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Andean andesites and crustal growth

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Over the last 200 Ma, the ensialic Andean plate margin has been characterized by calc-alkaline magmatism. The early (Mesozoic), activity was dominantly of basaltic volcanism while the Cainozoic volcanism was of intermediate, calc-alkaline character. The restriction of Recent volcanism to parts of the Andes underlain by thick wedges of asthenospheric mantle, and the Sr and Nd isotopic relations, indicate that the calc-alkaline parental magmas are derived from the asthenospheric mantle. There is no unequivocal geochemical and geophysical evidence that continental crust or sediment has contributed to the mantle source for Andean magmatism. The chemical compositions of the calc-alkaline volcanic rocks of the active volcanic zones are controlled by fractional crystallization, whereas O–Sr isotopic relations reflect crustal interaction of mantle-derived parental magma with the sialic basement of the Andes. The variable extent of fractional crystallization, partial melting, and mixing of crustal contaminant are related to the variable thickness and age of crust in the different volcanic provinces. Calc-alkaline magmatism was largely responsible for post-Mesozoic crustal growth in the Andes and would have depleted the underlying mantle unless balanced by circulation within the asthenospheric mantle wedge. In terms of net growth of the South American continent, it is not certain where the balance lies between growth by magmatic addition and shrinking by erosion.

1. INTRODUCTION

The basis of this contribution is that material added from the mantle to the crust above subduction zones represents local continental growth. The intermediate composition of the characteristic magmatic products of subduction zones, andesites and tonalites, resembles the bulk composition of the Earth's crust (Taylor 1977). Therefore, crustal growth should be dominated by addition of mantle-derived magmas above subduction zones. We examine here the processes of formation of subduction zone magmas, the role of pre-existing continental crust, and the accretion of these magmas to form continental crust.

2. THE ANDEAN BASEMENT

The Andean orogenic belt (figure 1*a*) 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 (16–28° S) and a southern zone in south Chile (33–52° S; figure 1*b*).

The basement below the Andean Cordillera has several components and the inferred areas of these are shown in figure 1. The western parts of Colombia and Ecuador are underlain by mafic rocks (Gansser 1973; Pichler *et al.* 1974). Gravity data indicate that these form a substantial fraction of the crust (Case *et al.* 1973; Meissner *et al.* 1976). The environment of formation of these rocks is discussed in more detail in § 3. The Recent and active volcanoes of

Colombia and Ecuador are located variously on the mafic rocks of the coastal Cordillera and the metamorphic basement of Mesozoic or older age of the Cordillera Oriental. In view of the evidence for a change in basement character south of 2° 30′ S (Henderson 1979) the active volcanic belt of central Ecuador might overlie Mesozoic metamorphic crust, while the basement of south Ecuador and north Peru might be of late Precambrian or Lower Palaeozoic age (figure 1*b*).

