic strata overlying granites in South-central Chile and the presence of granite pebbles in conglomerates and sandstones of Carboniferous age led to the recognition of an earlier plutonic event (Munoz Cristi 1960). Thus a group of earlier granitoids related to regionally metamorphosed rocks, and mainly exposed in the Coast Range of Central Chile, are separable from the post-Neoconican granitoids of the Andean region.

Since the early sixties there have been many publications concerning the dating of Chilean granitic and volcanic rocks mainly by the Pb-alpha and to a lesser degree the K-Ar method on biotites (Ruiz et. al. 1961, Halpern 1962, 1973; Levi et. al. 1963; Clark et. al. 1967, 1973; Sillitoe et. al. 1968, Farrar et. al. 1970; Corvalan and Munizaga 1972, and Aguirre et. al. 1974). These studies have led to the recognition of four major plutonic cycles (a) Upper Palaeozoic (b) Jurassic (c) Cretaceous and (d) Tertiary, which are defined by culminations of radiometric ages and partly on stratigraphic evidence. The late Silurian ages (around 400 m.y.) reported by Corvalen and Munizaga (1972), for granitoids around Valparaiso, indicates an even earlier plutonic event which equates extremely well with the ages obtained from the San Nicholas batholith.

(1) Northern Chile (latitudes 26 - 29° south)

Seven phases of plutonic activity have been recognised;

Oligocene - Miocene	23 - 22 m.y.
Eocene - Oligocene	44 - 34 m.y.
Palaeocene	67 - 59 m.y.
mid-late Cretaceous	107 - 87 m.y.
early Cretaceous	128 - 117 m.y.
late Jurassic	156 - 137 m.y.
early Jurassic	191 - 171 m.y.

These results are based on over 200 K-Ar age determinations on micas and the clustering of apparent ages have been referred to as periods of intrusive activity (see Clark et. al. 1973).

(2) Central Chile (latitude 30 - 35° south)

All radiometric age determinations obtained from central Chile have recently been summarised by Aquirre and others (1974). These ages fall into seven major groupings, most of which are broadly

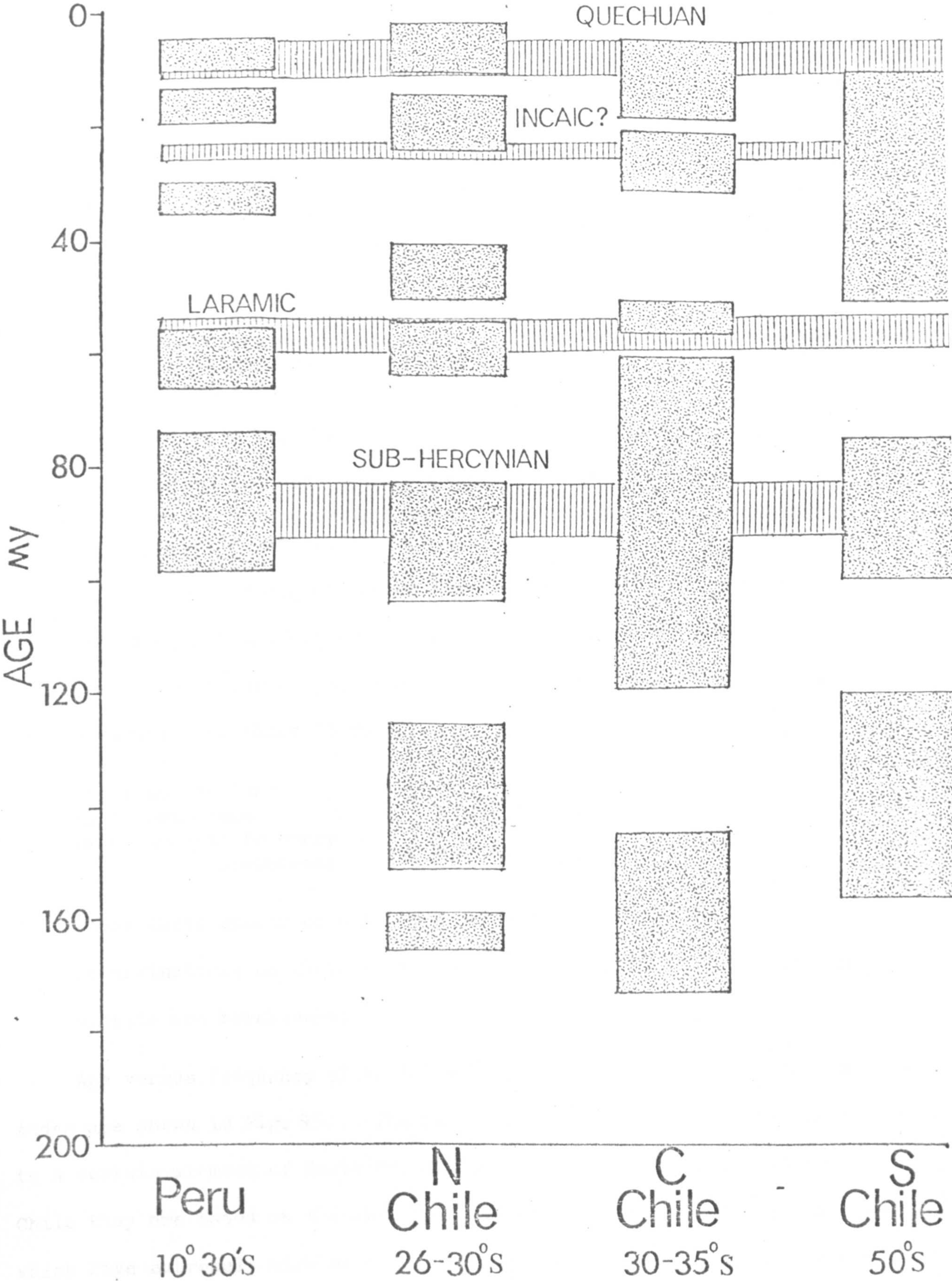

FIG.45 Chart summarising the relationships between the different plutonic cycles (as recognised by isotopic dating) of Chile and Peru, the main periods of Andean folding (after Aguirre et.al.1974) are also shown.

coeval with orogenic phases of activity:

late Miocene - Pliocene	18 - 4 m.y. (Aquirre, pers. comm.)
late Oligoce - early Miocene	32 - 22 m.y.
Eocene	57 - 44 m.y.
Cretaceous - Palaeocene boundary	70 - 62 m.y.
Middle Cretaceous	110 - 90 m.y.
Jurassic - Cretaceous boundary	158 - 133 m.y.
Lower to Middle Jurassic	173 - 167 m.y.

Their evidence for the Jurassic plutonism is based on nine Pb-alpha and two K.Ar determinations.

(3) Southern Chile (latitudes $> 50^{\circ}$s)

Plutonic rocks of the southern Andean (Patagonian) batholith also range in age between Jurassic and Tertiary (Halpern 1973). However only three igneous episodes have been recognised each having a duration of about 25 to 40 m.y.:

mid-late Tertiary	50 - 10 m.y.
late Cretaceous	100 - 75 m.y.
late Jurassic to early Cretaceous	155 - 120 m.y.

These three epochs of magma emplacement are defined by Rb-Sr determinations on whole rocks and minerals in addition to K.Ar on biotite and hornblende.

Age versus frequency plots for all three transects of the Chilean Andes are shown in Fig. 45. The validity of these groupings is open to a certain element of doubt for in the case of northern and central Chile they are based on the K-Ar method on micas, and a few Pb-alpha ages which have extremely high errors. It has been shown by the data presented in this thesis that 'reset' mica ages are common in the Peruvian Andes, for this reason the culminations of K-Ar ages may not necessarily define intrusive events.

Another influencing factor relates to the sampling of the plutons, many concealed stocks and plutons probably lie immediately below the volcanic cover in Chile and these may have been emplaced during the periods of apparent intrusive quiescence. Therefore in Chile the evidence of episodic plutonism is not as convincing as in North America where the episodicity is well defined by concordant hornblende-biotite pairs. However, when the broadest and most essential features of the "episodic arrangement" of plutonic events in Central Chile are exposed it can be seen that there is a close similarity with the two intrusive epochs defined by Lanphere and Reed (1973) for the Sierra Nevada - South California batholith (Aquirre et. al. 1974):

Cretaecous Epoch	Jurassic Epoch
(A Epoch)	(B Epoch)
106 - 79 m.y.	158 - 132 m.y.

Other general correlations are possible between Chile and Peru by reference to Fig.45, thus:

(i) Good correlation for a Sub-Hercynian - related plutonic event in Peru - N. Chile - C. Chile and S. Chile (A epoch of Lanphere and Reed)

(ii). There is good evidence for a Laramic related plutonic event in Peru, northern Chile and central Chile.

(iii) Incaic and Quechan; possible plutonic events in Peru and Chile

(iv) A late Jurassic plutonic event has not been recognised in Peru this contrasts with the other sectors of the western American Cordilleras which have been discussed.

Therefore in general terms it is possible to visualise a correlation of 'plutonic events' along parts of the Andean Cordillera. However, there is such an overlap of apparent ages that if the whole Cordillera is considered (see Fig 45) there has been no appreciable break (in plutonism?) since the Jurassic.

Episodic Granite Emplacement in Central Peru

In order to obtain an unbiased view of the timing of batholith emplacement the following criteria have to be fulfilled:

(1) Every individual pluton in the transect of the batholith under consideration has to be dated;

(2) and the age of emplacement has to be evaluated for each pluton in question.

The writer does not claim to have satisfied these criteria in this research, nevetheless the sector of the Coastal batholith which was examined was studied in extreme detail by the standards used in North America. Also representatives of all the visible plutons have been dated in this study area. The writer's main criteria for 'age of emplacement' have relied on a detailed knowledge of the stratigraphy and relative chronology of pluton emplacement combined with a large number of age determinations from a relatively small area.

The age data presented earlier in the thesis defines at least three periods of pluton emplacement for the Coastal batholith proper and possibly two younger periods of magma emplacement to the east of the main Coastal batholith (see Table 29). Once again these can be summarised:

Geological Age (after Smith et.al. 1964)	Maximum to Minimum age	
Pliocene	4 - 4 m.y.	(5)
Miocene	19 - 9 m.y.	(4)
Oligocene	35 - 30 m.y.	(3)
Upper Cretaceous - lower Tertiary	75 - 56 m.y.	(2)
Mid Cretaceous	98 - 85 m.y.	(1)

(1) Late Cretaceous epoch

The oldest age corresponds to the Purmacana tonalite and includes the emplacement of the main Santa Rosa and Paccho Super-units. The duration of the epoch is at least 15 m.y. but could perhaps be extended by incorporating members of the Patap Super-unit. Secondly the writer has purposely omitted the Humaya monzogranite (73 m.y.) from this epoch for it is debatable whether it should be part of epoch 1, on the basis of its compositional similarity, or epoch 2 because of its close temporal relationship.

(2) Upper Cretaceous - lower Tertiary epoch

Incorporates the granodioritic and monzogranite plutons of the Centred Acid complexes which were emplaced along the axial portion of the batholith.

(3) Oligocene epoch

Represented by large monzogranite plutons of the Pativilca type and these mark the final plutonic event of the Coastal batholith.

(4) Miocene epoch

Not recognised in the Coastal batholith but is reflected by a series of tonalite-granodiorite stocks to the east of the Coastal batholith and by members of the Cordillera Blanca batholith.

(5) Upper Miocene - Pliocene epoch

Possibly represented by the final plutonic activity in the Cordillera Blanca batholith and some shallow hypabyssal stocks of porphyritic granite on the Puna erosion surface.

It is likely that future research will redefine the boundaries used by the writer to delineate these five intrusive events. Epochs 2, 3 and 4 are convincingly separate pulses with a large hiatus of 20 m.y. (Eocene) separating the Centred Acid Complexes from the younger monzogranite plutons, for which no age determinations have been recorded.

Summary

One the whole the data presented throughout this thesis supports the findings from North American Batholith complexes of an episodic process of magma emplacement. It also seems that these 'epochs' of intrusive activity differ in age along the length of the Cordillera and eventually blur into a continuum. For example a few reconnaissance age determinations from the sector of the Coastal batholith inland from Chimbote produced Eocene ages, for the Puscao granodiorite (Sample A145) and Moro monzogranite (Sample A144) plutons. These fall into the inter-intrusive period between epochs 2 and 3 of the Huaura section.

It has already been shown (Fig. 45) that the epochs described in the study area broadly correlate with the epochs described in north Chile (Clark et. al. 1973) and central Chile (Aguirre et. al. 1974). In the author's opinion this linear correlation of plutonic events is rather premature when the majority of ages are based on K-Ar of micas. Undoubtedly future work by other dating methods will surely result in the strengthening of these preliminary findings.

