Sr, Nd, and Pb isotopic and trace element geochemical constraints for a veined-mantle source of magmas in the Michoacán-Guanajuato Volcanic Field, west-central Mexican Volcanic Belt

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This study reports new geochemical and radiogenic isotope data for Pliocene to Holocene (<2.8 Ma) alkaline (trachybasalt, basaltic trachyandesite, and trachyandesite) as well as subalkaline (basalt to dacite) volcanic rocks from the Michoacán-Guanajuato volcanic field (MGVF), located in the west-central part of the Mexican Volcanic Belt (MVB). There is no clear correlation of most geochemical parameters with differentiation indicators such as SiO₂. The rare-earth elements show light-REE enrichment, flat heavy-REE pattern, and absence of Eu anomaly. Depletion of Nb as compared to large ion lithophile elements such as Ba is observed for most rocks, probably suggesting involvement of subducted Cocos or Rivera plate. However, other HFSE such as Zr and Ti and key trace elements such as B and Be, and isotopic data do not support this conclusion. In most binary plots, the MGVF data lie at mantle compositions toward the lower end of subduction-input parameters, as is the case of magmas from well-known rifts; this contrasts with the data for subduction-related Central American Volcanic Arc (CAVA) rocks that clearly show high values of subduction input. The average isotopic ratios of the MGVF rocks show the following ranges: ⁸⁷Sr/⁸⁶Sr 0.70320–0.70439, ¹⁴³Nd/¹⁴⁴Nd 0.51273–0.51298, ²⁰⁶Pb/²⁰⁴Pb 18.62–18.88, ²⁰⁷Pb/²⁰⁴Pb 15.57–15.62, and ²⁰⁸Pb/²⁰⁴Pb 38.32–38.66. There are apparently no significant differences between the isotopic ratios for alkaline and subalkaline rocks, although the Sr and Pb isotopic ratios for alkaline rocks are somewhat higher and Nd isotopic ratios lower than those for subalkaline rocks. The available geochemical and isotopic evidence does not support the origin and evolution of the MGVF magmas by a simple model such as simple fractional crystallization (FC), nor by direct (slab melting) or indirect (fluid transport to the mantle) participation of the subducted Cocos plate. Instead, it appears that the MGVF basic magmas were generated in a heterogeneously veined-mantle source enriched in LILE, HFSE, and REE, but the intermediate and acid magmas could also contain a crustal component.

Keywords: geochemistry, subduction, rifting, isotopes, Mexico

INTRODUCTION

In the framework of plate tectonics, the Cocos plate has been subducting into the Middle America Trench (MAT) beneath the Pacific coasts of Mexico and Central America (North American and Caribbean plates; Fig. 1). There are two major Miocene to Holocene volcanic provinces in this area: Mexican Volcanic Belt (MVB) in southern Mexico and Central American Volcanic Arc (CAVA) in Central America. The Michoacán-Guanajuato volcanic field (MGVF) is located in the west-central part of the

Mexican Volcanic Belt (MVB) and is one of the key areas to understand the relationship of the MVB with the subduction of the Cocos plate (Fig. 1). In the western part of the MVB (Fig. 1), there is a well-developed rift system consisting of three major rifts: north-west-trending Tepic-Zacoalco Rift, north-south-trending Colima Rift, and east-west-trending Chapala Rift (e.g., Luhr *et al.*, 1985; Otsuki *et al.*, 1992). The latter extends into the MGVF and probably beyond this field into the central and eastern parts of the MVB. Additionally, a small oceanic plate—Rivera plate—has been subducting beneath the western MVB and may also exert an influence on the MGVF area.

In a series of papers, Hasenaka and colleagues (Hasenaka and Carmichael, 1985a, 1985b, 1987; Hasenaka, 1992a, 1992b, 1992c, 1994; Hasenaka *et al.*, 1994) presented geological, volcanological, and geochemical characteristics of the MGVF. According to these studies, the MGVF comprises nearly 400 medium-

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Fig. 1. Location and present tectonic setting of the Michoacán-Guanajuato volcanic field (MGVF) in the west-central part of the Mexican Volcanic Belt (MVB). The abbreviations are: MC = Mexico City; MAT = Middle America Trench; RI = Rivera plate (schematic location); TZR = Tepic-Zacoalco rift; CR = Colima rift; ChR = Chapala rift; SCN = Sierra de Chichinautzin; A = Amealco caldera; H = Huichapan caldera; Ac = Acapulco caldera; Hu = Los Humeros caldera; MRSJ = Meseta Río San Juan; TVF = Tizayuca volcanic field; EPR = East Pacific Rise; open triangle marked Par = Volcán Parícutín born in 1943; Jor = Historic Volcán Jorullo (1759–1774); symbols of crossed circles = IOPD-DSDP Leg 66 Sites 487 and 488; CAVA = Central American Volcanic Arc; G = Guatemala; S = El Salvador; H = Honduras; N = Nicaragua; C = Costa Rica; Yoh = Volcán Yohoa (Honduras); Tel = Volcán Telica (Nicaragua). Thin dashed lines schematically show tectonic features such as fractures and faults.

sized volcanoes and about 1,000 small monogenetic cones, distributed over an area of 40,000 km². These volcanoes are rarely reactivated after becoming dormant. Major and trace element geochemical data on samples from the MGVF were also presented by Luhr and Carmichael (1985) and McBirney *et al.* (1987).

Luhr and Carmichael (1985), in a detailed geochemical study of the historic Volcán Jorullo (1759–1774) and associated cinder cones (for the location of Volcán Jorullo see Fig. 1), confirmed the presence of two totally distinct types of magmas (subalkaline as well as alkaline) in this region. Thus, they documented the complexity of petrogenetic processes in this area of the MGVF. Luhr and Carmichael (1985) stressed that, although these two types of magmas are closely related both in space and time, their origin cannot be related to one another by any simple mechanism, and therefore must represent fundamentally different partial melting events in the mantle. In a detailed geochemical study of the famous Volcán Parícutín (1943–1952, born on 20th February, 1943 in a cornfield; Luhr and Simkin, 1993) located in the MGVF, McBirney *et al.* (1987) presented ⁸⁷Sr/⁸⁶Sr and δ¹⁸O isotopic data for lavas as well as crustal xenoliths. They inferred crustal assimilation, along with fractional crystal-

lization, as the dominant mechanism to explain the evolution of sub-alkaline magmas from the Volcán Parícutín. No hypothesis for the origin of parental magma was, however, proposed.

Yoshida (1992) presented an interesting comparison between the volcanoes of the W-MVB, including the MGVF, and those of northeastern Japan (Honshu arc), highlighting the differences and similarities in the geochemistry of the associated rocks. He found that, although there are no clear geochemical differences between rocks from the two regions (MGVF and northeast Honshu), the Mexican rocks are generally higher in their MgO/FeO ratios and are more enriched in the abundance of incompatible elements. Such differences led Yoshida to postulate significant differences in the nature of the source mantle beneath the two areas (MGVF and northeast Honshu), as well as to invoke different degrees of partial melting conditions. He also suggested that different stress regimes (tensional under the MGVF and compressional in northeast Honshu) and thermal conditions could explain the different types of volcanic edifices (short-lived small monogenetic cones in the MGVF and relatively long-lived large composite volcanoes in northeast Honshu).

Fig. 2. A simplified location map of the studied samples from the MGVF (this is an amplification of the area surrounding the MGVF in Fig. 1). Sampling locations are given using symbols included as inset and are the same as in Fig. 3. All samples are identified by their sample names (the letter H- before the sample names is excluded for simplicity). Note that the location of Volcán Parícutín (samples studied by McBirney *et al.*, 1987) almost coincides with the sample H-418. Also included is the location of La Huacana granite sample (LHG) from the MGVF (Luhr and Carmichael, 1985) and represents the location of possible upper crustal composition for this field.

Hochstaedter *et al.* (1996) used B and Be concentrations and B/Be ratio in selected rocks from the western MVB including the MGVF, to argue against a significant crustal assimilation and to prefer the model in which slab-derived fluids participate in magma genesis processes in the underlying mantle. In a study of primitive magmas from the western MVB, Luhr (1997) presented Sr, Nd and Pb isotopic data for a few samples, including 5 samples from the MGVF, and used them to propose a more complex magma genesis model. According to this model, sub-alkaline as well as strongly alkaline rocks were derived from contribution of the subducted slab, whereas some other alkaline magmas, with peculiar characteristics of intra-plate type lavas, originated from partial melting of convecting upper mantle that was assumed to be compositionally unaffected by subduction. A similar “hybrid” petrogenetic model was earlier proposed by Verma and Nelson (1989) and Luhr *et al.* (1989) for magmas from the western part of the MVB.

For numerous other areas of the MVB, including the key area of the Sierra de Chichinautzin (SCN, Fig. 1), the Sr, Nd and Pb isotopic and geochemical data have been used to propose that, in spite of the ongoing subduction, the Cocos plate does not contribute to the origin of magmas and that the underlying crust plays an important role in the evolution of the mantle-derived magmas (for the SCN: Verma, 1999, 2000a; Velasco-Tapia and

Verma, 2001a, b; Amealco caldera: Verma *et al.*, 1991; Huichapan caldera: Verma, 2001a; Los Humeros caldera: Verma, 2000b; Acapulco caldera: Verma, 2001b; Meseta Río San Juan: Verma, 2001c; Tizayuca volcanic field: Verma, 2003; for the entire southern Mexico: Verma, 2002).

Given this complexity of the MVB and the associated controversies, further constraints are required to resolve them. With this objective in mind, we selected a set of 30 samples from the MGVF and carried out the first detailed geochemical and Sr, Nd and Pb isotopic study of this area. Our database also included the published data for one additional sample from the MGVF as well as those for samples from the Volcán Parícutín. The main results, along with the petrogenetic implications for the origin and evolution of magmas from this key area of the MVB, are presented in this paper.