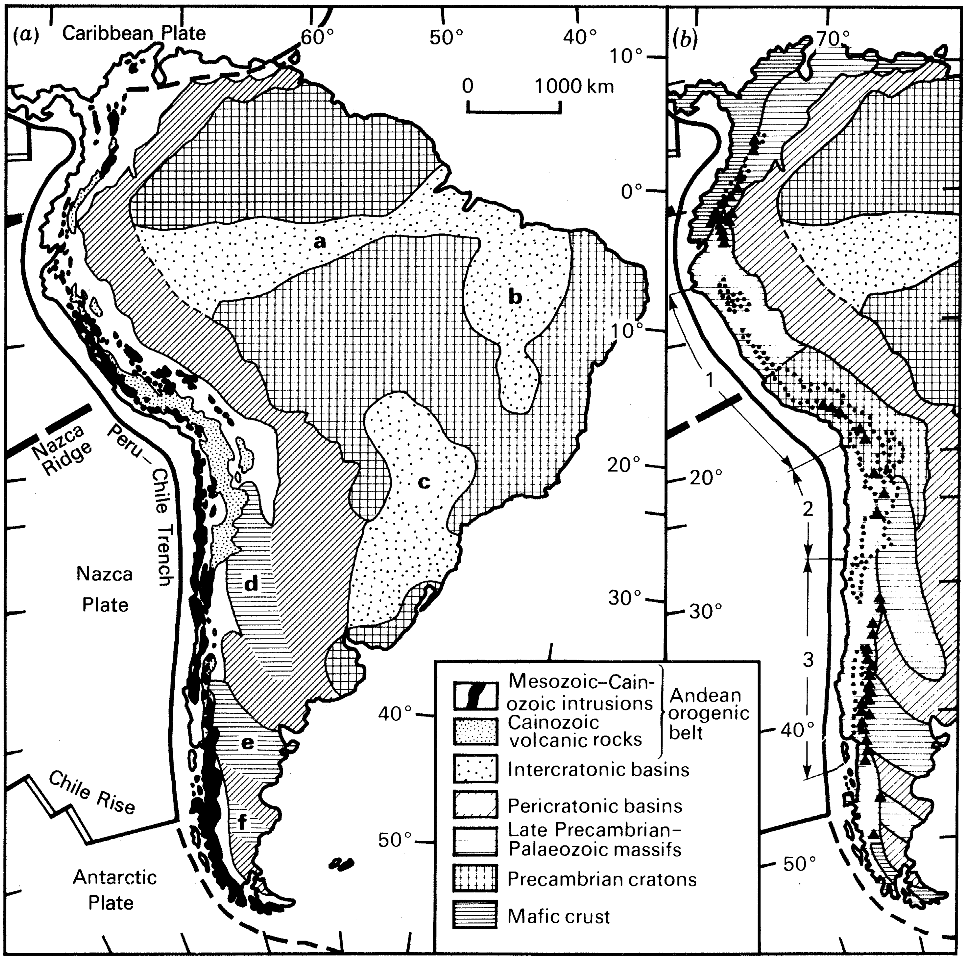

FIGURE 1. (*a*) Geological framework of South America (based on Harrington (1978)). (*b*) Geological framework as in (*a*), showing the inferred age of oldest basement below the Andean orogenic belt. The solid triangles are active volcanoes and the dotted lines outline areas of Cainozoic volcanic rocks (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, Paraña Basin; d, Pampean Ranges Massif; e, Deseado Massif; f, Patagonian Massif. See text for further discussion.

Evidence for much older basement occurs in central Peru, south of the latitude of Lima (12° S). Between 14 and 17° S an almost continuous strip of coastal gneisses, termed the Arequipa Massif, includes metamorphic rocks dated at *ca.* 2000 Ma B.P. (Shackleton *et al.* 1979). These rocks are of similar character and age to rocks recorded from drilling below the Bolivian Altiplano (see, for example, Lehmann 1978) and to the metamorphic rocks of the

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Brazilian Shield (Cordani *et al.* 1973). It is therefore considered that the Precambrian rocks continue below the Andean Cordillera to connect with the Brazilian Shield (Cobbing & Pitcher 1972; Shackleton *et al.* 1979). Thus the central active volcanic zone in south Peru and north Chile is built upon crust containing early Precambrian rocks.

In the southern Andes, there is no evidence for the presence of early Precambrian basement. 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 & Latorre 1973).

3. Mesozoic–Cainozoic volcanic history

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). The coastal plain of Ecuador is underlain by mafic crust (figure 1*b*), 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 (Henderson 1979). 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 (figure 2*a*). The active Ecuadorian volcanoes occur within both Eastern and Western Cordillera and consist largely of basaltic andesites and andesites (figure 2*a*).

The Cretaceous–Eocene basic volcanic rocks of Colombia and Ecuador are characterized by positive Bouger anomalies (Case *et al.* 1973; Feininger 1977) and 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 Cainozoic pelagic sediments (Gansser 1973; Gansser *et al.* 1979). These associations suggest an ophiolotic character and an origin either as part of the Pacific ocean crust or the crust of a small marginal basin. The major element characteristics of the Piñón Formation of Ecuador, however, 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 older oceanic crust.

Volcanic rocks of Jurassic 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, and can be divided in central Peru into a western group of submarine basalt–andesite lavas of the island-arc tholeiite association, erupted onto continental crust, and an eastern group composed chiefly of submarine and terrestrial dacites and rhyolites (figure 2*b*). These two groups are both of Lower Cretaceous age and are intruded by the coastal batholith, of Upper Cretaceous–Palaeocene age.

