ANDEAN ANDESITES AND CRUSTAL GROWTH

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RESUMEN

Durante los últimos 200 m.a., el cinturón orogénico ensiálico andino se ha caracterizado por su magmatismo calco-alcalino. La actividad inicial (Mesozoico) fue predominantemente basáltica con afinidades toleíticas, asociada con sedimentos submarinos. Por el contrario, el volcanismo cenozoico poseía un carácter intermedio, calco-alcalino. La restricción del volcanismo reciente a partes de los Andes que (1) están apoyadas sobre gruesas cuñas de manto astenosférico, (2) zonas de espesamiento de la corteza en ausencia de un acortamiento significativo, y (3) las relaciones isotópicas Sr y Nd, indican que los magmas calco-alcalinos derivaron directa o indirectamente de este manto astenosférico. No existe ninguna evidencia geoquímica o geofísica segura de que la corteza continental o el sedimento hayan sido sometido a subducción por debajo de los Andes, o que tales materiales hayan contribuido, en alguna forma, como fuentes del manto para el magmatismo andino. Las composiciones químicas de las rocas volcánicas calco-alcalinas, de las zonas volcánicas activas, reflejan una cristalización fraccionada, mientras que las relaciones isotópicas O-Sr muestran una interacción cortical del magma derivado del manto con el del basamento siálico de los Andes. La extensión variable de la cristalización fraccionada y asimilación, fusión parcial y mezcla del contaminante cortical, aparentemente, están controlados por el variable espesor y edad de la corteza en las diferentes provincias volcánicas. Sin embargo, debido a que el magmatismo calco-alcalino, como un proceso importante del crecimiento de la corteza en el post-Mesozoico de los Andes, requirió del aporte del manto infrayacente ésto, a su vez, necesitó de una circulación dentro de la cuña astenosférica del manto. Por otra parte, pese a que los Andes han experimentado un crecimiento cortical a largo plazo, el balance entre la adición por magmatismo y la degradación por erosión no puede ser definido. Por lo tanto, el hecho que la masa continental, como un todo, esté creciendo o haya alcanzado un estado estable, es algo incierto.

ABSTRACT

Over the last 200 m.y. the ensialic Andean orogenic belt has been characterized by calc-alkaline magmatism. The early (Mesozoic) activity was dominantly of basaltic volcanism, with tholeiitic affinities, associated with submarine sediments. In contrast, the Cenozoic volcanism was of intermediate, calc-alkaline character. The restriction of Recent volcanism to those parts of the Andes that are (1) underlain by thick wedges of asthenospheric mantle, (2) zones of crustal thickening in the absence of significant shortening, and (3) the Sr and Nd isotopic relationships, indicate that the calc-alkaline magmas are derived directly or indirectly from the asthenospheric mantle. There is no unequivocal geochemical and geophysical evidence that continental crust or sediment has been subducted beneath the Andes, or that such materials have, in any way, contributed to the mantle source for Andean magmatism. The chemical compositions of the calc-alkaline volcanic rocks of the active volcanic zones reflect fractional crystallization, whereas O-Sr isotopic relationships reflect crustal interaction of mantle-derived magma with the sialic basement of the Andes. The variable extent of fractional crystallization and assimilation, partial melting, and mixing of crustal contaminant are seemingly controlled by the variable thickness and age of crust in the different volcanic provinces. However, because calc-alkaline magmatism as a major process of post-Mesozoic crustal growth in the Andes necessitated depletion of the underlying mantle, this in turn requires circulation within the asthenospheric mantle wedge. On the other hand, although the Andes have experienced long-term crustal growth, the balance between addition by magmatism and degradation by erosion cannot be decided. So whether the continental mass, as a whole, is growing or has reached a steady-state, is uncertain.

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INTRODUCTION

The basis of this contribution is that material added from the mantle to the crust above subduction zones represents local continental growth. Subduction zone volcanic and intrusive activity is the dominant form of continental magmatism and the intermediate composition of the characteristic magmatic products -andesites and tonalites- resembles the bulk composition of the Earth's crust (Taylor, 1977). Therefore, crustal growth might be largely dominated by addition of mantle-derived magmas above subduction zones. With this model in mind, we examine the processes of formation of subduction zone magmas, the role of pre-existing continental crust, and the processes of accretion of such magmas to form continental crust. The role of intrusive subduction-zone magmas is examined by Brown (1979) so here we emphasize the role of andesites in crustal growth.

GEOLOGICAL FRAMEWORK OF SOUTH AMERICA

This section reviews the geological framework of South America and the basement of the Andean orogenic belt. The Andean orogenic belt (Fig. 1a) is characterized by magmatism of Mesozoic-Recent age. Active volcanism is restricted to three zones; a northern zone in south Colombia and Ecuador (5°N-2°S), a central zone in south Peru and north Chile (16°S-28°S) and a southern zone in south Chile (33°S-52°S; Fig. 1b). The major tectonic units are the early Precambrian Brazil-Guyana Shield, the late Precambrian-early Palaeozoic massifs (including the "Pampean Ranges"), and the Andean Cordillera with its associated "Sub-Andean Ranges" (Fig. 1a). The Brazil-Guyana Shield is locally covered by extensive undeformed Mesozoic-Cenozoic sedimentary deposits, including the Amazon, Parnaiba and Parana Basins.

The basement below the Andean Cordillera (within the active volcanic zones) has several components and the inferred areas of these are shown in Fig. 1. The western parts of Colombia and Ecuador (the "Coastal Cordillera" or "Costa") are underlain by mafic rocks (Gansser, 1973; Pichler *et al.*, 1974). Gravity date indicate that these form a substantial fraction of the crust (Case *et al.*, 1973; Meissnar *et al.*, 1976). The environment of formation of these rocks is discussed in more detail below. The Recent and active volcanoes of Colombia and Ecuador are in the "Inter-Andean Depression" which lies between the mafic rocks of the Coastal Cordillera and metamorphic basement of Mesozoic or older age forming the Cordillera Oriental. Metamorphic rocks of late Precambrian age are know from south Ecuador (N.J. Snelling, personal communication) and pre-Ordovician metamorphic rocks are known in north Peru (Cobbing, 1978). In view of the evidence for a change in basement character south of 2°30'S (Henderson, 1979) the active volcanic belt of Ecuador might overlie Mesozoic metamorphic crust, while the Andean basement of south Ecuador and north Peru might be of late Precambrian or Lower Palaeozoic age (Fig. 1b).

Evidence for much older basement occurs in central Peru, south of the latitude of Lima (12°S). Between 14 and 17°S, scattered inliers of "Precambrian gneisses" are known from the Andean Cordillera (e.g. northwest of Cuzco). An almost continuous strip of coastal gneisses between these latitudes, termed the Arequipa Massif, includes metamorphic rocks dated at *ca.* 2,000 m.y. (Shackleton *et al.*, 1979). These metamorphic rocks are of similar character and age to rocks recorded from drilling below the Bolivian Altiplano (e.g. Lehmann, 1976) and to the metamorphic rocks of the Brazilian Shield (Cordani *et al.*, 1973). It is therefore considered that the Precambrian rocks continue below the Andean Cordillera to connect with the Brazil Shield (Cobbing and Pitcher, 1972, Shackleton *et al.*, 1979). This being the case, the northern part of the central active volcanic zone (in south Peru and north Chile) is built upon crust containing early Precambrian rocks. The southern limit of this crust is unknown; it may underlie most of the central volcanic zone, and extend further south than shown in Fig. 1b.

To the south of the central Andes, there is no evidence for the presence of early Precambrian basement below the Andean orogenic balt. Here most of the basement appears to be late Precambrian to early Palaeozoic in age. To the east of the Andean Cordillera such rocks form the "Pampean Ranges" and the "Patagonian" and "Deseado" Massifs which consist of a variety of metamorphic rocks for which late Precambrian and early Palaeozoic ages have been reported (Halpern and Latorre, 1979).

