Geofísica Internacional (1996), Vol. 35, Num. 1 , pp. 27-39

Mineralogical and geochemical characteristics of volcanic rocks of the Valles-San Luis Potosí platform, Mexico: Geodynamic implications

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Received: March 3, 1995; accepted: September 26, 1995.

RESUMEN

La región, que abarca a la unidad paleogeográfica Mesozoica denominada Plataforma Valles-San Luis Potosí, tiene influencia volcánica tanto del dominio Cordillerano como del Golfo de México, por lo que es un área favorable para el estudio de los sucesivos episodios volcánicos y sus implicaciones tectónicas. El presente estudio reporta nuevos datos mineralógicos y geoquímicos, en 5 niveles volcánicos de la región.

La parte occidental de la plataforma muestra evidencias de dos eventos: el primero entre el Triásico y el Jurásico caracterizado por metabasitas toleíticas de tipo de arco; el segundo, de edad Cenozoica caracterizado por lavas cuya mineralogía (presencia de ortopiroxenos, clinopiroxena de carácter calcoalcalino) y geoquímica (fuerte enriquecimiento de elemento LFS y anomalías negativas distintivas de NB y Ti) indicando una afinidad andesítica. Estos dos eventos son posiblemente equivalentes a las series de emplazamientos orogénicos asociados a la subducción de la placa Pacífica desde el Triásico.

En la parte este de la plataforma, las lavas del Oligoceno-Plioceno son alcalinas (alto TiO_2-P_2O_5 conteniendo gran enriquecimiento de REE ligeras y elementos LFS) y son derivadas de una fuente tipo OIB con características diferentes a los de arco (sin anomalías Nb o Ti).

En la región de Guaxcamá (en la parte sudoeste de la plataforma), hay dos tipos de rocas volcánicas, unas intercaladas entre las evaporitas de probable edad Jurásica (34 S=15.3 en anhídrita y yeso) y las otras encima de las formaciones Cretácicas. Las secuencias recientes se encuentran diferenciadas variando en composición de basaltos moderadamente alcalinos, a riolitas. Estas difieren de las lavas básicas en las evaporitas, en el contenido de elementos incompatibles. Sus rasgos transicionales pueden reflejar cambios en la composición química y mineralógica de la fuente del manto entre los diferentes episodios eruptivos. De esta manera, la formación de las rocas de Guaxcamá, hasta ahora consideradas como un depósito tipo lagunar asociado con los depósitos de plataforma, puede ser el resultado de una interdigitación Tethyesiana relacionada a una zona de rift continental.

La actividad ígnea de la Plataforma de Valles-San Luis Potosí refleja la influencia de dos dominios tectónicos contrastantes separados por un lineamiento mayor denominado la Gran Falla, la cual delimita una zona hacia el Oeste con un magmatismo de tipo orogénico asociado con depósitos minerales y una zona este con un magmatismo distensivo desprovisto de mineralizaciones económicas.

PALABRAS CLAVE: Datos geoquímicos, evento volcánico, mineralogía, series ígneas orogénicas, zonas de rift continental, dominios tectónicos, depósitos minerales.

ABSTRACT

The present study reports new mineralogical and geochemical data on five volcanic suites from the Valles-San Luis Potosí Platform (VSLP). The western part of the platform shows evidence of two successive events: the first, of Triassic-Jurassic age, is characterized by metabasites of island-arc tholeiite type; the second, of Cenozoic age, is characterized by lavas whose mineralogy (presence of orthopyroxene, calc-alkaline characters of clinopyroxene) and geochemistry (strong LFS element enrichment, distinct Nb an Ti negative anomalies) indicate an andesitic affinity. These two volcanic suites are possibly equivalent to orogenic igneous series emplaced from Triassic times onwards in the Western Cordilleran province, which are associated with subduction of the Pacific plate. In the eastern platform, Cenozoic lavas are alkalic (high TiO_2-P_2O_5 contents, strong enrichment of light-REE and LFS elements) and are derived from an OIB-type source with no arc-type characteristics (no Nb or Ti anomaly). Two volcanic sequences are exposed in the Guaxcamá region (southwestern part of the platform); one is intercalated within evaporites of probable late Jurassic age and the other occurs above the Cretaceous formations. The latter sequence forms a differentiated suite varying in composition from moderately alkalic basalt to rhyolite; it differs from the older basic lavas within the evaporites in having lower transition and incompatible element contents. Their transitional features could reflect a change in the chemical and mineralogical composition of the mantle source between the two successive eruptive episodes. In this way, the formations of the Guaxcamá terrain, until now considered as typical of a lagoonal environment associated with platform deposits, may instead result from the interfingering of Tethyan units within a continental rift-zone.

The igneous activity of the VSLP platform reflects the influence of two contrasting tectonic domains separated by a major basement lineament, the "Gran Falla", which delimits a western zone with orogenic-type magmatism associated with mineral deposits, and an eastern zone with tensional magmatism devoid of economic mineralization.

KEY WORDS: Petrography, geochemical data, volcanic suites, geodynamic model, Mexico.

INTRODUCTION

The Valles-San Luis Potosí (VSLP) platform lies south of the Sierra Madre Oriental province, in the western part of the Mexican Gulf petroleum areas (Figure 1). It is bounded by three volcanic provinces:

(1) in the south, the dominantly calc-alkaline eastern Mexican Volcanic Belt, which has been active since Miocene times (Demant, 1981);

(2) in the east and north, a mafic alkalic volcanic province, Oligocene and Quaternary in age, which comprises the southward continuation of the Eocene Trans-Pecos province (Robin and Tournon, 1978);

(3) in the west, the Sierra Madre Occidental province, which is dominated by Miocene ignimbrite sheets and is partly overlain by Plio-Quaternary alkalic lavas (Cochémé, 1985).

The purpose of this paper is to characterize the geochemistry of the successive volcanic suites and to propose a geodynamic model for the VSLP platform.

GEOLOGICAL SETTING

The VSLP platform, mainly composed of massive carbonates of Mesozoic age (Carrillo-Bravo, 1971), is underlain by a poorly-exposed basement consisting of Precambrian gneiss, Ordovician micaschists, and Paleozoic granitoids. A compilation of regional geophysical and geological data (Valencia *et al.*, 1991; Valencia, 1993) indicates a basement made up of a mosaic of horsts and grabens that have influenced the distribution of Mesozoic sedimentary facies. These facies can be classified into four lithostratigraphic successions (or sedimentary tract systems):

1) The "rift assemblage", containing deposits related either to the opening of the Gulf of Mexico or the western part of Tethys (Tardy, 1980; Guzmán, 1991); deposition was continental from late triassic until the mid-Jurassic time and became marine in the late Jurassic, with massive evaporites cropping out over 250 km^2 in the Guaxcamá terrane.

2) The "Toliman volcano-sedimentary assemblage" associated with the development of a late Jurassic to early Cretaceous back-arc basin.

3) The "platform assemblage", composed predominantly of carbonates, laid down during the Cretaceous marine transgression (Carrillo-Bravo, 1971).

