Middle Jurassic volcanism in the Northern and Central Andes

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ABSTRACT

Stratigraphical, petrographical, geochronological and geochemical data available suggest that the various segments of the western margin of South America experienced a different geodynamic evolution throughout the Jurassic. In the early Jurassic, the Northern Andes were characterized by an extensional tectonic regime whereas in the Central Andes subduction led to the emplacement of a calc-alkaline magmatism. During the middle Jurassic (Bathonian to Oxfordian), an active subduction, perpendicular to the continental margin, generated a magmatic arc (Misahuallí/Colán arc) along the Northern Andes. The volcanic products are medium to high K calc-alkaline rocks composed of basaltic andesitic to rhyolitic lavas and acid pyroclastic rocks (ignimbrites, unwelded tuffs, volcanogenic sandstones and breccias). A new radiometric ^{40}Ar-^{39}Ar data gave an age of *ca.* 172 Ma for the Misahuallí Formation of Ecuador. The Central Andes, in the southern coastal region of Peru, were characterized by an oblique convergence between the Phoenix oceanic plate and the continental margin of South America. This subduction produced a medium to high-K, calc-alkaline andesitic volcanic series (Río Grande and Chala formations), comprising porphyritic basaltic andesites and emplaced as flows, intrusive rocks (dykes, 'si lls' and 'stocks') and acid pyroclastic rocks. New geochronological ^{40}Ar-^{39}Ar data confirm an age of *ca.* 165 Ma for the andesitic basalt flows of the Chala Formation.

Key words : Andes, Peru, Ecuador, Jurassic, Volcanism, Petrology, Geochemistry, Geochronology, Geodynamics, Active continental margins.

RESUMEN

Volcanismo del Jurásico Medio en los Andes del norte y centrales. Información estratigráfica, petrográfica, geocronológica y geoquímica disponible sugiere que los diferentes segmentos del margen occidental de Sudamérica tuvieron una evolución geodinámica diferente durante el Jurásico. En el Jurásico Inferior, los Andes del Norte

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se caracterizaron por un régimen tectónico extensional mientras que en los Andes Centrales procesos de subducción generaron un magmatismo calcoalcalino. Durante el Jurásico medio (Batoniano a Oxfordiano) la subducción ortogonal al margen continental generó un arco magmático (Arco Misahuallí-Colán) en los Andes del Norte. Los productos volcánicos de este arco son rocas calcoalcalinas de medio a alto K, que corresponden a andesitas basálticas y riolitas, y rocas piroclásticas ácidas (ignimbritas, tobas, areniscas volcanogénicas y brechas). Se obtuvo una nueva edad radiométrica ^{40}Ar-^{39}Ar de *ca.* 172 Ma para la Formación Misahuallí en Ecuador. Los Andes Centrales, en la región costera meridional del Perú, estuvieron caracterizados por una convergencia oblicua entre la placa oceánica Phoenix y el margen continental de Sudamérica. Este proceso de subducción produjo una serie volcánica andesítica calcoalcalina de medio a alto K (formaciones Río Grande y Chala) que incluye andesitas basálticas porfíricas emplazadas como lavas, diques, 'sills' y 'stocks', y rocas piroclásticas ácidas. Nuevas edades ^{40}Ar-^{39}Ar confirman una edad cercana a 165 Ma para los flujos de andesita basáltica de la Formación Chala.

Palabras claves: Andes, Perú, Ecuador, Jurásico, Volcanismo, Petrología, Geoquímica, Geocronología, Geodinámica, Márgenes continentales activos.

INTRODUCTION

According to several geodynamic reconstructions, the Andean margin was the site of a major plate reorganization during the latest Triassic-earliest Jurassic (Aspden *et al.*, 1987; Mourier, 1988; Jaillard *et al.*, 1990). According to these reconstructions, during the middle Jurassic (Bathonian-Bajocian), a subduction perpendicular to the continental margin was active along the Northern Andes, whereas the Central Andes were dominated by transform faulting with restricted subduction. In the latest Jurassic, a major reorganization of the plate motion took place. A new southwest-northeast convergence direction induced the accretion of continental and arc terranes in the Northern Andes in northern Peru, Ecuador and Colombia and the emplacement of subduction-related calc-alkaline volcanism in the Central Andes of Peru (Aspden *et al.*, 1987; Jaillard *et al.*, 1990). The authors present new petrological, mineralogical, geochronological and geochemical data concerning four Middle Jurassic volcanic formations located in these two different segments of the Andean margin (Figs. 1 and 2). Two of these formations crop out in the northern segment and are located in Ecuador (Misahuallí Formation, Fig. 1) and Northern Peru (Colán Formation, Fig. 1), whereas the other two (Río Grande and Chala Formations, Fig. 2) are located in the central segment and crop out along the southern coast of Peru.

These data place new constraints on the geodynamic interpretation of the Jurassic evolution of the Northern and Central Andes.

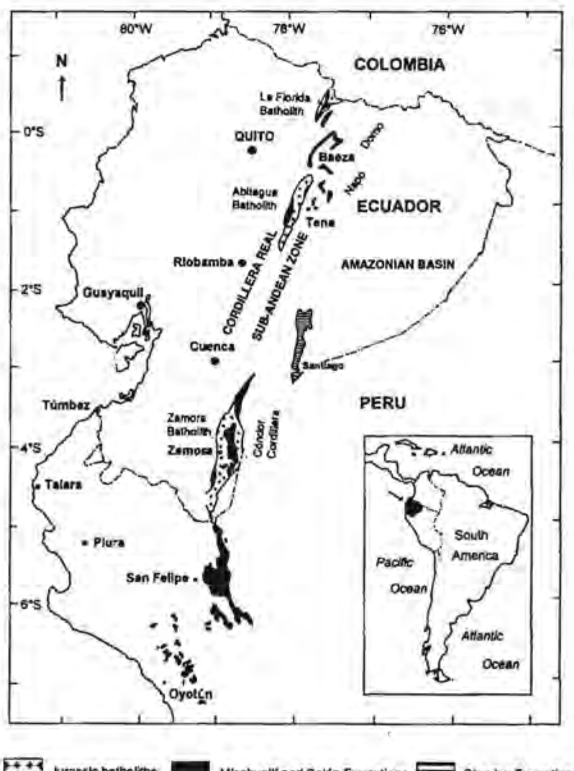

FIG. 1. Location of Jurassic outcrops of the Northern Andes in Ecuador and Northern Peru.