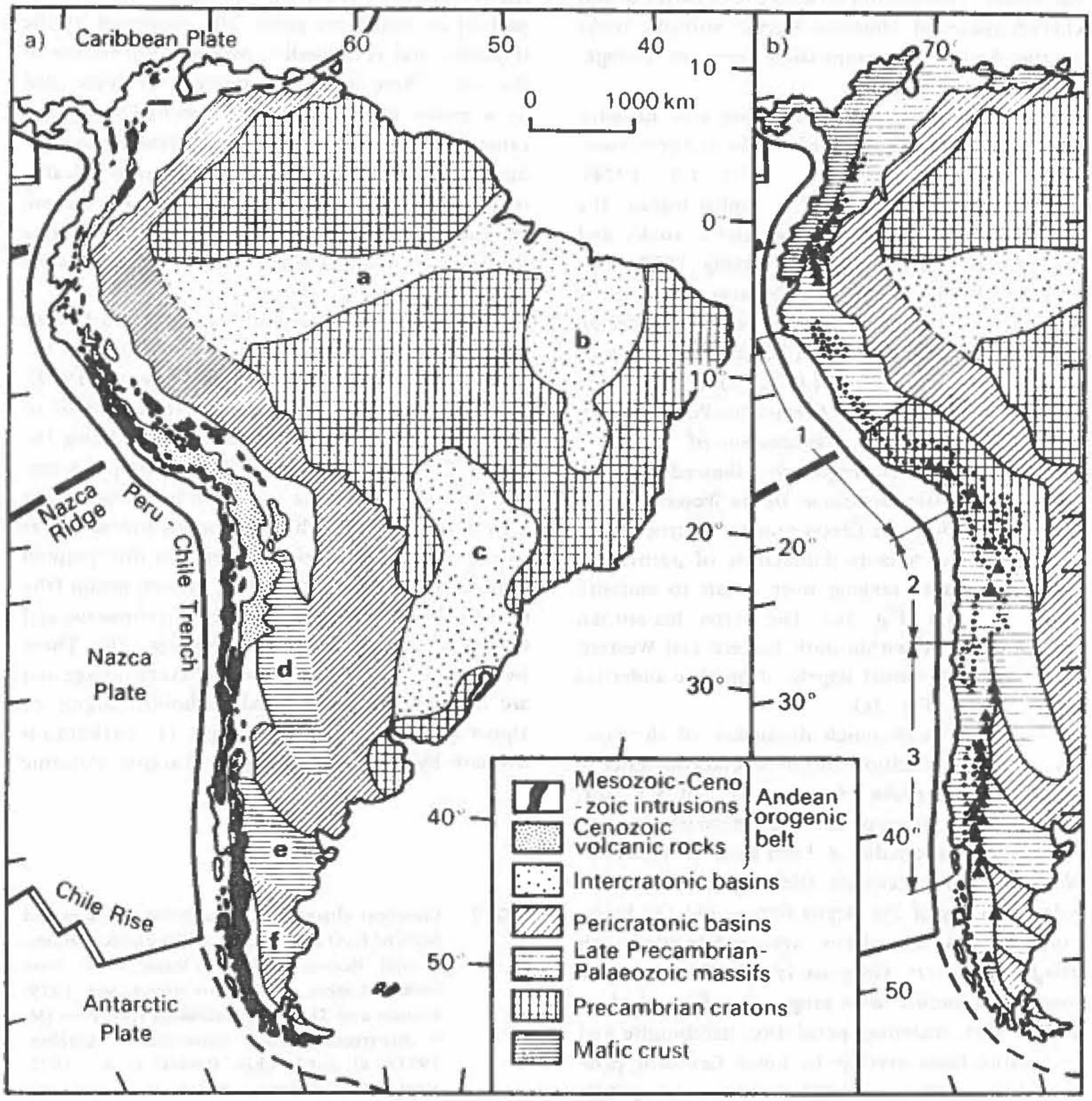


FIG. 1. a) Geological framework of South America (based on Harrington, 1978). b) Geological framework as in (a) showing the inferred age of oldest basement below the Andean orogenic belt. The solid triangles are active volcanoes and the dotted lines outline areas of Cenozoic volcanic rocks (from a)). The areas between the trench and continental margin labelled 1, 2, and 3 correspond to the physiographic provinces of Kulm *et al.* (1977, Fig. 3). Structural units are labelled as follows: a, Amazon Basin; b, Parnaiba Basin; c, Parana Basin; d, Pampean Ranges Massif; e, Deseado Massif; f, Patagonian Massif. See text for further discussion.

MESOZOIC-CENOZOIC VOLCANIC HISTORY

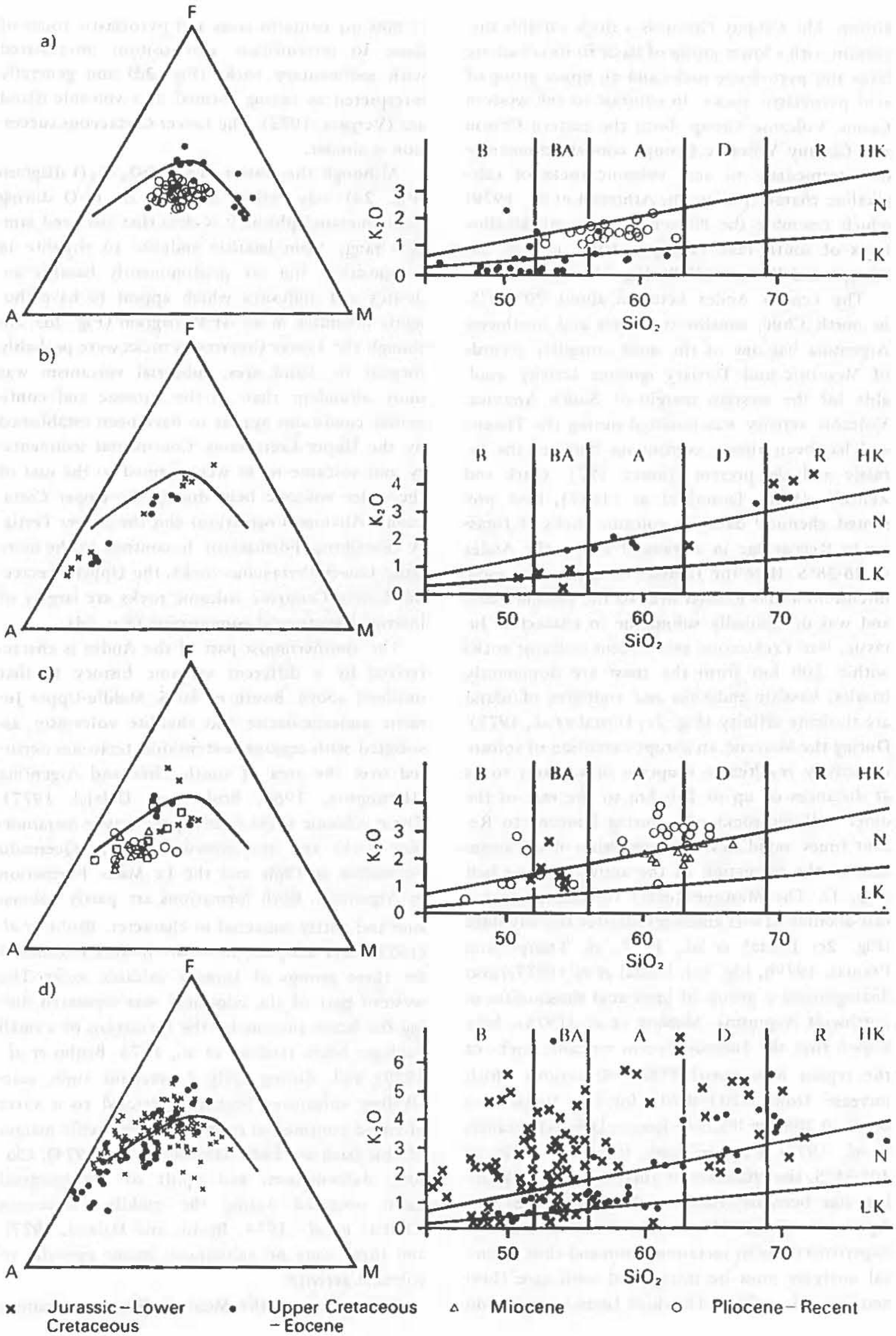
Although active Andean volcanism is restricted to the three zones described above, most parts of the Andes have experienced some post-Mesozoic volcanism. This section reviews the occurrence and characteristics of Mesozoic-Recent volcanic rocks of the Andes, and emphasizes temporal changes within individual areas.

