

GEOCHEMISTRY, PETROLOGY AND ORIGIN OF THE CENOZOIC VOLCANIC ROCKS OF THE NORTHERN ANDES IN ECUADOR

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ABSTRACT

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The Cenozoic volcanic rocks of the northern Andes in Ecuador for which only little petrological and geochemical information was available until now, display a strong geochemical and petrological zoning from west to east. The magmas of the volcanoes of the Western Cordillera (WC) are unique to the Andes. They belong to andesite-plagidacite series which is characterized by low and fairly constant K_2O contents ($1 \pm 0.2\%$), low abundances of large cation elements (Rb, Sr, Ba), rare earth elements, highly charged cations (Zr, U, Th), and relatively high Ni and Cr abundances.

The magmas of the volcanoes of the Eastern Cordillera (EC) belong to an andesite-dacite-rhyolite series which is characterized by Rb, Sr, Ba, REE, Zr, U, and Th contents higher than in the rocks of the WC and varying with the K_2O content. They have Ni and Cr versus MgO correlations similar to the rocks of the Western Cordillera. Even higher contents of K_2O and the above-mentioned elements are encountered in the volcanic rocks of the Sub-Andean Area (SAA). All of the rocks have the same $^{87}Sr/^{86}Sr$ ratio of 0.704. The rocks are chemically more closely related to the Mesozoic to Tertiary rocks of the Basic Igneous Complex (BIC) of Ecuador and Colombia than to those of the Central Andes.

It is suggested that the Cenozoic magmas of the volcanoes of the Western and Eastern Cordillera originated by hydrous partial melting of amphibolites and garnet amphibolites of the BIC-type in a subduction zone beneath the Cordilleras at pressures near 20 kbar which corresponds to a depth of about 70 km.

INTRODUCTION

The Andes of South America, which are part of the circum-Pacific volcanic belt, are a famous examples of the formation of andesites along continental margins. Miyashiro (1974) distinguished outer and inner arcs with tholeiitic and calc-alkaline volcanic zones in his work on the volcanic rock series in

island arcs and active continental margins. Proceeding from the trenches to the continents, the percentage of calc-alkaline rocks in the volcanic belts increases with increasing crustal thickness. In areas of thick continental crust, e.g. the central Andes, 95% of the rocks are calc-alkaline.

Among the Cenozoic volcanic rocks of the central and southern Andes, no tholeiitic rocks occur and virtually no basalt is encountered. The rocks mainly consist of andesites, dacites and rhyodacites. A great deal of information is available on these rocks (Siegers et al., 1969; Pichler and Zeil, 1972; Hörmann et al., 1973; Lefèvre, 1973; Kusssmaul et al., 1977; Dostal et al., 1977), but little is known about the Cenozoic volcanic rocks of the northern Andes of Ecuador and adjacent Columbia. In this area, such famous volcanoes as Cotopaxi and Chimborazo are situated which became the center of interest some hundred years ago through the travels of Alexander von Humboldt.

Except for a description of the rocks of the volcanoes Reventador and Sumaco (Colony and Sinclair, 1928; Pichler et al., 1976) and the Sr isotope analyses of the andesites of Tungurahua, Cotopaxi, Chimborazo, Punalica, Calpi and Sincholhua (Francis et al., 1977), no data are available. It is, therefore, the purpose of this paper to fill this gap and to provide the first petrological data for the Ecuadorian part of the North Andes. We will mainly be concerned with andesites, the origin of which has been the subject of many experimental studies. The most favoured theories explain the formation of andesitic melts either by partial melting of material from the upper mantle (e.g. Kushiro, 1972a,b, 1974; Kushiro et al., 1972; Mysen et al., 1974; Nicholls, 1974; Mysen and Boettcher, 1975a,b; 1976), or from basalt which had previously undergone high-pressure metamorphism into amphibolite or eclogite (e.g. Green and Ringwood, 1968; Holloway and Burnham, 1972; Allen et al., 1975; Allen and Boettcher, 1978; Stern and Wyllie, 1978). All investigators agree that the presence of water is essential. The results of experimental work on the partial melting of peridotite and basalt at high temperatures and pressures give information on the kind and composition of the residual phases coexisting with the melt and on the composition of the melt itself. Crystal-liquid distribution coefficients, although known only semiquantitatively, describe the distribution of the trace elements between crystals and melt (e.g. Gast, 1968; Higuchi and Nagasawa, 1969; Philpotts and Schnetzler, 1970; Shaw, 1972; Hart and Brooks, 1974; Wedepohl, 1975; Hanson, 1978; Gill, 1978). As a consequence, the chemical composition of magmas (major elements as well as trace elements) reflect the conditions of their formation: temperature, pressure, composition of phases, and residual phases.

The main problem in discussing the origin of andesites is to overcome the disagreement between petrological and geochemical data. Some data, e.g. the rare earth element (REE) distribution patterns (Dostal et al., 1977), favour a mantle origin. On the other hand, major element compositions as well as most of the trace element data, e.g. the Ni and Cr contents, are in better agreement with a basalt partial melting model. Taylor (1969) emphasized that the speci-

fic trace element content of andesites is explicable by a two-stage melting process: stage 1 would correspond to the formation of tholeiites by partial melting of mantle peridotites, and stage 2 to the partial melting of amphibolite or eclogite in a subduction zone. This agrees with the modern concepts of plate tectonics.

Objections against the origin of andesitic melts by partial fusion of metabasalts in subduction zones arise from the specific trace element composition of the oceanic tholeiites which are characterized by very low contents of the large-ion-lithophile elements (LILE), e.g. K, Rb, Ba, Th, U. It is argued that extensive partial melting of a material so poor in LILE cannot explain the high LILE content of the andesites, even if the distribution coefficients of the residual phases are low. However, in the continental margin systems, e.g. the North Andes, basalts are occasionally present which are already enriched in LILE (e.g. Goossens et al., 1977). Partial melting of these types could easily yield melts with the trace element content of andesites.

As no information on the composition of the andesites of the North Andes was available, both major and trace elements were determined from 52 rock samples collected in 1974 and 1976 from the volcanoes of the Western Cordillera (WC), the Inter-Andean Graben (IAG), and the Eastern Cordillera (EC).

GEOLOGICAL SETTING

The Andes of Ecuador consist of two mountain ranges, the Western Cordillera (WC) and the Eastern Cordillera (EC) both separated by the Inter-Andean Graben (IAG; Fig. 1). For details, the reader is referred to Sauer (1971) and the geological map of Ecuador in the scale 1:1000000 published by the Servicio Nacional de Geología y Minería in 1969. Cenozoic volcanic rocks cover a large area in the Ecuadorian part of the northern Andes from about 3° 30' southern latitude up to the frontier with Colombia. More than 50 volcanoes, 9 of which are active, are concentrated (Fig. 1): (1) in the eastern part of the Western Cordillera (WC), e.g. the volcanoes Cotacachi-Cuicocha, Pichincha, Atacazo and Corazón; (2) in the western part of the Eastern Cordillera (EC), e.g. the volcanoes Antizana and Tungurahua; and (3) in the Inter-Andean Graben (IAG), e.g. the volcanoes Imbabura, Mojanda, and Ilaló.

Some active and extinct volcanoes are situated within and on the eastern border of the EC, e.g. the volcano El Reventador. Farther to the east, in the Sub-Andean Area (SAA), only the Sumaco volcano and some small isolated volcanic zones are encountered.