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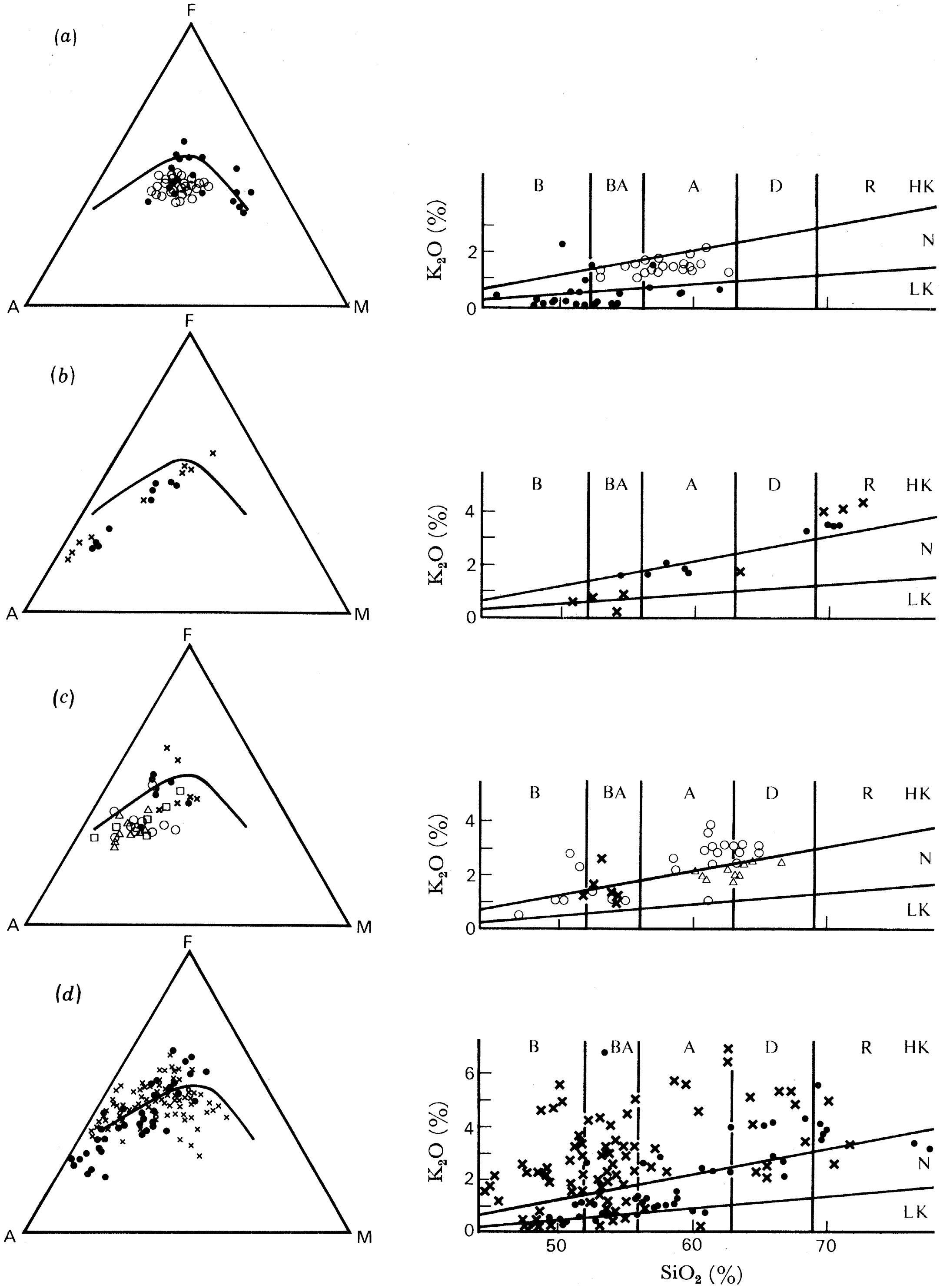

×, Jurassic–Lower Cretaceous; •, Upper Cretaceous–Eocene; △, Miocene; ○, Pliocene–Recent

FIGURE 2. Chemical characteristics on AFM (A, Na_2O+K_2O; F, total Fe as FeO; M, MgO) diagrams and plots of K_2O against SiO_2 of Mesozoic, Cainozoic and Recent Andean volcanic rocks from indicates areas. (*a*) Ecuador (Henderson 1979; R. S. Francis & P. W. Thorpe, unpublished results); (*b*) Peru (M. P. Atherton, personal communication; Lefevre 1973); (*c*) north Chile (Dostal *et al.* 1977); (*d*) central Chile (Vergara 1972) based on data in Oyarzun & Villalobos (1969)). The solid lines in the AFM diagrams separate the tholeiitic and calc-alkaline fields as defined by Irvine & Baragar (1971). The solid lines in the K_2O–SiO_2 plot are from Peccerillo & Taylor (1976), with B, basalt, BA, basaltic andesite, A, andesite, D, dacite, R, rhyolite, and HK, N and LK respectively high-, normal- and low-potassium series. See text for further discussion.