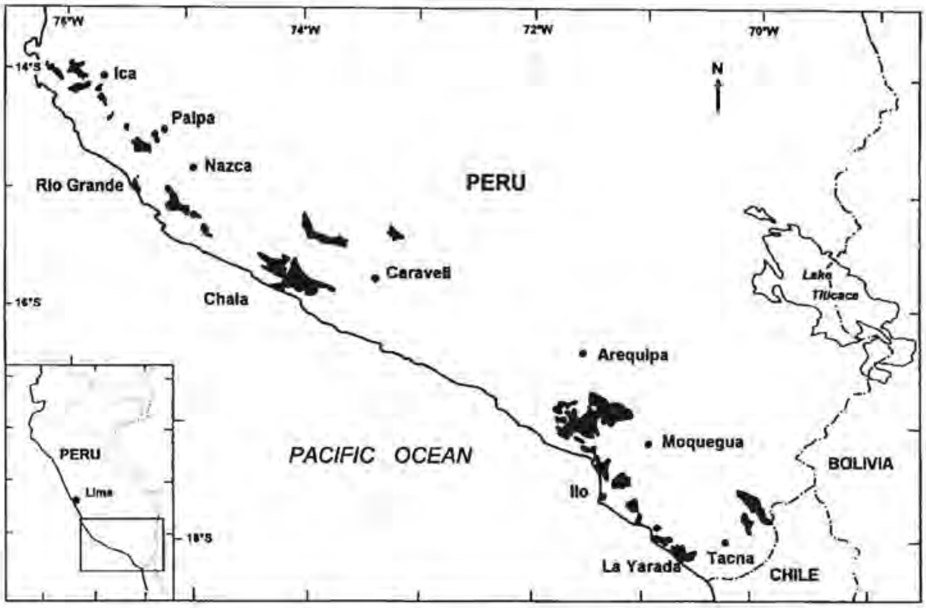

FIG. 2. Location of Jurassic volcanic outcrops (black areas) in the Central Andes, southern coastal Peru (after Carlier and Soler, unpublished).

JURASSIC VOLCANISM IN THE NORTHERN ANDES (ECUADOR AND NORTHERN PERU)

MISAHUALLI FORMATION

The Misahuallí Formation (Tschopp, 1956) crops out in the Subandean zone of Ecuador, to the east of the Cordillera Real. Two main outcrop zones are observed, one in the north in the Napo Dome, between the towns of Baeza and Tena, and the other in the south along the Cóndor Cordillera in the region of Zamora (Fig. 1). The predominantly volcanic Misahuallí Formation consists mainly of basaltic to rhyolitic lava flows and acid pyroclastic deposits (dacitic to rhyolitic ignimbrites and unwelded lapilli tuffs), erupted in a subaerial environment, but also includes subordinate amounts of intraformational volcanogenic sandstones and breccias (Table 1).

The base of the Misahuallí Formation has not been observed and its top is covered by the Aptian-Albian epicontinental sandstones of the Hollín Formation. The volcanic rocks are intruded by large calc-alkaline batholiths (Fig. 1) previously dated from 190 to 150 Ma (Herbert and Pichler, 1983; Pichler and Aly, 1983; Aspden *et al.*, 1992; Aspden and Litherland, 1992). The Misahuallí Formation seems to be intruded only by the youngest batholiths (*ca.* 150 Ma) and by the Abitagua Batholith (162 Ma; Aspden and Litherland, 1992).

The Misahuallí Formation was previously defined as the uppermost part of the detrital continental Chapiza Formation (Tschopp, 1956) and assigned to the Jurassic/Cretaceous boundary (Hall and Calle, 1982). This age was based on palynological evidence and a radiometric date of 132 Ma (K/Ar, whole-rock = w.r.), obtained from rocks of the Amazon basin (Hall and Calle, 1982). However, the authors' field observations and a new ^{40}Ar-^{39}Ar plateau age of 172.3±2.1 Ma (Fig. 3; Romeuf, 1994) suggest that the Misahuallí Formation, as originally named, consists of two volcanic units. This plateau age was obtained on a single grain of amphibole from an andesite (M-90). Because of the low K content (0.6-0.9%) and the small size of the grain, only three significant apparent ages could be obtained. Nevertheless, because of the high purity of the analysed sample, as demonstrated by a constant $^{37}Ar_{Ca}$-$^{39}Ar_{K}$ ratio (proportional to the Ca/K ratio) *versus* temperature, the calculated plateau age of 172.3±2.1 Ma is probably geologically significant. This age corresponds to the Misahuallí Formation proper, located in the Subandean zone and corresponds to Middle Jurassic age (*ca.* 190-150 Ma),

TABLE 1. MAIN CHARACTERISTICS OF JURASSIC VOLCANIC FORMATIONS IN THE NORTHERN AND CENTRAL ANDES.

	Northern Andes		Central Andes	
Formation	**Misahuallí**	**Colán**	**Río Grande**	**Chala**
Location	Sub-Andean Zone, Napo Range and Cóndor Cordillera Western Ecuador	Huancabamba Andes Northern Peru	Southern coastal Peru	Southern coastal Peru
Age	Middle Jurassic Bajocian	Middle Jurassic Oxfordian	Middle Jurassic Callovian	Middle Jurassic Aalenian to Bajocian
Environment	Aerial Continental	Aerial Continental	Littoral	Littoral
Lithology	Basaltic andesites Andesites Dacites Rhyolites Acic pyroclastic rocks	Basaltic andesites Andesites Dacites Acid pyroclastic rocks	Basaltic andesites Acid pyroclastic rocks	Basaltic andesite flows and intrusives Acid pyroclastic rocks
Mineralogy				
Plagioclase	K-rich Labradorite ($An_{53.1}Ab_{42.7}Or_{4.2}$) (Basaltic andesites) to andesine ($An_{35.2}Ab_{60.8}Or_{4}$) (Dacites)	Labradorite ($An_{58.3}Ab_{39.3}Or_{2.4}$) (Basaltic andesites)	K-rich Labradorite ($An_{55}Ab_{40.6}Or_{4.4}$) (Basaltic andesites)	Labradorite ($An_{59.9}Ab_{37.5}Or_{2.7}$) (Basaltic andesite flows) K-rich Labradorite ($An_{58.2}Ab_{37.8}Or_{4}$) (Basaltic andesite intrusives)
Pyroxene	Augite to diopside ($Wo_{44.3}En_{45}Fs_{10.7}$)	Augite to diopside ($Wo_{44}En_{43}Fs_{13}$)	Augite ($Wo_{37.5}En_{44.8}Fs_{17.7}$)	Ca-rich Augite ($Wo_{39.1}En_{46.9}Fs_{14}$)

whereas the younger one, or uppermost Chapiza Member, Jurassic/Cretaceous boundary (*ca.* 130 Ma) is restricted to the Amazonian Basin (Fig. 1), and is not considered further in this study.