The volcanoes of the western Cordillera rise directly from a basement built up from Mesozoic to early Tertiary basaltic rocks. This Basic Igneous Complex (BIC) is thought to have the chemical properties of oceanic tholeiites and island-arc andesites (Goossens and Rose, 1973; Pichler et al., 1974; Goossens et al., 1977; Henderson, 1979; Kehrer and Kaaden, 1979). It is intruded by many plutons of mostly tonalitic composition (Aly, 1980). Continental

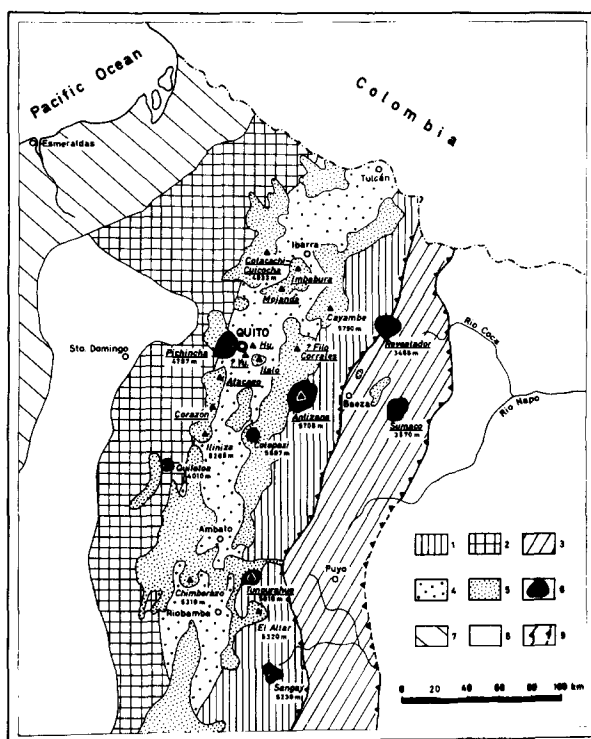


Fig. 1. Generalized geological map of Ecuador. 1 = Metamorphic rocks of the Eastern Cordillera; 2 = Mesozoic to Tertiary volcanic rocks and metasediments of the Western Cordillera with batholiths; 3 = Jurassic and Cretaceous metasediments of the Sub-Andean Area with large batholiths; 4 = Tertiary and Quaternary volcanic rocks and sediments of the Inter-Andean Graben: predominantly volcanoclastics; 5 = Tertiary and Quaternary volcanic rocks: predominantly lavas; 6 = main volcanoes; 7 = Mesozoic to Cenozoic sedimentary rocks of the coastal region with Cretaceous volcanic rocks; 8 = sediments of the Guayas depression and Amazonas basin (Miocene to Holocene); 9 = fault systems.

crust is supposed to be absent in this region; if this is so, where do the plutonic rocks come from?

The volcanoes of the Eastern Cordillera, on the other hand, are situated on a continental pre-Mesozoic basement consisting of low- to medium grade metamorphic rocks, mainly metapelites (Herbert, 1977), intruded by batholiths of granitic to dioritic composition. The basement of the IAG is most probably composed of the same Mesozoic to early Tertiary volcanic rocks which are so abundant in the BIC of the WC. According to radiometric age determinations (K/Ar data) the rocks are of Eocene age (Cotecchia and Zezza, 1969).

The arrangement of the volcanoes along specific zones and the different nature of the basements on which the volcanoes of the WC and EC are situated, suggests the existence of some kind of geochemical and petrological zoning in the Cordilleras of Ecuador. One would expect that the rocks of the

WC are more similar to andesites of the island arcs whereas those of the EC should belong to the typical Andean-type andesite series which is also present in the central and southern Andes (Siegers et al., 1969; Pichler and Zeil, 1972; Hörmann et al., 1973; Lefèvre, 1973; Kussmaul et al., 1977). Such a chemical (and temporal) zonation has been described by Dostal et al. (1977) from calc-alkaline volcanic rocks of northern Chile and Argentina: There, the Jurassic and Eocene lavas occurring nearest to the Peru-Chile-trench are comparable to volcanic rocks of the island-arc-association. Eastwards they are followed by the Miocene and Quaternary sequences of Andean-type andesites.

The petrological zonation is possibly related to a Benioff zone present beneath the Cordilleras of Ecuador. The existence of such a Benioff zone in adjacent Colombia was proven by Meissner et al. (1976). It dips at an angle of about 25° to the East under the Cordilleras. Case et al. (1973) and Pichler et al. (1974) suggested that the Cauca-Romeral fault system which continues from Colombia into Ecuador actually represents the outcrop of a Cretaceous Benioff plane.

Consequently, one could expect that the chemical variation of the andesitic rocks is possibly related to the depth of formation of the melts.

PETROGRAPHY

Western Cordillera (WC) and Inter-Andean Graben (IAG)

The rocks, mainly quartz andesites and plagioclase andesites, have a rather uniform modal composition. Strongly zoned corroded plagioclase (An 50-70) often filled with inclusions of glass, is the most abundant phenocryst followed by abundant tabular augitic clinopyroxene and subordinate hypersthene phenocrysts. Some samples contain small corroded olivine crystals. The more silica-rich rock types, extrusive lavas and pumices are characterized by phenocrysts and microphenocrysts of brown amphibole, and occasionally biotite. Resorbed hornblende sometimes occurs also in the andesitic lavas. The groundmass consists of microphenocrysts of augitic clinopyroxene, hypersthene and fine plagioclase laths (An 35-45) set in a glass matrix.

Eastern Cordillera (EC)

The quartz andesites and quartz latite andesites of this area have modal compositions very similar to those of the rocks of the WC. The most abundant phenocrysts are plagioclase (An 45-75), augitic clinopyroxene and hypersthene. The lavas of the volcano El Reventador are free from hypersthene and have large glomerophyric olivine (Fo₈₀), up to 8 mm in size. Occasionally, phenocrystic amphibole which is filled or totally replaced by granular magnetite is present. The quartz latites and latites of the EC, which occur mainly near the bases of the volcanoes Antizana and Tungurahua, contain the same phenocryst assemblage as the quartz andesites. However,

augitic clinopyroxene and hypersthene are present in equal amounts. The groundmass consists mainly of plagioclase microlites of An 35-45 set in glass. The rhyolite pumices and obsidian lavas from the Cerro Puntas region of the EC have modal compositions different from the other rock types. The glassy groundmass contains phenocrysts of amphibole, biotite and subhedral sanidine.

Sub-Andean-Area (SAA)

The composition and origin of the hauyne- and nepheline-bearing tephri-phonolites of the SAA will not be dealt within this paper.

GEOCHEMISTRY

Methods

Major element compositions were determined by colorimetry, atomic absorption spectrometry (AAS) and X-ray spectrometry (XRS). References are given by Hörmann et al. (1973). The trace elements Sr, Ba, Y, Ni, Cr were measured by XRS using internal standard methods (Jenkins and De Vries, 1967). The rare earth elements (REE) were determined by the neutron activation technique using BRC 1 as a standard.

