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CONTEMPORANEOUS ERUPTIONS OF CALC-ALKALINE AND ALKALINE MAGMAS ALONG THE VOLCANIC FRONT OF THE MEXICAN VOLCANIC BELT

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RESUMEN

De acuerdo con los modelos generales para los arcos volcánicos relacionados con la subducción, las composiciones del magma se hacen progresivamente más ricas en K_2O y los elementos incompatibles, a medida que aumentan la distancia desde la trinchera y el frente volcánico, y la profundidad de la zona de Benioff. Los magmas típicos de los arcos son característicamente normativos de hiperesteno y cuarzo. Los basaltos alcalinos normativos de nefelino se supone que son expulsados, si acaso, sólo a grandes distancias de la trinchera. Sin embargo, a lo largo del frente del Eje Volcánico Mexicano han hecho erupción magmas básicos alcálicos hídricos, normativos de nefelino en dos diferentes sitios durante el Período Cuaternario Tardío: en el graben del sur de Colima y en el campo volcánico del sur de Michoacán y Guanajuato. En ambos lugares hicieron erupción contemporáneamente magmas calcalcalinos normativos de hiperesteno y cuarzo, característioos de los frentes volcánicos. Estas secuencias contrastantes de magmas no pueden ser correlacionadas mediante un mecanismo simple; parecen registrar distintos episodios de fusión dentro del manto superior.

ABSTRACT

According to general models for subduction-related volcanic arcs, magma compositions become progressively richer in K_2O and incompatible elements with increasing distance from the trench and volcanic front and with increasing depth to the Benioff zone. Arc-type magmas are typically hypersthene- and quartz-normative. Nepheline-normative alkali basalts are expected to erupt, if at all, only at great distances from the trench. Along the volcanic front of the Mexican Volcanic Belt, however, hydrous, nepheline-normative, basic alkalic magmas have erupted at two different locations during the late-Quaternary Period: in the southern Colima graben and in the southern Michoacán-Guanajuato Volcanic Field. In both places, hypersthene- and quartz-normative calc-alkaline magmas with typical 'volcanic front' characteristics were erupting contemporaneously. These contrasting magma suites can not be related by any simple mechanism; they appear to record distinct melting events within the upper mantle.

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INTRODUCTION

In attempting to understand magmatic processes in orogenic arcs, petrologists have long been fascinated by across-arc variations in eruptive compositions. Through the pioneering work of Tomita (1935), Kuno (1959), and Sugimura (1960) in Japan and the work of Rittmann (1953) in Indonesia, it was established that the alkali contents of arc-type volcanic rocks generally increase with distance from a volcanic front. Recognizing that K_2O usually varies more systematically than Na_2O, Dickinson and Hatherton (1967) later proposed a relationship between the SiO_2-normalized K_2O content of a magma and the depth to the underlying Benioff zone. Subsequent studies have documented increases in incompatible trace element concentrations across specific arcs as well (Jakes and White, 1972; Gill and Gorton, 1973; Katsui *et al.*, 1978; Whitford *et al.*, 1979; Fujitani and Masuda, 1981; Gill, 1981). While these refinements of a generalized arc model were being pursued, however, contradictory evidence was also accumulating. Arculus and Johnson (1978) noted that the lavas of the Lesser Antilles Arc show increases in alkalies from north to south *along* the volcanic front at approximately constant depth to the Benioff zone. Other systematic along-arc variations in eruptive compositions are reviewed in Gill (1981). As an additional complication to generalized arc models, DeLong *et al.* (1975) cited nine occurrences of alkali basalts near the volcanic front in island arcs. In each case, the alkali basalt erupted where an unusual feature of the subducting slab projects beneath the arc: the edge of a plate, a fracture zone, or some other linear element.

In this paper we discuss two separate occurrences of hydrous alkali basalts which erupted along the volcanic front of the Mexican Volcanic Belt (MVB). In both cases, the alkali basalts erupted in close proximity to contemporaneous calc-alkaline volcanic rocks with typical 'volcanic front' characteristics. The alkaline and calc-alkaline suites can not be related by any simple mechanism and appear to represent fundamentally different melting episodes in the upper mantle.