4) The "synorogenic assemblage", predominantly terrigenous, related to eastward migration of the Laramide orogenic belt (Campanian-Eocene).

The style of regionally developed structures (fold and thrust fault systems) was controlled by basement-cover relations and by the lithology of the cover. In the western margin of the platform, we note the presence of a major N-S basement lineament, the "Gran Falla", which separates two contrasting tectonic domains (Figure 1). This lineament marks the boundary between the VSLP platform and the Mesozoic basin of Central Mexico, and the eastern boundary of the Sierra Madre Occidental igneous province and its associated mineralization (Valencia *et al.*, 1988). Recent metallogenic studies (Economic Geology, 1988) have shown the hydrothermal origin of the major Pb, Zn, Ag, Cu and Hg deposits, which are Oligocene in age.

The stratigraphic relationships and geochronology (K-Ar dates) of igneous rocks belonging to the VSLP platform have received considerable attention. Recently, Valencia (1993) presented additional data, which help define the following sequence, from base to top (Figure 1):

(1) The oldest exposed formations are made up of metabasic rocks, at Real de Catorce, interbedded within a thick Triassic-Jurassic volcano-sedimentary sequence. The metabasic rocks from the neighbouring Zacatecas province, located in the same Triassic formation, may be equivalent to the Real de Catorce metabasites (McGehee, 1976; Salvador and Green, 1980).

(2) The Guaxcamá evaporites contain "pillow-like" metabasites with very fine-grained rims and are often totally altered. This evaporitic formation, previously interpreted as a lagoon deposit of Aptian age, contains mainly anhydrite and gypsum; the δ^{34} values of the anhydrite and gypsum (15.3) are close to those of evaporites from neighbouring areas (Olvido: δ^{34}=16.2; Nunez: δ^{34}=15.3), which are late Jurassic in age (Claypool *et al.*, 1980; Valencia, 1993).

(3) The oldest exposed Tertiary unit is a quartz porphyry from Real de Catorce (53 ± 4 Ma, Mugica and Jacobo, 1983). Andesites from a plateau in the same area (44 ± 4 Ma, Labarthe *et al.*, 1982). Andesite also occurs within a thick trachyte, rhyolite and ignimbrite suite in the San Luis Potosí area (32-26 Ma, Labarthe *et al.*, 1982).

(4) In the Guaxcamá region, the Cretaceous formations are overlain by lavas forming a plateau similar to the basalts of Río Verde (Robin, 1977).

(5) In the Ciudad del Maiz region, some of the basalts may be equivalent to the alkali-basalts of the Sierra de Tamaulipas and Tampico basin (28-3 Ma, Cantagrel and Robin, 1978) and to the Quaternary eruptive centres of Ventura and Santo Domingo located in Central of San Luis Potosí State (Luhr *et al.*, 1989).

PETROGRAPHY AND WHOLE-ROCK GEOCHEMISTRY

Petrographic and geochemical data major elements only were previously available for a few volcanic rocks of the VSLP platform (Robin, 1977; Robin and Tournon, 1978; Aranda *et al.*, 1986). We present new mineralogical and geochemical data on volcanic rocks representative of the tectonic evolution of the VSLP platform (Tables 1 and 2).

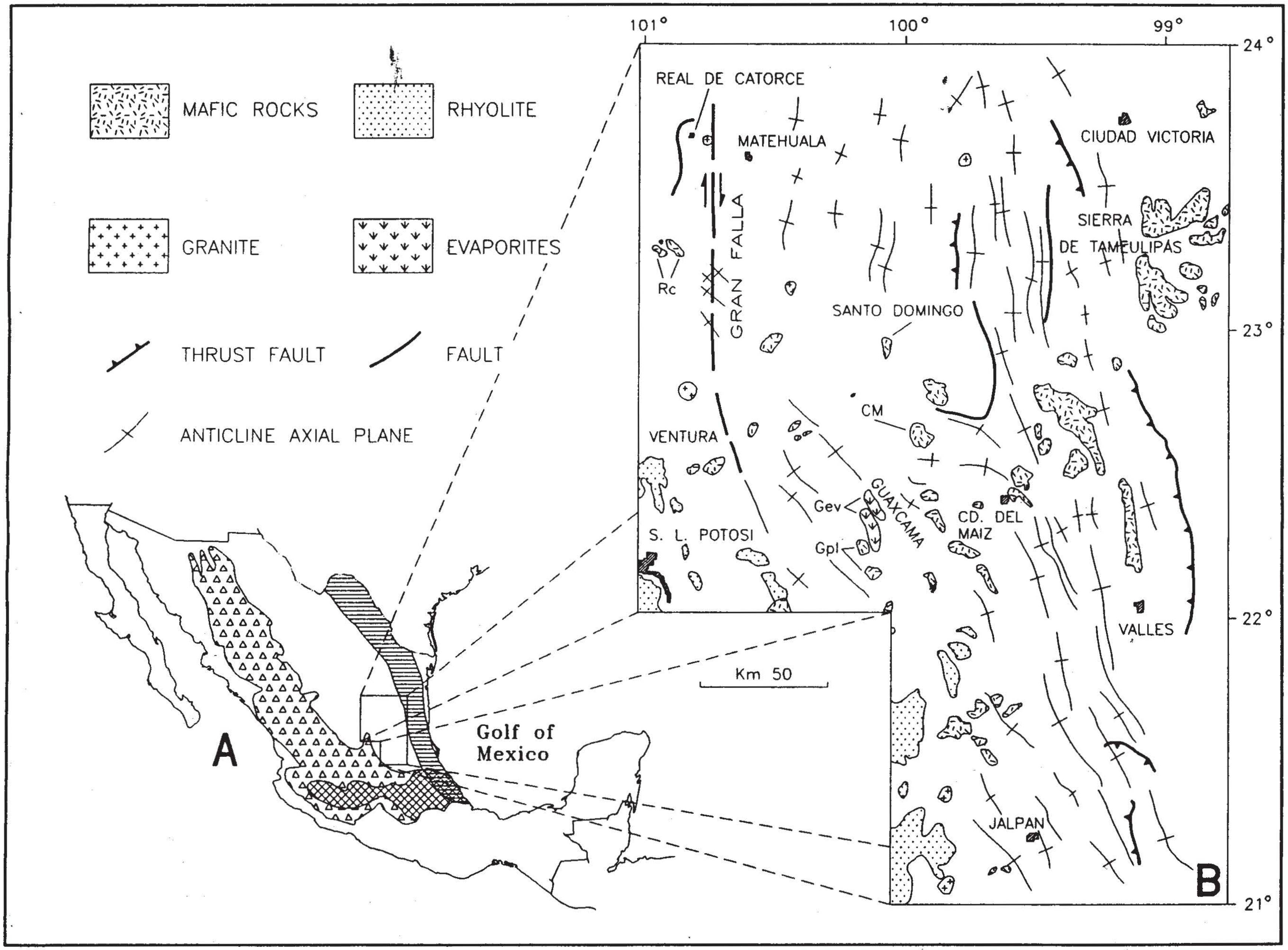

Fig. 1. (A) Major volcanic provinces in Mexico (after Demant and Robin, 1975); SMO: Sierra Madre Occidental; EAP: Estern Alkaline Province; MVB: Mexican Volcanic Belt; Z: Zacatecas; RC: Real de Catorce; CM: Ciudad del Maiz; Gev and Gpl: Guaxcamá. (B) Geological sketch map of the Valles-San Luis Potosí (VSLP) region with the locations of all volcanic types.

