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K-Ar GEOCHRONOLOGY OF THE LATE CENOZOIC VOLCANIC ROCKS OF THE CORDILLERA OCCIDENTAL, SOUTHERNMOST PERU

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ABSTRACT

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Twenty-four K-Ar radiometric ages are presented for late Cenozoic continental volcanic rocks of the Cordillera Occidental of southernmost Perú (lat. 16° 57′—17° 36′S). Rhyodacitic ignimbrite eruptions began in this transect during the Late Oligocene and continued episodically through the Miocene. The development of andesitic-dacitic stratovolcanoes was initiated in the Pliocene and continues to the present.

The earliest ignimbrite flows (25.3—22.7 Ma) are intercalated in the upper, coarsely-clastic member of the Moquegua Formation and demonstrate that this sedimentary unit accumulated in a trough, parallel to Andean tectonic trends, largely in the Oligocene. More voluminous ash-flow eruptions prevailed in the Early Miocene (22.8—17.6 Ma) and formed the extensively preserved Huaylillas Formation. This episode was coeval with a major phase of Andean uplift, and the pyroclastics overlie an erosional surface of regional extent incised into a Paleogene volcano-plutonic arc terrain. An age span of 14.2—8.9 Ma (mid-Late Miocene) is indicated for the younger Chuntacala Formation, which again comprises felsic ignimbrite flows, largely restricted to valleys incised into the pre-Huaylillas Formation lithologies, and, at lower altitudes, an extensive aggradational clastic facies. The youngest areally extensive ignimbrites, constituting the Sencca Formation, were extruded during the Late Miocene.

In the earliest Pliocene, the ignimbrites were succeeded by more voluminous calc-alkaline, intermediate flows which generated numerous large and small stratovolcanoes; these range in age from 5.3 to 1.6 Ma. Present-day, or Holocene, volcanism is restricted to several large stratovolcanoes which had begun their development during the Pleistocene (by 0.7 Ma).

The late Oligocene/Early Miocene (ca. 22—23 Ma) reactivation of the volcanic arc coincided with a comparable increase in magmatic activity throughout much of the Cordilleras Occidental and Oriental of the Central Andes.

INTRODUCTION

Integrated studies of restricted Cordilleran transects have shown that the Mesozoic and Cenozoic history of the Central Andean mobile belt of Perú

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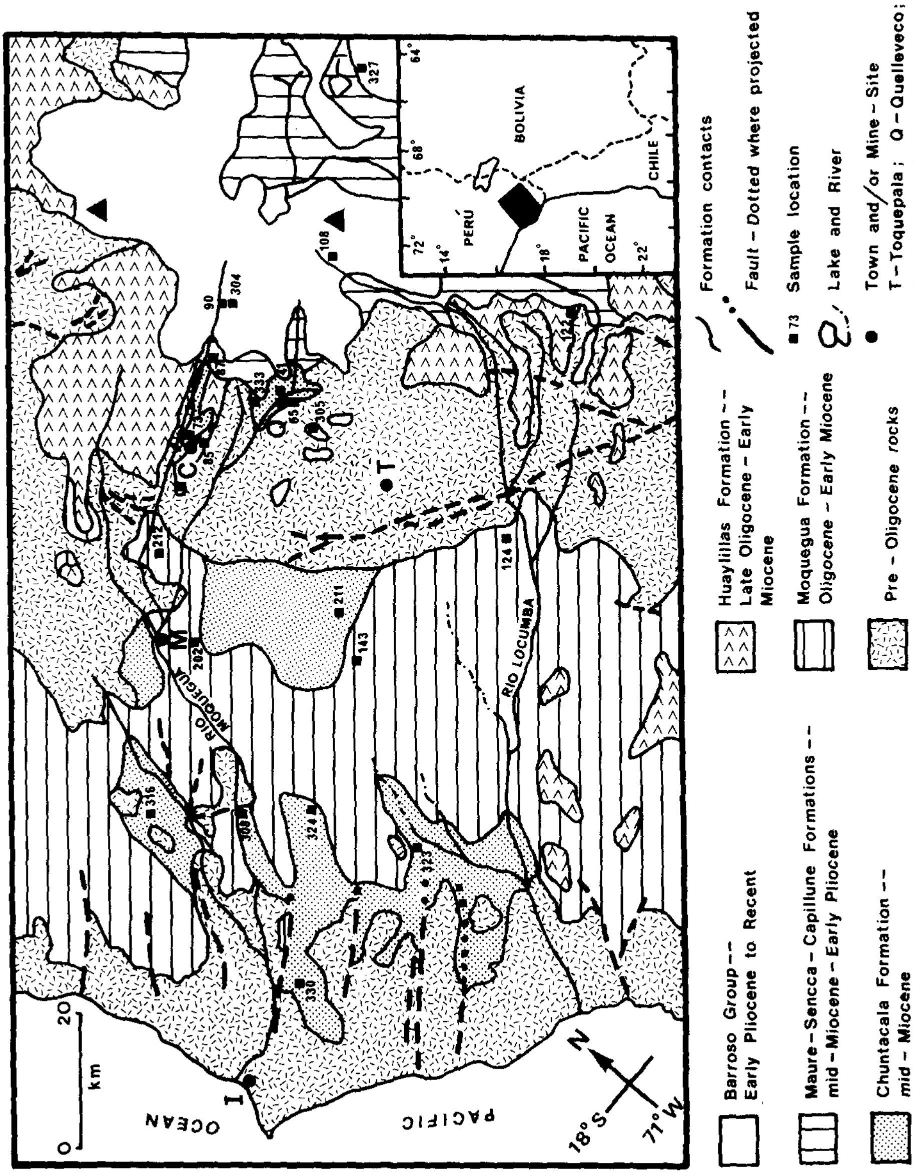