Li and Rb were separated from the rocks by an Amberlite IR 120 ion-exchange method (Hörmann and Eulert, 1980) and subsequently measured by AAS. Th was isolated by ion exchange on Dowex 50WX8 and determined colorimetrically by thorine (Korkisch and Antal, 1960). U was isolated by means of Dowex 1 \times 8 cation exchange resin (Korkisch and Steffan, 1972) and determined fluorometrically. Zr was measured fluorometrically by the molybdenum method (Geiger and Sandell, 1957). V was extracted by oxine and subsequently measured in a lithium tetraborate matrix by XRS. Cu and Co were extracted with dithizone and determined by AAS. Precision of major element measurements is better than $\pm 1\%$. The standard deviation of the Li, Rb, Ba, Sr, Zr, V, Ni, Cr determinations is about $\pm 10\%$ and $\pm 20\%$ for Th and U. The REE determinations have standard deviations of less than $\pm 10\%$. The methods were controlled by means of the AGV-1 andesite standard.

MAJOR ELEMENT COMPOSITION

Representative analyses of volcanic rocks of the Ecuadorian Andes are reported in Tables I and II. The variation of the compositions is shown by the QAPF-diagram of Fig. 2 (Streckeisen, 1978) and the AFM-diagram of Fig. 3. Although the mineralogical composition of the rocks is rather uniform, marked chemical differences are evident. This is shown by Tables I and I as well as by the K_2O versus SiO_2 diagram of Fig. 4.

Four different rock groups are discernible by specific trends (groups I-IV

TABLE I

Composition of andesite melts (in %) of the Western Cordillera (WC) and the Inter-Andean Graben (IAG)

	(1)	(2)	(3)
SiO ₂	60.44 ± 2.00	58.07 ± 3.13	70.45 ± 3.44
Al ₂ O ₃	16.11 ± 0.68	16.59 ± 0.75	14.57 ± 0.52
FeO	5.88 ± 0.74	6.58 ± 1.30	3.01 ± 1.88
MnO	0.12 ± 0.02	0.14 ± 0.03	0.08 ± 0.01
MgO	4.14 ± 1.25	4.12 ± 1.59	0.71 ± 0.19
CaO	6.35 ± 0.68	6.96 ± 0.96	3.03 ± 1.07
Na ₂ O	3.95 ± 0.41	3.83 ± 0.41	4.43 ± 0.41
K ₂ O	0.98 ± 0.31	1.06 ± 0.16	2.20 ± 0.45
TiO ₂	0.48 ± 0.09	0.59 ± 0.16	0.24 ± 0.10
P ₂ O ₅	0.13 ± 0.01	0.17 ± 0.03	0.11 ± 0.01
CO ₂	0.07 ± 0.03	0.11 ± 0.11	0.04 ± 0.01
H ₂ O	0.61 ± 0.40	1.00 ± 0.75	0.44 ± 0.10

(1) Composition of 19 quartz andesites and 5 plagioclites from the volcanoes Cotacachi-Cuicocha, Pichincha, Atacazo and Corazón (WC).

(2) Composition of 8 quartz andesites and 2 plagioclites from the volcanoes Huanguiltagua, Ilaló, Mojanda, Imbabura and the surroundings of Ibarra (IAG).

(3) Composition of 3 dacitic pumice samples from the volcanoes Yurapugro and Mojanda (IAG).

TABLE II

Composition of andesitic melts (in %) of the Eastern Cordillera (EC) and the Sub-Andean Area (SAA)

	(1)	(2)	(3)	(4)
SiO ₂	58.91 (56.94—66.08)	73.30	56.99 ± 1.22	50.42 (46.14—52.88)
Al ₂ O ₃	16.22 (15.24—17.52)	12.50	15.16 ± 0.22	18.92 (18.04—19.78)
FeO	6.32 (3.85— 8.40)	0.78	6.82 ± 0.13	5.65 (4.73— 7.50)
MnO	0.12 (0.08— 0.15)	0.05	0.13 ± 0.03	0.14 (0.13— 0.15)
MgO	4.29 (6.32— 1.44)	0.18	4.48 ± 1.09	3.00 (2.22— 4.91)
CaO	6.42 (4.33— 8.49)	0.94	6.36 ± 0.76	7.12 (6.33— 9.28)
Na ₂ O	4.07 (3.49— 4.57)	3.69	4.04 ± 0.50	5.04 (4.76— 5.24)
K ₂ O	1.70 (1.42— 2.99)	4.13	2.88 ± 0.10	3.83 (3.21— 4.47)
TiO ₂	0.79 (0.40— 1.25)	0.12	1.07 ± 0.18	0.74 (0.68— 0.84)
P ₂ O ₅	0.27 (0.19— 0.42)	0.02	0.48 ± 0.07	0.68 (0.42— 0.98)
CO ₂	0.07 (0.05— 0.08)	0.05	0.06 ± 0.02	not determined
H ₂ O	0.40 (0.17— 0.66)	4.01	0.88 ± 0.37	2.16 (0.90— 3.28)

(1) Composition of 2 andesites, 2 quartz andesites, 5 quartz latites from the volcanoes Antizana, Tungurahua and Reventador (EC).

(2) Composition of a rhyolite pumice sample from Cerro Puntas (EC).

(3) Composition of 2 quartz latites and 1 latite from the volcanoes Antizana, Tungurahua and from El Chaco.

(4) Tephritic and phonolitic rocks of the Sumaco volcano (SAA).

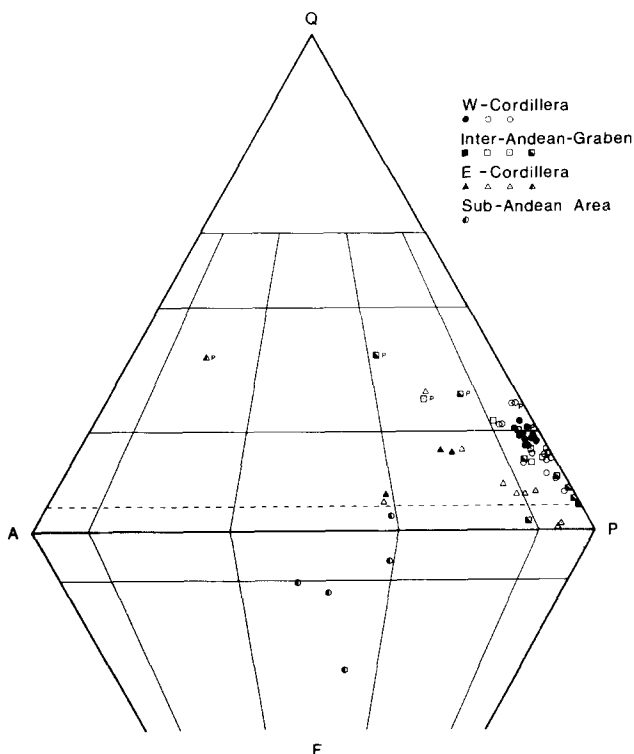


Fig. 2. QAPF diagram plot of Cenozoic volcanic rocks of Ecuador. Location of the analysed samples from the volcanoes: Cotacachi-Cuicocha ●, Pichincha ○, Corazón, Atacazo ○ (Western Cordillera); Imbabura, Ibarra □, Mojanda ■, Ilaló ■, Huanguiltagua ■ (Inter-Andean Graben); Antizana ▲, Tungurahua △, El Reventador ▼, Filo de los Corrales ▲ (Eastern Cordillera); Sumaco ○ (Sub-Andean Area).

in Fig. 4). The volcanic rocks of the WC and IAG belong to group I, those of the EC predominantly to group II. These two andesitic groups are the object of this investigation. The rocks of group III (latitic rocks of the EC) are closely related to group II. Group IV (foiid-bearing tephrites of the SAA) are not considered in this publication.

