Geofísica Internacional (1994), Vol. 33, Num. 1, pp. 125-138

Contrasting volcanism in the Michoacán-Guanajuato Volcanic Field, central Mexico: Shield volcanoes vs. cinder cones

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Received: July 28, 1993; accepted: November 18, 1993.

RESUMEN

El Campo Volcánico de Michoacán-Guanajuato (40,000 km^2), de la Faja Volcánica Trans-Mexicana (FVTM), contiene volcanes de tamaño pequeño y mediano, y carece de grandes volcanes compuestos. Los volcanes de tamaño pequeño incluyen a 900 conos cineríticos y 100 volcanes de otros tipos tales como conos, domos y gruesos derrames de lava no asociados con conos y maares. En contraste, los volcanes de tamaño medio incluyen más de 300 volcanes y algunos domos de lava. Ambos grupos de volcanes coexisten en tiempo y espacio. Las lavas asociadas a conos cineríticos poseen un amplio rango composicional de 47 a 67 % en contenido de SiO_2, con abundantes basaltos de olivino calcialcalinos y andesitas basálticas. Existen también unas cuantas rocas alcalinas. Las lavas de volcanes escudo son todas andesitas calcialcalinas que muestran un rango limitado de SiO_2 (comúnmente 55%-61%), con ocurrencia común de fenocristales de ortopiroxeno. Se han encontrado composiciones similares para flujos de lava que no están asociados a conos. Estas lavas y las de los escudos, representan erupciones efusivas, menos explosivas. Los volcanes escudo tienen derrames de lava más largos y volúmenes mayores que los derrames que no están asociados con conos, indicando con esto una tasa efusiva y un aporte de magma mayores que estos últimos. Debido a que sus lavas están más fraccionadas que las lavas calcialcalinas de conos cineríticos, pero que se grafican en el mismo tren composicional que éstas, posiblemente aquéllas sean producto de cristalización fraccionada de basaltos primitivos calcialcalinos, los cuales se encuentran en algunos conos cineríticos.

PALABRAS CLAVE: El Campo Volcánico de Michoacán-Guanajuato, volcanes escudo, conos cineríticos, flujos de lava, petrología, geoquímica.

ABSTRACT

The Michoacán-Guanajuato Volcanic Field (40,000 km^2) of the western Mexican Volcanic Belt contains both small- and medium-sized volcanoes, but lacks large composite volcanoes. The small-sized volcanoes include 900 cinder cones and 100 other volcanoes such as lava cones, lava domes, thick lava flows not associated with cones, and maars. In contrast, the medium-sized volcanoes include over 300 shield volcanoes, and a few lava domes and rare composite volcanoes. Both groups of volcanoes coexist in time and space. Cinder cone lavas have a wide compositional range from 47 to 65% SiO_2, with abundant calc-alkaline olivine basalts and basaltic andesites. They also contain a few alkaline rocks. Shield lavas are all calc-alkaline andesites, which show a limited SiO_2 range (mostly 55%-61%) with common occurrence of orthopyroxene phenocrysts. Similar compositions are found for the lava flows not associated with cones. These and shield lavas represent effusive and less explosive type of eruptions. Shield volcanoes have more extensive lava flow units and larger volums than the lava flows that are not associated with cones, indicating a greater effusion rate and a greater magma supply. Because their lavas are more fractionated than, but plot on the same compositional trend as the calc-alkaline cinder cone lavas, they may be products of fractional crystallization of primitive calc-alkaline basalts which are found in some of the cinder cones.

KEY WORDS: The Michoacán-Guanajuato Volcanic Field, shield volcanoes, cinder cones, lava flows, petrology, geochemistry.

INTRODUCTION

The Michoacán-Guanajuato Volcanic Field (MGVF) of the western Mexican Volcanic Belt (MVB) forms an area of extensive monogenetic volcanism (40,000 km^2). The volcanic field lacks the large composite volcanoes which are common in other parts of the MVB, and contains 900 cinder cones and other small-sized monogenetic volcanoes, such as maars, lava flows, and lava domes (Hasenaka and Carmichael, 1985a, 1985b). In addition to these small volcanic centers it also contains over 300 medium-sized volcanoes, among which shield volcanoes are dominant (Hasenaka and Carmichael, 1986). The surface morphology of shield volcanoes suggests no period of erosion nor long breaks in volcanic activity; thus they also are likely to be monogenetic, or they represent a short period of activity, even if not monogenetic. For a 0.66 Ma-old shield volcano from La Laja (north of Los Volcanes in Figure 1) in the western Mexican Volcanic Belt, dammed lake into which its lava flowed suggests that it formed within 20 to 40 years (Righter and Carmichael, 1992). Other medium-sized volcanoes include lava domes (or thick lava flows) and a few composite volcanoes.

These two different size groups of volcanoes in the MGVF seem to represent different modes of eruption. As stated in most volcanology textbooks, cinder cones are the products of Strombolian-type eruptions, whereas shield volcanoes are the products of Hawaiian-type eruptions which are less explosive with smaller eruption columns (MacDonald, 1972; Williams and McBirney, 1979; Cas and Wright, 1987). Williams and McBirney (1979) state