PACIFIC OCEAN
0 km 20
I
C
Q
T
M
RIO MOQUEGUA
RIO LOCUMBA
18°S
71°W
N
PERU
BOLIVIA
CHILE
PACIFIC OCEAN
Barroso Group -- Early Pliocene to Recent
Maure - Sencca - Capillune Formations -- mid - Miocene - Early Pliocene
Chuntacala Formation -- mid - Miocene
Huaylillas Formation -- Late Oligocene - Early Miocene
Moquegua Formation -- Oligocene - Early Miocene
Pre - Oligocene rocks
Holocene volcano
Formation contacts
Fault - Dotted where projected
Sample location
Lake and River
Town and/or Mine - Site
T - Toquepala ; Q - Quellaveco ; C - Cuajone ; M - Moquegua ;
I - Ilo

and northern Chile has been characterized by episodic orogenic activity, with an interplay of uplift, erosion, and magmatism (e.g., between 26° and 29° S: Clark et al., 1976; 9—12° S: Pitcher, 1978). In the Chilean Cordillera Principal (or, in Perú, Cordillera Occidental), the majority of the post-Paleozoic magmatic episodes conform to a spatial and temporal pattern involving a migration of the successive magmatic loci away from the present continental margin (Gilleti and Day, 1968; Farrar et al., 1970).

In the vicinity of the "Arica Elbow," at ca. 18° S, geological mapping by the Carta Nacional del Perú (now INGEMMET) and the Instituto de Investigaciones Geológicas, Chile, supported by recent reconnaissance geochronological studies (e.g., McBride, 1977; Bellón and Lefèvre, 1976; James et al., 1976), demonstrates that a broadly comparable succession, and migration, of distinct episodes of orogenic activity have occurred in the Cordillera Occidental. At higher altitudes, the geology in this transect is dominated by Neogene/Quaternary, continental, volcanic and sedimentary units. Pichler and Zeil (1972), following Brüggen (1950), here defined two main clans of late Cenozoic volcanic rocks in the Cordillera Occidental. On the one hand, large volumes of ignimbrite, primarily rhyolitic to rhyodacitic in composition, were erupted; several individual sheets cover in excess of 2000 km^2 (Francis and Baker, 1978), and have volumes of up to 100 km^3 (Guest, 1969). The second group of volcanic rocks, volumetrically preponderant, ranges in composition from andesite to rhyolite and was erupted from stratovolcanoes, many surpassing 5000 m in elevation, and from numerous cones of lesser size. These "andesitic" centres usually constitute discrete physiographic features easily distinguished from the extensive, but essentially subplanar, ignimbrite sheets. In some areas, a simple late Cenozoic volcanic sequence is evident, in which the andesitic cones developed upon earlier-formed ignimbritic plateaus. However, Mortimer et al. (1974) and Baker and Francis (1978), among others, have shown that this relationship is by no means ubiquitous in the Central Andes.

In southernmost Perú (16° 30′—18° 00′S: Fig.1), a sequence of older ignimbrites, intercalated with continental clastic sediments, is overlain by younger andesitic rocks. Twenty-four K-Ar radiometric age determinations (Appendix 1: K-Ar analytical techniques) for volcanic rocks from this transect, selected to include all recognized late Cenozoic formations, define a chronology of magmatic activity and permit tentative regional stratigraphic correlations. It is demonstrated herein that ignimbritic eruptions occurred throughout Miocene time, with peaks of activity in the Early Miocene and earliest Late Miocene. Widespread andesitic eruptions began during the Pliocene and continued into the Holocene, although no historic lava eruptions have been recorded.

Fig. 1. Generalized geologic map of the Cordillera Occidental of southernmost Perú, showing sample locations for the K-Ar age determinations. Modified after Servício de Geología y Minería, Lima, 1970. Inset map shows regional setting of study-area.

TABLE 1

Sample locations, radiometric data and lithologies of Late Cenozoic volcanic rocks, South Perú

Sample No.	Location (lat.; long.)	Material analysed[1]	K (%)	$^{40}Ar_{rad}$ $(cm^3/g\ STP) \times 10^{-6}$	%Atmos. contam.	Age and error (2σ) (Ma)[2]
Upper Moquegua Formation						
SPT 212	17°06′20″; 70°51′34″	B	7.245	7.171	34.3	25.3 ± 0.8
SP 143	17°23′32″; 70°47′40″	B	7.133	6.487	29.9	23.3 ± 0.8
SPT 202	17°14′24″; 70°54′39″	B	7.174	6.361	60.5	22.7 ± 0.8
Huaylillas Formation						
SPT 127f	17°05′15″; 70°44′35″	B	7.439	6.641	27.9	22.8 ± 0.7
SPT 122	17°17′29″; 70°13′55″	B	6.267	5.283	54.5	21.6 ± 0.7
SPT 305	17°08′39″; 70°38′53″	B	7.272	5.226	29.6	18.4 ± 0.6
SPT 124	17°24′47″; 70°35′42″	B	6.755	4.832	28.3	18.3 ± 0.6
SP 85	17°02′22″; 70°41′14″	B	7.271	4.832	28.3	17.6 ± 0.6
Chuntacala Formation						
SPT 330	17°36′38″; 71°12′25″	B	6.962	3.855	24.7	14.2 ± 0.4
SPT 65	17°06′52″; 70°37′37″	B	5.756	2.944	72.4	13.1 ± 0.7
SP 73	17°01′48″; 70°41′47″	B	6.495	3.293	44.2	13.1 ± 0.4
SPT 333	17°04′02″; 70°37′31″	B	5.486	2.668	70.4	12.5 ± 0.6
SPT 211	17°17′01″; 70°44′35″	B	5.570	2.422	88.9	11.2 ± 1.3
SPT 323	17°59′38″; 70°59′38″	B	7.334	2.972	32.2	10.4 ± 0.9
SPT 324	17°36′03″; 70°53′17″	B	7.401	2.952	38.0	10.2 ± 0.6
SPT 316	17°18′36″; 71°07′37″	B	7.199	2.847	38.7	10.2 ± 0.3
SP 41	17°05′25″; 71°37′01″	B	5.885	2.170	72.1	9.5 ± 0.5
SPT 308	17°24′42″; 71°02′47″	B	5.446	1.896	82.9	8.9 ± 0.6
Sencca Formation						
SP 87	16°59′08″; 70°35′20″	B	6.796	1.708	66.3	6.5 ± 0.3
Capillune Formation						
SP 90	16°57′24″; 70°33′10″	P	0.336	0.0916	74.2	7.0 ± 0.4
SP 90	16°57′24″; 70°33′10″	WR	1.666	0.2137	50.2	3.3 ± 0.1
Barroso Group						
SPT 304	16°58′09″; 70°31′49″	P	0.566	0.1162	59.2	5.3 ± 0.3
SPT 327	17°51′59″; 70°12′28″	B	7.068	0.4488	88.1	1.6 ± 0.2
SPT 108	17°01′17″; 70°23′01″	B	6.962	0.1966	94.5	0.7 ± 0.2