Episodicity of magma emplacement along the Andean chain is also reflected in the present day distribution of volcanic activity. Three volcanically active zones are present at several regions along the western

Andes (Casertano 1963, Katsui 1972); 1) the northern Andes of Ecuador 2) the central Andes (S. Peru - N. Chile) and 3) the southern Andes of Pategonia and Tierra del Fuego. Two large zones which are devoid of present day volcanic activity separate these three active belts. The present area of study represents such a zone of volcanic quiescence, here volcanic activity has probably not occurred since the mid-Pliocene (ignimbrites).

2. PLUTONS IN SPACE AND TIME

Introduction

In addition to the aforementioned episodicity a spatial pattern of pluton emplacement with time is emerging for Circum-Pacific batholiths. Noteworthy are the observed geographic distribution of intrusive cycles in northern and central Chile where Ruiz et.al. (1961) and Farrar et.al. (1970) have described and eastward younging of intrusive activity from the Jurassic to Tertiary over a distance of 110 kms. This feature has also been reported in other sectors of the Chilean Andes on the basis of both mapping and radiometric evidence (Aquirre and Egert 1970; Corvalan and Munizaga 1972; and Aquirre et.al. 1974).

In Peru a similar pattern has been recognised and is marked by the apparent younging of biotite K.Ar ages across the Andean trend (Giletti and Day 1968; Stewart et.al. 1974 and this report). Similar patterns of pluton emplacement have also been observed in North America; Gastil and others (1974) described a progression from early gabbros to younger acidic rocks in an easterly direction across the Southern California and West Mexico batholith. In the case of the Chilean batholiths this eastward younging has been interpreted as a migration of intrusive centres away from the trench (Farrar et.al. 1970) and a similar explanation has been furnished for the distribution of granitoids in Japan (Kuwano and Ueda 1970).

Neither is this apparent easterly migration entirely restricted to intrusive igneous activity for in central Chile a migration of volcanic activity has also been observed (Aquirre et.al. 1974; Vergara and Munizaga 1974). This eastward migration of magmatic activity is pronounced if the easterly position of the present day volcanic chain is considered relative to the Mesozoic-Cenozoic batholiths which parallel the edge of the South American continent.

The spatial distribution of Plutonic rocks in the area of study

Over 70 of the K.Ar age determinations described in this thesis are on biotite separates and these when examined independantly display a marked progressive younging in a north-easterly direction across the regional Andean trend.
In the Huaura region of the Coastal batholith, the biotite ages decrease from a maximum value of 92 m.y. to 31 m.y. between its western and eastern margins, over a distance of 50 kms. (see Fig. 46). A more striking change in this age pattern can be seen if the mica ages from granitoids to the east of the Coastal batholith are included. Here the ages decrease progressively to a minimum value of 3 m.y. corresponding to the Cordillera Blanca batholith at a distance of over 100 kms from the coast.

The diagram (Fig. 46) shows the irregularity of the age gradient across the area of study e.g. a break occurs at approximately 50 kms from the coast which demarks the eastern boundary of the Coastal batholith. To the east of this line the age gradient is regular and approximates 0.5 m.y./km which is comparable to the gradient reported in central Chile (Aquirre et.al. 1974). Three pronounced geographic divisions can be recognised and these broadly correlate with the

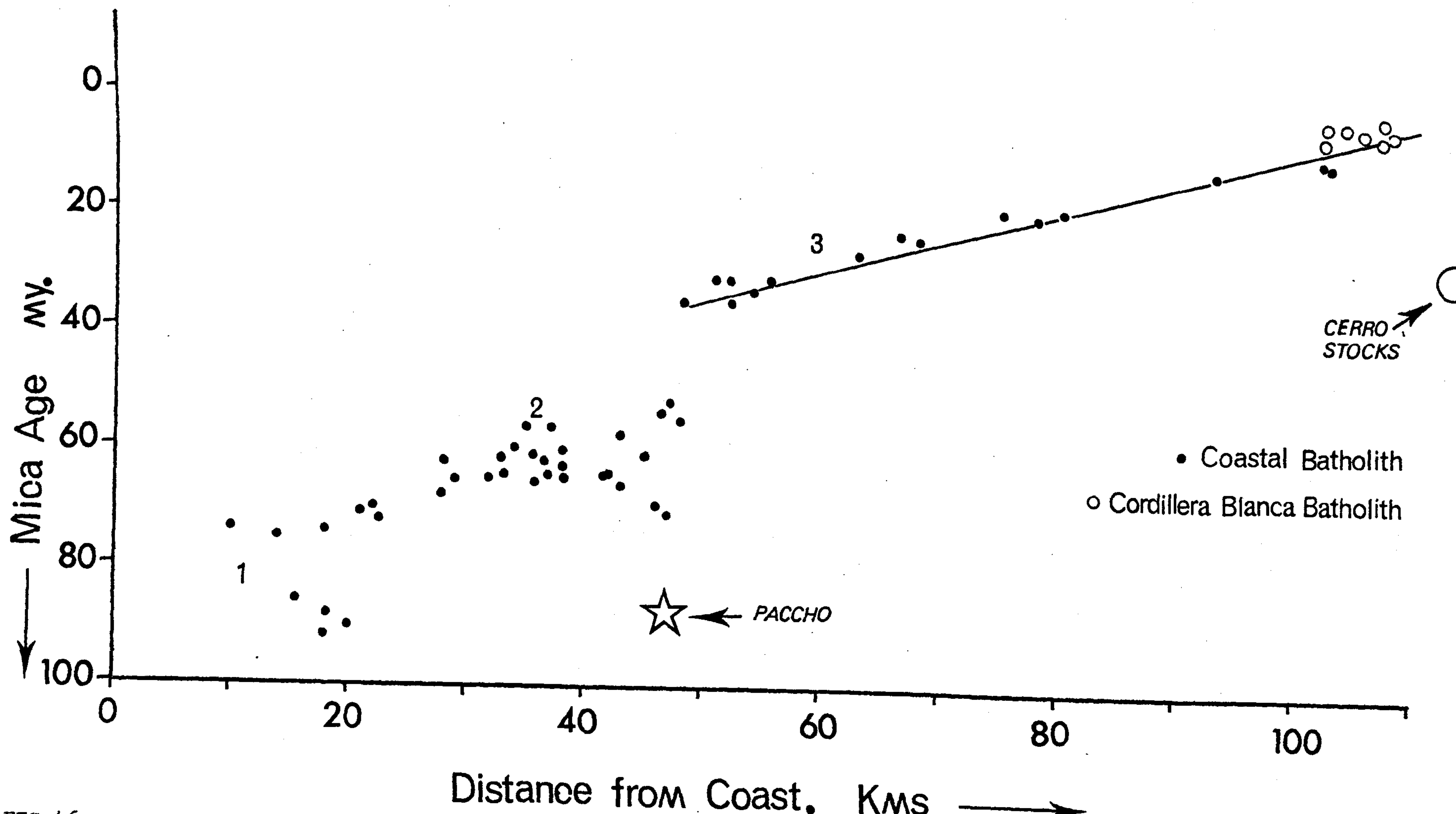

FIG. 46 Diagram relating age (mica) and geographical location (distance from coast) of granitoids of the area of study. The eastward polarity which is suggested by the diagram is not as obvious when the emplacement age (*) of the Paccho Super-unit is considered. The apparent age of the Cerro de Pasco stocks also diverge from the eastern polarity.

'epochs' of igneous activity which were described in the previous section.

(1) The western margin of the Coastal batholith between 10-25 kms from the coast, characterised by biotite ages of 92-72 m.y.

(2) The central part of the Coastal batholith 25-48 kms from the coast, with granitoids having mica ages of 68-54 m.y.

(3) The eastern margin of the Coastal batholith including the satellitic stocks and the Cordillera Blanca batholith, 50-110 kms east of the present coast line, and which yield mica ages between 32 and 3 m.y.

The Coastal batholith - localisation of magma emplacement

The apparent migration of intrusive activity implied by the spatial distribution of biotite ages for the Coastal batholith is unfounded in the light of the evidence for the age of the Pacco Super-unit (see page 105). The writer has shown that many of the biotite ages obtained from granitoids on the eastern margin of the batholith have been 'reset' as a consequence of delayed uplift and reheating by younger intrusions and therefore do not correspond to their true age of emplacement. For this reason the writer envisages an episodic process of magma emplacement over a period of at least 60 m.y. centred along a deep lineament (c.f. Myers 1975 a) with successive pulses of magma forming a composite batholith. Halpern (1973) has described a similar process in the evolution of the south Chilean batholith where magma emplacement, although episodic, was confined to a narrow belt of the crust for a period of 140 m.y.

Igneous activity to the East of the Coastal Batholith

Following the final stages of emplacement of the Coastal batholith igneous activity migrated to the east to become localised at the site of the Cordillera Blanca batholith. However this migration is by no means

as uniform as suggested by Fig.46 . Thus the Oligocene ages from the rhyo-dacite stocks near Cerro de Pasco correlate with the final stages in the evolution of the Coastal batholith and show that magma was being emplaced at two separate localities over 50 kms apart.
The greater number of these younger ages correspond to the Cordillera Blanca batholith where pluton emplacement has remained localised for a period probably in excess of 15 m.y. Since the mid-Miocene, granite emplacement has been totally confined to the Andean region of the western Cordillera. However it seems this region may have been the site of intermittent intrusive activity since the Oligocene.

This overall migration of intrusive activity is also accompanied by a shifting of volcanic activity. Age determinations combined with detailed structural observations, have shown the Centred Acid Complexes to have been an active source of volcanic rocks for as long as 40 m.y., between the mid-Cretaceous - lower Tertiary (see p.150 and Bussell and others in press). Following this period magmas were vented from stocks and fissures in the Callejon de Huaylas and the Cerro de Pasco area (Oligocene - Pliocene) some 30-50 kms further east.
An eastward change of volcanic activity is more pronounced in central-south Chile where volcanic centres of Miocene age outcrop near the coast and give way to vents of Pliocene - Holocene age approximately 100 kms inland (see Vergara and Munizaga 1974).

3. PETROGENESIS OF THE MAGMAS IN THE LIGHT OF THE RADIOMERIC AGE DETERMINATIONS

It is extremely difficult to arrive at any definite conclusions regarding petrogenesis and the author does not intend to discuss the problem at any length in this thesis. Nevertheless it is necessary to evaluate several parameters which have resulted from this study in future models for the origin of composite batholiths, these are :

(1) timing and apparent episodicity of magma intrusion.

(2) the spatial distribution of the plutons.

(3) the relationship between the timing and the geochemical evolution of the batholith.

The overall basic to acid trend of the Coastal batholith is easily discernable in the field and is particularly well defined by the geochemical work which has been referred to intermittently throughout this thesis (Taylor 1973, McCourt pers.comm.). With this knowledge, and combined with a general understanding of the chronology of emplacement of the various component plutons, it is now possible to arrive at some preliminary conclusions concerning the variation of bulk composition with time.

Chemical trends across Circum-Pacific batholiths have been recognised by many workers and probably the best documented trend is the increase of K_2O in an easterly direction away from the Pacific margin (Bateman and Dodge 1970). Dickinson (1970) has also noted the same feature in island arc environments. Bateman (1961) and Kistler and others (1971) have stated unequivocally that chemistry is independant of age in the Sierra Nevada batholith. On the other hand Tilling (1974) argues convincingly for a change of chemistry with time, albeit irregular, in the Boulder batholith of Montana.

In order to try and clarify the relationship between chemical composition and time, for the Coastal and Cordillera Blanca batholiths, the author has plotted Larsen index ($\frac{1}{3}$ SiO_2 + K_2O - FeO - MgO - CaO) against a geochronometric time scale for the samples which have been analysed. Thus Fig.47 shows that the gradual increase of acidity (Larsen index) with time is highly irregular, for example both monzogranites and tonalites were being emplaced during the lower tertiary. Unfortunately the diagram does not consider the relative volumes of magma produced. Thus the rocks of intermediate composition are subordinate to more acidic granitoids in the younger units of the batholiths.

The diagram however, shows an overall increase of acidity with time and this is presumably a reflection of the main 'deep seated' differentiation described by Cobbing and Pitcher (1972 a).

On a more localised scale magmas of different compositions were being emplaced coevally along different sectors of the batholith. This is exemplified by the Lamina granodiorite stock in the Quebrada Paros centre which was being emplaced at the same time as the Puscao and San Jeronimo monzogranites of the Huaura centre.

