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The Zitácuaro Volcanic Complex, Michoacán, Mexico: magmatic and eruptive history of a resurgent caldera

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RESUMEN

El Complejo Volcánico de Zitácuaro descansa sobre un basamento mesozoico constituido por rocas metamórficas (Jurásico Tardío-Cretácico Temprano), rocas volcánicas, calizas y capas rojas del Cretácico. La actividad volcánica propia del Cinturón Volcánico Mexicano comenzó en esta zona durante el Mioceno Temprano con la formación de un estratovolcán (30x15 km) constituido por rocas andesíticas calcialcalinas. Para el Mioceno Medio (12 Ma), un cambio importante en la actividad volcánica del edificio provocó la formación de una caldera denominada "Las Tres Chicas", la cual tiene un diámetro de 30 km aproximadamente. La actividad post-caldérica consistió de tres eventos eruptivos de resurgencia dómica que ocurrieron hace 12 Ma, 5 Ma y 0.5 Ma respectivamente. Cada evento estuvo caracterizado por la intrusión de domos dacíticos y la generación de flujos piroclásticos que se emplazaron en el interior del recinto caldérico, y por la emisión de flujos de lavas pericaldéricos. La periodicidad de la actividad volcánica, la presencia de domos relativamente jóvenes (e.g. Cacique) y la actividad sísmica registrada en la zona, son evidencias que sugieren que el Complejo Volcánico de Zitácuaro debe ser considerado como un área potencialmente activa.

PALABRAS CLAVE: Cinturón volcánico mexicano, caldera, resurgencia dómica.

ABSTRACT

The Zitácuaro Volcanic Complex (ZVC) rises on a basement of metamorphic rocks of Late Jurassic-Early Cretaceous age, and volcanic rocks, limestones, and red beds of Cretaceous age. Volcanic activity related to the Trans-Mexican Volcanic Belt started during Early Miocene with the eruption of calc-alkaline andesites that formed a primitive stratovolcano covering an area about 30 km x 15 km. A major change in eruptive style occurred during Middle Miocene, when a caldera structure formed, "Las Tres Chicas Caldera", approximately 30 km in diameter and dated about 12 Ma. Post-caldera activity consisted of three eruptive episodes of intra-caldera dome resurgence around 12 Ma, 5 Ma, and 0.5 Ma. Each episode featured the intrusion of dacitic central domes, the generation of pyroclastic flows and peri-caldera andesitic lava flows. The activity at the ZVC features recurrent volcanic episodes, the most recent one with emplacement of young resurgent domes such as Cacique. Local seismic activity in the area felt at Zitácuaro, is persistent. The ZVC should be considered as a potentially active volcanic zone.

KEY WORDS: Trans-Mexican volcanic belt, caldera, resurgent domes.

INTRODUCTION

The Zitácuaro Volcanic Complex (ZVC), located in the Trans-Mexican Volcanic Belt (TMVB), covers about 700 km^2 from Heroica de Zitácuaro, Michoacán, to Donato Guerra in the State of Mexico (Figure 1). The ZVC has not been systematically studied during this century, but a few geological studies were carried out during the last two decades. Previous studies (Demant, 1978; Silva-Mora, 1979) mention the Zitácuaro region as the type locality for the metamorphic Jurassic basement, but no reference to the volcanic rocks is made. Recently, the ZVC was mapped and identified for the first time as a dacitic dome complex (Pasquaré *et al.*, 1991); but the volcanic stratigraphy was not described. Demant (1978) described a fallout deposit in the Palizada region, NW of Zitácuaro, but identified it erroneously as a product of Nevado de Toluca Volcano (Lower Toluca Pumice).

Detailed geological reconnaissance of the ZVC was carried out by Garduño *et al.* (1993b), Capra *et al.* (1994), Capra (1994), Lafranconi (1994), and Lastella (1994). They produced a composite geological map (scale 1:25,000), based on the enlarged INEGI 1:50,000 topographic sheets. These studies recognize that the distribution of the volcanic products and collapse features are related to a caldera-like structure.

In this paper we present new geological data and we re-evaluate previous results on the volcanological evolution of this complex. We describe the tectonic setting of the ZVC in the geological context of the TMVB and its eruptive history based upon detailed stratigraphic data, chemical and petrographic analyses of selected rocks, and radiocarbon data.

REGIONAL TECTONIC SETTING

The ZVC is located in the central sector of the TMVB (Pasquaré *et al.*, 1987). It features three tectonic structures (Figure 2a) marked by lineaments of volcanic edifices and explosion craters. (1) The eastern area is dominated by a NNW-SSE fracture system corresponding to the San Miguel de Allende-Taxco normal fault system (Demant, 1978), or to the Querétaro fracture zone (Nixon *et al.*, 1987; Garduño and Gutiérrez, 1992). This system shows evidence of a Miocene transcurrent component and a reactivation during the Pliocene. (2) The southwestern area in–

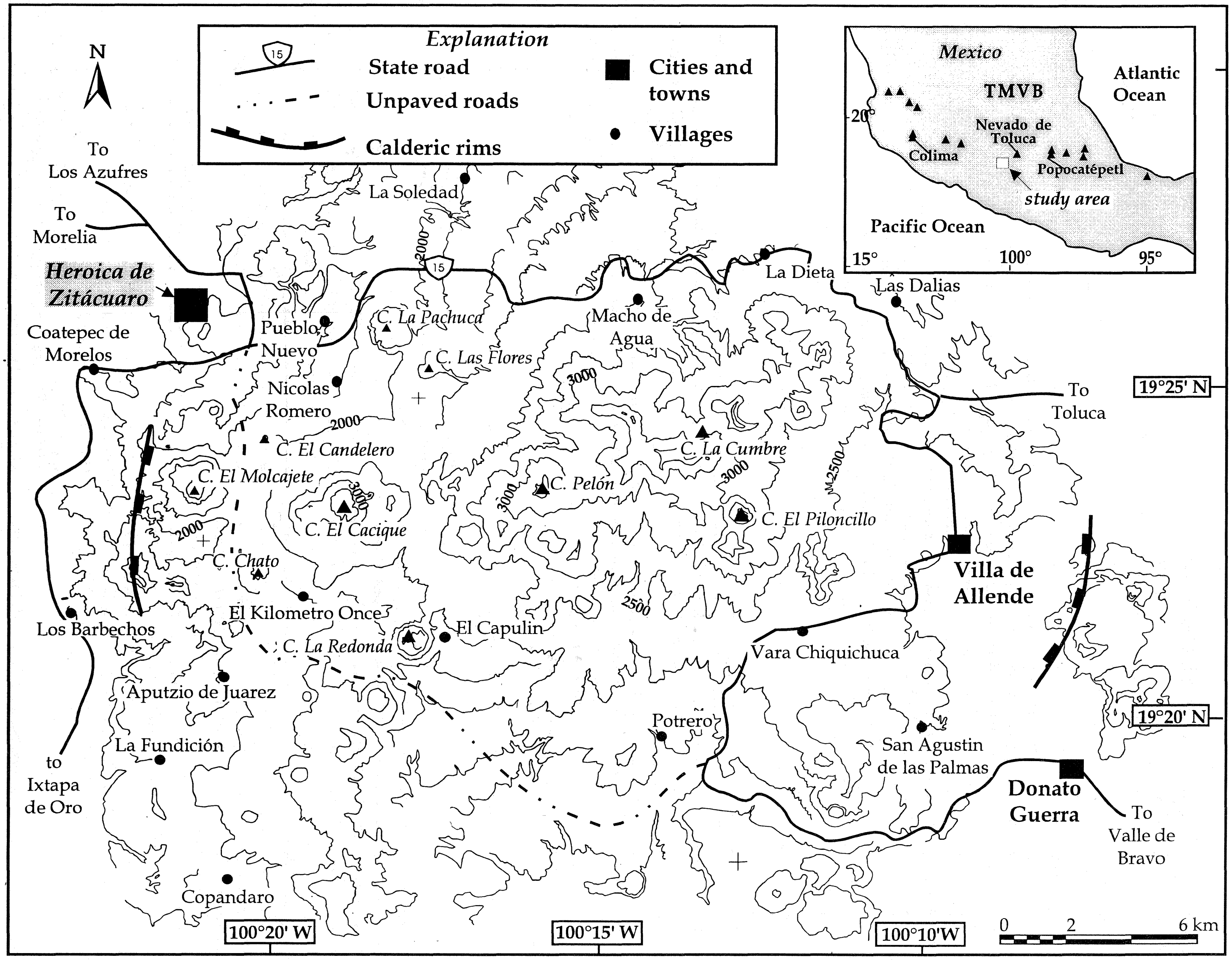

Fig. 1. Location map of the Zitácuaro Volcanic Complex (ZVC). Small inset shows the location of the study area within the TMVB. The two indented lines show the locations of the caldera remnants.