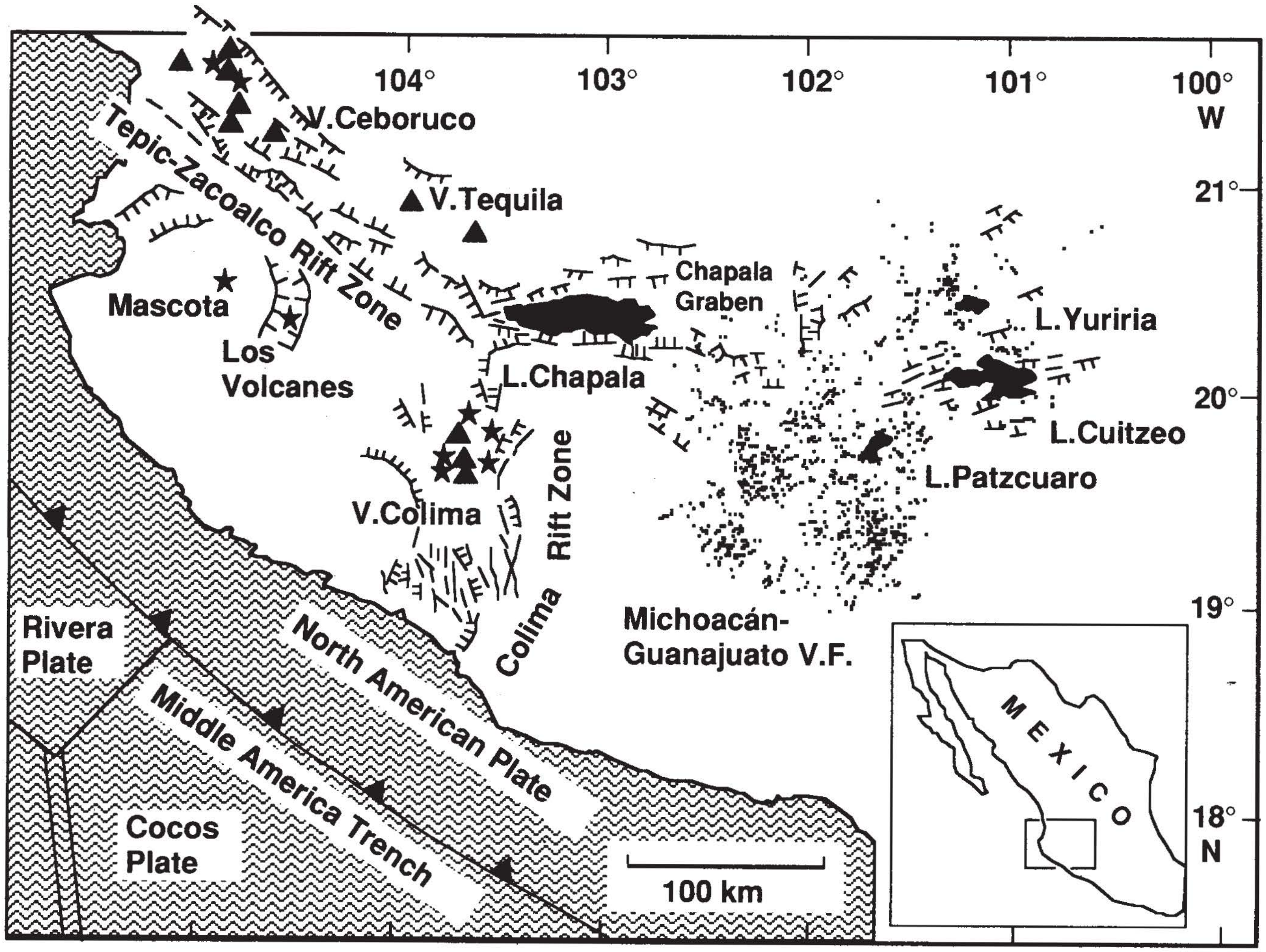

Fig. 1. Location of the Michoacán-Guanajuato volcanic field (small black dots) and tectonic boundaries.

that shield volcanoes are produced by rapid accumulation of fluid basaltic lavas; thus they are mostly made of lava flows. This seems true for most medium-sized volcanoes in the MGVF; however, there are some that show composite character, with interbedded pyroclastic layers. Cerro Tancítaro and Cerro Paracho in the Paricutín region are among such exceptions. This paper classifies all medium-sized volcanoes showing shield shape under "shield volcanoes", because the internal structure is hard to observe in most cases. Only medium-sized volcanoes with apparently different shape than "shield" volcanoes are classified as composite volcanoes. The detailed descriptions of size, distribution, and magma output rate for the medium-sized volcanoes in the MGVF are discussed in Hasenaka (1995).

Hasenaka and Carmichael (1985a) showed the monogenetic volcanism in the MGVF resulted not only from a facilitated transportation of magmas through crust but also from a small supply of magma to the crust. It is interesting to study the volcanism of shield volcanoes in comparison with the small monogenetic volcanism.

The purpose of this paper is to present a petrological description of lavas from shield volcanoes in the MGVF, and to compare their petrological features with those of small monogenetic volcanoes in an attempt to provide a model of plumbing system of the mostly monogenetic Michoacán-Guanajuato volcanic field.

TECTONIC SETTING AND VOLCANIC ACTIVITIES

The tectonic setting of the western Mexican Volcanic Belt is shown in Figure 1. Quaternary volcanism in this region is related to the subduction of the Cocos plate under the North American Plate. In addition to subduction, three grabens: Tepic-Zacoalco, Colima, and Chapala, modify the tectonics and the volcanism of this region. Luhr *et al.* (1985) proposed that these three grabens represent an active rift system that drives the southwestern segment of Mexican continent movement off the rest. The Chapala graben, a proposed aulacogen of the rift system, runs E-W in the northwestern part of the MGVF, and its morphology is similar to that of active grabens. The MGVF, as represented by 1,000 small monogenetic cones (dots) in Figure 1, and as enlarged in Figure 2, shows a wide distribution of volcanoes in contrast to the narrow band of NW-SE-trending composite volcanoes to the west of the volcanic field. East of the MGVF, the MVB forms an angle of 15° with the Middle America trench. Intermediate-depth earthquakes (<150 km) have been detected between the trench and the volcanic field, outlining a poorly-defined Wadati-Benioff zone (e.g. Hanus and Vanek, 1978; Burbach *et al.*, 1984). Because of this non-parallel relation between the trench and the volcanic belt, Mooser (1969) and Shurbet and Cebull (1984), among others, proposed that the volcanism is independent of subduction.

Although volcanoes of both different size groups in MGVF show distinct forms and modes of eruptions, they overlap in distribution and age patterns. Small monogenetic cones are distributed between 190 km and 440 km from the Middle America trench. They form several clusters as shown in Figure 2, and local alignments are observed in places. The medium-sized volcanoes are distributed in a similar area; but unlike small cones, they do not show clustering nor distinct alignments (Figure 2). The maximum small-cone density is observed around 250 km from the trench, but the highest concentration of shield volcanoes is found a little further from trench, around 270 km away (Hasenaka and Carmichael, 1986; Hasenaka, 1995). As the result of the shift of volcano frequency away from the trench, more shield volcanoes are found in the area farther from the trench. In contrast to the absence of cinder cones in the Chapala region immediately west of the MGVF, shield volcanoes are distributed continuously from the northwestern part of the volcanic field into the Chapala region.

The K-Ar age dating showed a southward migration of volcanism around 1 Ma (Ban *et al.*, 1992; Delgado *et al.*, 1993); thus volcanoes occurring in the north, or farther from the trench, probably represent an older volcanic activity of the MGVF. Although Figure 2 shows a wide across-arc distribution of volcanoes, this actually represents an overprinting of volcanism of different ages; i.e. 1-3 Ma volcanic activity in the north, and <1 Ma activity in the south. The medium-sized volcanoes are more abundant than the small ones in the northern part of the volcanic field, partly because of erosional effects in the small cones. Locally, medium-sized volcanoes also look older and more degraded than neighboring cinder cones. In general, however, in both the northern part and the southern part, the contrasting volcanism coexisted in time and space within the MGVF.

