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Long-lived magmatic phases at Los Azufres volcanic center, Mexico

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Abstract

The Los Azufres volcanic complex has had a long eruptive history of ~1.5 Myr or more (less than 3 Myr), subsequent to the building of a large Miocene and Pliocene andesitic complex.

Since about 1.5 Ma, its development consists of two main periods of volcanic activity. The first period, from ~1.5 to 0.8 Ma, had two magmatic cycles, about 200,000 years in duration, characterized by acidic, followed basaltic volcanism. Such a magmatic evolution suggests successive emptyings of a shallow reservoir in which differentiation previously occurred.

About 0.6 Ma, major deep magma supplies were probably responsible for the resurgent doming which led to uplift of the southern part of the caldera. From ~0.6 Ma to Present, the second period exposes volcanic products grading from basalts to rhyolites. Considering the recent age of the last ignimbrites (26,000 to 29,000 years), one can assume that the volcanic activity related to a voluminous differentiated magma body at shallow depth has not yet ended, especially in the southern area, in and around the resurgent zone occupied by the geothermal field.

1. Introduction

The Sierra Los Azufres lies in the Cuitzeo graben at 1900 m average elevation and culminates at about 3500 m. Surface hydrothermal phenomema are scattered over ~40 km^2 in the highest part of this sierra (Fig. 1). This area has been studied by the Comision Federal de Electricidad (Camacho and Palacios, 1979; Aumento and Gutierrez, 1980; De La Cruz et al., 1982; Combredet, 1983) and workers from Stanford University (Dobson, 1984; Dobson and Mahood, 1985). These two authors inferred the existence of a Pleistocene volcanic center. They indentified two periods of activity, characterized by three volcanic units: (1) Agua Fria rhyolitic group (about 1 Ma old); and (2) San Andres rhyodacites and dacites (about 0.3 Ma old) and La Yerbabuena rhyolitic group (0.3 to 0.15 Ma old). For Dobson and Mahood, the geothermal field — lying on the upper part of the intensively E–W faulted Sierra Los Azufres — was originated by these two episodes of high heat flow.

In order to solve the problem of the origin of the geothermal field in a larger volcano-tectonic setting, we initiated, in 1985, fieldwork, petrological and geochronological studies over a larger area, coarsely delimited by Acambaro, Maravatio, Ciudad Hidalgo and Zinapecuaro (Fig. 2). The Sierra Los Azufres is part of a large volcanic complex whose centre has collapsed, forming a nearly circular caldera, about 18×20 km wide, the floor of which is at ~2450 m altitude, 500–600 m above the graben (Pradal and Robin, 1985, 1986; Pradal, 1990; Robin and Pradal, 1993).

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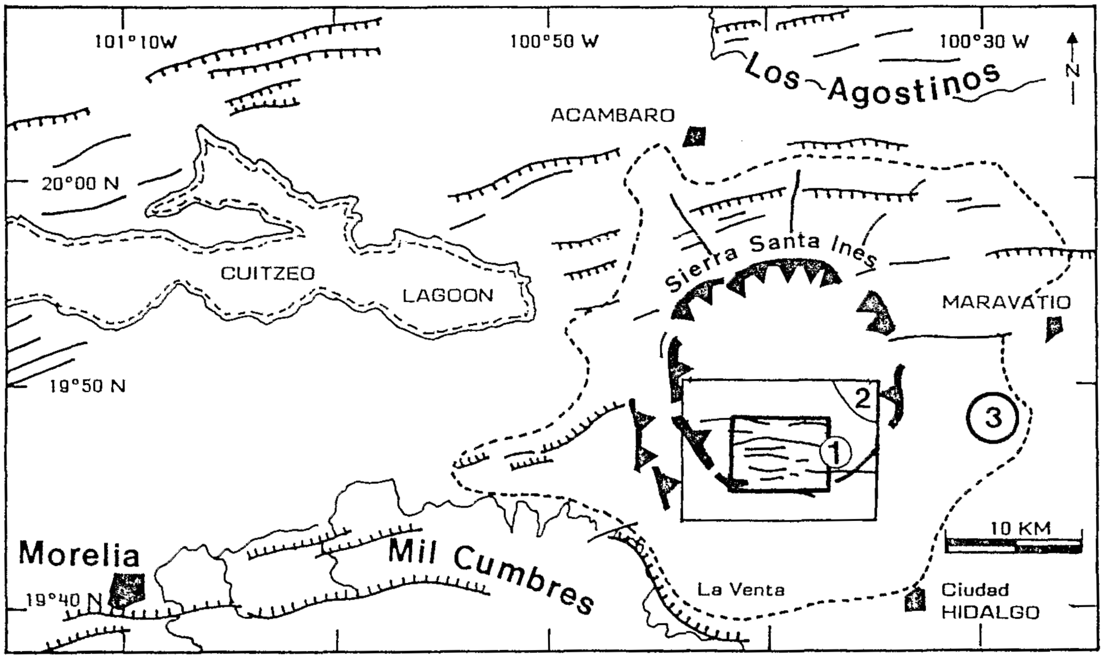

Fig. 1. Schematic structural map of Cuitzeo graben, from Morelia to Maravatio. *1* = location of geothermal field; *2* = approximate limits of the Los Azufres Sierra; *3* = extent of the Los Azufres volcanic complex.

The present paper deals only with the volcanic sequences emitted since the early evolutionary stages of the complex, i.e. since Late Pliocene or Early Pleistocene. From about 1.5 Ma to Present (Tables 1 and 2), two main periods have produced alternating mafic (andesites and/or basalts) and differentiated magmas (rhyolites and/or dacites). Such a pattern puts the most recent rhyolitic phase, which is less than 30,000 years old (Table 2), in a conspicuous position and allows us to propose a model for a better understanding of the geothermal field from the magmatic point of view.

Our data and interpretation about Los Azufres caldera (Pradal et Robin, 1985, 1986; Pradal, 1990), which differ from the model proposed more recently by Ferrari et al. (1991), are not the main topic of this paper. Our results about the collapse structure are discussed in a comment to Ferrari et al.'s paper (Robin and Pradal, 1993).

2. Structural framework

2.1. Basement

The oldest volcanic rocks of the area consist of Oligocene and Miocene andesitic lavas which are found in the Los Agostinos and Mil Cumbres sierras and as inliers within the graben. The largest outcrop is the Sierra Santa Ines (Fig. 2) which exposes an arcuate ridge of andesitic lavas that dip 10° north. This structure, together with the Miocene and Pliocene andesites in the Sierra Los Azufres, is interpreted as the remnant of an early volcanic field (Pradal, 1990).