COLAN FORMATION

The Colán Formation (Pardo and Sanz, 1979) represents the southward prolongation of the Misahuallí Formation in Northern Peru (Fig.1) and consists of subaerial basaltic andesitic to dacitic lava flows and pyroclastic beds (Table 1) that include fossil wood (Mourier, 1988). Its thickness varies from 1,000 m to 3,000 m (Mourier, 1988). Oxfordian ammonites (*Perisphinctes* sp., *Dichotomosphinctes* sp.) occur in penecontemporaneous sedimentary beds, derived from the reworking of the volcanic products of the Colán Formation (Mourier, 1988). Callovian bivalves were also reported in the Colán Formation (Mourier, 1988). The Colán Formation rests unconformably upon the Pliensbachian to Sinemurian Pucará carbonates (Loughman and Hallam, 1982) and is covered by the Neocomian quartzites of the Goyllarisquizga Group (Mourier, 1988). The Colán Formation is also reworked by the Tithonian Chicama Formation (Jaillard and Jacay, 1989). The Colán Formation is restricted to the area west of the Marañon geanticline. To the east, in the East Peruvian Trough, the Colán Formation is replaced by the contemporaneous continental detrital upper Jurassic Sarayaquillo Formation, equivalent of the Ecuadorian Chapiza Formation (Mourier, 1988; Jaillard and Jacay, 1989).

JURASSIC VOLCANISM IN THE CENTRAL ANDES (SOUTHERN COAST OF PERU)

This volcanism is represented by the Río Grande and the Chala formations situated along the southern coast of Peru in the Arequipa region (Fig. 2).

RIO GRANDE FORMATION

The Río Grande Formation (Rüegg, 1957; Olchauski, 1980) is composed of two units separated by a slight angular unconformity (Aguirre and Offler; 1985; Aguirre, 1988). The upper unit has yielded a K-Ar (w.r.) age of 164±4 Ma obtained on a weakly altered basaltic andesite flow of the upper unit (Aguirre and Offler, 1985; Aguirre, 1988). An Aalenian *Breydia manflasensis* assemblage zone was reported from the lower unit of the formation (Rüegg, 1957; Roperch and Carlier, 1992). The upper unit consists mainly of highly porphyritic basaltic andesites and acid pyroclastic rocks, whereas the lower unit is mainly composed of acid pyroclastic rocks: dacitic to rhyolitic ignimbrites as well as unwelded lapilli tuffs, including abundant volcanic shards (Table 1) and volcano-detritic rocks, sandstones and conglomerates. Some calcareous beds also occur in the lower unit.

CHALA FORMATION

The Chala Formation (Fig. 2) comprises a thick sequence of basaltic andesite flows intercalated with ignimbrites, unwelded lapilli tuffs, volcanigenic sandstones and breccias (Olchauski, 1980; Roperch and Carlier, 1992); various generations of cross-cutting stocks, sills and dykes are also present. Lava flows and subvolcanic basic intrusives have rather similar petrographic and mineralogical characteristics. The Chala Formation is contemporaneous with the sedimentary Guaneros Formation (Jaén *et al.*, 1963) and with the Río Grande Formation (Roperch and Carlier, 1992). A ^{40}Ar-^{39}Ar (w.r.) age of *ca.* 177 Ma was obtained from a basaltic flow from the base of the formation (Roperch and Carlier, 1992). Determinations by the ^{40}Ar-^{39}Ar method (w.r.) carried out on small intrusives cross-cutting the Chala Formation at the Ilo and Chala areas gave ages around 157 Ma (Roperch and Carlier, 1992).

New ^{40}Ar-^{39}Ar dates (plagioclases) were obtained on rocks of the Chala Formation (Fig. 3; Romeuf, 1994): a lava flow (CHA-50) and a dyke (MOR-1) cross-cutting the Guaneros Formation in the Tacna region. Very detailed age spectra (31 steps) were obtained on plagioclases to give precise information on the composition of the analysed plagioclases (Fig. 3). After the first four very disturbed apparent ages, MOR-1 age spectrum shows a low temperature flat region with ages around 157 Ma followed by lower ages at 154-155 Ma, then by a large region (corresponding to 48% of the total ^{39}Ar released) of concordant ages with a weighted mean of 157.2±0.4 Ma. The $^{37}Ar_{Ca}/^{39}Ar_K$ ratio spectrum (not given) clearly shows that the intermediate temperature lowest ages correspond to alteration phases characterized by lower Ca/K ratios

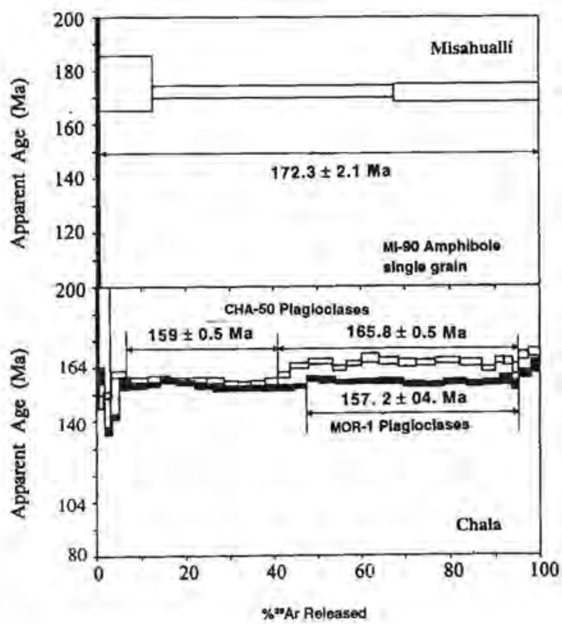

FIG. 3. $^{40}Ar/^{39}Ar$ age spectra of a- an amphibole single grain from the Misahuallí Formation (MI-90); b- two plagioclase bulk samples from the Chala Formation. Error bars are given at 1σ level. Age determinations by the ^{40}Ar-^{39}Ar method (single grains and bulk samples) were performed at the Laboratoire de Géochronologie, Université de Nice (France). The analytical method for age determinations is described in Ruffet (1990) and Zumbo (1993). The samples were irradiated in the McMaster reactor (Hamilton, Canada) with a total flux of $8.8x10^{18}$ neutron/cm^2. The irradiation standard was the amphibole MMhb 1 (Samson and Alexander, 1987; 520.4 Ma).

(probably affected by younger secondary K-rich phases). This age at 157.2±0.4 Ma probably corresponds to the dyke formation.