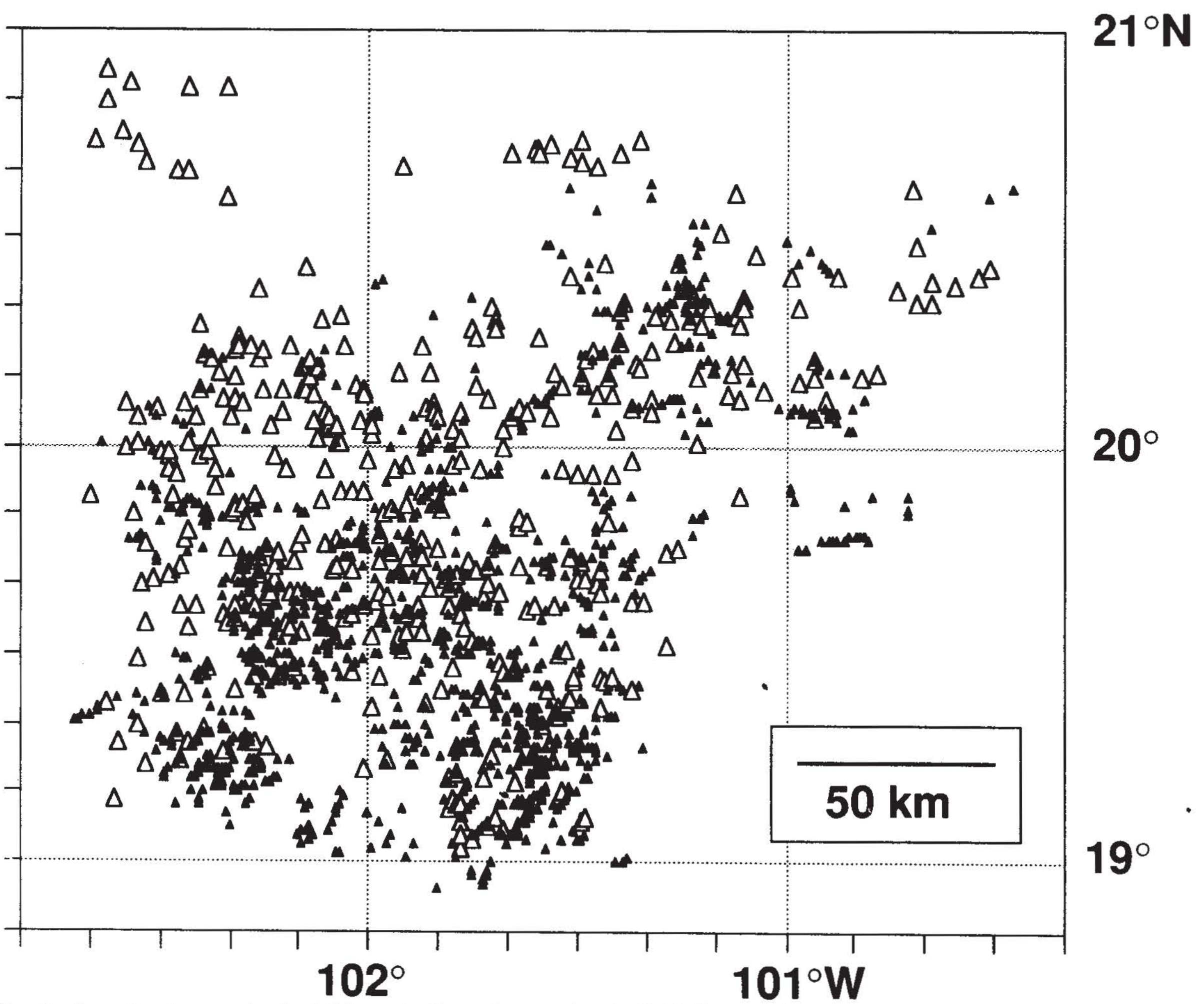

Fig. 2. Distribution of volcanoes in the Michoacán-Guanajuato volcanic field. Small filled triangles= small cones (mostly cinder cones and lava cones, with other volcanic forms including lava domes, thick lava flows that are not associated with cones, and maars), large open triangles = medium sized volcanoes (mostly shield volcanoes, with other volcanic forms including composite volcanoes and relatively large domes). Data from Hasenaka and Carmichael (1985b) and Hasenaka (1995).

PETROGRAPHY OF CINDER CONE AND SHIELD LAVAS

The petrological study of cinder cone magmas by Hasenaka and Carmichael (1987) shows that they are more primitive than lavas from the composite volcanoes elsewhere in the MVB, and that they include both calc-alkaline and alkaline rocks. Cinder cone lavas are not porphyritic, with modal percentages of total phenocrysts generally below 20%. The representative phenocryst assemblage is either olivine + plagioclase or olivine + augite + plagioclase (Figure 3). They are mostly basalt or basaltic andesite of the calc-alkaline suite with subordinate amounts of calc-alkaline andesite, or transitional or alkali basalt. Hornblende and orthopyroxene occur in calc-alkaline andesites and dacites. Hornblende also occurs in some alkali basalt. A disequilibrium phenocryst assemblage of olivine + hornblende, olivine phenocrysts with pyroxene reaction rims, and plagioclase with bimodal or wide compositional range are observed only in some calc-alkaline andesites, dacites and low-Mg alkali basalts.

In contrast to mostly augite-olivine phyric cinder cone lavas, all phenocryst assemblages also occur among shield volcano lavas, which are all of andesite composition (Figure 3). Modal analyses of representative samples are listed in Table 1. Occurrence of orthopyroxene phenocrysts are characteristic for most shield lavas. Some low-Mg pyroxene andesite lavas, however, also contain small amounts of olivine phenocrysts or microphenocrysts (e.g. Samples 718, 969, and 996 of Table 1). Hornblende phenocrysts also occur in some shield samples (e.g. Samples 969, 990) and in the medium-sized composite volcano of Tancítaro (Sample 1023 of Table 1), however, they seem to be unstable as they have opacite rims or are completely replaced by opacite. Occurrence of dusty plagioclase, or plagioclase

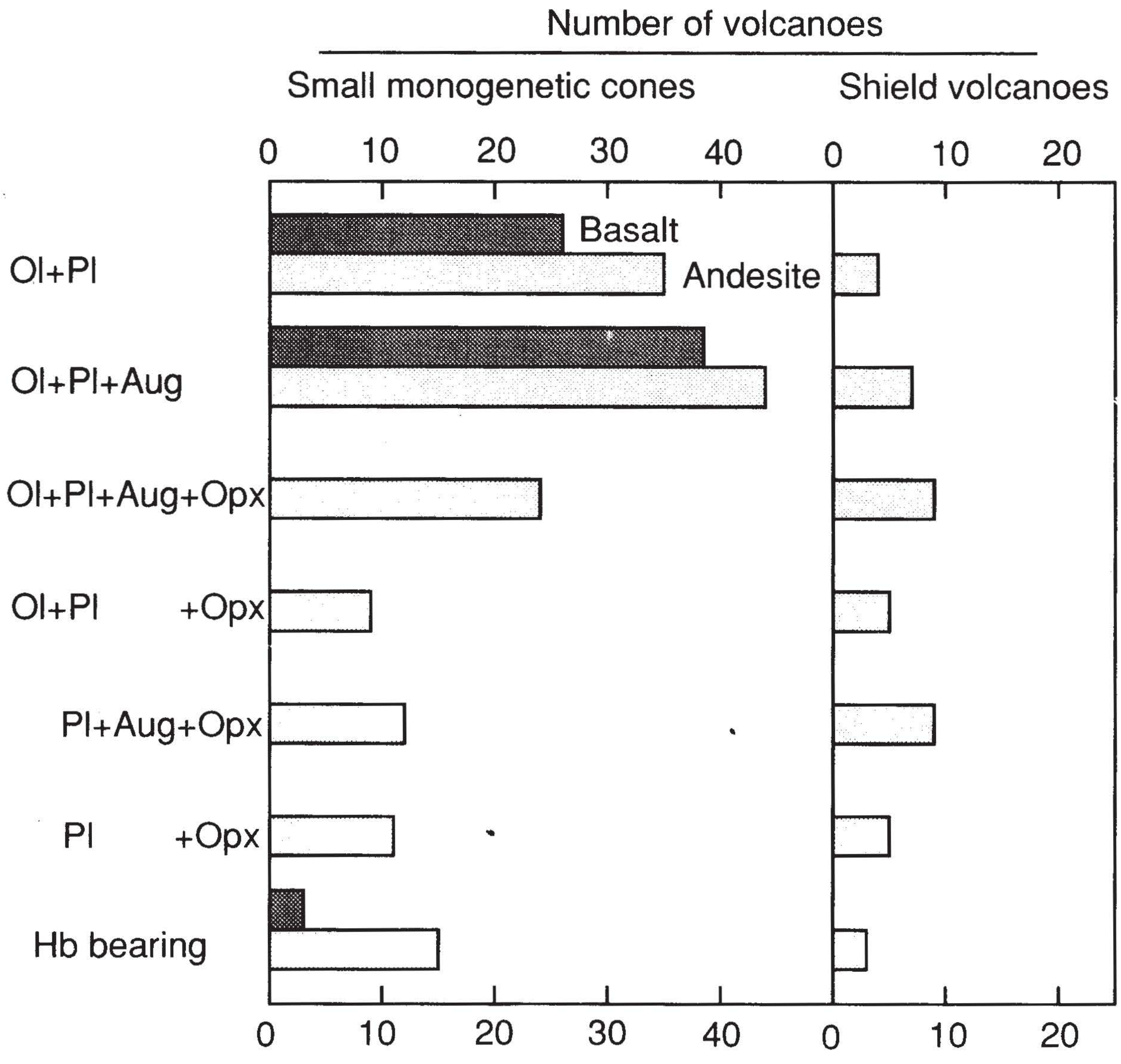

Fig. 3. Phenocryst assemblage of lavas. Ol=olivine, Pl=plagioclase, Aug= augite, Opx= orthopyroxene, Hb= hornblende. Basalt: SiO_2<53%, Andesite: 53%≤SiO_2<63%.