The batholith is overlain by the Eocene–Pliocene Calipuy volcanic group, a thick, variable succession containing a lower group of basic to intermediate lavas and pyroclastic rocks and an upper group of acid pyroclastic rocks, which resembles the Pliocene–Recent calc-alkaline lavas of S Peru (Atherton *et al.* 1979; Lefevre 1973; cf. figure 2*b* and Thorpe & Francis 1979*b*, fig. 1*b*).

The central Andes between about 20 and 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 & 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 basaltic andesites and andesites of island-arc tholeiite affinity. 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. During Pliocene to Recent times, rapid westward regression of volcanism lead to the formation of the active volcanic belt (figure 1). The Miocene–Recent volcanic rocks are calc-alkaline basalts andesites, dacites and rhyolites (figure 2*c*; Dostal *et al.* 1977; cf. Thorpe & Francis 1979*b*, fig. 1*c*).

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). The thick Jurassic succession (7000 m) contains lavas and pyroclastic rocks of basic to intermediate composition intercalated with sedimentary rocks (figure 2*d*) and is interpreted as having formed in a volcanic island arc (Vergara 1972). Although the scatter in the SiO_2–K_2O diagram (figure 2*d*) may reflect mobility of K_2O during burial metamorphism, the lavas are predominantly basaltic andesites and andesites that appear to have tholeiitic affinities in an AFM diagram (figure 2*d*). 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 Upper Cretaceous and lower Cainozoic times. In contrast to the more basic Lower Cretaceous rocks, the Upper Cretaceous – Lower Cainozoic volcanic rocks are largely of intermediate to acid composition (figure 2*d*).

The southernmost part of the Andes experienced a volcanic history different 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 1978; Bruhn & Dalziel 1977). The western part of the continent was separated during the latest Jurassic by the formation of a small back-arc basin 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. Closure, deformation and uplift of the marginal basin occurred during the middle Cretaceous and there were no subsequent major episodes of volcanic activity (Dalziel *et al.* 1974; Bruhn & Dalziel 1977).

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 Ma B.P. to the present day.

(*b*) There has been a general eastward migration of volcanism, with Jurassic and Cretaceous volcanic rocks frequently exposed near the coast, successively 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 than young Cainozoic–Recent volcanic rocks.

(*d*) Older Jurassic and Cretaceous volcanic rocks more frequently show evidence of submarine eruption than do the dominantly subaerial Cainozoic 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.

4. Subduction of continental crust below the Andes

Since the inception of magmatic activity in the Jurassic, the Andean 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 Deep Sea Drilling Project (D.S.D.P.) has yielded evidence of accretion at several continental arcs (see, for example, Moore *et al.* 1979). However, several contributors to this symposium propose that continental sediments or even pieces of continental crust may be locally subducted. We therefore examine geological evidence related to the 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 been reviewed by Kulm *et al.* (1977). These authors examined the morphological and geological characteristics of the Andean continental margins and divided it into three physiographic provinces (figure 1*b*: provinces 1, 2, 3). Provinces (1) and (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 that 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 Cainozoic, Kulm *et al.* 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 yr. [Ma])' (Kulm *et al.* 1977, p. 296). There is therefore no geological evidence that continental material has been recently subducted almong most of the Andean margin (provinces 1 and 3).

In contrast, Kulm *et al.* (1977) argued that province 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 as far as the trench axis (Ocola & Meyer 1971). James (1979) 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 continuously subducted' (James 1979, p. 566). It has also been suggested that westerly derivation of sediments in the Upper

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Palaeozoic and possibly the Mesozoic indicate 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 1978, p. 161). These characteristics of the central Andes constitute a plausible case for subduction of continental crust or sediment in this area.

It is clear, however, that much of the sediment eroded from the Andes is transported to the eastern part of South America and is deposited in basins to the east of the Andes (figure 1*a*). So any sediment within the trench must be derived from the 100–200 km wide strip 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 & Raitt 1962; Scholl *et al.* 1970). Since province 2 in figure 1*b* lies opposite the Atacama Desert (characterized by less than 2.5 mm of rainfall per month for at least 10 months per year), we consider that the distinctive features of the province, as recorded by Kulm *et al.* (1977), are 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 Ma.

The subduction of fragments of continental crust is more difficult to discount. 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. § 3). The Jurassic igneous rocks now exposed on the coast are in places less than 100 km from the active trench, and the axis of the Jurassic arc turns into the modern coastline at latitude 18° S. Noting that the characteristics of these rocks suggest formation in an island arc (Dostal *et al.* 1977) 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). Thus, while it might be argued that some crustal material might be missing, the total width involved cannot be large.