THE MEXICAN VOLCANIC BELT

The MVB is a complex continental arc with a well-defined, E-W trending volcanic front; magmatism is presumably related to subduction of the Cocos Plate beneath the North American Plate along the Middle America Trench (Fig. 1). The trench forms an angle of about 15° with the volcanic front, such that distance from the trench increases progressively eastward in the MVB from about 200 km in the west to over 400 km in the east. In keeping with the generalized arc model, the easternmost volcanoes, San Martín and El Chichón, are relatively alkali-rich. The Tuxtla volcanoes, which include the historically active San Martín, have erupted alkaline magmas ranging from picrites to hawaiites (Thorpe, 1977; Robin and Tournon, 1978). These unusual magmas are probably related to distensive faulting along the Gulf Coast, however, rather than to subduction of the Cocos Plate. The recent eruptions of El Chichón volcano involved relatively potassic trachyandesitic magma (Luhr *et al.*, 1984). The aseismic Tehuantepec Ridge is subducting beneath El Chichón, though, and may be influencing the alkalic nature of the magmas (DeLong *et al.*, 1975). Consequently, no firm evidence presently exists for increased alkali contents due solely to increased distance to the trench eastward along the front of the MVB.

In the main portion of the MVB, various lines of evidence indicate a general southward or trenchward migration of volcanism with time.

1) Most of the historically active volcanoes lie along the volcanic front at about 19°N latitude. Three of the largest active composite volcanoes (Colima, Popocatepetl, and Citlaltepec) mark the southern ends of N-S trending, southward-younging volcanic chains.

2) In the eastern MVB, Cantagrel and Robin (1979) documented a southward shift of magmatism since the Pliocene through K-Ar dating.

3) Hasenaka and Carmichael (1985) investigated ages of the numerous cinder cones in the Michoacán-Guanajuato Volcanic Field of the central MVB (Fig. 1). Of 71 cinder cones interpreted as younger than 40 000 years, all are situated in the south; cones in the north are older and more degraded.

An unfavorable distribution of volcanic centers in most portions of the MVB and a relative lack of published petrologic data make it difficult to appraise possible across-arc variations in eruptive composition. The Michoacán-Guanajuato Volcanic Field with some 900 cinder cones ranging from 200 to 440 km from the trench, however, is an ideal area to evaluate such trends. Hasenaka (1982) and Hasenaka and Carmichael

(1985) report that progressing northward, away from the trench and the volcanic front, volcanic rocks of the same SiO_2 content generally become poorer in Mg, Cr, and Ni, and richer in K, P, Zr, and other incompatible trace elements. These variations are consistent with generalized arc models. Hasenaka and Carmichael (1985) note, however, an interesting exception to these trends: nepheline-normative alkali basalts erupted from a cinder cone in the southernmost part of the field, near the historically active volcán Jorullo (Fig. 1). This volcano, cerro La-Pilita, is one of the two alkali basalt occurrences described in this paper. We begin with the other example from the southern Colima graben.