BRIEF SAMPLE DESCRIPTION AND ANALYTICAL METHODS

Locations of the selected samples are shown schematically using symbols according to the rock types (Fig. 2). Their modal mineralogy is presented in Table 1. The rocks have generally <15% phenocrysts. Trachybasalts have olivine (Ol) and plagioclase (Pl). Basaltic trachyandesites (BTA) contain Ol, Pl and clinopyroxene (Cpx), along with

Table 1. Modal mineralogy for selected volcanic rocks from the Michoacán-Guanajuato Volcanic Field (MGVF), Mexico

Sample	Rock type	Pl-ph	Pl-mph	Ol-ph	Ol-mph	Cpx-ph	Cpx-mph	Opx-ph	Opx-mph	Hbd-ph	Hbd-mph	Qtz-ph	Qtz-mph	Sp-ph	Sp-mph	Gdm	Sum
H-569A	TB	—	12.6	1.3	1.3	—	—	—	—	—	—	—	—	—	—	84.8	100.0
H-439	TB	10.9	2.0	3.1	1.0	—	—	—	—	—	—	—	—	—	—	83.0	100.0
H-542	TB	—	0.5	8.4	1.2	tr	1.6	—	—	—	—	—	—	—	—	88.3	100.0
Jor46	BTA	0.6	2.3	5.9	2.3	0.6	5.9	—	—	0.1	1.0	—	—	—	1.0	80.1	100.0
H-558A	BTA	6.1	8.4	0.5	2.3	—	—	—	—	—	—	—	—	—	0.8	81.9	100.0
H-555A	BTA	—	1.3	—	1.6	—	3.2	—	—	—	—	—	—	—	tr	93.9	100.0
H-520	BTA	0.3	0.2	5.7	1.7	2.9	7.1	—	—	tr	—	—	—	—	—	82.1	100.0
H-571B	BTA	3.6	4.6	2.9	0.3	0.8	0.1	—	—	—	—	—	—	—	0.5	87.2	100.0
Jor11	BTA	0.4	6.3	0.4	1.3	—	0.2	—	tr	0.1	0.8	—	—	—	—	90.5	100.0
H-564L	TA	4.2	3.8	0.7	1.3	—	tr	—	—	—	—	0.3	0.2	—	—	89.5	100.0
H-417A	B	—	0.3	5.7	0.5	—	—	—	—	—	—	—	—	—	—	93.5	100.0
H-408A	B	8.6	7.3	2.5	1.9	0.1	0.4	—	—	—	—	—	—	—	—	79.2	100.0
H-426B	B	0.2	0.9	6.9	1.6	—	0.1	—	—	—	—	—	—	—	—	90.3	100.0
H-536L	BA	tr	1.8	8.4	3.2	1.7	2.4	—	—	—	—	—	—	—	—	82.5	100.0
H-517A	BA	—	18.6	8.4	2.1	—	5.1	—	—	—	—	—	—	—	—	65.8	100.0
Jor44	BA	—	1.1	5.8	1.4	—	0.5	—	—	—	—	—	—	—	0.1	91.1	100.0
H-550	BA	12.2	8.0	2.6	3.6	0.0	0.1	—	—	—	—	—	—	—	—	73.5	100.0
H-736	BA	9.4	11.6	7.5	2.3	0.2	0.9	—	—	—	—	—	—	—	—	68.1	100.0
H-416A	BA	1.2	8.1	1.4	5.4	—	0.1	2.3	tr	—	—	—	—	—	—	81.5	100.0
H-640A	BA	—	0.6	1.6	0.8	—	0.6	—	1.6	—	—	—	—	—	—	94.8	100.0
H-622	BA	0.6	10.1	0.1	1.9	—	—	—	—	—	—	0.4(xen)	—	—	—	86.9	100.0
H-418	BA	—	39.4	2.3	3.3	—	—	—	—	—	—	—	—	—	—	55.0	100.0
H-510T	BA	—	12.6	1.3	1.3	—	—	—	—	—	—	—	—	—	—	84.8	100.0
H-400A	BA	4.1	4.5	—	tr	0.6	0.7	0.2	0.5	tr	0.1	—	—	—	—	89.3	100.0
H-437T	A	2.4	6.8	0.2	tr	—	—	—	—	0.7	0.3	—	—	—	—	89.6	100.0
H-821	A	0.3	14.1	0.4	0.8	5.7	1.1	0.9	0.6	—	—	—	—	—	—	76.1	100.0
H-422B	A	—	7.6	0.8	0.6	—	—	—	0.6	—	—	—	—	—	—	90.4	100.0
H-526L	A	—	0.6	—	—	—	0.2	1.9	0.8	—	—	—	—	—	—	96.4	100.0
H-423B	A	11.2	12.2	—	—	—	—	1.0	3.1	—	—	—	—	—	—	72.5	100.0
H-725	A	1.9	18.3	—	—	0.6	2.1	—	1.8	—	—	—	—	—	—	75.3	100.0
H-674	D	1.3	1.2	1.5	0.1	0.0	0.7	0.0	0.5	—	—	0.4	—	—	0.3	94.0	100.0

For "Rock type" see Table 2 (chemical criteria of TAS diagram). The abbreviations are: ph = phenocryst; mph = microphenocryst; xen = xenolith; Pl = Plagioclase; Ol = Olivine; Cpx = Clinopyroxene; Opx = Orthopyroxene; Hbd = Hornblende; Qtz = Quartz; Sp = Spinel; Gdm = Groundmass; tr = trace (<0.1). The data for "Jor" samples are from Luhr and Carmichael (1985).

small amount of spinel (Sp); a couple of samples also have small amount of hornblende (Hbd). Basaltic rocks also have a similar mineralogy but without Sp. Basaltic andesite and andesite rocks have Pl, Ol, Cpx, with some samples also having Opx. One andesite sample has Hbd instead of pyroxenes. Quartz (Qtz) is additionally present in one basaltic andesite, one trachyandesite and one dacite.

Major and trace elements, including Nb, were analyzed

by X-ray fluorescence spectrometry (XRF) at the University of California, Berkeley (U.S.A.). Rare-earth elements (REE) and selected trace elements were determined by instrumental neutron activation analysis (INAA) at the Lawrence Berkeley Laboratory (U.S.A.). Radiogenic isotopes were determined on two fully-automated triple- (for Nd and Pb) and double- as well as multi-collector (for Sr) MAT 261 mass spectrometers (Verma, 1992) at the

Table 2. Major element and CIPW norm data for selected volcanic rocks from the Michoacán-Guanajuato Volcanic Field (MGVF), Mexico

Magma type	Trachybasalt			Basaltic trachyandesite						Trachy-andesite
Sample	H-569A	H-439	H-542	Jor46	H-558A	H-555A	H-520	Jor11	H-571B	H-564L
Long. (°W)	101.22617	101.53267	102.07883	101.72617	101.21550	100.99800	101.49317	101.720	101.18233	101.22700
Lat. (°N)	20.24283	20.46517	19.01850	18.94683	20.53833	20.49733	19.39683	18.970	20.05967	20.38700
Rock type	TB, haw	TB, haw	TB, pot	BTA, sho	BTA, sho	BTA, sho	BTA, mug	BTA, mug	BTA, mug	TA, lat
Age (Ma)	Q (~1)	Q (1.23)	Plv2	Plv2-3	Plv1	P (2.78)	Plv1	Plv2-3	Plv1	Plv1
SiO ₂	47.18	47.76	49.93	49.21	50.12	52.48	50.86	54.18	54.91	54.93
TiO ₂	2.85	2.92	1.08	1.33	2.40	1.69	1.02	0.92	1.79	1.96
Al ₂ O ₃	17.82	17.06	16.29	14.19	16.24	16.98	16.18	18.74	17.29	17.13
Fe ₂ O ₃	2.82	5.82	3.40	4.55	3.54	3.67	3.42	2.47	2.23	2.40
FeO	7.53	5.78	4.63	3.75	7.69	4.80	4.64	4.31	6.58	5.56
MnO	0.16	0.17	0.13	0.12	0.20	0.13	0.14	0.11	0.15	0.14
MgO	5.40	4.68	8.72	8.32	4.27	4.47	8.48	4.64	3.96	3.05
CaO	8.78	8.15	9.18	7.68	6.48	7.86	8.78	7.87	6.64	5.97
Na ₂ O	3.99	3.66	3.26	4.59	4.12	3.94	4.39	4.52	4.09	4.57
K ₂ O	1.58	1.62	1.80	2.82	2.54	2.17	1.64	1.11	2.02	2.94
P ₂ O ₅	0.57	0.67	0.32	1.37	1.16	0.74	0.59	0.24	0.53	0.49
Total	98.68	98.29	98.74	97.93	98.76	98.93	100.14	99.47	100.19	99.14
(SiO ₂) _{adj}	47.83	48.75	50.65	50.38	50.78	53.13	50.86	54.71	54.80	55.41
(TiO ₂) _{adj}	2.89	2.98	1.10	1.36	2.43	1.71	1.02	0.93	1.79	1.98
(Al ₂ O ₃) _{adj}	18.07	17.41	16.52	14.53	16.46	17.19	16.18	18.92	17.26	17.28
(Fe ₂ O ₃) _{adj}	2.41	2.66	1.84	2.14	2.93	2.18	2.05	1.76	2.28	2.29
(FeO) _{adj}	8.04	8.86	6.14	6.11	8.38	6.24	5.87	5.02	6.52	5.73
(MnO) _{adj}	0.16	0.17	0.13	0.12	0.20	0.13	0.14	0.11	0.15	0.14
(MgO) _{adj}	5.48	4.78	8.84	8.52	4.33	4.52	8.48	4.68	3.95	3.08
(CaO) _{adj}	8.90	8.32	9.31	7.86	6.57	7.96	8.78	7.95	6.63	6.02
(Na ₂ O) _{adj}	4.04	3.74	3.31	4.70	4.17	3.99	4.39	4.56	4.08	4.61
(K ₂ O) _{adj}	1.60	1.65	1.83	2.89	2.57	2.20	1.64	1.12	2.02	2.97
(P ₂ O ₅) _{adj}	0.58	0.68	0.32	1.40	1.18	0.75	0.59	0.24	0.53	0.49
(Na ₂ O+K ₂ O) _{adj}	5.65	5.39	5.13	7.59	6.75	6.19	6.03	5.68	6.10	7.58
Q	—	—	—	—	—	—	—	—	2.80	0.52
Or	9.47	9.77	10.79	17.06	15.21	12.98	9.69	6.62	11.91	17.53
Ab	26.09	31.61	25.81	24.94	35.32	33.75	28.43	38.62	34.54	39.01
An	26.41	25.86	24.85	10.02	18.56	22.51	19.60	27.83	22.81	17.70
Ne	4.41	—	1.18	8.03	—	—	4.72	—	—	—
Di	11.38	8.98	15.44	15.91	5.22	9.84	16.14	8.12	5.42	7.33
Hy	—	0.97	—	—	4.64	10.68	—	13.32	14.59	9.69
Ol	11.93	11.70	16.42	15.11	9.46	2.08	15.14	0.60	—	—
Mt	3.50	3.85	2.67	3.10	4.25	3.16	2.98	2.55	3.31	3.32
Il	5.49	5.66	2.08	2.59	4.62	3.25	1.94	1.76	3.39	3.76
Ap	1.34	1.58	0.75	3.25	2.72	1.74	1.37	0.56	1.23	1.14
Mg#	54.84	49.02	71.96	71.31	47.92	56.39	72.03	62.48	51.94	48.92
FeO ^T /MgO	1.86	2.35	0.88	0.94	2.55	1.81	0.91	1.41	2.17	2.53
Salic	61.96	67.25	61.45	52.01	69.09	69.25	57.72	73.08	72.06	74.76
Femic	28.34	27.49	32.84	32.99	25.94	25.54	32.32	23.72	24.57	21.24
CI	49.59	43.92	61.66	47.21	31.56	42.06	56.88	46.06	35.70	31.26
DI	39.96	41.39	37.78	50.03	50.53	46.74	42.84	45.24	49.25	57.06
SI	25.38	22.04	40.27	34.98	19.32	23.65	37.80	27.33	20.97	16.48
AR	1.53	1.53	1.50	2.02	1.83	1.65	1.64	1.54	1.69	1.96