[1] B = biotite; WR = whole-rock; P = plagioclase.
[2] Error quoted at 95% confidence level (2σ). Decay constants used for age determinations: $\lambda_\epsilon = 0.581 \times 10^{-10}/yr$; $\lambda_\beta = 4.962 \times 10^{-10}/yr$; $^{40}K/K = 0.01167$ atom. % (Beckinsale and Gale, 1969; Steiger and Jäger, 1977).

Lithologies:
SPT 212 non-welded, vitroclastic, pumiceous, biotite-porphyritic ash flow.
SP 143 non-welded, vitroclastic, biotite/hornblende-porphyritic ash flow.

(continued p. 161)

PRE-NEOGENE MAGMATISM

The Mesozoic-Cenozoic magmatic arcs of the Central Andes are totally ensialic. The large volumes of volcanic and plutonic rocks emplaced during successive magmatic episodes overlie and intrude a metamorphic and plutonic basement complex which attains 2 Ga in age in southern Perú (Shackleton et al., 1979), but has not been shown to be older than the latest Precambrian in northern Chile (McBride et al., 1976).

In the transect studied, exposed Proterozoic rocks are restricted to the Cordillera de la Costa, where they occur as isolated outcrops which are overlain locally by a pre-Permian conglomerate (Narváez, 1964), and form the basement terrane for a composite Jurassic/mid-Cretaceous magmatic complex (Narváez, 1964; McBride, 1977). Subaerial conditions prevailed during the latest Cretaceous/Early Eocene volcanic activity and the emplacement of the broadly coeval ganodioritic batholith (Bellido, 1969; Stewart et al., 1974; McBride, 1977). The above-mentioned Precambrian to Early Eocene units underlie the late Cenozoic volcanic rocks which are the subject of the present discussion.

MIDDLE-TO-LATE CENOZOIC STRATIGRAPHY: DISCUSSION OF K-Ar AGES

In the study area (Fig.1), few radiometric ages have been previously reported. The majority of earlier studies concentrate on the Mesozoic and

SPT 127f	semi-welded, vitroclastic, pumiceous, biotite-porphyritic ash flow.
SPT 202	non-welded, vitroclastic, devitrified, biotite-porphyritic ash flow.
SPT 122	semi-welded, vitroclastic, biotite-hornblende-porphyritic ash flow.
SPT 305	semi-welded, vitroclastic, pumiceous, devitrified, biotite-porphyritic ash flow.
SPT 124	semi-welded, vitroclastic, devitrified, silicified biotite/hornblende-porphyritic ash flow.
SP 85	partially-welded, vitroclastic, devitrified, biotite-porphyritic ash flow.
SPT 330	unwelded, unconsolidated, biotite-porphyritic ash flow.
SPT 65	semi-welded, vitroclastic, devitrified, biotite-porphyritic ash flow.
SP 73	partially-welded, vitroclastic, pumiceous, devitrified, biotite- porphyritic ash flow.
SPT 333	semi-welded, vitroclastic, devitrified, biotite-porphyritic ash flow.
SPT 211	semi-welded, vitroclastic, pumiceous, biotite-porphyritic ash flow.
SPT 323	unwelded, unconsolidated, biotite-porphyritic ash flow.
SPT 324	unwelded, unconsolidated, biotite-porphyritic ash flow.
SPT 316	unwelded, biotite-porphyritic ash flow.
SP 41	semi-welded, vitroclastic, devitrified, biotite/hornblende-porphyritic ash flow.
SPT 308	unwelded, unconsolidated, biotite-porphyritic ash flow.
SP 87	semi-welded, vitroclastic, devitrified, biotite/hornblende-porphyritic ash flow.
SP 90	glomeroporphyritic, pilotaxitic andesite, with plagioclase, hypersthene, and hornblende phenocrysts.
SPT 304	porphyritic, pilotaxitic andesite, with plagioclase, hypersthene, hornblende, and biotite phenocrysts.
SPT 327	glomeroporphyritic, hyaloporphyritic dacite, with plagioclase, biotite, hornblende, and hypersthene phenocrysts.
SP 108	porphyritic, pilotaxitic dacite, with plagioclase, biotite, hornblende, and hypersthene phenocrysts.