Similar compositional variations are also reflected in the Pliocene volcanic record of Chile. Here the rhyolitic ignimbrites of the north-central Andes were erupted coevally with the high alumina basalt suites which predominate in the south-central Andes. The difference in chemical composition of these two areas has been explained as a contamination process, with a thick crust (60-70 kms) in the northern part of Chile (Antafogasta) as contrasted with a rather thin (30-35 kms) crust in the

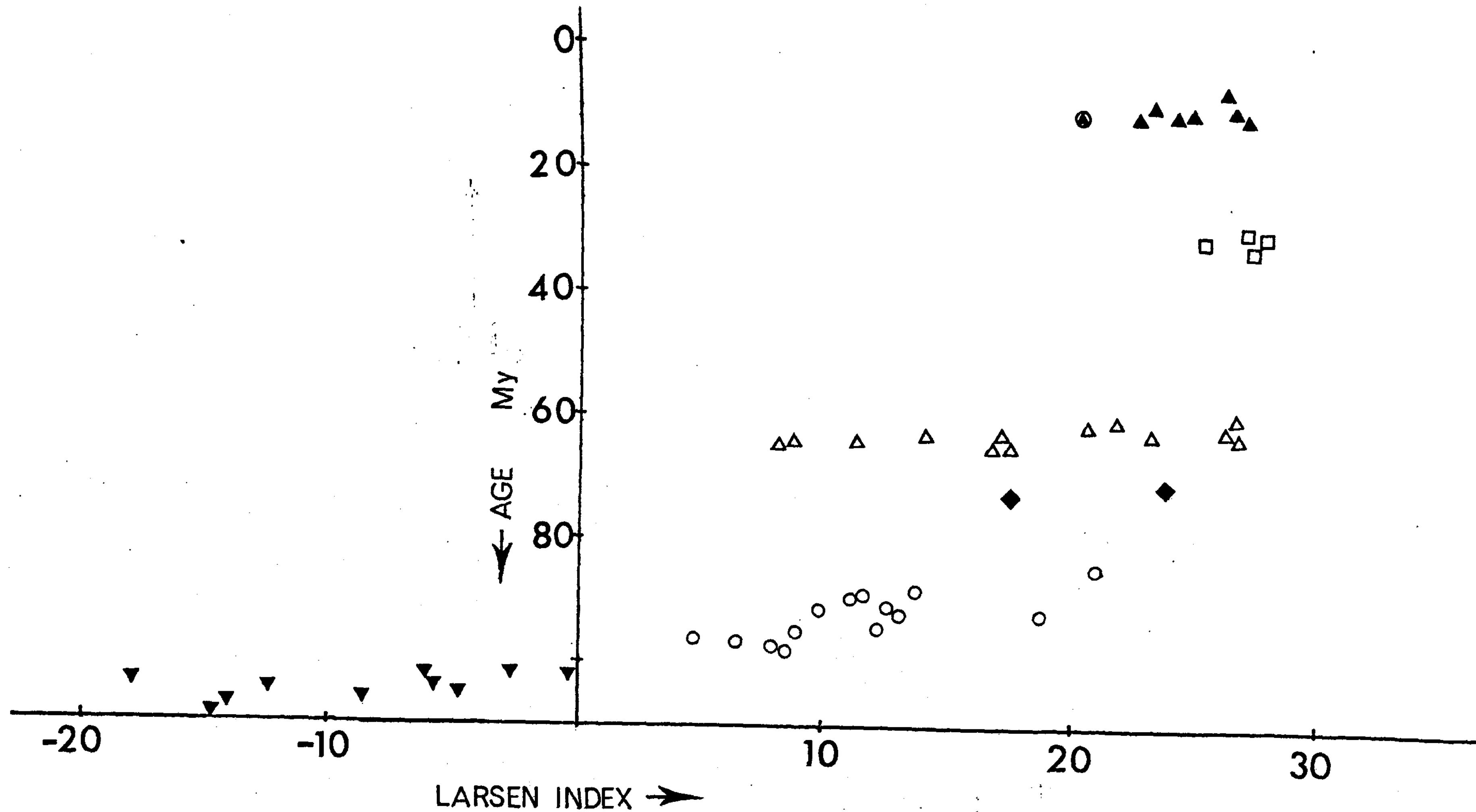

FIG.47. Diagram showing the relationship between age of intrusion (based on K-Ar ages and their relative chronology) and chemistry (expressed as Larsen index) for plutons of the Coastal and Cordillera Blanca batholiths. Key; (▼) gabbros, (O) Paccho and Santa Rosa Super-units, (◆) Humaya monzogranite, (Δ) La Mina, Cerro-Muerto tonalites and Centred monzogranites, (□) Pativilca pluton, (▲) Cordillera Blanca batholith, (●) Churin east stock.

south. (Aguirre pers.comm.).

Although the age determinations from Peru show episodic magma emplacement the writer envisages a more or less continuous process of magma generation to be operative at depth. This view disagrees with Evernden and Kistler (1970) and Kistler et.al. (1971) who have proposed an episodic process of magma generation on the basis of their findings from the Sierra Nevada batholith. Shaw and others (1971) have evolved a model to explain this episodic generation of magmas, by tidal energy. Larson and Pitman (1972) have related the culminations of intrusive activity to an increase in the spreading rate of the Pacific plate.

In the author's opinion the episodic emplacement of granitic magma which appears to characterise Circum Pacific batholiths may only be a reflection of their final emplacement and cooling, rather than implying an irregular generative mechanism. Perhaps the pulses of magma emplacement reflect the time at which the magma 'globules' attain dimensions, and the correct buoyancy, which provide the basic requisites for their final ascent and emplacement. On this basis the evolution of a batholith may diverge from a uniform basic to acid trend with time because of the complexities involved in the ascent of globules of magma from their source to their final level of emplacement.

A discussion of the origin and source of the magmas; particularly to what extent they represent material from the lower crust or upper mantle, is far beyond the scope of this thesis. However, the author would like to make reference to the available strontium isotope data from Peruvian granitoids. Snelling and Stewart (1972) have reported initial Sr^{87}/Sr^{86} ratios of 0.704 to 0.7055 for plutons of the Coastal batholith. These compare with values reported by Kistler and others (1971) from the Sierra Nevada batholith, who concluded that much of the magma was derived from the mantle with some assimilation of crustal material.

The spatial distribution of the plutons is another matter for debate. The localisation of magma emplacement for periods as long as 60 m.y. (Peru, Coastal batholith) and 120 m.y. (Patagonian batholith) contrasts with the regular eastward migration recognised in central and northern Chile. James (1971) readily accepted the hypothesis of eastward migration and listed a number of mechanisms which could produce such a migration. His models related to variations in physico-chemical conditions along a subduction zone. Needless to say these theories may be acceptable but future work has to consider how magma emplacement is stabilised for long periods of time along one zone, while migration is occurring in adjacent areas, under the same magmatogenic processes.

Finally the writer would like to point out that most Circum-Pacific batholiths have taken similar periods of time for their evolution. The rate of emplacement of batholiths forms the theme of a recent review by Pitcher (in press) who summarises the length of time involved in the evolution of the main Mesozoic-Cenozoic batholith complexes

Batholith	Duration of emplacement m.y.	Data sources
Alaska-Aleutian	50	Reed and Lanphere (1974)
Sierra Nevada	80-60	Bateman and Clarke (1974)
Southern California	85	Gastil et.al. (1974)
West Mexican	55	Mullan pers.comm.
Venezuela	100	Santamaria and Schubert (1974
Peru	70 (100) *	this thesis
Central Chile	150	Aguirre et.al. (1974)
Patagonia	140	Halpern (1973)

* including the Cordillera Blanca intrusions.

SUMMARY AND PROPOSALS FOR FUTURE RESEARCH

The writer has attempted to summarise the main findings arrived at as a result of this research in the concluding remarks at the end of each section of this thesis.

The original aims of the research have been fulfilled within the limits of the K-Ar dating method, and to a certain degree expanded to incorporate reconnaissance age determinations to help add to the general understanding of Peruvian geology. Thus the research has laid the foundations for more detailed dating projects, especially the time relationships between plutonic and volcanic activity in the western Cordillera and the chronology of emplacement of the San Nicholas batholith.

Potassium-argon dating has proved to be an extremely useful tool in the study of Peruvian granitoids and its major, if not only, limitation is reflected by the disturbance of the argon clocks of the older components of the Coastal batholith. For this reason any future geochronology projects ought to include both Rb-Sr and U-Pb dating. The writer has already instigated a U-Pb study by separating zircons from representatives of the Santa Rosa, La mina, Puscao and Canas plutons; the results of which should be available in the near future.

Once again the main points arising from the research can be summarised;

(1) The Coastal batholith has formed over a Period of 70 m.y. (from the Albian to Oligocene) by the episodic emplacement of plutons which show an overall increase of acidity with time. These plutons were emplaced along a single lineament in such a way that the early tonalitic components of the batholith comprised the host rocks of the younger monzogranites. However despite the reheating effects which must have

been involved many of the earlier units still have undisturbed isotopic systems.

Future dating projects on the Coastal batholith should try to ascertain the extent to which the 'epochs' of plutonic activity of the Huaura section can be extrapolated to other areas. In a more specific context the emplacement age of the Paccho Super-unit could be assessed by U-Pb dating on zircon and this may shed some light on the true significance of their Oligocene K-Ar ages as well as providing a more accurate estimate for a maximum age of the batholith.

(2) The Cordillera Blanca batholith has yielded reconnaissance K-Ar ages of between 16 - 3 m.y. At this juncture the author feels that more K-Ar ages are unnecessary, at least until the batholith has been mapped in more detail, so that samples can be preferentially selected for dating.

(3) The present study has confirmed that there is a considerable overlap between plutonic and volcanic activity in the western Cordillera of central Peru. Unfortunately the volcanic record is incomplete in the Huaura area and the few age determinations presented in this thesis hardly justify the intimate connection between plutonic and volcanic activity.

Therefore future work should be directed towards the dating of the volcanic sequences which are so well exposed around Ica in south-central Peru.

(4) Finally the few age determinations reported from the San Nicholas batholith are significant in that they depict a pre-Silurian age for

part of the batholith. The exceptionally poor exposure and hazardous nature of the terrane restricts any future, more detailed, work on this batholith. However, the relationship of the batholith to the Marcona iron-ores ought to be examined in more detail, for if the observation of the batholith cutting and metamorphosing the ores is correct they could be of Cambro-Ordovician or even Pre-Cambrian age.

ACKNOWLEDGEMENTS

The author would like to acknowledge the invaluable help and encouragement which he has received from his supervisor Professor W.S. Pitcher during the whole of his research. He is also indebted to his supervisor for critically reading the rough manuscript of the thesis.

Sincere thanks are also expressed to Dr. N.J. Snelling and his colleagues at the Isotope Geology Unit (I.G.S.) for providing excellent research facilities and many fruitful discussions on all aspects of Isotope geology. They are also thanked for contributing to the enjoyment of the author's frequent visits to London.

Mr. W.J. McCourt made available unpublished geochemical data which is gratefully acknowledged. Dr. M.P. Atherton and Mr. D.A. Briggs are thanked for their guidance in the initial stages of sample preparation.

Mr. C.C. Rundle donated much time in explaining the operation of the analytical equipment while Mr. D. Tiggins carried out the X-Ray diffraction analysis of the feldspars, both are thanked for their kind assistance.

All the members of the Peru project have contributed their time to useful discussions on Peruvian geology; special thanks are extended to Dr. M.P. Atherton, Mr. M.A. Bussell, Dr. E.J. Cobbing, Mr. W.J. McCourt and Dr. H.S. Mullan.

Professor L. Aguirre, Dr. H.S. Mullan and Mr. W.J. McCourt read various drafts of the thesis and the author acknowledges their constructive criticisms.

Finally thanks are expressed to Miss Skillicorn and Miss Taylor for their rapid and efficient typing of this thesis.

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APPENDIX I

SAMPLE PREPARATION FOR K.Ar DATING

Whole rock samples of intrusive igneous rocks are unsuitable for K.Ar dating for two reasons; firstly, it is difficult to obtain a representative sample especially since the argon and potassium analyses are carried out on separate aliquots of the sample. Secondly the rock will contain a number of mineral phases which have differing argon retentivities, consequently the resulting age will be a 'hybrid' of all the individual mineral ages.

Therefore pure mineral concentrates are required for K.Ar dating and their preparation from the initial rock sample is the most time-consuming part of K.Ar dating.

Before separation commences a thorough microscopic examination is necessary to determine the suitability of the various constituent minerals for dating. Once the sample has been selected any superficially weathered material is removed by grinding and the sample washed and dried. The rock is then crushed to liberate the minerals present: the samples are reduced to large chips by use of a manually operated rock-splitter and fed through a Jaw crusher until their largest dimension is below 0.5 cm. At this stage the product is screened at 30/60, 60/100 and 100/120 mesh and each fraction examined under a binocular microscope. The size range finally selected is largely controlled by the natural grain size of the mineral in the rock, and separation is usually carried out at the coarsest possible grain size where non-composite grains predominate. It is important to ensure the mineral grains required are totally free, because composite grains tend to interfere in the later stages of separation. Furthermore overgrinding has to be avoided because this may cause distortion and destruction of the crystal lattice resulting in a loss of radiogenic argon from the mineral. This has been demonstrated for both micas and feldspars by Gentner and Kley (1957) and Gerling and others (1960). The effective liberation point for minerals in the granitic rocks studied in this project falls within the 30/100 mesh range.

Once the most suitable size fraction has been ascertained further size reduction of the coarse fraction is carried out using a tema mill, the product is continually screened and the coarse fraction repassed to reduce the proportion of untreatable fines. The selected size fraction is then washed and any fine dust decanted off, the sample is dried overnight leaving a clean dry sand ready for the mineral separation.