We conclude from the discussion above that there is little evidence for major subduction of continental crust, and none for crustally derived sediments, below the Andean plate margin. However, we emphasize that crustal material may be returned to the mantle via crust-derived elements fixed in altered oceanic crust, or in pelagic sediments trapped within subducted oceanic crust (Fyfe 1978; Magaritz *et al.* 1978). Mantle isotopic heterogeneities might be attributed to such recycling (De Paulo & Wasserburg 1979; Cohen *et al.* 1980).

5. 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 & Isacks 1976, 1978); (ii) 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.* 1977); and (iii) the evidence of recent crustal growth in areas that have not experienced significant crustal shortening (James 1971; Brown 1977).

The petrological and chemical characteristics of Andean volcanic rocks from the active zones have been reviewed in Thorpe & Francis (1979*a*, *b*) and are briefly summarized here.

The volcanic rocks of the northern zone are basaltic andesites and andesites with 53–61 %† SiO_2 (Pichler *et al.* 1977), $^{87}Sr/^{86}Sr$ 0.7044, $^{143}Nd/^{144}Nd$ 0.5130 and $\delta^{18}O$ 6.5–7.7‰ (Harmon *et al.* 1981). By contrast, the volcanic rocks of the central zone, in south Peru and north Chile are predominantly andesites and dacites with 56–66 % SiO_2, higher and more variable $^{87}Sr/^{86}Sr$ ratios, between 0.705–0.7113, $^{143}Nd/^{144}Nd$ 0.5125 and $\delta^{18}O$ 7.0–10.8‰ (Magaritz *et al.* 1978). The central province also has a prominent component of dacite–rhyolite ignimbrite sheets, which have relatively high and variable initial $^{87}Sr/^{86}Sr$ ratios and $\delta^{18}O$ values (Klerkx *et al.* 1977; Thorpe *et al.* 1979). The southern zone is dominated by high-alumina basalt, basaltic andesite and andesite (with less frequent dacite and rhyolites), which are characterized by uniformly low initial $^{87}Sr/^{86}Sr$ ratios of 0.7035–0.7040 independent of rock composition (Klerkx *et al.* 1977; B. Déruelle & S. 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, dehydration would occur (Anderson *et al.* 1978). This could in itself initiate mantle partial melting and contribute large-ion lithophile (l.i.l.) 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 $^{18}O/^{16}O$ (Harmon *et al.* 1981). The isotopic character of the more primitive northern and southern zone lavas is compatible with derivation from such an 'enriched' mantle source, which we consider to be the major source of Andean magmas.

We consider that the parent magmas are derived from the asthenospheric mantle by partial melting followed by fractional crystallization. Evidence for fractional crystallization of the parent magmas includes the ubiquitous low Ni and Cr concentrations in high-alumina basalts, basaltic andesites and andesites compared with the concentrations expected in mantle-derived primary magmas. Such depletions are generally thought to be produced by crystal fractionation of olivine and pyroxene (see, for example, Lopez-Escobar *et al.* 1976, 1977). In north Chile, andesitic volcanic rocks have Rb, Sr and rare-earth element (r.e.e.) variations indicative of fractional crystallization of both plagioclase and pyroxene, whereas variation among dacite and rhyolitic rocks is dominated by fractional crystallization of plagioclase (Thorpe *et al.* 1979). These data strongly suggest that the volcanic associations evolved by fractional crystallization from more basic parent magmas.

Isotopic data indicate that the volcanic rocks of the central zone contain a substantial component of crustal material, which is not observed in the northern or southern zones. We emphasize 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), central Peru (Noble *et al.* 1975), and south Chile (Klerkx *et al.* 1977; B. Déruelle & S. Moorbath, personal communication) all lie within the range 0.7035–0.7045. This is within the range of Sr isotope ratios characteristic of island arcs distant from sources of continental detritus and clearly indicates that significant amounts of such material are not involved in the petrogenesis of volcanic rocks in these provinces (cf. figure 1*b*). This is consistent with the conclusion from geological evidence summarized in § 4.

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 crustal component, and argued that the best

† Unless stated otherwise, all compositions (% and ‰) in the paper are by mass.

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candidate for such a contaminant was geosynclinal sediment 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 on the absence of an O–Sr correlation within individual volcanic areas. As we have argued earlier, subduction of continental sediments below the Andes is unlikely and therefore the crustal 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 isotopic characteristics required to explain the O-, Sr-, and Nd-isotopic variations observed in the Andean lavas (Harmon *et al.* 1981).