The western parts of Colombia and Ecuador are characterized by volcanic rocks of Cretaceous-Eocene age (Gansser, 1973; Pichler *et al.*, 1974). The basic volcanic rocks of Colombia include the Dagua Group of lavas and pyroclastic rocks, and the intrusive "Diabase Group" (Irving, 1975; Pichler *et al.*, 1974). In Ecuador, Cretaceous to Eocene volcanic activity has been described by Henderson (1979). The coastal plain ("Costa") of Ecuador is underlain by mafic crust (Fig. 1b), and the main volcanic rock unit is the Cretaceous Piñón Formation which comprises a succession of at least 2 km of basaltic lavas, frequently pillowed, with basic and ultrabasic intrusions. In the Western Cordillera of Ecuador, the Cretaceous to Eocene Macuchi Formation consists dominantly of pyroclastic rocks with lavas ranging from basalt to andesite in composition (Fig. 2a). The active Ecuatorian volcanoes occur within both Eastern and Western Cordillera and consist largely of basaltic andesites and andesites (Fig. 2a).

There has been much discussion of the environment of formation of the Cretaceous-Eocene basic volcanic rocks of Colombia and Ecuador. The volcanic outcrops are characterized by positive Bouguer anomalies in both Colombia (Case *et al.*, 1973) and Ecuador (Feininger, 1977). The volcanic rocks of the Dagua Group and the Piñón Formation include pillow lavas interbedded with pelagic sediments. Gorgona Island off the Pacific coast of Colombia has a range of mafic and ultramafic rocks, including peridotite, harzburgite and komataiite lavas overlain by lower Cenozoic pelagic sediments (Gansser, 1973; Gansser *et al.*, 1979). These associations clearly suggest an ophiolitic character and an origin either as part of the Pacific ocean crust or the crust of a small marginal basin. However, the major element characteristics of the Piñón Formation of Ecuador are characteristic of island arc lavas, and trace element abundances (Ti, Zr, Cr) in samples from the Piñón Formation and Dagua Group (Colombia) reported by Pichler *et al.* (1974), also have island arc affinities. Henderson (1979) has argued that these basic volcanic rocks do not have an oceanic crustal origin, and that the Piñón Formation represents the tholeiitic part of an island arc more fully expressed by the tholeiitic and calc-alkaline Macuchi Formation to the east. These interpretations can be reconciled by a model in which the Cretaceous-Eocene volcanic rocks formed as part of an island arc system built upon oceanic crust. Pliocene-Recent volcanic rocks of Ecuador are dominantly basaltic andesites which are richer in SiO_2 and K_2O and show less iron enrichment than the Cretaceous-Eocene volcanic rocks (Fig. 2a).

Volcanic rocks, largely of Cretaceous to Eocene age, form the country rocks and cover rocks of the Peruvian Coastal Batholith (Atherton *et al.*, 1979). The country rock volcanics range from Jurassic to Cretaceous in age, the dominant group being the Upper Cretaceous Casma Volcanic Group. In central Peru these volcanic rocks can be considered as a western group of submarine basalt-andesite lavas of the island arc tholeiite association (but erupted onto continental crust) and an eastern group (the Churin Group) composed chiefly of submarine and terrestrial dacites and rhyolites (Fig. 2b). These two groups are both of Lower Cretaceous age and are intruded by the Coastal Batholith, largely of Upper Cretaceous-Palaeocene age. The batholith is overlain by the Eocene-Pliocene Calipuy Volcanic

FIG. 2. Chemical characteristics on AFM diagrams and plots of K_2O against SiO_2 of Mesozoic, Cenozoic and Recent Andean volcanic rocks from indicated areas. a) Ecuador (Henderson, 1979; Francis and Thorpe, unpublished); b) Peru (M. P. Atherton, personal comunication; Léfèbre, 1973); c) north Chile (Dostal *et al.*, 1977; Vergara, 1972, based on data in Oyarzun and Villalobos, 1969). The solid line in the AFM diagrams separate the tholeiitic and calc-alkaline fields as defined by Irvine and Baragar (1971). The solid lines in the K_2O-SiO_2 plot are from Peccerillo and Taylor (1976), with B = basalt, BA = basaltic andesite, A = andesite, D = dacite, R = rhyolite; HK, N and LK refer to high, normal - and low-potassium series, respectively. See text for further discussion.


a)
b)
c)
d)
F
A
M
B
BA
A
D
R
HK
N
LK
K_2O
SiO_2
50
60
70
× Jurassic – Lower Cretaceous
• Upper Cretaceous – Eocene
△ Miocene
○ Pliocene – Recent

Group. The Calipuy Group is a thick variable succession with a lower group of basic to intermediate lavas and pyroclastic rocks and an upper group of acid pyroclastic rocks. In contrast to the western Casma Volcanic Group, both the eastern Churin and Calipuy Volcanic Groups consist dominantly of intermediate to acid volcanic rocks of calc-alkaline character (Fig. 2b; Atherton *et al.*, 1979) which resemble the Pliocene-Recent calc-alkaline lavas of south Peru (Lefevre, 1973. cf. Fig. 2b; Thorpe and Francis 1979b, Fig. 1b).

The central Andes between about 20°-30°S, in north Chile, southwest Bolivia and northwest Argentina has one of the most complete records of Mesozoic and Tertiary igneous activity available for the western margin of South America. Volcanic activity was initiated during the Triassic and has been almost continuous between the Jurassic and the present (James, 1971; Clark and Zentilli, 1972). Dostal *et al.* (1977), have presented chemical data for volcanic rocks of Jurassic to Recent age in a transect across the Andes at 26-28°S. Here the Jurassic volcanism was most intense in a belt located near to the present coast and was occasionally submarine in character. Jurassic, late Cretaceous and Eocene volcanic rocks within 100 km from the coast are dominantly basalts, basaltic andesites and andesites of island arc tholeiite affinity (Fig. 2c; Dostal *et al.*, 1977). During the Miocene, an abrupt extension of volcanic activity resulted in eruption of volcanic rocks at distances of up to 250 km to the east of the older volcanic rocks and, during Pliocene to Recent times, rapid westward regression of volcanism lead to the formation of the active volcanic belt (Fig. 1). The Miocene-Recent volcanic rocks are calc-alkaline basalts andesites, dacites and rhyolites (Fig. 2c; Dostal *et al.*, 1977; cf. Thorpe and Francis, 1979b, Fig. 1c). Dostal *et al.* (1977), also distinguished a group of basic-acid shoshonites in northwest Argentina. McNutt *et al.* (1975), have shown that the Jurassic-Recent volcanic rocks of the region have initial $^{87}Sr/^{86}Sr$ rations which increase from 0.703-0.704 for the Jurassic to 0.706-0.708 for Pliocene-Recent lavas (cf. Francis *et al.*, 1977). Further south, in central Chile, at 30°-35°S, the character of Jurassic-Recent volcanism has been described by Vergara (1972) and Aguirre *et al.* (1974). Most volcanic rocks have experienced burial metamorphism and thus chemical analyses must be interpreted with care (Levi and Corvalán, 1964). The thick Jurassic succession (7,000 m) contains lavas and pyroclastic rocks of basic to intermediate composition intercalated with sedimentary rocks (Fig. 2d) and generally interpreted as having formed in a volcanic island arc (Vergara, 1972). The Lower Cretaceous succession is similar.