Mineral Separation The required minerals are separated by utilising the many differences in their physical properties i.e. density, shape and magnetic susceptability. The various techniques which are generally used, have been described by Smales and Wager (1960), Harriss and others (1967) and summarised by Dalyrymple and Lanphere (1969). The methods adopted by the writer were mainly controlled by the equipment which was available; initial preparation took place at Liverpool and the final stages of purification were carried out in the Mineralogy Unit of the I.G.S.

The highly magnetic opaque minerals were first removed by passing the powder through a Davis tube magnet which prevents them from blocking up the more powerful electro-magnets which are used later. The sand is then split into magnetic (mafic) and non-magnetic (felsic) portions by repeatedly passing the powder over a 'Davis Disc' magnet. The course of further separation depends on which minerals are required and each case will now be briefly discussed.

Biotite   Biotite being slightly magnetic is concentrated in the magnetic fraction produced by the 'Davis Disc' magnet. An asymmetric vibrator is used to isolate the flat biotite cleavage flakes from any rounded grains of hornblende or quartzo-feldspathic material. The concentrate is upgraded by use of a Franz isodynamic magnetic separator and by heavy liquids using methylene iodide adjusted to densities of 3.08 - 3.15.

Chlorite forms the main contaminant in the biotite concentrate and can be partly removed by utilising its slightly weaker magnetic properties and lower density. However, an overlapping of physical properties between biotite and chlorite often render the two inseparable and in such cases the chlorite can be removed by hand-picking.

Muscovite   Muscovite concentrates with the felsic minerals in the non-magnetic product of the 'Davis Disc'. An asymmetric vibrator separates the muscovite from the rounded quartzo-feldspathic grains and the concentrate is upgraded using Bromoform of density 2.8 - 2.9. Biotite forms the most common contaminant and can be easily removed from the less magnetic muscovite on a Franz isodynamic separator.

Hornblende   Hornblende concentrates with biotite in the magnetic fraction of the Davis Disc and is partly separable from the flat mica flakes on the asymmetric vibrating plate. Hornblende has a lower magnetic susceptability than biotite and a higher density (3.15 - 3.25), it is therefore possible to obtain a mica free hornblende sample by repeatedly passing the concentrate over a Franz separator, and through Methylene iodide of density between that of biotite and hornblende. The main contaminants in the hornblende concentrates are sphene and apatite which, being non-magnetic, can be removed on the Franz separator.

Feldspars A quartzo-feldspathic sand free of mafic minerals can easily be produced by repassing on a Davis Disc magnet at different current settings. The feldspars are further isolated using Bromoform, which is adjusted to the required density by the addition of diethylamine-formamide; Potassium feldspars have lower densities (2.57) than plagioclase feldspars (2.65 - 2.76). It is extremely difficult to separate sodic plagioclase from quartz, due to an overlap in their densities, for this reason plagioclase was not used for dating the more silicic rocks of the batholith.

In every case where heavy liquid separations were used the sample was sonically cleaned in acetone, to remove any remaining heavy liquid, and then thoroughly washed in deionised water and dried. This cleaning is essential because heavy liquids tend to interfere with the resolution of the argon analysis by producing spurious peaks in the 35 - 40 mass range.

Purity of Mineral Concentrates

One of the major sources of errors in K.Ar dating arises from the problems encountered when the mineral concentrate is split into two separate fractions for the potassium and argon analysis. Thus, sample splitting errors are involved and it is important to have some means of assessing how representative the smaller sample used in the K analysis, is of the whole.

Engals and Ingamells (1970) used the potassium content as an estimate of sample purity, and concluded that for a biotite sample to be

pure it has to have 8-9% $K_{2}O$; any lower value they attributed to impurities in the sample.
For the purpose of this study most concentrates were in the order of >98% pure, which accounts for the good reproducibility of the duplicate potassium analyses. The only impurities present in the concentrates were from minerals which had similar physical characteristics (i.e. chlorite and biotite). In all stages of sample preparation contamination by foreign material was carefully avoided by thoroughly cleaning the laboratory and all the equipment before use.

The concentrate was examined under a binocular microscope at every stage of the separation process and grain counts were carried out on a few selected samples.

Selection and Preparation of Material for Whole Rock dating

Pyroclastic rocks are generally unsuitable for K.Ar dating due to the presence of xenoliths which may contribute significant amounts of inherited argon-40. Lavas on the other hand often provide suitable material for dating although their fine grain size often dismisses the possibility of isolating different minerals. It is therefore necessary to use the whole rock for dating which is satisfactory providing the sample is first subjected to a rigorous petrographic examination.
A key factor in obtaining reliable results from whole rocks concerns the distribution of potassium bearing phases throughout the rock. Miller and Mussett (1963) examined a diabase dyke and concluded that potassium concentrates in the last component to crystallise and resides in the groundmass. Therefore the nature of the groundmass is of paramount

importance in controlling the argon retention properties of volcanic rocks.

A certain amount of volcanic glass can be tolerated before argon loss becomes significantly important (see Dalyrymple 1964, and MacDougall 1966). Alteration of the K bearing phase forms the major criterion for assessing the suitability of volcanic rocks for whole rock dating. Miller and Mussett (1963) have demonstrated that the apparent age decreases as a function of the degree of alteration of the groundmass. The general concensus of opinion is that material should be rejected for dating if there is any alteration of the K-bearing phases (Dalyrymple 1964, Evernden and James 1964). Alternatively the alteration of minerals which contain a negligible amount of potassium probably have little or no effect on the age.

Preparation After initial crushing the rock is screened and the 30/72 mesh fraction is retained, this is sonically washed and any dust decanted off. The sample is then split and one fraction is ground to -100 mesh for potassium analysis, the remainder being retained for the argon analysis.

APPENDIX II

BRIEF OUTLINE OF ANALYTICAL PROCEDURE AND ESTIMATION OF EXPERIMENTAL ERRORS

ARGON ANALYSIS

In order to calculate the age of a rock or mineral the geochronologist has to determine the amount of K^{40} and radiogenic Ar^{40} in the sample concerned. With respect to argon, there are two essential processes involved because the argon gas has to be extracted from the sample before it can be measured quantitatively.

The Argon Extraction System

The argon extraction system used at the Isotope Geology Unit (London) was initially developed at Oxford by Dodson and Snelling and for a detailed description of the apparatus the reader is referred to Rex (1967). A few modifications have been introduced over the last few years and are briefly described in the following section.

For ease of discussion the system may be divided into three sections 1) the vacuum pumping system, 2) the sample fusion section and 3) the clean up section. (see Fig. 48).

An ultrahigh vacuum of 10^{-7} to 10^{-5} torr is required in the system and is achieved by using an oil diffusion pump backed by a mechanical rotary pump. A valve (V_1) enables the pumps to be isolated from the system.

The sample fusion section originally contained two pyrex glass furnaces; a third being added in 1973. Each sample is loaded into a molybdenum crucible and then suspended in a fusion furnace by means of silica tube. Fusion is carried out by a radiofrequency generator which is capable of temperatures of over 1500° C.

Once the sample has been fused it is necessary to purify the gases which are released. The clean up section is designed to separate the inert gases, including argon, from the reactive gases. This part of the system was originally made of pyrex glass but has gradually been replaced by an

1. Sample fusion section.
2. Clean up section.
3. Spike section.
4. Mass Spectrometer.

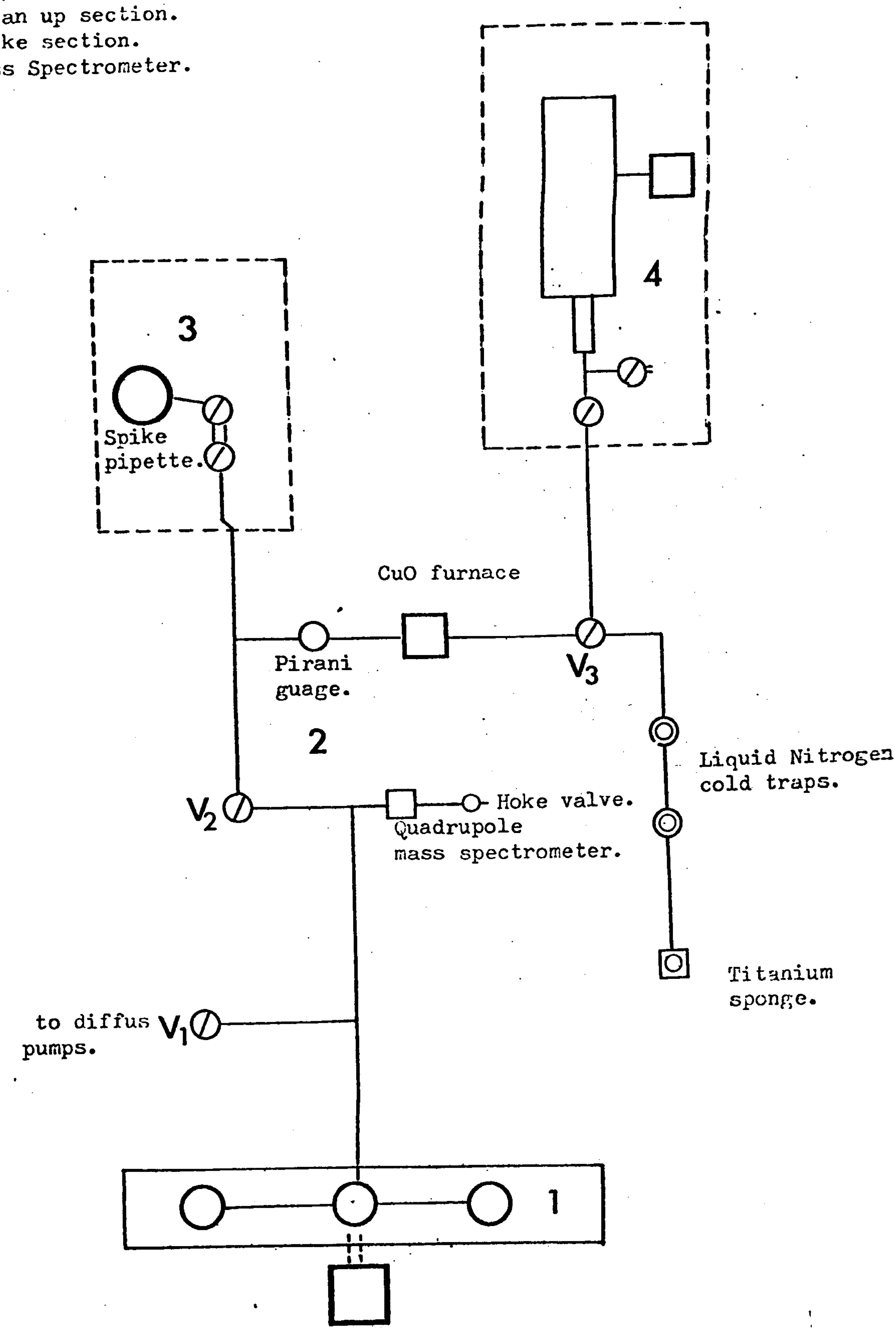


FIG.48 Plan of the equipment used in London for the analysis of Argon.