The CHA-50 age spectrum is more difficult to interpret because the lowest low temperature apparent ages (the first four steps excepted) do not correspond to significantly different $^{37}Ar_{Ca}/^{39}Ar_{K}$ ratios (spectrum not given). The authors suspect that these lower ages (weighted mean of 159±0.5 Ma) correspond to albitized phases observed in thin section. The higher temperature flat region, corresponding to 51% of the ^{39}Ar released, gives a weighted mean age of 165.8±0.5 Ma which may represent the lava flow fornation. It is, nevertheless, noticeable that the low temperature age of 159±0.5 Ma is almost concordant with the small 'plateau age' of the previous sample.

The upper unit of the Río Grande Formation exhibits the same petrological and field characteristics than the Chala Formation. These two broadly contemporaneous sequences would probably represent the same volcanic unit.

PETROGRAPHY AND MINERALOGY

PETROGRAPHY

Almost all the lavas are highly porphyritic, sometimes amygdaloidal, with a phenocryst content from 17 to 49% (Table 2). The Río Grande lava flows and the Chala intrusive rocks are generally richer in phenocrysts than the Misahuallí and Colán lavas. The mineralogy of the basaltic andesites is rather similar, consisting of phenocrysts of plagioclase, clinopyroxene and sometimes pseudomorphosed olivine, with Fe-Ti oxides as phenocrysts and microphenocrysts. The intersertal groundmass is composed of microliths of the same minerals and glass. In the Misahuallí and Colán formations, the dacites contain plagioclase, hornblende and Ti-Fe oxides as phenocrysts in a devitrified glassy matrix. Apatite occurs as an accessory mineral in the dacites and in the pyroclastic rocks.

MINERALOGY

OLIVINE

Olivine is rather scarce, but appears in basaltic andesites of all formations as phenocrysts. It is always pseudomorphosed by chlorite, titanite and opaques although it is identifiable by its morphology.

PLAGIOCLASE

The plagioclase is ubiquitous and represents the most abundant mineral in all the formations (plagioclase phenocryst content is in the range 2-46%). This mineral, often albitized and sericitized, appears as euhedral phenocrysts up to 1 cm long, microphenocrysts and microliths in the groundmass (Table 2). In some lavas of the Río Grande and Chala samples (e.g., CHA 50 and RG21), the plagioclase constitutes more than 50% of the mineral assemblage (Table 2) as phenocrysts and microliths. In some basaltic andesites of the different formations, the plagioclase has sieved or poikilitic textures and sometimes include small pyroxenes and glass.

In the Misahuallí Formation the plagioclase is rather K-rich labradorite ($An_{47-65}Ab_{32-69}Or_{2.3-5.8}$) in the basaltic andesites and more sodic in the andesites and dacites ($An_{30-48}Ab_{53-64}Or_{2.7-9.5}$). In the Colán, Chala and Río Grande formations, the plagioclase is labradoritic with compositions $An_{51-68}Ab_{29-50}Or_{1.5-3.1}$ (Colán), $An_{55-63}Ab_{34-40}Or_{2.2-6.5}$ (Chala), and $An_{31-61}Ab_{35-66}Or_{2.5-5.4}$ (Río Grande). In all the formations, the plagioclase has rather restricted compositional variation between the core and rim of phenocrysts and the microliths.

In the Misahuallí, Chala and Río Grande formations, the plagioclase is rather K-rich with a mean Or content of about 4% (Fig. 4). The plagioclase in the basaltic flows of the Chala and Colán formations are less K-rich (Or content at about 2%). The Or-contents (Fig. 4) of the plagioclases are rather similar to those of plagioclases in recent high-K calc-alkaline and shoshonitic lavas of the Andean margin (Peru, Lefèvre, 1979; Tata Sabaya volcano, Chile; de Silva *et al.*, 1993) and of Cenozoic high-K calc-alkaline lavas of the Sierra Madre Occidental, Mexico (Delpretti, 1987). The fact is that the high Or content of the plagioclase seems to be linked to a rather high primary K_2O content of the host rock.

TABLE 2. MODAL COMPOSITION OF ROCKS FROM THE JURASSIC VOLCANIC FORMATIONS IN THE NORTHERN AND CENTRAL ANDES.

Formation	Río Grande		Chala			Colán	Misahuallí			Misahuallí	
Sample	RG14	RG21	CHA 50	CHA 168	CHA 115	OY 13	MI 246	MI 247		MI 141	MI236
Lithology	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic andesite	Basaltic intrusive	Basaltic andesite	Basaltic andesite	Basaltic andesite		Dacite	Dacite
Phenocrysts									**Phenocrysts**		
Plagioclase	46.0	40.0	2.0	23.5	38.0	21.0	17.0	22.0	Plagioclase	36.0	27.0
Altered pyroxene	0.0	0.0	0.0	2.5	4.0	4.0	3.0	2.0	Altered ferromagnesians (amphibole, biotite)	4.5	0.3
Augite	0.5	6.5	14.0	1.5	4.0	6.5	5.0	2.0	Amphibole	3.1	
Olivine	1.0	2.0	0.0	3.0	0.0	0.0	0.1		Fe-Ti oxides	1.2	0.2
Fe-Ti oxides	0.8	1.0	0.3	0.3	0.3	1.0	1.5	2.0	Apatite	0.1	
Total phenocrysts	**48.3**	**49.5**	**16.3**	**30.8**	**46.3**	**32.5**	**26.6**	**28.0**	**Total phenocrysts**	**44.9**	**27.5**
Groundmass				69.0	54.0	68.0			**Groundmass**		
Glass	25.0	26.0	38.0				30.0	32.0	Devitrified glass	55.0	72.5
Microliths	26.0	7.0	1.5				44.0	41.0			
Plagioclases microliths		18.0	44.0								
Total groundmass	51.0	51.0	83.5	69.0	54.0	68.0	74.0	73.0	**Total groundmass**	55.0	72.5
TOTAL	99.3	100.5	99.7	99.8	100.3	100.5	100.6	101.0	TOTAL	99.9	100.0
Number of points counted	2,260	>2,000	3,790	>2,000	>2,000	2,254	2,313	2,215		2,311	1,082

