Pole 1

Cretaceous and Paleogene volcanic rocks of Ecuador

M. LEBRAS *Office de la Recherche Scientifique et Technique Outre-Mer. 24, ruê Bayard, 75008 Paris, France,* and *Centre Géologique et Géophysique, Université des Sciences et Techniques du Languedoc, 34060 Montpellier, France*
F. MÉGARD, C. DUPUY *Centre Géologique et Géophysique, Université des Sciences et Techniques du Languedoc, 34060 Montpellier, France*
J. DOSTAL *Department of Geology, Saint Mary's University, Halifax, Nova Scotia B3H 3C3, Canada*

ABSTRACT

Pre-collision Cretaceous–lower Tertiary volcanic rocks of western Ecuador from the coastal area (Piñón and San Lorenzo Formations) and Western Cordillera (Macuchi and Celica Formations) consist of three rock suites. The first suite includes tholeiites of ocean-floor affinities that have distinct light REE-depleted patterns and low La/Nb, La/Hf, and Th/Hf ratios. The island-arc tholeiites of the second suite have lower contents of Ti, Zr, Hf, and Nb. The third suite comprises calc-alkalic rocks, mainly continental-margin andesites and dacites. The continental volcanic-arc rocks crop out in an area east of the tholeiitic rocks. The boundary between the two areas is the major suture separating continental South America from accreted terranes to the west.

A model is suggested for the geodynamic evolution of what is now western Ecuador during the Late Cretaceous. It includes two east-dipping subduction zones of Turonian to Santonian ages and the accretion of the oceanic island arc to the continent.

INTRODUCTION

Along the Andean belt, the post-orogenic Pliocene-Quaternary magmatism is relatively well documented, especially in Chile and Peru (for example, Thorpe and others, 1982). Few data are available, however, for the older, pre-collision magmatic episodes (Chile: Bruhn and others, 1978; Saunders and others, 1979; Dalziel and others, 1974; Peru: Atherton and others, 1983; and Colombia: Marriner and Millward, 1984; Millward and others, 1984). The Andean belt has been divided, according to the type of pre-collision magmatism, into two main segments (Aubouin, 1972; Mégard, 1986): (a) the Northern segment, called "Cordilleran Andes," marked by the presence of oceanic volcanic rock types composing accreted terranes and (b) the Central and Southern segment, called "Liminal or Marginal Andes," where the Mesozoic volcanic rocks were mainly emplaced on a continental basement. In this context, Ecuador is particularly interesting because it is located at the transition between these two main segments. The purpose of this paper is to present new geochemical data on the pre-collision volcanics in Ecuador and to discuss their geodynamic implications.

GEOLOGIC SETTING

The Ecuadorian Andes are largely composed of igneous rocks of late Mesozoic to Tertiary age, part of which rest on an older basement. Basic to intermediate volcanic and plutonic rocks of Cretaceous to Eocene age crop out extensively in the coastal area and the Western Cordillera (Fig. 1). The occurrence of pre-collision volcanic rocks was first noticed by Wolf in 1892 and was later divided into units by Tschopp (1948) and Sauer (1950). More recently, the geology and petrology of the rocks have been described by Goossens and Rose (1973), Henderson (1979), and Feininger and Bristow (1980).

The studied samples were collected from the three major pre-collision magmatic units in Ecuador, namely the Piñón, Macuchi, and Celica Formations (Direccion General de Geologia y Minas, 1982; Bristow and Hoffstetter, 1977). Samples of basic effusive rocks from Cabo San Lorenzo and neighboring coastal areas that are associated with Cretaceous sedimentary rocks were also included in the study as a separate unit, the San Lorenzo Formation. The distribution of the various formations is shown in Figure 1.

The Piñón and San Lorenzo Formations

The Piñón Formation (Tschopp, 1948; Bristow and Hoffstetter, 1977) comprises mostly pillow lavas and associated hyaloclastites as well as massive dolerites that form a dense net of dikes and sills. Cumulate gabbros are associated with Piñón dolerites in a hill 3 km northeast of Cerro de Masvale (area 3 in Fig. 1). North (8 km) of Guayaquil, isolated outcrops of peridotites, among them the Pascuales harzburgite, are also considered to be part of the Piñón Formation (Goossens, 1968; Goossens and others, 1977). The pillow lavas range from aphyric to porphyritic, containing phenocrysts of plagioclase and subordinate augite set in a matrix composed of plagioclase, clinopyroxene, and Fe-Ti oxides. Massive fine-grained dolerites contain the same mineral phases but display intersertal or ophitic texture. Pervasive hydrothermal alteration and mineralization (Fe-Cu sulfides) are common in the Piñón basalts and dolerites, and low-grade metamorphism of zeolite, pumpellyite-prehnite, and in some cases greenschist facies has also been reported (Lebras, 1985).

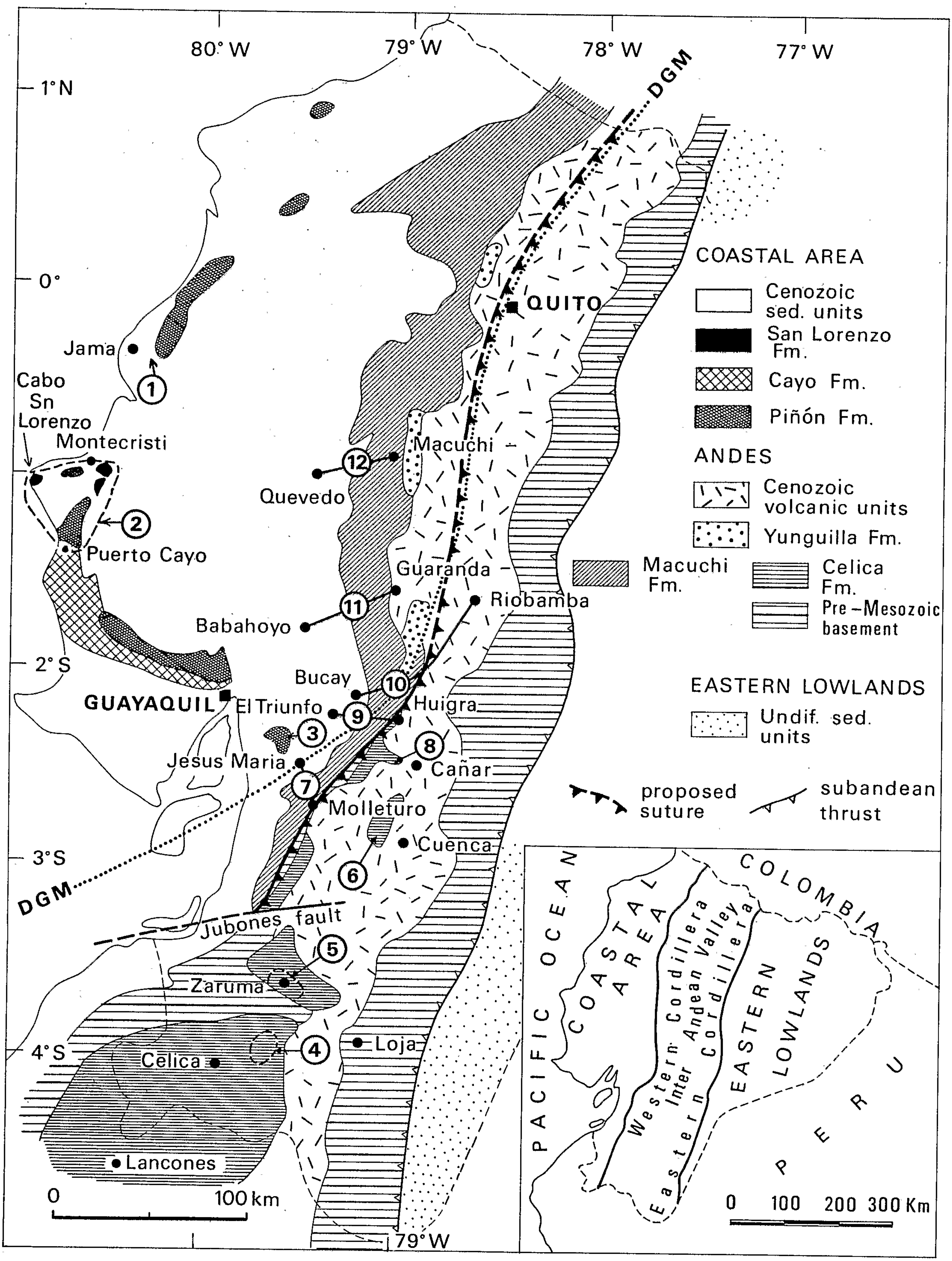
Goossens and Rose (1973) considered the Piñón as part of the Basic

---

Additional material for this article (table of chemical analyses) may be obtained free of charge by requesting Supplementary Data 87-23 from the GSA Documents Secretary.