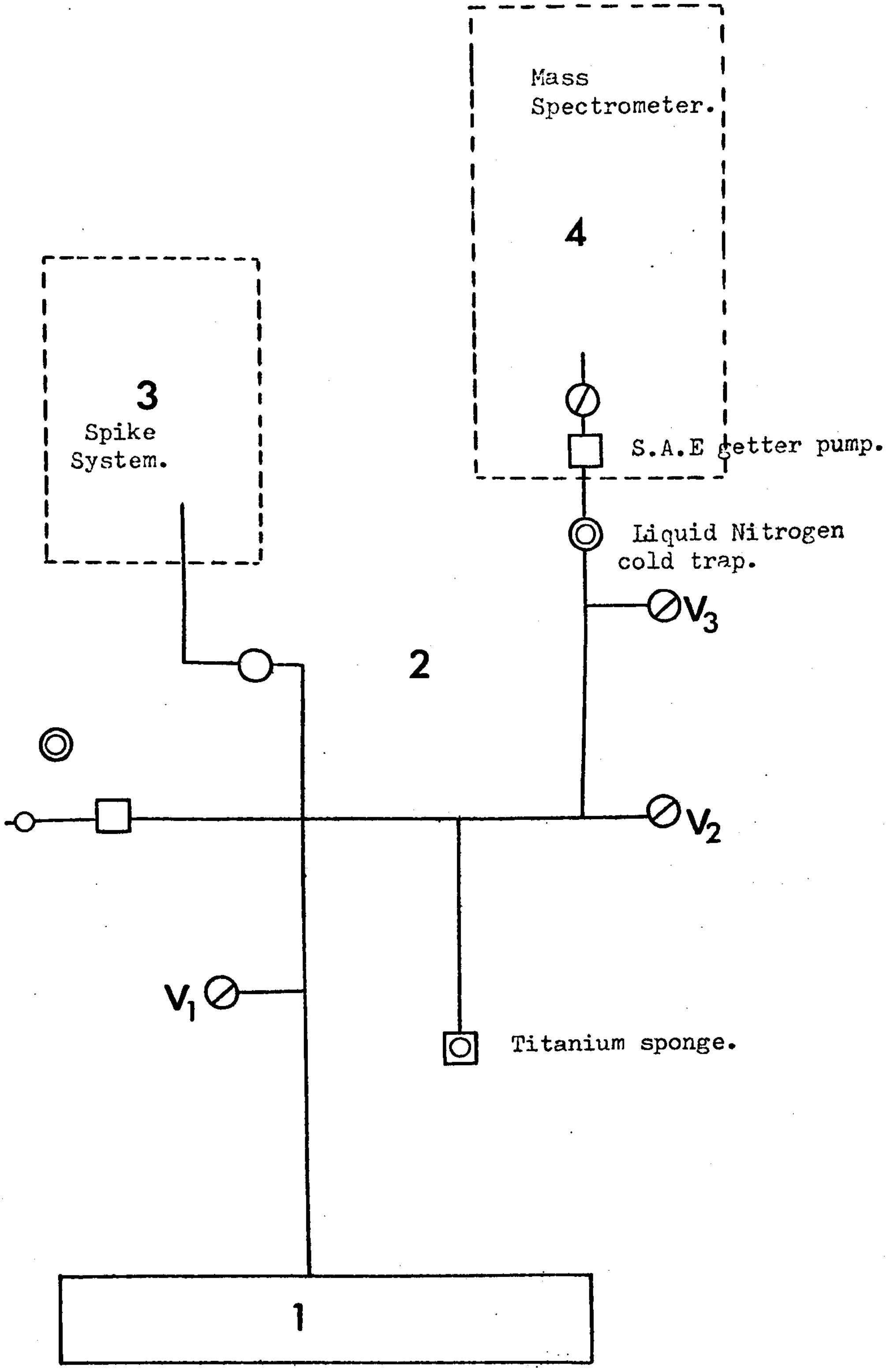


FIG.48b. Modified version of the Argon analytical equipment, adapted for equilibrated runs (May, 1975).

unbreakable stainless steel system. The main components of the 'clean up' section are the liquid nitrogen cold traps, a titanium sponge and a copper oxide furnace. The copper oxide furnace is maintained at a temperature of 450° - 550° C and converts hydrogen to water and oxidises, or ignites, hydrocarbons. The titanium sponge is heated to around 800° C and removes all the reactive gases (O_2, N_2 etc.); this is a reversible process so the titanium can be used continually. The liquid nitrogen cold traps condense water vapour and carbon dioxide from the system.

Argon Analysis

Argon is analysed by stable-isotope dilution using almost pure Ar^{38} as a tracer or spike. The spike is contained within a two litre stainless steel flask, which is connected to the rest of the system by two valves (Fig.48). A tube between these two acts as a gas pipette allowing a measured aliquot of spike to be passed into the system. The volume of spike used during each analysis has to be know accurately. Thus, the calibration of the spike is the only absolute measurement used in the argon analysis and comprises one of the major sources of error, for this reason it is discussed in some detail.

There are two methods in general use for determining the volume of spike in each aliquot, firstly by comparison with a known amount of atmospheric argon, and secondly, by comparison with a mineral of known radiogenic argon content. The former method is normally used in London and has been outlined in some detail by Rex (1967). A small glass capsule is filled with a known volume of dry air and sealed at atmospheric pressure. This is then loaded into the extraction system and broken under vacuum in the presence of an aliquot of spike. The air-argon mixture is cleaned in the usual way and then analysed on a mass spectrometer. Since the volume of air in the capsule is known the volume of Ar^{38} in the spike can be calculated from the following expression :

$$\text{Vol } Ar^{38} \text{ in spike} = \text{Vol } Ar^{40} \text{ in air capsule} \times \frac{A}{B}$$

$$\text{where } A = 1 - \frac{40/38\text{ m} - 40/385\text{p}}{40/38\text{ a} - 40/385\text{p}}$$

$$\text{and where } B = {}^{40}/_{38\text{m}} - (A \times {}^{40}/_{385\text{p}})$$

where ${}^{40}/_{38\text{m}}$ = measured Ar^{40} / Ar^{38}

${}^{40}/_{38\text{sp}}$ = spike " "

${}^{40}/_{38\text{a}}$ = atmospheric " "

A spike calibration is carried out on every tenth aliquot and plotted graphically. The volume of spike in the reservoir decreases exponentially according to the equation;

$$Ar^{38}_{5p} = To^{e - ex}$$ (c.f. Dalyrymple and Lanphere, 1969 p.59)

where To is a constant and X is the spike number. The volume of each aliquot of spike is determined by linear regression treatment applied to the calibration points.

Since the spike is not pure Ar^{38} its composition has to be known accurately in order to account for the small increment of Ar^{40} it will contribute to the measured Ar^{40} peak. The spike in present use at London has the following composition :

Ar^{36}/Ar^{38} = 5×10^{-5}

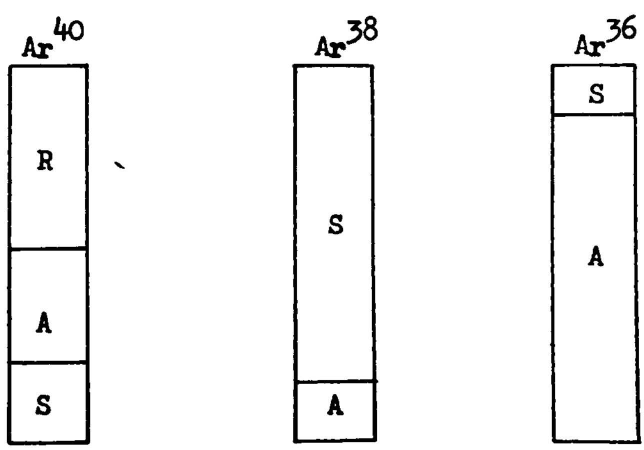
Ar^{40}/Ar^{38} = 1.7×10^{-3}

The argon isotopes are analysed on an A.E.I. MS.10 mass spectrometer run in the static mode, it is connected to a digital output system to facilitate easier reading.

The sample (and spike) is admitted into the mass spectrometer via a variable leak valve, for this reason an orafice correction has to be applied to take into consideration the fractionation of the argon isotopes. This is because under conditions of molecular flow the lighter isotopes diffuse more rapidly than the heavier ones (see Gale and Beckinsale, 1974). However, this method of leaking the gases into the mass spectrometer is no longer used in London because it was found that the orafice correction did not always apply to whole rock samples, where poor 'clean up' often leaves a number of interfering gases (C.C. Rundle, pers. comm). Therefore the leak valve system was changed in April 1975 and the gases are now allowed to equilibrate into the MS.10 without needing to apply an orafice correction.

The Determination of Radiogenic Argon

The Argon which is finally admitted for analysis on the MS.10 consists of three components, radiogenic argon (Ar^{40} rdg), spike argon (Ar_s) and atomospheric argon (Ar_a). The argon is made up of three isotopes Ar^{36}, Ar^{38} and Ar^{40} which are contributed from these three sources and shown diagrammatically in the following equations :



$$Ar^{40}_{m} = Ar^{40}\,rdg + Ar^{40}_{a} + Ar^{40}_{sp}$$

$$Ar^{38}_{m} = Ar^{38}\,sp + Ar^{38}_{a}$$

$$Ar^{36}_{m} = Ar^{36}_{a} + Ar^{36}_{s}$$

where Ar^{i}_{m} denotes no. of atoms of isotope i in the mixture.

The amount of radiogenic argon in the sample can be easily calculated from knowledge of the isotopic composition of the spike and of atmospheric argon. The contribution of atmospheric argon to the total 40-peak can be easily calculated from the known Ar^{40}/Ar^{36} atmospheric ratio. At London the MS.10 gives a mean value of 293 for the Ar^{40}/Ar^{36} atmospheric ratio.

Since the volume of spike is known the amount of radiogenic argon^{40} can be calculated from the ratio Ar^{40} rdg/Ar^{38}sp. In practice the peak heights are measured and the isotopic ratios expressed algebraically to give the following general relationship :

$$Ar^{40}\,rdg = Ar^{38}_{sp} \times {}^{40}/_{38\,m} - \left({}^{40}/_{38\,sp} + \left({}^{36}/_{38\,m} - {}^{36}/_{38\,s} \right) \times {}^{40}/_{36a} \right)$$

A x B

POTASSIUM ANALYSIS

The numerous methods of analysing for potassium have been summarised by Dalyrymple and Lanphere (1969) who concluded that for simplicity and speed, without the sacrifice of accuracy and precision, flame photometry is the most useful method. The application of the flame photometric method has been examined in great detail by Cooper (1963).

The chemical procedures outlined by Shapiro and Brannock (1962) are adopted, thus equal volumes of hydrofluoric and perchloric acids are added to a known weight of sample and the silica removed by evaporating to dryness. The residuum is dissolved in deionised water and made up to a known volume and to it is added a known amount of Lithium to act as an internal standard. The solution is analysed on an Eel 170 digital flame photometer which utilises an air-propane flame. The lithium internal standard is employed to minimise direct interference effects from other cations. Standard solutions of K+ are used to calibrate the photometer and the values are read off directly in ppm. The weight of the sample and the final dilution factor are adjusted to enable the concentration to be the same order of magnitude as the 24k standard solution, this approximates :

0.1 gms of <u>mica</u>	made up to 250 mls	(6-8% K)
0.2 gms of <u>hornblende</u>	made up to 100 mls	(1% K)

The intensity of the flame produced by the unknown is compared with the intensity produced by the standard; the potassium content of the sample is easily determined from knowledge of the sample weight and dilution factor. The proportion of K^{40} in the sample is estimated from knowledge of the atomic abundances of the potassium isotopes, the ratio of K^{40}/K total is 0.0019% which is the value recommended by Smith (1964). Once the volume of radiogenic Ar^{40} and amount of K^{40} have been evaluated the age is calculated from the K.Ar age equation (see Part 2).

ANALYTICAL ERRORS IN K.Ar DATING

Many factors contribute to the errors of an age determination and these can be divided into two broad categories. Firstly, experimental errors which are allied to the uncertainties in the analysis of K^{40} and Ar^{40}. Secondly, the geological error which is related to the geological history of the sample, a discussion of which forms the theme of Part 2 of this thesis.

In order for an age to be useful it has to be accompanied by some estimate of its reliability, in this respect analytical errors are important because they provide a criterion for comparing the ages of different samples. Normally an age is followed by some statistical parameter which is a measure of the precision of the age determination, at London this is routinely estimated to one standard deviation (1) at the 68% confidence level.

In the case of young rocks the analytical error is mainly a function of the error in the Ar^{40}/K^{40} ratio. For older samples this error decreases because the age is a logarithmic function of the Ar^{40}/K^{40} ratio and the error is therefore time dependent (c.f. Dalyrymple and Lanphere, 1969, p.102).

Errors in the determination of Ar^{40} rdg.

Replicate analyses of argon determinations are not carried out in practice due to the expense and time involved. It is therefore necessary to have a method of estimating the precision of a single age determination. It has been shown that the volume of radiogenic argon is calculated from knowledge of the spike volume, the Ar^{40}/Ar^{38} ratio and the $Ar^{36}/$-Ar^{38} ratios, which are measured on the mass spectrometer, and the Vol Ar^{40}_{rdg} =

(A) x (B) (see equation on p.275).

The largest error in the determination of radiogenic argon is related to the uncertainty in the volume of Ar^{38} spike. (A) The error in the volume of the spike is estimated by linear regression treatment applied to the spike calibration data which is taken to be $\pm$ 1.5%. On the other hand the error in expression B (see equation) varies according to the amount of atmospheric contaminant, i.e. a larger error is introduced if the atmospheric argon contaminant increases (see Fig. 49) and explanatory note). For very young samples the proportion of atmospheric argon may be large and then comprises the largest contributory factor to the error in the volume of Ar^{40} rdg. In the case of the samples used in this thesis the radiogenic Ar^{40} generally comprises $< 50\%$ of the total Ar^{40} and this error magnification is therefore significant.

A general formula for the estimation of analytical precision of the argon alaysis has been derived by Cox and Dalyrymple (1967) the modified version used in London is;

Error on volume of radiogenic Ar^{40} = (A)

$$(A) = \left[(\%\ \text{error in spike volume})^2 + \left(\frac{x^2 + \frac{A}{T}\, y^2}{1 - \frac{A}{T}} \right)^2 \right]^{\frac{1}{2}}$$

where $T = {}^{40}/_{38\,m}$

$A = 296\ {}^{36}/_{38\,m} - {}^{36}/_{38\,s}$

x = % error on T

y = % error on A

The estimation of precision, derived from the formula, is periodically checked by running an internal standard, usually every tenth sample.