Although the scatter in the SiO_2-K_2O diagram (Fig. 2d) may reflect mobility of K_2O during burial metamorphism, it is clear that analyzed samples range from basaltic andesite to rhyolite in composition, but are predominantly basaltic andesites and andesites which appear to have tholeiitic affinities in an AFM diagram (Fig. 2d). Although the Lower Cretaceous rocks were probably formed in island arcs, subaerial volcanism was more abundant than in the Jurassic and continental conditions appear to have been established by the Upper Cretaceous. Continental sedimentary and volcanic rocks were formed to the east of the older volcanic belt, during the Upper Cretaceous (Abanico Formation) and the Lower Tertiary (Farellones Formation). In contrast to the more basic Lower Cretaceous rocks, the Upper Cretaceous-Lower Cenozoic volcanic rocks are largely of intermediate to acid composition (Fig. 2d).

The southernmost part of the Andes is characterized by a different volcanic history to that outlined above. South of 40°S, Middle-Upper Jurassic andesite-dacite and rhyolite volcanism, associated with regional extensional tectonics occurred over the area of south Chile and Argentina (Harrington, 1962; Bruhn and Dalziel, 1977). These volcanic rocks overlie pre-Jurassic metamorphic rocks and are known as the El Quemado Formation in Chile and the Le Maire Formation in Argentina. Both formations are partly submarine and partly subaerial in character. Bruhn *et al.* (1978) have adopted the term Tobifera Formation for these groups of Jurassic volcanic rocks. The western part of the continent was separated during the latest Jurassic by the formation of a small back-arc basin (Dalziel *et al.*, 1974; Bruhn *et al.*, 1979) and, during early Cretaceous time, calc-alkaline volcanism became restricted to a sliver of rifted continental crust along the Pacific margin of this back-arc basin (Dalziel *et al.*, 1974). Closure, deformation, and uplift of the marginal basin occurred during the middle Cretaceous (Dalziel *et al.*, 1974; Bruhn and Dalziel, 1977), and there were no subsequent major episodes of volcanic activity.

This review of the Mesozoic-Recent volcanism in the Andes leads to some important generalizations.

a) In many parts of the Andes calc-alkaline andesite volcanism has occurred from *ca.* 150-100 m.y. to the present day.

b) There has been a general eastward migration of volcanism with Jurassic and Cretaceous volcanic rocks are frequently exposed near the coast, the younger rocks inland, and the active volcanic belt located 200-300 km from the coast.

c) Within individual areas, older (Jurassic and Cretaceous) volcanic rocks have a greater proportion of more basic lavas (basalts and basaltic andesites), may have less K_2O for a given SiO_2 content, and show more Fe-enrichment in an AFM diagram, than younger Cenozoic-Recent volcanic rocks.

d) Older Jurassic and Cretaceous volcanic rocks more frequently show evidence of submarine eruption than the dominantly subaerial Cenozoic and Recent volcanic rocks.

e) Much of the volcanism occurred upon older sialic crust of Palaeozoic or Precambrian age, and only in Colombia and northern Ecuador (north of 2°S) and south Chile (south of 50°S) are there occurrences of ophiolitic rocks.

SUBDUCTION OF CONTINENTAL CRUST BELOW THE ANDES

The Andes have been the site of more-or-less continuous subduction-related volcanic activity since the Jurassic or Cretaceous. During this period the continental margin might have undergone net westwards extension by accretion of oceanic and continental sediment; remained substantially unaffected; or experienced a net eastwards migration by erosion and subduction of the continental leading edge. Research by the DSDP has yielded evidence of accretion at several continental arcs (e.g. Moore *et al.*, 1979). However several authors (Atherton and Tarney, 1979) propose that continental sediments or even pieces of continental crust may be locally subducted.

The scale of such a process is fundamental to modern crustal growth. We therefore examine, in some detail, geological evidence related to subduction of continental material along the Andean plate margin and in a later section consider isotopic evidence relevant to this problem.

The geological characteristics of subduction zones characterized by accretion and consumption (and a possible transitional state) have recently been reviewed by Kulm *et al.* (1977). These authors examined the morphological ang geological characteristics of the Andean continental margins and divided it into three physiographic provinces (Fig. 1b, 1, 2, and 3). Province 1 and Province 3 are characterized by: long prominent benches on the lower continental slope, sedimentary basins on the shelf and upper slope, and thick trench deposits; features are all considered to be characteristic of continental accretion. Noting that depositional centres in some of the upper continental slope basins in Province 1 have formed and experienced uplift throughout the Cenozoic, Kulm *et al.* (1977) propose that "Provinces 1 and 3 are those regions where accretion has occurred along the outer continental margin over the long term (i.e. the past 10 m.y.)" (Kulm *et al.*, 1977, p. 296). There is therefore no geological evidence that continental material has been recently subducted along most of the Andean margin (Provinces 1 and 3).

In contrast, Kulm *et al.* (1977) argued that Provinces 2 (19,5°-27°S) is characterized by several features that are best explained by a model of continental consumption. These include the absence or weak development of benches on the continental slope and the absence or small size of sedimentary basins on the continental shelf. In addition, Palaeozoic and Mesozoic igneous rocks crop out on the coast and crystalline rocks might extend beneath the upper slope, possibly almost as far as the trench axis (Ocola and Meyer, 1973). James (1978) has further argued that the absence of detritus from the Andean orogen to the west of the central Andes indicates that "continentally derived sediments are being continuosly subducted" (James, 1978, p. 566). It has also been proposed that westerly derivation of sediments in the Upper Palaeozoic and possibly the Mesozoic suggest that older crust once extended further west from the present outcrop in south Peru and may have been "tectonically eroded and dragged beneath the Andes" (Pitcher, 1979, p. 161). These characteristics of the central Andes, around Province 2 of Kulm *et al.* (1977) constitute a plausible case for subduction of continental crust or sediment in this area.

However, careful examination of the geological characteristic of the central Andes places considerable doubt upon any model involving tectonic erosion and subduction of continental material. Firstly, it is clear that much of the detritus eroded from the Andes as a whole has been transported to the eastern part of South America and is deposited within "pericratonic" and "intracratonic" basins to the east of the Andes (Fig. 1a). So any sediment within the trench must be derived from the 100-200 km wide area between the western coast and the Andean cordillera. It has also been shown that the amount of sedimentary material in the trench is a direct function of annual rainfall in coastal regions (Fisher and Raitt, 1962; Scholl *et al.*, 1970). Since Province 2 in Fig. 1b lies opposite the Atacama desert (characterized by less than 2.5 mm rainfall per month for at least 10 months per year), we considerer that the distinctive features of the province, as recorded by Kulm *et al.* (1977), are much more likely to reflect the climatic characteristics of the adjacent section of the Andes, than subduction of continental sediments. Furthermore, geomorphological and geochronological studies (Mortimer, 1973; Baker, 1977) show that the climate of this region has remained substantially unchanged for at least 20 m.y.

The second problem that must be considered concerns the possible subduction of fragments of continental crust. The Andean volcanic history of the area adjacent to Province 2 is dominated by Jurassic igneous rocks and associated Palaeozoic basement on the coast, with progressively younger intrusive and extrusive volcanic rocks occurring inland towards the active volcanic zone (cf. Section 3). The Jurassic igneous rocks now exposed on the coast are in places less than 100 km from the active trench. Noting that the characteristics of these rocks suggest formation in an island arc (Dostal *et al.*, 1976) and that the intrusive axes of such arcs are about 50 km in width, then the "arc-trench" gap corresponding to these volcanics would be in the range 100-150 km, corresponding to values for active oceanic arcs (Dickinson, 1973). Dickinson (1973) has further shown that the widths of modern arc-trench gaps are proportional to the duration of past magmatic activity in the arcs, this reflecting a combination of prograde trench migration and retrograde volcanic arc migration. In this case, the measured arc-trench gaps of 300-400 km in Province 2 are fully consistent with the Jurassic age of inception of volcanism in the area related to a trench near the position of the active trench.

A final point to note is that the regional geological patterns established from the Andes in Province 2 of Kulm *et al.* show no significant difference (such as the systematic absence of older volcanic rocks) to that of the adjacent Provinces 1 and 3 where no geological characteristics of consumption are apparent.