Max-Planck-Institut für Chemie, Mainz (Germany). Average counting uncertainties (relative standard deviation in %) for XRF and INAA were reported by Hasenaka and Carmichael (1987). Nb data for samples with low concentrations (<8 ppm) may be of poorer quality than those for samples with higher Nb concentrations as well as for most other trace elements analyzed by XRF. Therefore, photon activation data of Hasenaka *et al.* (1993) determined at Tohoku University were used for all such samples. The analytical procedures and uncertainties were shown in Yoshida *et al.* (1986). The analytical uncertain-

ties for isotopes are directly quoted for each sample. CIPW norms were calculated for all samples on an anhydrous 100% adjusted basis, with $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios depending on rock types, which, in turn, were based on total alkalis-silica (TAS) classification (Le Bas *et al.*, 1986; Le Bas, 1989, 2000; Middlemost, 1989; Verma *et al.*, 2002). For all samples, $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, proposed by Middlemost (1989) as the minimum pre-eruptive (pre-oxidation effects due to weathering) “fresh rock” values depending on rock-types, were assigned before the CIPW norm computation (Verma *et al.*, 2002).

Table 2. (continued)

Magma type	Subalkali basalt			Basaltic andesite						
Sample	H-417A	H-408A	H-426B	H-536L	H-517A	Jor44	H-550	H-736	H-416A	H-640A
Long. (°W)	102.29267	102.21967	101.91317	101.63850	102.09533	101.750	100.71050	102.12900	102.22300	100.65167
Lat. (°N)	19.56533	19.84550	19.29783	19.27283	19.61217	18.990	19.87933	19.58867	19.55267	20.52033
Rock type	B, subal	B, subal	B, subal	BA	BA	BA	BA	BA	BA	BA
Age (Ma)	Plv2	Plv1	Plv2 (0.37)	Plv2	Plv2-3	Hv (235y)	Plv1	Plv3	Plv1	Q (~1.2)
SiO ₂	50.22	50.30	51.17	51.80	51.99	52.10	51.88	53.29	53.06	55.03
TiO ₂	1.18	1.20	0.83	0.72	0.81	0.81	0.76	0.84	0.98	1.58
Al ₂ O ₃	16.55	17.44	17.09	16.60	16.58	16.44	18.18	16.97	17.84	16.50
Fe ₂ O ₃	1.95	2.28	2.36	1.48	2.32	1.56	1.57	—	2.41	—
FeO	6.40	6.14	5.60	5.52	5.17	6.05	5.08	7.21	4.87	7.93
MnO	0.14	0.14	0.14	0.13	0.13	0.14	0.12	0.13	0.12	0.14
MgO	8.78	6.74	9.02	9.26	9.40	9.29	6.73	8.06	6.61	5.51
CaO	8.91	10.19	8.91	8.39	8.73	8.46	9.84	8.79	8.61	7.57
Na ₂ O	3.20	3.15	3.22	4.04	2.92	3.47	3.08	3.63	3.83	3.40
K ₂ O	1.12	0.56	0.67	0.76	0.95	0.74	0.84	0.81	0.96	1.30
P ₂ O ₅	0.23	0.18	0.13	0.14	0.22	0.10	0.11	0.13	0.21	0.41
Total	98.68	98.32	99.14	98.84	99.22	99.16	98.19	99.86	99.50	99.37
(SiO ₂) _{adj}	50.92	51.21	51.67	52.40	52.43	52.53	52.84	53.27	53.37	55.27
(TiO ₂) _{adj}	1.20	1.22	0.84	0.73	0.82	0.82	0.77	0.84	0.99	1.59
(Al ₂ O ₃) _{adj}	16.78	17.75	17.26	16.79	16.72	16.58	18.52	16.96	17.94	16.57
(Fe ₂ O ₃) _{adj}	1.40	1.41	1.32	1.64	1.73	1.78	1.56	1.70	1.67	1.88
(FeO) _{adj}	7.01	7.07	6.61	5.46	5.76	5.92	5.21	5.68	5.57	6.27
(MnO) _{adj}	0.14	0.14	0.14	0.13	0.13	0.14	0.12	0.13	0.12	0.14
(MgO) _{adj}	8.90	6.86	9.11	9.37	9.48	9.37	6.85	8.06	6.65	5.53
(CaO) _{adj}	9.03	10.37	9.00	8.49	8.80	8.53	10.02	8.79	8.66	7.60
(Na ₂ O) _{adj}	3.24	3.21	3.25	4.09	2.94	3.50	3.14	3.63	3.85	3.42
(K ₂ O) _{adj}	1.14	0.57	0.68	0.77	0.96	0.75	0.86	0.81	0.97	1.31
(P ₂ O ₅) _{adj}	0.23	0.18	0.13	0.14	0.22	0.10	0.11	0.13	0.21	0.41
(Na ₂ O+K ₂ O) _{adj}	4.38	3.78	3.93	4.86	3.90	4.24	3.99	4.44	4.82	4.72
Q	—	—	—	—	—	—	—	—	—	5.51
Or	6.71	3.37	4.00	4.54	5.66	4.41	5.06	4.79	5.71	7.72
Ab	27.46	27.14	27.51	34.58	24.92	29.61	26.54	30.71	32.59	28.90
An	27.87	32.36	30.49	25.20	29.57	27.32	33.91	27.61	28.82	26.03
Di	12.46	14.57	10.72	12.80	10.15	11.51	12.15	12.18	10.31	7.31
Hy	6.32	11.68	13.15	3.14	20.86	14.27	18.09	15.90	14.54	17.84
Ol	14.34	6.09	10.32	15.64	4.27	8.53	0.25	4.46	3.24	—
Mt	2.03	2.05	1.92	2.37	2.51	2.57	2.26	2.47	2.42	2.73
Il	2.27	2.32	1.59	1.38	1.55	1.55	1.47	1.60	1.87	3.01
Ap	0.54	0.42	0.30	0.33	0.51	0.23	0.26	0.30	0.49	0.95
Mg#	69.37	63.38	71.07	75.36	74.57	73.83	70.12	71.68	68.01	61.13
FeO ⁷ /MgO	0.93	1.22	0.86	0.74	0.77	0.80	0.96	0.89	1.06	1.44
Salic	62.04	62.87	62.00	64.33	60.15	61.33	65.52	63.10	67.12	68.16
Femic	33.91	31.77	34.74	32.48	37.01	35.70	30.95	33.50	29.49	28.51
CI	59.79	61.98	60.60	59.75	60.45	59.76	62.14	58.30	53.99	44.73
DI	34.17	30.50	31.50	39.13	30.58	34.02	31.60	35.49	38.30	42.13
SI	41.04	35.89	43.44	43.94	45.41	43.97	38.91	40.54	35.53	30.06
AR	1.41	1.31	1.35	1.48	1.36	1.41	1.32	1.42	1.44	1.48

RESULTS

The compositions and CIPW norms of the MGVF rocks selected for detailed isotopic work are reported in

Table 2. Their trace element concentrations and radiogenic isotope ratios are presented in Tables 3 to 5. Two distinct magma types are recognized: (i) alkaline magmas—trachybasalt (3 samples), basaltic trachyandesite (5

Table 2. (continued)