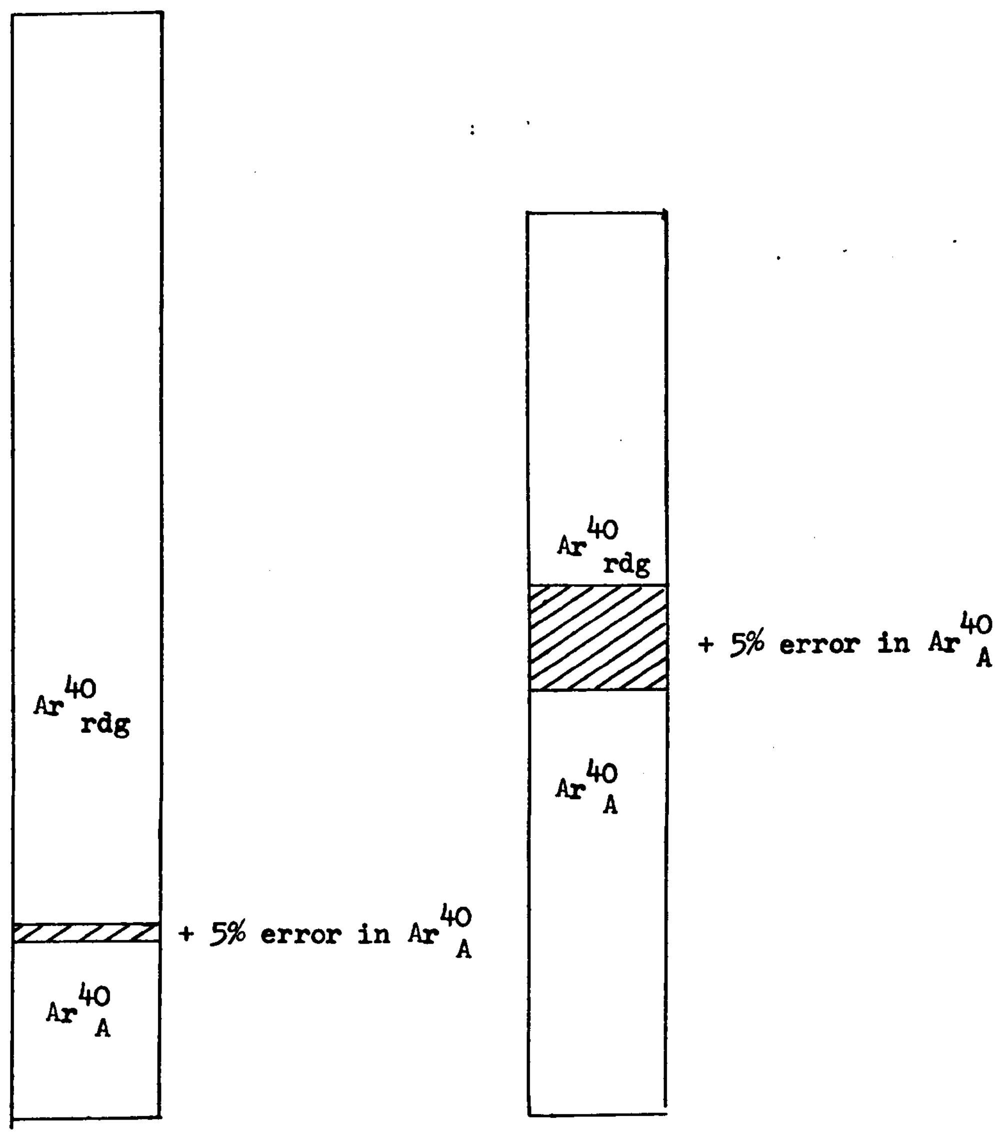


Fig. 49 Diagram showing the error in the atmospheric argon correction for small and large percentages of radiogenic argon (after Dalyrymple and Lanphere, 1969).

$$Ar^{40}\ rdg \quad = \quad Ar^{40}_{total} \; - \; Ar^{40}_{atmospheric}$$

i.e. if $Ar^{40}_{ats} > 90\%$ of Ar^{40}_{T} then a 1% error in Ar^{40}_{A} will produce approximately a 10% error in the quantity of Ar^{40} rdg.

Table of Replicate Argon Analyses

Sample	Run.no	Mineral	%K	Vol rdg Ar^{40} ss/gm x 10^{-5}	Age
A18	73.129 75.31	B	7.45	18.76 18.613	62.1 61.5
A22	74.127 75.130	B	5.92	15.348 14.645	63.9 61.0
A34	73.121 73.128	B	7.15	3.6979 3.2258	12.9 11.3
A82	74.134 75.36	B	6.4	8.8219 9.0914	34.3 35.3
A126	74.166	B	4.67	16.138 16.2204	85.5 85.1
A130	75.34 75.41	B	7.4	16.496 16.313	55.1 54.4
A139	74.135 75.32	B	6.87	4.3398 4.0024	15.7 14.5
A10	75.20 75.21	H	0.78	2.1314 2.2132	67.1 69.6
A62	75.33 74.165	H	0.62	1.5897 1.6379	63.2 65.0
A126	74.81 75.40	P	0.63	2.4331 2.3334	94.8 91.0

B = biotite

H = hornblende

P = Plagioclase

Table Replicate analysis of radiogenic Argon on 90 m.y. old biotite. (Sample A89)

Volume $Argon^{40}$ scc/gm x 10^{-5}

	% error
2.3741	1.54
2.3683	1.57
2.3616	0.8
2.4048	0.79
2.4044	0.74
2.3254	0.78
2.4213	0.72
2.4172	0.72
2.4104	0.74

mean volume 2.3836 $\pm$ 1.37%

Errors in the Potassium Analysis

Often when determining the age of very young rocks the precision of the potassium determinations is of secondary importance as the greater degree of uncertainty lies in the argon analysis. However the majority of samples analysed by the author have greater than 50% radiogenic argon content and in such cases the precision of the potassium analysis is important.

The degree of accuracy and precision attainable using an Eel flame photometer has been discussed by Cooper (1963) who concludes that a reproducibility of $\pm$ 1.5% is possible in the range of 0.1 - 10% K.

In practice a pooled standard deviation is used, mainly because the large number of samples to be analysed ruled out the feasibility of replicate analyses on each individual sample. Thus, the samples are routinely analysed in duplicate and a pooled standard deviation is calculated for the mineral species which have a similar range of K contents. This is in effect the same as carrying out a large number of replicate analyses on a small number of selected samples. A formula for the pooled standard deviation has been given by Bennet and Franklin (1954);

$$S = \sqrt{\frac{(xi - x)^2}{n - 1}}^{2}$$

where n = no. of determinations i.e. n = 2 if in duplicate
where $(xi - x)^2$ = sum of squared deviations.

For example a random selection of 14 biotites gave a pooled standard deviation of ± 0.9% of their average K content. To ensure that this represents a realistic estimate two micas of different K values were analysed a number of times and the results are tabulated below :

Sample No.	K%
A10 - biotite	7.681 ± 0.051 (0.66%) 5 determinations
N8 - biotite	4.556 ± 0.031 (0.69%) 5 determinations

The errors calculated for a K determination also provide an internal check of the sample homogeneity because relatively small aliquots of the sample are used in the analysis. When duplicate analyses on a sample have an error of > 1.5% the third analysis is carried out and the precision is determined separately. This method was only used in the case of a few hornblende and plagioclase separates where the poor reproducibility is a function of sample impurity. With the exception of whole rock samples the powdering of samples for K analysis was avoided for this provides an erroneous impression of sample purity.

Once the errors in the estimation of radiogenic argon^{40} and potassium have been evaluated the error on the K.Ar age is expressed by the following equation :

$$\text{Error on age (m.y.)} = \left[A^2 + \left(\frac{V}{\%K}\right)^2 \right]^{1/2} \times \text{age}$$

where V = standard error on mean of the K%
where A = error on volume of radiogenic argon

Accuracy of the Age Determinations

In the preceding section the author briefly outlined the methods used in evaluating the reproducibility of an age determination, this however is not a measure of its accuracy with which precision is frequently confused. Accuracy is here defined as the degree to which the analysis represents the true K^{40} and Ar^{40} values, of the sample in question. An estimate of the accuracy of an age determination is of particular importance when correlating the results with data from other laboratories or using a 'radiometric' time scale.

The accuracy of both potassium and argon analyses are assessed by reference to analyses of interlaboratory standards. Those carried out during the course of this investigation are shown below.

	%K	Recommended value
U.S.G.S. G2	3.76	3.74
U.S.G.S. BCR.1	1.43 $\pm$ 0.02 (9 determinations)	1.41
BERN 4M Muscovite	8.75	8.7 $\pm$ 0.11
GL-O glauconite	6.726 $\pm$ 1.02%	*
	Vol Ar^{40} x 10^{-6} scc/gm	
GL.O glauconite	25.0796 $\pm$ 0.18 (0.7%)	*

* Recommended value to be reported in International Symposium on Geochronology, Paris (1974).

APPENDIX III

K.Ar AGE DETERMINATIONS

Sample No.	Laboratory No.	Rock type	Mineral	%K	^{40}Ar rdg x 10^{-5} scc/gm*	Apparent Mineral age (m.y.)	Preferred age (m.y.)
A01	74-170	Gabbro	P	0.208	0.07686	90 ± 2	90 ± 2
"	74-169	"	H	0.315	0.09379	73 ± 3	73 ± 3
A05	73-123	Tonalite	B	6.95	0.91809	33 ± 0.5	33 ± 0.5
"	73-124	"	H	0.513	0.12368	59.4 ± 1.9	59.4 ± 1.9
A08	73-127	Q diorite	B	6.65	1.9015	70.3 ± 1.1)	71.7 ± 1.1
"	73-132	"	H	0.481	0.14881	73.9 ± 1.4)	
A10	75-21	Diorite	H	0.782	0.21723 *	68.2 ± 1.2	68.2 ± 1.2
"	75-19	"	B	7.74	2.3209	74 ± 1.4	74 ± 1.4
A12	73-133	Tonalite	B	4.88	1.8495	92.6 ± 1.4	92.6 ± 1.4
"	73-130	"	H	0.396	0.13534	83.8 ± 2.2	83.8 ± 2.2
A13	74-128	Microdiorite dyke	WR	1.202	0.35811	73.2 ± 1.9	73.2 ± 1.9
A14	74-129	Microdiorite dyke	WR	3.418	1.02261	73.5 ± 1.97	73.5 ± 1.9
A18	73-135	Tonalite	H	0.61	0.17276	69.8 ± 1.8	69.8 ± 1.8
"	75-31	"	B	7.46	1.8687 *	61.9 ± 1.4	61.9 ± 1.4
A19	74-82	Pegamatite	Q	0.007	0.05489	1345 ± 44	1345 ± 44
"	74-91	"	K	9.616	1.63009	42 ± 1	42 ± 1

Sample No.	Laboratory No.	Rock type	Mineral	%K	Ar^{40}rdg x 10^{-5} scc/gm	Apparent Mineral age (m.y.)	Preferred age (m.y.)
A21	74-126	Monzogranite	B	6.915	1.80763	64.4 ± 1.6	64.4 ± 1.6
A22	74-161	"	K	9.775	2.41322	60.8 ± 1.0	61.7 ± 0.7
"	75-30	"	B	5.92	1.49969 *	62.4 ± 0.9	
A26	74-31	Lamprophyre	H	0.306	0.08534	68.5 ± 2.8	68.5 ± 2.8
A27	73-124	Monzogranite	B	6.83	1.814 *	64.9 ± 1.1	64.9 ± 1.1
"	73-137	"	K	9.15	1.4722	39.9 ± 0.6	39.9 ± 0.6
A33	73-125	Q diorite	B	7.21	0.54467	18.8 ± 0.3	18.8 ± 0.3
"	73-139	"	H	0.442	0.05511	30.9 ± 1.0	30.9 ± 1.0
A34	73-138	Granodiorite	P	0.72	0.04063	12.9 ± 0.3	12.6 ± 0.2
"	73-128	"	B	7.15	0.34564 *	12.4 ± 0.24	
A37	75-68	Q diorite	B	5.78	0.45847	19.8 ± 0.6	19.8 ± 0.6
A38	74-151	"	B	1.23	0.26734	46.6 ± 1.2	46.6 ± 1.2
A41	73-126	Aplite	B	5.15	1.51006	72 ± 1.1	72 ± 1.1
"	73-140	"	K	9.77	2.63838	66.5 ± 1.6	66.5 ± 1.6
A42	75-45	Monzogranite	B	6.9	1.91926	68.4 ± 1.3	68.4 ± 1.3