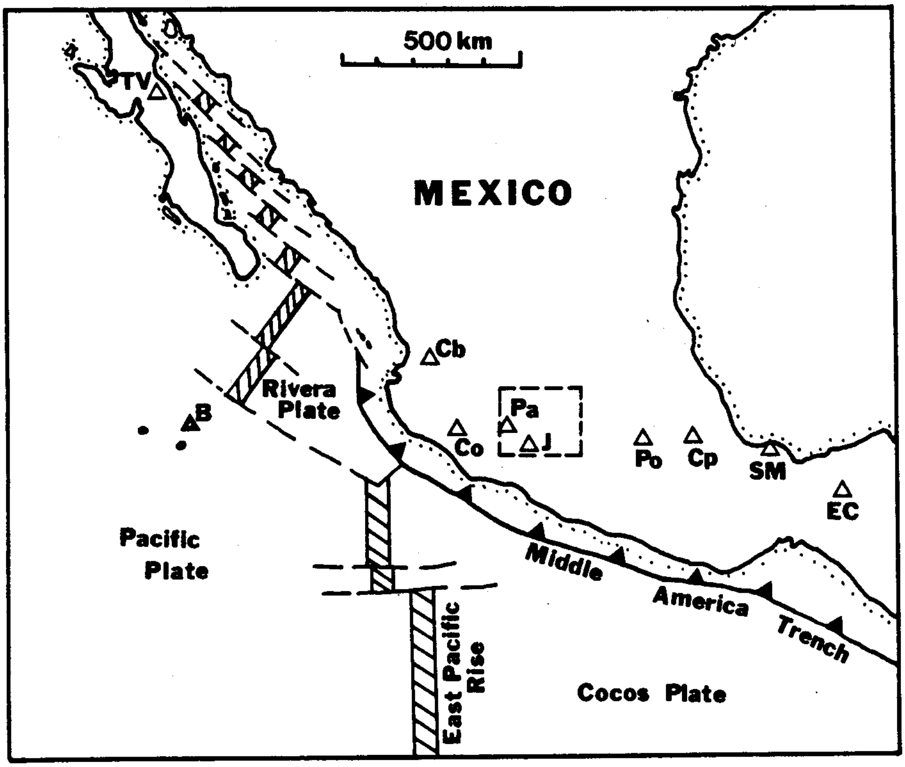

Fig. 1. Generalized map of Mexico and important tectonic elements in the adjacent Pacific Ocean basin. Open triangles show the historically active volcanoes of Mexico: TV - Tres Vírgenes, B - Bárcena, Cb - Ceboruco, Co - Colima, Pa - Paricutín, J - Jorullo, Po - Popocatepetl, Cp - Citlaltepetl, SM - San Martín, EC - El Chichón. The dashed rectangle outlines the Michoacán-Guanajuato Volcanic Field (after Hasenaka and Carmichael, 1985).

THE SOUTHERN COLIMA GRABEN

The western portion of the MVB is dominated by three major graben structures which intersect just south of the city of Guadalajara. These grabens are interpreted as manifestations of an active episode of continental rifting involving the eastward jumping of an East Pacific Rise ridge segment beneath the Mexican mainland (Luhr *et al.*, 1985).

The Colima graben extends some 80 km southward from the graben intersection area. Over the last one million years, a southward-younging chain of andesitic composite volcanoes has developed on the southern graben floor (Fig. 2). The oldest of these andesitic centers, volcán Cántaro, is highly dissected. To its south is the massive Nevado de Colima, which has a summit caldera 5 km in diameter. A post-caldera cone grew within the southern part of the caldera. This peak, which has been extensively glaciated, now marks the highest point in the chain at 4 320 m. The ancestral volcán Colima then developed on the southern flank of Nevado. About 4 300 years ago the southern sector of this cone collapsed to form a horeseshoe-shaped, 'Mount St. Helens-type' caldera 5 km in diameter. The southern slopes of the volcano are covered by a hummocky debris avalanche (Siebert, 1985) resulting from this event. Continuing the southward progression of magmatism along this chain, the presently active cone of volcán Colima then developed in the southern portion of the caldera. Colima has been the most active volcano in the MVB during historic times. The historical record of activity is detailed in Luhr (1981). The third historical cycle began with the eruption of hornblende-andesite lava in 1869 and ended with a major pyroclastic event in 1913 involving relatively basic hornblende-andesite magma. The present eruptive cycle commenced in 1961 with extrusion of a small hornblende-andesite lava flow. Subsequent hornblende-andesite lava eruptions occurred in 1975-76 and 1982. The mineralogy and petrology of andesites from these last two eruptive cycles are discussed in Luhr and Carmichael (1980). These calc-alkaline andesites have compositions and mineralogies typical of volcanic-front lavas (Table 1). Although no basalts have been found within the Cántaro-Colima chain proper, a hypersthene-normative calc-alkaline basalt (Table 1) which erupted from volcán Tezontal, a cinder cone 25 km east of Nevado de Colima (Fig. 2), represents a plausible parental magma to the quartz-normative calc-alkaline andesites of the southern Colima graben (Luhr and Carmichael, 1981).