2.2. Faulting

Contrasting with the dense array of E–W-trending faults related to the graben (Dobson and Mahood, 1985), arcuate fractures (Figs. 1 and 2) presumably associated with the caldera form

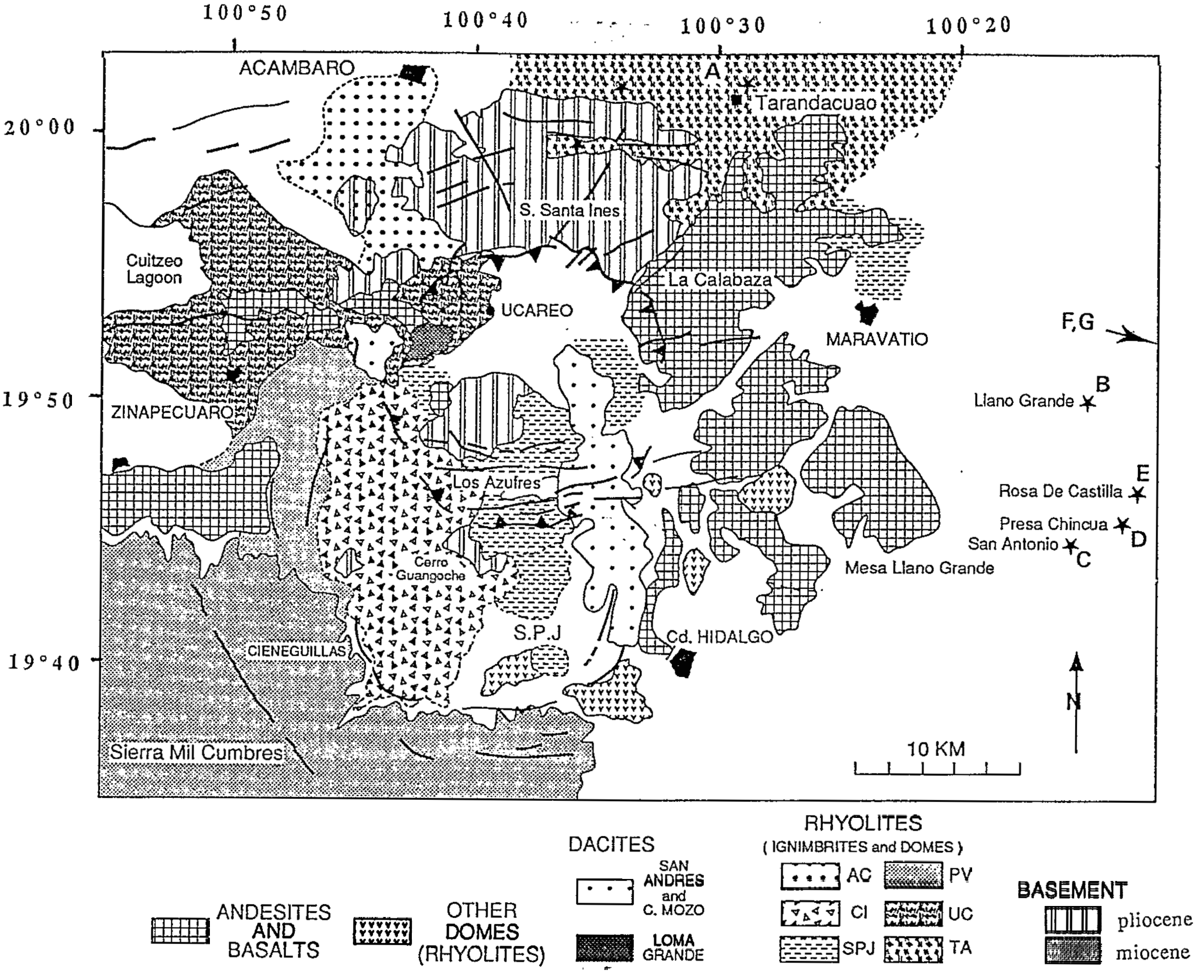

Fig. 2. Geological sketch map of the Los Azufres volcanic complex. For clarity, domes from the Ucareo (*UC*), Pueblo Viejo (*PV*), San Pedro Jacuaro (*SPJ*) and Cieneguillas (*CI*) sequences of rhyolites have not been depicted (see location of these domes Fig. 3). *AC*=Acambaro ignimbrites; *SPJ*=San Pedro Jacuaro village. Solid stars refer to studied outcrops (Fig. 5) from the Tarandacuao (*TA*) sequence (see sections Fig. 5; sections F and G are located about 35 km east of the caldera).

a nearly circular pattern (Pradal, 1990; Robin and Pradal, 1993). At the edge of the Valle de Juarez Plain, the difference in altitude between the top of the andesites cut by the ring fracture (2600–2700 m) and the plain shows a minimal vertical throw of 200 m. 1:50,000 aerial photos and SPOT orbital images at 1:100,000 scale emphazise the complexity of the fracture zone: extra-caldera concentric faults and radial fractures also affect the basal andesites in Sierras Santa Ines in the north and Mil Cumbres in the south. The outer section of the concentric faults is uplifted, with respect to the inner one. In the southwest, the extracaldera fault system — associated with important fault breccia — results in two curved ramparts 100 to 250 m high and about 7 km long (Rio El Real and La Venta; Figs. 2 and 3). Nevertheless, in this region it is diffi-