Table 1

Representative whole-rock chemical analyses

	Zac1	RCT1	RCC1	RCC2	Gpl1	Gpl2	Gpl3	Gev1	CM1	CM2
SiO_2	52.84	38.92	57.50	55.03	48.84	61.34	73.00	45.71	45.21	46.42
TiO_2	0.65	1.41	1.12	1.25	2.00	0.75	0.19	1.22	2.12	1.86
Al_2O_3	15.03	13.41	15.51	16.60	15.92	16.89	12.24	12.24	14.61	15.98
FeO	8.16	10.69	6.80	7.66	11.91	3.95	2.25	7.50	12.55	11.69
MnO	0.19	0.24	0.07	0.12	0.15	0.01	0.00	0.07	0.19	0.15
MgO	6.69	4.07	5.00	4.82	5.80	2.04	0.28	5.00	6.74	5.84
CaO	8.33	13.13	6.16	7.05	8.91	4.37	1.20	12.58	9.83	9.74
Na_2O	3.54	3.79	2.72	3.15	3.54	4.33	2.22	2.62	3.35	3.65
K_2O	1.45	0.03	2.66	1.70	1.31	1.92	5.16	1.45	1.58	1.18
P_2O_5	0.12	0.60	0.34	0.30	0.45	0.27	0.03	0.93	0.59	0.51
L.I.	2.71	13.37	1.66	1.93	0.82	3.67	3.03	9.33	1.99	0.28
Total	99.71	99.66	99.55	99.61	99.65	99.56	99.61	99.06	99.67	99.70
Cr	263	800	225	263	217	31	5	448	293	252
Co	26	48	19	23	37	8	5	27	33	47
Ni	88	259	85	108	121	15	6	181	70	126
V	262	221	126	155	192	70	6	170	198	218
Ba	295	340	1227	982	488	711	1512	1508	421	309
Rb	55	6	66	32	20	46	190	35	25	21
Sr	223	185	622	470	593	1241	96	2156	764	597
Th	<5	12	8	6	5	7	9	11	7	5
Nb	<5	14	7	7	20	5	5	18	40	29
Zr	33	247	217	193	158	142	257	198	191	141
Y	14	41	20	23	24	13	42	26	23	21
La	2.33	25.10	39.60	29.50	26.10	43.90	59.80	71.60	31.47	23.00
Ce	6.93	54.60	77.00	53.90	48.10	66.10	98.60	146.70	56.63	44.24
Nd	5.22	31.10	38.67	30.76	25.66	45.00	55.73	79.10	29.25	22.01
Sm	1.99	7.72	8.00	6.90	6.45	8.49	11.60	14.60	6.25	4.95
Eu	0.65	1.94	1.83	1.77	1.99	2.16	1.52	3.98	1.89	1.56
Gd	1.75	7.69	6.52	6.07	5.70	5.17	8.95	10.39	5.09	4.24
Dy	2.15	6.88	4.24	4.68	4.40	2.88	7.41	5.33	4.59	4.06
Er	1.28	3.63	2.00	2.20	1.93	1.45	3.81	2.12	1.68	1.93
Yb	1.28	2.75	1.77	2.06	1.73	0.98	3.75	1.76	1.55	1.51
Lu	0.18	0.36	0.26	0.27	0.26	0.16	0.60	0.24	0.22	0.25

Zac: Zacatecas; RCT and RCC: Triassic and Cenozoic lavas from Real de Catorce; Guaxcamá plateau lavas Gpl and intraevaporitic lavas Gev; CM: Ciudad del Maiz.

Analyses were performed by XRF spectrometry for major elements (weight %) and by ICP-Atomic Emission Spectrometry for trace elements (ppm) at C.R.P.G. Nancy. Loss on ignition (L.I.) was performed at 900°C in a muffle furnace. Accuracy of analysis is 1% for major elements and 2% for trace elements. Microprobe analyses were obtained at Laboratoire de Minéralogie, Toulouse, using a CAMECA SX 50; concentrations are accurate within 1%.

Triassic-Jurassic metabasites

The intensely altered rocks from Real de Catorce (RCT) are essentially carbonates with accessory quartz, in a fine-grained matrix of albite and chlorite. The Zacatecas samples, used for comparison, exhibit a secondary paragenesis containing epidote and albite.

The Zacatecas metabasites (Table 1) have high Ni (90 ppm) and Cr (260 ppm) contents consistent with a basaltic composition, and low incompatible element contents (Th and Nb<5 ppm, Zr<35 ppm, Y<15 ppm, TiO_2=0.65 wt%) with flat Rare Earth element (REE) pattern (La/Yb=2, Figure 2). The Real de Catorce metabasites (RCT1, Table 1) can be distinguished from the Zacatecas metabasites on the basis of their higher Ni and Cr (260 and 800 ppm, respectively) and incompatible element contents (Th=12 ppm, Zr=250 ppm, Y=40 ppm, and TiO_2=1.40 wt%). The REE are 2-10 times more abundant than in the Zacatecas metabasites, with a light REE-enriched pattern (La/Yb = 9, Figure 2).

Table 2

Representative microprobe analyses.

	Amphibole		Olivine				Magnetite		Ilmenite
	Gpl2	Gpl2	Gpl1	Gev1	RCC1		RCC1	RCC1	Gpl2
	1	2	3	4	5		6	7	8
SiO_2	42.21	39.43	38.85	39.45	39.08	$SiO_2$2	0.05	0.26	0.05
TiO_2	2.90	2.53	0.06	0.00	0.00	TiO_2	22.83	0.00	39.85
Al_2O_3	12.03	13.11	0.03	0.10	0.11	Al_2O_3	0.53	0.05	0.00
Cr_2O_3	0.01	0.15	0.08	0.07	0.11	Cr_2O_3	0.24	0.02	0.09
FeO	9.66	9.37	18.78	11.79	21.31	FeO	23.49	23.50	31.97
MnO	0.06	0.18	0.30	0.09	0.21	Fe_2O_3	52.62	58.69	24.51
MgO	13.75	14.15	41.34	49.01	39.69	MnO	0.14	0.00	0.53
CaO	11.42	11.35	0.20	0.00	0.16	NiO	0.00	2.91	0.00
Na_2O	2.48	2.55	0.00	0.00	0.00	MgO	0.31	0.00	1.83
K_2O	0.54	0.42	0.00	0.00	0.00	ZnO	0.00	0.09	0.17
Total	94.98	96.04	99.64	100.51	100.57	Total	100.21	85.52	99.00
Si	6.29	5.96	1.00	0.97	1.00	Ti	0.60	0.00	0.76
AlIV	1.71	2.04	0.00	0.00	0.00	Al	0.02	0.00	0.00
AlVI	0.41	0.30	0.00	0.00	0.00	Cr	0.01	0.00	0.00
Fe^{3+}	0.18	0.64	0.00	0.00	0.00	Fe^{2+}	0.68	0.89	0.68
Ti	0.33	0.29	0.00	0.00	0.00	Fe^{3+}	1.37	2.00	0.47
Mg	3.06	3.19	1.59	1.80	1.52	Mn	0.00	0.00	0.01
Fe^{2+}	1.02	0.54	0.40	0.24	0.46	Ni	0.00	0.11	0.00
Ca	1.82	1.84	0.00	0.00	0.00	Mg	0.02	0.00	0.07
Na	0.72	0.75	0.00	0.00	0.00				
K	0.10	0.08	0.00	0.00	0.00				