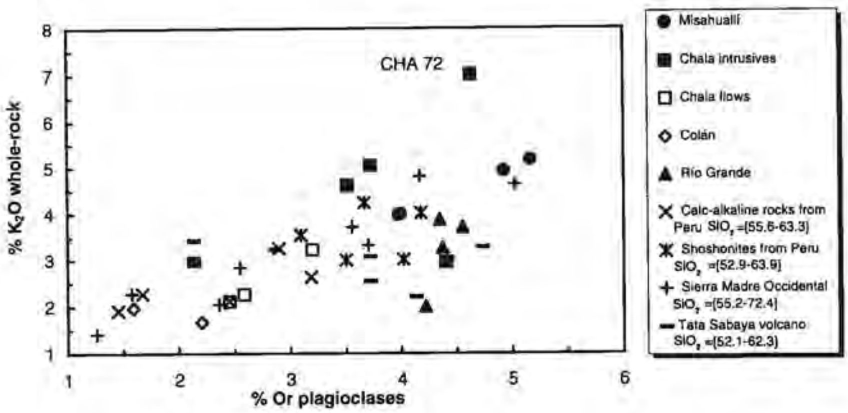

FIG. 4. Comparison of Or-content in plagioclase *versus* K_2O content of whole rock of Jurassic volcanic rocks in Northern and Central Andes. Other recent volcanic units of the Andean margin are included for reference Miocene to Recent calc-alkaline rocks with SiO_2 in the range 55.6-63.3% and shoshonites with SiO_2 in the range 52.9-63.9% of Peru; Lefèvre, 1979. Late Quaternary to Recent, Tata Sabaya volcano, Chile with SiO_2 in the range 52.1-62.3%; de Silva *et al.*, 1993. Tertiary high-K volcanic rocks from Sierra Madre Occidental of Mexico with SiO_2 in the range 55.2-72.4%; Delpretti, 1987. The mineral chemistry was determined by microprobe analyses at the Université de Montpellier (France) using a CAMEBAX probe under operation conditions of 15 kV, 15 nA and a beam width of 1 µm.

PYROXENES

Pyroxenes are present in the basaltic andesites and andesites of all formations as euhedral phenocrysts, microphenocrysts and as microliths in the groundmass. They frequently include glass and Fe-Ti oxides and may appear as glomerocrysts. They are generally augites with a rather homogeneous composition. In the basaltic andesites of the Northern Andes (Misahuallí and Colán formations), they are Ca-richer and plot between the augite and diopside fields of the pyroxene composition diagram (Morimoto *et al.*, 1988). In some lavas, two generations of pyroxene seem to be present: the first is always altered to chlorite, titanite and epidote, whereas the second is preserved. Their compositions show little variations: $Wo_{38-46}En_{40-52}Fs_{5-13}$ in the Misahuallí basaltic andesites, $Wo_{41-45}En_{41-48}Fs_{7-18}$ in the Colán rocks; $Wo_{35-43}En_{40-47}Fs_{4-23}$ in the Río Grande Formation and $Wo_{34-44}En_{43-55}Fs_{5-22}$ in the basaltic andesitic flows and intrusives of the Chala area. There is no significant compositional variation between phenocryst rims and cores as well as between the phenocrysts and the microliths. The chemistry of these pyroxenes is typical of orogenic lavas according to their Ca, Na, Cr and Ti contents (Leterrier *et al.*, 1982).

No orthopyroxene was found in the lavas from the different formations either because they are completely pseudomorphosed, or absent. Some petrographical evidences such as an altered core with a rim composed of clinopyroxene suggest that orthopyroxene was originally present in the basaltic andesites and that it is now altered.

AMPHIBOLES

Amphiboles occur in the acid lavas of the Misahuallí and Colán Formations. According to Leake's classification (1978), they correspond to pargasitic hornblende, ferroan pargasitic hornblende, ferro-pargasitic hornblende and pargasite. Their rather high $(Na+K)_A$ content, ranging from 0.57 to 0.89, is typical of orogenic lavas belonging to the high-K calc-alkaline series (Gill, 1981).

BIOTITE

Biotite occurs only in rhyolitic unwelded tuffs and ignimbrites from the Misahuallí Formation. It is generally completely altered and only a few chemical analyses are available. Its composition is typical of the calc-alkaline lavas (Abdel-Rahman, 1994).

METAMORPHISM

The rocks of the different formations described here have suffered very low-grade metamorphism (Romeuf, 1994) characterized by the crystallisation of secondary minerals (i) as replacement of the groundmass, notably of the glass, (ii) as pseudomorphs after igneous minerals and (iii) as void infillings. This metamorphism explains the relatively high mobility of elements such as Na, K, Ca, Ba, Rb and Sr, expressed as plagioclase albitization, olivine pseudomorphism and glass replacement. This phenomenon precludes the use of the above elements for discriminating the geochemical affinity of the lavas.

GEOCHEMISTRY

The volcanic rocks of the different formations show a medium-high K calc-alkaline affinity typical for magmas emplaced at a continental margin. All these rocks have suffered strong mobilization of lithophile elements (Na, K, Ca, Rb, Sr, Ba..). Thus, only immobile elements such as Ti, Zr, Y, Th, Ta, Nb, and REE, were used to discriminate the magmatic affinity. Selected whole-rock analyses are presented in table 3. These rocks were chosen on the basis of their rather low alteration pattern.

MISAHUALLI FORMATION

The Misahuallí rocks are calc-alkaline (Figs. 5, 6, and 7), suggesting their formation in an active continental margin. They display typically low TiO_2 (0.35-0.85%), Nb (7-13 ppm) and FeO_t (6.8-9.3%) contents, high Th/Ta ratios (9-17.5) and relatively high Al_2O_3 (15.5-17.8%), Zr (110-300 ppm), and REE contents; there is no Fe-enrichment during differentiation. The REE patterns are characteristic for calc-alkaline lavas with selective enrichment of LREE relative to HREE (La_N/Yb_N=5-10) (Figs. 5 and 8). The multi-element patterns of the basaltic andesites exhibit a great enrichment in LILE compared to MORB (Fig. 6).

The basic rocks of this formation plot in the calc-alkaline fields of several discriminant diagrams (*e.g.*, Pearce and Cann, 1973; Fig. 7).

COLAN FORMATION

These rocks present similar geochemical characteristics as the Misahuallí volcanic rocks and correspond to calc-alkaline lavas emplaced in a continental arc setting (Figs. 5-7). They are characterized by low TiO_2 (0.5-0.8%) and Nb (1-5 ppm), high Zr (100-400 ppm), Al_2O_3 (16.6-17.2%) and LILE contents, and very high Th/Ta ratios (45-57). Their REE patterns