Paleogene terranes. The only radiometric data for the late Cenozoic rocks are the scattered dates of Bellón and Lefèvre (1976), a single Rb-Sr whole-rock isochron age for a Miocene ignimbrite (James et al., 1976; see below), and one K-Ar age by Laharie (1973), again for a Miocene ignimbrite. Bellón and Lefèvre (1976) present K-Ar ages for volcanic rocks of the Tacaza, Huilacollo, and Huaylillas Formations (see below) in the general region of study. However, the dates are incompletely documented and the sample locations are only approximately delimited, hindering detailed comparison with our data.

Our 24 K-Ar ages (Table 1), together with the previously reported ages, provide a chronology for the late Cenozoic volcanic and sedimentary rocks in southernmost Perú, and constitute a basis for stratigraphic correlation with other areas in the Central Andes. They also form a framework for clarification of the geomorphological evolution of this region of the Cordillera Occidental, to be discussed in a subsequent paper (Tosdal, Clark, and Farrar, in preparation).

MOQUEGUA FORMATION

In the southernmost Peruvian Andes, clastic debris was shed southwestward in the mid-Tertiary from the subaerial Late Cretaceous/Early Eocene arc terrane into a longitudinal trough. These unfossiliferous, continental, sandstones, siltstones, and conglomerates are grouped as the Moquegua Formation (Bellido and Landa, 1965; Bellido and Guevara, 1963), comprising two members separated by a slight angular unconformity. The thickness of the Moquegua Formation is extremely variable, and is not known in detail, but Bellido and Guevara (1963) reported a thickness in excess of 500 m in the northwestern part of the transect.

The lower member is composed of evenly bedded, fine- to medium-grained, predominantly tuffaceous siltstones with an irregular basal contact. The upper member comprises several hundred meters of coarse sandstone and pebble to cobble conglomerate that locally becomes coarser towards the exposed stratigraphic top of the member. Near the top of the upper member, several ignimbrites up to 10 m thick are conformably interbedded with the clastic rocks (Fig.2). Samples of these ignimbrites (SPT 212, 143, and 202; Fig.1) from three widely separated localities yield distinct K-Ar ages of between 25.3 and 22.8 Ma (Table 1). The youngest of these ignimbrites (SPT 202) exhibits remarkable similarities in lithology, areal location, and isotopic age to an ignimbrite (SPT 127f) of the lower Huaylillas Formation, and is considered to be correlative. These Late Oligocene/Early Miocene ages support the previously inferred mid-Tertiary age of the Moquegua Formation (Bellido, 1969), but also demonstrate that the bulk of the formation was deposited during Oligocene, rather than Miocene, times, as had been suggested.

In this context it is of interest that Bellón and Lefèvre (1976) provide a

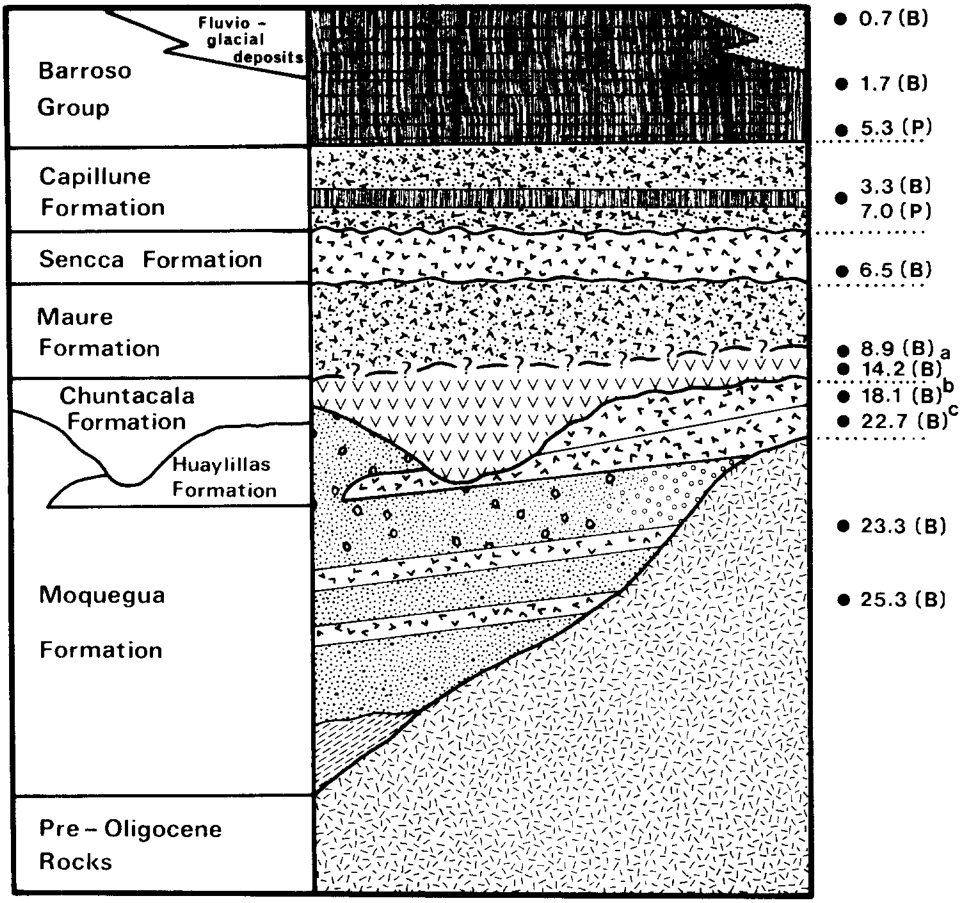

Fig.2. Late Tertiary stratigraphy of the southernmost Peruvian Andes. K-Ar ages of the volcanic rocks are given on the right (in Ma). Abbreviations after the ages indicate the materials analysed: B = biotite, P = plagioclase, and WR = whole-rock. Superscript "a" denotes the time range of the Chuntacala Formation only; "b" denotes the average of three separate age determinations; and "c" indicates that the quoted age represents only a single K-Ar date, and excludes an ignimbrite age in a similar stratigraphic position (i.e., SPT 122).