We conclude from the discussion above that there is no firm geological evidence that significant subduction of continental crust or crustally derived sediments below the Andean orogenic belt is taking place, or has taken place since the Mesozoic. However, we emphasize that we do consider that crustal material may be returned to the mantle via crustal-derived elements fixed in altered oceanic crust, or in pelagic sediments trapped within subducted oceanic crust (Fyfe, 1978; Magaritz *et al.*, 1977). There is a growing tendency to consider the possibility that mantle isotopic heterogeneities might be attributed to such recycling (De Paolo and Wasserburg, 1979; Cohen *et al.*, 1980). In view of the inherent plausibility of such a process, in comparison with that of subduction of continental crust or sediment, we considerer that the latter process is not a significant factor in crustal recycling or growth.

PETROGENESIS OF ANDEAN VOLCANIC ROCKS

Several lines of evidence indicate that Andean magmas originate within the mantle. These are: (i) the restriction of the three zones of active volcanism to parts of the Andes underlain by relatively thick wedges of asthenospheric material (Barazangi and Isacks, 1976, 1978), the Sr and Nd isotope characteristics of volcanic rocks of the northern and southern zones (Francis *et al.*, 1977; Hawkesworth *et al.*; 1979, Klerkx *et al.*, 1978) and (iii) the evidence of recent crustal growth in areas that have not experienced significant shortening (James, 1971; Brown, 1977). Accepting that Andean volcanic rocks do not contain a substantial component of subducted continental material and hence consist of mantle-derived material, this section explores their petrogenesis.

The petrological and chemical characteristics of Andean volcanic rocks from the active zones have been reviewed in Thorpe and Francis (1979a, 1979b) and are briefly summarized here. The volcanic rocks of the northern zone are basaltic andesite with 53-61 per cent SiO_2 (Pichler *et al.*, 1977) and with $^{87}Sr/^{86}Sr \sim 0.7044$, $^{143}Nd/^{144}Nd \sim 0.5130$ and $\delta^{18}O$ 6.5-7.7‰. By contrast, the volcanic rocks of the central zone, in south Peru and north Chile are predominantly andesites and dacites with 56-66 per cent SiO_2. These have higher and more variable $^{87}Sr/^{86}Sr$ ratios, generally between 0.706-0.708, $^{143}Nd/^{144}Nd \sim 0.5125$ and $\delta^{18}O$ 7.0-10.8‰ (Magaritz *et al.*, 1978). Some volcanic areas of the central zone are characterized by wider ranges of Sr and O isotopic composition. These include the Sierra de Lipez area of southwestern Bolivia and the Cerro Galán area of northwestern Argentina where the basalt-basaltic andesite-andesite-dacite association of Cerro Galán is characterized by initial $^{87}Sr/^{86}Sr$ ratios between 0.7054-0.7113 which correlate with $\delta^{18}O$ values between 8.2-10.6‰ (Deruelle and Moorbath, personal communication, Francis *et al.*, 1980). This central province has a prominent component of dacite-rhyolite ignimbrite sheets which have relatively high and variable initial $^{87}Sr/^{76}Sr$ ratios and $\delta^{18}O$ values (Klerkx *et al.*, 1978; Thorpe *et al.*, 1979). In contrast to the northern and central province, the southern zone is dominated by high-alumina basalt, basaltic andesites and andesites (with less frequent dacites and rhyolite) which are characterized by uniformly low initial $^{87}Sr/^{86}Sr$ ratios of 0.7035-0.7040 independent of rock composition (Klerkx *et al.*, 1978; Deruelle and Moorbath, personal communication).

The asthenospheric mantle wedge below the Andes overlies the subducted oceanic lithosphere of the Nazca plate. Although it is uncertain whether such oceanic lithosphere would melt to contribute to magmatism, it is clear that dehydration would occur (Anderson *et al.*, 1978). This could in itself initiate mantle partial melting and contribute large ion lithophile (LIL) elements to the mantle wedge (Thorpe *et al.*, 1976; Anderson *et al.*, 1978; Hawkesworth *et al.*, 1979). Dehydration would also be expected to cause enrichment of the mantle wedge in $^{18}O/^{16}O$. This isotopic character of the more primitive northern and southern zone lavas are compatible with derivation from such an "enriched" mantle source which we thus consider as the source of orogenic magmatism in the Andes.

We consider that the parent magmas are derived by partial melting and asthernospheric mantle. Evidence for fractional crystallization of such parent magmas includes the ubiquitous low Ni and Cr concentrations in high-alumina basalts, basaltic andesites and andesites in comparison with concentrations expected in mantle-derived primary magmas. Such depletion is generally thought to be produced by crystal fractionation of olivine and pyroxene (e.g. Lopez-Escobar *et al.*, 1976, 1977). In north Chile, andesitic volcanic rocks have Rb, Sr, and REE variations indicative of fractional crystallization of plagioclase and pyroxene, whereas variation among dacite and rhyolitic rocks is dominated by fractional crystallization of plagioclase (Thorpe *et al.*, 1979). The data reviewed above strongly suggest that the volcanic associations might have evolved by fractional crystallization from more basic parent magmas.

Although data reviewed above indicate that fractional crystallization has had an important role in the post-partial melting evolution of the Andean magmas, the varied isotopic data indicate that the volcanic rocks of the central zone also contain a substantial component of crustal material. Before commenting on the nature of this component we note that the regional variation in initial Sr-isotope ratios precludes significant involvement of subducted continental crust in the petrogenesis of Andean volcanic rocks. The initial Sr-isotope ratios of volcanic rocks from Ecuador (Francis *et al.*, 1977), the northern part of the Peruvian batholith (the Lima "segment"; Atherton *et al.*, 1979), and central Peru (Noble *et al.*, 1975), and the volcanic rocks of south Chile (Klerkx *et al.*, 1978; Deruelle and Moorbath, personal comunication) all lie within the range 0.7035-0.7045. These areas encompass most of Province 1 and 3 of Kulm *et al.* (1977). This is within the range of Sr-isotope ratios characteristic of island arcs distant from sources of continental detritus and clearly indicate that significant amounts of such material are not involved in the petrogenesis of volcanic rocks in these provinces (cf. Fig. 1b). This is consistent with the conclusion from geological evidence.

Magaritz *et al.* (1978) and James (1979) recognized that the high $\delta^{18}O$ values of the andesitic lavas of south Peru (7.0-8.6‰) required a sialic component, but argued that the best candidate for such a contaminant was geosynclinal sediments that had been subducted and become involved in the melting process at depth. This view was based on analogy with the situation in the Banda Arc and the absence of an O-Sr correlation within individual volcanic areas that exists on a regional scale across the Andes. As we have argued earlier subduction of continental sediments below the Andes is unlikely and therefore a sialic component in Andean lavas is most likely to be derived from the crystalline basement through which the magmas passed on their way to the surface. This largely Precambrian granitic and gneissic terrain has the required isotopic charactericties to explain the O-, Sr-, and Nd-isotopic variations observed in the Andean lavas. The primitive nature of the Ecuadorian lavas, and the more evolved and isotopically more variable character of the north Chilean and south Peruvian lavas, are all consisten with a mantle origin for the volcanic rocks throughout the Andes, but with the lavas of the central zone subsequently modified by crustal contamination and crystal fractionation prior to eruption. It can be simply shown that the heat required for bulk assimilation of continental crust by an uprising magma must be de-