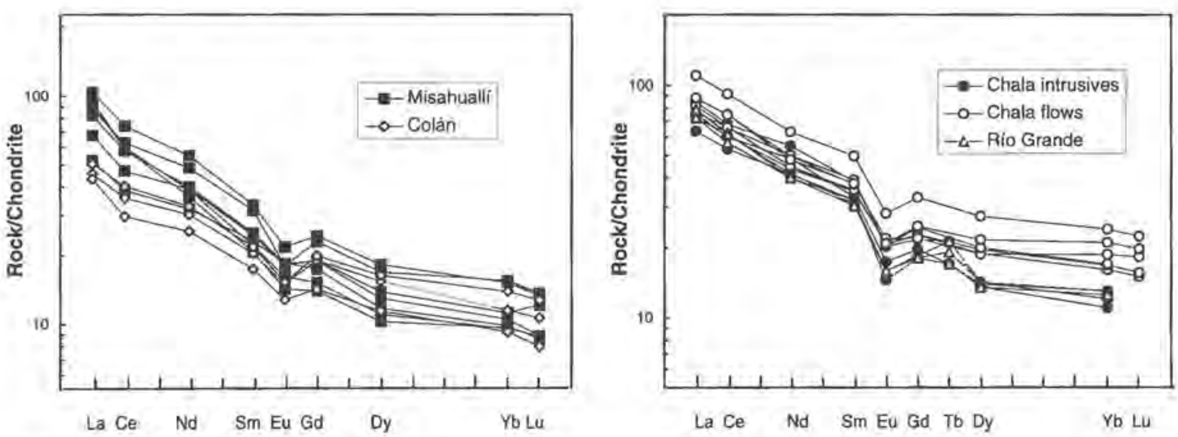

FIG. 5. REE patterns for Jurassic volcanic rocks of Northern and Central Andes (normalized after Haskin *et al.*, 1968).

TABLE 3. SELECTED ANALYSES OF JURASSIC VOLCANIC ROCKS IN THE NORTHERN AND CENTRAL ANDES.*

	Misahuallí				Colán		Chala					Río Grande		
	MI247	MI90	MI141	MI145	OY3	OY13	CHA50	CHA124	CHA168	CHA115	CHA154	RG14	RG18	RG21
SiO_2	55.42	58.87	65.65	71.86	61.33	54.85	52.84	63.16	57.37	52.03	75.44	55.26	56.73	55.08
TiO_2	0.86	0.71	0.48	0.23	0.52	0.75	1.29	1.23	1.58	1.10	0.35	0.96	0.96	0.99
Al_2O_3	16.86	17.02	16.38	14.81	16.89	16.97	15.14	14.11	15.66	15.09	10.67	17.59	17.33	16.78
Fe_2O_3	3.06	2.39	1.74	2.34	1.53	2.73	7.48	4.86	8.01	7.77	2.06	5.61	4.74	6.46
FeO	4.10	3.20	1.48	0.00	2.06	4.79	1.87	1.59	1.03	1.77	0.08	1.36	1.34	1.66
MnO	0.12	0.15	0.10	0.06	0.08	0.20	0.12	0.16	0.16	0.52	0.02	0.13	0.13	0.12
MgO	3.58	2.38	1.16	0.32	2.82	5.31	4.99	1.48	3.95	5.42	0.41	3.20	2.70	3.72
CaO	6.25	4.24	2.55	0.20	3.68	7.12	8.09	2.53	5.38	5.13	1.04	4.92	5.65	5.46
Na_2O	3.06	5.13	4.44	3.28	5.65	2.69	2.81	4.72	0.60	3.05	3.31	3.58	3.23	3.05
K_2O	3.56	2.90	3.55	5.15	1.30	1.67	2.11	3.65	3.23	4.61	5.08	3.87	3.71	3.27
P_2O_5	0.29	0.29	0.19	0.08	0.19	0.16	0.33	0.37	0.38	0.37	0.09	0.36	0.32	0.33
H_2O+	1.98	2.14	1.35	1.37	3.14	2.72	1.50	1.22	1.99	2.05	1.55	1.72	1.60	1.85
H_2O-	0.09	0.12	0.15	0.24	0.13	0.07	0.80	0.12	0.70	0.45	0.15	0.92	0.60	0.57
Total	99.23	99.54	99.22	99.94	99.32	100.03	99.37	99.20	100.04	99.36	100.25	99.48	99.04	99.34
Li	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	67	22	15	24	92	25	34	44
Rb	92	76	100	130	38	44	55	63	139	155	78	153	136	120
Sr	596	667	529	229	621	357	274	239	235	343	27	660	445	530
Ba	1,078	1,230	1,398	1,218	370	605	489	724	749	2,849	545	1,001	2,520	807
Co	22	16	11	5	14	26	26	7	29	25	2	16	16	18
Cu	86	36	21	14	31	90	33	9	58	52	9	21	58	18
Cr	61	26	3	5	29	77	202	5	57	52	7	22	19	22
Ni	15	44	7	36	38	48	69	6	18	25	6	13	10	14
V	190	118	57	9	8	213	280	77	234	223	28	198	186	202
Zn	74	66	65	35	39	85	85	77	61	285	14	174	207	138
Nb	10	9	8	10	1	2	8	10	8	8	8	5	6	5
Zr	136	208	220	156	399	105	150	265	220	195	204	158	162	180
Y	25	24	22	22	11	22	29	42	29	31	28	29	30	30
La	19.00	27.30	30.60	31.60	10.10	14.30	24.20	29.00	27.00	24.00	23.30	24.00	26.00	26.00
Ce	29.00	50.80	52.70	60.40	21.00	26.10	53.40	66.00	58.00	53.00	39.70	50.00	54.00	55.00
Nd	23.00	24.10	21.90	22.90	12.20	15.30	26.30	29.80	30.00	29.00	14.90	24.00	25.00	24.00
Sm	4.48	4.53	3.87	3.95	2.29	3.15	6.32	6.80	7.10	6.30	3.16	5.50	5.60	5.80
Eu	1.23	1.27	1.04	0.65	0.78	0.88	1.42	1.51	1.40	1.20	0.72	1.10	1.10	1.10
Gd	4.41	4.33	3.45	3.18	2.26	3.53	5.64	5.47	6.10	5.20	3.03	4.50	4.50	4.60
Dy	3.91	3.62	3.07	3.00	1.66	3.52	5.85	5.81	6.20	4.50	4.21	4.20	4.40	4.40
Yb	2.16	1.96	1.80	2.05	0.59	1.84	3.21	3.73	3.40	2.60	3.53	2.50	2.60	2.60
Lu	0.40	0.29	0.28	0.32	0.13	0.27	0.51	0.62	n.d.	n.d.	0.60	n.d	n.d	n.d

* Rock analyses were performed at the Université d'Aix Marseille III (France, Laboratoire de Pétrologie Magmatique) by M.O. Trensz and J.C. Germanique using an ICP-OES (Jobin-Yvon) according to the analytical method of Germanique (1994). Several samples were analysed by neutron activation at Cornell University (Ithaca, N.Y., U.S.A.) by P. Soler. This study is based upon 68 whole-rock analyses.

display selective enrichment in LREE compared to the HREE with La_N/Yb_N in the range 4-10. (Figs. 5 and 8). They fall within the field represented by the samples of the Misahuallí Formation. A calc-alkaline, subduction-related affinity was already suggested for the Colán Formation (Mourier, 1988; Soler, 1991).