Geological Society of America Bulletin, v. 99, p. 569–578, 4 figs., 3 tables, October 1987.

O.R.S.T.O.M. Fonds Documentaire
N° : 24 297 ex. 1



80° W
79° W
78° W
77° W
1° N
0°
2° S
3° S
4° S
DGM
Jama
1
Cabo Sn Lorenzo
Montecristi
2
Puerto Cayo
Quevedo
12
Macuchi
QUITO
Guaranda
11
Babahoyo
Riobamba
Bucay
10
GUAYAQUIL
El Triunfo
9
Huigra
3
8
Jesus Maria
Cañar
7
Molleturo
Cuenca
6
Jubones fault
5
Zaruma
4
Loja
Celica
Lancones
0
100 km
79° W
COASTAL AREA
Cenozoic sed. units
San Lorenzo Fm.
Cayo Fm.
Piñón Fm.
ANDES
Cenozoic volcanic units
Yunguilla Fm.
Macuchi Fm.
Celica Fm.
Pre-Mesozoic basement
EASTERN LOWLANDS
Undif. sed. units
proposed suture
subandean thrust
PACIFIC OCEAN
COASTAL AREA
Western Cordillera
Inter Andean Valley
Eastern Cordillera
EASTERN LOWLANDS
COLOMBIA
PERU
0
100
200
300 Km

Figure 1. Generalized geologic map of Ecuador (modified from the geological map of Ecuador, scale 1:1,000,000, Direccion General de Geologia y Minas, Quito, 1982). Numbers refer to areas of sampling reported in Table 2. DGM = Dolores-Guayaquil megashear, dotted line indicates approximate location.

igneous complex of the coastal area and the Western Cordillera of Ecuador and, along with Feininger and Bristow (1980), interpreted it to be a segment of oceanic floor. Henderson (1979), however, considered this formation to be a part of the volcanic arc which in a more developed form, continues as the Macuchi Formation to the east. The K/Ar ages of 113 ± 10 and 107 ± 15 m.y. obtained for the Piñón rocks (Kennerley, 1980) are compatible with foraminiferas and Inoceramus from the base of the overlying sedimentary Cayo Formation, which indicate an age ranging between Cenomanian and Maastrichtian (Faucher and Savoyat, 1973; Bristow and Hoffstetter, 1977). Most of the Cayo Formation consists of turbiditic series comprising thick debris flows including blocks, cobbles, and pebbles of volcanic rocks ranging from basic andesites to rhyolitic welded tuffs. Shales and cherts of Maastrichtian age form the top of the Cayo Formation, and its total thickness reaches 3,000 m. It is disconformably overlain by the middle to upper Eocene San Eduardo Formation, consisting of reworked reefal limestones (Bristow, 1975; Bristow and Hoffstetter, 1977).

The basic rocks that are grouped here under the informal name "San Lorenzo Formation" are basaltic dikes, sills, and flows, the latter comprising pillow basalts. Petrographically, they resemble equivalent rocks from the Piñón Formation, although they may also contain orthopyroxene and quartz in the groundmass. These rocks are less metamorphosed and hydrothermally altered than are the Piñón basalts and dolerites. They yielded K/Ar ages of 87 ± 10 and 66 ± 5 m.y. (Kennerley, 1980), and plagioclase from the pillow basalts of Cabo San Lorenzo has been dated at 72.7 ± 1.4 m.y. by the $^{39}Ar/^{40}Ar$ method (F. Féraud, 1984, personal commun.). These ages and the fact that the San Lorenzo basalts are locally emplaced into sedimentary rocks of Danian age suggest that they should be designated as a separate formation.

In most places, the Piñón, Cayo, San Eduardo, and San Lorenzo Formations are only slightly tilted, but in a few outcrops east of the Guayaquil Gulf (or Guayas River), the Piñón and Cayo Formations are strongly sheared and locally cleaved (for example, area 3 in Fig. 1).

The Macuchi Formation

The pre-collision volcanic rocks of the Western Cordillera were also considered to be part of the Basic igneous complex (Goossens and Rose, 1973). Later, Henderson (1979) postulated that these rocks belong to a discrete island-arc suite called the "Macuchi Formation."

The Macuchi Formation (Henderson, 1979; Feininger and Bristow, 1980) includes lavas ranging from basalts to dacites, as well as associated volcaniclastic rocks, tuffs, and, in many cases, fine-grained sedimentary rocks containing Senonian faunas. The basaltic rocks are fine grained, usually aphyric, composed primarily of plagioclase, augite, and subordinate Fe-Ti oxides. More evolved rocks (andesites and dacites) are porphyritic, containing phenocrysts of plagioclase, hornblende, and/or augite in a fine-grained matrix also containing Fe-Ti oxides. Biotite, quartz, and K-feldspar are present in the more differentiated rocks. These rocks are generally affected by burial metamorphism of zeolite, pumpellyite-prehnite, and greenschist facies (Aguirre and Atherton, 1986). The Macuchi Formation is predominantly overlain by flysch series which are Maastrichtian to Paleocene in age (Faucher and Savoyat, 1973). At latitude 1°S in the Western Cordillera, however, Eocene reefal limestones are both intercalated with and overlie the Macuchi volcanic assemblages, suggesting that the Macuchi island arc was active up to the Eocene (Henderson, 1979). The arc was probably the source of the volcanic debris flows included in the coeval Cayo Formation.

The Macuchi Formation also includes slivers of various sizes caught in the suture zone between the Macuchi island arc and the continent. These slivers have been interpreted as dismembered ophiolites and consist mostly of mid-ocean ridge basalt (MORB)–type rocks which are intercalated with thin layers of silicified shale, but they also include peridotites and layered gabbros intruded by dolerite dikes that crop out 20 km southwest of Quito (Juteau and others, 1977). The basalts are commonly aphyric and contain plagioclase and pyroxene as principal constituents and Fe-Ti oxides in subordinate amounts. Most of the rocks suffered metamorphism of greenschist facies grade.

The Macuchi Formation and associated sedimentary rocks either dip regularly to the east or are affected by north-south open chevron folds. Upright chevrons that have wave lengths of a few hundred metres and the associated axial-plane fracture cleavages are common in the Upper Cretaceous flysch. Penetrative deformation is present only near the major faults and thrusts.