During the late-Pleistocene, nepheline-normative basic alkalic magmas also erupted on the floor of the southern Colima graben in the form of nine cinder cones and associated lavas. Eight of these cones lie to the west of volcán Cántaro and Nevado de Colima and one cone lies east of the andesitic chain (Fig. 2). The mineralogy and petrology of these unusual basic alkalic magmas are discussed in Luhr and Carmichael (1981). Scoria and lava samples include basanites, leucite basanites, and phlogopite-analcime-bearing minettes. Compared to the

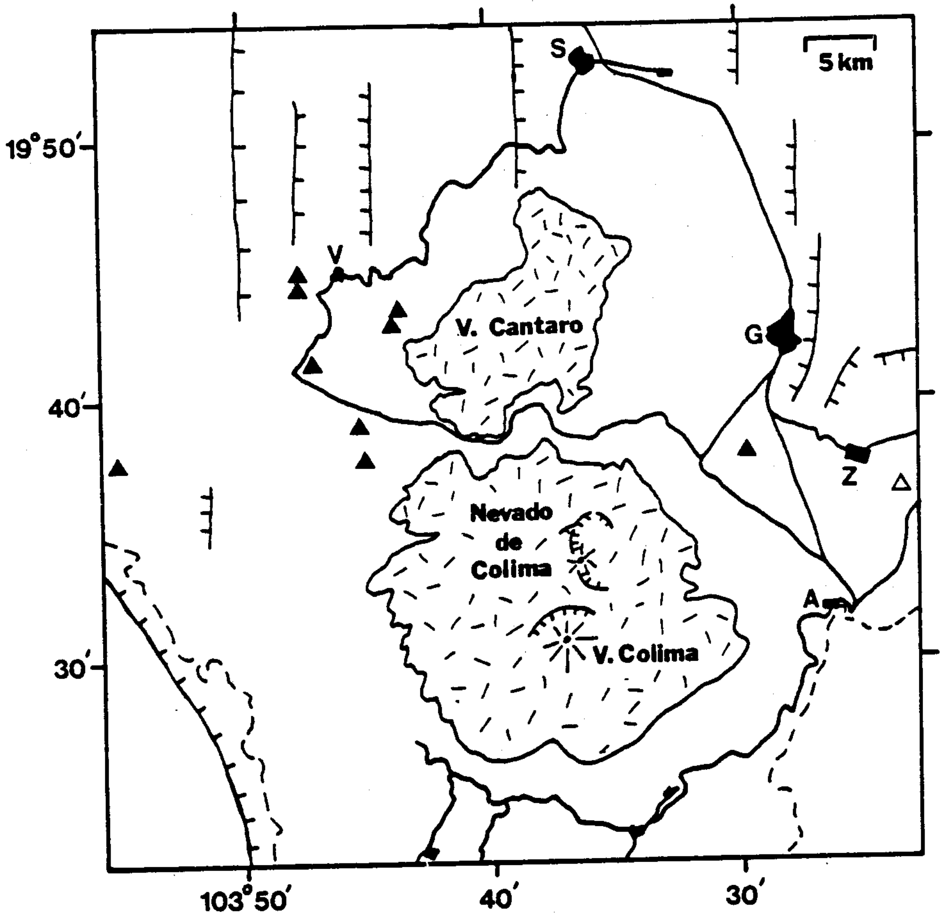

Fig. 2. Sketch map of the southern Colima graben. Solid lines show major paved roads. Cities and towns are black: S - Sayula, V - Venustiano Carranza, G - Ciudad Guzmán, Z - Zapotiltic, A - Atenquique. Normal fault scarps are indicated by solid lines with hashures on the downdropped side. Dashed lines show rivers. The calc-alkaline andesitic volcanoes Cantaro, Nevado de Colima, and Colima are shown in random-dash pattern and labeled. The open triangle indicates volcán Tezontal, constructed of calc-alkaline basalt. The closed triangles show the basic alkaline cinder cones of the southern graben.