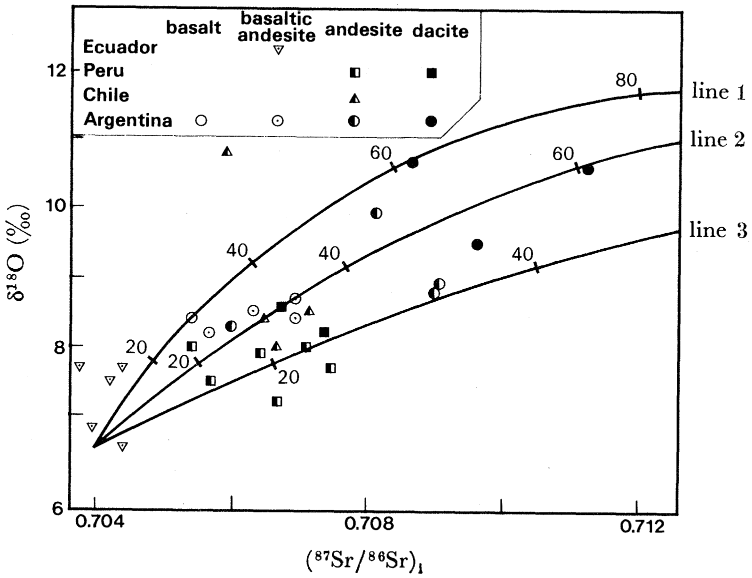

FIGURE 3. Plot of $\delta^{18}O$ (‰ standard mean ocean water) against initial $^{87}Sr/^{86}Sr$ for Andean volcanic rocks. Lines show effects of mixing between a mantle component with $\delta^{18}O = 6.5$ and $^{87}Sr/^{86}Sr = 0.704$ (cf. Ecuadorian andesites) and crustal components with $\delta^{18}O = 13$ 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).

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 consistent with a mantle origin if the lavas of the central zone were modified by crustal contamination and crystal fractionation before eruption. It can be simply shown that the heat required for assimilation of continental crust by an uprising magma must be derived 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 Galan volcanic area of Argentina (figure 3) 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.

On the basis of $\delta^{18}O$ values (figure 3), the basaltic andesites of the northern zone fall into the 'L' and 'I' groups (5.5–7.7‰) of Taylor (1968), considered to be typical of mantle-derived igneous rocks. By contrast, all of the rocks of the central zone fall into the 'H1', 'H2' and 'HH'

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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.

Evidence for crustal involvement in the production of the central zone lavas comes from the strong positive inter-regional correlation observed between $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ initial ratios (figure 3). Similar O–Sr correlations have been documented for other calc-alkaline provinces, the Peninsular Ranges batholith of southern Baja and California (Taylor & 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 & Halliday, 1980). Such O–Sr correlations in volcanic or plutonic environments 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 that produce high-^{18}O sedimentary minerals (Savin & Epstein 1970) and igneous and metamorphic processes that act to recycle such materials within the crust. In contrast, old crystalline rocks and the sediments derived from them have accumulated ^{87}Sr through the decay of ^{87}Rb. Although the O–Sr correlation in each of these calc-alkaline areas extrapolates downward to mantle compositions, the slopes of the general trends are different, thus suggesting the participation of different crustal O and Sr reservoirs in the contamination process. It has been suggested that subducted sediments have been involved in the production of the magmas of the Banda arc (Magaritz *et al.* 1978) and the British granite O–Sr isotope relation has been interpreted in terms of assimilation, partial melting, and mixing of ^{18}O- and ^{87}Sr-enriched upper-crustal metamorphic rocks, and/or upper-crustal geosynclinal sediments, with primitive mantle-derived magmas (Harmon & 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 (figure 3).

For the Andes, we consider that basic parental magmas formed within the mantle wedge fractionate during ascent through the mantle, until their ascent is slowed when they rise into lower-density crust. Since such magmas will be unlikely to intersect the solidus exactly at the base of the crust throughout the Andes the magmas probably experience significant fractional crystallization within the lower crust. 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 magmas evolution will occur before eruption, during storage in upper crustal reservoirs (Thorpe & Francis 1979*b*).

The arguments outlined above have an important implication for the process of crustal growth. 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* the composition of magma added to the crust must be an intermediate magma formed *within* the mantle, *or* the intermediate magma is not formed within the mantle, but is formed from more basic magma by fractional crystallization and contamination in the crust.

As argued above, we regard intermediate magmas as having formed by fractional crystallization of more basic parent magmas at lower crustal depths. In this case, to conserve the intermediate composition of the crust, removal of ultrabasic and basic cumulates resulting from fractional crystallization is essential to ensure active crustal growth. Removal of these cumulates requires circulation within the mantle wedge, and we propose that this is one of the 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 & Isacks 1976, 1978). Circulation within such asthenospheric material is also required from considerations of the rate of growth of Andean crust.