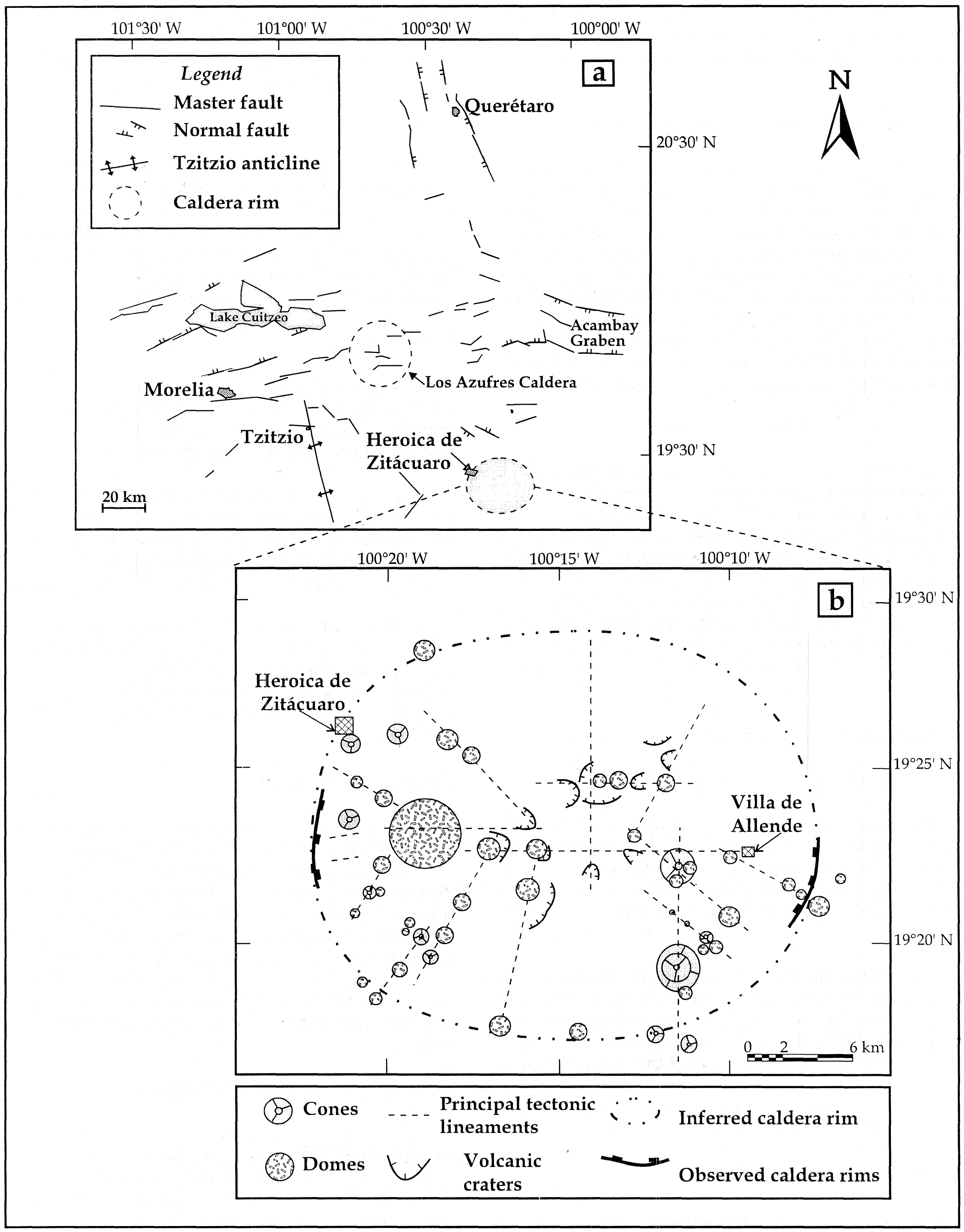

Fig. 2. (a) Regional tectonic map showing the grabens of Querétaro and Acambay, the Tzitzio anticline, Los Azufres caldera, and the study area (after Ferrari *et al.*, 1991). (b) Tectonic map of the ZVC showing radial lineaments related to the caldera structure. The N-S and E-W lineaments are related to regional tectonic structures.

cludes the Tertiary Tzizio antiform system (Mauvois 1977; Bonassi, 1994; Mennella, 1994; Ferrari *et al.*, 1990); (3) The northern area accommodates an E-W fault system related to the Acambay graben of Pleistocene age (Suter *et al.*, 1992).

MORPHOTECTONIC ANALYSIS

The ZVC contains a large central volcanic complex characterized by several craters with internal domes (Figure 3). The central complex is surrounded by a plain of pyroclastic flows outlined in the distal areas by volcanic cones or by morphological barriers. Other dome structures developed along radial or concentric lineaments (Figure 2b). Two remnants of crater rims forming vertical walls are located east and west of the dome complex (Figure 3). A circular "caldera-like" structure is suggested by connecting these rims with the alignment of volcanic cones and the limits of the pyroclastic flow deposits (Figures 2b and 3).

STRATIGRAPHY

The composite stratigraphic column of the ZVC is shown in Figure 4. Lithostratigraphic units are named after field descriptions, petrography, and chemical characteristics. Figures 5 and 6 show a simplified geological map of the ZVC and some selected stratigraphic columns. Modal analyses of selected samples are presented in the following. The percentage values between brackets (vol.%) represent the average modal value of phenocryst phases. The abreviations are as follows: plagioclase (pl), clinopyroxene (cpx), biotite (bt), hornblende (hbl), olivine (ol) and quartz (qz).

Mesozoic-Tertiary basement

Upper Jurassic-Lower Cretaceous

The metamorphic basement is composed of low-grade mica schist and calcschist that range in age from Late Jurassic to Early Cretaceous (Israde and Martínez, 1986). This is only exposed in the NNW portion of the area and forms an uplifted block probably associated to NW-SE lineaments.

The Lindavista unit overlies discontinuously the metamorphic basement in the western sector of the area. It is composed of andesitic pillow lavas and andesitic lava flows interbedded with volcanoclastic breccias. According to Pasquaré *et al.* (1991), the Lindavista unit has an age of Late Jurassic-Early Cretaceous because it is intruded in the southwestern region by a dioritic body (*Los Barbechos unit*) dated at 99 Ma (CFE, 1986).

Middle-Upper Cretaceous

Las Pilas unit consists of bioclastic fossiliferous-reef limestones. The fossil assemblage has a Tethyan affinity of Albian-Aptian age (Israde and Martínez, 1986). This unit is overlain unconformably by the *Capas Rojas Formation*, molasses of Eocene-Oligocene age (Islas *et al.*, 1989). Red conglomerates contain decimeter-size clasts of quartz, limestone, andesite, diorite and metamorphic rocks in sandstone matrix. This formation is described for the first time; previous studies had detected this unit only in the Tuzantla area southwest of the ZVC (Islas *et al.*, 1989).

Miocene

The Sierra de Angangueo unit, consisting of basaltic-andesite lava flows and volcaniclastic breccias of Miocene age, is located in a narrow strip in the northern part of the ZVC (Pasquaré *et al.*, 1991). This unit represents the marginal part of the Sierra de Angangueo Volcanic Complex located to the north of the ZVC. It has no direct stratigraphic relation to the volcanic units of the ZVC.

Upper Miocene

The following units represent the earliest volcanic activity in the ZVC that may be attributed to the TMVB domain (Pasquarè *et al.*, 1991). Actual volcanic vents are not recognizable, but their products are evident.

The Coatepec de Morelos unit to the west and the *Cerro Los Muñecos unit* to the east of the studied area feature andesitic lava flows with abundant clinopyroxene phenocrysts (cpx 8-16%). A sample from the *Coatepec de Morelos unit* yielded a K-Ar age of 12 Ma (CFE, 1986).

El Lindero unit represents pyroclastic products of the same volcanic complex. It is composed of well-lithified block-and-ash flow deposits containing andesitic fragments with abundant clinopyroxene and hornblende phenocrysts (cpx 20%, hbl 10%), pumice and cm-sized scoria in a sandy matrix.

Pliocene-Quaternary

During the Pliocene-Quaternary, monogenetic cones formed in the west and east sectors of the study area and some dome intruded in its central part. This type of activity was repeated during three distinct episodes, each causing dome resurgence in the central part of the area (*Barranca el Agur, San Jerónimo, and Guacamaya units*). Around the margins, we find andesitic lava flows (*Pueblo Nuevo, Cerro Gordo, Los Venados, La Asunción, and La Fundición units*). All these units were grouped in three eruptive episodes according to their stratigraphic position as follows.

First episode of dome resurgence

The Santiago unit consists of thick (decameter scale) andesitic lava flows with abundant olivine (ol 4.5%). The *Santa Cruz unit* consists of augite-bearing andesite lava flows (cpx 12%). *Barranca el Agur unit* is composed of dacitic dome intrusions forming volcanic edifices about 3000-m high and andesitic lava flows whose vents are not recognizable. Younger pyroclastic flow deposits (*Kilometro Once unit*) are associated with the *Barranca el Agur unit*. The rocks from the central domes contain plagioclase,

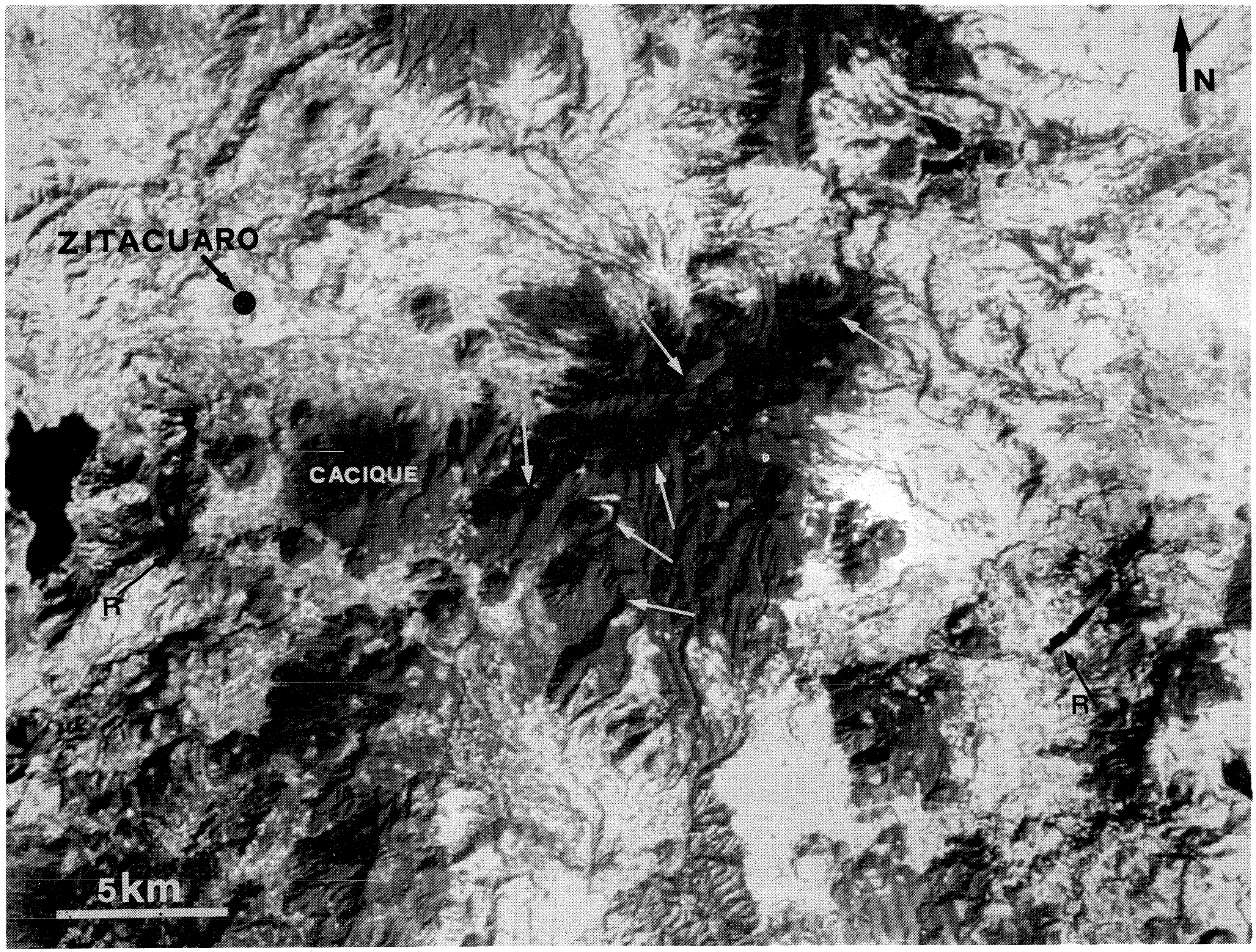

Fig. 3. Landsat image of the ZVC. R, the caldera rim remnants. The white arrows indicate the explosion craters of the main resurgent domes.