mean age of 22.00 ± 1.2 Ma for a volcanic rock of the predominantly andesitic Huilacollo Formation (Wilson and García, 1962), from a locality in the Palca quadrangle close to the Chilean border. Wilson (1963) demonstrates that, in that type area, the Huilacollo Formation is *older* than the Moquegua Formation, and although the reported isotopic ages (Bellón and Lefèvre, 1976) may be considered suspect on stratigraphic grounds, they support our conclusion that the resumption of volcanism in this region took place in the latest Oligocene and Early Miocene. More detailed investigations are required to resolve this apparent stratigraphic problem.

HUAYLILLAS FORMATION

The western slopes of the Cordillera Occidental in this region are dominated by essentially rectilinear ridge crests and inclined surfaces underlain by the ignimbrite sheets of the Huaylillas Formation. The formation, defined by Wilson and García (1962), conformably overlies the Moquegua Formation or unconformably covers Late Cretaceous/Paleogene strata (Bellido and Landa, 1965; Jaén, 1965; Wilson, 1963). The unconformity beneath the Huaylillas Formation is of regional extent, and has been tentatively correlated (e.g., Jaén, 1965) with the extensive Puna Surface of central Perú (McLaughlin, 1924).

Rhyodacitic ignimbrite sheets are the dominant and characteristic component of the Huaylillas Formation; these are intercalated with minor, local, reworked tuffs and conglomerate beds (Fig.2). Several members have been defined in contiguous areas to the southeast (Wilson, 1963; Wilson and García, 1962; Jaén, 1965), where an overall thickness of up to 600 m is exposed.

In the vicinity of the Cuajone copper mine (Fig.1), two ignimbrite flows are in erosional contact with one another, and are locally separated by conglomerate lenses up to 10 m in thickness (Manrique and Plazolles, 1974). The lower ignimbrite yields an age of 22.7 Ma (SPT 127f). This Early Miocene age is sensibly identical to that of one of the ignimbrites (SPT 202; see above) intercalated in the uppermost Moquegua Formation. The latter flow lies down-paleoslope from the former, and, although they cannot be mapped as a continuous unit, the two flows are assumed to represent the same eruptive event. The erosional upper contact of the lower ignimbrite (SPT 127f) near Cuajone, and the conformable contacts of the youngest flow in the Moquegua Formation, imply a temporal overlap of the two formations in this area. Elsewhere, southeast of Toquepala, another ignimbrite (SPT 122), which also unconformably overlies the Late Cretaceous/Paleogene arc terrane, yields an Early Miocene date of 21.6 Ma. This further defines the Early Miocene age (21—23 Ma) of the lower member of the Huaylillas Formation, and thereby indicates an earliest Miocene minimum age for the sub-Huaylillas erosion surface.

The upper ignimbrite near Cuajone yields an age of 17.6 Ma (Sp 85; Table 1). Elsewhere in the area, ignimbrites of the Huaylillas Formation have ages of 18.3 Ma (SPT 124) and 18.4 Ma (SPT 305). In the vicinity of the Río Locumba, ignimbrite SPT 124 conformably overlies the cobble conglomerate of the upper Moquegua Formation, and thus defines an Early Miocene minimum age for the formation. The ages of 17.6—18.4 Ma found for the younger ignimbrites of the Huaylillas Formation differ considerably from the 15.8 Ma age reported by Laharie (1973) for the upper ignimbrite near Cuajone, but are in excellent agreement with those (18.3 and 18.4 Ma) reported by Bellón and Lefèvre (1976) for the Huaylillas Formation.

It is of interest to note that ages reported herein for ash-flow tuffs of the

Huaylillas Formation coincide approximately with the whole-rock dates (21.70—15.85 Ma) determined by Bellón and Lefèvre (1976) for volcanic rocks of the Tacaza Formation, which covers considerable areas of the region between Arequipa and Puno. The Tacaza Formation differs from the Huaylillas in comprising predominantly andesitic to dacitic lavas and pyroclastics.

The source areas of the Huaylillas Formation ash-flow tuffs are uncertain. Examination of ERTS imagery (Fig.3) of the transect reveals a large, circular, topographic feature immediately southeast of the immediate study area. This is 20—25 km in diameter and is located astride a major pre-Moquegua Formation fault (Figs.1 and 3). Within the circular structure, the northwest-