calc-alkaline magmas of the Cantaro-Colima chain, they are greatly enriched in K_2O, P_2O_5, Sr, Ba, and many other incompatible elements (Table 1). High f_{O_2} and f_{H_2O} values in these basic alkalic magmas are evidenced by high ferric/ferrous ratios (Sack *et al.*, 1980) and by the

Table 1

Whole-rock compositional data for representative lava and scoria samples from the southern Colima graben and the Jorullo area.

	Southern Colima Graben			Jorullo Area		
	SAY 22E	COL 9	SAY 7E	JOR 44	JOR 11	JOR 46
(wt%)						
SiO_2	49.42	61.02	48.20	52.10	54.18	49.21
TiO_2	0.77	0.64	1.64	0.81	0.92	1.33
Al_2O_3	16.92	17.72	11.62	16.44	18.74	14.19
Fe_2O_3	4.40	1.77	4.22	1.56	2.47	4.54
FeO	5.30	3.46	3.27	6.05	4.31	3.75
MnO	0.15	0.10	0.11	0.14	0.11	0.12
MgO	9.27	2.76	11.81	9.29	4.64	8.32
CaO	10.12	5.92	8.32	8.46	7.87	7.68
Na_2O	2.49	4.70	3.28	3.47	4.52	4.59
K_2O	0.65	1.40	3.58	0.74	1.11	2.82
P_2O_5	0.20	0.21	1.32	0.14	0.24	1.37
H_2O	0.19	0.16	1.96	0.44	0.36	1.19
Total	99.88	99.86	99.33	99.64	99.47	99.11
(ppm)						
Sc	35.5	12.7	26.7	27.9	19.1	18.1
V	196	150	265	186	216	217
Cr	378	25	691	516	75	338
Ni	221	10	436	261	44	248
Cu	24	27	90	60	35	72
Zn	66	70	80	61	66	172
Rb	7	19	73	10	16	17
Sr	444	568	3,079	397	615	2,250
Y	18	17	29	20	21	18
Zr	92	152	554	100	130	203
Ba	161	510	4,230	221	355	1,222
La	9.3	12.4	82.3	7.9	12.6	91.5
Ce	22	27.1	188	18.3	29.4	172
Nd	12	12	93	10	17	67
Sm	2.96	2.93	15.24	2.65	3.39	7.79
Eu	1.13	0.98	4.50	0.90	1.12	2.04
Tb	0.61	0.43	1.20	0.48	0.48	0.62
Dy	3.7	3.1	5.5	3.11	2.94	2.68
Yb	2.08	1.83	1.74	1.95	1.70	1.25
Lu	0.26	0.25	0.18	0.26	0.22	0.17
Hf	2.6	3.5	17.9	2.44	3.46	5.60
Th	0.44	2.01	7.13	0.73	1.14	5.19
U	0.33	0.78	2.41	0.29	0.39	1.18

Data sources:

Col 9 from Luhr and Carmichael (1980)
SAY 22E and SAY 7E from Luhr and Carmichel (1981)
Jor 44, Jor 11, and Jor 46 from Luhr and Carmichael (1985)

presence of phlogopite and primary analcime in the minettes. These nepheline-normative magmas are very unusual for a subduction-related arc, particularly in lying so close to the volcanic front. While they were erupting on the southern graben floor, calc-alkaline magmas continued to erupt along the Cantaro-Colima chain. Evidence of physical mixing between these two end-member magma series has been observed in a sequence of scoria- and ash-fall deposits of latest-Pleistocene age on the upper slopes of volcán Colima (Luhr and Carmichael, 1982). The calc-alkaline and alkaline suites of the Colima graben have fundamentally different mineralogies and bulk compositions. No plausible mineral assemblage can relate the two suites through crystal fractionation or assimilation. They appear to have distinct ancestries, involving different mantle source regions and ascent paths. The walls of the Colima graben expose a Plio-Pleistocene sequence of volcanic rocks in which Allan and Carmichael (1985) have described interbedded calc-alkaline and alkaline lavas up to 4.5 m.y. old. Thus, these two magma series appear to have been erupting contemporaneously in the area of the Colima graben since the Pliocene.