The Celica Formation

The Celica Formation (Feininger and Bristow, 1980) consists of volcanic rocks which belong to an intracontinental arc in northwestern Peru and southwestern Ecuador. They comprise mostly lavas and pyroclastic flows of andesitic composition. Scarce basalts, dacites, and rhyolites are also present. The andesites and dacites are porphyritic and have phenocrysts of plagioclase and rare hornblende and microphenocrysts of clinopyroxene and abundant Fe-Ti oxides. In addition to these minerals, quartz is present in the groundmass. The rocks of the Celica Formation were affected by zeolite, pumpellyite-prehnite, and greenschist facies metamorphism. The Celica Formation is equivalent in age to the Aptian sandstones, middle Albian limestones, and Senonian to Campanian flysch series that are widespread in the Lancones-Celica basin of southwestern Ecuador and northwestern Peru (Fig. 1). Granitoid plutons with K/Ar ages of ~110 m.y. (Kennerley, 1980) intrude Celica volcanics and so the age of the formation could be partly Neocomian. In the geologic map of Ecuador (Direccion General de Geologia y Minas, 1982), the Celica Formation is restricted to an area south of the east-west Jubones fault (3°20′S). However, we also include in the Celica Formation (Fig. 1) similar volcanic rocks that crop out (i) in the upper slopes of the Western Cordillera between the Jubones fault and 2°S and (ii) in the western part of the Eastern Cordillera, where they consist of pillow lavas and volcanic breccias intercalated with slates and metaquartzites.

ANALYTICAL METHODS

Fifty-nine volcanic rocks were analyzed, by atomic absorption, for major elements and for Li, Rb, Sr, Ba, V, Cr, Co, Ni, Cu, and Zn. Forty-nine rocks were selected from this set for determinations of rare-earth elements (REE's) Th, Hf, and Sc by instrumental neutron activation and Zr, Y, and Nb by X-ray fluorescence. The precision and accuracy of the analytical methods were described by Dostal and Dupuy (1984). In general, the precision of the data is better than 10%. The major- and trace-element composition of 12 representative samples is given in Table 1,

TABLE 1. SELECTED ANALYSIS OF PRE-COLLISION VOLCANIC ROCKS FROM ECUADOR

Ref:	Piñón Formation		San Lorenzo Fm.		Macuchi Formation						Celica Formation	
	MORB		IAT		MORB			IAT			calc-alkali	
	8251	8271	8264*	8253	82119	82126	82106	Pi 51	8243	8290	8297	8294
SiO_2	47.4	47.2	53.6	54.3	48.8	51.7	46.9	50.5	51.6	55.3	56.3	66.5
Al_2O_3	13.2	14.5	13.4	14.8	13.9	13.3	13.2	16.0	14.6	14.4	16.8	14.7
Fe_2O_3	9.77	9.59	8.38	11.5	11.2	10.6	12.5	10.6	12.6	10.8	6.30	4.17
MnO	0.21	0.16	0.14	0.17	0.15	0.18	0.20	0.17	0.24	0.18	0.23	0.07
MgO	10.9	10.0	3.82	3.63	8.50	7.13	8.06	4.44	5.17	4.57	3.57	1.15
CaO	13.1	14.8	7.36	8.06	9.97	9.14	10.6	7.90	4.65	7.42	6.63	3.09
Na_2O	1.07	1.24	2.82	3.14	1.71	3.50	3.00	4.63	5.55	2.48	3.72	4.36
K_2O	0.44	0.05	2.00	1.13	0.36	0.04	0.06	1.07	0.21	1.00	0.36	2.18
TiO_2	0.76	0.72	1.20	1.08	1.05	1.02	1.55	0.82	1.01	0.43	0.54	0.47
P_2O_5	0.10	0.07	0.42	0.41	0.08	0.08	0.13	0.17	0.32	0.10	0.20	0.17
H_2O^+	2.81	1.70	4.84	1.08	3.33	2.52	3.56	3.56	3.45	2.38	4.09	2.51
H_2O^-	0.66	0.38	1.12	0.49	0.47	0.30	0.03	0.52	0.22	0.14	0.46	0.17
Total	100.42	100.41	99.10	99.79	99.52	99.51	99.79	100.38	99.62	99.20	99.20	99.54
[Mg]†	.71	.70	.49	.41	.62	.60	.58	.48	.47	.48	.55	.41
Li (ppm)	11	5	9	7	10	4	13	11	12	7	5	16
Rb	5	3	32	20	10	2	2	15	2	17	8	99
Sr	73	93	378	423	133	100	179	367	216	179	602	198
Ba	80	20	285	260	80	15	65	410	125	290	325	660
Sc	51	50	25	31	47	44	51	36	37	44	15	12
V	260	238	354	396	336	318	335	346	401	250	138	63
Cr	500	353	35	20	190	190	310	18	7	14	46	8
Co	50	50	24	29	44	40	52	32	36	35	11	8
Ni	156	164	25	20	104	80	106	19	16	22	24	6
Cu	73	191	363	276	142	139	148	140	92	100	40	3
Zn	56	49	83	111	94	95	88	95	104	85	137	66
La	1.71	1.26	15.0	12.8	3.18	2.55	3.34	5.03	6.79	2.47	11.6	21.6
Ce	4.17	2.86	34.9	29.8	7.80	6.38	9.72	11.1	15.4	5.11	23.8	42.5
Sm	1.52	1.13	6.30	5.57	2.24	1.94	2.88	2.65	3.23	1.46	2.76	4.51
Eu	0.56	0.47	1.47	1.36	0.77	0.63	0.87	0.87	1.10	0.48	0.78	0.95
Tb	0.44	0.31	0.91	0.89	0.58	0.49	0.69	0.54	0.58	0.36	0.30	0.40
Yb	1.46	1.08	3.33	2.86	2.38	2.10	2.49	1.96	2.38	1.80	1.28	2.36
Lu	0.24	0.19	0.44	0.45	0.41	0.34	0.43	0.30	0.39	0.33	0.21	0.38
Y	16	13	35	29	22	21	28		25	17	15	
Hf	0.94	0.60	3.41	3.43	1.47	1.35	2.15	1.48	1.90	0.87	2.26	4.77
Zr	33	24	120	110	54	47	75		72	29	86	
Nb	3	3	3	3	4	5	6		3	2	4	
Th	0.10	0.09	1.67	1.45	0.31	0.32	0.40	0.93	0.90	0.69	3.97	8.36

*Strongly altered samples. †Mg/(Mg+Fe^{2+}) with Fe^{3+}/Fe^{2+} taken as 0.15.

TABLE 2. DESCRIPTION AND LOCATION OF ROCKS LISTED IN TABLE 1

Number	Type	Formation	Area*	Location
8251	Basalt	Piñón	2	80°40′00″W 1°22′00″S
8271	Basalt	Piñón	2	80°44′52″W 1°18′57″S
8264	Dolerite	San Lorenzo	2	80°32′42″W 1°03′19″S
8253	Pillow basalt	San Lorenzo	2	80°54′20″W 1°03′17″S
8294	Dacite	Celica	9	79°03′31″W 2°19′18″S
8297	Andesite	Celica	9	79°00′55″W 2°13′45″S
82106	Dolerite	Macuchi	7	79°26′52″W 2°35′31″S
8290	Dolerite	Macuchi	9	79°11′15″W 2°17′31″S
82119	Pillow basalt	Macuchi (sliver)†	10	78°56′49″W 2°08′31″S
82126	Pillow basalt	Macuchi (sliver)	10	78°58′18″W 2°07′22″S
8243	Basalt	Macuchi	10	79°10′41″W 1°34′39″S
Pi 51	Dolerite	Macuchi	12	79°03′00″W 0°56′00″S

*Location shown in Figure 1. †Tectonic sliver in the suture zone.

and their locations and short descriptions are listed in Table 2. Chemical analyses of other samples can be obtained upon request from the GSA Data Repository.[1]

ALTERATION EFFECTS

Major and trace elements are mobile during low-grade metamorphism, and the effects of such a secondary process are well documented (for example, Condie and others, 1977; Hellman and others, 1979; Dostal and others, 1980). In most of the analyzed samples, the primary magmatic assemblage is modified by low-grade metamorphism, mostly of zeolite facies grade. In some samples, metamorphism is of pumpellyite-prehnite facies, whereas greenschist facies with actinolite is locally present in the Piñón and Macuchi Formations.