with inclusions of glass or minute grains of pyroxenes and opaque minerals, is observed in a few shield samples. The total phenocryst content of shield lavas is relatively small, between 10 and 30% by volume, and they are comparable to the andesite lavas from cinder cones. Olivine basalt and basaltic andesite lavas (Samples 929 and 1005) have intergranular texture with relatively large groundmass minerals of plagioclase, clinopyroxene, orthopyroxene, olivine ± opaque minerals. Groundmass minerals greater than 0.03 mm are found in 3 basalt or basaltic andesite lavas in Table 1 (Samples 929, 1000, and 1005). They indicate a slower post-eruptive cooling rate than cinder cone lavas of similar composition. In contrast, orthopyroxene andesite or two-pyroxene andesite lavas have intersertal to hyalo-ophitic texture with groundmass plagioclase, clinopyroxene, orthopyroxene, opaque minerals, and (in many cases) abundant brown glass.

Samples from lava flows have similar mineral assemblages to the shield lavas, with occurrence of nearly all phenocryst assemblages. They are not associated with cones, and are found in small-sized volcanoes in the MG VF: in the following section they will be shown to have similar compositions to shield volcanoes.

CHEMISTRY OF CINDER CONE AND SHIELD LAVAS

Bulk chemical analyses were made at the Institute of Mineralogy, Petrology, and Economic Geology of Tohoku University. Both standard and unknown samples were analyzed, using a Rigaku 3080 XRF wavelength dispersive spectrometer for major and trace elements. Samples were hand-crushed using an iron mortar and pestle to ~1 mm size grains. These coarse powders were then finely crushed using an automatic agate mortar. For major element determinations, glass discs of both standards and samples were made by fusing powders mixed with $LiBO_5$ in the ratio 1: 5. Pressed powdered discs for trace element determination were made from a mixture of rock powder and a small amount of polyvinyl alcohol. The measured X-ray intensities were corrected for peak overlap, X-ray absorption, and background. The calibration lines (or in some cases, curves) obtained for nearly 20 standards, mostly from the Geological Survey of Japan, were used to calculate the concentrations.

The chemical composition of lavas from cinder cones and other small monogenetic cones for comparison is taken from Hasenaka (1986) and Hasenaka and Carmichael (1987). These analyses were carried out at the University of California, Berkeley using energy dispersive X-ray fluorescence. Samples were hand-crushed using a tungsten carbide mortar and pestle to several mm size grains, then finely ground in an alcohol slurry in a tungsten carbide SPEX shatterbox. Powders were pressed into aluminum cups and these undiluted pellets were used for both major and trace element determinations. Selected samples from the MGVF were analyzed by wet chemistry (Analysts: Ian Carmichael and Joachim Hampel) and used as XRF standards for 10 major elements.

Several reference standards were also analyzed at Tohoku University to check if the XRF analyses showed values similar to the recommended. About 20 samples analyzed both at Tohoku and Berkeley revealed a systematic difference in XRF analyses between the two laboratories. SiO_2 and Al_2O_3 analyses are higher by 1wt.% and 0.5wt.% respectively on the average, and total Fe as Fe_2O_3 is lower by 0.5wt.% on the average at Berkeley than at Tohoku. For trace elements, the Nb numbers at Berkeley are also higher by a factor of two or three, and the Ni and Cr numbers at high concentration range are also higher than those at Tohoku. These systematic errors probably do not cause problems in comparing shield volcano lavas with cinder cone lavas, because samples of both volcano types were analyzed and checked at Tohoku University, and the compositional differences are larger than the systematic errors.

Some 56 lava samples were analyzed in this study. Representative samples are listed in Table 1, and all available analyses are plotted in Figure 4, where shield lavas, composite volcanoes, lava flows and cinder cone lavas are shown with different symbols. In contrast to the cinder cone magmas, which have a wide range of silica content (48% to 70%), the shield volcano lavas show a small silica range (Figure 4). The majority of the samples fall between 55wt.% and 61wt.%, of the silica content. High silica content in a shield volcano is unexpected in a gently-sloping shield which suggests a low viscosity. Typical shields in Hawaiian eruptions in Hawaii and Iceland produced very fluid lava flows of basaltic composition and resulted in gently-shaped (5°-10°) shield volcanoes (Williams and McBirney, 1979). Volcán La Laja from the Atenguillo graben in the western Mexican Volcanic Belt (north of Los Volcanes in Figure 1) also has a shield shape with an 8° to 10° slope angle, but it features 5-10 m thick alkali basalt lava flows (Righter and Carmichael, 1992).

The MgO contents of shield lavas are mostly less than 5% which indicate their fractionated nature; they contrast with most cinder cone lavas which are more magnesian (Figure 4). A MgO content of 6.69% for Cerro Buenavista (Sample 929) is unusually high for a collection of shield samples. The Cerro San Miguel lava with 7.16% MgO content (Sample 537) does not represent typical shield lavas, because the volcano has a shape between a dome and a lava flow, and its size is close to that of cinder cones. Samples from lava flows that are not associated with cones also show low-MgO contents, except two samples which contain unusually high MgO and Cr values (Figure 4). Samples with unusually high Sr contents (>1000 ppm) are also found in some shield volcanoes, in a composite volcano, and in a lava flow. However, they plot in an area of the Harker diagram which is different from that of cinder cone samples of different SiO_2 content. These unusually high Sr contents are difficult to explain by fractional crystallization of observed phenocrysts or by accumulation of plagioclase. They probably represent different partial melting events or different sources than most lavas in the MGVF. A relatively large dispersion is found in the SiO_2 vs. K_2O plot, probably because they represent a collection

Table 1

Chemical and modal analyses of representative samples from the medium-sized volcanoes in the MGFV.