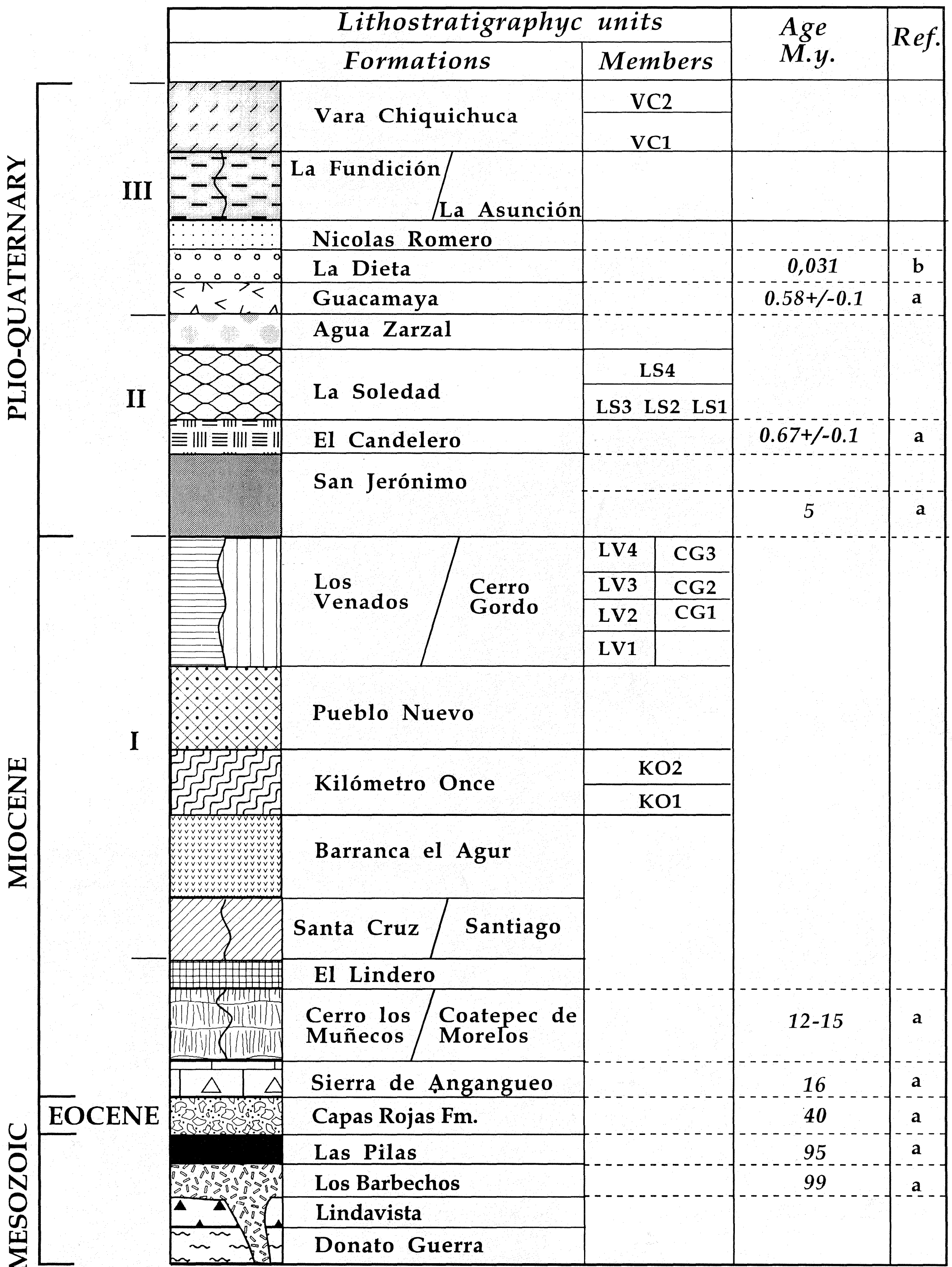

Fig. 4. Stratigraphy of the ZVC as shown in Figure 5. References: (a) CFE, 1986, and (b) this work.

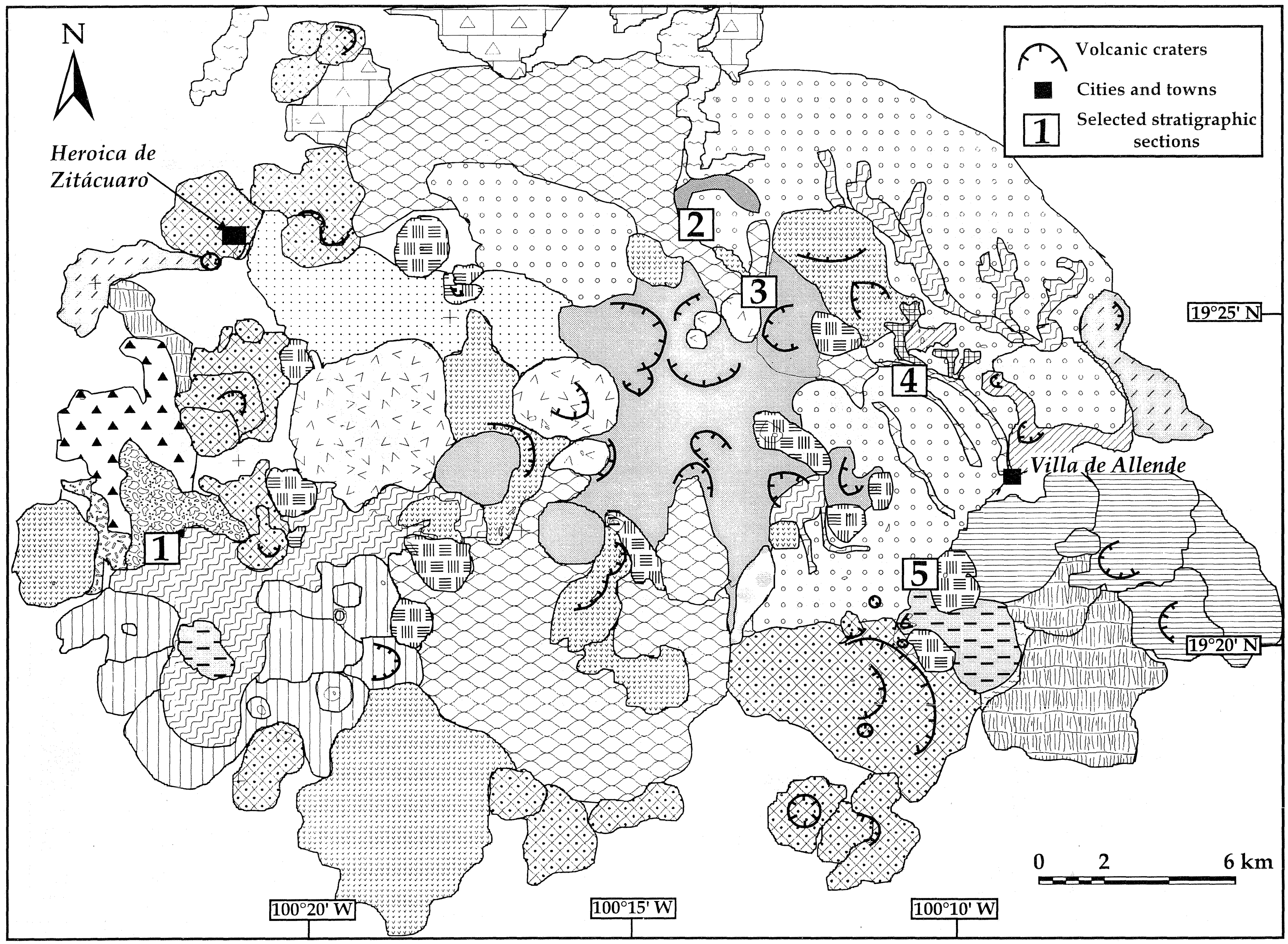

Fig. 5. Simplified geological map of the ZVC; the numbers refer to stratigraphic columns shown in Figure 6.