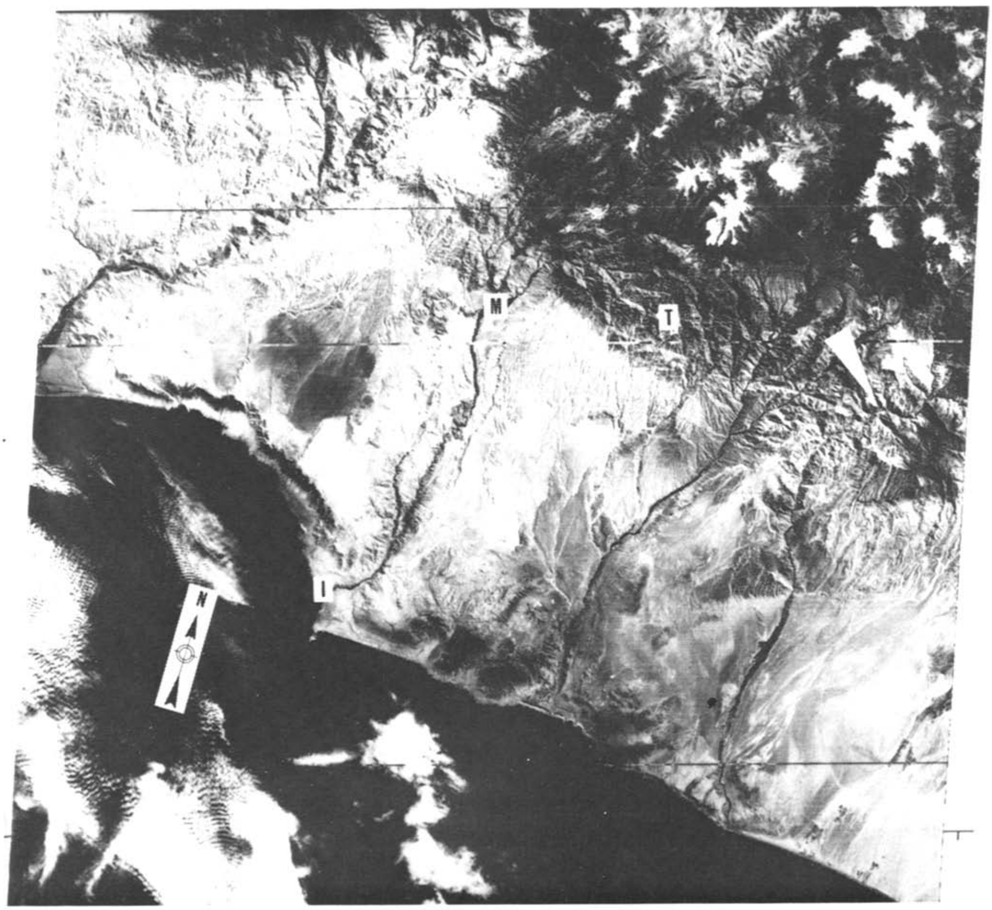

Fig.3. ERTS imagery of the southernmost Peruvian Andes. The circular structure inferred to have been one source for ignimbrites of the Huaylillas Formation is located near the center-right margin (white arrow points toward the perimeter). Width (left-right) of field of view is ca. 180 km. T = Toquepala; M = Moquegua; I = Ilo.

southeast trace of the fault disappears, but a north-northeast-trending ridge is visible. A radial drainage pattern is developed on the prominent southern ramparts of the circular feature, which had previously been interpreted as a fault scarp (Wilson and García, 1962). This structure is now tentatively considered to be a caldera formed during the eruption of the younger ignimbrites of the Huaylillas Formation.

CHUNTACALA FORMATION

Several isolated, areally restricted, ignimbrites are found in settings which are, in terms of their stratigraphic and paleo-geomorphologic positions, distinct from those of the regionally extensive ignimbrites of the Huaylillas Formation. These ignimbrites usually infill paleo-valleys, and are intercalated with sediments which accumulated in basins eroded in the Huaylillas Formation and in older rocks. Previously considered to be part of the Huaylillas Formation (Bellido and Landa, 1965), these ignimbrites near the Chuntacala valley, now the site of the Cuajone mine, were assigned by Manrique and Plazolles (1974) to a distinct, younger formation. Our K-Ar age data and more regional studies support the distinction of the formation, and define its distribution.

An ignimbrite exposed adjacent to the Cuajone mine (SP 73), and those in nearby areas (SP 41, SP 65, and SP 73), all yield mid-Miocene ages, ranging from 13.1 to 9.5 Ma (Table 1). In good agreement with the age (13.1 Ma) of SP 73, James et al. (1976) report a similar Rb-Sr whole-rock isochron age of 12.5 Ma for the ignimbrites of the Cuajone mine area. The latter date was originally considered to represent the age of the Huaylillas Formation, but the sample location (D.E. James, personal communication, 1978) is within the Chuntacala Formation. Thus, an age of ca. 13 Ma may be accepted for the base of the Chuntacala Formation at the type locality.

Several areally restricted ignimbrites elsewhere in the region yield similar mid-Miocene ages, and are therefore assigned to the Chuntacala Formation. These range in age from 14.2 (SPT 330) to 8.9 Ma (SPT 308), and either lie within paleo-drainage channels incised into the Moquegua or Huaylillas Formations, or are intercalated in the coarse, unconsolidated, alluvial plain gravels which accumulated at the base of, or form veneers on, the surface of several mid-Miocene pediments (Tosdal, 1978). These ignimbrites have hitherto been unrecognized and unmapped, while the associated pediment gravels were interpreted as Quaternary alluvium (e.g., Bellido and Landa, 1965). The close association of these alluvial gravels with ignimbrites that yield K-Ar ages similar to those of the Chuntacala Formation in its type locality implies that the definition of the formation should be extended to include areally extensive alluvial facies of extremely variable thickness (Figs.1 and 2).

MAURE, SENCCA, AND CAPILLUNE FORMATIONS

A sequence of late Cenozoic continental clastic sedimentary and volcanic rocks of variable lithology covers extensive areas of the *altiplano* of southern Perú and northern Bolivia. In southernmost Perú, the sequence has been divided into three formations separated by unconformable to disconformable contacts (e.g., Mendívil, 1965). The clastic Maure Formation unconformably overlies the Huaylillas Formation and older rocks and, in turn, is overlain unconformably by ignimbrites of the Sencca Formation. A slight disconformity separates the Sencca Formation from the third and youngest formation, the clastic Capillune Formation (Mendívil, 1965).