In addition to petrography, evidence of the influence of alteration is provided chemically by high LOI and by the presence of normative nepheline in the albitized samples. The relative mobility of some elements is made apparent by a comparison of the contents of trace elements in samples 8264 and 8253 (Table 1); strongly altered sample 8264 has significantly higher K and Rb and lower Ca and Sr values. This sample has slightly higher values for light REE's (LREE's), but compared with 8253, the abundances of all other incompatible trace elements are within the range of analytical error. In the Macuchi Formation, sample 82122, with vesicles containing quartz, calcite, and chlorite, is depleted in most trace elements, including REE's, Sr, and Ba, and displays a REE pattern marked by a LREE enrichment (Fig. 2C).

With the exception of a few most altered samples, only the abundances of alkalies, and occasionally also Sr and Ba, were significantly affected by low-grade metamorphism. The other elements do not appear to be affected by secondary processes.

GEOCHEMISTRY

Coastal Area

The analyzed samples can be subdivided into two groups according to their geochemical characteristics, age, and geologic setting. Most samples have features typical of MORB and were collected in the pre-Senonian Piñón Formation. The others are similar to island-arc tholeiites (IAT) and are from the San Lorenzo Formation of latest Cretaceous to Danian age.

Rocks with MORB Affinities: Piñón Formation. These rocks are hypersthene-normative basalts. The [Mg] values $[Mg/(Mg+Fe^{2+})$ with $Fe^{3+}/Fe^{2+} = 0.15]$ range between 0.71 and 0.52, indicating that the rocks have undergone low-pressure fractionation mainly involving plagioclase and clinopyroxene. The influence of plagioclase is shown by a small negative Eu anomaly in the most differentiated samples and the constancy of Sr when plotted against the [Mg] whereas the role of clinopyroxene is indicated by the steeper decrease of Cr relative to Ni and the approximately constant content of Co. In addition, Ti and V increase with differentiation. All of these features are typical of a tholeiitic trend. The REE patterns of these rocks (Fig. 2A) display a slight but distinct depletion of LREE's, with $La/Yb < 1.4$. Such convex-upward REE patterns are characteristic of some MORB (Frey and others, 1974) and are similar to those of the Nazca plate (Batiza and others, 1982). The low Sr and Ba contents and the low La/Nb, La/Hf, and Th/Hf ratios (Table 3) also indicate affinities with depleted MORB (Saunders and others, 1979). The geochemical patterns of the rocks (Fig. 3) resemble those of some MORB and are characterized by an enrichment of Nb relative to moderately incompatible elements (Zr, Hf, and Sm).

Rocks with Volcanic-Arc Affinities: San Lorenzo Formation. This group of rocks (Table 1) differs from the previous group in several respects. Compared to the MORB-like samples, the rocks are more differentiated with higher SiO_2 concentrations and higher normative quartz and have low Ti/V ratios ($\leqslant 20$). The low Ni and Cr content is typical of orogenic volcanic rocks (Gill, 1981) whereas the incompatible elements are enriched. The chondrite-normalized REE patterns (Fig. 2B) display LREE enrichment with La/Yb = 4–5. Such patterns have been recognized in three different geologic settings: intracontinental (Dupuy and Dostal, 1984), oceanic floor (Wood and others, 1979), and island arc (Jakes and Gill, 1970). The first environment may be eliminated on the basis of the low Ti/Y, Nb/Y, and Zr/Y ratios in the studied samples. Although the Th/La ratio (<0.13) is low and similar to that of oceanic basalts, ratios such as La/Nb and Th/Hf (Table 3) are relatively high and tend to be more characteristic of subduction-related basalts (Saunders and others, 1979). Their MORB-normalized trace-element pattern (Fig. 3) is typical of volcanic-arc settings, with an enrichment of Th relative to the elements from the segment between Ce and Yb and a distinct negative Nb anomaly (Gill, 1981). There is some similarity between this group and back-arc basin basalts such as those from the Sarmiento ophiolite complex (Saunders and Tarney, 1979). The latter, however, has features which are transitional between MORB and IAT whereas the studied samples have characteristics of IAT.

Macuchi Formation

In the Macuchi Formation, at least two rock types have been identified on the basis of major and trace elements. The first type includes rocks that have MORB affinities and that are located at the base of the formation or form elongated tectonic slices in the suture zone parallel to the grain of the Cordillera. The second type comprises rocks with volcanic-arc affinities which form the main component of the Western Cordillera.

---

[1] The table of chemical analyses (Table A) may be obtained free of charge by requesting Supplementary Data 87-23 from the GSA Documents Secretary.

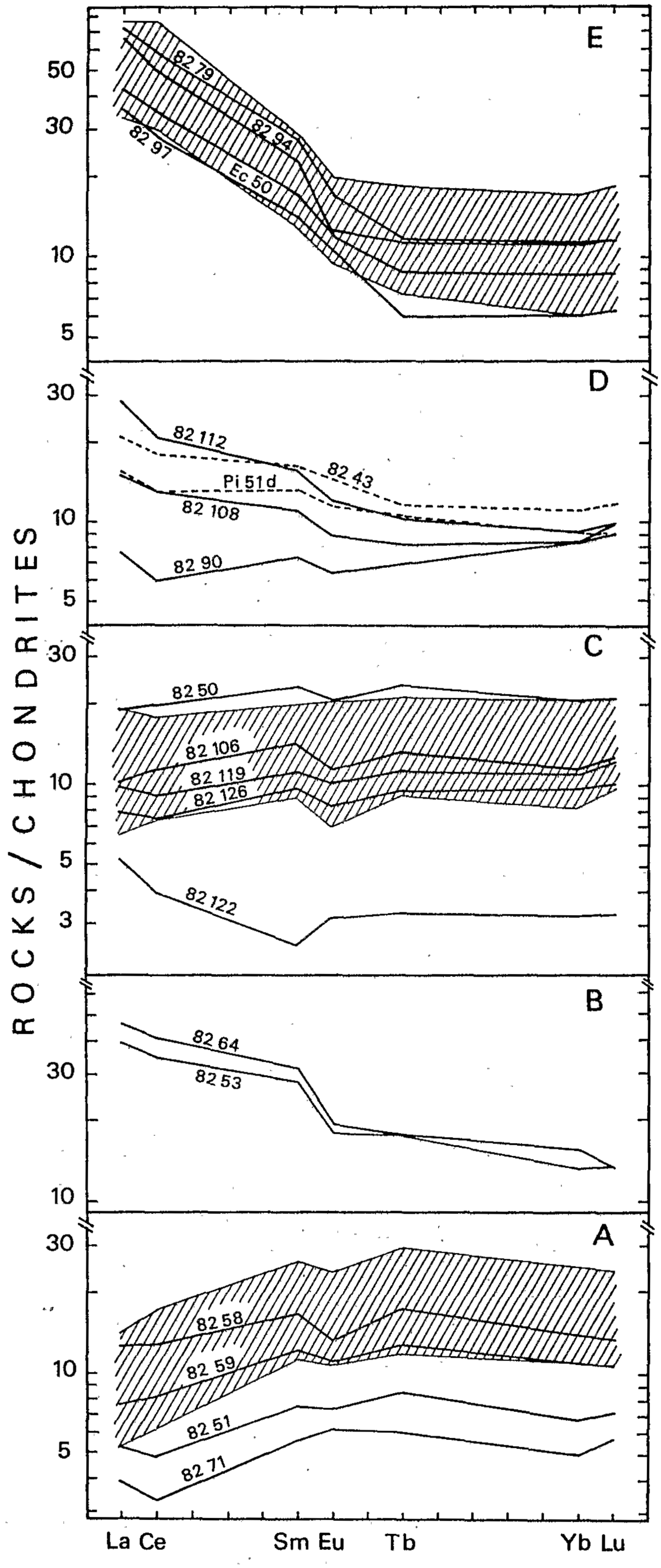


Figure 2. Chondrite-normalized REE abundances in pre-collision volcanic rocks from Ecuador.

A. Piñón Formation: basalts that have MORB affinities. Shaded area denotes the field of MORB from the Nazca plate (Batiza and others, 1982).