Western Cordillera (WC) and Inter-Andean Graben (IAG)

The rocks here (group I of Fig. 4), predominantly quartz andesites and plagiodacites, are characterized by low K_2O (0.7–1.2%) as well as low SiO_2 contents (52.5–63%). In the QAPF-diagram of Fig. 2 their compositions lie along the Q-P-side. This trend is typical of andesitic island-arc series, but is absent in Andean-type andesites. The series is calc-alkaline in terms of the AFM-diagram of Fig. 3. The rocks have the typically low TiO_2 contents of the circum-oceanic Cenozoic lavas (Chayes, 1964). Iron enrichment is some-

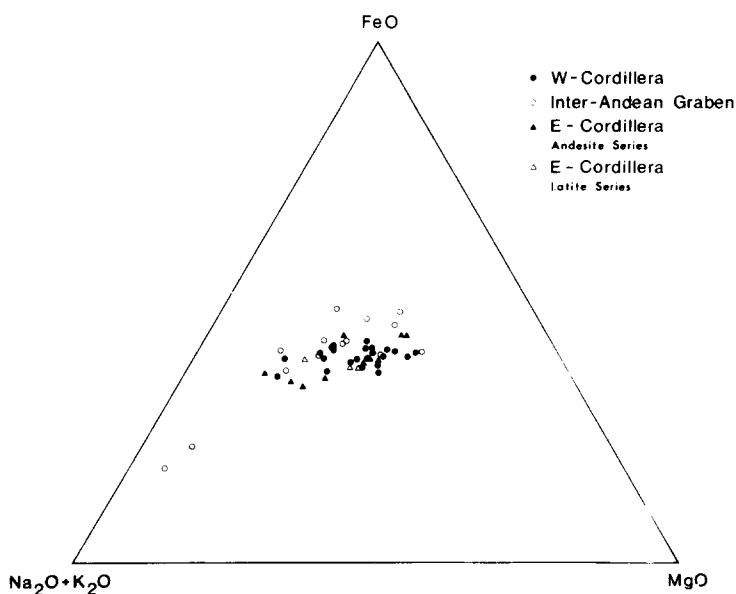


Fig. 3. AFM diagram plot of Cenozoic volcanic rocks of Ecuador. The rocks are calc-alkaline in terms of this diagram.

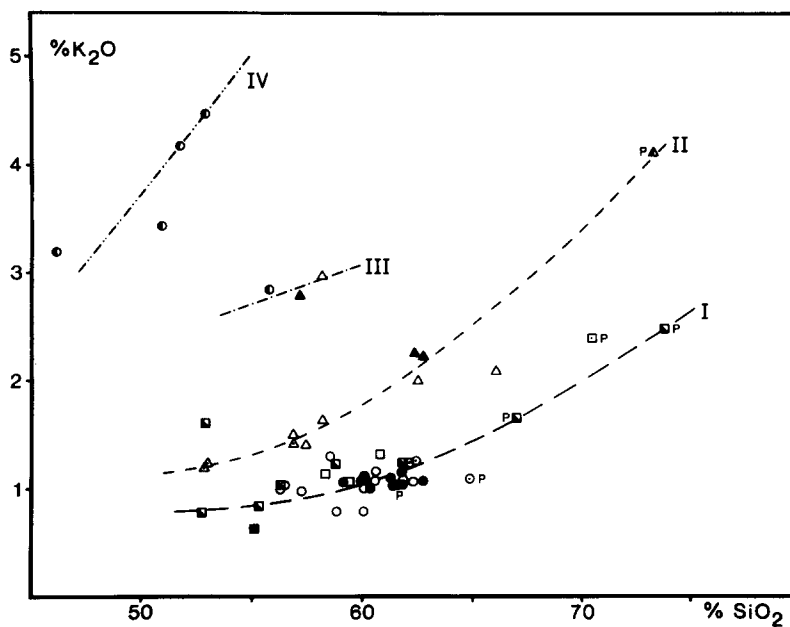


Fig. 4. K₂O versus SiO₂ diagram of Cenozoic volcanic rocks of Ecuador. Rocks of group I: andesite series of the Western Cordillera (WC) and Inter-Andean Graben. Rocks of group II: andesite series of the Eastern Cordillera (EC). Rocks of group III: latite series of the Eastern Cordillera (EC). Rocks of group IV: foid-bearing volcanics of the Sub-Andean Area (SAA). Signatures as in Fig. 2.

what more pronounced in the rocks of the IAG where the average FeO/MgO ratio is 1.6 compared to 1.4 in the rocks of the WC. Some rare samples of pumice, which are light products of fractional crystallization of the andesites, have higher K₂O (1.7–2.5%) and SiO₂ contents (68–74%).

Eastern Cordillera (EC)

The rocks (group II of Fig. 4) usually have higher K₂O (1.4–3.0%) and SiO₂ (57–66%) contents than the corresponding rocks of the WC. They are mainly quartz andesites, quartz latianandesites and dacites (Fig. 2). The group also comprises some rhyolitic pumice and obsidian samples. In the QAPF-diagram of Fig. 2 the compositions follow a trend which is characteristic of the andesite series of the central and southern Andes (e.g. Hörmann et al., 1973). The average FeO/MgO ratio is 1.5, similar to the andesites of the WC. The most primitive andesites of this series are closely related to the andesites of the IAG and WC. However, the occurrence of the latite series (group III in Fig. 4) is unique to the EC and SAA. The coexistence of lavas of the andesite and latite series, even in lavas of the same volcano, is a common feature of the Andean-type calc-alkaline volcanic rocks, not only in Ecuador, but also in the Central Andes and Mexico (Richter and Negendank, 1976; Weyl, 1977).

TRACE-ELEMENT COMPOSITION

In addition to the major element compositions, the rocks of the WC and EC also have different trace element contents as shown by the data of Tables III, IV and V and by the variation diagrams of Figs. 5a–i. In these figures, K₂O or MgO is used as a differentiation index.

Western Cordillera and Inter-Andean Graben

The data of Table III indicate that the rocks here have lower contents of large-ion-elements (Rb, Sr, Ba), large highly charged cations (Th, U, Zr) and light rare earth elements (La, Ce) and Y than corresponding rocks of the EC.

A correlation of the Rb, Sr, Ba, La, Ce, Y and Th contents with K₂O is absent. On the other hand, the Ni and Cr abundances are correlated with the MgO contents (Figs. 5h,i). The trace element contents correspond neither to those of the tholeiitic nor to the calc-alkaline island arc associations (Table IV) and are completely different from those of the calc-alkaline rocks of the central Andes (Table V).