Magma type	Basaltic andesite				Andesite					Dacite	
Sample	H-622	H-418	H-510T	H-400A	H-437T	H-821	H-422B	H-526L	H-423B	H-725	H-674
Long. (°W)	101.43383	102.25117	102.06883	102.54617	101.76867	102.60850	101.64133	101.47950	101.81333	101.99250	101.89367
Lat. (°N)	19.71250	19.49250	19.44350	19.90233	19.90600	19.15550	19.51067	19.19883	19.49917	19.53883	19.82600
Rock type	BA	BA	BA	BA	A	A	A	A	A	A	D
Age (Ma)	Plv4 (0.017)	Hv (50y)	Q (~1.2)	Plv1	Plv2-3	Plv2	Plv2	Hv	Plv2-3	Hv (0.0047)	Plv2-3
SiO ₂	54.71	55.48	55.04	55.88	56.14	58.24	59.39	61.04	60.33	59.63	65.95
TiO ₂	1.27	1.11	0.97	1.07	0.72	1.13	0.75	0.90	0.73	0.67	0.60
Al ₂ O ₃	17.26	17.33	18.07	17.99	17.86	16.77	17.41	17.52	17.16	16.99	15.29
Fe ₂ O ₃	—	1.30	2.82	1.45	1.69	—	1.40	0.93	0.84	—	—
FeO	7.58	6.05	4.58	5.10	4.31	5.79	4.36	4.35	4.32	4.74	3.65
MnO	0.13	0.13	0.12	0.12	0.12	0.11	0.11	0.10	0.09	0.09	0.11
MgO	4.52	5.43	4.39	3.78	3.62	3.62	4.00	2.90	3.38	2.95	3.76
CaO	6.91	6.92	7.57	7.23	7.47	6.29	6.27	5.97	5.76	5.75	4.48
Na ₂ O	4.08	4.16	4.10	3.94	3.77	3.64	3.99	4.23	3.70	3.62	3.71
K ₂ O	1.43	1.21	0.86	1.38	0.98	1.71	1.51	1.70	1.66	2.06	2.43
P ₂ O ₅	0.36	0.33	0.21	0.24	0.18	0.35	0.17	0.27	0.17	0.24	0.10
Total	98.25	99.45	98.73	98.18	96.86	97.65	99.36	99.91	98.14	96.74	100.08
(SiO ₂) _{adj}	55.58	55.76	55.81	56.91	57.97	59.55	59.77	61.07	61.44	61.56	65.83
(TiO ₂) _{adj}	1.29	1.12	0.98	1.09	0.74	1.16	0.76	0.90	0.74	0.69	0.60
(Al ₂ O ₃) _{adj}	17.54	17.42	18.32	18.32	18.44	17.15	17.52	17.53	17.48	17.54	15.26
(Fe ₂ O ₃) _{adj}	1.82	1.71	1.70	1.54	1.60	1.58	1.50	1.38	1.38	1.30	1.07
(FeO) _{adj}	6.06	5.71	5.68	5.14	4.58	4.50	4.30	3.95	3.93	3.72	2.68
(MnO) _{adj}	0.13	0.13	0.12	0.12	0.12	0.11	0.11	0.10	0.09	0.09	0.11
(MgO) _{adj}	4.59	5.46	4.45	3.85	3.74	3.70	4.02	2.90	3.44	3.04	3.75
(CaO) _{adj}	7.02	6.96	7.68	7.36	7.71	6.43	6.31	5.97	5.87	5.94	4.47
(Na ₂ O) _{adj}	4.14	4.18	4.16	4.01	3.89	3.72	4.02	4.23	3.77	3.74	3.70
(K ₂ O) _{adj}	1.45	1.22	0.87	1.40	1.01	1.75	1.52	1.70	1.69	2.13	2.42
(P ₂ O ₅) _{adj}	0.37	0.33	0.21	0.24	0.19	0.36	0.17	0.27	0.17	0.25	0.10
(Na ₂ O+K ₂ O) _{adj}	5.60	5.40	5.03	5.42	4.90	5.47	5.54	5.93	5.46	5.86	6.13
Q	3.14	2.83	4.04	5.90	8.66	11.53	10.06	12.27	14.03	13.60	19.42
Or	8.59	7.19	5.15	8.30	5.98	10.33	8.98	10.05	9.99	12.57	14.33
Ab	35.07	35.38	35.18	33.96	32.94	31.49	33.97	35.81	31.88	31.62	31.33
An	24.95	25.17	28.76	27.83	29.86	24.91	25.29	23.81	25.78	24.80	17.86
Di	6.12	5.82	6.48	5.81	5.87	3.78	3.98	3.32	1.78	2.47	2.95
Hy	16.19	18.24	15.54	13.33	12.53	12.64	13.71	10.41	12.73	11.17	11.18
Mt	2.64	2.48	2.47	2.23	2.32	2.28	2.18	2.00	2.00	1.89	1.55
Il	2.45	2.12	1.87	2.07	1.41	2.19	1.43	1.71	1.41	1.31	1.14
Ap	0.85	0.77	0.49	0.56	0.43	0.83	0.40	0.63	0.40	0.57	0.23
Mg#	57.44	63.00	58.27	57.20	59.27	59.44	62.52	56.72	60.95	59.33	71.40
FeO ^T /MgO	1.68	1.33	1.62	1.69	1.61	1.60	1.40	1.79	1.50	1.61	0.97
Salic	71.75	70.56	73.14	75.99	77.43	78.26	78.31	81.94	81.68	82.59	82.95
Femic	25.12	26.78	23.94	21.27	20.00	19.65	19.99	16.22	17.32	15.96	16.14
CI	40.01	41.90	43.95	41.21	43.23	36.00	37.21	32.72	33.95	33.03	28.55
DI	46.81	45.39	44.38	48.16	47.58	53.35	53.01	58.13	55.90	57.79	65.09
SI	25.41	29.85	26.39	24.15	25.22	24.27	26.19	20.49	24.23	21.86	27.53
AR	1.59	1.57	1.48	1.54	1.46	1.60	1.60	1.68	1.61	1.67	1.90

Abbreviations: The subscript “adj” refers to adjusted data from SINCLAS; Salic = sum of salic normative minerals; Femic = sum of femic normative minerals; CI = Crystallization Index; DI = Differentiation Index; SI = Solidification Index; AR = Alkalinity Ratio. Mg# = $100 \text{ Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+})$, atomic; FeO^T = total iron expressed as FeO; TB = Trachybasalt; haw = hawaiite; pot = Potassic; BTA = Basaltic trachyandesite; sho = shoshonite; mug = mugearite; B, subal = Subalkali basalt; BA = Basaltic andesite; TA = Trachyandesite; lat = latite; A = Andesite; D = Dacite. Rock-types are presented according to total alkalis versus silica diagram (Le Bas et al., 1986; Le Bas, 1989, 2000) and CIPW norms are on an anhydrous 100% adjusted basis and using $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio after Middlemost (1989), using the SINCLAS computer program (Verma et al., 2002). The actually measured ages are reported when available (Hv = Holocene; Q = Quaternary; P = Pliocene); geomorphologically inferred ages are as follows: Plv1 = 0.7 Ma; Plv2 = 0.4 Ma; Plv2-3 = 0.04 Ma; Plv3 = 0.03 Ma; Plv4 = 0.017 Ma; for Q the ages quoted as (–) are approximate values.

Table 3. Trace element data for selected volcanic rocks from the Michoacán-Guanajuato Volcanic Field (MGVF), Mexico

Magma type	Trachybasalt			Basaltic trachyandesite						Trachyandesite	
	H-569A Cone # Volcano name	H-439 648 San Jorge	H-542 390 Cerro La Cruz	Jor46 641 Cerro La Pilita	H-558A 918 La Cal	H-555A 988 Santa Teresa	H-520 774 Cerro El Tecolote	Jor11 634 Volcán El Jorullo	H-571B 981 Cerro El Melón	H-564L 930 Hacienda Estrada	
Rock type	TB, haw	TB, haw	TB, pot	BTA, sho	BTA, sho	BTA, sho	BTA, mug	BTA, mug	BTA, mug	TA, lat	TA, lat
Ba (XRF)	344	495	866	1271	58.1	850	744	352	565	450	
Nb (PA)	37.7	38.7	5.6	19.7	361	18.6	9.8	9*	31.1	51.3	
Zr (XRF)	169	203	150	203	44	240	122	130	239	237	
Y (XRF)	21	22	19	18	544	32	14	21	27	30	
Sr (XRF)	648	696	1211	2250	544	1419	1151	615	557	561	
Rb (XRF)	24	22	11	17	38	30	15	16	27	63	
Ga (XRF)	20	21	18	25	26	23	19	18	21	22	
Zn (XRF)	93	94	83	172	111	104	116	66	99	67	
Cu (XRF)	33	35	64	72	25	27	79	35	14	15	
Ni (XRF)	38	30	209	248	18	44	174	44	37		
Cr (INAA)	25	59	515	293	40		367	51	60		
V (XRF)	316	280	198	217	186	223	190	216	206	163	
B (OES)**	3.6	3.8	3.8	5.2	2.9						
Be (OES)**	1.85	1.68	1.68	3.21	2.88						
La (INAA)	34	33	33	91.5	54			12.6			
Ce (INAA)	65.9	71.0	71.0	172	116			29.4			
Nd (INAA)	31	34	34	67	60			17			
Sm (INAA)	6.70	4.97	4.97	7.79	10.96			3.39			
Eu (INAA)	2.32	1.47	1.47	2.04	3.30			1.12			
Tb (INAA)	0.90	0.56	0.56	0.62	1.55			0.48			
Dy (INAA)	5.43	2.96	2.96	2.68	7.89			2.94			
Yb (INAA)	2.25	1.55	1.55	1.25	4.15			1.70			
Lu (INAA)	0.28	0.22	0.22	0.17	0.55			0.22			
Cs (INAA)	0.3	0.8	0.8	0.6	0.6			0.39			
Hf (INAA)	5.23	4.14	4.14	5.60	8.78			3.46			
Sc (INAA)	22.2	26.4	26.4	18.11	19.2			19.11			
Th (INAA)	2.87	2.02	2.02	5.19	5.04			1.14			
U (INAA)	0.83	0.58	0.58	1.18	1.42			0.39			

Magma type	Subalkali basalt				Basaltic andesite							
	H-417A	H-408A	H-426B	B, subal	H-536L	H-517A	Jor44	H-550	H-736	H-416A	H-640A	Cerro Las Brujas
	234	153	564		803	260	634	1020	256	245	1040	
Volcano name	Zacan	Cerro Colorado	Cerro Pelón		Cerro El Cajete	Cerro San Miguel	Volcán El Jorullo	La Loma	Cerro Los Añoles			
Rock type	B, subal	B, subal	B, subal		BA	BA	BA	BA	BA	BA	BA	
Ba (XRF)	362	224	218		220	344	204	163	242	297	512	
Nb (PAA)	6.6	4.2	6*		2.4	5.2	2.3	6*	4.7	5.2	12.7	
Zr (XRF)	143	116	93		77	120	100	67	105	99	263	
Y (XRF)	22	13	18		12	17	20	13	19	11	32	
Sr (XRF)	540	579	445		457	893	397	656	484	723	589	
Rb (XRF)	22	9	7		8	13	10	10	11	9	19	
Ga (XRF)	16	18	18		17	17	16	20	18	18	19	
Zn (XRF)	76	73	66		65	73	61	57	66	75	90	
Cu (XRF)	53	96	44		48	28	60	25	53	43	16	
Ni (XRF)	230	84	198		259	258	261	83	126	142	60	
Cr (INAA)	373	183	556		660	416	643	209	388	142	164	
V (XRF)	190	190	184		156	147	186	161	178	139	143	
B (OES)**	5.8	2.8	5.6			6.5	2.8	1.7				
Be (OES)**	1.05	0.85	0.64			0.97	0.64	0.57				
La (INAA)	17	16	7.0				7.9					
Ce (INAA)	34.7	28.8	16.5				18.3					
Nd (INAA)	18	15	11				10.0					
Sm (INAA)	4.19	3.47	2.49				2.65					
Eu (INAA)	1.37	1.26	0.88				0.90					
Tb (INAA)	0.65	0.60	0.43				0.48					
Dy (INAA)	3.72	3.60	2.78				3.11					
Yb (INAA)	2.06	2.11	1.69				1.95					
Lu (INAA)	0.26	0.29	0.24				0.26					
Cs (INAA)	0.7	0.4	0.4				0.57					
Hf (INAA)	3.67	2.99	2.09				2.44					
Sc (INAA)	29.2	31.7	27.0				27.85					
Th (INAA)	0.87	0.86	0.39				0.73					
U (INAA)	0.58	0.40	0.22				0.29					