	Clinopyroxene								Orthopyroxene	
	Gev1	Gev1	Gpl1	Gpl1	RCC1	RCC1	RCC2	RCC2	RCC2	RCC1
	9	10	11	12	13	14	15	16	17	18
SiO_2	50.06	52.76	50.01	48.78	50.12	49.51	52.59	51.60	54.53	54.08
TiO_2	1.09	0.59	1.50	1.42	0.85	1.21	0.94	1.30	0.34	0.22
Al_2O_3	4.61	2.78	2.28	5.86	3.02	3.48	1.23	1.68	0.84	2.55
Cr_2O_3	0.06	0.44	0.13	0.53	0.79	0.37	0.08	0.09	0.21	0.78
FeO	7.39	5.02	8.97	7.71	6.45	7.23	11.57	13.10	14.01	10.24
MnO	0.25	0.13	0.21	0.17	0.15	0.22	0.24	0.36	0.37	0.22
MgO	13.58	16.09	14.04	14.20	15.34	14.97	15.23	14.15	27.01	29.60
CaO	21.41	21.47	21.14	19.97	21.42	21.47	17.35	17.14	2.03	1.25
Na_2O	0.67	0.49	0.42	0.48	0.23	0.32	0.17	0.21	0.04	0.02
K_2O	0.00	0.00	0.01	0.00	0.02	0.01	0.01	0.00	0.00	0.00
Total	99.12	99.77	98.71	99.12	98.39	98.79	99.41	99.63	99.38	98.96
Si	1.87	1.93	1.89	1.82	1.88	1.85	1.98	1.95	1.97	1.93
Ti	0.03	0.02	0.04	0.04	0.02	0.03	0.03	0.04	0.01	0.01
Al	0.20	0.12	0.10	0.26	0.13	0.15	0.06	0.08	0.04	0.11
Cr	0.00	0.01	0.01	0.02	0.02	0.01	0.00	0.00	0.01	0.02
Fe^{3+}	0.05	0.00	0.07	0.04	0.06	0.09	0.00	0.00	0.00	0.01
Fe^{2+}	0.18	0.15	0.22	0.20	0.14	0.14	0.36	0.41	0.42	0.30
Mn	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.76	0.88	0.79	0.79	0.86	0.83	0.85	0.80	1.46	1.57
Ca	0.86	0.84	0.86	0.80	0.86	0.86	0.70	0.69	0.08	0.05
Na	0.05	0.04	0.03	0.04	0.02	0.02	0.01	0.02	0.00	0.00

Amphiboles (1 and 2): structural formulae and Fe^{3+} calculated by normalizing the sum of cations (except Ca, Na and K) to 13 (Richard and Clarke, 1990); olivines (3 to 5); magnetites (6 and 7) and ilmenite (8): Fe_2O_3 and FeO have been calculated from total FeO by assuming 4 oxygens, 2 trivalent cations in the spinel formula from magnetite and 3 oxygens with R_2O_3 stoechiometry for ilmenite; clinopyroxenes (9 to 16) and orthopyroxenes (17 to 18): structural formulae calculated by assuming 6 oxygens (Cebria Gómez, 1990).

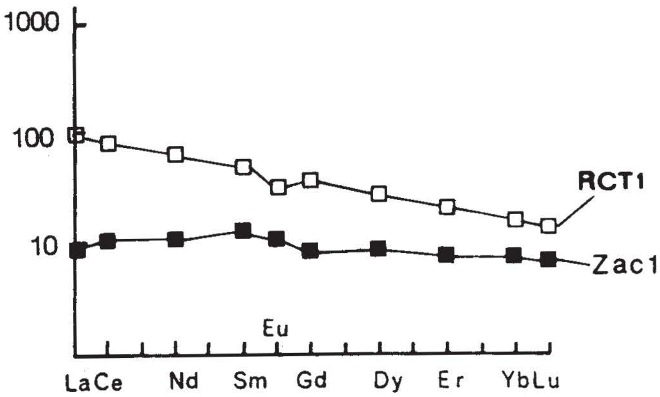

Fig. 2. Chondrite-normalized rare-earth element patterns of Triassic-Jurassic volcanic rocks. RCT: Real de Catorce; Zac: Zacatecas. Normalization values from Bougault (1980).

Volcanic rocks intercalated within the Guaxcamá evaporite formation

These volcanic rocks (Gev) are vuggy with a phyric texture. They contain fresh olivine (Fo 90-85) and clinopyroxene phenocrysts. The fine-grained microlitic groundmass comprises well-preserved plagioclase laths (An65), pyroxene, olivine, titanomagnetite, and apatite grains as well as a devitrified brown glass. The vugs are filled with dolomite or quartz, with well-developed reaction rims with clay minerals and Febearing cryptocrystalline phases. Some samples present a more phyric texture, with cm-scale glomeroporphyritic aggregates of olivine, pyroxene, and rare interstitial plagioclase.

The pyroxenes comprise diopside (En_{40-45} Fs_{8-13} Wo_{44-47}) and magnesio-augite (En_{43-49} $Fs_{7.5-11.5}$ Wo_{42-45}, Figure 3a, Table 2). Since they show a large variation in Ti, Na and Al contents, they plot near the boundary between the sub-alkalic and alkalic fields (Figure 3b).

In the alkalis vs. SiO_2 diagram (Figure 4), these rocks plot clearly in the alkalic field. Their multi-element abundance patterns exhibit a strong light-REE and low-field-strength (LFS) element (Ba, Rb, Th) enrichment (200-1000 times chondritic) with a La/Yb of 40 and distinct NB and Ti negative anomalies (Figure 5b).

Cenozoic andesites from Real de Catorce

These rocks have a microlitic, weakly porphyritic texture. Orthopyroxene makes up almost 90% (by volume) of the phenocrysts; clinopyroxene, plagioclase (An 75-50) and olivine (Fo75), generally replaced by iddingsite, account for the remaining 10% (Table 2). Olivine and a nickeliferous magnetite (up to 3 wt% NiO, anal. 7, Table 2) included within orthopyroxene were the early phases to crystallize. The groundmass comprises plagioclase laths (An 50), clinopyroxene and accesory titanomagnetite with fine ilmenite exsolution lamellae.