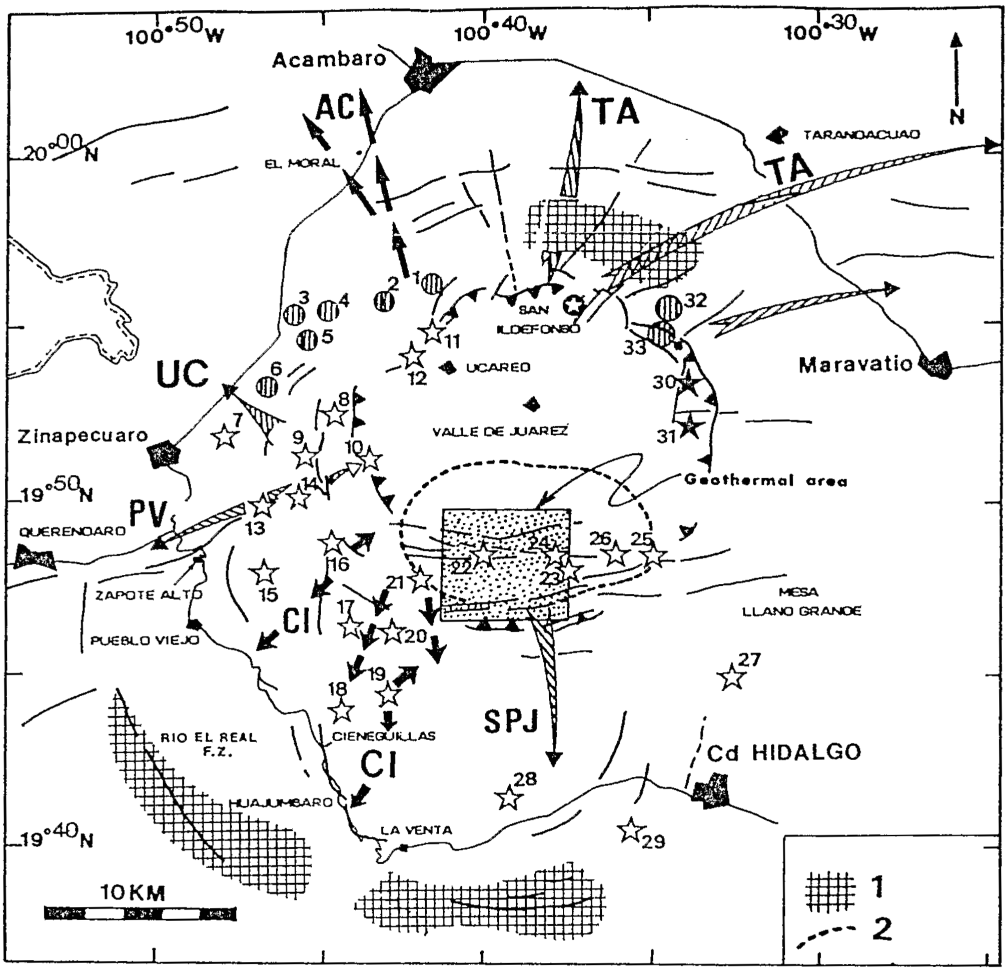

Fig. 3. Sketch map showing domes, vents, and flow directions of the main ignimbrites. Hachured circles = andesitic mounts (cerros). Open stars = dacite and rhyolite domes. Solid stars = andesitic vents. The figure also shows: (a) areas of clay alteration of the basement [1]; and (b) the limit of the zone affected by the resurgent doming [2]. Local names: *1* = Cerro El Gallo; *2* = C. El Muerto; *3* = C. El Molcajete; *4* = C. La Manzana; *5* = C. Los Caballos; *6* = C. Palos Amarillos; *7* = Mesa La Comalera; *8* = Mesa Grande; *9* = Mesa Picado; *10* = C. Mozo; *11* = Mesa La Palma; *12* = C. Las Penitas; *13* = C. Colorado; *14* = C. Cuate; *15* = C. Monterrey; *16* = C. Carpintero; *17* = C. La Palma; *18* = C. El Mirto; *19* = C. Guangoche; *20* = Mesa El Rosario; *21* = C. El Bosque; *22* = C. La Providencia; *23* = C. Pizcuaro; *24* = C. Zacatonal; *25* = C. El Leon; *26* = C. San Andres; *27* = C. Prieto; *28* = C. Los Coyotes; *29* = C. La Cruz; *30* = C. La Calabaza; *31* = C. La Capilla; *32* = C. La Hierba; *33* = C. La Cruz.

cult to distinguish between the movements related to the graben subsidence from those related to the concentric outer fracturing because of local overlapping of the two systems.

3. Volcanic products

3.1. Rhyolites

The rhyolites consist of six sequences of ignimbrites and domes which correspond to at least three main phases of silicic activity (Fig. 4, Tables 1 and 2): (1) the 'ancient' Tarandacuao and Ucareo series (TA and UC) whose age — ~1.5 Ma or more — will be discussed below; (2) the intermediate (about 1 Ma old), San Pedro Jacuaro (SPJ) and Pueblo Viejo (PV) sequences; and (3) the 'recent', Cieneguillas and Acambaro (CI and AC) groups of ignimbrites and domes, less than 0.2 Ma. Representative chemical compositions of these rhyolites are reported Table 3.

The Tarandacuaro (TA) and Ucareo (UC) ignimbrites are widely distributed on the eastern, northern and western sides of the collapse structure (Fig. 4).

Outcrops of the TA sequence are well exposed in the region of Tarandacuao and at Presa Santa Ines. Here, the contact of the ignimbrite and the underlying andesites is unconformable, suggesting that faulting in the basement rocks predates the deposition of the pyroclastic flows (Pradal,