Sample No.	Laboratory No.	Rock type	Mineral	%K	$Ar^{40}rdg \times 10^{-5}$ scc/gm	Apparent Mineral age (m.y.)	Preferred age (m.y.)
A50	75-35	Monzogranite	K	8.94	1.1616	32.3 ± 1.2	31.4 ± 0.6
"	74-87	"	B	6.212	0.8059	31 ± 0.7	
A54	75-48	Granodiorite	B	6.66	1.66674	61.7 ± 1.2	61.7 ± 1.2
A56	75-49	Pegmatite	B	6.38	1.47675	57.1 ± 1.2	57.1 ± 1.2
A61	74-120	Tonalite	H	0.616	0.15478	62 ± 2.1	62 ± 2.1
"	74-90	"	B	5.497	1.1592	52.1 ± 1.2	52.1 ± 1.2
A67	74-164	Tonalite	B	5.44	2.0004	90 ± 1.7	89 ± 1.3
"	74-180	"	P	0.583	0.20915	87.8 ± 1.98	
A71	74-94	Andesite	WR	0.386	0.08205	52.5 ± 2.35	52.5 ± 2.3
A72	74-119	"	WR	1.047	0.1012	24.1 ± 2.2	24.1 ± 2.2
A74	74-118	"	WR	1.436	0 .08565	14.9 ± 2.4	14.9 ± 2.4
A77	74-143	Granodiorite	B	6.41	0.60206	23.4 ± 0.7	23.4 ± 0.7
"	74-144	"	H	0.65	0.08685	33 ± 1.5	33 ± 1.5
A79	74-88	Monzogranite	B	6.46	0.71563	27.6 ± 0.7	27.6 ± 0.7
A80	74-162	"	K	9.845	1.14409	28.9 ± 0.5	29.5 ± 0.4
	74-135	"	B	6.659	0.8189	30.6 ± 0.7	

Sample No.	Laboratory No.	Rock type	Mineral	%K	$Ar^{40}rdg \times 10^{-5}$ scc/gm	Apparent Mineral age (m.y.)	Preferred age (m.y.)
A81	74-133	Monzogranite	B	6.648	0.92551	34.6 ± 0.8	34.6 ± 0.8
A82	75-36	"	B	6.39	0.89567 *	34.8 ± 0.5	34.1 ± 0.4
"	74-175	"	K	9.28	1.248	33.4 ± 0.5	
A89	74-177	Tonalite	B	6.17	2.2091	87.6 ± 2.0	87.6 ± 2.0
A91	74-130	Lamprophyre	H	0.516	0.12475	59.6 ± 2.4	59.6 ± 2.4
A92	75-33	Tonalite	H	0.62	0.16138 *	64.1 ± 1.6	64.1 ± 1.6
A93	74-133	Granodiorite	B	7.75	2.34338	74.3 ± 1.7	74.3 ± 1.7
A95	74-174	Monzogranite	K	8.66	2.3978	68.2 ± 1.2	68.2 ± 1.2
A97	74-173	"	K	10.18	2.6838	64.9 ± 1.1	64.9 ± 1.1
A103	74-89	Granodiorite	B	5.84	1.6346	68.8 ± 3.4	68.8 ± 3.4
A105	75-42	Granophyre	B	7.01	1.59605	56.2 ± 1.0	56.2 ± 1.0
A106	74-167	Tonalite	B	5.53	1.40292	62.5 ± 1.2	61.7 ± 1.0
"	74-186	"	P	0.847	0.20685	60.2 ± 1.4	
A107	74-168	Granodiorite	B	6.134	1.627	65.3 ± 1.2	65.3 ± 1.2

Sample No.	Laboratory No.	Rock type	Mineral	%K	$Ar^{40}rdg \times 10^{-5}$ scc/gm	Apparent Mineral age (m.y.)	Preferred age (m.y.)
A109	75-46	Monzogranite	B	6.98	2.1358	75.1 ± 1.4	75.1 ± 1.4
A115	74-86	"	B	4.55	1.1899	64.4 ± 1.6	62.6 ± 0.8
"	74-172	"	K	9.82	2.4687	61.9 ± 1.0	
A119	74-183	Granodiorite	P	2.71	0.18961	17.4 ± 1.0	18.4 ± 0.4
"	74-141	"	B	6.67	0.50023	18.7 ± 0.5	
A120	74-122	Q diorite	B	6.05	0.57815	23.8 ± 0.6	23.8 ± 0.6
A122	74-156	Tonalite	B	3.41	0.76249	55.2 ± 1.3	56.6 ± 1.0
"	74-185	"	P	0.545	0.13099	59.3 ± 1.8	
"	74-157	"	H	0.52	0.191912	90.3 ± 4.6	90.3 ± 4.6
A123	74-80	Tonalite	P	0.43	0.13055	74.7 ± 1.8	74.7 ± 1.8
"	74 171	"	K	8.66	1.9329	55.1 ± 0.9	56.6 ± 0.7
"	74 142	"	B	6.54	1.5747	59.4 ± 1.3	
A124	74-170	Tonalite	K	7.36	1.83661	61.5 ± 1.1	61.5 ± 1.1
A126	74-145	Tonalite	H	0.362	0.14538	97.9 ± 3.2	95.3 ± 1.7
"	75-40	"	P	0.627	0.2383 *	94.2 ± 2.1	
"		"	B	4.675	1.6269 *	85.3 ± 1.2	85.3 ± 1.2
A127	74-92	Granodiorite	B	5.67	1.43094	62.2 ± 1.2	62.2 ± 1.2

Sample No.	Laboratory No.	Rock type	Mineral	%K	$^{40}Ar_{rdg} \times 10^{-5}$ scc/gm	Apparent Mineral age (m.y.)	Preferred age (m.y.)
A129	75-38	Tonalite	B	7.37	0.93113	31.4 ± 0.6	31.4 ± 0.6
"	75-37	"	H	1.126	0.1765	38.8 ± 0.7	38.8 ± 0.7
A130	75-41	"	B	7.39	1.6313 *	54.4 ± 1.0	54.4 ± 1.0
A133	74-115	Ignimbrite	B	7.29	0.17206	58.4 ± 0.2	58.4 ± 0.2
A134	74-176	Granodiorite	B	5.714	0.16439	70.7 ± 1.6	70.7 ± 1.6
"	74-187	"	P	0.414	0.10547	62.8 ± 1.3	62.8 ± 1.3
A135	74-148	Monzogranite	K	9.41	2.20794	57.9 ± 0.9	59.1 ± 0.8
"	74-140	"	B	6.17	1.55111	61.9 ± 1.4	
A136	74-150	Porphyritic granite	K	9.95	2.21299	54.9 ± 0.9	55.6 ± 0.7
"	74-159	" "	B	5.81	1.3303	56.5 ± 1.3	
A137	74-149	Quartz-feldspar porphyry	K	9.13	2.29131	61.7 ± 1.0	61.7 ± 0.8
"	74-158	" "	B	6.29	1.5654	61.3 ± 1.2	
A138	75-73	Ryho-dacite porphyry	P	0.994	0.12818	32 ± 0.55	32 ± 0.55
A139	75-32	Ignimbrite	B	6.87	0.40019	14.5 ± 0.3	14.5 ± 0.3
A140	75-74	Ryho-dacite porphyry	P	2.06	0.23816	28.7 ± 0.5	28.7 ± 0.5
A141	74-154	Ignimbrite	B	7.35	0.18307	6.2 ± 0.2	6.2 ± 0.2

Sample No.	Laboratory No.	Rock type	Mineral	%K	Ar^{40} rdg x 10^{-5} scc/gm	Apparent Mineral age (m.y.)	Preferred age (m.y.)
A143	74-179	Tonalite	P	1.344	0.19314	35.7 ± 0.7	
"	74-121	"	H	0.556	0.07685	34.3 ± 1.9	35.3 ± 0.5
"	74-137	"	B	6.613	0.9338	35 ± 0.9	
A144	74-136	Monzogranite	B	7.18	1.30486	45 ± 1.0	45 ± 1.0
"	74-147	"	K	9.72	1.96417	50 ± 0.8	50 ± 0.8
A145	74-138	Granodiorite	B	5.95	1.0475	43.6 ± 1.0	43.4 ± 0.8
"	74-139	"	H	0.653	0.11390	43.2 ± 1.3	
A148	74-146		K	10.185	2.4642	59.7 ± 0.9	59.7 ± 0.9
"	74-93		B	5.675	1.52143	66 ± 1.5	66 ± 1.5
A149	75-43	Tonalite	H	0.43	0.13065	74.6 ± 1.8	72 ± 1.0
"	75-44	"	B	7.49	2.1535	70.6 ± 1.3	
A153	74-123	Granophyre	B	4.54	1.0969	59.6 ± 1.4	61.4 ± 0.8
"	74-160	"	K	10.02	2.5391	62.4 ± 1.0	
A168	75-72	Tonalite	B	2.262	0.58441	63.6 ± 1.0	63.6 ± 1.0
B1	75-69	Monzogranite	B	7.23	1.7483	59.6 ± 0.9	60.4 ± 0.7
B3	75-77	"	B	7.163	1.7930	61.7 ± 1.1	

Sample No.	Laboratory No.	Rock type	Mineral	%K	$Ar^{40}_{rdg} \times 10^{-5}$ scc/gm	Apparent Mineral age (m.y.)	Preferred age (m.y.)
B4	75-65	Monzogranite	B	6.72	1.64406	60.3 ± 1.0	60.3 ± 1.0
B5	75-66	"	B	6.54	1.6157	60.9 ± 0.98	60.9 ± 1.0
B9	75-67	"	B	6.97	1.7251	61.9 ± 0.97	61.9 ± 1.0
		CORDILLERA BLANCA BATHOLITH					
CB3	75-22	Leucogranodiorite	M	8.78	0.216001	6.15 ± 0.2	6.15 ± 0.2
CB4	75-23	"	B	7.62	0.10106	3.3 ± 1.2	3.3 ± 0.12
CB5	75-26	"	M	9.0	0.161801	4.5 ± 0.17	4.2 ± 0.1
"	75-24	"	B	7.02	0.14833	4.1 ± 0.1	
CB6	75-27	"	B	7.19	0.13038	4.5 ± 0.2	4.5 ± 0.2
"	75-28	"	M	10.11	0.24264	6.0 ± 0.12	6.0 ± 0.12
CB9	75-25	"	B	7.89	0.15437	4.9 ± 0.17	4.9 ± 0.17
CB10	74-153	Ignimbrite	B	7.3	0.22117	7.6 ± 0.2	7.6 ± 0.2
CB11	74-152	"	B	7.65	0.190441	6.2 ± 0.2	6.2 ± 0.2

Sample No.	Laboratory No.	Rock type	Mineral	%K	$Ar^{40}_{rdg} \times 10^{-5}$ scc/gm	Apparent Mineral age (m.y.)	Preferred age (m.y.)
380	75-76		B	7.51	0.296138	9.9 ± 0.17	9.9 ± 0.17
"	75-75		H	0.88	0.05654	16.0 ± 0.46	16.0 ± 0.46
386	75-70		B	6.123	0.22353	9.12 ± 0.21	9.12 ± 0.2
"	75-71		H	0.666	0.02968	11.14 ± 0.58	11.1 ± 0.6
			SAN NICHOLAS BATHOLITH				
N6	74-124	Diorite	WR	0.608	0.66047	254 ± 6.1	254 ± 6.1
N8	74-85	Granodiorite	B	4.56	8.4372	442.5 ± 10.4	441 ± 7.0
"	74-136	"	H	0.918	1.8083	438 ± 9.4	
N9	74-83	"	H	0.898	1.69136	421 ± 10.9	425 ± 8.0
"	74-84	"	B	3.239	6.2074	427 ± 12.2	

Note : B = biotite, H = hornblende, P = plagioclase, K = K feldspar, WR = Whole rock

* indicates analysis in duplicate

APPENDIX IV

LOCALITIES AND BRIEF DESCRIPTIONS OF ANALYSED SAMPLES

Notes :

(1) Map references are given in brackets and refer to the 1 : 100,000 topographic maps published by the Instituto Geographico Militar Lima Peru. The quadrange name precedes the grid reference, in the following abbreviated form :

Hu = Huacho, Hl = Huaral, C = Canta, O = Oyon,
A = Ambar, B = Barranca, H = Huayllapampa
CP = Cerro de Pasco, CM = Casma.

(2) Where possible rock names are based on modal analyses, and using the classification nomenclature outlined by Streckeisen (1974). More complete sample descriptions are incorporated in the text.

Sample number	Name and Locality

A.1 Hornblende gabbro, small quebrada south-east of Cerro Huncayo. (Hl, 448.469).

A.5 Hornblende-biotite tonalite (Paccho) Rio Huaura 100 m south of Quebrada Yungay. (Hl, 705.792).

A.8 Quartz-diorite (Santa Rosa), Cerro La Caida (Hl, 470.600).

A.10 Hornblende-diorite (Santa Rosa), Cerro Pampa Afeura (Hl, 459.464).

A.12 Leucocratic tonalite (Santa Rosa), north of Cerro Cenicero (Hl, 315.750).

A.13 Microdiorite dyke, western slopes of Cerro Perla (Hl, 492.578).

A.14 Porphyritic microdiorite dyke, locality as above.

A.18 Hornblende-biotite tonalite (La Mina), Quebrada west of the orange plantation, Cerro Santa Maria (Hl, 480.658).

A.19 Quartz-orthoclase pegmatite (Sayan, roof facies of Sayan pluton in Quebrada Conguay and Cerro Yeta Negra (Hl, 657.698).