Sample		929	983	903	1023	978	718	969
Volcano name		Cerro Buenavista	Cerro Curiane	Cerro Paracho	Cerro Tancítaro	Brinco del Diablo	Cerro El Metate	Cerro Zirahuen
Volcano Type		SH	SH	SH	CV	SH	SH	SH
Volume(km^3)		17	9.6	7.6	49	3.2	16	4.7
Slope angle(°)		6.4	9.8	21	15	15	11	15
Latitude(S)		19°09.3'	19°53.5'	19°35.4'	19°25.0'	19°56.4'	19°32.2'	19°27.3'
Longitude(W)		102°36.5'	102°04.1'	102°02.4'	102°19.1'	101°43.9'	101°59.6'	101°40.8'
Map		B48	B19	B29	B39	A11	A21	A31
Location		CW	CE	CE	CW	NE	SW	NE
DFT (km)		191	289	261	231	311	258	266
SiO_2	(wt.%)	53.49	56.04	59.88	58.12	60.20	59.06	58.50
TiO_2		1.06	0.86	0.77	0.81	0.76	0.70	0.84
Al_2O_3		16.74	17.16	17.30	17.57	17.72	16.92	18.14
Fe_2O_3t		8.84	7.93	5.88	6.41	6.34	6.53	6.97
MnO		0.13	0.11	0.09	0.09	0.09	0.10	0.09
MgO		6.69	4.76	2.72	3.54	2.73	3.82	2.68
CaO		7.94	7.22	5.89	6.64	5.47	6.27	5.72
Na_2O		3.72	3.56	3.83	4.02	3.90	3.83	4.16
K_2O		1.03	1.24	1.99	1.28	1.69	1.75	1.60
P_2O_5		0.24	0.26	0.19	0.21	0.18	0.21	0.20
Total		99.88	99.14	98.54	98.69	99.08	99.19	98.90
V	(ppm)	159	149	114	129	120	117	133
Cr		231	117	18	78	35	109	19
Ni		130	64	21	42	11	40	13
Pb		5	3	10	8	9	12	9
Rb		14	15	42	15	34	32	28
Sr		531	709	490	1408	577	760	555
Y		22	20	18	12	17	17	34
Zr		135	158	167	96	134	145	137
Nb		8	7	7	4	6	12	7
Ba		397	400	725	441	619	546	579
	Mode (%)							
Ol	Ph	3.5	--	--	--	--	0.1	tr
	Mph	--	--	--	--	--	tr	tr
Aug	Ph	--	0.5	tr	--	0.9	2.1	--
	Mph	--	0.9	tr	tr	0.1	1.4	0.1
Pl	Ph	--	2.5	17.3	6.2	10.4	6.2	15.1
	Mph	--	17.5	7.6	3.7	15.3	18.1	12.3
Opx	Ph	--	0.6	1.1	--	1.4	0.4	1.2
	Mph	--	2.2	1.2	--	1.2	2.7	0.9
Hb	Ph	--	--	--	1.1	--	--	0.2
	Mph	--	--	--	--	--	--	--
Opac	Ph	--	--	--	5.8	--	--	--
	Mph	--	--	--	1.6	--	--	--
Gdm		96.5	75.8	72.8	81.6	70.7	69.0	70.2

Table 1 (Cont.).

Sample		537	1000	1005	617	994	990	996
Volcano name		Cerro San Miguel	Volcán Grande	Cerro Las Ventanas	Cerro El Aguila	Cerro La Tetilla	Cerro Prieto	Cerro Grande
Volcano Type		Dm	CV	SH	SH	SH	SH	SH
Volume(km^3)		0.33	21	9.6	20	2.9	2.7	54
Slope angle(°)		15	12	8.6	12	8.1	6.3	5.0
Latitude(S)		19°12.2'	20°05.5'	19°57.8'	19°37.3'	20°21.1'	20°09.7'	20°24.5'
Longitude(W)		101°43.7'	101°38.1'	101°22.1'	101°22.0'	101°05.8'	101°12.6'	101°52.6'
Map		A41	C82	A12	A22	C73	C83	C74
Location		NE	CW	NE	CE	CE	CC	CW
DFT (km)		239	330	331	297	382	358	398
SiO_2 (wt.%)		56.34	56.41	55.78	58.98	59.37	61.02	56.48
TiO_2		0.68	1.14	1.02	1.00	1.07	0.68	1.27
Al_2O_3		15.53	16.66	16.59	16.29	16.54	17.2	16.85
Fe_2O_3t		7.19	7.68	7.89	6.97	7.12	5.79	8.24
MnO		0.11	0.12	0.12	0.10	0.10	0.09	0.12
MgO		7.16	4.59	5.42	3.55	3.56	2.39	3.72
CaO		6.58	6.92	6.99	5.69	5.82	5.25	6.62
Na_2O		3.63	3.75	3.76	3.59	3.67	3.80	3.83
K_2O		1.45	1.62	1.67	2.22	1.97	2.01	1.43
P_2O_5		0.20	0.33	0.27	0.26	0.27	0.18	0.35
Total		98.87	99.22	99.51	98.65	99.49	98.41	98.91
V (ppm)		112	148	159	120	118	100	149
Cr		415	116	153	95	86	34	80
Ni		153	47	63	25	22	9	17
Pb		7	7	5	14	10	7	7
Rb		25	33	37	55	49	39	28
Sr		597	461	445	443	422	627	592
Y		23	30	24	24	34	18	33
Zr		125	251	209	218	275	158	233
Nb		6	14	13	16	13	6	15
Ba		556	631	546	600	663	641	537
Mode (%)								
Ol	Ph	7.2	0.1	4.4	--	--	--	--
	Mph	0.7	--	--	--	--	--	0.5
Aug	Ph	3.5	--	--	--	--	--	--
	Mph	1.2	--	--	--	--	--	--
Pl	Ph	4.6	12.4	2.5	10.9	8.7	11.6	2.5
	Mph	4.6	--	--	9.1	10.4	14.0	7.1
Opx	Ph	0.1	2.6	--	1.9	1.6	1.3	--
	Mph	0.9	--	--	2.0	2.7	1.8	tr
Hb	Ph	--	--	--	--	--	tr	--
	Mph	--	--	--	--	--	--	--
Opac	Ph	--	--	--	--	--	tr	--
	Mph	--	--	--	--	--	--	--
Gdm		77.2	84.9	93.1	76.1	76.6	71.3	89.9

Volcano Type --- SH= shield volcano, CV= composite volcano, Dm=dome. Volume is calculated from the shape of a cone or a truncated cone using the following formula: Vol=πh (W_{cr}^2+$W_{cr}W_{co}$+W_{co}) /12 where h=height of the cone, W_{cr}= diameter of the crater or flat top part (=0 in the case of a cone shape), W_{co}=basal diameter. Slope angle (in degrees): calculated as the arc-tangent of the slope as tan (2H/ (W_{co}-W_{cr})) Map=Map number of DETENAL 1:50,000 topographic map. N. B. samples are arranged in the order of map number, so that volcanoes are arranged in general order of west to east, and in each section from north to south. Location= Location in map. N= north, S= south, W=west, E=east, C=center. DFT= Distance from the Middle America Trench (in km). Fe_2O_3t=Total iron as Fe_2O_3. Mode in volume %. Ol=olivine, Aug=augite, Pl=plagioclase, Opx=orthopyroxene, Hb= hornblende, Opc= opacite, Gdm= groundmass, Ph=phenocryst (>0.3 mm), Mph= microphenocryst (>0.03 mm and <0.3 mm). Groundmass minerals of samples 929, 1000 and 1005 are mostly microphenocryst size.