Orthopyroxenes and clinopyroxenes are enstatites and augites respectively. (Opx=$En_{72-83}Fs_{14-25}Wo_{2,5-4}$; Cpx=$En_{42-49}Fs_{9-22}Wo_{36-45}$) (Table 2).

The clinopyroxene compositions plotted on discrimination diagrams in (Figure 3 b and c) indicate an affinity with calc-alkaline basalts.

The Cenozoic andesites from Real de Catorce (RCC, Table 1), as well as those from the San Luis Potosí area, are subalkaline in character (Figure 4) with samples clearly plotting in the calc-alkaline field of the AFM diagram (Figure 6). Their multi-element abundance patterns exhibit a strong LFS element enrichment (100-400 times chondritic), with La/Yb of 15-25 and distinct Nb and Ti negative anomalies broadly typical of calcalkaline subduction magmas (Mc Culloch and Gamble, 1991).

Cenozoic volcanic rocks of the Guaxcamá plateau

Variously differentiated volcanic rock-types are exposed, including:

(1) Microlitic porphyritic basalt (Gp11) containing plagioclase (An_{75-60}) and olivine (Fo_{80}), partly replaced by iddingsite, occuring as phenocrysts in a fine-grained groundmass with clinopyroxene grains, plagioclase laths and titanomagnetite with fine ilmenite exsolution lamellae; olivine phenocrysts include both Cr-spinel and pentlandite with chalcopyrite.

(2) Microlitic porphyritic intermediate lava (Gp12) containing amphibole and plagioclase (An_{60-40}), including numerous ilmenite grains, occuring as phenocrysts; the groundmass comprises plagioclase, quartz, alkali feldspar and apatite.

(3) Microlite porphyric silicic lava (GP13) containing plagioclase (An_{30-10}), quartz and alkali feldspar as phenocrysts in a felsitic groundmass with biotite and magnetite grains.

Amphiboles are always calcic (Na+Ca>1.34, Leake, 1978). They have a composition of magnesio-hastingsite and pargasitic hornblende. Pyroxenes are diopside and magnesio-augite ($En_{41-44}Fs_{12-15}Wo_{43-46}$). Their affinities are those of clinopyroxene from alkalic lavas (Figure 3).

Except for the more differentiated samples which plot in the subalkalic field, the basic lavas of Guaxcamá and Río Verde plot in the alkalic field (Figure 4).

Incompatible elements of Guaxcamá samples (e.g. La, Th, Figure 7) plot on a straight line going almost through the origin. For transition element Ni vs. La plots on a logarithmic scale, samples fall within a very narrow field corresponding to linear depletion of Ni with a strong negative slope both consistent with fractional crystallization (Joron and Treuil, 1977).

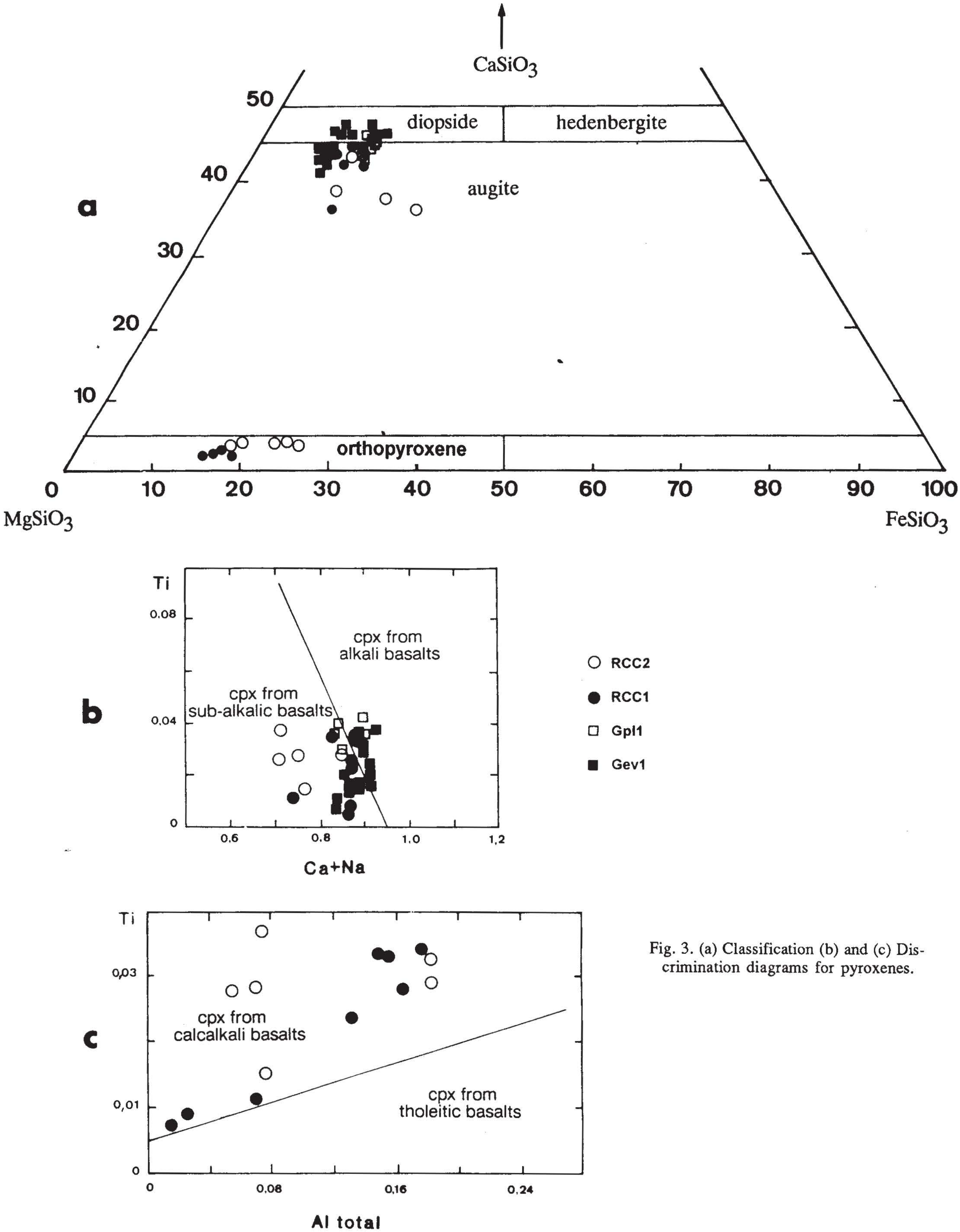

Fig. 3. (a) Classification (b) and (c) Discrimination diagrams for pyroxenes.