The Maure Formation consists of up to 500 m of semiconsolidated sandstones, pebbly conglomerates, and agglomerates, commonly with a tuffaceous matrix (F. Stevenson, personal communication, 1977; Mendívil, 1965). These rocks are considered by Laharie (1973) to be lacustrine in origin. The relative ages of the Maure and Chuntacala Formations are unknown, but the geological relationships northeast of the Cuajone mine suggest that the Maure Formation here may unconformably overlie the ash flows of the Chuntacala Formation (Fig.2). However, it is possible that the Maure Formation is contemporaneous with parts of the Chuntacala Formation. No rocks suitable for age determinations were found in these unfossiliferous sediments.

The Sencca Formation is composed of latest Miocene (6.5 Ma; SP 87) rhyolitic ignimbrites, which range in thickness from 50 to 200 m. These ignimbrites are of regional extent, and provide stratigraphic marker horizons for the correlation of strata in southern Perú and northern Bolivia (Mendívil, 1965). Mid-to-late Pliocene ages have generally been assigned to this formation in Bolivia (Ahlfeld, 1972).

The Capillune Formation in this area is composed of up to 950 m of finely bedded, reworked, tuffs, and tuffaceous siltstones to pebble conglomerates, with several intercalated andesite flows. These rocks are commonly in slightly discordant contact with the underlying Sencca Formation. The sediments of the Capillune Formation are lithologically very similar to those of the Maure Formation, and have likewise been interpreted by Laharie (1973) as lacustrine.

K-Ar analysis of the oldest andesite in the Capillune Formation yielded ambiguous results. Ages of 7.0 Ma (plagioclase) and 3.3 Ma (whole-rock) were obtained from sample SP 90 (Fig.1; Table 1). Both ages are considered to be unreliable. Thus, the apparent age of the feldspar is greater than that for biotite from the stratigraphically older Sencca ignimbrite, while the whole-rock date is significantly younger than that found for plagioclase in the basal unit of the overlying Barroso Group (see below). The stratigraphic relationships suggest, however, that these andesitic flows are latest Miocene or earliest Pliocene in age.

BARROSO GROUP

The Barroso Group comprises the voluminous young andesitic volcanic rocks which dominate the crest of the Cordillera Occidental in this region, forming stratovolcanoes whose eruption clearly straddled in time the Pleistocene alpine glaciation. Mendívil (1965) subdivided the group into three formations, and assigned the most recent flows and cones to a fourth formation. We prefer to include all post-Capillune Formation volcanics in the Barroso Group.

Plagioclase from an andesite (SPT 304, Fig.1), from one of the lowest-exposed members of the Barroso Group yields an Early Pliocene age (5.3 Ma). The dated flow makes up part of the exposed base of an eroded stratovolcano with an elevation of 5100 m, and, if the age is reliable, provides a datum for the initiation of this episode of intermediate volcanism. Bellón and Lefèvre (1976) report similar Lower Pliocene ages for whole rocks (4.45 and 4.10 Ma) for early flows of young stratovolcanoes northeast of Arequipa, while Weibel et al. (1978) demonstrate that the Coropuna volcano in southern Perú has an eruptive history extending back into the Late Miocene (⩾ 5 Ma).

The high plateau of southernmost Perú is studded by numerous extinct, glacially sculpted, volcanic cones which appear to be smaller than both the currently active stratovolcanoes and the Early Pliocene volcanoes. Lavas from these smaller cones coalesced to form intermontane basins in which glacially derived debris accumulated. Biotite from a dacite (SPT 327) exposed at the base of one of these cones gave an Early Pleistocene age of 1.6 Ma.

Andesitic volcanism in southern Perú is now restricted to a narrow chain of isolated, unglaciated, stratovolcanoes rising well about 5000 m. A dacite from the northwest flank of the northern, unglaciated, summit of Volcán Tutupaca (Fig.1) yields a mid-Pleistocene biotite age of 0.7 Ma (SP 108).

REGIONAL STRATIGRAPHIC CORRELATIONS

A comparison of the stratigraphy of southernmost Perú and western Bolivia shows that, in Bolivia, the late Cenozoic strata broadly correlative with the above-mentioned formations consist of hundreds of meters of continental clastic sedimentary and volcanic rocks, named the Mauri Formation (Ahlfeld, 1972). A major unconformity separates the five lower members of this formation from the sixth and uppermost member. Based upon published reconnaissance K-Ar ages (Evernden et al., 1977; Kussmaul et al., 1975) this unconformity is regionally time-transgressive. The lower, predominantly clastic, units were deposited during Oligocene through Early Miocene time (Evernden et al., 1977), contemporaneous with the Moquegua and Huaylillas Formations. The sixth member, which is mainly volcanic, was deposited in mid-Miocene to Pliocene times (Evernden et al., 1977).

Mendívil (1965) correlates the unconformity within the Bolivian Mauri Formation with the contact between the Sencca Formation and the underlying Maure Formation in southern Perú. In the latter region, the Chuntacala, Maure, Sencca, and Capillune Formations lie unconformably above the Huaylillas Formation, which is an unequivocable age correlative of the lower members of the Bolivian Mauri Formation. Moreover, the Sencca Formation is clearly laterally equivalent to the tuffs of the sixth member of the Bolivian Mauri Formation (Mendívil, 1965), while the Chuntacala Formation and, probably, the (Peruvian) Maure Formation are also age-correlative with parts of the sixth member of the Bolivian Mauri Formation. It is, therefore, suggested that the simple correlation proposed by Mendívil should be modified in favor of a more complex relationship involving several unconformities, reflecting episodic uplift in southernmost Perú, that merge toward the east into the major unconformity within the Bolivian Mauri Formation, or that this major unconformity is polyphase and not a simple stratigraphic discontinuity.