B. San Lorenzo Formation: basalts that have IAT affinities.

C. Macuchi Formation: basalts that have MORB affinities. Shaded area indicates the field of Cretaceous tholeiites from Colombia (Millward and others, 1984; Marriner and Millward, 1984).

D. Macuchi Formation: basalts (dashed lines) and andesites (solid lines) of volcanic-arc affinities.

E. Celica Formation andesites. Shaded area delineates the field of continental volcanic-arc andesites (Bailey, 1981).

Rocks with MORB Affinities. These rocks have basaltic composition with hypersthene in their norm. They display an increase of Ti and V during differentiation and a Ti/V ratio (19–30) characteristic of MORB (Shervais, 1982). As in the coastal area, these basaltic rocks have undergone low-P fractionation marked by crystallization of clinopyroxene and plagioclase as shown by the negative Eu anomaly (Fig. 2C) and a sharper Cr decrease compared to Ni during *differentiation.* With the exception of sample 82122 which is altered and partly cumulative, all of the basalts display subparallel REE patterns (Fig. 2C) with a slight depletion of LREE's (La/Yb < 1.4). Ratios involving large-ion–lithophile elements (LILE's) and high-field-strength elements (for example, La/Hf, Th/Hf, and La/Nb) are low (Fig. 3) and characteristic of the T-type MORB (Sun and others, 1979). These rocks are very similar to some volcanic rocks from the coastal area and also to Colombia Cretaceous tholeiitic volcanic rocks (Millward and others, 1984; Marriner and Millward, 1984), as is evident from the REE patterns (Fig. 2C) and various trace-element ratios (Table 3).

Rocks with Volcanic-Arc Affinities. These rocks occur on the western side of the suture over the entire Macuchi Formation (Fig. 1). Compared with the previous group, these rocks display a large range of composition (50%–67% SiO_2), and all have normative quartz. Ti does not show any significant variation during differentiation whereas V tends to decrease with the increase of SiO_2. The corresponding Ti/V ratio in basalts is low and ranges between 14 and 18. All of these features are typical of IAT. Additional evidence for such affinities is the low and relatively constant [Mg] value and the depletion of Cr and Ni content, with V/Cr > 7 and Ni/Co of ~1.

The REE patterns (Fig. 2D) display a lack of heavy-REE fractionation and an enrichment of LREE's with La/Yb between 2 and 5. Negative Eu anomalies are found only in acid andesites. The Zr, Hf, and Nb contents are relatively low in this group, and the La/Nb and Th/Hf ratios are higher than those of MORB but typical of volcanic-arc rocks (Bailey, 1981). The geochemical pattern of these rocks (Fig. 3), characterized by a distinct negative Nb anomaly, strongly resembles that of some rocks of the coastal area which have volcanic-arc affinities. Compared to the Tonga tholeiites (Ewart and others, 1977), their LILE contents tend to be higher but very similar to those of New Hebrides volcanic rocks (Dupuy and others, 1982), which are transitional between IAT and calc-alkalic island-arc rocks.

TABLE 3. AVERAGE TRACE-ELEMENT RATIOS

	Ecuador							Colombia
	Coastal zone		Western Cordillera					Western Cordillera
			Macuchi				Celica	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Th/Hf	.11	.47	.21	.60	.72	1.3	1.7	.20
Th/La	.06	.11	.11	.18	.19	.29	.35	.12
La/Hf	1.8	4.1	2.0	3.4	3.5	4.4	4.7	1.8
La/Nb	.6	5.2	.7	2.0	1.8	2.5	2.3	.6
La/Yb	1.3	4.5	1.3	2.6	3.8	9.6	7.9	1.2
Ti/V	24	17	22	16				21
Zr/Nb	13	44	11	21	19	20	21	11
Nb/Y	.20	.09	.21	.13	.19	.26	.29	.17

(1), (3) Basalts that have MORB affinities.
(2), (4) Basalts that have IAT affinities.
(5) Andesites that have IAT affinities.
(6), (7) Andesites that have calc-alkali affinities.
(8) Cretaceous tholeiitic volcanic rocks from the Western Cordillera of Colombia (Millward and others, 1984, Marriner and Millward, 1984).

Celica Formation

With the exception of sample Ec 70, which has the composition of a high-alumina basalt, all of the volcanics are andesites that have a SiO_2 content between 56% and 60% and that have quartz in their norms. They are characterized by high Al and Ca and low Mg and Ti. Most samples have $FeO_{tot}/MgO < 2.8$ and can be classified as medium-K andesites (Gill, 1981) on the basis of their K_2O content, which ranges between 1.4% and 2.0%. The transition elements, particularly Cr and Ni, are depleted, with $Ni/Co < 1$ and $V/Cr > 3$. These values are typical of calc-alkalic andesites (Taylor and others, 1969). The abundances of the most incompatible elements, including Sr, Ba, and Rb, and some element ratios such as Zr/Nb (Table 3) are comparable to those of medium-K andesites. The exception is Th, which is enriched in the studied samples. The Th/La ratio is also relatively high and close to that of recent Andean andesites. The REE patterns (Fig. 2E) show an enrichment of LREE's, with La/Yb between 6.4 and 9.5 and fall within the range of continental island-arc andesites (Bailey, 1981).

This suite has geochemical features intermediate between island-arc calc-alkalic andesites and typical continental-margin andesites (for example, Dostal and others, 1977). They closely resemble andesites emplaced on a moderately thick continental crust such as those found in New Zealand (Ewart and others, 1977) or in some parts of the Chilean Andes (Deruelle, 1982). It is noteworthy that the few available data on recent andesites from Ecuador (Hawkesworth and others, 1979) show a resemblance to those on the studied rocks.

GEODYNAMIC IMPLICATIONS

Two large areas in western Ecuador can be distinguished using the distribution of the various types of pre-collision volcanic rocks: (a) an area characterized by the presence of tholeiites that have MORB affinities, which are in part associated with the Macuchi island-arc tholeiitic suite, and (b) an area east of the first, containing volcanic suites of the continental volcanic-arc type. In the first area, the Piñón, Macuchi, and San Lorenzo Formations represent different paleotectonic environments. The Piñón Formation consists of a segment of oceanic floor underlying volcaniclastic

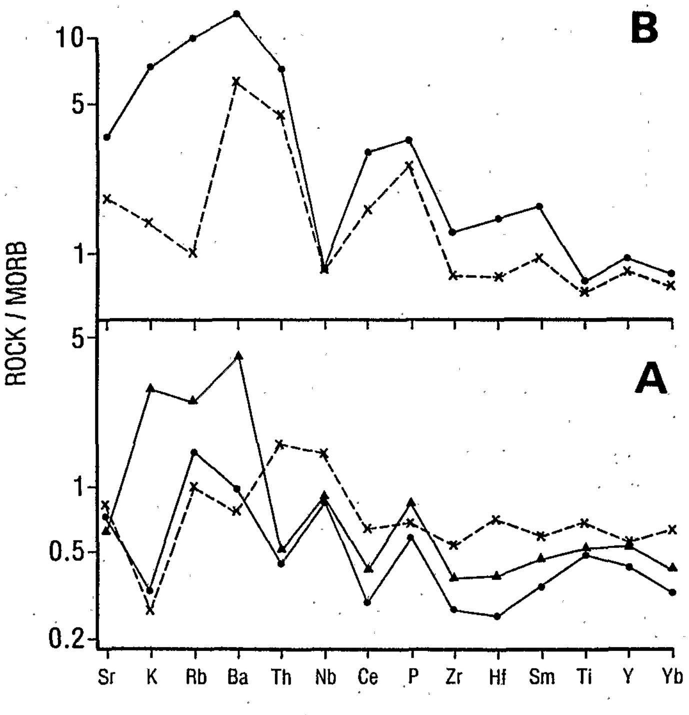


Figure 3. MORB-normalized trace-element patterns for the pre-collision volcanic rocks of Ecuador. A. Basalts that have MORB affinities: Piñón Formation = solid triangles for sample 8251 (slightly altered) and solid circles for sample 8271; Macuchi Formation = x's, sample 82126. B. Basalts that have IAT affinities: San Lorenzo Formation = solid circles, sample 8253; Macuchi Formation = x's, sample 8243. Normalizing values after Pearce (1982).