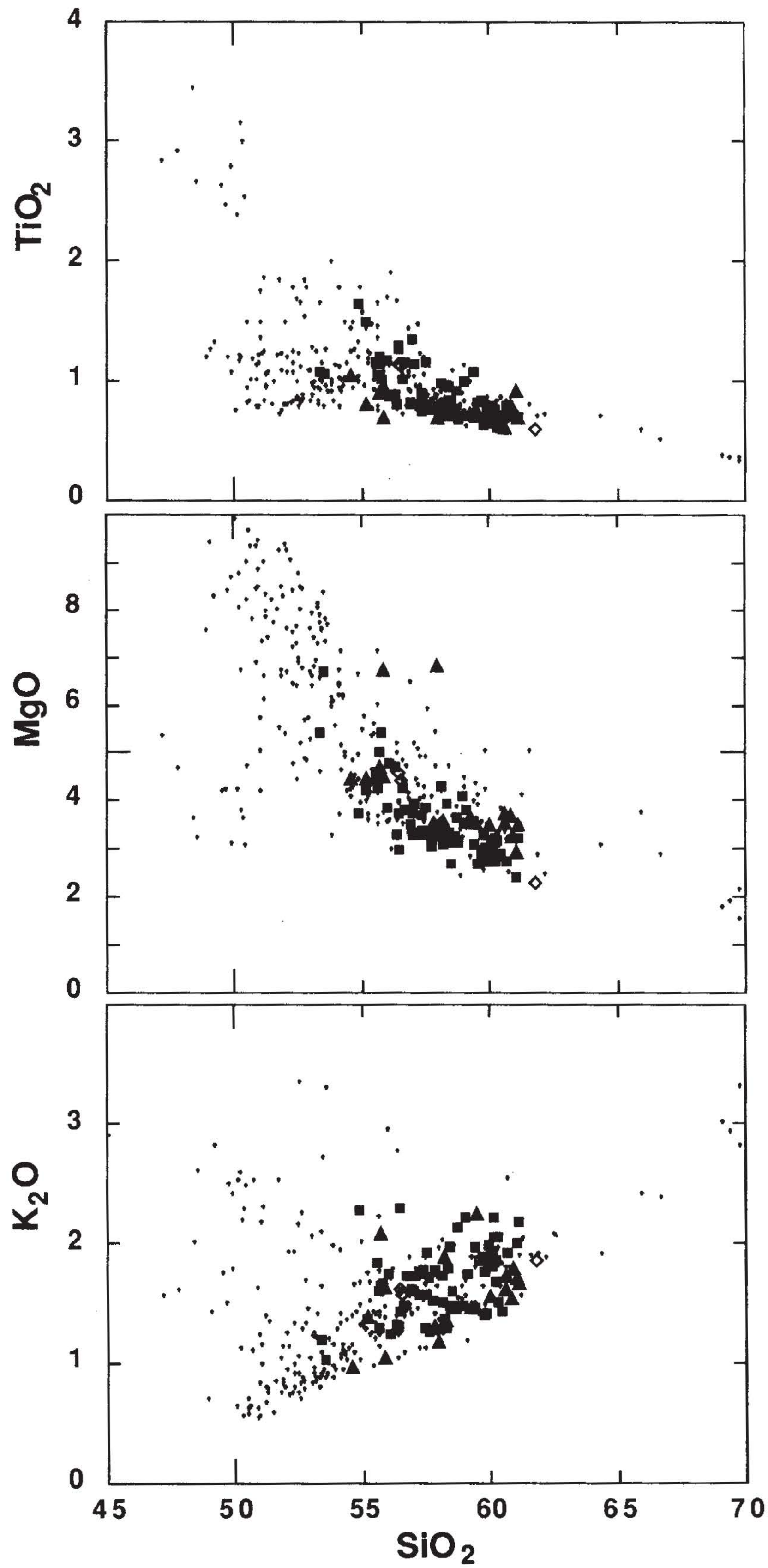

Fig. 4. Harker diagrams showing the composition of lavas from shield volcanoes. Filled square: shield volcano, open diamond: composite volcano, filled triangle: lava flow, small dots: cinder cone. Data from Hasenaka (1986), Hasenaka and Carmichael (1987) and this study.

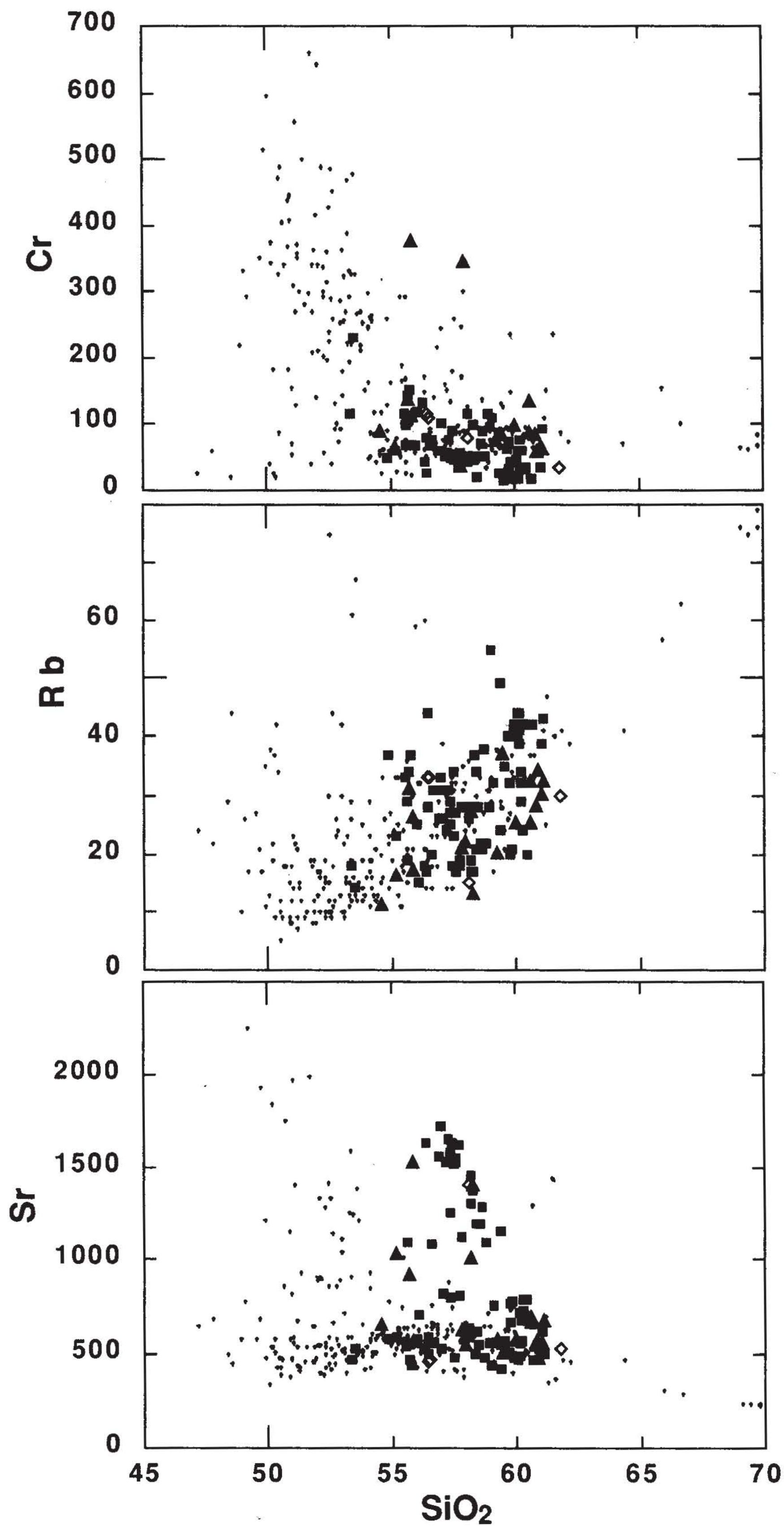
700
600
500
400
300
200
100
0
Cr
60
40
20
0
R b
2000
1500
1000
500
0
Sr
45
50
55
60
65
70
SiO2

Fig. 4. (Cont.).

of samples from a wide area in the volcanic field (190 to 340 km from the trench), and from different ages (3 Ma - present), thus reflecting a difference in source composition through time and space. In detail, after the exceptional samples are removed, the shield lavas seem to have slightly lower MgO content and slightly higher Rb contents than lava flows that are not associated with cones. In general, shield lavas, medium-sized composite volcanoes, and thick lava flows as grouped in small monogenetic volcanoes all show similar compositional ranges and differ from a much wider compositional range of cinder cone lavas; however, their compositions are mostly included in the differentiation trend of cinder cones.