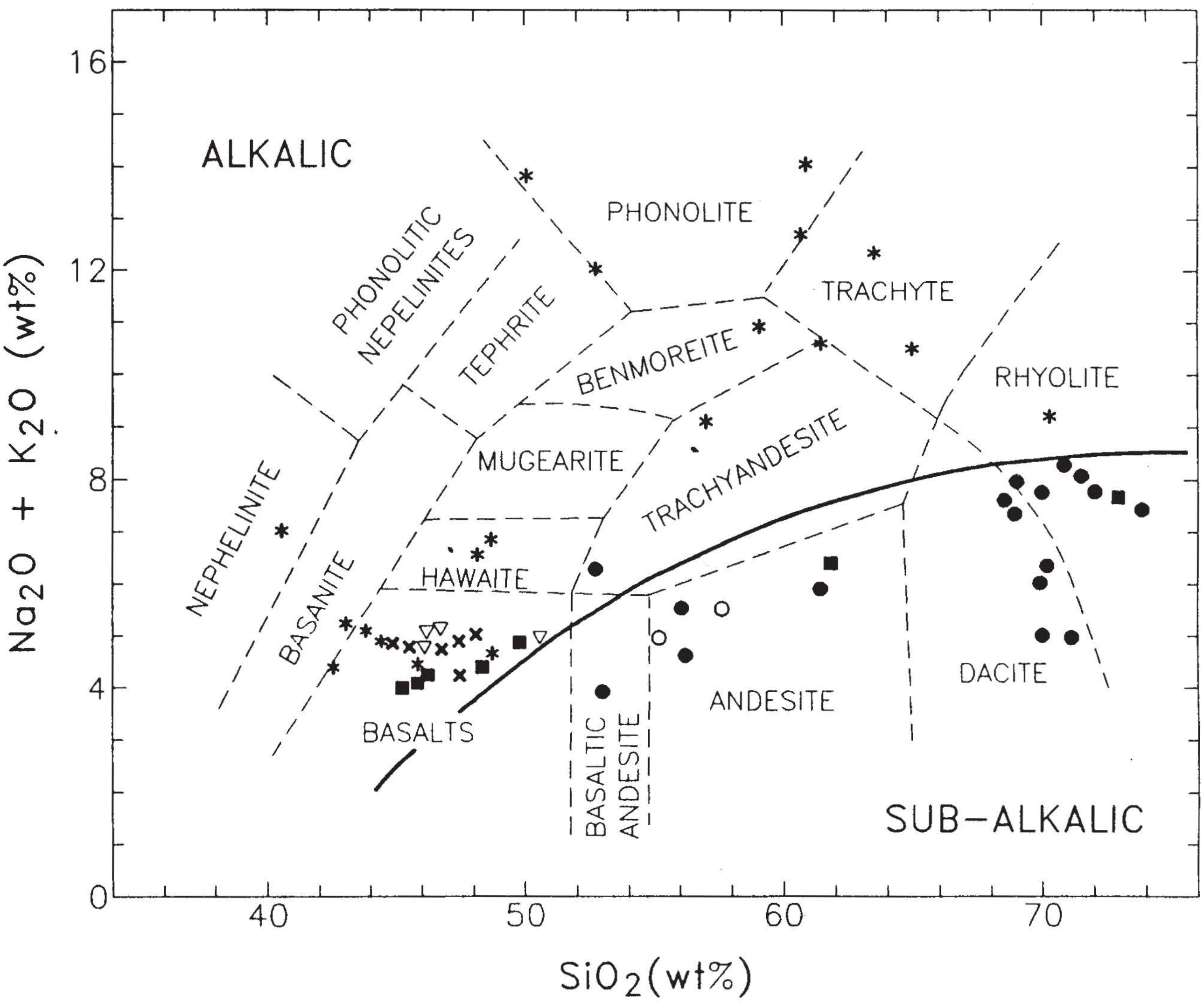

Fig. 4. Plot of Na_2O+K_2O versus SiO_2. The dividing line between alkalic and sub-alkalic magma series is from Miyashiro (1978); Guaxcamá plateau lavas Gpl (□) and intraevaporitic lavas Gev (■); Real de Catorce RCC (O); Ciudad del Maiz CM (x); Rio Verde (∇, Robin, 1977); San Luis Potosí (●, Aranda, *et al.*, 1986; Labarthe and Tristan, 1986); Sierra de Tamaulipas and Tampico basin (*, Robin, 1974).

In these diagrams (alkali-SiO_2, Ni-La, La-Th), the least differentiated Guaxcamá sample (Gp11) plots close to those of alkalic lavas from Ciudad del Maiz. Moreover, the multi-element abundance pattern (Figure 5) is similar to that of alkali lavas except for the presence of a slight negative Nb anomaly.

Cenozoic basalts of Ciudad del Maiz

These rocks consist of olivine, clinopyroxene and plagioclase occuring as phenocrysts in an essentially glassy groundmass with plagioclase microlites.

As with the coeval basalts from the Sierra de Tamaulipas, the Tampico Basin, and the Ventura and Santo Domingo centers, these basalts (CM) are alkalic with high-TiO_2 (1.8 wt%) and P_2O_5 (0.4-0.6 wt%) contents. On a multi-element diagram (Figure 5d), there is a strong enrichment in light-REE and LFS elements, and a lack of Nb and Ti depletion, typical of alkalic basalts. Relative to the Nb-rich Ventura basanite, the Ciudad Del Maiz basalts are similar to the Nb-poor Santo Domingo alkali basalt (Luhr *et al.*, 1989).

PETROGENESIS OF THE LAVAS

The geochemical characteristics of the Triassic-Jurassic volcanic rocks of Zacatecas and Real de Catorce are similar to those of island-arc tholeiites and calc-alkali basalts, respectively (Rouer *et al.*, 1988; Bailey *et al.*, 1989). However, because of the intense hydrothermal activity, the initially tholeiitic Real de Catorce lavas may have been altered to greenschist facies of apparent calc-alkaline affinity accompanied by an increase of immobile element contents.