JORULLO VOLCANO AND CERRO LA PILITA

Of the 900 morphologically youthful cinder cones in the Michoacán-Guanajuato Volcanic Field (Fig. 1), only two have erupted since the Spanish Conquest: Jorullo (1759-1774) and Paricutín (1943-1952). As shown in Fig. 2 of Hasenaka and Carmichael (1985), the concentration of cinder cones in this field is highest at about 250 km distance from the Middle America Trench. Paricutín erupted within this zone of maximum cone concentration. Jorullo (Fig. 3) sits about 75 km southeast from Paricutín as one of the southernmost cinder cones in the field. Contrary to the usual patterns of compositionally zoned eruptions. both Jorullo and Paricutín produced progressively more silica-rich magmas with time. The early Jorullo lavas are primitive olivine basalts with 52 wt% SiO_2 (Table 1). These evolved to hornblende- or orthopyroxene-bearing basaltic andesites with 55% SiO_2 (Table 1) by the close of activity (Luhr and Carmichael, 1985). Similarly, the Paricutín magmas progressed from early olivine-bearing basaltic andesites with 55% SiO_2 to late-stage orthopyroxene-andesites with 60% SiO_2 (Wilcox, 1954). The products of Jorullo and Paricutín are typical hypersthene- and quartz-normative calc-alkaline magmas, similar in composition and mineralogy to the magmas of volcán Colima and other volcanic front eruptive centers.

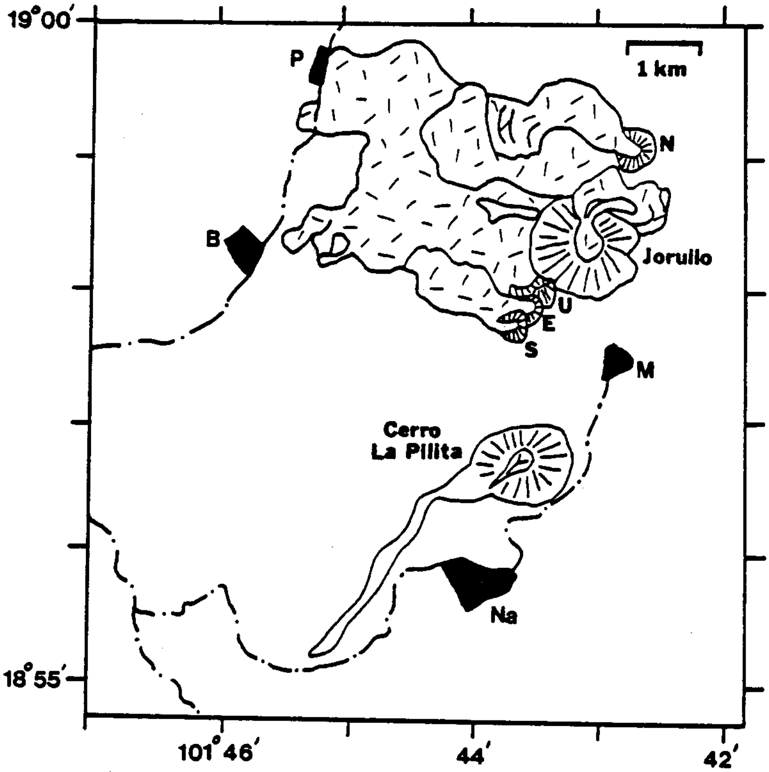

Fig. 3. Sketch map of the area near Jorullo volcano and its associated cinder cones (N - Volcán del Norte, U - unnamed, E - Volcán Enmedio, S - Volcán del Sur), all of which formed during the 1759-1774 activity. These cones fed the lava field (random-dash pattern) that extends westward. Just to the south of Jorullo is the late-Pleistocene basic alkaline cinder cone Cerro La Pilita and the 4-km-long tongue of hornblende-trachybasalt lava that flowed from it to the southwest. Dashed-dot lines show unimproved roads. Villages are black: P - La Puerta de la Playa, B - Agua Blanca, M - Mata de Plátano, Na - El Naranjo del Jorullo.