The light rare earth elements (LREE) are slightly enriched compared to the Heavy rare earths (HREE). Using the data of Table III, the chondrite-normalized values are La_N 23, Ce_N 14, and Yb_N 8.4. Thus, the LREE La and

TABLE III

Trace element contents of Cenozoic volcanic rocks of Ecuador. Contents of elements in ppm, oxides in weight percent

Element or oxide	(1)		(2)	
	Average	Range	Average	Range
K ₂ O	1.17	0.63— 2.50	2.51	1.21— 4.47
Li	12	7 — 21	15	9 — 22
Rb	32	11 — 73	65	30 — 140
Sr	422	292 — 727	650	110 —1171
Ba	590	363 —1289	938	600 —1378
MgO	4.00	0.51— 7.21	4.04	0.18— 6.32
Ni	36	1 — 136	38	1 — 81
Co	14	1 — 45	13	1 — 30
Cu	38	6 — 160	59	2 — 134
Cr	93	1— — 289	62	1 — 165
V	119	18 — 165	103	14 — 152
La	7	1 — 17	19	3 — 52
Ce	12	1 — 36	31	1 — 68
Yb	1.6	0.9 — 3.3	1.7	1.2 — 2.6
Y	7	1 — 31	33	6 — 62
Zr	69	39 — 222	126	72 — 235
Th	3.9	1 — 18	8.3	4.4 — 16
U	1.0	0.6 — 1.8	1.5	0.5 — 6.9
Th/U	3.9	1 — 11	7.8	1 — 18
K/Rb	331	124 — 654	284	203 — 396

(1) Composition of 38 andesites, plagidacites and dacites from the volcanoes of the Western Cordillera and Inter-Andean Graben (group I of Fig. 4).

(2) Composition of 14 andesites, latianandesites and latites of the Eastern Cordillera (groups II and III of Fig. 4). For correlation see Figs. 5a-i.

Ce are higher by a factor of 1.7–2.7 than the HREE Yb in a chondrite-normalized representation. In comparison to oceanic tholeiites, the LREE are slightly enriched, the HREE depleted. The REE distribution patterns are intermediate between those of the A and B group andesites of the central Andes (Dostal et al., 1977). The main trace element characteristics are: high Ba but also high Ni and Cr contents, and very low Y contents.

Eastern Cordillera

The rocks are characterized by Rb, Ba, Sr, La, Ce, Y, Th, U and Zr contents higher than in corresponding rocks of the WC (Table III). These elements, except for U, are correlated with the K₂O contents (Figs. 5a–g). This is a main characteristic of the rocks of the EC. The Ni and Cr contents, as in rocks of the WC, are strongly correlated with the MgO contents. (Figs. 5h, i).

The trace element abundances correspond closely with those of the calc-alkaline volcanic rocks of the central Andes (Table V). The REE distribution

TABLE IV

Trace element composition of andesitic melts of the Western Cordillera of Ecuador

	(1)	(2)	(3)	
		Th	CA	
Rb	32	6	30	15—25
Ba	590	100	270	370—563
Ni	36	20	18	22—26
Cr	93	15	25	10—50
La	7	2.4	11.9	8—16
Ce	12	—	24	20—40
Y	7	—	21	—
Yb	1.6	2.4	1.9	2.1—3.7
U	1.0	0.3	0.7	—
Th	3.9	0.3	2.2	—

(1) Trace element contents of andesites and plagiadacites of the Western Cordillera of Ecuador, data from Table III. For comparison: (2) Contents of tholeiitic (Th) and calc-alkaline (CA) andesites from island arcs, according to Jakes and White (1962).

(3) Contents of calc-alkaline adesites (groups I and II) from the Chilean transect of Dostal et al. (1977).

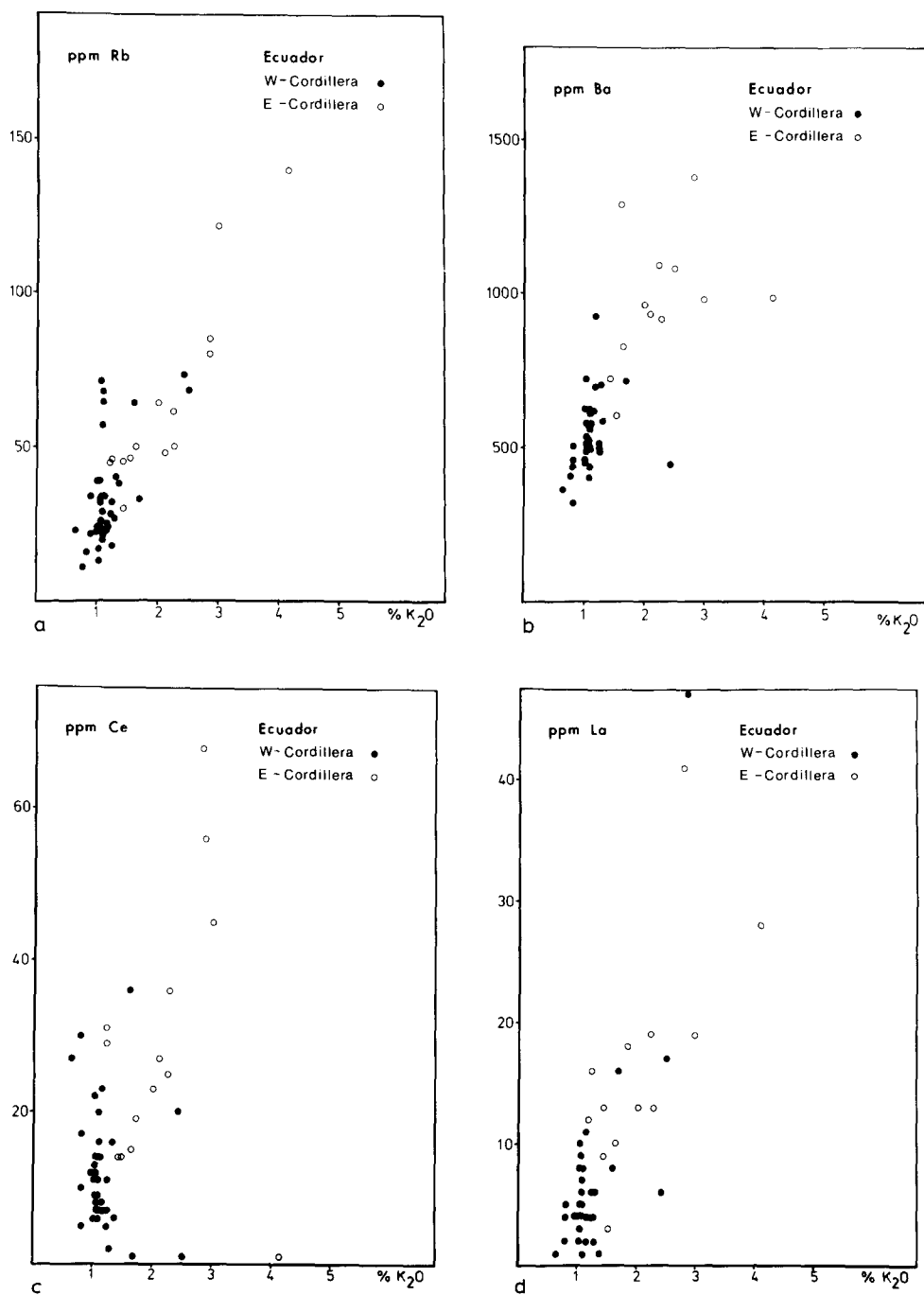
TABLE V

Trace element composition of andesitic melts of the Eastern Cordillera

	(1)	(2)	(3)
Rb	65	(30—140)	30—45
Ba	938	(600—1378)	270—520
Ni	38	(1—81)	18—5
Cr	62	(1—165)	25—13
La	19	(3—52)	12—14
Ce	31	(1—68)	24—19
Y	33	(6—62)	21—20
Yb	1.7	(1.2—2.6)	1.9—1.4
U	1.5	(0.5—6.9)	0.7—0.6
Th	8.3	(4.4—16)	2.2—1.7

(1) Trace element contents of andesites, dacites and rhyolites of the Eastern Cordillera of Ecuador. Data from Tab. 3 For comparison on: (2) Contents of cald-alkaline andesites and dacites of island arcs, according to Jakes and White (1962).