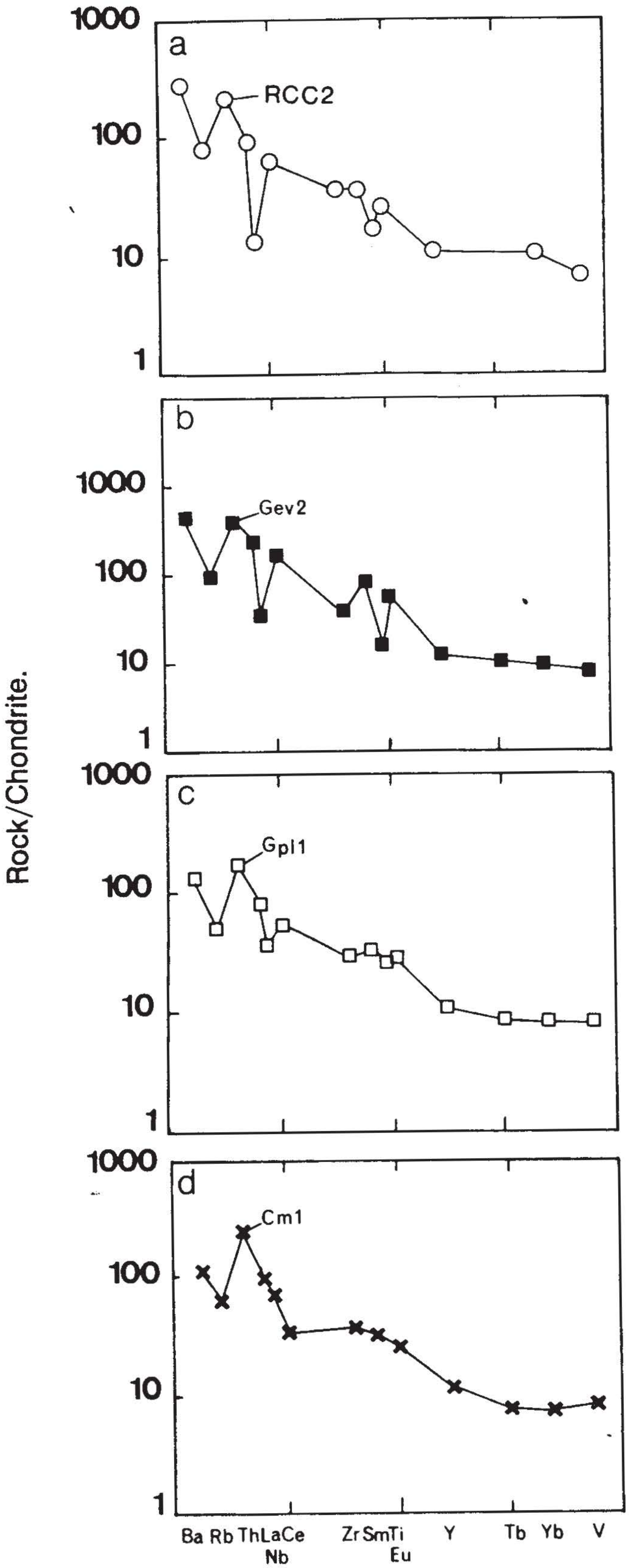

Fig. 5. Chondrite-normalized multi-element abundance patterns. (a) Cenozoic lavas from Real de Catorce; (b) Intraevaporitic lavas from Guaxcamá; (c) Lavas from Guaxcamá plateau; (d) Cenozoic lavas from Ciudad del Maiz. Normalization coefficients and classification of Bougault (1980).

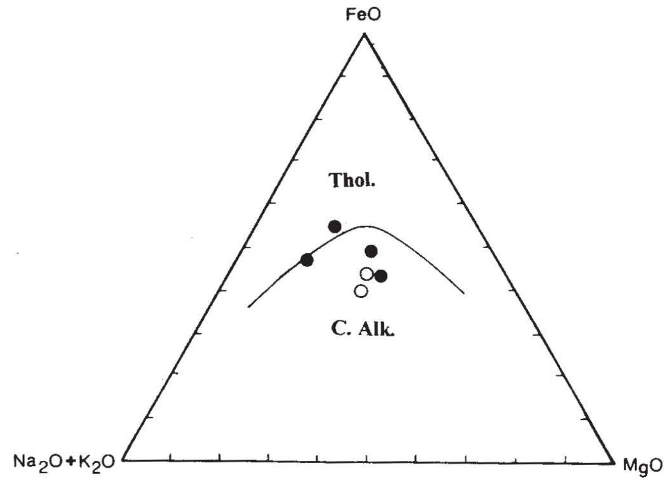

Fig. 6. Na_2O+K_2O-FeO-MgO diagram (Cox *et al.*, 1979). Real de Catorce RCC (○) and San Luis Potosí (●).

This type of behaviour had been observed in other greenschist facies basaltic rocks, e.g., the Archean Matagami volcanic rocks, Quebec (McGeehan and McLean, 1980). These lavas may represent the volcanic equivalents of orogenic igneous suites emplaced, since Triassic times in the western Cordilleran domain of the Pacific plate margins (Tardy *et al.*, 1986), and they could be related to island-arc migration (in part marine) in reponse to oblique subduction of the Kula plate (Coney, 1983).

The lavas intercalated the Guaxcamá evaporite formation are enriched in transition and incompatible elements with respect to the lavas from the Guaxcamá plateau, suggesting a different fractionation trend. The accesory secondary paragenesis (dolomite filling amygdules, Fe-rich argillaceous cryptocrystalline phases replacing brown glass) may account for the high CaO, Sr, K_2O and volatile (H_2O and CO_2) contents, but not for the difference in transition and incompatible element contents (Henderson, 1982).

The volcanic rocks of the Guaxcamá plateau, ranging from mildly alkalic basalts to rhyolites (Figure 4), make up a fractional crystallization suite (Figure 7). A similar differentiation trend is observed in transitional lavas from continental rift zones, e.g. Río Grande suite (Dungan *et al.*, 1986) or Boina centre, Ethiopia (Barberi *et al.*, 1975).

Thus, the Guaxcamá volcanic rocks may be derived from two different parental magmas, as illustrated on the Di-An-Fo diagram (Figure 8), at a pressure of about 7 kbar, i.e. 20 km (Presnall *et al.*, 1978). The least differentiated basalt from the plateau (Gp11) plots near the forsterite-spinel cotectic line, whereas other basic lavas (Gev) plot in the diopside field. Petrographic study shows that the liquidus phases are olivine + Cr-spinel in sample Gp11 and augite ± olivine in sample Gev.

A lower degree of partial melting of the mantle source could theoretically produce the higher contents of incom–