All shield lavas are typical calc-alkaline andesites; there are no alkaline shield volcanoes. They show no iron enrichment in the AFM diagram and they plot in the calc-alkaline field of the Miyashiro (1974) diagram. The MORB-normalized trace element patterns (not shown) indicate that all shield samples have negative Nb anomalies. Negative Nb anomalies are found among all calc-alkaline cinder cone lavas and alkaline lavas erupted close to the trench, but not among some of the relatively old alkaline cinder cone lavas occurring farther from the trench (see analyses in Hasenaka and Carmichael, 1987).

Spatial variations in composition are not distinctive, because most of the lavas show similar compositions. An increase of K_2O and other incompatible element concentrations with the increasing distance from the trench, as shown by cinder cone andesite magmas (Hasenaka and Carmichael, 1987), is not found among shield volcano lavas. In contrast, Mg, Cr and Ni contents in cinder cone lavas show a decrease with increasing distance from the trench (Hasenaka and Carmichael, 1987). This again is not seen in mostly fractionated shield lavas.

ORIGIN AND FRACTIONATION OF SHIELD LAVAS

As shown by the petrography and chemistry, shield lavas are more fractionated than, but plot along the same trend as, the cinder cone magmas. They show very similar petrographical and chemical features when compared to fractionated cinder cone andesites. Compositional variations of a series of cinder cone lavas ranging from augite olivine basalt to two pyroxene andesites were studied at Jorullo volcano by Luhr and Carmichael (1985). They showed that differentiated andesite lavas were products of crystal fractionation of olivine, plagioclase, augite, from a calc-alkaline olivine basalt magma at high to moderate pressures. Although a series of lavas sampled from the same cone show a limited compositional range (Wilcox, 1954; Luhr and Carmichael, 1985), lavas collected from different cones of the entire volcanic field show a wide compositional range that could cover an entire range of fractionation, which probably occurred at varying depths (Luhr and Carmichael, 1985; Hasenaka and Carmichael, 1987). Because the compositional trend of shield lavas is the same as that of the differentiated cinder cone lavas, magmas forming shield volcanoes are possibly crystal fractionation products of the same primitive basalts as the cinder cones. These compositional differences might be attributed to the different chemical characters of the source. However, the MORB-normalized trace element patterns (not shown) are all very similar. Thus difference in source composition may have played a minor role in producing a wide compositional range except for the high-Sr shield lavas described above. Because primitive calc-alkaline basalt magmas with similar trace element characteristics were erupted in the volcanic field, it is natural to deduce that the calc-alkaline shield lavas were derived from them, mainly by fractional crystallization.

The composition of shield lavas is projected onto the system olivine-augite-quartz which shows the 1-b plagioclase-saturated liquidus boundaries (Grove *et al.* , 1982) and the 8-kb dry liquidus boundary for Atka high-alumina basalts (Baker and Eggler, 1983, 1987). Hasenaka and Carmichael (1987) found that a series of nonfractionated calc-alkaline magmas with phenocrysts of olivine, augite, and plagioclase form a trend quite similar to this high-pressure olivine-augite-plagioclase cotectic for Atka. They also showed that other olivine-augite-plagioclase phyric andesitic lavas plot between this high-pressure cotectic and the one-atmosphere cotectic. They explained the scattered plot of cinder cone lavas by polybaric fractionation products at pressures between mantle-crust boundary and near the surface. The compositions of shield lavas plot on the fractionated part of the trend formed by primitive calc-alkaline cinder cone lavas, but away from the one-atom olivine-augite-plagioclase cotectic (Figure 5a). Because the phase boundaries were drawn mostly from dry experiments and under different oxygen fugacity conditions from actual magmas, the pressure estimate contains inevitably large uncertainties. Even so, the fact that the trend of shield magmas is continuous from a deduced high pressure cotectic of primitive cinder cone magmas suggests a common parental magma and a similar fractionation path for the cinder cone magmas. Fractionation from the primitive calc-alkaline magma to most shield magmas might have occurred at high to moderate pressures, but the crystallization of phenocryst orthopyroxene and plagioclase ± olivine ± augite possibly occurred at a relatively shallow level, as the orthopyroxene bearing shield lavas plot close to the one-atom olivine-orthopyroxene cotectic or orthopyroxene field, and the phenocryst assemblage agrees with the 1-atm near liquidus phases.

DIFFERENCE BETWEEN SHIELD LAVAS AND CINDER CONE LAVAS

The difference in eruption mode between cinder cones (Strombolian-type) and shield volcanoes (Hawaiian-type) suggests that shield magmas contain less volatiles prior to eruption. The main component of the volatile is probably H_2O; gas phases such as SO_2, H_2S and CO_2 are probably minor, since anhydrites and carbonates are absent in the lavas and bombs from shield volcanoes and cinder cones.

Lange and Carmichael (1990) showed that crystallization of olivine rather than orthopyroxene (in addition to