6. Volumetric considerations

The geochemical arguments reviewed above imply 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 independent 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* determination of the rate at which observable volcanic and plutonic process have occurred, and estimation of their total 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. Figure 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 4600 km^3. Because the marine Jurassic rocks are not found in the highest part 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.* 3550 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.* 25000 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 % 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 asthenospheric mantle.

Such circulation processes have been proposed for the mantle wedge behind subduction zones by McKenzie (1969) and convection has been proposed as the cause of back-arc spreading by several authors (see Toksöz & Hsui 1978). 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 & 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.

Taking the modern situation into account, it thus seems probable that back-arc basins formed in the northern Andes (Colombia and Ecuador) and in south Chile during the Mesozoic, when relatively old oceanic lithosphere was subducted. But we speculate that, regardless of the age of subducted lithosphere, the occurrence of ancient continental lithosphere in the central Andes has inhibited the formation of such basins there. 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 crustal thickening that is characteristic of the central Andes.

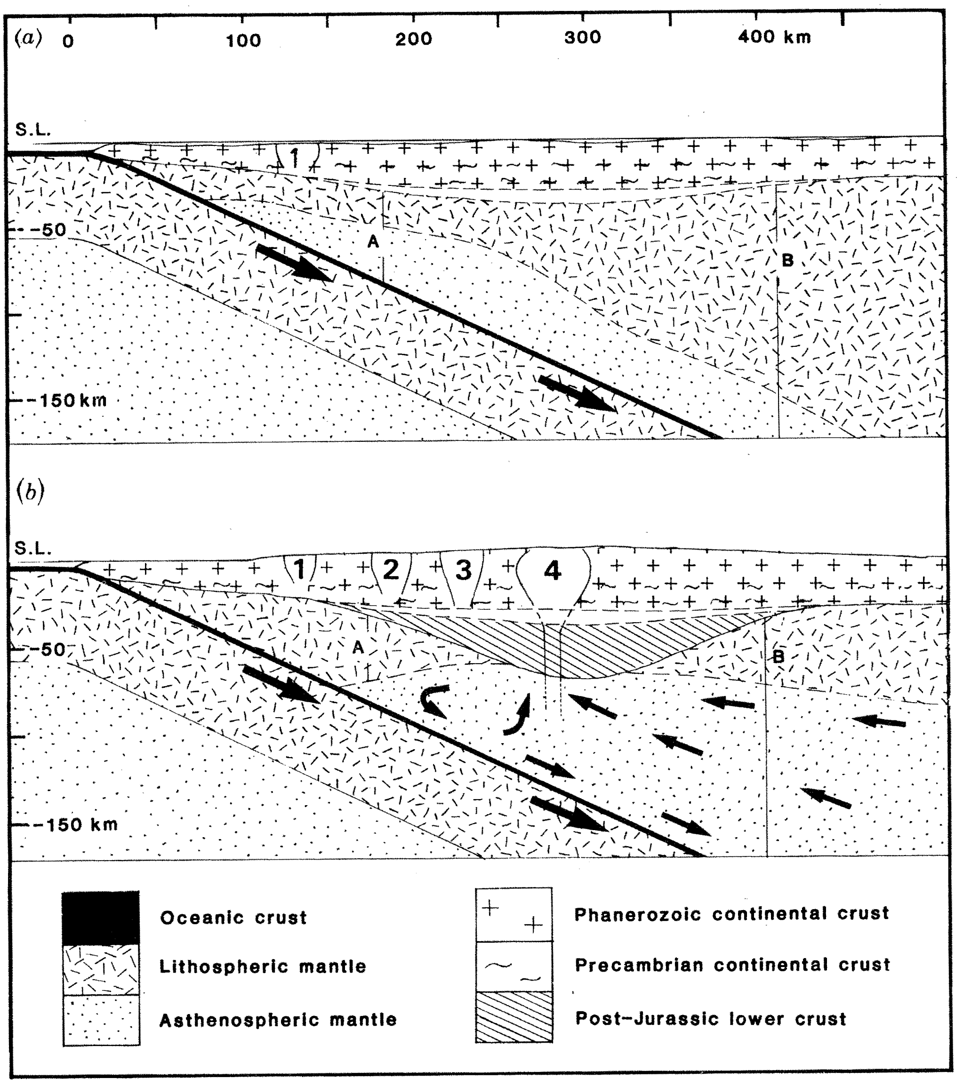

FIGURE 4. Schematic diagram showing development of the crustal structure beneath the central Andes at latitude 21° S (*a*) during the Jurassic and (*b*) at the present day. The ornament refers to rock units as described in the key. In (*a*) and (*b*) the dashed lines enclose alternative estimates of crustal thickness in the Jurassic; 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, Cainozoic; 4, postulated intrusive rocks below the active volcanic belt. See text for further discussion. S.L., sea level.