(3) Contents of calc-alkaline rocks of the Central Andes, according to Siegers et al. (1969), Ce, La, Yb from Dostal et al. 1977, Y from Taylor (1969), U from Zentilli and Dostal (1977).



Figs. 5a-i. Trace element contents of Cenozoic volcanic rocks of the Andes of Ecuador. K₂O or MgO is used as a differentiation index.

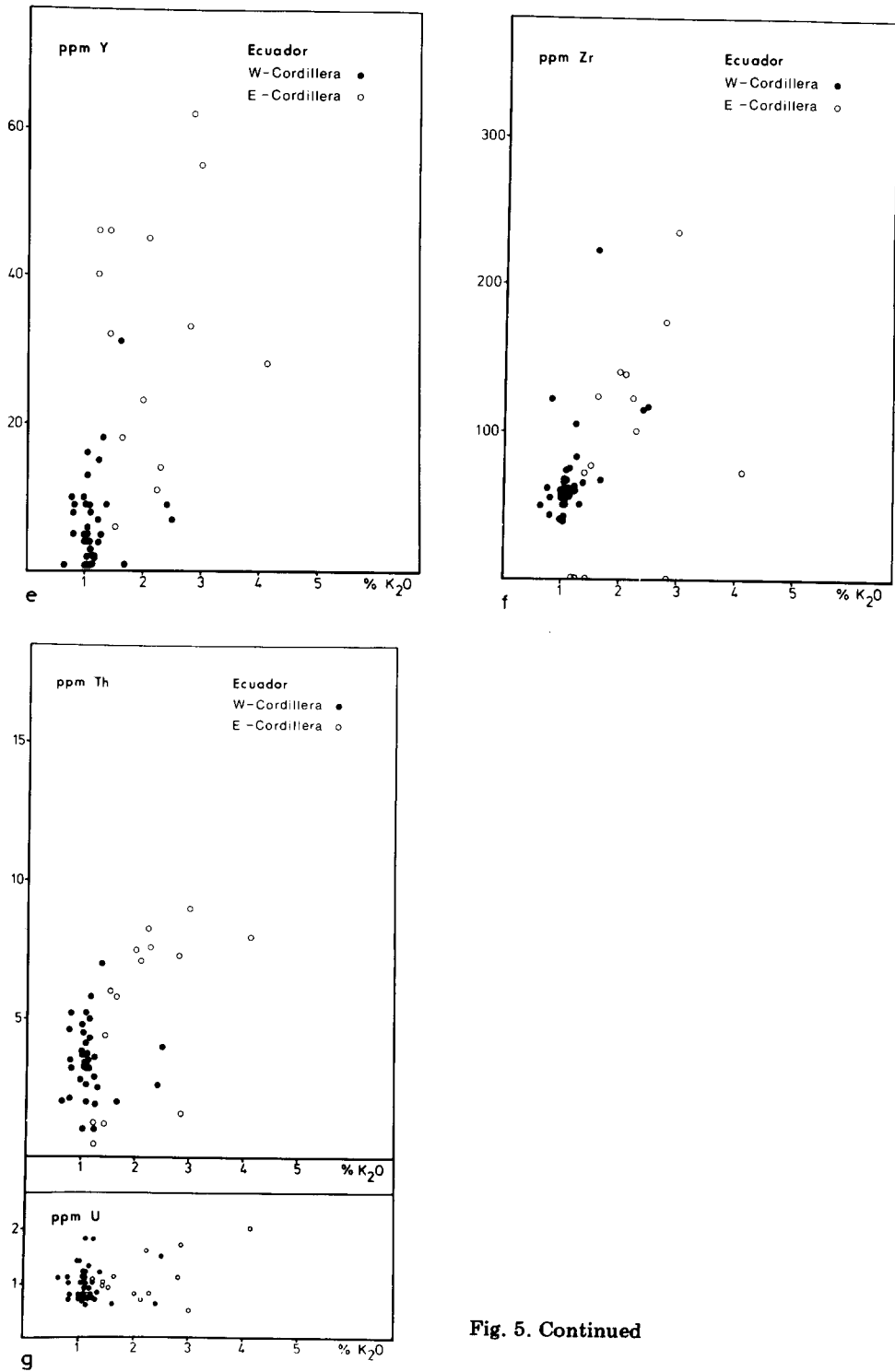


Fig. 5. Continued

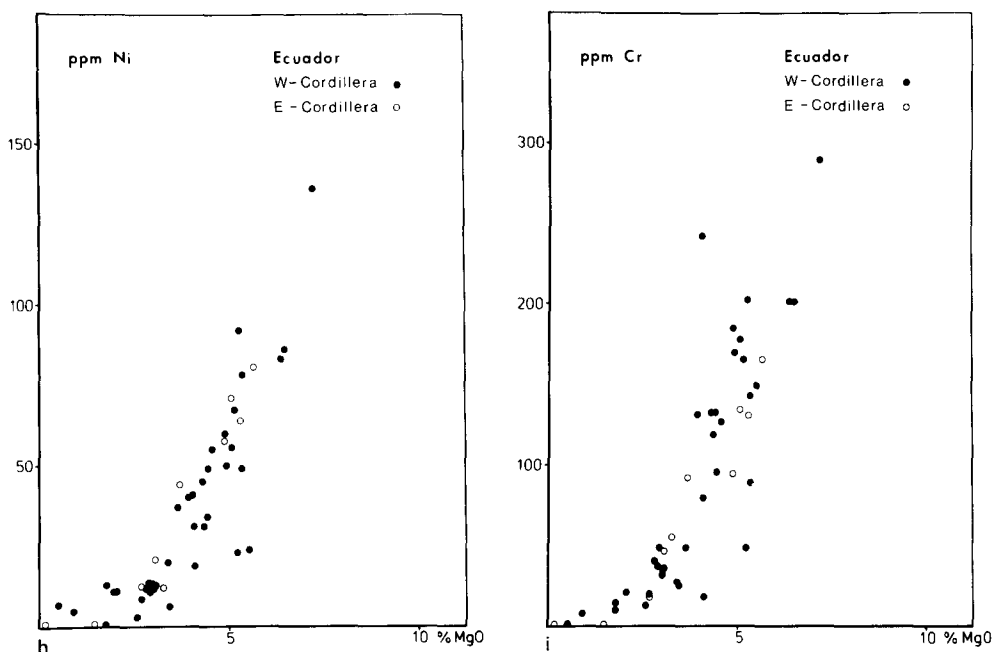


Fig. 5. Continued.

patterns are characterized by a stronger enrichment of all of the REE. The chondrite-normalized values are: La_N 61, Ce_N 37, Yb_N 9. Thus, the LREE are higher by a factor of 4–7 compared with the HREE. The trace element characteristics of the rocks here are those of the Andean-type andesitic rocks (e.g. Siegers et al., 1969; Dostal et al., 1977) and there exists no similarity to the rocks of the island-arc associations (e.g. Jakes and White, 1972; Ewart et al., 1973).