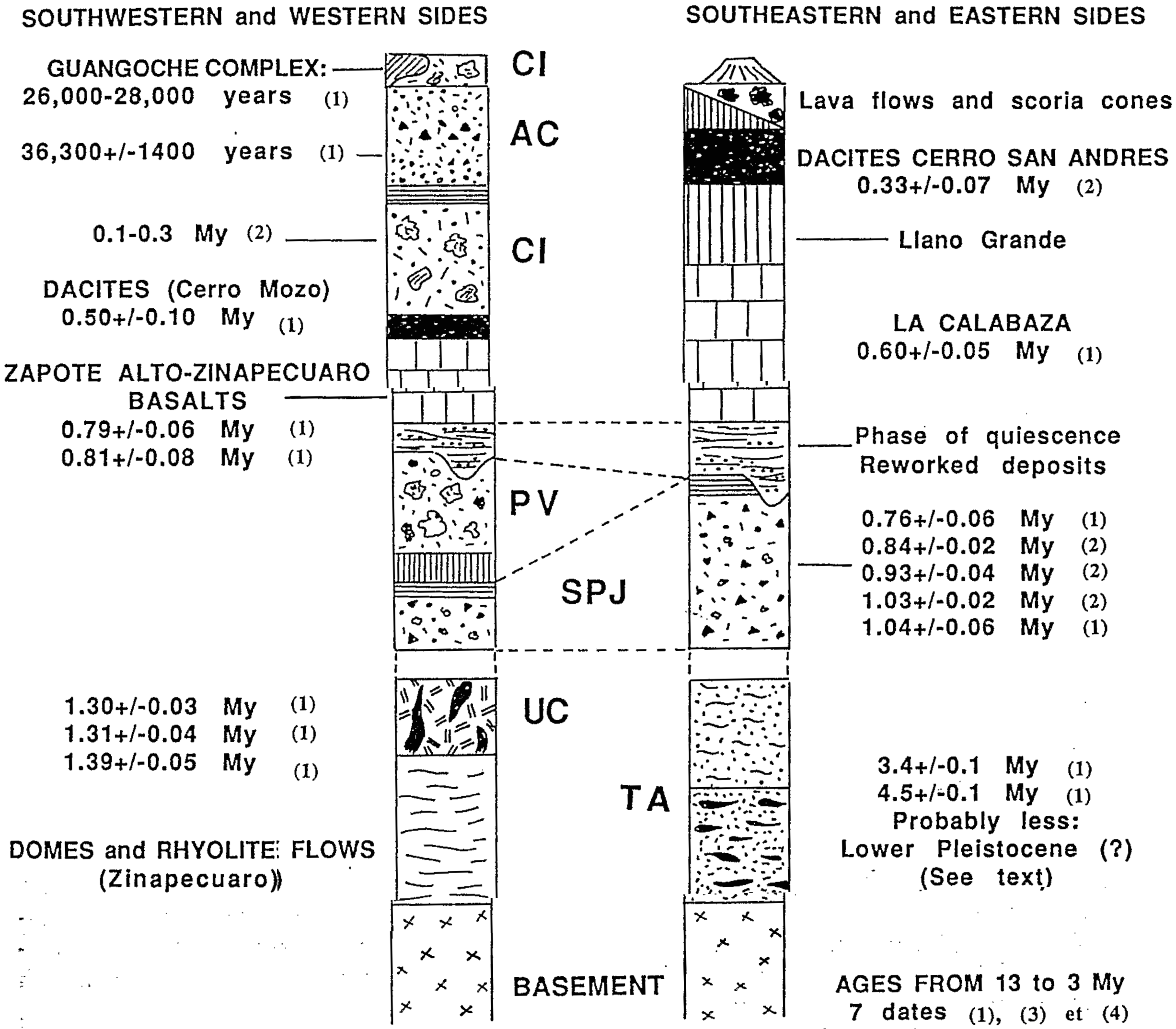

Fig. 4. Synthetic stratigraphic column of Los Azufres volcanic center. (1) = our dates; (2) = dates from Dobson and Mahood (1985); (3) = Demant et al. (1975); (4) = Aumento and Gutierrez (1980).

Table 1
Summary of K/Ar dates for The Los Azufres complex.

Sample	Locality	Long. W	Lat. N	Mat.	K (%)	Ar40* (ng/g)	Ar Atm (%)	Age (Ma)
Cieneguillas								
Rhyolite	Mesa El Carpintero	100°43′15	−19°48′05	glass	3.92–3.93		81.7	0.14±0.02 (1)
Rhyolite	Mesa El Bosque	100°42′27	−19°47′41	biotite	5.51		98.5	0.15±0.05 (1)
Rhyolite	Cerro El Rosario	100°42′52	−19°45′32	biotite	5.69 6.03		96.8	0.30±0.07 (1)
Dacitic domes	Cerro San Andres	100°37′30	−19°46′38	plagiocl.	1.5–1.55		95.5	0.33±0.07 (1)
	Cerro Mozo	100°43′55	−19°51′25	WR	1.46	0.050	95.4	0.50±0.10 (2)
La Calabaza	Andesite AZ 130	100°35′50	−19°52′00	WR	1.14	0.047	89.3	0.60±0.05 (2)
Zapote Alto	Basic andesite AZ 124	100°44″50	−19°50′30	WR	1.87	0.103	87.2	0.79±0.06 (2)
	Basic andesite AZ 74	100°48′45	−19°48′25	WR	1.71	0.096	90.3	0.81±0.08 (2)
Pueblo Viejo – San Pedro Jacuaro								
Rhyolite AZ 157	Agua Fria	100°39′30	−19°47′20	WR	3.82	0.201	88.0	0.76±0.06 (2)
Rhyolite	Geothermal field	100°40′22	−19°48′46	glass	3.87–3.90		49.7	0.84±0.02 (1)
Rhyolite	Geothermal field	100°39′46	−19°46′58	WR	3.73–3.87		87.0	0.93±0.04 (1)
Rhyolite	Geothermal field	100°39′26	−19°56′21	gws	3.88–3.91		47.1	1.03±0.02 (1)
Obsidian 122	San Pedro Jacuaro	100°39′30	−19°44′00	WR	3.95	0.285	84.2	1.04±0.06 (2)
Loma Grande	Dacite AZ128	100°43′30	−19°52′30	WR	1.94	0.165	87.2	1.22±0.09 (2)
Ucareo								
Rhyolite AZ 121	Zinapecuaro	100°50′5o	−19°51′30	WR	3.84	0.347	61.8	1.30±0.03 (2)
Rhyolite AZ 11	Ucareo	100°41′55	−19°53′25	WR	3.97	0.360	67.9	1.31±0.04 (2)
Rhyolite AZ 82	Cerro Cuate	100°45′25	−19°50′30	WR	3.57	0.343	77.1	1.39±0.05 (2)
Tarandacuao								
ignimbrite AZ 146	Presa Sta Ines	100°36′030	−19°59′25	WR	2.71	0.640	68.7	3.40±0.10 (2)
ignimbrite AZ 148	La Virgen	100°34′20	−20°00′40	WR	2.87	0.891	55.6	4.50±0.10 (2)

(1)=Dobson and Mahood (1985); (2)=this work and Pradal (1990) (dates from K/Ar laboratory Department of Earth Sciences, Clermont-Ferrand University); (3)=Demant et al. (1975); (4)= Aumento and Gutierrez, 1980. (1) (2) (4): new decay constants. (2): $^{40}K=0.01167$atom%. (1) (4): $^{40}K/K=1.161\times10-4$atom/atom; $\lambda\epsilon=0.581.10^{-10}yr^{-1}$; $\lambda\beta=4.962.10^{-10} yr^{-1}$. $^{40}Ar/^{36}Ar=295.5$. (3) unknown decay constants

1990). This sequence, 25 to 30 m thick in the inner ring fracture zone delimiting the caldera (section A, Fig. 5), consists of two composite ash-flow units separated by a 1.5-m-thick layer of ash and pumice airfall and surge deposits. The lower unit, ochre to pale-pink in color, is massive and clearly welded; about 50% of the volume consist of elongated dark-grey pumice fragments, 1 to 5 cm in size. Thirty km to the east, the deposit is still 5–8 m thick (section G, Fig. 5). The upper member is a densely welded tuff, showing columnar jointing. In thin section, the texture is vitroclastic, with broken crystals of alkali feldspar, biotite and amphibole (Pradal, 1990).