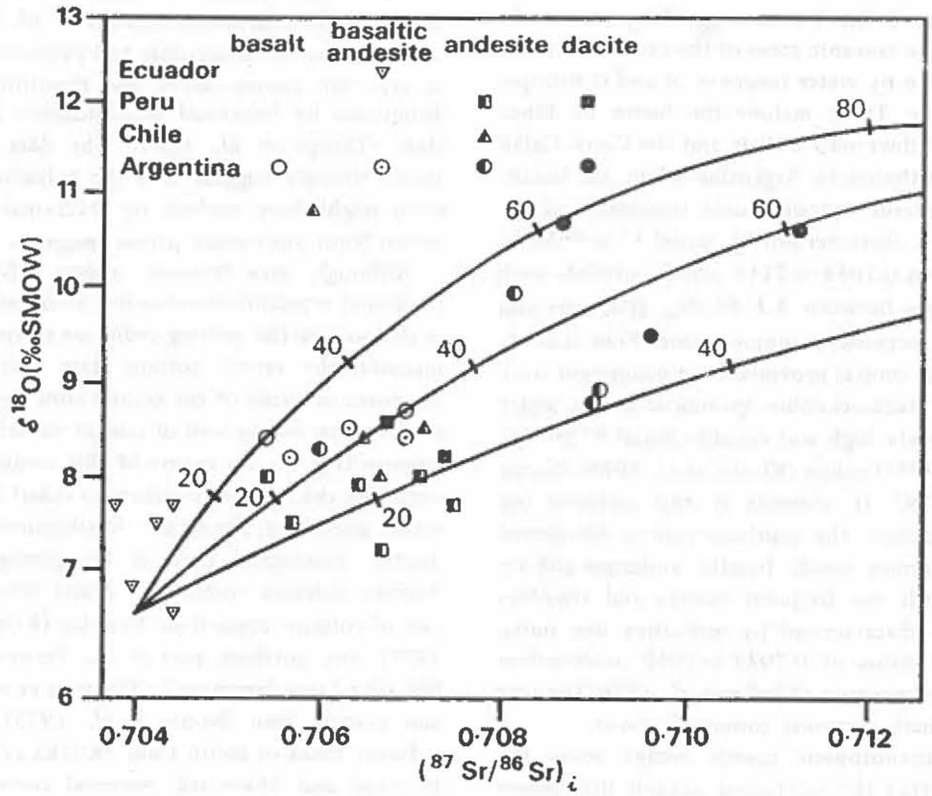


FIG. 3. Plot of $\delta^{18}O$ (‰ SMOW) against initial $^{87}Sr/^{86}Sr$ for Andean volcanic rocks. The solid lines show effects of mixing between a mantle component with $\delta^{18}O = 6.5$ and $^{87}Sr/^{86}Sr = 0.704$ (cf. Ecuadorian andesites) and crustal components with $\delta^{18}O = 13$ and $^{87}Sr/^{86}Sr = 0.75$ (line 1), $^{87}Sr/^{86}Sr = 0.73$ (line 2) and $^{87}Sr/^{86}Sr = 0.72$ (line 3). For each case the ratio of Sr concentration in the mantle end-member to that in the crust is 4:1, and the numbers on the lines indicate the proportion of crust involved. The data for Peru are from Magaritz *et al.*, (1978).

rived almost entirely from the latent heat of crystallization (Pushkar *et al.*, 1973; Taylor *et al.*, 1979). Hence, the systematic O- and Sr-isotopic variations observed within the Cerro Galán volcanic area coincident with progressive chemical and compositional change in this basalt-dacite association indicate that crystal fractionation and contamination within the crust must be concurrent and that the overall compositional and isotopic characteristics are a result of this complex interaction.

Oxygen and strontium-isotope data for the volcanic rocks of the Andes (Magaritz *et al.*, 1978) are shown in Fig. 3. The first poin to note from this figure is that the lavas of the central zone are characterized by higher and more variable $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ ratios than those of the northern zone; the second is that there is the progressive increase in both $\delta^{18}O$ values and $^{87}Sr/^{86}Sr$ initial ratios accompanying the basalt-dacite association within the Cerro Galán volcanic area in northwest Argentina. On the basis of the $\delta^{18}O$ values, the basaltic andesites of the northern zone fall into the "L" and "I" Groups (5.5–7.7‰) of Taylor (1968), being typical of igneous rocks thought to have been mantle derived. By contrast, all of the rocks of the central zone fall into the "H1" and "H2" and "HH" Groups (7.8- > 10.2‰), which is suggestive of a high - ^{18}O component in these samples. In fact, it is difficult to explain the five andesite and dacite samples with $\delta^{18}O$ values in excess of 9.5‰ other than by melting or assimilation of continental crust.

We have previously noted that there is much evidence to indicate that the compositional variations observed within the different volcanic provinces are produced by crystal fractionation of either olivine, pyroxene and plagioclase in the case of the northern zone or pyroxene and plagioclase in the case of the central zone (Thorpe and Francis, 1979a, 1979b). Such a process cannot explain the high $^{18}O/^{16}O$ ratios of the central zone andesites and dacites. Garlick (1966) noted that mineral fractionation factors were small at magmatic temperatures, Taylor (1968) observed that the average $\delta^{18}O$ values for basalts, andesites, trachytes and syenites are within the range 5.9-6.3‰, and Matsuhisa *et al.* (1973), documented that less than 1‰ change in $^{18}O/^{16}O$ ratio occurred in a compositional sequence of andesitic lavas related by crystal fractionation. Thus, another mechanism is required to explain the difference in $^{18}O/^{16}O$ ratios between the northern and central zones and the variation within the Cerro Galán volcanic area of northwest Argentina.

Evidence for crustal involvement in the production of the central zone lavas also comes from the strong positive interregional correlation observed between $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ initial ratios (Fig. 3). Similar O-Sr correlations have been documented for other calc-alkaline provinces; the Peninsular Ranges batholith of Southern California and Baja (Taylor and Silver, 1978), the Recent andesitic volcanics of the Banda Island Arc (Magaritz *et al.*, 1978), and the Early Palaeozoic "Newer" granites of the British Caledonides (Harmon and Halliday, 1980). Such O-Sr correlations in volcanic or plutonic environment require the involvement of materials of crustal origin in the magmatic process because the enrichment of ^{18}O and ^{87}Sr in the continental crust occurs via two geochemically independent mechanisms (Taylor *et al.*, 1979). The continental crust is rich in ^{18}O as a result of near surface, low temperature processes which produce high - ^{18}O sedimentary minerals (Savin and Epstein, 1970) and igneous and metamorphic processes which act to recycle such materials within the crust. In contrast, old crystalline rocks and sediments derived from them have accumulated ^{87}Sr through the decay of ^{87}Rb. It is however, important to note that although the O-Sr correlation in each of these calc-alkaline areas extrapolates donward to mantle compositions, the slopes of the general trends are different, thus suggesting the participation of different crustal O and Sr reservoir in the contamination process (Fig. 3). It has been suggested that subducted sediments have been involved in the production of the Banda Arc magmas (Magaritz *et al.*, 1978) and the British Caledonide granite O-Sr isotope O-Sr relationship has been interpreted in terms of assimilation, partial melting, and mixing of ^{18}O and ^{87}Sr enriched upper crustal metamorphic rocks of immature lower crust, and/or upper crustal geosynclinal sediments with primitive mantle-derived magmas (Harmon and Halliday, 1980). By contrast, extrapolation of the Andean trend to higher $^{18}O/^{16}O$ and $^{87}Sr/^{86}Sr$ ratios indicates contamination by a different source, namely ancient, highly evolved and more radiogenic continental crust (Fig. 3).

The environment of fractional crystallization and crustal interaction can be inferred from the geological characteristics of the Andean orogenic belt (Fig. 1b). Parental magmas formed within the mantle wedge will fractionate as they rise to the base of the crust where their ascent may be slowed when they rise into lower density crust. Since such magmas will be unlikely to intersect the solidus exactly at the base of a crust throughout the Andes because of its variation in depth (30–70 km), the magmas probably experience significant fractional crystallization within the lower crust. This is, as we demostrate later, of particular significance for crustal growth. Where more acid compositions have developed, andesitic magmas rise, fractionate, and interact with the crust; the extent of these processes depends respectively upon the time of ascent and the degree of local chemical equilibrium. The final stage of magma evolution will occur prior to eruption during storage in upper crustal reservoirs (Thorpe and Francis, 1979b).