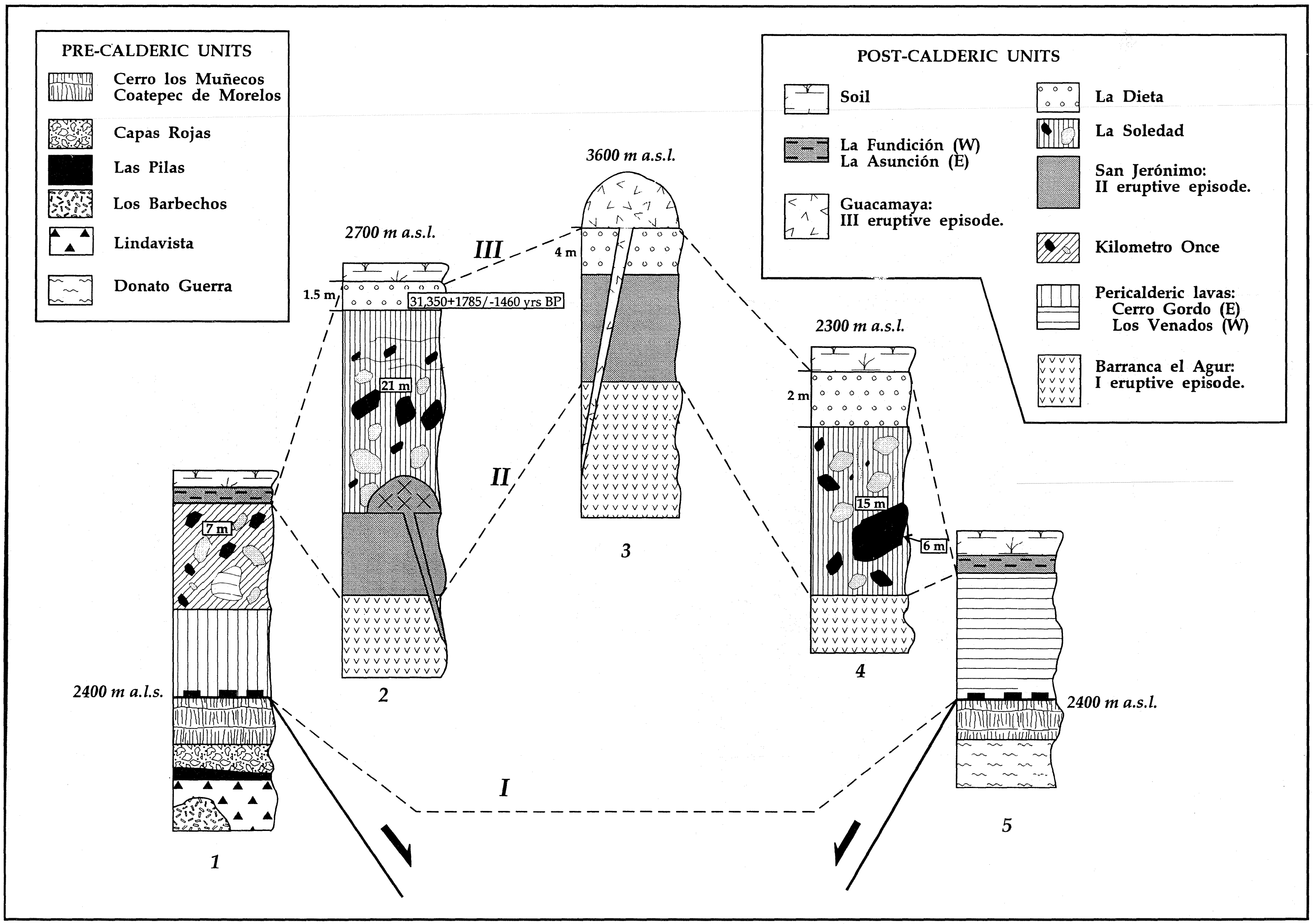

Fig. 6. Composite stratigraphic sections of the ZVC.

clinopyroxene, hornblende and biotite (pl 20%, cpx 4%, hbl 8%, bt 2%).

Las Dalias flow deposit (KO1 member) ranges in thickness from 10 to 100 cm; scarce outcrops of this unit did not allow estimation of its areal extent and volume. Las Dalias comprises two flow units: a block-and-ash flow deposit covered by an ash flow deposit.

Kilometro Once flow deposit (KO2 member) has a mean thickness of 10 m and covers an area of about 30 km^2, yielding a minimum estimated volume of 0.12 km^3 (DRE=Dense Rock Equivalent). It is a massive block-and-ash flow deposit, which contains amphibole-rich (hbl 12%) dacitic, juvenile clasts with various degrees of vesiculation and rare clasts from the metamorphic basement set in a sandy matrix. Clasts range in size from 2 cm to 1.5 m.

In the western sector of the area, two more units were identified: *Pueblo Nuevo and Cerro Gordo units*. The first is constituted mainly by volcanic cones reaching altitudes of 2700 m (Curungueo, Pueblo Nuevo, Belvedere, El Naranjo, Molcajete, Comunidad, San Lucas). Lithologically, it is composed of andesitic lava flows and two block-and-ash flow deposits with dacitic juvenile lithics.

Cerro Gordo unit consists of domes and volcanic edifices that reach up to 2800-m altitude, with their associated andesitic lava flows (cpx 32%, pl 8%). These lava flows can be subdivided into three members according to their stratigraphic position (CG1, CG2, CG3).

In the eastern sector, we identify the *Los Venados unit*, which is characterized by volcanic structures up to 2800-m high composed of andesitic lava flows containing abundant clinopyroxene and olivine (cpx 28%, ol 8%). Based on the location of the vent and their stratigraphic position, these lava flows can be subdivided into four members (LV1, LV2, LV3, LV4).

Second episode of dome resurgence

The San Jerónimo unit is located near the central part of the area; it consists of andesitic lava flows and dacitic dome intrusions, some up to 3500-m high. Crater rim scars are still recognizable on these domes (Figure 2). They are probably related to explosive activity that produced significant pyroclastic flow deposits (*La Soledad unit*). The San Jerónimo products have a paragenesis characterized by plagioclase, quartz, hornblende and biotite (pl 21%, qz 0.7%, hbl 7.5%, bt 0.9%). A K-Ar date of this unit yielded an age of 5 Ma (CFE, 1986).

Cerro las Palomas unit, which is exposed in the central part of the area, consists of andesitic lava flows (meters thick) with abundant clinopyroxene phenocrysts (cpx 16%).

Eleven endogenic dacitic dome structures as high as 300 m form the *El Candelero unit* (e.g., Las Flores, Candelero, Pachuca, Rededonda, Piloncillo, Chato, Chilesdo, Silla). Minor radial lava flows flank these domes.

La Soledad unit is subdivided into four members, each one representing a pyroclastic flow deposit. *Las Palomas* flow (LS1 member) consists of a massive block-and-ash flow deposit (20 m thick) rich in dacitic juvenile clasts 10 cm to 6 m in size. It covers an area of about 40 km^2. Due to the scarcity of sections it was not possible to make a volume estimation.

La Soledad flow (LS2 member) is composed of three deposits: a pumice flow covered by a block-and-ash flow and an ash flow interbedded with surges at the base. La Soledad flow deposits have a mean thickness of about 22 m; they contain dacitic juvenile clasts in a sandy matrix. This unit extends over an area of about 63 km^2 with an estimated volume of 0.4 km^3 (DRE=0.3 km^3).

El Capulin flow (LS3 member) is a block-and-ash flow deposit (mean thickness 15 m) rich in juvenile dacitic clasts. At some outcrops, it can be subdivided into four distinct units. El Capulin flow covers an area of 56 km^2 with a minimum volume of 0.3 km^3 (DRE=0.2 km^3).

El Potrero flow (LS4 member) is composed of a basal block-and-ash flow and an ash flow deposit. All these deposits have similar phenocryst assemblages: qz (1%), pl (30%), cpx (1%) hbl (15%) bt (5%) in a glassy matrix with plagioclase microphenocrysts. This unit extends for about 15 km^2; however, due to poor outcrops, it was not possible to estimate a volume.

The Agua Zarzal unit is characterized by a chaotic epiclastic deposit (2 m thick) rich in rounded quartz, metamorphic and volcanic clasts embedded in a sandy matrix.

La Dieta unit is represented by a fall deposit consisting of two main parts separated by a sequence of lapilli-sized horizons. The lower part is clast-supported, inversely graded, pumice-rich (94%), frequently banded with maximum diameters of 7 cm and minor clasts (6%). The upper part is massive, clast-supported, constituted by 98% in pumice and scoria fragments with maximum diameters of 15 cm and 2% of cm-size lithics. Two charcoal samples from this unit yielded radiocarbon ages of 31,350 + 1785/ -1460 yr. B.P. and 30,630 +/- 520 yr. B.P.

Third episode of dome resurgence

The *Guacamaya unit* represents the last episode of dome resurgence. It consists of monogenetic dacitic domes, one of which gave a radiometric age of 0.6 Ma (CFE, 1986). The polygenetic dome of Cerro Cacique reaches up to 3300m; it is composed of five dome intrusions with associated autobrecciated lava flows. Petrographically, it is characterized by an enrichment of hornblende crystals (hbl 18%) as compared to the other domes. The Cerro Pelón dome is the only one that produced a pyroclastic flow, here called *Nicolas Romero unit*, which extends for about 23 km^2. This deposit can be subdivided into four flow units consisting of dacitic juvenile clasts with a similar paragenesis to that of the *La Soledad unit* but with more quartz phenocrysts (15%).

Marginal effusive activity in the eastern and western parts of the study area is represented by the *Asunción* and *La Fundición units* respectively. *La Asunción unit* forms a cone structure with andesitic lava flows while *La Fundición unit* includes an andesitic lava flow followed by a dome intrusion. Products of these two units feature an enrichment of augitic clinopyroxene phenocrysts (cpx 12%).

The youngest volcanic deposits in the ZVC are pyroclastic flow deposits (*Vara Chiquichuca unit*) represented by two members: VC1, San Francisco crater, and VC2, Hoya de Zitácuaro crater.

GEOCHEMISTRY

Major (SiO_2, TiO_2, Al_2O_3, MnO, CaO, K_2O) and trace elements (Sr, Rb, Zr, Y, Nb, La, Ce, Ba) were determined by x-ray fluorescence (Franzini *et al.*, 1972). Na_2O and MgO were measured by atomic absorption spectrophotometry, Fe++ by titration, P_2O_5 by the colorimetric method and loss-on-ignition (LOI) by constant weight heating at 950° C. CIPW norms were calculated excluding the LOI value. All these analyses were performed at the University of Florence with the assistance of L. Francalanci. The results are shown in Table 1 (from Capra, 1994 and Lafranconi, 1994).

Chemical classification of the products

The alkali vs SiO_2 diagram (Cox *et al.*, 1978) is shown in Figure 8a (see Figure 7 for the meaning of symbols). All rocks of the ZVC have andesitic to dacitic composition and fall within the calc-alkaline field series typical of volcanic arc environments. The most primitive magmas of the ZVC are represented by pre-resurgent dome andesitic lavas (SiO_2=58.3%, VAL 75), andesitic products from la Hoya (SiO_2=57.91%-58.78%, ZIT81-ZIT09), and the earliest andesitic products of the first post-resurgent episode (SiO_2=59.88%, VAL68). On the other hand, the most evolved magmatic rocks are represented by dacitic products of the post-resurgence activity (SiO_2=60.04%-67.61%, VAL40-ZIT94). The AFM diagram of Irvine and Baragar (1971) shows that the ZVC products exhibit Fe-enrichment (Bowen Trend) typical of the calc-alkaline series (Figure 8b). All volcanic products of the ZVC are quartz-normative with values ranging from qz=6%-10% for andesitic lavas, to qz=16%-24% for dacitic products (see Table 1).