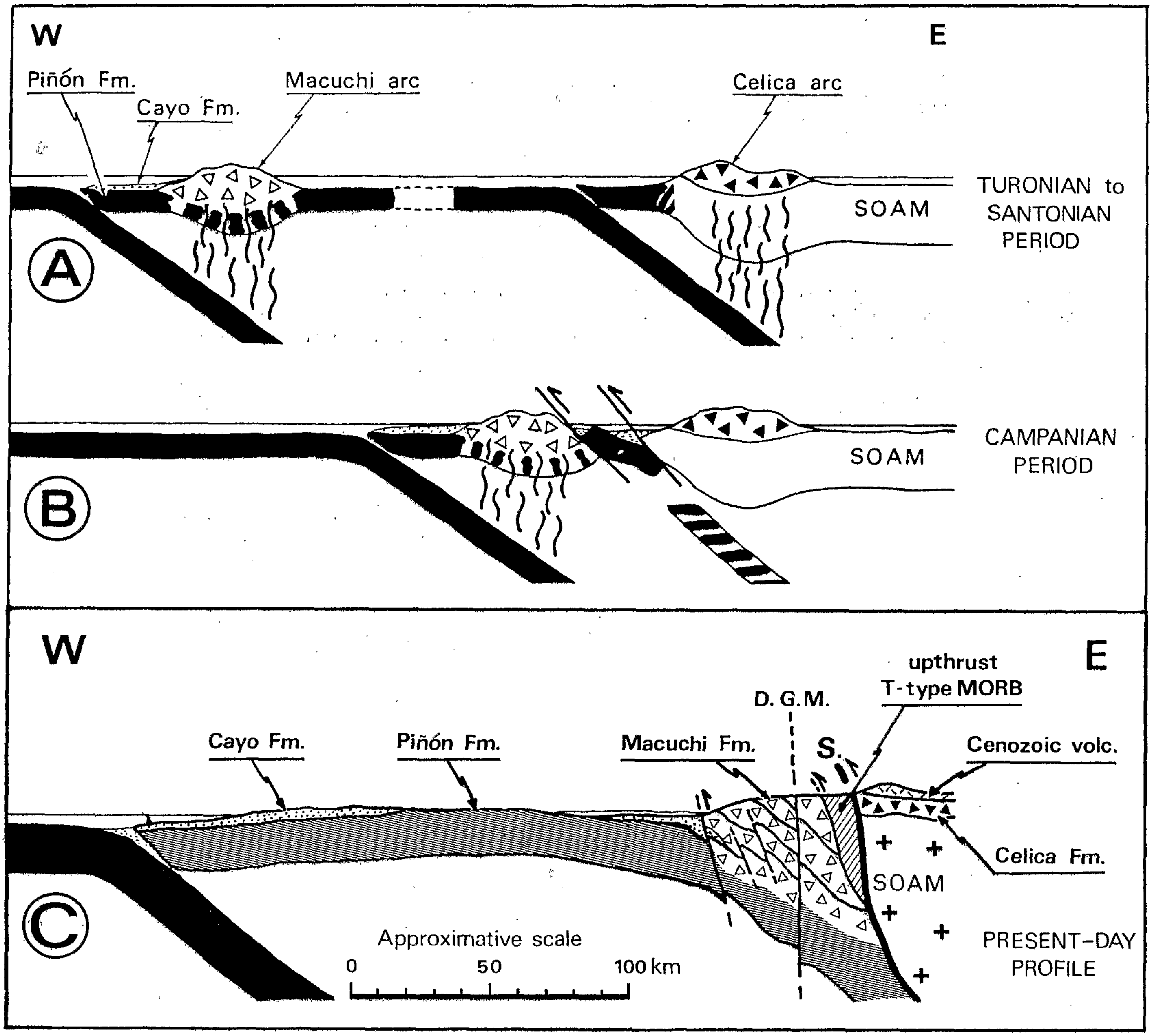


Figure 4. Schematic cross sections showing the proposed plate-tectonic regimes at the beginning (A) and the end (B) of the Late Cretaceous. C is the present profile of the Nazca plate and of the coastal and western parts of the Cordillera of Ecuador at ~2° south latitude (with vertical exaggeration of ~2). DGM = Dolores-Guayaquil megashear; S = suture zone; SOAM = continental South America.

layers that issued from the Macuchi island arc, implying that the Piñón and Macuchi Formations were contiguous. The San Lorenzo Formation consists of a limited amount of island-arc tholeiites erupted on top of the Piñón oceanic floor and isolated from the Macuchi arc. In contrast, the Celica volcanic arc of the second area formed on the lip of the continent.

The boundary between the two areas is a major north-northeast–trending suture. Near the Equator, it is located between the continental crust underlying the town of Quito (Bruet, 1949) and the ophiolite complex 20 km farther southwest. This slice parallels the suture and extends for at least 100 km southward as suggested by north-south–trending residual positive gravity anomalies that are conspicuous in the gravimetric map (Feininger, 1977). Along the El Triunfo–Canar cross section at a latitude of 2°30′S and farther southward, the suture lies between the Macuchi volcanics to the west and steeply eastward-dipping basement rocks (Servicio National de Geologia y Mineria, 1969) which underlie the Celica volcanics to the east. The dip of the suture (60° to 80° east) can be deduced from a few large upthrusts that run closely parallel to it (Juteau and others, 1977; Lebras and others, 1985). The generalized cross section of Figure 4C, based on available data, suggests that the buoyant Macuchi island arc and adjacent Piñón area were added to the continent by accretion and not by obduction. The accretion process probably began in the Campanian when the Celica arc volcanism died down in southern Ecuador (Feininger and Bristow, 1980). Unlike the Celica continental arc, the Macuchi oceanic arc continued to be active during the Paleocene and Eocene (Henderson, 1979). Therefore, the subduction under the Macuchi arc probably continued during and after its collision with the continent, suggesting that an east-dipping Macuchi subduction zone was located west of the arc during the Cretaceous and Eocene. After collision, this subduction zone probably underwent only minor changes in its geometry and finally was connected to that of Peru-Chile. The subsequent activity of this single subduction zone gave rise to the classical Andean Cenozoic magmatic arc. The plate tectonic model proposed for the Turonian to Santonian period (Fig. 4A) thus comprises two east-dipping subduction zones and is similar to the present state of the Pacific–Philippine sea–Eurasian plates (Uyeda and Miyashiro, 1974; Hirakara, 1981). The north-south extent of the Macuchi subduction zone in Late Cretaceous times was probably <600 km because the related Macuchi arc disappears south of 3°20′S and was not recognized by Millward and others (1984) along a transect of the western and central Cordilleras of Colombia at about 3°45′N. In the proposed model, the Piñón tholeiites of the coast of Ecuador are in the arc-trench gap (Fig. 4).

The MORB and the periodotites, gabbros, and dolerites found in the steep tectonic slivers stacked in the suture zone may be oceanic rocks formed in a back-arc or a marginal-sea environment. These rocks could also be interpreted, however, as upthrust basement of the Macuchi arc.

Similar structural settings have been described in other areas, particularly in the western United States. The western Sierra Nevada, much like Ecuador, comprises an island-arc assemblage dipping to the northeast and bounded by a northeast-dipping steep upthrust zone which is considered to be a suture. The upthrust block to the east comprises an Andean-type arc and older complexes that represented the western edge of North America in Late Jurassic times. Jones and others (1976) proposed a model very similar to our Ecuadorian scheme to explain its structure. Similarly, Roure and Blanchet (1983) related the Franciscan evolution of northern California and southern Oregon to the simultaneous activity of two parallel subduction zones resulting ultimately in the accretion of an arc along the continent.