A.21 Biotite monzogranite (Canas), Cerro Piedra Agacha (Hl, 535.705).

A.22 Biotite monzogranite, Quebrada Calambacu, Cerro La Cruz (Hl, 546.709).

A.26 Hornblende-porphyrite dyke, north of Cerro Ferregros Pampa Lhuanco (Hl, 520.568).

A.27 Biotite monzogranite (Puscao), north-west of Cerro Pan de Azucar (B, 378.920).

A.33 Quartz diorite (stock), road-cutting between Paccho Tingo and Churin (O, 880.788).

A.34 Hornblende-biotite granodiorite (stock), road-cutting between Churin and Oyon (

A.37 Quartz diorite (stock), Quebrada Paccho near the village of Colcapampa (O, 862.931).

A.38 Quartz diorite (Paccho), Rio Huaura near Fundo Bellavista (Hl, 708.785).

A.41 Aplo-granite dyke (Humaya), south-west of graveyard near Hacienda Humaya (Hl, 369.738).

A.42 Biotite monzogranite (Santa Rosa),sampled by small acequia 1.5 kms north-east of Hacienda Santa Rosa.

A.50 Biotite monzogranite (Sayan), 80 m west of Puento Alco along road-cutting (Hl, 689.812).

A.54 Hornblende-biotite granodiorite (Puscao), Quebrada Puscao northern slopes of Cerro Tres Cruces (Hl, 618.749).

A.56 Biotite pegmatite (Puscao), Cerro Pan de Azucar (B, 382.916).

A.61 Tonalite (Paccho), Quebrada Salitre south of the Rio Chico (Hl, 745.655).

A.67 Biotite tonalite (Santa Rosa), sampled on Cerro Mercaod near Hacienda San Bosco (Hl, 446.579).

A.71 Andesite (Calipuy), basal lava flow 2 kms north-east of Tapacocha.

A.72 As above

A.74 As above

A.77 Hornblende-biotite granodiorite (stock ?), along the Pativilca valley 1 km east of Fundo La Toma (A, 572.337).

A.79 Biotite monzogranite (Pativilca), 1 km west of Mayush along the Pativilca valley (A, 538.337).

A.80 Biotite monzogranite (Pativilca), 4 kms west of Mayush sampled in road-cutting (A, 520.327).

A.81 Biotite monzogranite (Pativilca), 6 kms north-east of Cahua (A, 472.310).

A.82 Biotite monzogranite (Pativilca), 6 kms west of Cahua (A, 382.265).

A.89 Hornblende-biotite tonalite (Santa Rosa), small quarry north of the Rio Huaura at Cerro Caldera (Hl, 321.738).

A.91 Porphyritic dyke, cutting Santa Rosa tonalite in Quebrada Capilla (Hl, 595.461).

A.92 Hornblende tonalite (Santa Rosa), Quebrada Capilla (Hl, 624.473).

A.93 Biotite granodiorite (Humaya), fallen blocks in small quebrada near Cerro Perla (Hl, 498.557).

A.95 Biotite monzogranite (Santa Rosa), scree slope on Cerro San Martin 5 kms north-east of Hacienda Santa Rosa (Hl, 577.608).

A.97 Monzogranite (La Mina), inner facies of the San Miquel stock fresh blocks on north-west slopes of Cerro San Martin (Hl, 460.678).

A.103 Granodiorite (Aynaca), samples south-east of the village of Aynaca at mouth of Quebrada Huancar (A, 516.970).

A.105 Granophyre (San Jeronimo), west of Jaiva along the northern part of the Supe valley (A, 392.942).

A.106 Hornblende-biotite tonalite (La Mina), Quebrada Mesa Rodunda (A, 371.030).

A.107 Biotite granodiorite (La Mina), Quebrada east of Jaranjito Alto, the San Miguel stock (Hl, 452.400).

A.109 Biotite monzogranite (Lachay), deep level of weathering sampled in fresh landslips on Quebrada Guayabito (Hl, 432.451).

A.115 Biotite monzogranite (Lumbre), Quebrada Lumbre south of Cerro de La Mina (Hl, 757.436).

A.119 Biotite granodiorite (Acos E stock), due west of Lacsa village and Quebrada Cocha, Rio Chancay (C, 093.546).

A.120 Quartz diorite (Acos stock), sampled at base of cliff east of Acos village (C, 040.544)

A.122 Tonalite (Paccho), fallen fresh blocks by graveyard in Quebrada Quisque Baco (Hl, 848.464).

A.123 Tonalite (Pacaybamba), road section along Quebrada Silla (Hl, 942.358).

A.124 Tonalite (Cayan), sampled along Q. Pacaybamba east of Polvaredo (Hl, 879.312).

A.126 Tonalite (Purmacana), main outcrop near Hacienda La Canada, fallen blasted blocks by acequia (B, 979.217).

A.127 Biotite granodiorite (Cerro Muerto), east of Quebrada Piedras Gordas (A, 302.255).

A.129 Tonalite (La Mina ?), sampled from earthquake avalanche Quebrada Huanchay (A, 356.348).

A.130 Tonalite (Cerro Muerto), ioma north of Quebrada Muertos (A, 173.342).

A.133 Fortaleza ignimbrite, fallen blocks at base of cliff on Cerro Huana Cayan (H, 240.773).

A.134 Biotite granodiorite, road-cutting along Rio Purisima 2 kms east oc Chasquitambo (H, 153.592).

A.135 Biotite monzogranite, outer ring of Fortaleza complex sampled in Quebrada 4 kms east of Antu (H, 010.522).

A.136 Porphyritic microgranite, Fortaleza complex (H, 112.491).

A.137 Quartz-feldspar porphyry, Fortaleza complex (H, 110.503).

A.138 Ryo-dacite porphyry, outcrops as small stock south-east of Pampacancha (CP, 487.323).

A.139 Ignimbrite, north-west of Cerro de Pasco and north-east of Lago Quilchay Machay (CP, 607.225).

A.140 Rhyo-dacite porphyry, Rio Panamarca east of Cerro de Pasco (CP, 725.250).

A.141 Ignimbrite, Cerro Shayhua Cruz eastern shore of Lago Junin (CP, 538.855).

A.143 Hornblende-biotite tonalite (Puscao), Q Puca Pampa east of Brena (CM, 218.854).

A.144 Biotite monzogranite (Moro), south-east slopes of Cerro San Juan (CM, 094.919).

A.145 Granodiorite, earthquake blocks on Cerro Motocachay (CM, 035.908).

A.148 Biotite monzogranite (Nepana), by road-cutting by Pampa Cóndor (CM, 870.896).

A.149 Tonalite (Santa Rosa), scree slope at opening to Quebrada Tambera (Hl, 490.503).

A.153 Granophyre (San Jeronimo), southern extremity of the Huaura centre, Cerro Lhuanco (Hl, 542.611).

A.168 Tonalite (Santa Rosa), Pan American highway, Casma.

B.1 Biotite monzogranite (Canas), Cerro Ibis 10 metres from contact with Sayan (Hl, 582.704).

B.3 Biotite monzogranite (Canas), Cerro Ibis 3 metres from contact with Sayan.

B.4 Biotite monzogranite (Sayan), Cerro Ibis 20 metres from contact with Canas.

B.9 Biotite monzogranite (Sayan), Cerro Ibis collected north of Fundo Chuquiquintay (Hl, 621.715).

CB.3 Muscovite pegmatite, Quebrada de Llanganuco section Cordillera Blanca.

CB.4 Muscovite-biotite leucogranodiorite

CB.5 Muscovite-biotite leucogranodiorite

CB.6 Muscovite-biotite, cliff to north of Lago Llanganuco.

CB.9 Foliated muscovite-biotite leucogranodiorite, eastern extremity of Lago Llanganuco.

CB.10 Ignimbrite, 2 kms east of the village of Yungay.

CB.11 Ignimbrite, road section 5 km north of Caraz, Callejon de Huaylas.

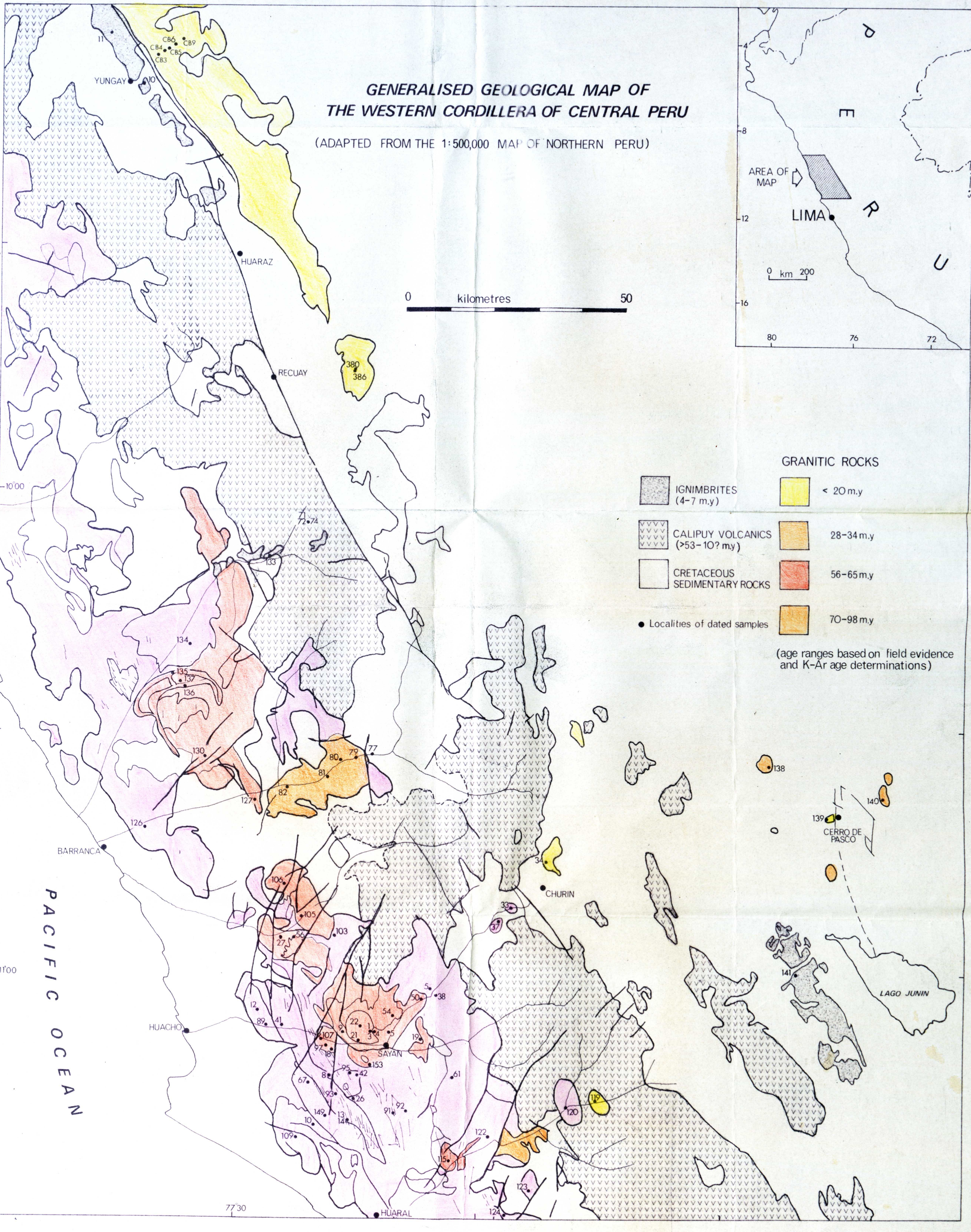
380 Tonalite, stock to the east of Huaras collected by E.J. Cobbing, exact locality unknown.

386 Granodiorite, Cordillera Blanca batholith to the east of Huaras.

N.6 Pyroxene diorite, small quarry 4 kms east of Marcona.

N.8 Hornblende granodiorite, road section approximately 11 kms noth-east of Marcona.

N.9 Hornblende granodiorite, fresh blasted blocks by roadside in San Nicholas bay.



GENERALISED GEOLOGICAL MAP OF
THE WESTERN CORDILLERA OF CENTRAL PERU
(ADAPTED FROM THE 1:500,000 MAP OF NORTHERN PERU)
0 kilometres 50
IGNIMBRITES (4-7 m.y)
CALIPUY VOLCANICS (>53-10? m.y)
CRETACEOUS SEDIMENTARY ROCKS
Localities of dated samples
GRANITIC ROCKS
< 20 m.y
28-34 m.y
56-65 m.y
70-98 m.y
(age ranges based on field evidence and K-Ar age determinations)
PERU
AREA OF MAP
LIMA
0 km 200
YUNGAY
HUARAZ
RECUAY
BARRANCA
HUACHO
SAYAN
HUARAL
CHURIN
CERRO DE PASCO
LAGO JUNIN
PACIFIC OCEAN
10°00
11°00
77°30