The observed temporal relationships between the eruptions of rhyodacitic-rhyolitic ignimbrites and the younger stratovolcanic andesite-dacite association defined in the present study closely parallel those originally emphasized by Brüggen (1950), who considered the ignimbrites of northern Chile to constitute a basal platform for the construction of the Neogene/Quaternary stratovolcanoes. However, more recent geological and radiometric studies in northern Chile have revealed a more complicated relationship between these two dominant eruptive modes. Thus, in the Copiapó region (ca. 27° S), major andesitic-dacitic stratovolcanoes of Late Oligocene/Early Miocene age constitute the Cordillera de Domeyko (Quirt, 1972; Mortimer, 1973). Here, the eruption of andesites apparently persisted into the mid-Miocene, overlapping in time with the emplacement of ignimbritic flows (Clark et al., 1967). Similarly, in the Early Pliocene, ash-flow eruptions occurred during the early growth of the enormous andesitic stratovolcanoes making up the Ojos del Salado Massif.

Mortimer et al. (1974) and Baker (1977) have demonstrated a comparable overlap of andesitic and felsic ignimbrite eruption in northernmost Chile (19° 20′—ca. 21° 30′S) in the Upper Miocene, confirming the earlier observations of Guest (1964). Such an overlap of andesitic and felsic ignimbrite eruption is also possible within and adjacent to the present study transect, as suggested by our work and that of Bellón and Lefèvre (1976). Further, Weibel et al. (1978) have shown that the development of the Coropuna stratovolcano in southern Perú was interrupted briefly by the extrusion of rhyodacitic ignimbrites ca. 2 Ma ago.

Despite these variations in eruptive sequence in the Cordillera Occidental of the Central Andes, the observed chronology of ignimbrite and stratovolcano development in southernmost Perú displays several features of regional application. Although ash-flows had erupted in northern Chile (ca. 27° S.) in the Late Cretaceous, Paleocene, and Eocene (Quirt, 1972: Mortimer, 1973; Zentilli, 1974), the initiation of major extrusion of felsic ignimbrites in the study area in the latest Oligocene (ca. 25 Ma) is in striking coincidence with comparable events over wide areas of the cordillera, from central Perú (Noble et al., 1974) to northern Chile (Baker, 1977). Secondly, it is evident that the episode of andesitic-dacitic volcanism that has dominated the western Andes in Plio-Quaternary times similarly had its beginnings in the Late Miocene/Early Pliocene, at least between 15° and 27°S.

In broader context, the initiation of voluminous ignimbritic eruption at ca. 25 Ma in the Cordillera Occidental coincided closely with the reactivation of the long-dormant felsic magmatic arc of the Cordillera Oriental of northern and central Bolivia (Evernden et al., 1977; McBride et al., in 1981) and southern Perú (unpublished data). Moreover, this widespread mid-Tertiary event very shortly followed the radical reorganization of spreading axes in the contiguous eastern Pacific basin, as documented by Herron (1972) and Handschumacher (1976).

SUMMARY AND CONCLUSIONS

K-Ar radiometric ages of Late Cenozoic volcanic rocks from a transect of the Cordillera Occidental in southernmost Perú provide a chronological framework for the non-fossiliferous continental strata of that region. Several periods of ignimbrite eruption occurred, largely during the Miocene, following an extended mid-Tertiary period of volcanic quiescence, and heralded by several ash-flow eruptions in the Late Oligocene Upper Member of the Moquegua Formation. These Miocene ignimbrites are assigned to three distinct formations: the Early Miocene Huaylillas; the mid-Miocene Chuntacala; and the Late Miocene Sencca. These were emplaced in different geological-geomorphological environments as the southern Peruvian Andes were episodically uplifted (Tosdal, Clark, and Farrar, in preparation). The andesitic volcanism which currently dominates extended segments of the Cordillera Occidental was first manifested at, or near, the Mio-Pliocene boundary at these latitudes, and probably attained its greatest development during the Late Pliocene/Early Pleistocene. At present, andesite output is restricted to a narrow chain of large stratovolcanoes.

The volcanic stratigraphy in the study area may be matched in other transects of the Central Andean orogen, while similar relationships between ignimbrite and andesite extrusion and regional erosion are evident in the Sierra Madre Occidental of Mexico (McDowell and Keizer, 1977) and in the Thirty-Nine Mile Volcanic Field of Colorado (Stevens, 1975). In particular, it is evident that the *major* pulses of ignimbrite eruption in many areas do not coincide with eposides of stratovolcanic development. Because plutonic activity in the western Cordillera of the Central Andes has been essentially coeval with the development of the andesitic-dacitic stratovolcanoes (Clark et al., 1976; Pitcher, 1978), it is suggested that the enormous ignimbrite successions characteristic of the region may have only a tenuous relationship with batholith emplacement (cf., Hamilton, 1969). Rather, these ignimbrite extrusions appear to have occurred predominantly during intervals of plutonic quiescence, coinciding with waning stages of regional erosional bevelling of the Pacific slope of the cordillera, and with episodes of uplift.

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APPENDIX 1: K-Ar ANALYTICAL TECHNIQUES

The K-Ar isotopic ages were determined in the Geochronology Laboratory at Queen's University. Argon extractions were made in a high-vacuum line by means of fusion in a niobium crucible by induction heating. Samples of biotite, plagioclase, or whole-rock fractions were baked for 16—18 hours at temperatures averaging 160°C. Argon isotope ratios were determined on an A.E.I. MS-10 mass spectrometer, operated in the static mode, using standard isotope dilution techniques. Potassium concentrations were determined in duplicate or triplicate analyses on separate sample aliquots with an I.L. 143 flame photometer, employing a lithium internal standard and a sodium buffer.

Sample locations, petrographic descriptions, and radiometric analytical data are given in Table 1, where quoted errors represent the analytical precision at the 95% confidence level. The time scale employed is that of van Eysinga (1975).

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