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We now consider estimates of the rates of magmatic processes themselves. Francis & Rundle (1976) and Baker & Francis (1978) have shown that the rate of volcanic activity in the central Andes is about 1.6 km^3 per kilometre length per million years. The rate of plutonic activity is probably much greater, but more difficult to estimate since the shapes of batholiths at depth are unknown. Assuming the model that 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), one can 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 *ca.* 18 $km^3\ km^{-1}\ Ma^{-1}$, roughly ten times greater than the rate of volcanic eruption.

If the estimates for the Peru batholith are then added to those measured for Cainozoic volcanic activity, the figure for magmatic addition to the crust is therefore *ca.* 20 $km^3\ km^{-1}\ Ma^{-1}$. At this rate, the volume of 'new' crust required to create the present crustal keel (*ca.* 3550 km^3) could have been produced in *ca.* 180 Ma, a figure that corresponds closely with the length of time since the onset of magmatism during the Jurassic.

It is clear that magmatism beneath the Andes has been episodic rather than continuous (Baker & Francis 1978) and that the rate of magmatism obtained is highly dependent on models used for batholith shape. Nonetheless, it seems certain that: (*a*) most of the volume of 'new' crust must have been intruded in the form of large plutons; and (*b*) 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 & Isacks 1976).

We have demonstrated that the Andean crust is presently growing by addition of mantle-derived material. Conversely, continents that lack such magmatic activity and are experiencing erosion must be diminished in volume. Most crustal growth models indicate an exponentially decreasing rate of active growth, or even a net decrease in continental volume (cf. Fyfe 1978; Brown 1979). If the proposition argued above, that calc-alkaline material added to the crust above subduction zones represents local continental growth, is accepted, a simplistic approach can be made as follows. There are *ca.* 1.48×10^8 km^2 of continental crust in the world. If one assumes an average thickness of 30 km, this yields a volume of *ca.* 4.4×10^9 km^3. At a continental accretion rate of 0.5–1 km^3 (Francis & Rundle 1976) this continental crust could be formed in 4000–9000 Ma (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 Ma, with a decreasing rate to the present (see, for example, O'Nions *et al.* 1979). The fact that the accretion times calculated above are similar to and exceed the age of the Earth probably reflects this decreasing rate.

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 indicates 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 the plate tectonic mass balance indicates the difficulty of assessing net crustal growth during the recent geological past. The mass of basaltic ocean crust is *ca.* 7×10^{21} kg.

If we assume that this formed during the last 200 Ma, this is equivalent to an accretion rate of *ca.* 3.5×10^{13} kg a^{-1}, or about 10 km^3 a^{-1} (cf. Fyfe 1978).

If oceanic crust contains any continental components and is quantitatively subducted, then the rate of net crustal growth will depend on the proportion of crustal components. If between 5 and 10% of the subducted 10 km^3 is continental in origin, 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 the return of continental material to the mantle is ignored! However, large uncertainties exist 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; the approach of the ocean mass to a steady state; and the differences in behaviour between different elements. In view of these uncertainties and the evidence for 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 whether it has reached a steady state.

Conclusions

(i) The Andean plate margin 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.* 2 Ga B.P.) and Palaeozoic or Mesozoic.

(ii) Andean volcanism is characterized by a transition from more basic associations with tholeiitic affinities locally with evidence of submarine eruption, in the Mesozoic, to more calc-alkaline associations of the active volcanic zones.

(iii) Parent magmas of calc-alkaline lavas are largely derived from the wedge of asthenospheric mantle underlying the Andean belt, but experienced fractional crystallization and contamination by partial melting and assimilation, partial melting during rise through the continental crust. There is no evidence to suggest that subduction of sialic sediments has taken place during the history of the Andean orogenic belt and little to suggest that continental crust has been subducted. Hence, the chemistry of erupted calc-alkaline rocks probably reflects the duration of crustal ascent and the age and composition of the underlying sialic crust.

(iv) To conserve the intermediate composition of the continental crust, and to ensure continued growth, the crustal growth must have been accompanied by circulation within the asthenospheric source.

(v) Although *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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