The Ucareo deposit is a poorly welded tuff containing up to 20% of obsidian blocks 1–10 cm in size. It extends on the western side of the complex, north of Zinapecuaro and inside the caldera at Ucareo where it appears associated with domes.

On the northwestern side of the complex, at least 8 domes (Fig. 3; numbers 7 to 14) associated with voluminous rhyolite lava flows ex-

Table 2
^{14}C data for the Los Azufres complex: this work and Pradal et al. (1988) (Analysis from "Centre des Faibles Radioactivités" ^{14}C laboratory, Gif sur Yvette)

	Locality	Coordinates	Age (years)
Cieneguillas Unit			
AZ 88	Zirandaro	100°45′20″–19°45′50″	28,000±650
AZ 120	Cieneguillas	100°45′00″–19°42′40″	26,800±900
AZ 136	Agua Blanca	100°43′45″–19°41′55″	26,700±450
Acambaro Unit			
AZ 126	El Moral quarry	100°44′30″–19°59′20″	36,300±1400

truded shortly following the UC ignimbrites. Some of them, such as Cerro Colorado and Cerro Cuate, are ~1.4 Ma old. They have the same mineralogical and chemical composition as the ignimbrites (Pradal, 1990). All these 'ancient' extrusions mark the western boundary of the caldera and are faulted by subsequent readjustments of the ring fractures.

The estimated volume of magma (Dense Rock Equivalent: DRE) released by the eruptions of the TA and UC rhyolites, calculated from the thicknesses and extents of the deposits (Pradal, 1990), seems about 100 km^3: 70–80 km^3 for the Tarandacuao ignimbrites and 10–15 km^3 for the Ucareo series, including the domes.

The SPJ and PV rhyolites: The SPJ sequence of ignimbrites crops out mainly on the southern side of Sierra Los Azufres (Fig. 2). It corresponds partly to the Agua Fria group defined by Dobson and Mahood (1985). Deposits commonly reach 30 m in thickness. North of San Pedro Jacuaro, a 15-m-thick flow deposit consists of 25% obsidian blocks, pumice and xenoliths in a poorly welded ashy matrix. Airfall ash and pumice layers, commonly 5–6 m thick, overlie the SPJ ignimbrites. The PV ignimbrite sequence lies on the western part of the complex and covers over at least 100 km^2 forming large outcrops along the Zinapecuaro–Huajumbaro road where it is strongly eroded in barrancas up to 60 m deep. The PV deposits consist of white ash with 15–25% pumice fragments (5–10 cm) and dense vesiculated rhyolite blocks; it also includes about 6% basaltic scoria. The volume of the SPJ and PV rhyolites (including the domes) is about 20 km^3 DRE (Pradal, 1990).

The CI and AC rhyolites: The Cieneguillas (CI) group of ignimbrites partly filled valleys inside the deeply eroded PV deposits on the southwestern side of the complex. Each non-welded deposit of ash and pumice is 6–10 m thick at 5–8 km from the edge of the caldera; the sequence commonly reaches 40 m in thickness (Pradal, 1990). These ash-flow deposits are interbedded and overlain by numerous airfall layers, commonly 2–5 m thick. Six domes located near the ring fracture zone or emplaced on the southwestern slope of the complex belong to the CI group (Fig. 3). They correspond to thick tabular extrusions, 100–200 m high, forming flat-topped hills as wide as 2–3 km. We include in this group two domes from the La Yerbabuena sequence, defined by Dobson and Mahood in 1985, (Cerros Carpintero and El Bosque) that were dated ~0.15 Ma (0.15±0.05 and 0.14±0.02 Ma). However, some extrusions and their pyroclastic products are much more recent (26,000 to 29,000 years; Table 2), showing that the CI group belongs to a long phase of rhyolitic magmatism that is still going on. The rhyolitic dome of Cerro Guangoche intrudes ash-flow deposits dated at 26,700±450 years (Pradal et al., 1988) and therefore represents the youngest rhyolitic manifestation in the Los Azufres region.

The volume of the CI rhyolites is on the order of 10 to 12 km^3 DRE and crops out over 180 km^2.

South of Acambaro, the AC ash and pumice flow deposit covers at least 20 km^2. It reaches 25 m in thickness and its volume is estimated at 1 km^3 DRE (Pradal, 1990). This deposit is

Table 3
Representative analyses of the main volcanological series of the Los Azufres volcanic center (atomic absorption laboratory, Department of Earth Sciences, Clermont-Ferrand University)

A

	TA 100°36'00 19°59'25	TA 100°34'20 20°00'40	UC 19°53'28 100°41'43	UC 100°45'25 19°50'30	UC 100°50'50 19°51'30	LOMA Gde 100°43'30 19°52'30	Caldera NW side 100°48'45 19°46'20	 100°45'25 19°50'30
SiO_2	70.00	69.00	75.80	76.40	77.54	63.60	54.50	53.60
Al_2O_3	14.50	14.10	12.60	12.80	12.02	16.80	16.80	18.20
Fe_2O_3	4.80	4.60	0.49	1.10	1.13	1.99	3.15	5.23
FeO	*	*	0.73	0.00	0.00	3.52	3.92	3.08
MgO	0.37	0.45	0.05	0.07	0.05	2.10	7.13	4.90
CaO	1.40	1.40	0.45	0.44	0.53	4.85	6.90	7.85
Na_2O	4.50	4.80	3.80	4.00	3.90	3.80	3.20	3.70
K_2O	2.80	3.50	4.51	4.50	4.74	2.80	1.90	1.10
TiO_2	0.70	0.55	0.10	0.15	0.06	0.90	1.20	1.40
MnO	0.06	0.10	0.02	0.03	0.02	0.10	0.12	0.12
P_2O_5	0.04	0.06	nd	nd	nd	0.09	0.00	0.27
LOI	0.89	0.93	0.45	0.20	0.20	0.01	1.10	0.07
	100.06	99.49	99.00	99.84	100.19	100.56	99.92	99.52