RIO GRANDE FORMATION

The chemistry of these basaltic andesites suggests a calc-alkaline affinity for the Río Grande lavas. Their REE patterns (Fig. 5) are typical of volcanic arc rocks emplaced at a continental margin with a high LREE enrichment with regard to HREE (La_N/Yb_N=5.6-8.3, Fig. 8), low TiO_2 (<1%) and Nb (5-6 ppm) and high Al_2O_3 (16.8-17.6) and Zr (150-180 ppm) contents. The enrichment in LIL elements observed in the multi-element diagram (Fig. 6) is interpreted as a primary feature despite the mobility of some of these elements, because of the very high enrichment of these elements relative to MORB, the high Zr content of the rocks and of the high Or-content of the plagioclase.

CHALA FLOWS AND INTRUSIVE ROCKS

The chemistry of these rocks suggests a calc-alkaline magmatism, emplaced on an active continental margin (Figs. 5, 6, and 7). A strong element

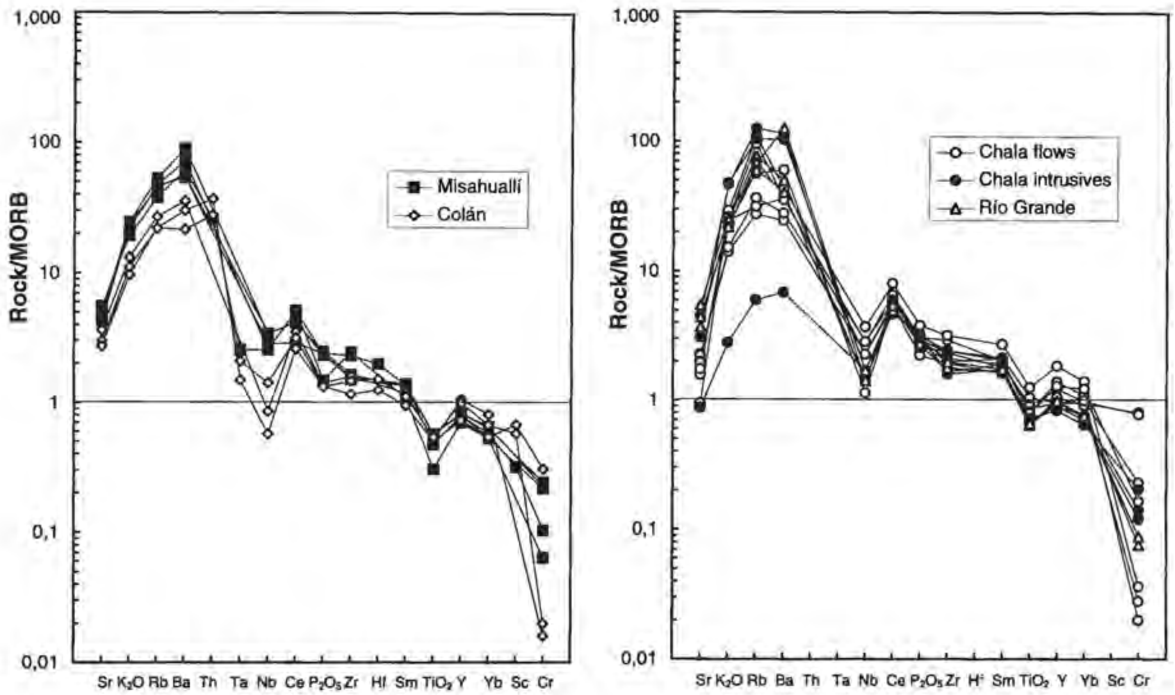

FIG. 6. Spidergrams (Pearce, 1983) for basic to intermediate Jurassic volcanic rocks of Northern and Central Andes.

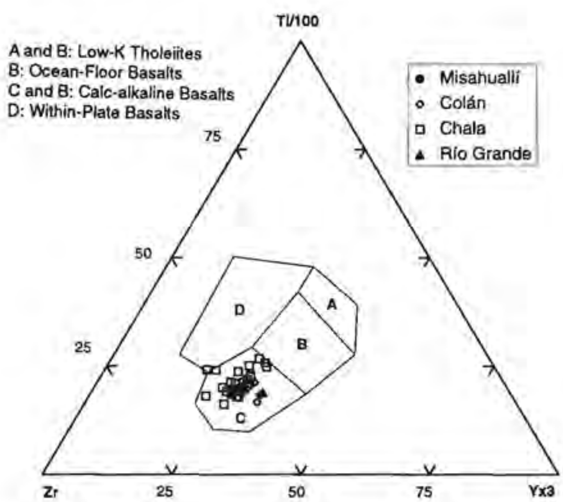

FIG. 7. Ti/100-Zr-3Y diagram (after Pearce and Cann, 1973) for basic Jurassic volcanics of Northern and Central Andes. Legend as in figure 4.

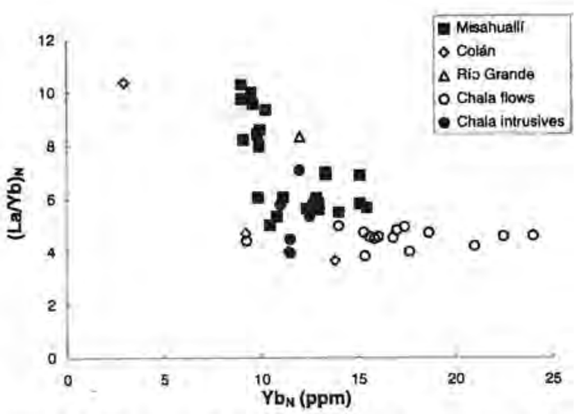

FIG. 8. La/Yb *versus* Yb diagram for Jurassic volcanic rocks of Northern and Central Andes.

mobility is indicated by K_2O enrichment in some rocks of the Chala Formation (K_2O up to 7% in some basalts). This disturbance was detected in the first steps of the ^{40}Ar-^{39}Ar analyses. Comparison between the Or-content in plagioclase and the whole-rock K_2O shows that some of the samples have clearly experienced secondary enrichment (*e.g.*, Fig. 4; sample CHA72).

Nevertheless, the multi-element diagrams show an important primary LILE enrichment compared to MORB (Fig. 6). The REE patterns (Fig. 5) of the lavas and subvolcanic intrusives are rather similar and characteristic of calc-alkaline magmas with a La_N/Yb_N in the range 4-7. The Río Grande flows and the Chala intrusive rocks exhibit a rather similar composition, whereas the chemistry of the Chala flows is slightly different, the latters having a lower K_2O content. This feature is also reflected in the Or content of the plagioclase present in the basaltic andesites.