DISCUSSION

Petrogenesis of andesitic magmas

It was postulated that andesitic magmas can form by hydrous partial melting of either perioditic rocks from the upper mantle or metabasaltic rocks of the oceanic crust (amphibolite versus eclogite). However, the formation of the andesites of the North Andes by the partial fusion of upper mantle material under hydrous conditions is not very likely. The liquids produced in natural and model peridotite systems at water pressure above 10 kbar (Kushiro et al., 1972; Kushiro, 1974; Mysen and Boettcher, 1975) are quartz-tholeiites and magnesian andesites rather than andesites of the Andean type.

The major element composition of the synthetic liquids is characterized by very high CaO and very low K₂O contents. The andesitic composition of Kushiro's experiments in the system Mg₂SiO₄—SiO₂—0.5 CaAl₂Si₂O₈—0.5 NaAlSi₃O₈ was achieved after addition of 10% KAlSi₃O₈ (Kushiro, 1974). Mysen and Boettcher (1975a,b) found that at higher degrees of partial melting the K₂O content of the melts remains low, even if phlogopite is added to the charges. The low K₂O content is not expected to increase notably during subsequent fractionation, neither at high pressures where amphibole coexists with the melts, nor at low pressures where plagioclase is stable, because both phases incorporate K₂O in similar amounts as it is present in the melts. In addition, the experimentally produced liquids are not calc-alkaline but tholeiitic in terms of the AFM-diagram. Objections arise also from the trace element contents of the natural andesites.

Whereas the REE distribution pattern of the andesites is explicable by the partial melting of 10–30% of a perioditic source rock (Dostal et al., 1977), the other trace element abundances are not compatible with such an origin: higher Ni and Cr contents and lower contents of LILE elements (K, Rb, Ba etc.) would be expected. Thorpe et al. (1976) and Dostal et al. (1977) discussed the problem of the low Ni and Cr contents of the andesites in some detail. They state that the magmas underwent a fractionation of olivine ± spinel ± clinopyroxene at depths greater than 35 km and thus the Ni and Cr contents of the melts would be greatly reduced.

However, the fractionation of these magnesium-rich phases would thereby emphasize the tholeiitic trend of the melt compositions in the AFM diagram which contradicts the facts. The high contents of LILE elements necessitate the assumption of an "enriched" upper mantle. James et al. (1976) argued that the upper mantle beneath the Andes could be enriched in dispersed elements due to liquids from the asthenosphere. Mysen (1979) found in an experimental investigation that water-rich vapors coexisting with peridotite at high pressures concentrate the REE. This could also occur for the LILE elements (Best, 1975). In fact, hydrous partial melting of an hypothetical uppermost mantle "enriched" by the action of such fluids could explain the trace element composition of andesite, but not the calc-alkaline trend in the AFM-diagram. Because of these objections the investigators believe that andesitic magmas originate rather by partial fusion of metabasalts (amphibolite, garnet amphibolite, eclogite) than from peridotite.

In basalt systems the subsolidus transformations and melting behaviour are controlled by the relation of water pressure to total pressure. If $p_{\text{H}_2\text{O}} = p_{\text{total}}$ a transformation of amphibolite into garnet amphibolite occurs near 500–600°C at 6–10 kbar (Raith et al., 1977). The solidus temperatures are near 700°C in the 6–25 kbar pressure range with a minimum near 15 kbar (Hill and Boettcher, 1970). When the temperature is raised above the solidus, rhyodacitic, dacitic, andesitic, or basaltic liquids are formed. The composition of the liquids depends on the composition of the source rock, on the degree of partial melting, and the nature and composition of the minerals coexisting with the melt.

At pressures lower than 10 kbar, hydrous partial melting generates a variety of calc-alkaline liquids ranging from rhyodacitic to olivine andesitic composition (Holloway and Burnham, 1972). Increasing temperatures (750–1150°C) cause the mineral assemblages coexisting with melt to change from $\text{amph} + \text{cpx} + \text{ol} + \text{sp} \pm \text{plag}$ to $\text{cpx} + \text{ol} + \text{sp}$, and $\text{cpx} + \text{ol}$. Since this kind of andesite formation necessitates unrealistically high geothermal gradients, it needs no longer be discussed. Moreover, olivine is usually absent in the andesites of the northern Andes.

In the pressure range of 10–20 kbar (750–1150°C) plagidacitic and andesitic liquids coexist mainly with $\text{amph} + \text{cpx} \pm \text{opaques}$, or cpx alone (Allen et al., 1975; Allen and Boettcher, 1978). Between 16 and 20 kbar, minor amounts of garnet enter the assemblages. The liquids are calc-alkaline and similar to the andesites of the North Andes. It will be discussed in the following section that the geochemical and petrological data favour this kind of andesite formation. At pressure between 20–30 kbar (800–1150°C) hydrous partial melting of basalt generates a variety of andesitic liquids coexisting mainly with $\text{cpx} + \text{gar}$, or gar alone (Green and Ringwood, 1968; Allen et al., 1975; Stern and Wyllie, 1978).

Objections against the application of this model arise from the REE distribution patterns of the andesites of the North Andes. Melts coexisting with large fractions of garnet should be characterized by a marked depletion of the HREE which are preferentially incorporated into garnet, i.e. by a high Ce_N/Yb_N ratio (Gill, 1978).

The authors are aware that the compositional variation of the andesite series (groups I and II of Fig. 4) could also be interpreted as the result of extensive amphibole and clinopyroxene fractionation of a tholeiitic magma, at least on the basis of the petrological data available (see above). Enormous volumes of fractionates would be generated which could amount up to 30% of the original magma mass. Fragments of the fractionates should be present as xenoliths in the andesites. Such xenoliths which would be easily detectable were never observed in the andesites of the North Andes. Consequently, among all the hypotheses, the formation of andesitic magmas by the hydrous partial fusion of amphibolites at pressures of 10–20 kbar, most likely near 20 kbar where small amounts of garnet enter the assemblages, seems to be the process involved.

Generation of the andesitic to plagidacitic magmas of the Western Cordillera and the Inter-Andean Graben

It was postulated above that the andesitic magmas of the WC and IAG most likely originated by partial melting of basalts metamorphosed to amphibolite. Fusion may have occurred at pressures near 20 kbar ($p_{\text{H}_2\text{O}} = p_{\text{total}}$) and temperatures of more than 750°C. According to Allen et al. (1975), the melts coexist mainly with amphibole, clinopyroxene and opaques. With increasing temperatures the fraction of amphibole decreases whereas the fractions of clino-

pyroxene and melt increase. Small amounts of melt have a dacitic composition, higher weight fractions of melt (20–30%) coexisting with variable fractions of amphibole (70–30%) and clinopyroxene (10–30%) are plagiadacitic to andesitic. The chemical composition of the hypothetical source amphibolite can be recalculated by means of the mineral compositions reported by Allen et al. (1975), the composition of the andesitic melts (Table I) and the weight fractions (see above).