B

	PV 100°46'00 19°50'24	PV 100°48'15 19°50'30	SPJ 100°35'00 19°52'31	SPJ 100°39'21 19°43'15	Caldera NW side 100°49'48 19°47'53	 100°48'45 19°48'31	 100°28'30 19°50'00
SiO_2	73.75	73.80	73.40	74.50	54.80	55.40	53.10
Al_2O_3	12.45	12.00	13.80	13.00	15.60	15.20	17.30
Fe_2O_3	1.30	1.20	0.70	0.38	4.86	3.10	4.08
FeO	*	*	0.59	0.87	3.32	4.19	5.42
MgO	0.10	0.04	0.09	0.04	7.45	6.83	3.60
CaO	0.54	0.47	0.51	0.47	7.65	6.70	6.80
Na_2O	3:05	3.40	3.66	4.00	3.70	3.60	3.90
K_2O	4.75	5.00	5.12	4.75	1.60	1.95	2.00
TiO_2	0.05	0.15	0.16	0.20	1.40	1.20	2.10
MnO	0.02	0.02	0.04	0.02	0.14	0.13	0.13
P_2O_5	0.00	0.04	0.00	0.02	0.22	0.22	0.36
LOI	3.10	2.93	1.93	0.81	0.10	0.73	0.45
	99.11	99.05	100.00	99.06	100.84	99.25	99.24

C

	La Calabaza 100°35'50 19°52'00	 100°34'00 19°50'10	C. Mozo 100°43'55 19°51'25	S. Andres 100°36'30 19°49'30	Cieneguillas 100°42'33 19°48'18	 100°45'20 19°42'40	Acambaro 100°44'30 19°59'20	Parasitic cone 100°27'27 19°46'21
SiO_2	55.50	56.70	64.80	67.75	76.50	75.20	75.80	52.80
Al_2O_3	17.70	18.30	17.40	16.01	12.70	12.50	12.30	17.46
Fe_2O_3	2.01	3.91	4.23	3.49	1.31	0.13	0.51	8.68
FeO	5.13	3.23	*	*	*	0.87	0.57	nd
MgO	5.60	3.90	0.65	1.11	0.07	0.08	0.05	4.83
CaO	7.60	7.00	4.20	2.10	0.70	0.51	0.49	8.55
Na_2O	3.60	3.60	3.70	3.93	3.40	3.50	3.60	4.02
K_2O	1.50	1.80	1.65	3.28	3.60	4.75	5.00	1.53
TiO_2	1.30	1.17	0.60	0.47	0.20	0.20	0.00	1.44
MnO	0.10	0.12	0.08	0.06	0.02	0.02	0.03	0.13
P_2O_5	0.12	0.26	0.08	nd	0.02	0.00	0.00	nd
LOI	0.37	0.33	1.97	1.80	0.59	1.44	0.98	0.29
	100.53	100.32	99.41	100.00	99.11	99.20	99.35	99.73

* Fe measured as Fe_2O_3.

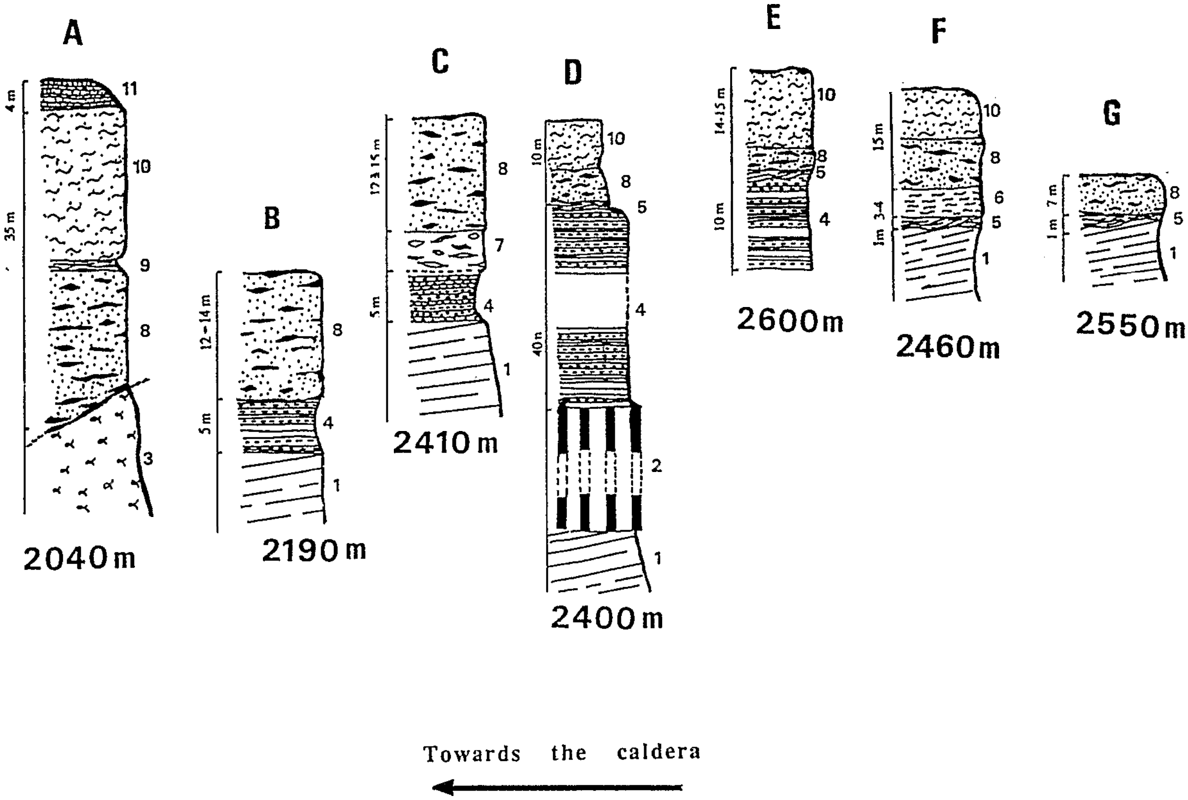

Fig. 5. Stratigraphic columns of the Tarandacuao sequence. *A*=Presa Santa Ines; *B*=Llano Grande; *C*=San Antonio; *D*=Presa Chincua; *E*=Rosa de Castilla; *F*=El Gigante; *G*=La Cantera Nueva. Differences in altitude outline the Pleistocene tectonism of the graben. Note the thickening of the ignimbrites towards the caldera. *1*=basement; *2*=basalts (Pliocene); *3*=andesites from Sierra Santa Ines; *4*=Plio-Pleistocene sediments from the graben; *5*=surge deposits; *6*=vitric tuff (obsidian), only at site F; *7*=welded tuff, including pumice (only at site C); *8*=TA tuff, lower member; *9*=surge deposits and airfall deposits; *10*=TA tuff, upper member, densely welded; *11*=ash and pumice airfall deposits.