Harker diagrams

As typically observed for calc-alkaline rocks, negative correlations of SiO_2 vs Al_2O_3, FeO_{TOT}, MgO and CaO are observed. In contrast, positive correlations are observed for the SiO_2 vs K_2O and SiO_2 vs Na_2O diagrams as elsewhere in the Trans-Mexican Volcanic Belt (Verma, 1987). Of the trace elements, only Rb shows a better positive correlation with SiO_2. In the following we discuss the geochemistry of the resurgent units, using Harker diagrams to illustrate the chemical affinities of the three resurgent eruptive episodes described above.

Pre-resurgent units: TMVB domain

Pre-resurgent units were described only in terms of their petrographic features. The marginal lavas (western *Lindavista and Coatepec de Morelos units*, eastern *Cerro los Muñecos unit*) have an andesitic and basaltic-andesitic composition. Their anhydrous paragenesis is essentially composed of olivine and pyroxene. The earliest hydrous minerals (hornblende and biotite) appear in the El Lindero pyroclastic flow deposit, which is clearly distinct from the younger flow deposits because of its andesitic composition of juvenile clasts.

First eruptive period.

Within this episode, two groups with different chemical features can be distinguished. The central intrusive complex (*Barranca el Agur unit*) and the marginal edifices composed of lava flows (western *Pueblo Nuevo and Cerro Gordo units*, eastern *Los Venados unit*). Both have a negative correlation for Al_2O_3, MgO, FeO_{TOT} and CaO (Figure 9). However for a given SiO_2 content, the central intrusive complex has higher Al_2O_3 values than is common for effusive products and lower abundances of MgO and the other elements. All products feature positive correlations for Na_2O, K_2O, and Rb; the western lavas show the highest enrichment. Despite slight variations, the chemical characteristics of the *Kilometro Once unit* are more similar to those of the marginal lava flows.

Second eruptive period.

This episode can be subdivided into two main groups: The central intrusive complex (*San Jerónimo unit*), and the juvenile products of the pyroclastic flow deposits (*Soledad unit*) which originated from this complex. All these rocks have a negative correlation for Al, Ca, Mg, and Fe, while Na, K, and Rb show a positive trend (Figure 10). Pyroclastic flow deposits show larger values for Al, Na, and lower values for Ca, Mg, and Fe elements as compared to the central domes.

Third eruptive period.

We have less data for this episode. The analyzed rocks have negative trends for Ca, Mg, Fe and Al. The central dome complex (*Guacamaya unit*) shows relative enrichment in Na, K, and Rb (Figure 11).

Collectively, the available data suggest that all the ZVC volcanic products have similar chemical trends in all three eruptive periods. Marginal lava flows have higher contents of Ca, Mg, and Fe elements and a positive correlation in the Na and K diagrams, while pyroclastic deposits and products of the intrusive central activity have larger contents in Al and, generally, a limited variation range in the Harker diagrams. *The San Jerónimo unit* (second episode) can be distinguished from the Barranca el Agur unit (first episode) because the latter has a lover content of FeO_{TOT} and is enriched in Al_2O_3 and Na_2O. The Cerro

Table 1

Major (% on H_2O-free basis), trace (ppm) element analyses and CIPW norm (%Qz) for the volcanic products of ZVC.

	ZIT13	VAL22	PEL56	ZIT95	ZIT96	ZIT93	PEL45	PEL62	PEL34B	PEL02	PEL02A	ZIT69	ZIT69B	ZIT81
SiO2	67.37	62.71	67.44	67.44	62.30	62.48	65.94	67.26	66.68	64.98	67.23	66.93	66.99	57.91
TiO2	0.50	0.76	0.50	0.45	0.56	0.58	0.46	0.52	0.57	0.57	0.55	0.54	0.53	0.81
Al2O3	15.45	16.83	15.84	15.70	17.85	17.54	16.61	16.31	16.07	17.11	16.10	15.41	15.27	17.06
Fe2O3	1.23	1.58	1.30	1.43	1.99	1.92	1.45	0.83	1.08	1.45	0.71	1.7	1.63	1.7
FeO	2.10	3.00	2.16	1.56	1.74	1.86	1.76	2.50	2.70	2.44	2.98	1.88	0.192	3.96
MnO	0.06	0.07	0.06	0.06	0.07	0.07	0.06	0.06	0.07	0.07	0.07	0.06	0.07	0.09
MgO	1.98	3.52	2.16	1.67	3.74	3.76	2.16	2.14	1.84	1.94	1.85	2.43	2.62	6.2
CaO	3.96	5.23	3.75	3.69	3.92	4.02	4.02	3.80	4.10	4.19	3.88	4.48	4.4	6.98
Na2O	4.01	3.51	4.12	4.23	3.68	3.71	3.98	4.03	4.38	4.23	4.34	4.11	4.01	3.81
K2O	2.25	1.64	2.13	2.29	1.84	1.90	1.81	1.87	1.88	1.68	1.87	2.09	2.12	1.17
P2O5	0.10	0.04	0.11	0.12	0.14	0.14	0.11	0.11	0.11	0.13	0.11	0.13	0.13	0.13
LOI	1.00	1.10	0.42	1.36	2.18	2.04	1.64	0.56	0.52	1.22	0.30	0.24	0.32	0.18
TOT	100.01	99.99	99.99	100.00	100.01	100.02	100.00	99.99	100.00	100.01	99.99	100	100.01	100
Rb	41	25	44	43	1	1	35	41	38	40	39	35	36	22
Sr	574	1098	548	757	773	777	536	629	529	675	514	883	883	1083
Y	15	17	15	14	14	14	19	16	18	14	18	15	16	18
Zr	145	163	141	150	163	160	162	134	154	148	155	153	156	151
Nb	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Ce	38	46	35	40	51	52	39	36	39	39	39	43	44	52
Ba	470	395	507	488	597	599	487	452	478	536	504	302	510	351
La	16	21	16	16	22	22	17	15	16	18	17	20	19	18
Qz	23.63	18.35	23.39	23.63	19.93	19.35	23.71	24.20	21.52	21.32	22.20	22.44	22.7	6.98

Data from Capra L. (1994) and Lafranconi P. (1994).

	PEL10	PEL17	ZIT02	PEL49	VAL40	VAL32	VAL31	PEL30	PEL31	PEL06	PEL42	VAL75	VAL68	PEL64
SiO2	66.46	65.86	66.58	62.77	60.04	64.92	65.86	60.48	63.19	66.53	61.36	58.3	59.88	64.86
TiO2	0.59	0.62	0.50	0.69	0.65	0.55	0.54	0.76	0.17	0.56	0.65	1.66	0.88	0.667
Al2O3	16.64	16.70	15.59	17.95	19.50	16.80	16.06	17.50	16.39	16.44	19.12	16.95	16.9	16.44
Fe2O3	1.51	1.29	1.46	1.80	2.95	1.78	1.77	2.08	1.31	1.04	1.86	2.75	1.06	1.28
FeO	2.42	2.72	1.90	2.76	1.44	2.02	1.96	2.98	3.24	2.72	2.60	4.4	4.42	2.86
MnO	0.07	0.08	0.06	0.08	0.08	0.07	0.06	0.08	0.08	0.07	0.08	0.12	0.09	0.07
MgO	1.87	1.89	2.47	2.12	3.33	2.98	2.80	4.19	3.71	1.85	3.06	3.26	5.53	3.11
CaO	3.56	4.11	4.26	4.55	5.08	4.50	4.59	5.49	5.51	4.01	3.94	5.73	5.75	4.88
Na2O	4.25	4.14	4.08	4.10	4.06	4.20	4.11	3.36	3.75	4.28	3.74	3.86	3.71	3.8
K2O	1.85	1.70	1.99	1.66	1.08	1.18	1.60	1.40	1.66	1.92	1.10	1.65	1.57	1.46
P2O5	0.11	0.12	0.09	0.14	0.11	0.11	0.11	0.13	0.15	0.09	0.13	0.44	0.2	0.11
LOI	0.68	0.78	1.02	1.38	1.68	0.90	0.54	1.56	0.30	0.50	2.36	0.9	0.02	0.5
TOT	100.01	100.01	100.00	100.00	100.00	100.01	100.00	100.01	100.00	100.01	100.00	100.02	100.01	100
Rb	37	32	53	34	1	1	nd	nd	25	38	1	40	31	23
Sr	491	554	724	561	928	843	nd	nd	1182	531	678	839	823	877
Y	14	19	16	22	17	16	nd	nd	18	19	14	20	20	16
Zr	158	161	144	196	174	157	nd	nd	166	156	152	340	195	165
Nb	1	1	1	10	1	1	nd	nd	1	1	1	1	1	1
Ce	30	48	38	44	44	44	nd	nd	56	41	34	102	58	46
Ba	487	505	454	565	525	610	nd	nd	505	532	437	462	482	396
La	15	22	16	21	19	17	nd	nd	21	18	11	63	24	16
Qz	23.48	22.59	22.43	18.87	16.75	21.53	21.82	16.73	17.09	21.67	21.70	12.46	10.10	20.89

Data from Capra L. (1994) and Lafranconi P. (1994).

Table 1 (Cont).