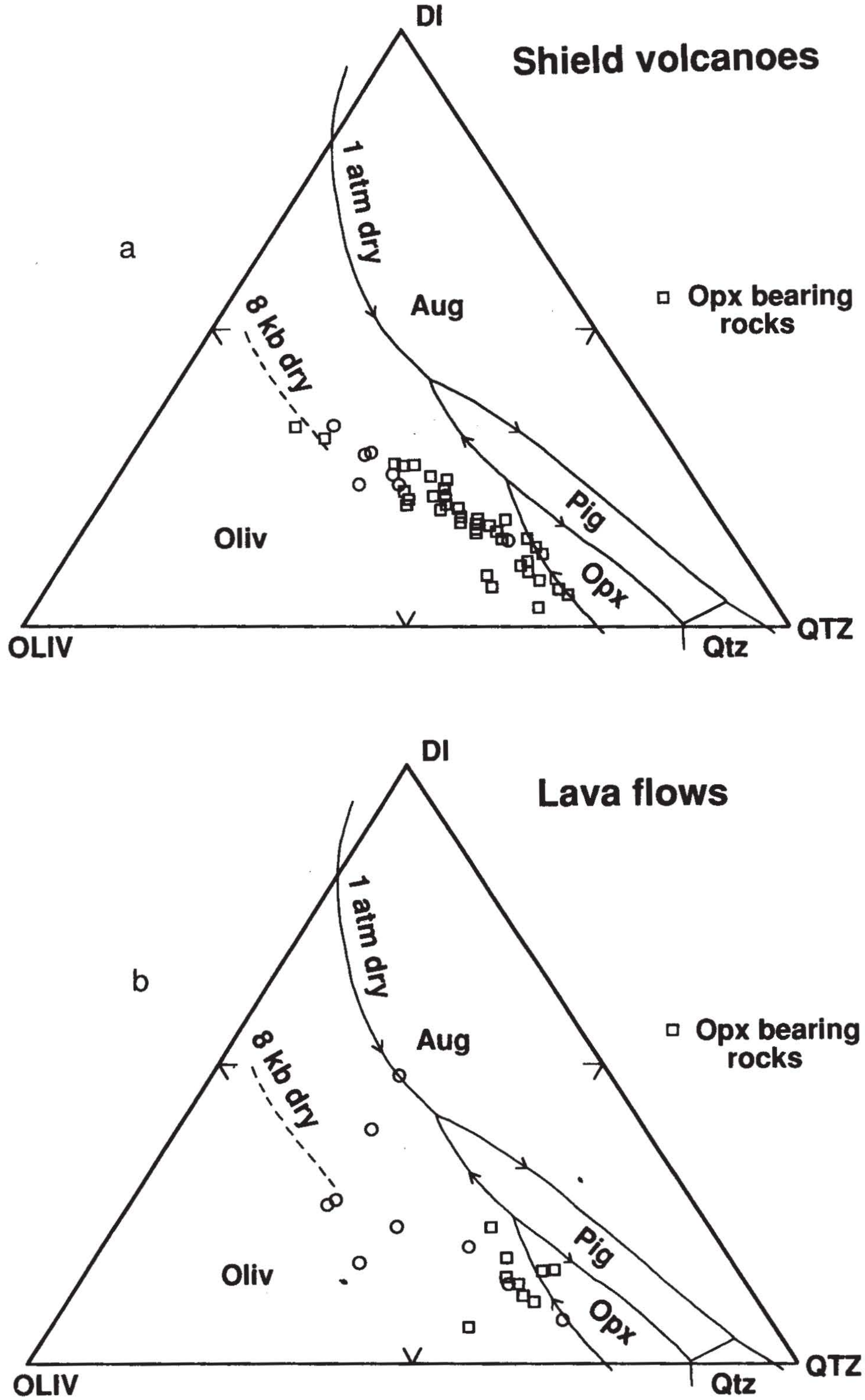

Fig. 5. Composition of MGVF lavas projected onto the system olivine (OLIV)- augite (DI)- quartz (QTZ) join. The 1-b plagioclase-saturated liquidus boundaries of Grove *et al.* (1982) and the 8-kb liquidus boundary for anhydrous high-alumina basalts of Baker and Eggler (1983, 1987) are also shown. Ferric-ferrous ratios of the MGVF lavas were recalculated at oxygen fugacities of NNO buffer (T-1000°C, log f_{O_2}=-10.18). Each component was normalized to equal oxygen content. **a.** Lavas from shield volcanoes, **b.** Lavas from thick lava flows which are not associated with cones. Open squares = orthopyroxene bearing samples. Open circles = others.

plagioclase and clinopyroxene) in the groundmass indicates a higher H_2O content in magma for a given composition and cooling rate. From a petrographical examination of lavas in the MGVF, and in the Mascota volcanic field (Figure 1) in the western MVB, they concluded that magmas erupted in the MGVF contain less H_2O than in the latter. Indeed most MGVF lavas contain orthopyroxene instead of olivine in the groundmass. One exception is a cinder cone sample (400A), an olivine hornblende bearing two-pyroxene andesite (Hasenaka and Carmichael, 1987), which contains groundmass olivine and lacks orthopyroxene. Except for olivine basalt samples which contain both olivine and orthopyroxene in the groundmass, all shield andesite lavas contain groundmass orthopyroxene, thus indicating relatively small H_2O contents. The difference of H_2O content between shield lavas and cinder cone lavas, however, is not clear as most andesites of both groups have the same groundmass mineral assemblage.

The difference in volcano size indicates that shield magmas might have reached the near surface as a larger magma batch than cinder cone magmas. Magma batches with a large volume might have a greater chance of erupting on the surface, because they are thermally more stable. Small magma batches which represent cinder cones and other monogenetic cones are more likely to solidify before reaching the surface. In the same context, the larger magma reservoirs of shield volcanoes are likely to have a longer residence time in the crust, and thus a greater chance of undergoing processes such as fractionation, assimilation and magma mixing. The shield lavas indicate a greater degree of fractionation; however, disequilibrium features suggesting magma mixing due to replenishment of magma reservoir by unfractionated magma are not common. Thus, the life span of such magma batches is probably still shorter than for typical composite volcanoes which show complicated magmatic histories (e.g. Luhr and Carmichael, 1980). In contrast, the petrological study of monogenetic small cones indicates that their magmas were modified little in composition from their original composition at the source (Hasenaka and Carmichael, 1987).

COMPARISON OF SHIELD LAVAS WITH LAVA FLOWS THAT ARE NOT ASSOCIATED WITH CONES

An interesting result from this study is the compositional similarity between lavas of shield volcanoes and thick lava flows that are not associated with cones. Both contain similar petrographical and chemical features. Because they are on the same fractionation trend, they were probably derived from similar sources, and may represent similar degrees of fractionation. The composition of these thick lava flows projected onto the system olivine-augite-quartz is also similar to those of shield volcanoes despite a wider scatter (Figure 5b), suggesting a similar fractionation path to shield magmas. Shield volcanoes and thick lava flows represent different size groups, but both have high ratios of lava flows to pyroclastic materials, and their eruption mode is different from that of cinder cones. The similarity in composition and fractionation trend between shield lavas and thick lava flows suggests that the magmas feeding these different volcanic systems may originate from a similar source, have a similar migration history and may have similar interaction with crustal materials. The major difference is the total magma output, reflecting magma supply or supply rate to the shallow crust level. It follows that the shield volcanoes in the MGVF may have developed from lava flows, due to the large magma supply.

It seems strange that more fractionated, (i. e., relatively low-temperature and more viscous) magmas should have produced apparently fluid lavas and formed shield volcanoes. A comparison of similar-size shield volcanoes in the MGVF and in Iceland suggests that the Mexican volcanoes have higher slope angles (mostly around 10°) against around 5° for Iceland. The different volcano forms may result from different viscosities of lavas or different effusion rates (Walker, 1973). No eruptions of shield volcanoes in the MGVF were witnessed historically; therefore an estimation of the effusion rate of lava flows is difficult. There is a compositional difference between most andesitic lava flows from the MGVF and most basaltic lava flows from Iceland; hence a definite difference in the viscosity of the lava flows exists between the two, which should affect the effusion rate as well.

It is also possible, in the case of MGVF shields, that pyroclastic materials near the vent elevate the base level of the summit resulting in a higher slope angle. The slope of most shield volcanoes in the MGVF is covered by lava flows, but a few shield volcanoes (such as Cerro Paracho) have pyroclastic summit cones and show interbedded pyroclastic materials in deeply eroded gullies. This indicates a relatively higher volatile content in magmas from such shields than from other MGVF shields or typical shield volcanoes elsewhere.

SUMMARY AND CONCLUSIONS

Shield volcanoes representing medium-sized volcanoes in the MGVF are built of lava flows with a different petrography and chemistry than that of cinder cone lavas of small size. However, shield lavas show similar composition and petrography to thick lava flows not associated with cones. In contrast to cinder cone magmas, most of which represent unfractionated calc-alkaline basaltic magmas, the shield and lava flow magmas represent fractionated calc-alkaline andesite magmas. Compositional trends are continuous from primitive calc-alkaline basalts (from cinder cones) to calc-alkaline andesites (from shield volcanoes and lava flows). Thus the latter are possibly products of fractional crystallization of the former at high pressures. Relatively gentle Hawaiian-type eruptions of shield volcanoes and lava flows suggest a smaller vapor pressure of the pre-eruptive magma than in the explosive Strombolian-type eruptions of cinder cones. Thus a smaller pre-eruptive H_2O content is expected for shield volcano lavas than for lavas from cinder cones. However, the difference in H_2O content is not obvious from the groundmass mineral assemblage. Although silica-rich and probably viscous lava flows are not expected from apparently fluid shield lavas, the slope angles of andesitic MGVF shield volcanoes are definitely steeper than in the basaltic shields of Iceland.

ACKNOWLEDGEMENTS

Field work was carried out in December, 1989 and November, 1991 in a joint project with Universidad Nacional Autónoma de Mexico (Japanese leader, Prof. K. Aoki, Mexican leader Prof. J. Urrutia-Fucugauchi). The field work was supported by a grant from Monbusho International Scientific Research Program (#03041014 to K. Aoki), and the laboratory work by a Monbusho Research Grant (#01740468, #02740398) to T. Hasenaka. The authors wish to thank Prof. K. Aoki, Dr. T. Yoshida, and Dr. H. Fujimaki for their encouragement and support of the project, and Dr. N. Tsuchiya for his help in XRF work at Tohoku University. Comments and suggestions by two anonymous reviewers improved the style and organization of this paper.

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