The result of such calculations is always a tholeiitic source rock. This confirms our model that the magmas of the WC and IAG can form by partial melting of a basaltic amphibolite. The model explains the small variation of the Na content of the andesitic melts which seems to be buffered by two Na-bearing solid phases: amphibole and clinopyroxene. Na-rich amphibole breaks down through a temperature range of more than 200°C into Na-poor clinopyroxene and Na-rich andesitic melt.

The trace element data are in agreement with this notion. The LILE elements K, Rb, Ba are enriched in the melts compared to the basaltic source rock because both amphibole and clinopyroxene have crystalliquid distribution coefficients in the $0.0X-0.X$ order of magnitude (e.g. Gill, 1978).

The REE and Y, with distribution coefficients of $0.0X-0.X$ for amphibole and clinopyroxene (Wedepohl, 1975; Gill, 1978) become also enriched in the melts. The contents of the REE decrease with increasing melt fraction. The decrease is less pronounced for the HREE (e.g. Yb) than for the LREE (e.g. Ce), because the former have the higher distribution coefficients. Consequently, the Ce/Yb ratio decreases with increasing degree of partial melting. Like the REE, U, Th and Zr become enriched in the melts compared to the basaltic source rock.

The contents of Ni and Cr with distribution coefficients in the XO order of magnitude (Gill, 1978), for both amphibole and clinopyroxene increase with increasing degree of melting and the Ni and Cr versus MgO correlation becomes established. The absence of a correlation of the Rb, Ba, Y, REE, U, Th and Zr contents with K_2O may be due to variable abundances of these elements in the source rocks.

Generation of the andesitic to rhyodacitic magmas of the Eastern Cordillera

The magmas of the WC and EC show some geochemical features common to both series: identical $^{87}Sr/^{86}Sr$ ratios of 0.704 (Francis et al., 1977) and identical Ni and Cr versus MgO correlations (Figs. 5h,i).

The compositions of the EC magmas differ from those of the WC mainly by the higher and variable K_2O contents, the Rb, Ba, Y, Th, Zr versus K_2O correlations, and by a stronger enrichment of the LREE ($Ce_N 37$ versus $Ce_N 14$), the HREE being similar ($Yb_N 8$ to 9). A theory on the origin of the magmas has to consider these aspects. Because of the low $^{87}Sr/^{86}Sr$ ratios the generation of the magmas by partial fusion of continental crust can be excluded. The REE distribution patterns with Ce_N/Yb_N ratios only twice to three

times that of the WC rocks prevent the application of an eclogite partial melting or eclogite fractionation model (Gill, 1978). Because of the absence of negative Eu anomalies it seems also unlikely that the andesitic types developed into rhyodacitic by extensive plagioclase fractionation, or that the rhyodacitic magmas generated by partial melting of metabasalts at pressures < 10 kbar where plagioclase is stable (Holloway and Burnham, 1972).

If these facts are taken into account then the following hypothesis could prove true: The magmas of the EC, like those of the WC, are generated by the partial fusion of amphibolites, i.e. by the process already discussed in the previous chapter.

The LREE_N higher by a factor of 2–3 could be related to a small fraction of garnet which enters the assemblage $\text{amph} + \text{cpx} \pm \text{opaques} + \text{melt}$ near the upper pressure limit of the range 10–20 kbar (Allen et al., 1975; Allen and Boettcher, 1978). At very low degrees of partial melting the liquids are rhyodacitic and develop into andesitic as the fraction of melt increases.

Source rocks

It is suggested that the metabasalts which underwent partial melting were of the type now present in the Mesozoic to Cretaceous Basic Igneous Complex of Ecuador and Colombia. This rock unit extends from the Pacific coast to the Eastern Cordillera over a distance of about 200 km and consists of olivine tholeiites of MORB composition as well as quartz tholeiites of the island-arc type, the latter being enriched in the elements K, Rb, Ba, Th and U (Hörmann, et al., in prep.). Such basalt types, transformed into amphibolite or garnet amphibolite, could also occur in the subduction zone beneath the Cordilleras.

The existence of a Benioff plane was proven by Meissner et al. (1976) in adjacent south Colombia where it dips at an angle of about 25° to the east, its upper delimitation being 80–150 km beneath the Western and Central Cordillera (EC in Ecuador). Seismic foci at depths of 50–80 km were related to wedges of oceanic material from older subduction processes (Case et al., 1973; Meissner et al., 1976). However, the hypocenter data set is small and it cannot be decided whether this is true or whether the recent underthrust plate is broken into segments which dip into the mantle at various angles. On the basis of available information the geophysical data do not contradict the opinion that the Cenozoic magmas of the WC and EC are generated by the partial melting of amphibolites at pressures near 20 kbar.

If one accepts that the subducted oceanic crust had a composition similar to the Mesozoic BIC of Ecuador (see above) then the different andesite series of the Ecuador Andes could originate by the partial melting of chemically different source rocks: olivine tholeiitic amphibolite being the source of the andesite-plagidacite series of the WC, enriched quartz tholeiitic amphibolites the source of the andesite-rhyodacite series of the EC.

RESULTS

The investigations of the andesitic volcanic rocks of the volcanoes of the WC and EC of Ecuador have revealed a characteristic zoning of the Cenozoic magmatism.

The volcanic rocks of the WC belong to a calc-alkaline andesite-plagiodacite series which is characterized by only small variations in chemical composition. The contents of large cations (Rb, Ba, Sr), REE (La, Ce) and Y and large highly charged cations (Th, U, Zr) are not correlated with K_2O . The K_2O content of this series is nearly constant ($\sim 1\%$ K_2O). Cr and Ni are strongly correlated with MgO. Th/U ratios are low (3.90) because of low Th contents. The rocks have primitive REE distribution patterns and low $^{87}Sr/^{86}Sr$ ratios (0.704). There exists some similarity with the calc-alkaline volcanic rocks of island arcs. It is suggested that the WC magmas were formed by partial melting of amphibolite of olivine tholeiitic composition at pressures lower than 20 kbar ($p_{H_2O} = p_{total}$) in or above a subduction zone. The rock type of the WC of Ecuador is unique to the Andes and was unknown previously.

The volcanic rocks of the EC are members of an andesite-dacite-ryhodacite series which is typical also for the central and southern Andes. The rocks are characterized by a correlation of the large cations (Rb, Ba, Sr), REE (La, Ce) and Y, and the large cations (Th, Zr), but not U, with K_2O . The K_2O contents are variable (1–3.6%). Cr and Ni are strongly correlated with MgO. Th/U ratios are high (7.80) because of high Th contents. The rocks display moderately fractionated REE distributions with slightly enriched LREE but have also low $^{87}Sr/^{86}Sr$ ratios (0.704).

It is suggested that the magmas of the EC originated by partial melting of garnet amphibolite of quartz tholeiitic composition which was already enriched in K_2O , large cations and highly charged cations.

The major element data demonstrate that the K_2O content of the volcanic rocks of the North Andes increases from west to east, from the WC to the IAG and EC. This corresponds to the hypothesis of Dickinson and Hatherton (1967) who correlated the potassium content of volcanic rocks from orogenic provinces to the depth of formation in or above a Benioff zone.

All volcanic rocks of Ecuador (BIC, WC, IAG, EC) have some common geochemical characteristics which are: Relatively high Ba, U and Th contents, similar K/Rb ratios, and the same Ni and Cr versus MgO correlation.

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