	ZIT88	ZIT51	ZIT103	ZIT71	ZIT71A	ZIT65	ZIT64	ZIT58	ZIT94	VAL52	ZIT69A	ZIT109	PEL58
SiO2	64.34	64.87	64.95	64.83	67.4	63.32	63.79	66.73	67.61	63.1	65.55	58.78	66.97
TiO2	0.55	0.57	0.54	0.53	0.048	0.59	0.56	0.43	0.44	0.73	0.52	0.81	0.58
Al2O3	16.2	16.59	16.34	17.77	16.13	16.2	16.28	16.35	15.71	16.12	15.16	17	15.74
Fe2O3	1.47	1.25	1.09	1.35	1.13	1.35	1.8	1.51	1.42	1.59	2.14	1.86	3.19
FeO	2.5	2.88	3.06	2.32	2.16	2.9	2.32	1.86	1.48	2.68	1.5	3.52	0.84
MnO	0.07	0.08	0.08	0.07	0.06	0.07	0.07	0.07	0.06	0.07	0.06	0.09	0.07
MgO	3.79	2.44	3.08	1.67	1.55	4.32	3.49	1.95	1.6	4.8	3.11	5.75	1.33
CaO	5	4.49	4.61	3.9	3.75	4.86	4.65	4	3.71	5.38	4.78	6.52	3.87
Na2O	4.19	4.19	4.19	4.28	4.33	4.07	4.11	4.26	4.23	3.88	3.78	3.53	3.94
K2O	1.68	1.77	1.8	1.77	2.04	1.9	2.05	2.18	2.34	1.45	2.23	1.48	2.02
P2O5	0.12	0.1	0.09	0.12	0.12	0.14	0.13	0.11	0.12	0.18	0.12	0.15	0.12
LOI	0.1	0.76	0.18	1.4	0.84	0.28	0.74	0.56	1.28	0.02	0.94	0.52	1.32
TOT	100.01	99.99	100.01	100.01	99.99	100	99.99	100.01	100	100	99.98	100.01	99.99
Rb	25	38	38	39	45	29	32	42	42	22	41	26	44
Sr	805	513	494	541	524	863	808	643	755	1122	946	1098	773
Y	14	19	17	18	18	16	15	16	14	15	15	18	33
Zr	144	144	138	170	160	164	174	182	149	165	152	158	147
Nb	1	1	1	1	1	1	1	1	1	1	1	1	1
Ce	41	40	35	38	40	55	50	45	41	54	50	60	45
Ba	410	459	461	595	532	461	473	503	476	387	525	413	497
La	16	16	14	19	17	21	21	21	17	20	19	23	31
Qz	17.08	19.25	18.05	21.63	23.33	18.21	16.83	21.73	23.77	16.35	21.2	9.87	26.15

Data from Capra L. (1994) and Lafranconi P. (1994).

	unit	symbol	sample number
III	Vara Chiquichuca	◆	zit13
	Assunción	◇	val22
	Guacamaya	×	zit93 zit62 zit06 zit95 zit96
II	La Soledad	▲	pel34b pel2a pel2 pel17 pel10 zit02 pel49 val31 val32 val40
	San Gerónimo	△	pel30 pel31 val67
I	Los Venados	■	val53 val52
	Cerro Gordo	□	zit58 zit64 zit94 zit65
	Pueblo Nuevo	□	zit51 zit88 zit109 zit81 zit71a zit71 zit103
	Kilómetro Once	●	val68 zit69b zit69 zit69a
	Barranca el Agur	○	pel42 pel45 pel62 pel56 pel58 pel64 pel6

Fig. 7. Names and symbols of units described in Figure 8. The Roman numerals refer to eruptive episodes.

Cacique dome is different from the *Guacamaya unit* (third episode), because of its low SiO_2 and Na_2O contents and its higher value of Fe and Al_2O_3 respect to other domes.

MAGMATIC EVOLUTION

Pre-resurgent activity generated andesitic-basaltic anhydrous products with minimal magmatic differentiation, suggesting that these products originated from a single shallow magmatic reservoir. Intrusive and pyroclastic activity during the resurgence period was more differentiated. The Harker diagrams of these rocks suggest that fractional crystallization was the main magmatic process during resurgent activity. The high MgO content for the marginal products as compared with resurgent domes and pyroclastic flows could be explained by assuming two different magma sources with different chemical compositions that fed the resurgent activity at the ZVC. Marginal effusive products can be easily distinguished from central dome intrusions: the evolutionary trends suggest that fractionation of femic minerals prevailed among the marginal lavas while fractionation of plagioclase was more important in the generation of central domes and the pyroclastic flows, which represented the most highly evolved members. Marginal activity generated rapid emissions of poorly differentiated products that tapped magmatic liquids from a deeper level, which rose along tectonically weak zones. The central intrusion domes probably rose from shallower reservoirs where the magma had time to differentiate and to allow magma-water interaction, leading to phreatomagmatic activity. The equilibria of mineralogical phases among the various products of the ZVC reflect the pressure and temperature conditions of the magmatic reservoirs.

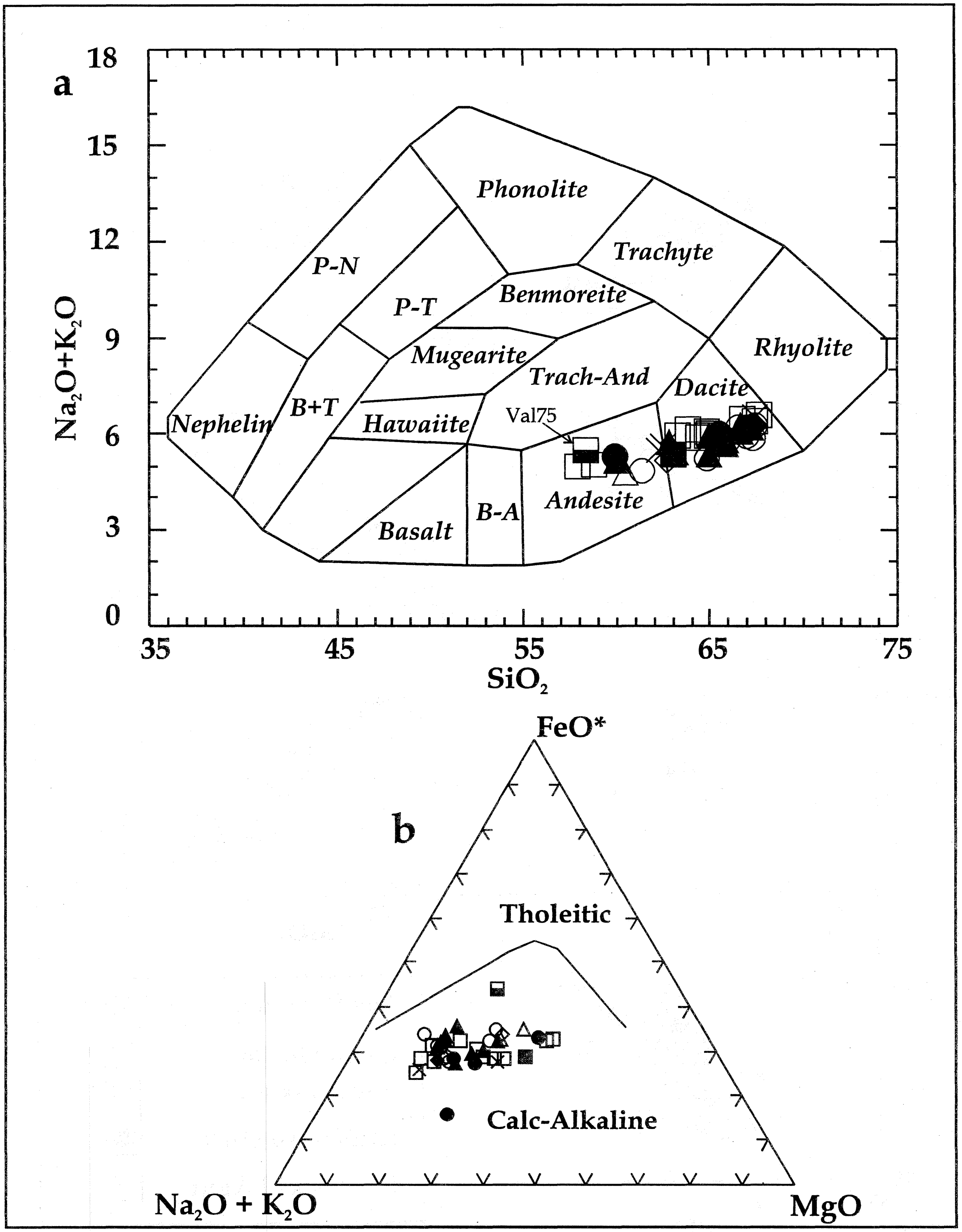

Fig. 8. Chemical classification diagrams of the ZVC volcanic products. (a) Alkali vs. SiO2 diagram (Cox *et al.*, 1978); (b) AFM diagram (Irvine and Baragar, 1971).

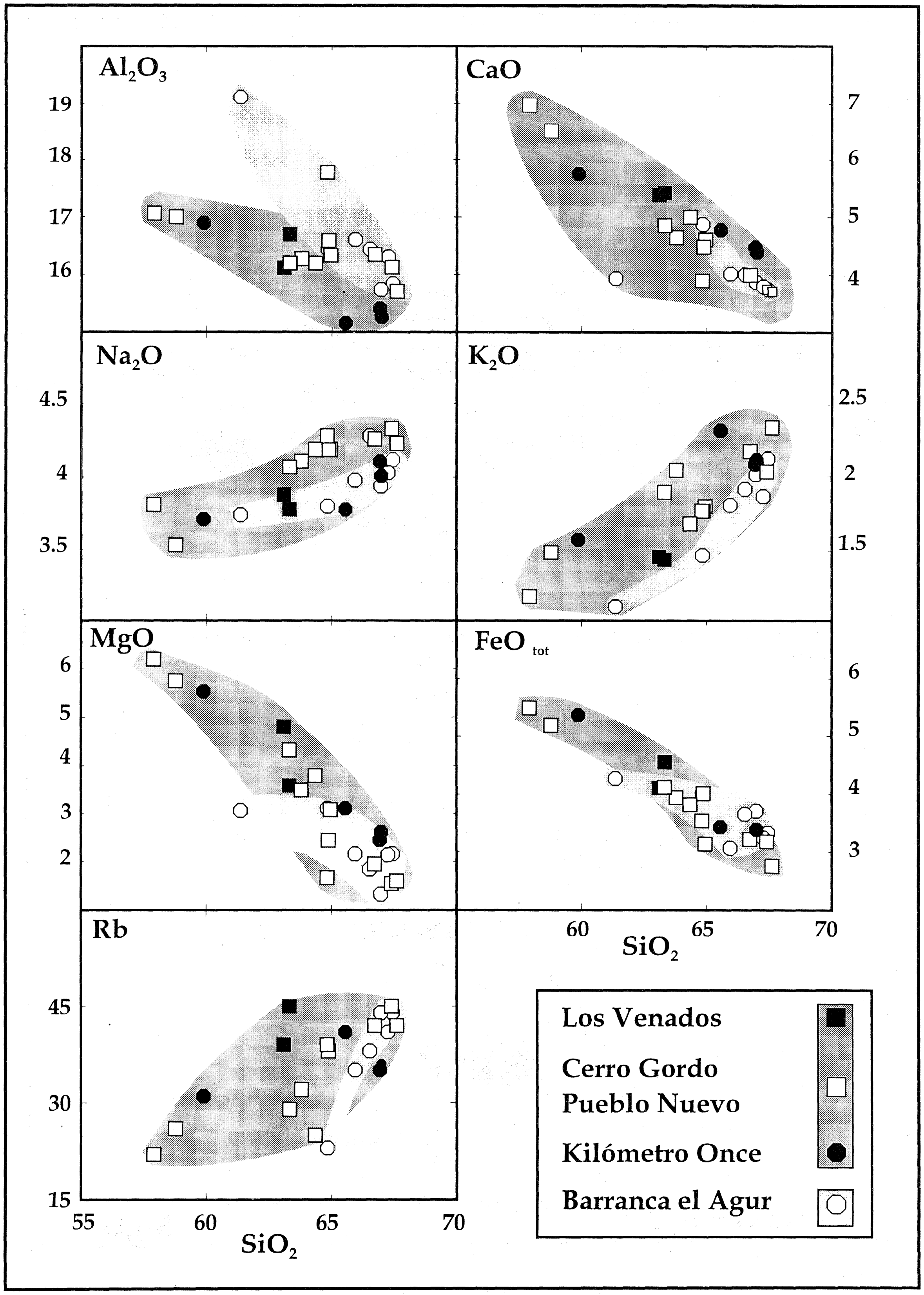

Fig. 9. Selected Harker diagrams of major and trace elements of rocks belonging to the First eruptive episode.