Just four km south of the main cone of Jorullo lies the late-Pleistocene cinder cone Cerro La Pilita (Fig. 3). Scoria and lava samples from this volcano are nepheline-normative hornblende-trachybasalts (Luhr and Carmichael, 1985). They contain phenocrysts of forsteritic olivine plus Mg-Cr-Al spinel, hornblende, augite, and plagioclase, and microphenocrysts of apatite. These trachybasalts are greatly enriched in K_2O, P_2O_5, Sr, Ba, and other incompatible trace elements compared to the nearby calc-alkaline magmas of Jorullo (Table 1). High ferric/ferrous ratios and the presence of hornblende indicate that the trachybasalts also formed under significantly higher f_{O_2} and f_{H_2O} conditions. Calc-alkaline magmas were erupting intermittently in the southern part of the volcanic field in close proximity to Cerro La Pilita throughout the Quaternary period. As in the case of the Colima graben, no simple mechanism can relate the calc-alkaline magmas, such as those from Jorullo, to the alkaline suite of Cerro La Pilita; the two seem to represent fundamentally different melting events.

DISCUSSION

According to generalized arc models, nepheline-normative alkali basalts should be found only at great distances from the trench. In both the southern Colima graben and the southern Michoacán-Guanajuato Volcanic Field, however, hydrous basic alkalic magmas erupted along the volcanic front in close proximity to contemporaneous calc-alkaline magmas. Table 1 gives representative whole-rock analyses for the contrasting volcanic suites of these two areas, and Fig. 4 shows plots of K_2O and Ba versus SiO_2 for a larger data set. In both cases the alkaline magmas are greatly enriched in K_2O, Ba, and other incompatible elements compared to the well-defined calc-alkaline trends of increasing incompatible elements with increasing SiO_2. Judging from their high whole-rock $Mg/Mg+Fe^{+2}$ ratios and Ni and Cr contents, and the Mg-rich nature of their olivine phenocrysts, both the basic alkaline magmas and the calc-alkaline basalts probably represent direct partial melts from the mantle with only limited fractionation on route to the surface. In view of the experimental studies of Kushiro (1968), the nepheline-normative alkaline basalts were probably generated at considerably greater depths than the hypersthene-normative calc-alkaline basalts. The relationship of these depths of melting to the depth of the subducted slab, however, is unclear The 3- to 10-fold enrichments of K_2O and other incompatible elements in the alkaline suites relative to the calc-alkaline suites may be explained by much smaller degrees of partial melting of a similar source material (Gast, 1968). Alternatively, these enrichments may simply mirror enrichments in the source region of the alkaline magmas, perhaps as a result of metasomatism in this deeper portion of the mantle (Lloyd and Bailey, 1975).

The Colima graben overlies the subducting, left-lateral boundary between the Cocos and the Rivera Plates (Fig. 1). In this respect, the presence of basic alkaline magmas in the graben might be governed by the