Table 3. (continued)

Sample Cone # Volcano name Rock type	Basaltic andesite				Andesite				Dacite	
	H-622	H-418	H-510T	H-400A	H-437T	H-821	H-422B	H-526L	H-423B	H-725
	725 Volcán La Mina	289 Volcán Parícutín	326 Costo	18 Cerro El Comalito	423 Hacienda La Alberca	101 Cerro Buena-vista	741 Volcán El Estribo	888 M. El Malpais	533 Hacienda El Tiguicho	499 Cerro El Metate
	BA	BA	BA	BA	A	A	A	A	A	A
Ba (XRF)	459	400	345	440	349	537	535	609	691	731
Nb (PAA)	15.5	9.9	6.6	7.9	4.0	16.2	6.7	10.8	6.6	8.8
Zr (XRF)	192	154	108	154	97	208	147	160	144	177
Y (XRF)	27	18	19	14	13	23	14	16	13	19
Sr (XRF)	575	586	619	651	1135	824	528	548	520	732
Rb (XRF)	26	17	15	21	15	26	28	30	33	42
Ga (XRF)	20	20	22	23	24	18	18	21	18	23
Zn (XRF)	95	88	81	93	71	73	81	74	74	72
Cu (XRF)	30	39	28	88	21	24	31	29	38	25
Ni (XRF)	107	107	72	15	27	67	48	35	34	23
Cr (INAA)	62	187	60	23	141	100	94	62	83	60
V (XRF)	140	152	149	153		155	127	125	120	117
B (OES)**	8.8			7.4						
Be (OES)**	1.39			1.14						
La (INAA)		16		20					21	
Ce (INAA)		39.9		38.5					38.2	
Nd (INAA)		21		21					18	
Sm (INAA)		4.22		3.97					3.46	
Eu (INAA)		1.44		1.29					1.04	
Tb (INAA)		0.58		0.58					0.46	
Dy (INAA)		3.80		3.31					2.77	
Yb (INAA)		1.96		1.82					1.43	
Lu (INAA)		0.29		0.26					0.18	
Cs (INAA)		0.3		0.9					1.1	
Hf (INAA)		4.01		3.96					3.65	
Sc (INAA)		18.9		18.4					14.5	
Th (INAA)		1.54		1.80					2.24	
U (INAA)		0.46		0.54					0.63	

Ref.: XRF (X-ray fluorescence) data are from Hasenaka and Carmichael (1987) and Hasenaka (1992c); PAA (photon activation analysis) data for Nb are by Hasenaka et al. (1993).

*Nb data by XRF; INAA (instrumental neutron activation analysis) data on selected samples are from Hasenaka and Carmichael (1987), except for Jor44, Jor11, and Jor46 from Luhr and Carmichael (1985). Cr concentration data by XRF are given when INAA data were not available.

**B and Be data are from Hochstaedter et al. (1996).

samples), and trachyandesite (1 sample); and (ii) sub-alkaline magmas—basalt (3 samples), basaltic andesite (11 samples), andesite (6 samples) and dacite (1 sample). All alkaline samples analyzed in this study are Ol-normative (four Ol + Ne and four Ol + Hy), except two high-silica rocks (H-571B and H-564L) that are Q- and

Hy-normative. The sub-alkaline rocks are either Ol- and Hy-normative (three basalt and six basaltic andesite samples) or Q- and Hy-normative (the remaining twelve basaltic andesite to dacite samples). All samples (basaltic andesite and andesite) from the Volcán Parícutín, studied by McBirney *et al.* (1987) and compiled in our database, are Q- and Hy-normative.

The MGVF rocks analyzed in this study cover an age range of Pliocene to Holocene (<2.8 Ma); in fact, with the exception of one sample (H-555A of 2.78 Ma), all other rocks are considerably younger (≤ 1.2 Ma). On a TAS diagram (Fig. 3) the subalkaline rocks seem to show a somewhat coherent differentiation trend, as opposed to the alkaline rocks, which are characterized by a wide variation in total alkali contents. Mg# values for the MGVF rocks do not show a good correlation with their SiO₂ contents (Fig. 4a). However, a correlation seems to exist for Mg# with modal olivine, particularly for subalkaline rocks (Fig. 4b). For alkaline rocks Mg# are widely distributed (~48–72), with a few samples showing large values (three samples with Mg# > 70). The subalkaline rocks show a similar range (~57–75), with two basalt and five SiO₂-poor basaltic andesite samples showing large Mg# (~70). Subalkaline rocks present a good positive linear correlation on a SiO₂–K₂O diagram (Fig. 4c), whereas the alkaline rocks show a wide scatter on this diagram. The alkaline rocks seem to show a better trend (negative correlation) on a SiO₂–P₂O₅ diagram (Fig. 4d) than on any other

Fig. 3. A total alkali-silica (TAS) diagram for the MGVF rocks. The abbreviations for the samples (and the respective fields) are: TB = trachybasalt; BTA = basaltic trachyandesite; TA = trachyandesite; B = basalt; BA = basaltic andesite; A = andesite; D = dacite. Other fields are: T = trachyte; TD = trachydacite; R = rhyolite. Published data (McBirney *et al.*, 1987) for samples from Volcán Parícutín are also included using smaller symbols than those for the samples from this study.

Fig. 4. Binary plots for some selected parameters for the MGVF rocks. For the symbols used see Fig. 3. (a) SiO₂–Mg#; (b) Modal Olivine–Mg#; (c) SiO₂–K₂O; (d) SiO₂–P₂O₅.

Table 4. New Sr and Nd isotope data for selected volcanic rocks from the Michoacán-Guanajuato Volcanic Field (MGVF), Mexico

Sample	Rock-type	(SiO ₂) _{adj} (wt %)	⁸⁷ Sr/ ⁸⁶ Sr		¹⁴³ Nd/ ¹⁴⁴ Nd		ε _{Nd}	Initial ratios		
			Individual runs	Average	Individual runs	Average		(⁸⁷ Sr/ ⁸⁶ Sr) _i	(¹⁴³ Nd/ ¹⁴⁴ Nd) _i	(ε _{Nd}) _i
H-569A	TB, haw	47.83	0.703569 ± 31 0.703547 ± 32 0.703586 ± 30	0.703567 ± 20	0.512884 ± 14		4.80	0.703566	(0.512884)	4.8
H-439	TB, haw	48.75	0.703376 ± 26		0.512881 ± 17		4.74	0.703374	0.512879	4.7
H-542	TB, pot*	50.65	0.704178 ± 25		0.512779 ± 19 0.512775 ± 15	0.512777 ± 3	2.71	0.704178	0.512777	2.7
Jor46	BTA, sho*	50.38	0.704333 ± 23 0.704344 ± 39	0.704338 ± 8	0.512728 ± 32 0.512739 ± 17	0.512734 ± 8	1.87	0.704338	0.512734	1.9
H-558A	BTA, sho	50.78	0.703704 ± 22		0.512875 ± 19		4.62	0.703702	0.512874	4.6
H-555A	BTA, sho	53.13	0.704390 ± 32 0.704398 ± 28	0.704394 ± 6	0.512771 ± 12		2.59	0.704392	(0.512771)	2.6
H-520	BTA, mug*	50.86	0.704313 ± 24		0.512785 ± 14		2.87	0.704313	(0.512785)	2.9
Jor11 Θ	BTA, mug	54.71	0.70404		0.51285		4.2	(0.70404)	(0.51285)	4.2
H-571B	BTA, mug	54.80	0.703874 ± 17		0.512853 ± 16		4.19	0.703873	(0.512853)	4.2
H-564L	TA, lat	55.41	0.703380 ± 13		0.512834 ± 22		3.82	0.703377	(0.512834)	3.8
H-417A	B, subal*	50.92	0.703765 ± 32		0.512910 ± 16		5.31	0.703764	0.512909	5.3
H-408A	B, subal*	51.21	0.703199 ± 32		0.512977 ± 15		6.61	0.703199	0.512976	6.6
H-426B	B, subal*	51.67	0.704044 ± 19		0.512834 ± 16		3.82	0.704044	0.512833	3.8
H-536L	BA*	52.40	0.704030 ± 28 0.704038 ± 25	0.704034 ± 6	0.512825 ± 16		3.65	0.704034	(0.512825)	3.6
H-517A	BA*	52.43	0.703254 ± 36 0.703325 ± 18	0.703290 ± 50	0.512964 ± 19		6.36	0.703290	(0.512964)	6.4
Jor44	BA*	52.53	0.703841 ± 28		0.512873 ± 23		4.58	0.703841	0.512873	4.6
H-550	BA*	52.84	0.703455 ± 24 0.703474 ± 19 0.703476 ± 22	0.703468 ± 12	0.512905 ± 10		5.21	0.703468	(0.512905)	5.2
H-736	BA*	53.27	0.703899 ± 29		0.512834 ± 18		3.82	0.703899	(0.512834)	3.8
H-416A	BA*	53.37	0.703791 ± 29 0.703807 ± 28 0.703823 ± 47	0.703807 ± 16	0.512856 ± 14		4.25	0.703807	(0.512856)	4.3
H-640A	BA	55.27	0.704026 ± 32 0.704023 ± 22	0.704024 ± 2	0.512742 ± 13		2.03	0.704020	(0.512742)	2.0
H-622	BA	55.58	0.703979 ± 25 0.703975 ± 26	0.703977 ± 3	0.512784 ± 20		2.85	0.703977	(0.512784)	2.8
H-418	BA	55.76	0.703815 ± 33		0.512843 ± 13		4.00	0.703815	0.512843	4.0
H-510T	BA	55.81	0.704162 ± 23		0.512782 ± 19		2.81	0.704161	(0.512782)	2.8
H-400A	BA	56.91	0.703745 ± 25		0.512810 ± 20		3.36	0.703744	0.512809	3.3
H-437T	A	57.97	0.703369 ± 30		0.512900 ± 21 0.512884 ± 23	0.512892 ± 11	4.95	0.703369	(0.512892)	5.0
H-821	A	59.55	0.703582 ± 26 0.703540 ± 21	0.703561 ± 30	0.512805 ± 22 0.512825 ± 20	0.512815 ± 14	3.45	0.703560	(0.512815)	3.5
H-422B	A	59.77	0.704204 ± 30 0.704178 ± 22	0.704191 ± 18	0.512749 ± 14		2.17	0.704190	(0.512749)	2.2
H-526L	A	61.07	0.704036 ± 16		0.512786 ± 22		2.89	0.704036	(0.512786)	2.9
H-423B	A	61.44	0.704194 ± 21		0.512762 ± 11		2.42	0.704194	0.512762	2.4
H-725	A	61.56	0.704031 ± 31		0.512804 ± 12		3.24	0.704031	(0.512804)	3.2
H-674	D	65.83	0.703879 ± 18 0.703920 ± 23	0.703900 ± 29	0.512810 ± 23		3.36	0.703900	(0.512810)	3.4