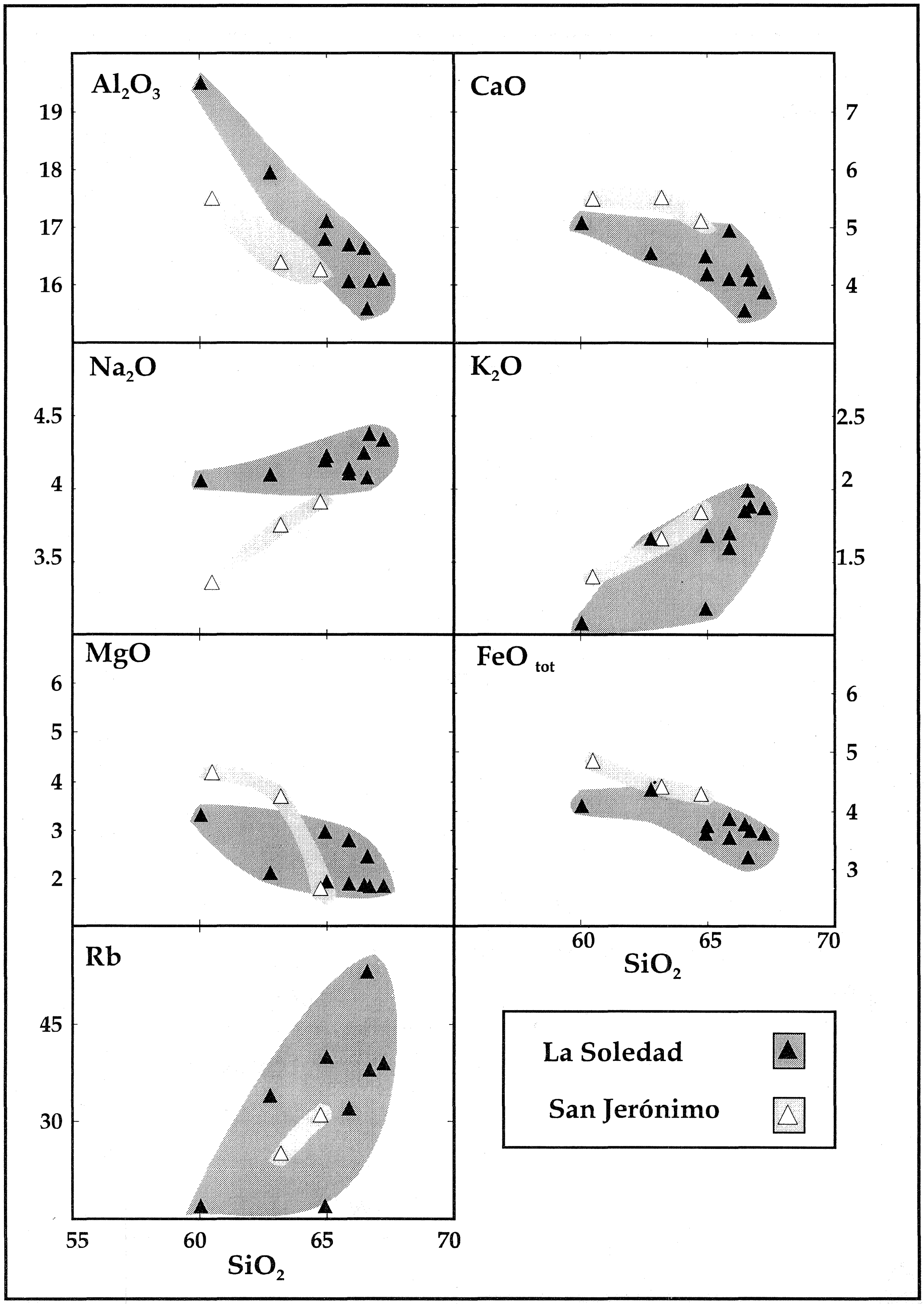

Fig. 10. Selected Harker diagrams of major and trace elements of rocks belonging to the Second eruptive episode.

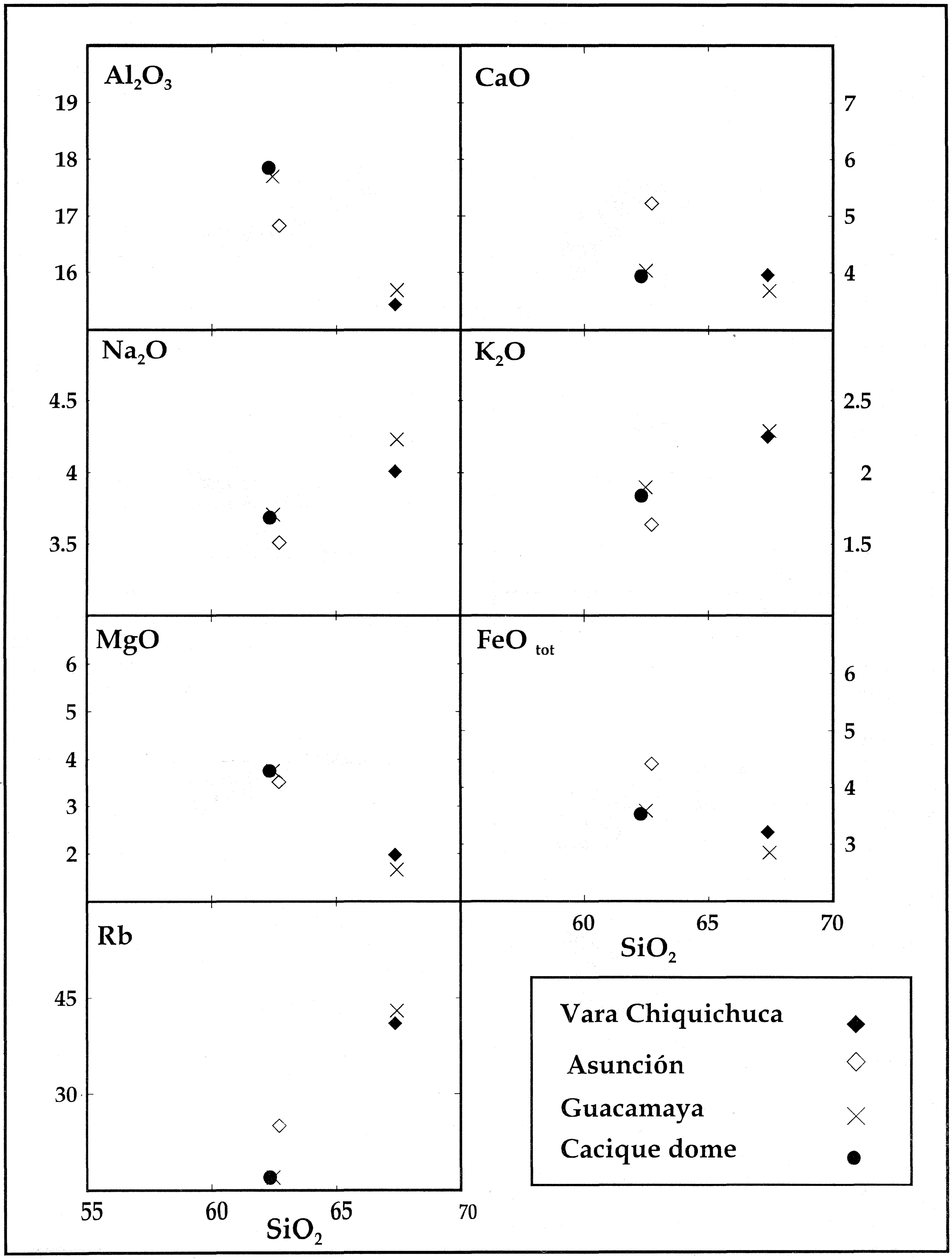

Fig. 11. Selected Harker diagrams of major and trace elements of rocks belonging to the Third eruptive episode.

As all resurgent products of the ZVC have a similar magmatic evolution, despite the fact that these magmas were fed by different shallow reservoirs, we infer that they may have been linked by a common deeper magma reservoir.

ERUPTIVE HISTORY OF THE ZVC

Walker (1984) proposed to define a resurgent caldera as a volcanic collapse followed by an activity located along radial and circular structures related to caldera formation. Post-resurgent activity is characterized by intrusion of dacitic domes in the central area and by development of andesitic to basaltic lava cones around the caldera rim. Such calderas have been recognized in different parts of the word, including the Long Valley Caldera and the Valles Caldera, California, and the Los Azufres Caldera, Michoacán, in the Trans Mexican Volcanic Belt (Pradal and Robin, 1985; Ferrari *et al.*, 1991), or the Aguajito Pleistocene caldera in Southern Baja California (Garduño *et al.*, 1993a). In the latter cases, while morphological features of a caldera structure were lacking, the stratigraphic evidence led the authors to concluded that the dome complex originated from post-caldera resurgent activity.

Miocenic volcanism and the TMVB domain

The earliest volcanic activity at the ZVC began in the Miocene; it features a stratovolcano on a metamorphic and volcano-sedimentary basement of Jurassic-Oligocene age. Its products (*Coatepec de Morelos and Cerro Los Muñecos units*) have an andesitic and andesitic-basaltic composition with an anhydrous paragenesis characteristic of poorly evolved magmas. The petrographic analyses of these rocks may suggest the presence of a shallow magmatic source.