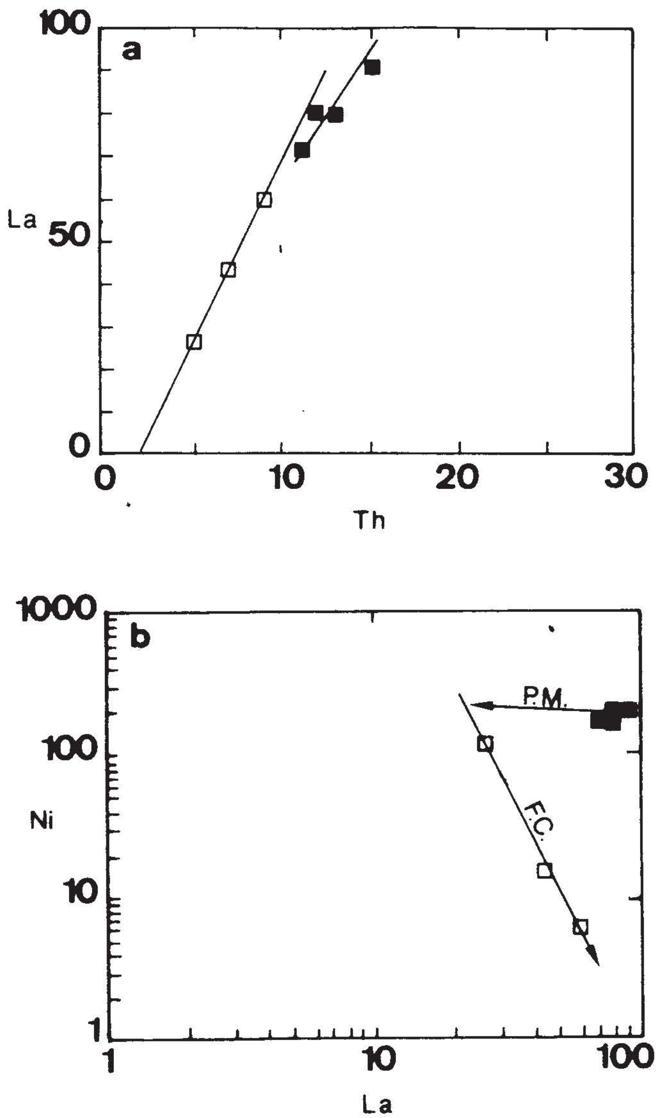

Fig. 7. Process identification diagrams for the Guaxcamá lavas (P.M.: partial melting model, F. C.: fractional crystallization model, Joron and Treuil, 1977). Symbols as in Figure 4. a, La versus Th, b, Ni versus La.

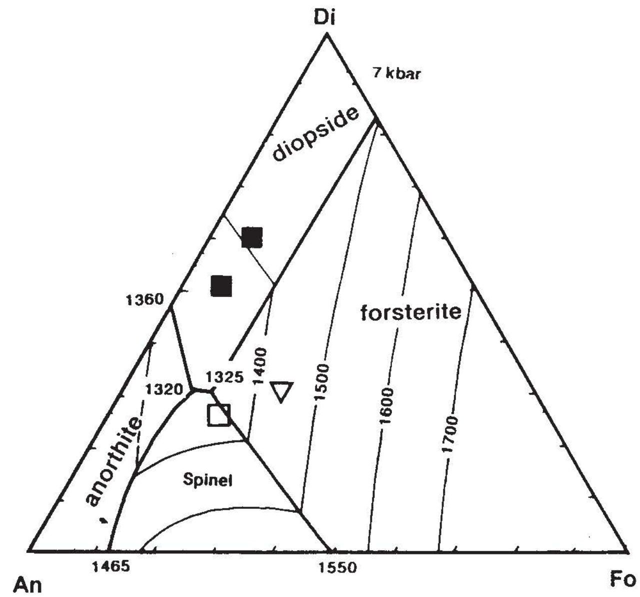

Fig. 8. Liquidus phase relatios diagram for the forsterite (Fo)-diopside (Di)-anorthite (An) system, after normative compositions of the Guaxcamá lavas (symbols as in Figure 4) and the Rio Verde lava. E: eutectic; Sp: spinel (Presnall *et al.*, 1978); (∇) RV16 sample from Robin (1977).

patible elements in the Gev lavas (Allegre and Minster, 1978), but this does not explain their strong Nb and Ti depletions. Moreover, the low K/P ratios (close to 3) speak against significant crustal contamination (values of 0 up to 7 in oceanic basalt, Hart *et al.*, 1989). Hence, the peculiar features of the two Guaxcamá magma types might reflect a change of chemical and mineralogical composition of the mantle source between the two successive eruptive events:

(1) During the Jurassic, the mantle source which had been affected by previous metasomatic events above a subducted oceanic crust generated widespread calc-alkali igneous activity in the western Cordilleran province (Servais *et al.*, 1986; Monod *et al.*, 1990). The Gev lavas show specific features, such as the Nb and Ti negative anomalies, which are characteristic of initial magmas generated in post-orogenic settings.

(2) In Early Cenozoic times, the mantle source continued to be slightly modified by a subduction component. The Gpl lavas show features typical of transitional basalts from continental rift zones, similar to lavas from the neighbouring eastern alkaline province but with a slight Nb negative anomaly.

The mineralogy (presence of orthopyroxene, calc-alkaline affinity of clinopyroxene) and geochemistry (SiO_2= 55-57 wt%) of Cenozoic lavas from Real de Catorce indicate an andesitic nature.

The massive rhyolitic and ignimbritic suite seen only in the western part of the VSLP platform (Aranda *et al.*, 1986; Labarthe and Tristan, 1986) is related to this cenozoic magmatic event. The granitoids could also be linked to a coeval magmatic event in the Sierra Madre Occidental (Mc Dowell and Clabaugh, 1981; Cochémé, 1985; Demant *et al.*, 1989) and the Southern Basin and Range provinces (Damon *et al.*, 1981).

The development of this magmatic belt is associated with the eastward migration of the Laramide volcanic arc.

The Cenozoic lavas of Ciudad del Maiz, Sierra de Tamaulipas and Tampico basin are alkalic in character (Figure 4) and may be linked to the eastern mafic alkalic volcanic provinc (Robin and Demant, 1974 and 1975), considered to be the southward continuation of the alkalic volcanism of West Texas (Robin, 1976) as it is derived from an intraplate (OIB-type) source devoid of any arc signature (no Nb or Ti anomaly).

Recently, Pier *et al.* (1989) and Luhr *et al.* (1989) also concluded that isotopic and trace element characteristics of the Quaternary lavas from the Ventura and Santo Domingo volcanic fields reflected at least three end-member components in their sources.

CONCLUSIONS

The volcanic rocks of the VSLP platform could be derived from partial melting of a multi-component source with the contribution of each component changing in time. The evolution of lava geochemistry in the Guaxcamá terrain possibly reflects the gradual fading of an orogenic signature inherited from mantle sources. This after-effect is similar to that recorded in the Stephanian-Triassic post-collisional volcanic suite of the Pyrénées (Cabanis and Le Fur-Balouet, 1989; Béziat *et al.*, 1991), in the Permo-Triassic volcanic province of Corsica (Cabanis *et al.*, 1990) and also in the Cenozoic-Quaternary volcanic formations of the northern Sierra Madre Occidental (Cochémé, 1985; Cochémé and Demant, 1991).

The sedimentary facies of the Guaxcamá terrain were previously considered as typical of a lagoon environment associated with a platform. We propose instead that the sequence accumulated in a continental rift zone during its initial stages of opening. This rift could represent the northwesterly continuation of the Rio Verde graben, resulting from the interfingering of Tethyan-type units within the continental domain (Tardy *et al.*, 1986).

Chauve *et al.* (1985) postulated that the Higuerillas Thrust (Sierra Madre Oriental) represents the boundary between the Tethyan and Cordilleran domains. We propose additionally that the VSLP platform underwent different histories in contrasting tectonic settings on either side of a line that corresponds broadly to the Gran Falla. Thus, the terrane could be subdivided as follows.

(1) A western zone characterized by island-arc migration associated with subduction related processes at the Pacific margin, accompanied by mineralizations of economic interest.

(2) An eastern zone whose tectonic evolution is related to the opening of the Gulf of Mexico. Here there is no development of economic mineralization.

ACKNOWLEDGEMENS

This research was supported by grants from the Instituto Mexicano del Petróleo. We are very grateful to Baldomero Carrasco V. and M.S.N. Carpenter for the correction of the English text.

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