Another plate-tectonic model has been proposed for Ecuador by Feininger and Bristow (1980). According to this model, the Macuchi arc formed along a west-dipping intra-oceanic subduction zone that died out in Maastrichtian times. The arc then drifted northeastward by slipping along a Dolores-Guayaquil megashear (DGM) until it was thrust under South America before or during the middle Eocene, in an east-dipping subduction zone. This rather complex model fails to explain the continuous volcanic activity of the Macuchi arc from Turonian to Eocene times as documented by Henderson (1979) and Henderson and Evans (1980), however.

Alternatively, Kennerley (1980) suggested that the Macuchi and Celica arcs are parts of a single arc built upon an oceanic basement in the case of the former arc and upon a continental basement in the latter case; both basements are parts of the South American plate. In this model, there was only one east-dipping subduction zone lying along western Ecuador since the Cretaceous. This hypothesis, however, does not account for the presence of the partly coeval, contiguous western Macuchi island-arc assemblages and eastern Celica intracontinental arc assemblages as documented between 2°20′S and about 3°S (Fig. 1 and 4C) nor for the slivers of oceanic rocks in many cases found between both assemblages.

The fact that three markedly different plate-tectonic models have been proposed for the Ecuadorian Andes is mostly due to the limitations of the available information on the geology of this region. A major unanswered question is the time of the initial large dextral displacements along the DGM (Campbell, 1968; Case and others, 1971; and Fig. 1). This fault zone is commonly taken to be the boundary between the continental and oceanic lithospheres in the Andes of Colombia and Ecuador (Case and others, 1971, 1973; Feininger and Seguin, 1983). Feininger and Bristow (1980) asserted that the DGM acted as a transform fault from Santonian to middle Eocene time, when it became inactive, whereas Shepherd and Moberly (1981) considered that the opening of the Gulf of Guayaquil in Miocene to Quaternary time is related to an 80- to 100-km dextral displacement along the DGM. This paper, however, points out that the DGM is distinct from the suture (Fig. 1 and 4C) and postulates that the megashear is a post-collisional subvertical wrench fault superimposed over the earlier steep suture north of 2°S, probably at the beginning of the Tertiary.

ACKNOWLEDGMENTS

This research has been supported by a cooperative agreement between the Escuela Superior Politécnica del Litoral (Guayaquil, Ecuador), the Office de la Recherche Scientifique et Technique Outre-Mer (France), the Centre Géologique et Géophysique, Montpellier (France), and the Natural Sciences and Engineering Research Council of Canada (Operating Grant A3782). The traveling expenses of F. Mégard were supported by a travel grant from the Institut Français d' Etudes Andines. We thank T. Donnelly and J. Davidson for their critical reviews of the manuscript and L. Aguirre, F. Dugas, and Th. Juteau for providing some of the analyzed samples.

REFERENCES CITED

Aguirre, L., and Atherton, M. P., 1986, Low-grade metamorphism in relation to volcanism and geodynamics, Western Cordillera of Ecuador: Journal of Metamorphic Geology (in press).

Atherton, M. P., Pitcher, W. S., and Warden, V., 1983, The Mesozoic marginal basin of central Peru: Nature, v. 305, p. 303–306.

Aubouin, J., 1972, Chaines liminaires (andines) et chaines géosynclinales (alpines): International Geological Congress, 24th, Montreal, Canada, section 3, p. 438–461.

Bailey, J. D., 1981, Geochemical criteria for a refined tectonic discrimination of orogenic andesites: Chemical Geology, v. 32, p. 139–154.

Batiza, R., Oestrike, R., and Futa, K., 1982, Chemical and isotopic diversity in basalts dredged from the East Pacific Rise at 10° S, the fossil Galapagos Rise and the Nazca plate: Marine Geology, v. 49, p. 115–132.

Bristow, C. R., 1975, The age of the Cayo Formation, Ecuador: Newsletters on Stratigraphy 4, p. 169–173.

Bristow, C. R., and Hoffstetter, R., 1977, Lexique stratigraphique international (2nd ed.): Paris, France, Centre National de la Récherche Scientifique.

Bruet, E., 1949, Les enclaves des laves des volcans de Quito, Republique de l'Equateur: Société Géologique de France Bulletin, v. 19, p. 477–491.

Bruhn, R. L., Stern, C. R., and de Witt, M. J., 1978, Field and geochemical data bearing on the development of a Mesozoic volcano-tectonic rift zone and back-arc basin in southernmost South America: Earth and Planetary Science Letters, v. 41, p. 32–46.

Campbell, C. J., 1968, The Santa Marta wrench fault and its regional setting: Caribbean Geological Conference, 4th, Port-of-Spain, Trinidad, 1965, Transactions, p. 247–261.

Case, J. E., Duran, L. G., Lopez, A., and Moore, W. R., 1971, Tectonic investigations in western Colombia and eastern Panama: Geological Society of America Bulletin, v. 82, p. 2685–2712.

Case, J. E., Barnes, J., Paris, G., Gonzales, H., and Vina, A., 1973, Transandean geophysical profile, southern Colombia: Geological Society of America Bulletin, v. 84, p. 2895–2904.

Condie, K. C., Viljoen, M. J., and Kable, E.J.D., 1977, Effects of alteration on element distributions in Archean tholeiites from the Barberton greenstone belt, South Africa: Contributions to Mineralogy and Petrology, v. 64, p. 75–89.

Dalziel, I.W.D., de Witt, M. J., and Palmer, K. F., 1974, Fossil marginal basin in the Southern Andes: Nature, v. 150, p. 291–294.

Deruelle, B., 1982, Petrology of the Plio-Quaternary volcanism of the south central and meridional Andes: Journal of Volcanology and Geothermal Research, v. 14, p. 77–124.

Direccion General de Geologia y Minas, 1982, Mapa geologico national de la Republica del Ecuador: Quito, Ecuador, Ministerio de Recursos Naturales y Energeticos, scale 1:1,000,000.

Dostal, J., and Dupuy, C., 1984, Geochemistry of the North Mountain basalts (Nova Scotia, Canada): Chemical Geology, v. 45, p. 245–261.

Dostal, J., Dupuy, C., and Lefevre, C., 1977, Rare earth distribution in Plio-Quaternary volcanic rocks from southern Peru: Lithos, v. 10, p. 173–183

Dostal, J., Strong, D. F., and Jamieson, R. A., 1980, Trace element mobility in the mylonite zone within the ophiolite aureole, St. Anthony complex, Newfoundland: Earth and Planetary Science Letters, v. 49, p. 188–192.

Dupuy, C., and Dostal, J., 1984, Trace element geochemistry of some continental tholeiites: Earth and Planetary Science Letters, v. 67, p. 61–69.

Dupuy, C., Dostal, J., Marcelot, G., Bougault, H., Joron, J. L., and Treuil, M., 1982, Geochemistry of basalts from central and southern New Hebrides arc: Implications for their source composition: Earth and Planetary Science Letters, v. 60, p. 207–225.

Ewart, A., Brothers, R. N., and Mateen, A., 1977, Mineralogical and chemical evolution of the Tonga–Kermadec–New Zealand island arc: Journal of Volcanology and Geothermal Research, v. 2, p. 205–250.

Faucher, B., and Savoyat, E., 1973, Esquisse géologique des Andes de l'Equateur: Revue de Géographie Physique et de Géologie Dynamique 15, p. 115–142.

Feininger, T., 1977, Mapa gravimetrico Bouguer del Ecaudor: Quito, Ecuador, Instituto Geografico Militar, scale 1:1,000,000.

Feininger, T., and Bristow, C. R., 1980, Cretaceous and Paleogene geologic history of coastal Ecuador: Geologische Rundschau, v. 69, p. 849–874.