COMPARISON WITH OTHER ANDEAN VOLCANIC SERIES

The Andean Jurassic volcanic rocks studied here have been compared with the medium- to high-K, Quaternary calc-alkaline volcanic series of Chile and Bolivia. The former were represented by the Laguna del Maule series located in the Southern Volcanic Zone (SVZ, Frey *et al.*, 1984) and the latter by the Nevados de Payachata series in the Central Volcanic Zone (CVZ; Wörner *et al.*, 1988; Davidson *et al.*, 1990). This comparison shows that the compositions of all these lavas are rather similar for several major and trace elements (SiO_2, TiO_2, FeO_t, MgO, K_2O, Ba, Sr...). However, the HREE, Zr, Th, Hf, and Ta contents of the Jurassic lavas are depleted relative to the reference series, whereas the LREE, Y, and MnO contents are generally higher. Similar variations in the HREE and LREE contents have been explained by different degrees of partial melting of asthenospheric material in Quaternary Andean lavas belonging to the Chilean Villarrica and Lanín volcanoes (Hickey-Vargas *et al.*, 1989). The Jurassic lavas of Ecuador and Peru exhibit some chemical characteristics (Nd, Sm, Eu, and Zr contents) transitional between the medium-K calc-alkaline volcanics of the Laguna del Maule (Frey *et al.*, 1984), emplaced on a 'normal' continental crust, and the high-K calc-alkaline rocks of the Nevados de Payachata (Wörner *et al.*, 1988; Davidson *et al.*, 1990), emplaced on a thick continental crust.

CONCLUSIONS AND GEODYNAMIC SETTING

The four volcanic units described are broadly contemporaneous and correspond to an important volcanic activity that took place in two segments of the Andean margin during the middle Jurassic.

In the Northern Andes, the Misahuallí and Colán formations display similar petrological, mineralogical and geochemical characteristics, which strongly suggest the existence of a magmatic arc emplaced on the Andean margin in the present-day Subandean zone. This magmatism was associated with an active subduction along the Northern Andes. The age of this volcanism was dated, in Ecuador (Misahuallí Formation), at about 172 Ma (Romeuf, 1994), whereas in northern Peru, the Colán volcanic rocks seem to be slightly younger (Oxfordian).

In the Central Andes, the Río Grande and Chala Formations exhibit similar characteristics and also correspond to a subduction-related medium to high-K calc-alkaline magmatism. The Misahuallí and Colán formations constitute a complete differentiation series from basalt to dacite and rhyolite, whereas the Chala-Río Grande rocks consist of a broadly bimodal series, with basaltic andesites and acid pyroclastic rocks. The Chala-Río Grande lavas are K-richer than the Misahuallí-Colán formations, a fact also reflected in the Or-rich component of the plagioclase (Fig. 4). The Zr content of the basaltic andesites is higher in the Chala-Río Grande lavas than in the Misahuallí-Colán rocks. These petrological and geochemical differences observed between the lavas from the Northern Andes (Misahuallí-Colán arc in Ecuador and Northern Peru) and those of the Central Andes (Chala-Río Grande formations of southern coastal Peru) might be explained by different degrees of partial melting and/or by differences in thickness of the continental crust.

However, this volcanism indicates that active subduction took place along the Peruvian segment during the middle Jurassic, but the extensional and strike-slip tectonics associated to the formation of the contemporaneous Yura basin, in the same segment in back-arc position (Vicente, 1981; Vicente, *et al.*, 1982), suggest that this subduction was oblique.

According to recent geodynamic reconstructions of the early Mesozoic evolution of the Andean margin (Jaillard *et al.*, 1990), the Northern Andes and the Central Andes were characterized by different tectonic settings during the middle Jurassic. From the latest Lias to the Kimmeridgian (180-145 to 140 Ma), the Andean margin (Fig. 9) was characterized by a global northeast-southwest convergence between the oceanic Phoenix plate and South America (Aspden *et al.*, 1987; Mourier, 1988; Jaillard *et al.*, 1990). This

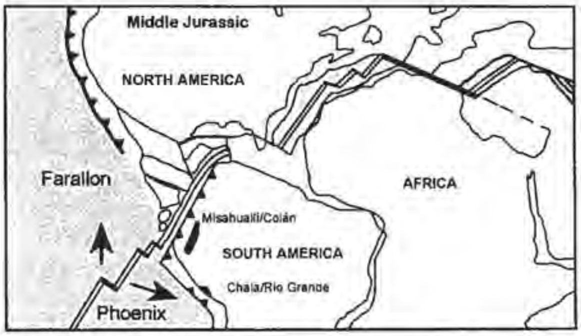

FIG. 9. Geodynamic reconstructions of Northern Andean margin for latest Lias to Kimmeridgian period, modified after Jaillard *et al.*, 1990, to show significant convergence required for production of Río Grande and Chala volcanic formations.

convergence, broadly orthogonal in the Northern Andes, was responsible for the southeastward subduction of the oceanic plate beneath the western South American margin and resulted in the formation of a magmatic arc at the continental margin in Ecuador, Northern Peru and Colombia (Fig. 9). A turbiditic trough, the existence of emergent areas and the scarcity of magmatism would suggest that only very local subduction took place contemporeanously along the Peruvian segment (Jaillard *et al.*, 1990). According to these authors, the southeastward direction of the subducting oceanic plate would have induced left-lateral transform motion along the Peruvian segment (Aspden *et al.*, 1987; Jaillard *et al.*, 1990) (Fig. 9).

The authors' data would support the existence of southeastward subduction beneath the Northern Andes, resulting in the emplacement of the Misahuallí-Colán magmatic arc during the middle Jurassic (190-150 Ma) with the intrusion of large granodioritic batholiths and the effusion of lavas at the same time (172.3±2.1 Ma for the Misahuallí volcanic rocks and Oxfordian for the Colán Formation). The presence of a calc-alkaline volcanism in the southern coastal Peru at the same period (Bajocian-Bathonian) also indicates the presence of a subduction zone in this area. Thus, the motion of the Phoenix oceanic plate was not just southeastward, but rather WNW-ESE. Another explanation can be that the Jurassic morphology of the Peruvian segment was different from the present-day morphology as suggested by the important counter-clockwise rotations recorded by the Jurassic and Cretaceous volcanic rocks in coastal Southern Peru and northernmost Chile (Heki *et al.*, 1983; Roperch and Carlier, 1992).

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