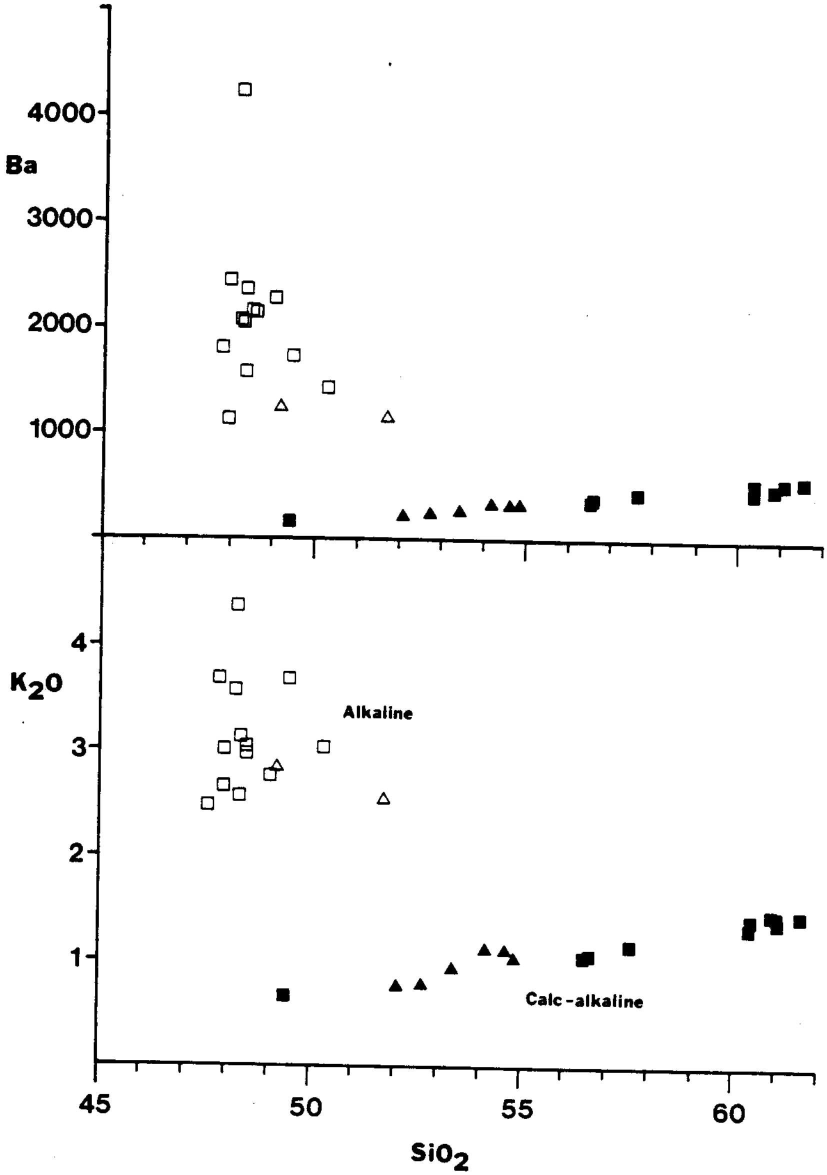

Fig. 4. Plots of whole-rock concentrations of Ba (ppm) and K_2O (wt%) versus SiO_2(wt%) for the samples discussed in this paper. Calc-alkaline specimens are shown in solid symbols: solid triangles - basalts and basaltic andesites from Jorullo (Luhr and Carmichael, 1985), solid squares - historical hornblende-andesites from Volcán Colima and the calc-alkaline basalt from Volcán Tezontal (Luhr and Carmichael, 1980 and 1981). Alkaline specimens are shown in open symbols: open triangles - hornblende-trachybasalts from Cerro La Pilita (Luhr and Carmichael, 1985), open squares - basanites, leucite-basanites, and minettes from the cinder cones of the southern Colima graben (Luhr and Carmichael, 1981).

'plate-edge effect' postulated by DeLong *et al.* (1975) to ease passage of such magmas to the surface. These basic alkaline magmas also conform to the general association of such magma types with areas of continental rifting (Carmichael *et al.*, 1974; Lloyd and Bailey, 1975). Cerro La Pilita, on the other hand, neither overlies a known discontinuity in the subducting Cocos Plate, nor lies within a recognizable graben structure. These facts cast doubt on any simplistic empirical models for the eruption of alkaline magmas near volcanic fronts of subduction-related arcs.

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