The ⁸⁷Sr/⁸⁶Sr ratios were normalized to ⁸⁶Sr/⁸⁸Sr = 0.11940 and adjusted to SRM987 ⁸⁷Sr/⁸⁶Sr ratio of 0.710230. The measured ⁸⁷Sr/⁸⁶Sr ratio for the SRM987 standard during the period of measurements of this study was 0.710216 ± 11 (1σ; n = 36). The ¹⁴³Nd/¹⁴⁴Nd ratios were normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.72190 and adjusted to La Jolla ¹⁴³Nd/¹⁴⁴Nd ratio of 0.511860. The measured ¹⁴³Nd/¹⁴⁴Nd ratio for the La Jolla standard was 0.511833 ± 12 (1σ; n = 82) during the period of measurement of about 1 year (September, 1986–August, 1987). ε_{Nd} = [(¹⁴³Nd/¹⁴⁴Nd)_m/(¹⁴³Nd/¹⁴⁴Nd)_{CHUR}] - 1/10⁴, using (¹⁴³Nd/¹⁴⁴Nd)_{CHUR} = 0.512638. Further, the errors reported for individual Sr and Nd isotope ratios are 2 times the standard error of the mean (2σ_E) multiplied by 10⁶. For average isotope ratios the errors are one standard deviation of the mean values, also multiplied by 10⁶. Rock-types are same as in Table 1. In-situ growth corrections were carried out using the actually measured Rb/Sr and Sm/Nd ratios (Table 2), and measured or in some cases assumed ages (Table 1). The data in parenthesis (initial Nd isotopic ratios) are the actually measured ratios because for them Sm/Nd values are not available; nevertheless, both sets of Nd isotopic ratios are practically identical considering the corresponding analytical errors and very young ages. Θ = Data from Jor11 are from Luhr (1997).

*"Primitive" rocks as inferred from the criteria proposed by Luhr (1997).

Table 5. New Pb isotope data for selected volcanic rocks from the Michoacán-Guanajuato Volcanic Field (MGVF), Mexico

Sample	Rock-type	(SiO ₂) _{adj} (wt %)	²⁰⁶ Pb/ ²⁰⁴ Pb		²⁰⁷ Pb/ ²⁰⁴ Pb		²⁰⁸ Pb/ ²⁰⁴ Pb	
			Individual runs	Average	Individual runs	Average	Individual runs	Average
H-439	TB, haw	48.75	18.875	18.878 ± 4	15.592	15.596 ± 5	38.653	38.659 ± 11
			18.877		15.595		38.654	
			18.883		15.602		38.672	
Jor46 Θ	BTA, sho*	50.38	18.702		15.600		38.518	
H-558A	BTA, sho	50.78	18.782	18.783 ± 1	15.603	15.603 ± 2	38.612	38.620 ± 9
			18.782		15.601		38.618	
			18.784		15.605		38.630	
H-520	BTA, mug*	50.86	18.705	18.705 ± 2	15.608	15.609 ± 2	38.522	38.523 ± 1
			18.707		15.611		38.524	
			18.703		15.609		38.523	
Jor11 Θ	BTA, mug	54.71	18.645		15.616		38.380	
H-564L	TA, lat	55.41	18.768	18.769 ± 1	15.601	15.602 ± 1	38.596	38.598 ± 3
			18.770		15.602		38.600	
H-417A	B, subal*	50.92	18.672	18.672 ± 1	15.584	15.584 ± 1	38.399	38.401 ± 3
			18.673		15.585		38.403	
H-408A	B, subal*	51.21	18.640		15.569		38.315	
Jor44 Θ	BA *	52.53	18.619		15.571		38.344	
H-418	BA	55.76	18.686		15.610		38.509	
H-400A	BA	56.91	18.687	18.688 ± 1	15.599	15.600 ± 1	38.464	38.466 ± 2
			18.689		15.601		38.467	
H-821	A	59.55	18.676	18.676 ± (0)	15.592	15.592 ± (0)	38.429	38.432 ± 4
			18.676		15.592		38.435	
H-423B	A	61.44	18.697	18.699 ± 3	15.603	15.606 ± 4	38.496	38.505 ± 13
			18.701		15.609		38.514	
H-674	D	65.83	18.714	18.714 ± 1	15.602	15.603 ± 1	38.507	38.507 ± (0)
			18.715		15.604		38.507	

The Pb isotope ratios are corrected for fractionation estimated by running simultaneously the NBS982 standard and are relative to values of $^{206}\text{Pb}/^{204}\text{Pb} = 36.73845$, $^{207}\text{Pb}/^{204}\text{Pb} = 17.15946$, $^{208}\text{Pb}/^{204}\text{Pb} = 36.74432$, and $^{207}\text{Pb}/^{206}\text{Pb} = 0.46707$ for this standard. All Pb data are corrected for mass fractionation (a factor of 1.48 ± 0.04 ; 1σ ; $n = 9$). The analytical uncertainties quoted for Pb isotopes are represented by one standard deviation values of duplicate measurements and are multiplied by 10^3 . Rock-types are same as in Table 1.

Θ = Data from Jor46, Jor11, and Jor44 are from Luhr (1997); * “Primitive” rocks as inferred from the criteria proposed by Luhr (1997).

binary plot.

All chondrite-normalized REE patterns show enrichment of light-REE but relatively flat heavy-REE, and with no Eu anomaly (Fig. 5). For alkaline rocks (trachybasalt and basaltic trachyandesite) the $[\text{La}/\text{Yb}]_N$ (chondrite-normalized) ratios are similar (~5–14) except one sample (Jor46) that shows a light-REE highly-enriched pattern ($[\text{La}/\text{Yb}]_N \sim 50$). For subalkaline rocks this enrichment is generally somewhat lower ($[\text{La}/\text{Yb}]_N \sim 3$ –10).

Multi-element MORB-normalized patterns for alkaline and subalkaline rocks from the MGVF are compared with similar rocks from the CAVA in Figs. 6 and 7 respectively. Most rocks, except a few alkaline samples, show Nb depletion as compared to large ion lithophile elements (LILE) and REE. For comparison, is also included (Fig. 6a) a granite sample (LHG) outcropping in this area.

The average isotopic ratios of all MGVF rocks (Tables 4 and 5) show the following ranges: $^{87}\text{Sr}/^{86}\text{Sr}$

0.70320–0.70439, $^{143}\text{Nd}/^{144}\text{Nd}$ 0.51273–0.51298, $^{206}\text{Pb}/^{204}\text{Pb}$ 18.62–18.88, $^{207}\text{Pb}/^{204}\text{Pb}$ 15.57–15.62, and $^{208}\text{Pb}/^{204}\text{Pb}$ 38.32–38.66. For comparison, these ratios for the alkaline rocks range as follows: $^{87}\text{Sr}/^{86}\text{Sr}$ 0.70337–0.70439, $^{143}\text{Nd}/^{144}\text{Nd}$ 0.51273–0.51288, $^{206}\text{Pb}/^{204}\text{Pb}$ 18.64–18.88, $^{207}\text{Pb}/^{204}\text{Pb}$ 15.60–15.62, and $^{208}\text{Pb}/^{204}\text{Pb}$ 38.38–38.66. Similarly, the subalkaline rocks show the following ranges: $^{87}\text{Sr}/^{86}\text{Sr}$ 0.70320–0.70419, $^{143}\text{Nd}/^{144}\text{Nd}$ 0.51274–0.51298, $^{206}\text{Pb}/^{204}\text{Pb}$ 18.62–18.71, $^{207}\text{Pb}/^{204}\text{Pb}$ 15.57–15.61, and $^{208}\text{Pb}/^{204}\text{Pb}$ 38.32–38.51. There are some differences, although not highly significant, between the isotopic ratios for alkaline and subalkaline rocks. The alkaline rocks have slightly higher $^{87}\text{Sr}/^{86}\text{Sr}$, lower $^{143}\text{Nd}/^{144}\text{Nd}$, and higher Pb isotopic ratios as compared to the subalkaline rocks.

In order to understand possible involvement of the crust, Sr and Nd isotopic data are plotted against SiO₂ and Mg# (Fig. 8). However, a large dispersion is observed in all plots (Figs. 8a–d) making it difficult to infer any

Fig. 5. Chondrite-normalized REE plots for the MGVF rocks (BTA, TB, B, BA and A are the same as in Fig. 3). The chondrite REE data used for normalization are (in ppm): La = 0.329; Ce = 0.865; Pr = 0.112; Nd = 0.63; Sm = 0.203; Eu = 0.077; Gd = 0.276; Tb = 0.047; Dy = 0.343; Ho = 0.07; Er = 0.225; Tm = 0.03; Yb = 0.22; and Lu = 0.0339 (after Nakamura, 1974; Haskin et al., 1968). All rocks are identified by their SiO₂ concentrations (adjusted 100% anhydrous basis). (a) Alkaline rocks (trachybasalt and basaltic trachyandesite); (b) Subalkaline basic rocks (basalt); (c) Subalkaline intermediate rocks (basaltic andesite and andesite); (d) Subalkaline intermediate rocks (basaltic andesite and andesite) from Volcán Parícutín (data from McBirney et al., 1987). Note different y-axis scale for alkaline rocks.

petrogenetic information.