36,300±1400 years old (Table 2 and Pradal et al., 1988). Obsidian-rich levels indicate that it was emplaced as several flows. The AC deposits can be followed from the Acambaro Plain up to a zone marked by large obsidian dikes and small rhyolitic extrusions close to the edge of the central collapse zone and aligned parallel to it.

3.2. Dacites

A large dacitic extrusion in the northwestern part of the complex was dated 1.22±0.09 Ma (Loma Grande, Figs. 2, 4; Tables 1 and 3) and seems to follow the first rhyolitic series of ignimbrites and domes. Nevertheless, the major dacitic phase in Los Azufres volcanic complex belongs to the emplacement of Cerros Monterrey, Mozo and San Andres from ~0.5 to ~0.3 Ma (dacites of Cerro San Andres were dated by Dobson and Mahood in 1985).

3.3. Andesites and basalts

At least one period of mafic volcanism occurred between the eruption of the lower ignimbrites (TA and UC) and the intermediate rhyolite sequence (PV and SPJ ignimbrites). It is represented by a small volume of basaltic lava flows associated with scoria of basaltic andesite composition (Pradal, 1990); identical scoria are present in the younger Pueblo Viejo rhyolitic ashflow deposits, showing that these basalts have been reworked. This implies the presence of cones close to the western edge of the structure, after initial stage of evolution. Probably, the andesite lava flows which overlie the Ucareo tuff, northwest of Ucareo (Fig. 2), belong to the same eruptive period.

Three series of basalts and andesites, younger than the SPJ and PV ignimbrites (Table 1), are exposed on the western and eastern sides of the caldera (Fig. 2):

(1) In the west, olivine basalts and andesite lava flows with a total thickness of 100 to 120 m spread from Zapote Alto, near the caldera edge at 2350 m, towards Querendaro, forming a plateau of about 70 km^2 (Fig. 2). Two samples from this series (8 km^3 of basalts) have been dated at 0.8–0.75 Ma (Table 1).

(2) At about 0.6 Ma, andesites and basalts from Cerro La Calabaza partly covered the eastern edge of the caldera and spread out over 120 km^2 with a maximum thickness of about 300 m (20 to 25 km^3 of magma).

(3) This series is overlain by airfall products from the San Andres dome complex dated at 0.33 ± 0.07 Ma.

On the southeast slopes, the Mesa Llano Grande (100 km^2) consists of a pile of basaltic flows which commonly reaches 150 m in thickness. At least 10 km^3 of basalt have been emitted during this basaltic phase (Pradal, 1990).

Mafic magmas which are not directly related to the volcanic complex development also erupted during the Upper Pleistocene (Pradal, 1990). This led to the construction of numerous scoria cones outside the volcanic complex, along fractures parallel to the caldera edge, and further along the extension of the E–W regional faults.

3.4. Volcaniclastic lacustrine deposits

Volcaniclastic lacustrine sediments cover the major part of the Valle de Juarez Plain. The most representative outcrop is that of San Ildefonso (Fig. 3) whose lower 16 m of deposits are exposed in a barranca perpendicular to the caldera wall (Pradal and Robin, 1985). These deposits consist of layers of coarse white ashes containing pumices with a clayey to siliceous cement and marly levels which grade upwards into white or light-grey, compact layers of fine reworked ash.

4. Discussion — volcanic history of the complex

4.1. Age of the Tarandacuao ignimbrites

The age of the Ucareo rhyolites is well defined (1.4–1.3 Ma). A problem exists concerning the age of the earlier TA ignimbrites: two different dates (4.5 ± 0.1 and 3.4 ± 0.1 Ma) have been obtained on the same ignimbrite unit sampled at two places (Pradal, 1990; ages Table 1). This difference is probably due to the heterogeneity of these rocks since they contain a few percent of andesite xenoliths. Lo Bello et al. (1987) have shown that only 0.075% Hercynian feldspar may be responsible for a large deviation (50%) in the calculated age of Pleistocene sanidines. Thus, we consider 3.4 Ma as an upper limit for the age of the collapse. Other stratigraphic constraints allow us to propose a Late Pliocene or Lower Pleistocene age for the TA ignimbrite. Remains of an *Elephas Imperator Leidy*, which is believed to be Early Pleistocene — i.e. 1.6–1.4 Ma — in the American Continent (Chaline, 1985), has been discovered at the top of the thick sediment sequence which refills the Cuitzeo graben (Garduno, 1987). The ignimbrite is always found overlying these sediments (Fig. 5), suggesting that the age of the older welded tuff is probably Lower Pleistocene, i.e. about 1.5 Ma. Large differences in altitude between the outcrops of the same group correlated in Fig. 5 illustrate significant vertical movements within the graben since the deposition of the TA tuff.

4.2. Comparison with other calderas

Principal pieces of evidence for existence of a caldera structure, as defined by Williams (1941), occur at Los Azufres (Pradal, 1990; Robin and Pradal, 1993): (1): the outpourings of large ignimbrite deposits whose volume is compatible with a large collapse; (2) a circular ring fault system; (3) external concentric fractures and radial faults; and (4): the distribution of the domes in

Table 4
Comparison of Los Azufres with other large calderas. (1): this work and Pradal, 1990. (2): Ferriz and Mahood, 1984, 1987. (3) Mahood, 1980. (4): Newhall and Dzurizin, 1989. (5): Aramaki, 1984

Name	Diameter (km)	Tectonic setting	Age (Myr)	Associated ash flow units	Magma chamber inferred volume	Resurgent dome	Hydrothermal activity
LOS AZUFRES Mexico (1)	18×20	Extensional set. Cuitzeo Graben	1.5–1.4	Tarandacuao and Ucareo tuffs Rhyolites 80 km³	800 km³ min.	Doming on the S rim; probably ~0.6 Myr ago	Exploited geoth. field, hot-water dominated system
LOS HUMEROS Mexico (2)	15×21	Extensional setting	0.47	Xaltipan ign. Rhyolites 115 km³	?	Minor uplift S of Los Potreros caldera	hot springs, fumarolic activity, expl. geoth. field
LA PRIMAVERA Mexico (3)	11	Extensional setting	0.95	Tala Tuff Rhyolites 20 km³	?	asymetrical uplift 60,000 years ago	Geoth. field vapor dominated
AMATITLAN Guatemala (4)	14×16	NNE–SSW graben	0.24	unnamed Rhyolites 70 km³	?	uplift inferred	hot springs, fumarolic activity
VALLES (Jemez Mts.) New Mexico (4)	20×22	Extensional setting	1.1	Bandelier Tuff Rhyolites 150 km³	3500 km³	Redondo Dome	geoth. field, hot springs, fumaroles
LONG VALLEY California (4)	17×32	Extensional setting	0.7	Bishop Tuff Rhyolites 500 km³	2400 km³	present uplift	major subsurface hydrothermal reserv., hot springs
YELLOWSTONE Idaho–Wyoming (4)	85×45	Extensional setting	0.6	Lava Creek Tuff Rhyolites > 1000 km³	15,000 km³	3 resurgent domes (1 on the NW caldera rim)	major hydrothermal system, hot springs, fumaroles
AIRA Japan (5)	20	Extensional setting	0.022	Osumi, Tsumaya, Ito Rhyolites 140 km³	?	none, intracaldera active cone	fumaroles