Before considering the implications of this model of Andean magmatism for crustal growth we make two general points. Firstly, one of the distinctive features of the composition of andesites is the depletion of high field strength (HFS) elements relative to large ion lithophile (LIL) elements (Tarney and Saunders, 1979; Saunders *et al.*, 1980). This may reflect either retention of such elements in the source or fractional crystallization of HFS minerals within the lower crust. Secondly, for parental magmas rising from similar mantle depths, an ascent through thin crust (i.e. thick mantle) will result in more basic magmas with tholeiitic affinities such as Fe-enrichment (due to mantle fractionation of olivine), than will a rise through thick continental crust. The more tholeiitic character of Jurassic and Cretaceous volcanics as compared to that of the volcanic rocks of the active zones, particularly the central zone thus suggests that crustal thickening has taken place over this time scale.

The data summarized above have an implication for the process of crustal growth by orogenic volcanism. It is generally agreed that the continental crust is of overall intermediate chemical composition and has been characterized by such a composition throughout much of geological time (Taylor, 1977). Therefore, either (a) the composition of magma added to the crust must be an intermediate magma formed within the mantle, or (b) the intermediate magma is not formed within the mantle, but is formed from more basic magma by fractional crystallization and contamination in the crust. There has been much discussion of the possibility of deriving intermediate magmas by direct melting of mantle peridotite (Mysen and Boettcher, 1975). However, noting some of the difficulties involved (Mysen *et al.*, 1974) and accepting that fractional crystallization is required, we regard intermediate orogenic magmas as having formed by fractional crystallization of more basic parent magmas at lower crustal depths (cf. earlier). In this case, to conserve the intermediate composition of the crust, removal of ultrabasic and basic cumulates from this fractional crystallization is essential to ensure active crustal growth. Removal of such cumulates requires circulation within the mantle wedge, and we propose that this is one of the basic reasons that active andesite volcanism is restricted to areas underlain by a wedge of asthenospheric mantle in which removal of such cumulates is possible (Barazangi and Isacks, 1976, 1978). Circulation within such asthenospheric material is also required from considerations of the rate of growth of Andean crust (see below).

VOLUMETRIC CONSIDERATIONS

The geochemical arguments reviewed above indicate that a large proportion of the andesitic magmas involved in igneous processes at the Andean plate margin are of mantle origin. This directly implies that there has been a steady transfer of material from mantle to crust since Jurassic time. It is therefore appropriate to enquire into the rate at which this process has been taking place and to assess the extent of the addition of "new" crust that has occurred. Two indenpendant methods are available: either direct estimation from geophysical consideration of the volume of crust that has been added since the onset of magmatism in the Jurassic or by determination of the rate at which observable volcanic and plutonic processes have occurred, and estimation of their volumetric contribution to the crust in the period under consideration.

The first method is based upon the suggestion by James (1971) that the occurrence of marine Jurassic rocks on the western slopes of the present cordillera (14-22°S) indicates that the region was formerly underlain by much thinner crust than at present, and that in spite of the absence of evidence for crustal shortening, it has almost doubled in thickness since then. Fig. 4 illustrates this hypothesis. If the Jurassic crust were uniformly 30 km thick (i.e. similar to modern submarine continental crust) an additional 40 km thickness of crust must have been added beneath the crustal keel of the Central Andes. The volume of "new" crust in a 1 km wide section across the Andes is thus ~ 4,600 km^3. Because the marine Jurassic rocks are not found in the highest parts of the cordillera, nor on its eastern flanks, it seems clear that part of this region may have been elevated during Jurassic times, and that the crustal thickness therefore may have been greater, perhaps as much as 40 km. On this basis, the volume of "new" crust would be *ca.* 3,550 km^3.

It is instructive to compare the volumes calculated above with the volume of the mantle wedge beneath the cordillera. Considering the whole of the wedge from the trench to the extreme eastern zone of cainozoic magmatic activity, the total volume is *ca* 25,000 km^3. The volume of "new" crust is therefore *ca.* 14% of the mantle volume. James (1971) estimated that the increase in volume between Cretaceous time and the present implied that the mantle above the underthrust plate had undergone 18-36 per cent partial melting. Since production of the range of magmas under consideration would involve partial fusion of the mantle of much less than any of these estimates (all of which would result in basic and ultrabasic magmas!) it is clear that, on this basis alone, replenishment of the depleted mantle must have taken place, presumably by circulation of asthenorspheric mantle.

Such circulation processes have been proposed for the mantle wedge behind subduction zones by McKenzie (1969) and such convection has been proposed as the cause of back arc spreading by several authors (see Toksoz and Hsui, 1978). Such back arc basins characterize the western Pacific where the subducted oceanic lithosphere is relatively old and dense, thus favouring steep subduction and seaward migration of trenches with consequent development of back arc basins (Molnar and Atwater, 1978). In contrast, the eastern Pacific area, including the Andean Cordillera, is characterized by shallow angle subduction of young buoyant oceanic lithosphere below continental lithosphere of Proterozoic and Palaeozoic age (see earlier). In this setting, back arc basins formed in the Northern Andes (Colombia and Ecuador) and in south Chile during the Mesozoic when, presumably older oceanic lithosphere was subducted. But we speculate that regardless of the age of subducted lithosphere, the occurrence of relatively strong Proterozoic lithosphere in the Central Andes has inhibited the formation of such basins in this part of the Andean Cordillera. We further speculate that the mantle material melted to form back arc basins (and resorbed into the mantle upon closure) has become accreted to the base of the crust below the Central Andes thereby causing the magmatism and crustal thickening which is characteristic of the crustal growth in the Central Andes.

We now consider estimates of the rates of magmatic processes themselves. Francis and Rundle (1976) and Baker and Francis (1978) have shown that the rate of volcanic activity in the Central Andes is about 1.6 km^3 per km length per million years. The rate of plutonic activity is probably much greater, but more difficult to estimate. The chief problem is a geometric one, i.e. the shapes of batholiths at depth. Assuming the model which predicts the largest volume, namely that they are carrot shaped, and extend to a depth of 50 km (approximately the level of the bottom of the crust beneath the Peru batholith) it is possible to make an estimate of the rate of formation of the Peru batholith, the outcrop and geochronology of which are well known (Pitcher, 1978). This figure is ~ 18 km^3 per km per million years, roughly ten times greater than the rate of volcanic eruption.

If the estimates for the Peru batholith are then added to those measured for Cenozoic volcanic activity, the figure for magmatic addition to the crust is therefore ~ 20 km^3 per km per million years. At this rate, the volume of "new" crust required to create the present crustal keel (~ 3,550 km^3) could have been produced in ~ 180 million years, a figure which corresponds closely with the length of time since the onset of magmatism during the Jurassic.