On a conventional Sr–Nd isotope diagram (Fig. 9) all MGVF data plot within the mantle array. Although there is a large spread for all rock types, the alkaline rocks tend to show somewhat higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ than the subalkaline rocks. Furthermore, for the differentiated rocks there seems to be a progressive shift of $^{87}\text{Sr}/^{86}\text{Sr}$ to higher values and $^{143}\text{Nd}/^{144}\text{Nd}$ to lower ones. There is also a slight tendency for the evolved rocks to lie away from the isotopic characteristics of the upper part of the subducting Cocos plate (Fig. 9). This could be taken as evidence in favor of at least some crustal involvement in the origin of the MGVF differentiated magmas and could as well explain Nb depletion observed in most of these evolved samples. It is interesting to note that, as expected from subduction relationships, the basic rocks (SiO₂ < 52%) as well as most of the intermediate and acid rocks (SiO₂ > 52%) from the CAVA fall in the field towards the isotopic characteristics of the subducting Cocos plate (Fig. 9). Some of these higher silica rocks from the CAVA also fall in the same general area covered by some MGVF rocks.

Sr, Nd and Pb isotope data from the MGVF as well as

CAVA are plotted in Fig. 10. The upper crustal component represented by granite LHG does not seem to lie in the correct direction to explain the isotopic composition of the MGVF rocks, i.e., LHG does not lie along the evolution of magmas from basic to intermediate and acid compositions although $^{208}\text{Pb}/^{204}\text{Pb}$ – $^{206}\text{Pb}/^{204}\text{Pb}$ diagram seems to be the only exception (Fig. 10d). Finally, other petrogenetically useful parameters for the MGVF and CAVA rocks (Fig. 11) show that the MGVF rocks occupy a distinct field than the CAVA rocks. The implications of these results are discussed below.

DISCUSSION

The most important geochemical characteristics of the MGVF magmas that must be explained by any model are: (i) Both alkaline and subalkaline magma types, closely related in space and time, erupted in the MGVF; (ii) A wide dispersion of trace element and isotopic ratios, especially for the alkaline rocks, on binary diagrams against differentiation indicators such as SiO₂, MgO or Mg#; (iii) Overlapping rare-earth element contents and patterns for different rock types but a wide variation for a given

Fig. 6. Multi-element MORB-normalized diagrams for alkaline rocks from the MGVF and comparison with similar rocks from the Central American Volcanic Arc (CAVA). The MORB values for normalization (in ppm) are from Sun and McDonough (1989): Cs = 0.0070; Rb = 0.56; Ba = 6.30; Th = 0.120; U = 0.047; K = 600; Nb = 2.33; La = 0.132; Ce = 7.50; Sr = 90; P = 510; Nd = 7.30; Hf = 2.05; Zr = 74; Sm = 2.63; Eu = 1.02; Ti = 7600; Gd = 3.68; Tb = 0.67; Dy = 4.55; Y = 28; Er = 2.97; Yb = 3.05; and Lu = 0.455. All rocks are identified by their SiO_2 concentrations (adjusted 100% anhydrous basis). (a) Trachybasalt samples from the MGVF, also included here is a granite sample LHG from the MGVF area; (b) Trachybasalt samples from the CAVA (samples names are given as reported in CAVA database; all three samples are from Volcán Yohoa, at about 350 km from the trench; see Fig. 1 for location); (c) Basaltic trachyandesite samples from the MGVF (note that, in the absence of photon activation analysis Nb data for Jor11, Ta-normalized value is plotted in place of Nb); (d) Basaltic trachyandesite from Volcán Yohoa.

rock-type; (iv) A wide variation of radiogenic isotopic ratios for all rock types; (v) All Sr and Nd isotopic ratios plotting well within the mantle-array and a slight shift of these ratios for evolved rocks, as compared to basic rocks, toward a crustal component but away from the subducting slab; (vi) The generally similar isotopic compositions of alkaline and subalkaline rocks being a strong argument in favor of a similar, probably veined-type mantle source; (vii) Widely varying incompatible element concentrations, including the high field strength elements (HFSE) such as Ti, Zr and Nb; and (viii) Significant differences of most geochemical and isotopic characteristics between the MGVF and CAVA rocks.

Several different models are evaluated using the available geochemical and isotopic data from the MGVF as well as compositions of altered Mid-Ocean Ridge Basalt (MORB) and sediments from IPOD-DSDP Site 487 located at the subducting Cocos plate corresponding to the central part of the MVB (Fig. 1; Verma, 2000a).

Origin of intermediate magmas from partial melting of the subducted slab

Some authors have argued that the slab can melt to generate arc magmas in subduction of young slabs (e.g., Defant *et al.*, 1991; Peacock *et al.*, 1994; Morris, 1995), or old slabs at plate edges (e.g., Yogodzinski *et al.*, 2001). When subduction occurs at a shallow angle, and the subducted lithosphere is young and hot, dehydration melting of the slab rather than the overlying mantle wedge can occur (Drummond and Defant, 1990). The actual position of the subducted Cocos plate beneath the MVB, including the MGVF, is poorly constrained due to the absence of deep earthquakes (below about 80 km). The plate becomes largely aseismic before reaching the volcanic front in this part of the MVB (e.g., Pardo and Suárez, 1995). However, the subducted Cocos plate is relatively young and can, therefore, melt, in principle, to generate andesitic and dacitic magmas of the MGVF. Such a slab melting would probably produce magmas (termed

Fig. 7. Multi-element MORB-normalized diagrams for subalkaline rocks from the MGVF and comparison with similar rocks from the Central American Volcanic Arc (CAVA). The MORB values for normalization are the same as in Fig. 6. All rocks are identified by their SiO_2 concentrations (adjusted 100% anhydrous basis); n is the total number of samples used for computing average values plotted here. (a) Basalt samples from the MGVF; (b) Basalt samples from the CAVA (N-CAVA is the northern part of this province; for location of Volcán Telica see Fig. 1; CAVA-Barc is the back-arc area of this province); (c) Basaltic andesite samples from the MGVF; (d) Basaltic andesite samples from the CAVA; (e) Andesite samples from the MGVF, including Volcán Parícutín (for samples W-47-9 and FP-5-49, Ta-normalized values are plotted in the place of Nb); (f) Andesite samples from the CAVA.

Fig. 8. Binary plots for the MGVF rocks. Symbols used are the same as in Fig. 3. La Huacana granite sample (LHG) from the MGVF is also plotted (Luhr and Carmichael, 1985; Luhr, 1997) to show the probable upper crustal composition in this area. Although additional published $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are available for Volcán Parícutín (McBirney et al., 1987), they are not plotted here because they are characterized by relatively large errors. (a) SiO_2 – $^{87}\text{Sr}/^{86}\text{Sr}$; (b) SiO_2 – $^{143}\text{Nd}/^{144}\text{Nd}$; (c) $\text{Mg\#}$ – $^{87}\text{Sr}/^{86}\text{Sr}$; (d) $\text{Mg\#}$ – $^{143}\text{Nd}/^{144}\text{Nd}$.

Fig. 9. $^{87}\text{Sr}/^{86}\text{Sr}$ – $^{143}\text{Nd}/^{144}\text{Nd}$ plot for the MGVF rocks. The symbols used are the same as in Fig. 3. Approximate trace of “mantle-array” is shown for reference using dashed lines. The mixing curve identified by 2, 5, 10, and 20% and “subducting slab” represents a physical mixture of Site 487 altered MORB + sediment, where the numbers refer to the % of the sediment component in this mixture (Verma, 1999, 2000a). For comparison are included all samples from the CAVA compiled in the database; small crosses are used for basic rocks ($\text{SiO}_2 < 52\%$) whereas stars are for intermediate and acid rocks ($\text{SiO}_2 > 52\%$). La Huacana granite sample (LHG) from the MGVF is plotted schematically (Luhr, 1997) to show the probable upper crustal composition in this area.

Fig. 10. Isotope–isotope diagrams for the MGVF rocks. Also included for comparison are the data for similar samples from the CAVA, using the same symbols as in Fig. 9. La Huacana granite sample (LHG) from the MGVF is also plotted (Luhr, 1997) to show the probable upper crustal composition in this area. The arrow in all plots show schematically possible crustal assimilation trend for the isotopic data from the MGVF. (a) $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{87}\text{Sr}/^{86}\text{Sr}$; (b) $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{143}\text{Nd}/^{144}\text{Nd}$; (c) $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$; (d) $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{208}\text{Pb}/^{204}\text{Pb}$.

adakites) with steep rare earth element pattern (high La/Yb ratio) with low Y, yet high Sr and lack of a negative Eu anomaly (Defant and Drummond, 1990). This term (adakite) was recently defined by Yogodzinski *et al.* (2001) to describe “calc-alkaline andesites and dacites that are relatively Mg-rich (low $\text{FeO}^{\text{T}}/\text{MgO}$, high Mg#) and also have anomalously high Sr/Y (>50) compared to ‘normal’ arc volcanic rocks”. All andesite and dacite samples studied from the MGVF (Table 3) have low Sr/Y (17–40) except one sample H-437T with Sr/Y ~ 87. Their La/Yb ratio is also lower than that expected for adakitic rocks. This particular andesite, H-437T, is the only one that has hornblende but no pyroxenes. Fractional crystallization of hornblende as part of the evolutionary process to generate this andesite magma from a basaltic magma may explain its higher Sr/Y ratio, because in hornblende Y is much more compatible than Sr (Torres-Alvarado *et al.*, 2003). Unfortunately, no REE data are available on this sample, which makes it difficult to corroborate further any particular petrogenetic model. Nevertheless, all samples, including H-437T, show isotopic compositions different from the subducting slab; in Fig. 9 they plot far away from the basalt-sediment mixing curve. One may

argue that the composition of the upper part of the subducting slab available for only a few locations in this area (Fig. 1; see also Verma, 2000a), may not be representative of the entire subduction zone of the Cocos plate corresponding to the MGVF. This may be true, but, at present, data for the upper part of the slab are the only available information, which is not consistent with the hypothesis of slab melting. We, therefore, conclude from geochemical and isotopic data that magmas representing slab melts are not observed in the MGVF.

Origin of basic magmas from the underlying mantle with/without the participation of subducted slab

Basic magmas (trachybasalt, basalt, or low-silica basaltic trachyandesite or basaltic andesite) can originate from partial melting of the underlying mantle. The simplest way proposed for this mantle melting to occur is to incorporate fluids released from the slab into the mantle, thus reducing its melting point and facilitating its partial melting, or else the slab melts can add to the mantle and cause its partial melting (e.g., Tatsumi *et al.*, 1986; Peacock, 1990; Hawkesworth *et al.*, 1991; Rollinson, 1993).