Caldera collapse

During the Miocene, volcanic activity at ZVC proceeded with the emission of large amounts of andesitic magma emplaced as lavas or pyroclastic flows (*El Lindero unit*). This activity emptied the upper part of the reservoir causing a partial collapse of its roof and the formation of a caldera structure 30 km in diameter (Las Tres Chicas Caldera). The rim is morphologically expressed in the eastern and western sectors of the study area; elsewhere it is obliterated by pericalderic volcanic edifices (Figure 2).

Post-caldera resurgent activity

About 12 million years ago, post-caldera resurgent activity began at the ZVC. It consisted of three eruptive episodes separated by periods of roughly 5 Ma. Evolved magma of andesitic-dacitic composition was extruded. As it rose, the magma was stored in different reservoirs in an environment of high water content. From the chemistry and the modal analyses of these products it is likely that fractional crystallization dominated in these reservoirs. Different chemical and petrological variations observed among products of these three eruptive episodes suggest that these reservoirs evolved under different specific conditions.

First resurgent episode

Barranca el Agur unit, which represents the first resurgent phase, occurred about 12 Ma ago. Its products are andesitic (SiO_2=59%) to dacitic (SiO_2=63%), the latter representing the central dome complex. Later during this episode, this dome complex gave rise to explosive activity that produced block-and-ash flow deposits (*Kilometro Once unit*). Andesitic lava flows were extruded in the near-caldera areas (*Pueblo Nuevo, Cerro Gordo and Los Venados units*), from radial fractures related to the caldera structure.

Second resurgent episode.

The second episode began approximately 5 Ma ago with a dacitic intrusion which emplaced a series of domes in the central area (*San Jerónimo unit*). These domes filled the crater formed during the first period of activity. Monogenetic intrusions (*El Candelero unit*) of dacitic composition were emplaced along radial structures. Pyroclastic activity was restricted to the resurgent central complex (*San Jerónimo unit*), and generated block-and-ash flow deposits (*La Soledad unit*). These flows were not able to overtop the caldera rim but they partly filled the caldera depression (Figure 3). The *La Dieta fallout unit*, only 31,000 yr. ago, suggests that this episode of resurgent activity coexisted with the most recent one.

Third resurgent episode.

The latest resurgent period occurred about 0.5 Ma ago and produced the *Guacamaya unit*. It is characterized by dome intrusions of dacitic composition within explosion craters formed during the second eruptive episode. The intrusions fed andesitic lava flows in near-caldera areas (*La Asunción and La Fundición units*). This activity ended with the emplacement of the Nicolás Romero block-and-ash flow deposit originating from Cerro Pelón dome. The last activity related to the caldera structure was hydromagmatic, along NNW-SSE tectonic structures.

CONCLUSIONS

An Upper-Miocene caldera structure has been recognized and mapped in the ZVC. We name this structure the "*Las Tres Chicas Caldera*". Post-caldera activity at Las Tres Chicas took place in three different resurgent episodes beginning about 12 Ma ago with quiet intervals of ca. 5 Ma. Each episode was characterized by intracaldera dacitic intrusions followed by a pyroclastic phase with simultaneous andesitic effusive activity in the near-caldera area. Eruptive products belong to the calc-alkaline series, as is commonly observed in the TMVB. The chemistry of the rocks suggests that the resurgent activity was fed from different shallow reservoirs which were probably derived from a common deeper magma chamber.

The periodicity of the resurgent activity at the ZVC may pose potential volcanic hazards for the surrounding areas, including the city of Heróica de Zitácuaro (population of circa 70,000). This city is located 3 km from Cerro

Cacique dome which belongs to the youngest episode of major volcanic activity. Relatively recent volcanic activity is represented by the La Dieta fall unit (circa 31,000 yr. B.P., present work). The periodicity of the volcanic activity and the fact that inhabitants of the city of Zitácuaro have reported frequent local seismic activity during this century contribute to suggesting that the ZVC should be considered as a potentially active volcanic zone.

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BIBLIOGRAPHY

BONASSI, O., 1994. Studio geologico e strutturale del bacino Capas Rojas Tuzantla-Michoacan-México. Unpublished thesis, Universitá degli studi di Milano, Italia. 115 pp.

CAPRA, L., 1994. Distretto Vulcanico di Zitácuaro (Mich., MEX): modalitá di messa in posto dei depositi di flusso piroclastico: B. A. Unpublished thesis, Universitá degli studi di Milano, Italia. 255 pp.

CAPRA, L., P. LAFRANCONI, R. LASTELLA, V. H. GARDUÑO-MONROY and J. L. MACIAS, 1994. Geology of the Zitácuaro domes, Michoacan, Mexico. Colima Volcano Fourth International Meeting. Colima, Mexico, 64 pp.

CFE (Comisión Federal de Electricidad), 1986. Dataciones radiométricas en rocas del NW de Michoacán. Reporte GG 10/86. Oficina de geología, Depto Expl. Ined.

COX, K. G., J. D. BELL and R. J. PANKHURST, 1978. The interpretation of igneous Rocks, Allen and Unwin, London, 450 pp..

DEMANT, A., 1978. Características del eje neovolcánico transmexicano y sus problemas de interpretación. *UNAM Inst. Geol. Rev. 2,* 172-187.

FERRARI, L., G. PASQUARÈ and A. TIBALDI, 1990. Plio-Quaternary tectonics of central Mexican Volcanic Belt and some constraints on its rifting mode. *Geofís. Int., 29,* 5-18.

FERRARI, L., V. H. GARDUÑO, G. PASQUARÈ and A. TIBALDI, 1991. Geology of Los Azufres caldera, Mexico, and its relationships with regional tectonics. *J. Volcanol. Geotherm. Res. 47,* 129-148.

FRANZINI, M., L. LEONI and M. SAITTA, 1972. A simple method to evaluate the matrix effect in x-Ray flouroscence analysis. *X-R Spectometry, 1,* 151-154.

GARDUÑO-MONROY, V. H., H. VARGAS-LEDEZMA and J. O. CAMPOS-ENRIQUEZ, 1993a. Preliminary geologic studies of Sierra El Aguajito (Baja California, Mexico): a resurgent-type caldera. *J. Volcanol. Geotherm. Res. 59,* 47-58.

GARDUÑO-MONROY, V. H., J. L. MACIAS, R. LASTELLA, L. CAPRA and P. LAFRANCONI, P. 1993B. Field guide for the Cuitzeo lake, Los Azufres, and the Zitácuaro Domes excursion, Michoacán, Mexico. First International Workshop Environmental Volcanology, Morelia, Mich, Mexico, 7 pp.

GARDUÑO, V. H. and L. C. A. GUTIERREZ-NEGRIN, 1992. Magmatismo, hiatus y tectonismo de la Sierra Madre Occidental y del Cinturón Volcánico Mexicano. *Geofís. Int. 31,* 417-429.

IRVINE, T. N. and W. R. A. BARAGAR, 1971. A guide to the chemical classification of the common rocks. *Can. F. Earth Sci. 8,* 523-548.

ISLAS, A., A. ORTIZ, J. ROBLES and J. C. SANCHEZ, 1989. Estudio estratigráfico-estructural y tectónico de la parte norte del pliegue de fondo de Tzitzio, Michoacán: B.S. thesis, Instituto Politécnico Nacional, México, D.F., 144 pp.

ISRADE, I. and L. MARTINEZ, 1986. Contribución al estudio geológico de la transición Pacífico-Tethis en el área de Zitácuaro, Michoacán: B.S. thesis, Instituto Politécnico Nacional, México, D.F., 128 pp.

LAFRANCONI, P., 1994. Distretto Vulcanico di Zitácuaro (Mich., MEX): petrografia, geochimica ed evoluzione magmatologica: B.A. Unpublished thesis, Universitá degli studi di Milano, Italia. 240 pp.

LASTELLA, R., 1994. Distretto Vulcanico di Zitácuaro (Mich, MEX): stratigrafia ed evoluzione di una caldera risorgente: B.A. Unpublished thesis, Universitá degli studi di Milano, Italia. 180 pp.

MAUVOIS, R., 1977. Cabalgamiento miocénico en la parte centromeridional de México.*UNAM Inst. Geol. Rev. 1,* 48-63.

MENNELLA, L., 1994. Geologia e tettonica Post-Laramide nelle unitá del fianco sud-orientale del piegamento di Tzitzio, Michoacán, México. Unpublished thesis, Universitá degli studi di Milano, Italia. 111 pp.

NIXON, G. T., A. DEMANT, R. L. ARMSTRONG and J. E. HARAKAL, 1987. K - Ar and geological data bearing on the age and evolution of the Transmexican Volcanic Belt. *Geofís. Int. 26,* 109-158.

PASQUARÈ, G., L. VEZZOLI and A. ZANCHI, 1987. Morphological and structural model of Mexican Volcanic Belt. *Geofís. Int.* Spec. Vol. on MVB. Part. *3b, 26,* 159-176.

PASQUARÈ, G., L. FERRARI, V. H. GARDUÑO, A. TIBALDI and L. VEZZOLI, 1991. Geologic map of the central sector of the Mexican Volcanic Belt, state of Guanajuato and Michoacán, Mexico: Geol. Soc. of Am., Map and Chart Series MCH072.

PRADAL, E. and C. ROBIN, 1985. Découverte d'une caldera majeure associée au champ géothermique de Los Azufres (Mexique). C. R. Acad. Sc. Paris, S. II, 14, 301-316.

SILVA-MORA, L., 1979. Contribution à la connaissance de l'Axe Volcanique Transmexicain; étude géologique et pétrografique des laves du Michoacán oriental: Marseille. Univ. Aix-Marseille III. B.A. thesis, 230 pp.

SUTER, M., O. QUINTERO and C. A. JOHNSON, 1992. Active faults and state of stress in the central part of the Mexican Volcanic Belt: the Venta de Bravo fault. *J. Geophys. Res. 97,* 11983-11994.

VERMA, S. P. 1987. Mexican Volcanic Belt: Present state of knowledge and unsolved problems. *Geofís, Int.* Spec. Vol. On MVB - *Part. 3b, 26,* 309-340.

WALKER, P. L. 1984. Downsag calderas, ring faults, caldera sizes, and incremental caldera growth. *J. Geophys. Res. 89,* 8407-8416.

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