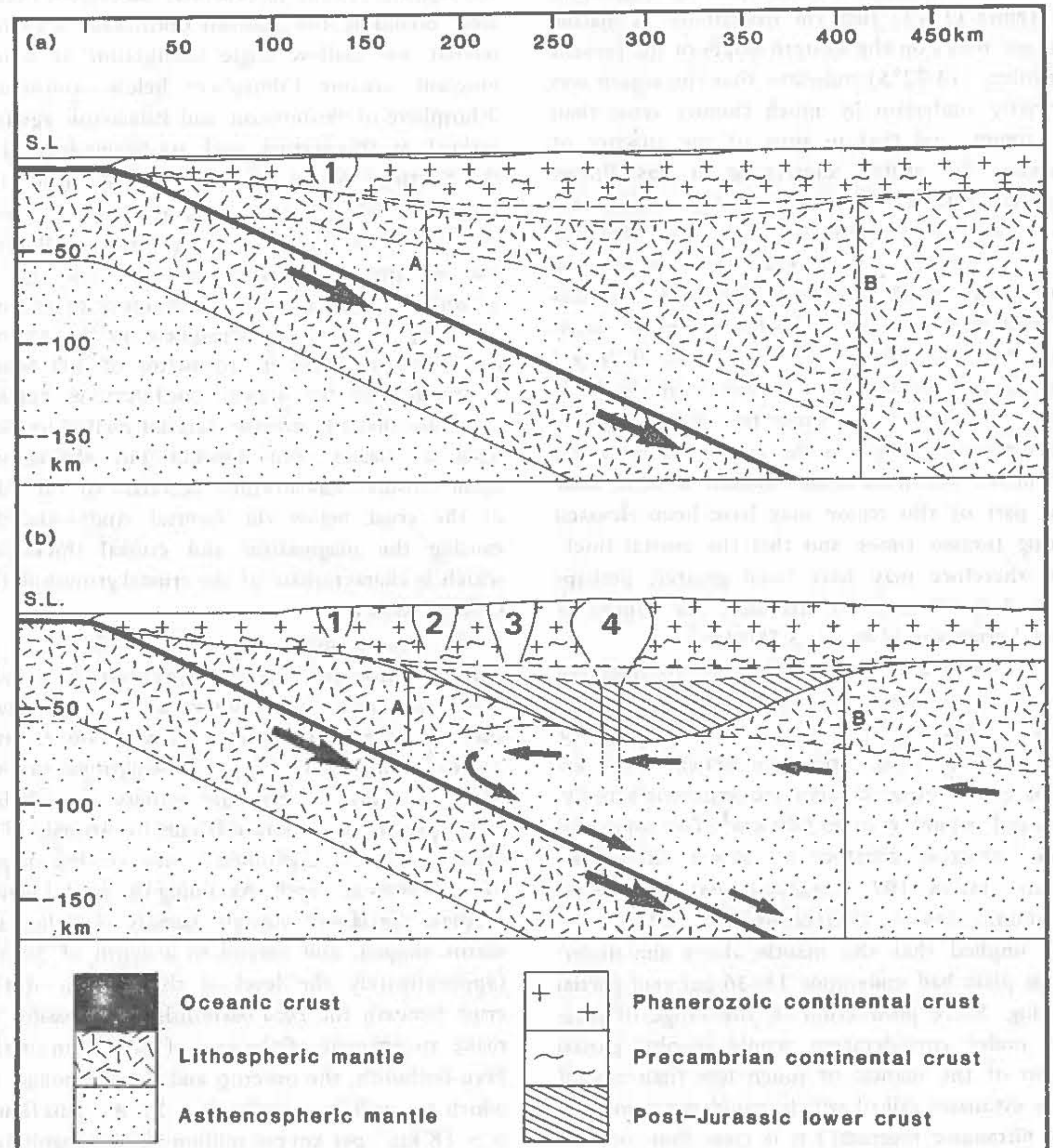


FIG. 4. Cartoon showing development of the crustal structure beneath the central Andes at latitude 21°S: a) during the Jurassic and b) at the present day. The ornament refers to rock units as described in the key. In a) and b) the dashed lines enclose alternative estimates of crustal thickness in the Jurassic, and the lined area in b) represents lower crust added since the Jurassic. The vertical lines A and B outline the mantle volume used as a possible source for the Andean crust. Intrusive rocks are shown as follows: 1, Jurassic; 2, Cretaceous; 3, Cenozoic; 4, postulated intrusive rocks below the active volcanic belt. See text for further discussion.

It is clear now also that magmatism beneath the Andes has been episodic rather than continuous (Baker and Francis, 1978) and that the rate of magmatism obtained is highly dependant on models used for batholith shape. None the less, it seems certain that:

a. most of the volume of "new" crust must have been intruded in the form of large plutons, and
b. that formation of this new crustal material must have been accompanied by replacement of depleted mantle source material.

The need to replace depleted mantle material for magmatism to continue may explain the observation that magmatism is extinct beneath the Peruvian and north-central Chilean sectors of the Andean cordillera, where the Benioff zone is so gently inclined that it is much closer to the crustal keel (cf. Barazangi and Isacks, 1976).

We have demonstrated that the Andean crust is presently growing by addition of mantle-derived material. Currently, continents which lack such magmatic activity and are experiencing erosion must be diminishing in volume. Much of the present crust has grown during geological time, and most crustal growth models indicate an exponentially decreasing rate of active growth, or even a decrease in continental volume (cf. Fyfe, 1978; Brown, 1979). Accepting the proposition argued above, that calc-alkaline material added to the crust above subduction zones represents local continental growth, a simplistic approach can be made as follows. There are $\sim 1.48 \times 10^8$ km^2 of continental crust in the world. Assuming an average thickness of 30 km, this yields a volume of $\sim 4.4 \times 10^9$ km^3. At a continental accretion rate of 0.5 - 1 km^3 (Francis and Rundle, 1976) this continental crust could be formed in 4000 - 9000 m.y. (cf. Brown, 1979). Many models of crustal growth in which growth rates are linked with global heat production infer a maximum in crustal growth at *ca.* 3000 m.y. with a decreasing rate to the present (e.g. O'Nions *et al.*, 1979). The fact that the accretion times calculated above are similar to and exceed the age of the Earth might therefore reflect this fact.

However, we noted earlier that continent-derived elements must be present within the oceanic crust, as trapped pelagic sediments or fixed in altered basalt. The fact that such continental components must be subducted back into the mantle suggests that the simplistic approach to net crustal growth (above) is not fully valid. This is true, of course, regardless of whether such subducted continental material contributes to mantle-derived calc-alkaline magmatism. A consideration of plate tectonic mass-balance indicates the difficulty of assessing net crustal growth during the recent geological past. The mass of basaltic ocean crust is $\sim 7 \times 10^{24}$g. If we assume that this formed during the last 200 m.y., this is equivalent to an accretion rate of $\sim 3.5 \times 10^6$g a^{-1}, or about 10 km^3 per year (cf. Fyfe, 1978).

If this material contains some continental components and is quantitatively subducted then the rate of net crustal growth will depend on the proportion of crustal components. If between 0.5 - 1.0 km^3 or 5 - 10 per cent of the subducted 10 km^3 is continental in derivation then the continental mass will be in a steady-state. As noted by Fyfe (1978, p. 97) the mass balance between subduction and continental accretion is critical to consideration of net crustal growth rates. Clearly net continental growth rates cannot be calculated from crustal accretion rates while ignoring the return of continental material to the mantle! However, the situation is complex because of the large uncertainties in the proportion of alteration and trapped pelagic sediment in the subducted oceanic crust, the balance of elements in the oceans derived from the mantle, young and ancient crustal sources, and the approach of the ocean mass to a steady state. In addition the balance of these factors will vary between different elements. In view of the uncertainties noted above, and noting that most thermally-based continental growth models predict a steadily decreasing rate of growth towards the present (cf. Fyfe, 1978) it is difficult to evaluate whether the continental mass is presently growing or has reached a steady state.

CONCLUSIONS

1. The Andean orogenic belt has been characterized by calc-alkaline magmatism between the Mesozoic and the present. The products intrude and overlie sialic basement of age varying between middle Precambrian (*ca.* 2000 m.y.) and Palaeozoic or Mesozoic.

2. Andean volcanism is characterized by a transition from more basic associations with tholeiitic affinities, associated with submarine sediments, in the Mesozoic, to more calc-alkaline associations of the active volcanic zones.

3. Parent magmas of calc-alkaline lavas are largely derived from the wedge of asthenospheric mantle underlying the Andean belt, but experience fractional crystallization and contamination by assimilation, partial melting, and mixing during rise through the continental crust. There is no evidence to suggest that significant subduction of continental crust or sialic sediments has taken place during the history of the Andean orogenic belt. Hence, the compositional character of erupted calc-alkaline rocks partly reflects the duration of crustal ascent and the age and composition of the underlying sialic crust.

4. In view of 1 - 3 above the Andes are a zone of active crustal growth by intrusion and eruption of calc-alkaline magmas. To conserve the intermediate composition of the continental crust, and to ensure continued growth, the growth must have been accompanied by circulation within the asthenospheric source.

5. Although we have established that *local* crustal growth must occur at the Andean subduction zone, it is difficult to assess whether such contributions cause *net* crustal growth. However, we note that many models of crustal growth rates predict decreasing rates from the early Precambrian to the present. If the continental crust is not presently in a steady state, this might well characterize the next phase of continental evolution in the geologically near future.

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