Fig. 11. Binary plots for the MGVF rocks. La/Yb – Ba/Zr plot for the MGVF rocks. The symbols used are the same as in Fig. 3. Also included for comparison are the data for similar samples from the CAVA, using the same symbols as in Fig. 9. (a) Ba/Zr – Ba/La ; (b) La/Yb – Sr/Ce ; (c) SiO_2 – B/Be ; (d) $\text{Ti}/1000$ – V .

Twelve samples of “primitive” rocks (high $\text{MgO} > 6$ wt %; $\text{Mg\#} > 62$) as defined by Luhr (1997) were analyzed in this study (Table 2; Fig. 4a). These include: 1 trachybasalt (sample H-542), 2 basaltic trachyandesite (Jor46 and H-520), 3 subalkali basalt (H-417A, H-408A, and H-426B), and probably 6 basaltic andesite (H-536L, H-517A, Jor44, H-550, H-736 and H-416A). These rocks may represent direct partial melts of the underlying mantle.

The average isotopic ratios of the “primitive” alkaline rocks (Tables 4 and 5) show the following ranges: $^{87}\text{Sr}/^{86}\text{Sr}$ 0.70418–0.70434, $^{143}\text{Nd}/^{144}\text{Nd}$ 0.51273–0.51278, $^{206}\text{Pb}/^{204}\text{Pb} \sim 18.70$, $^{207}\text{Pb}/^{204}\text{Pb} \sim 15.60$, and $^{208}\text{Pb}/^{204}\text{Pb} \sim 38.52$. The average isotopic ratios of the “primitive” subalkaline rocks are as follows: $^{87}\text{Sr}/^{86}\text{Sr}$ 0.70320–0.70404, $^{143}\text{Nd}/^{144}\text{Nd}$ 0.51283–0.51298, $^{206}\text{Pb}/^{204}\text{Pb} \sim 18.64$, $^{207}\text{Pb}/^{204}\text{Pb} \sim 15.57$, and $^{208}\text{Pb}/^{204}\text{Pb} \sim 38.35$. Although the differences between the isotopic compositions of primitive alkaline and subalkaline rocks are small, the former seem to be derived from a source that has higher Sr and Pb isotopic ratios but lower Nd isotopic ratios. A veined-mantle source with such isotopic characteristics as the primitive rocks could be easily hypothesized for the MGVF (e.g., Menzies and Murthy, 1980; Tiepolo *et al.*, 2000; Sheth *et al.*, 2000).

Arguments in favor of the involvement of slab-derived

fluids seem to be LILE-enrichment, especially Ba, and HFSE-depletion, especially Nb, observed in most of these samples. However, other HFSE and key trace elements such as B and Be, and isotopic data do not support this conclusion (Fig. 11; Table 3). In most binary plots, the MGVF data lie at the low end of subduction-input parameters, and are similar to the data for magmas from well-known rifts; this contrasts with the data for subduction-related Central American Volcanic Arc (CAVA) rocks that clearly show high values of subduction input.

For northeast Japan arc, Sano *et al.* (2001) argued that boron and other trace element data are consistent with a 90:10 proportion of altered oceanic crust and trench sediments in the fluids released in the mantle wedge. If this were the case in the MGVF, the Sr and Nd isotopic data for these rocks, particularly the basic rocks, should be shifted toward the subducting slab (Fig. 9) which is clearly not observed; instead, the MGVF samples lie well within the mantle array.

Harry and Green (1999) have argued that, in subduction systems involving very young oceanic lithosphere (≤ 20 Ma), early release of fluids may take place at shallow depths close to the trench in the fore-arc region, inhibiting fluid or melt metasomatism of the mantle beneath the arc itself. This might be the case for the MGVF (Fig. 11). Such an early fluid-release process would probably

render a subdued fluid signal in the corresponding arc as was hypothesized by Harry and Green (1999) for Costa Rica. However, as suggested by Verma (2002) this should result in clear differences between the front and the back arc regions, i.e., a still more subdued or nearly absent subduction fluid signal in the back arc area as compared to the weak signal in the front arc. This is not actually observed in the MGVF for any of the subduction signal variables such as Ba/Nb, Ba/Zr, Ba/La, $\epsilon_{\text{Nd}}/\epsilon_{\text{Sr}}$, etc. (3D plots not shown). Therefore, we conclude that the Cocos plate is not really contributing, in any significant way, to magma genesis in the MGVF. Further arguments against the subduction scenario include the lack of trend in Sr and Nd isotopic data towards the subducting plate (Fig. 9) and the distinct fields occupied by the MGVF rocks from the CAVA subduction-related samples (Fig. 11).

Alternatively and even more likely, the continental lithosphere might be the source for magmas in the MGVF because the data are consistent with such a hypothesis (Fig. 11). Such a source is likely to have a negative Nb anomaly (e.g., Saunders *et al.*, 1992; Kent, 1995), which would be inherited to the resulting basic magmas.

Simple differentiation of basic magmas

The alkaline rocks do not show any simple relationships on binary element–element or isotopic ratio–element diagrams (Figs. 3, 4 and 8). There is also a large spread on isotope–isotope diagrams (Figs. 9 and 10). For subalkaline rocks, a large spread is observed for isotopic data and in some of the element–element plots (e.g., Figs. 8 and 9). Their REE contents do not change systematically with their SiO₂ contents (Fig. 5); a systematic change is expected for lavas related through a fractional crystallization mechanism of common minerals. Heterogeneous nature of the basic magmas, however, makes it difficult to evaluate such a model. Nevertheless, because the intermediate and acid rocks show, on the average, slightly higher $^{87}\text{Sr}/^{86}\text{Sr}$ and Pb-isotopic ratios and somewhat lower $^{143}\text{Nd}/^{144}\text{Nd}$, a simple differentiation mechanism, such as fractional crystallization, for the evolution of basic magmas seems less likely.

Crustal assimilation of basic magmas

Because of the large spread in isotopic ratios observed for all magma types and only a limited information available on the underlying crust (see Sr, Nd and Pb isotopic data for granite LHG; Figs. 9 and 10), the role of crust in the evolution of basic magmas cannot be quantitatively evaluated. From combined Sr–Nd isotopic data (Fig. 9), it appears that LHG has a little too high $^{143}\text{Nd}/^{144}\text{Nd}$ to explain the isotopic variation of the MGVF rocks. Similarly, on other isotope–isotope plots (Fig. 10), this assimilant can probably explain the combined $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ only (Fig. 10d), but not the other isotopic

ratios, for example, see the deviation of the MGVF data from the mixing trend on Figs. 10b and 10c. On the other hand, in terms of trace elements such an assimilant (LHG in Fig. 6a) could contribute to the negative Nb anomaly observed in most evolved magmas from the MGVF.

Veined mantle source

From a study of the Sierra de Chichinautzin volcanic field (SCN in Fig. 1), Wallace and Carmichael (1999) proposed a model for the MVB, according to which slab-induced convection in the mantle wedge beneath the MVB causes advection of asthenospheric mantle from behind the arc to the region of magma generation. Some of the problems with this model are: (i) it requires the involvement of the subducting Cocos plate in the genesis of subalkaline magmas, which is not supported from the MGVF data presented here, nor from other studies in the SCN (e.g., Verma, 1999, 2000a; Velasco-Tapia and Verma, 2001a, b; Torres-Alvarado and Verma, 2003); (ii) it supposes the existence of a well-defined mantle wedge according to the extrapolations by Pardo and Suárez (1995), which are shown to be arbitrary (Verma, 2001b, 2002); (iii) it cannot explain extremely low Be concentrations for alkaline and subalkaline magmas (Rodríguez-Lara, 1997), nor can it account for negligible ^{10}Be contents (within the analytical error and the limit of detection) of a sample of subalkaline basalt (Tera *et al.*, 1986); (iv) it predicts certain isotopic differences between alkaline (originating from partial melting of an upwelling asthenospheric mantle) and sub-alkaline (originating from subduction-fluid induced melting of the mantle wedge) magmas that are not observed in any area from west-central to eastern MVB (this study on the MGVF; for other areas of the MVB, see Verma, 1999, 2000a, 2000b, 2001a, 2001b, 2001c, 2002, 2003). We, therefore, conclude that a distinct model is required to explain the geochemical and isotopic characteristics of the MGVF magmas.

Sheth *et al.* (2000) argued for a veined mantle source for magmas throughout the MVB. Their veined mantle was envisaged as the one having enriched, metasomatic veins on the scale of kilometers. According to Sheth *et al.* (2000), the source of metasomatic fluids may be related to location of the MVB along an ancient suture or fault structure (De Cserna, 1960) and, following Bailey (1983), to a “passive” triggering of mantle metasomatism by the formation of the lesion in the overlying plate (the proto-MVB). The development of a shallow, metasomatized, LILE, HFSE and REE-enriched, veined mantle below the MVB was made possible, due to volatiles in a large region of the underlying mantle reservoir being drained through this narrow crack. The normal, unveined or poorly-veined peridotite would produce subalkaline magmas by melting and probably by subsequent crustal assimilation, and veined peridotite (prob-

ably amphibole and/or phlogopite rich veins) on melting would generate alkaline magmas. Different degrees of partial melting of such a heterogeneous mantle source could explain the origin of most basic magmas from the MGVF. The alkaline magmas should probably undergo somewhat less crustal contamination because of their arguably faster rise through the crust as compared to the subalkaline magmas. Such a model could explain all geochemical and isotopic characteristics of the MGVF magmas. Further research on the probable mantle source characteristics must await more precise and accurate geochemical data for a larger number of samples of MGVF primitive magmas.

In this way, the origin of magmas in the MGVF might be related more to ongoing rifting processes rather than the subduction of the Cocos plate. Such a rifting model has, in fact, been recently proposed by Márquez *et al.* (2001). More recently, Verma (2002) has shown that, as opposed to the CAVA, no slab input seems to be present in basic magmas throughout southern Mexico. Furthermore, he has proposed a rift-upwelling heterogeneous mantle model to explain the trace element and isotopic characteristics of these magmas. The present MGVF data are consistent with these conclusions.

CONCLUSIONS

On the basis of new geochemical and isotopic data for a variety of rocks from the MGVF and published data from the upper part of the subducting Cocos plate and upper crust, the origin of these magmas can be visualized in terms of a heterogeneous mantle source, likely a veined mantle. The contribution from the subducted slab seems to be minimal or even absent as judged from the geochemical and isotopic data for the MGVF magmas and those for the subducting Cocos plate. Finally, the underlying crust may have contributed to the genesis of evolved magmas from the MGVF.

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