Feininger, T., and Seguin, M. K., 1983, Simple Bouguer gravity anomaly field and the inferred crustal structure of continental Ecuador: Geology, v. 11, p. 40–44.

Frey, F. A., Bryan, W. B., and Thompson, G., 1974, Atlantic Ocean floor: Geochemistry and petrology of basalts from Leg 2 and 3 of the Deep Sea Drilling Project: Journal of Geophysical Research, v. 79, p. 5507–5527.

Gill, J., 1981, Orogenic andesites and plate tectonics: Berlin–Heidelberg–New York, Springer-Verlag, 390 p.

Goossens, P. J., 1968, Geologia y metalogenia de la Costa Ecuatoriana entre Manta y Guayaquil: Estudios Geologicos Bulletin 1, p. 5–17.

Goossens, P. J., and Rose, W. I., 1973, Chemical composition and age determination of tholeiitic rocks in the Basic igneous complex, Ecuador: Geological Society of America Bulletin, v. 84, p. 1043–1052.

Goossens, P. J., Rose, W. I., and Flores, D., 1977, Geochemistry of tholeiites of the Basic igneous complex of northwestern South America: Geological Society of America Bulletin, v. 88, p. 1711–1720.

Hawkesworth, C. J., Norry, M. J., Roddick, J. C., Baker, P. E., Francis, P. W., and Thorpe, R. S., 1979, ^{143}Nd/^{144}Nd, ^{87}Sr/^{86}Sr, and incompatibale trace element variations in calc-alkaline andesites and plateau lavas from South America: Earth and Planetary Science Letters, v. 42, p. 45–57.

Hellman, P. L., Smith, R. E., and Henderson, P., 1979, The mobility of the rare earth elements: Evidence and implications from selected terrains affected by burial metamorphism: Contributions to Mineralogy and Petrology, v. 71, p. 23–44.

Henderson, W. G., 1979, Cretaceous to Eocene volcanic arc activity in the Andes of northern Ecuador: Geological Society of London Quarterly Journal, v. 136, p. 367–378.

Henderson, W. G., and Evans, C.D.R., 1980, Ecuadorian subduction system: Discussion: American Association of Petroleum Geologists Bulletin, v. 64, p. 280–283.

Hirakara, K., 1981, Three-dimensional seismic structure beneath southwest Japan: The subducting Philippine Sea plate: Tectonophysics, v. 79, p. 1–44.

Jakes, P., and Gill, J., 1970, Rare earth elements and the island arc tholeiitic series: Earth and Planetary Science Letters, v. 9, p. 17–28.

Jones, D. L., Blake, M. C., and Rangin, C., 1976, The four Jurassic belts of northern California and their significance to the geology of the southern California borderland, *in* Howell, M., ed., Aspects of the geologic history of the California continental borderland: American Association of Petroleum Geologists, Pacific Section, Publications, v. 24, p. 343–362.

Juteau, T., Megard, F., Raharison, L., and Whitechurch, H., 1977, Les assemblages ophiolitiques de l'occident equatorien: Nature petrographique et position structurale: Société Géologique de France Bulletin, v. 19, p. 1127–1132.

Kennerley, J. B., 1980, Outline of the geology of Ecuador: Overseas Geology and Mineral Resources, London, 55, 17 p.

Lebras, M., 1985, Caractérisation géochemique du volcanisme anté-orogénique de l'Occident équatorien; implications géodynamiques: Documents et Travaux du Centre Géologique et Géophysique, Montpellier, 6, 118 p.

Lebras, M., Megard, F., Juteau, T., and Calle, J., 1985, Pre-orogenic volcanic assemblages and structure in the Western Cordillera of Ecuador between 1°40'S and 2°20'S: Geologische Rundschau, v. 74, p. 343–351.

Marriner, G. F., and Millward, D., 1984, The petrology and geochemistry of Cretaceous to Recent volcanism in Colombia: The magmatic history of an accretionary plate margin: Geological Society of London Quarterly Journal, v. 141, p. 473–486.

Mégard, F., 1986, Cordilleran Andes and Marginal Andes; a review of Andean geology north of the Arica elbow (18°S), *in* Monger, J.W.H., ed., Circum-Pacific orogenic belts and the evolution of the Pacific Ocean basin: American Geophysical Union Geodynamic Series (in press).

Millward, D., Marriner, G. F., and Saunders, A. D., 1984, Cretaceous tholeiitic volcanic rocks from the Western Cordillera of Columbia: Geological Society of London Quarterly Journal, v. 141, p. 847–860.

Pearce, J. A., 1982, Trace element characteristics of lavas from destructive plate boundaries, *in* Thorpe, R. S., ed., Andesites: Orogenic andesites and related rocks: New York, John Wiley & Sons, p. 525–548.

Roure, F., and Blanchet, R., 1983, A geological transect between the Klamath Mountains and the Pacific Ocean (southwestern Oregon): A model for paleosubductions: Tectonophysics, v. 91, p. 53–72.

Sauer, W., 1950, Mapa geologico del Ecuador: Quito, Ecuador, Universidad Central, scale 1:1,500,000.

Saunders, D. A., and Tarney, J., 1979, The geochemistry of basalts from a back-arc spreading center in the East Scotia Sea: Geochimica et Cosmochimica Acta, v. 43, p. 555–572.

Saunders, D. A., Tarney, J., Stern, C. R., and Dalziel, I.W.D., 1979, Geochemistry of Mesozoic marginal basin floor igneous rocks from southern Chile: Geological Society of America Bulletin, v. 90, p. 237–258.

Servicio National de Geologia y Mineria, 1969, Mapa geologico de la Republica del Ecuador: Quito, Ecuador, Ministerio de Recursos Naturales y Energeticos, scale 1:1,000,000.

Shepherd, G. L., and Moberly, R., 1981, Coastal structure of the continental margin, northwest Peru and southwest Ecuador, *in* Kulm, L. D., and others, eds., Nazca plate: Crustal formation and Andean convergence: Geological Society of America Memoir 154, p. 351–392.

Shervais, J. W., 1982, Ti-V plots and the petrogenesis of modern and ophiolitic lavas: Earth and Planetary Science Letters, v. 59, p. 101–118.

Sun, S. S., Nesbitt, R. W., and Sharaskin, A. Y., 1979, Geochemical characteristics of mid-ocean ridge basalts: Earth and Planetary Science Letters, v. 44, p. 119–138.

Taylor, S. R., Kaye, M., White, A.J.R., Duncan, A. R., and Ewart, A., 1969, Genetic significance of Co, Cr, Ni, Sc and V in andesites: Geochimica et Cosmochimica Acta, v. 33, p. 275–286.

Thorpe, R. S., Francis, P. W., Hammil, M., and Baker, M.C.W., 1982, The Andes, *in* Thorpe, R. S., ed., Andesites: Orogenic andesites and related rocks: New York, John Wiley & Sons, p. 187–206.

Tschopp, H. J., 1948, Geologische skizze von Ekuador: Bulletin de l'Association Suisse de Géologie, v. 15, p. 14–45.

Uyeda, S., and Miyashiro, A., 1974, Plate tectonics and the Japanese islands: A synthesis: Geological Society of America Bulletin, v. 85, p. 1159–1170.

Wolf, T., 1892, Geografia y geologia del Ecuador: Leipzig, Germany, Brockhaus, 671 p.

Wood, D. A., Tarney, J., Varet, J., Saunders, A. D., Bougault, H., Joron, J. L., Treuil, M., and Cann, J. R., 1979, Geochemistry of basalts drilled in the North Atlantic by IPOD Leg 49: Implications for mantle heterogeneity: Earth and Planetary Science Letters, v. 42, p. 77–97.

MANUSCRIPT RECEIVED BY THE SOCIETY APRIL 8, 1986
REVISED MANUSCRIPT RECEIVED JANUARY 13, 1987
MANUSCRIPT ACCEPTED JANUARY 26, 1987

Printed in U.S.A.