Table 5
$^{87}Sr/^{86}Sr$ data of three volcanic units of the second magmatic cycle from the Los Azufres complex. Analysis from Rb-Sr laboratory, Department of Earth Sciences, Clermont-Ferrand University. See Tables 1 and 2 for samples location

	La Calabaza andesite	Cieneguillas rhyolite	Recent parasitic cone
$^{87}Sr/^{86}Sr$	0.70357±2E−5	0.70553±4E−5	0.70367±3E−5
Age (Myr)	0.6	0.026	0.03?

an arcuate pattern. There were at least two major ignimbrite eruptions, the TA and UC ignimbrites, which released a considerable volume of acidic magma (probably more than 100 km^3) and lead to collapse of the Los Azufres caldera. Four less voluminous series of ash and pumice flow deposits are also seen: the PV, SPJ, CI and AC series.

Each paroxysmal ignimbritic phase coincides with (or is followed by) the extrusion of domes. A comparison with other calderas on volcanological aspects such as volume of magma released, diameter and duration of activity is presented in Table 4. With a collapse zone of about 20×18 km, the Los Azufres structure is comparable in size with the Los Humeros caldera, located to the east of Mexico City (Ferriz and Mahood, 1984), and to Sierra La Primavera (Mahood, 1980), particularly with respect to the presence of domes along fractures. The development of the central caldera collapse at Los Azufres occurred together with extracaldera ring and radial fracturing affecting a larger region, a feature also seen at Timber Mountain volcanic center in Nevada (Christiansen et al., 1965). At Los Azufres, basement rocks subject to this extracaldera faulting are strongly hydrothermally altered, indicating an important role of fluids (Pradal, 1990), logically related to the ascent of a magma body, in this volcano-tectonic setting. Moreover, radial faulting and weakly outward-tilted Pliocene sediments (<5°) from the graben, north and south of the complex near Acambaro and Cieneguillas (Fig. 3), point out the existence of a regional doming, prior to the ignimbrite emissions: the tilted sediments located north of the complex, outside the caldera, are too far from the resurgent dome —located in the southern part of the caldera— for attributing their tilting to the resurgent doming, a more local phenomenom. The regional doming is probably related to the ascent of a magmatic body, like in other calderas systems (Vincent, 1963; Smith and Bailey, 1968).

4.3. Alternating mafic and silicic magmatisms; evolution of the magmatic reservoir

Since about 1.5 Ma, the Los Azufres complex developed alternating phases of acidic and mafic magmatism during two main volcanic periods (from about 1.5 to 0.8 Ma and 0.6 Ma to Present). The first magmatic cycle was initiated by the eruption of the Tarandacuao–Ucareo rhyolitic tuffs and related domes, was followed by a small amount of dacitic lavas (Loma Grande) and then basalts. The second major volcanic activity occurring in this first magmatic cycle took place between ~1 and 0.8–0.75 Ma, with the emission of the SPJ and PV rhyolitic ignimbrites. Mafic volcanism then, with El Zapote Alto andesites, ended this first magmatic cycle. This order in the magmatic events globally suggests the emptying of a compositionally zoned magma chamber. Important ring and radial faulting associated in space with hydrothermal alteration and volcanic activity show that the magmatic chamber is shallow (geobarometers calculations agree with field data and give a depth of about 6 km for the roof of the chamber, Pradal, 1990).

A period of quiescence from ~0.75 Ma to ~0.6 Ma, allowed weathering of SPJ and PV units.

The second magmatic cycle began with the emission of voluminous series of mafic lava flows, which gave rise to the La Calabaza and

Mesa Llano Grande units. As for the lavas of Zapote Alto, the vents are located near the edge of the caldera and the lavas flowed essentially outwards on the external slopes of the structure. Important slickensides on these units show that new phases of subsidence of the graben occurred since this period (Pradal, 1990). These basic formations initiate a long period of volcanism which progressively grades into dacitic magma (Cerro San Andres and Cerro Mozo, 0.5 to 0.3 Ma) and then rhyolitic compositions (CI and AC units, from 0.3 Ma to present).

The latest paroxysmal events, between 38,000 and 26,000 yr BP, are represented by the Acambaro ignimbrites and the youngest ignimbrites of the Cieneguillas group associated with Cerro Guangoche at the northwestern and the southwestern portions of the caldera structure, respectively.

It is worth noting that the two main periods of continued volcanism have reversed magmatic compositional trends: eruptive products from the first (Lower–Middle Pleistocene) globally shifted from rhyolites to basalts with time, while volcanism during the second cycle (Upper Pleistocene) changed from mafic magmas to rhyolites. If progressive emptying of a magma chamber, in which differentiation previously occurred, can explain magmatic evolution during the first period, the second one suggests progressive differentiation in the magmatic system; this one seems to be periodically opened; this is consistent with the recent (Upper Pleistocene) supplies of basic magmas pointed out by the construction of young numerous scoria cones outside the caldera and by geochemical data such strontium isotopic ratios (Table 5; Pradal, 1990): the low values for mafic lavas compared to rhyolites ones agree with field data. Moreover, the distribution of the recent cones suggests a 'shadow zone' for the basaltic volcanism, suggesting the persistence of a voluminous differentiated magma chamber (Pradal, 1990).

4.4. Implications for the geothermal field

Uplift has affected the Sierra Los Azufres where the geothermal field is located (Pradal, 1990; Robin and Pradal, 1993). This is documented by: (1) the raising of the lower andesite series up to 3,000 m; (2) the outward and inward dips and the faulting of the SPJ ash and

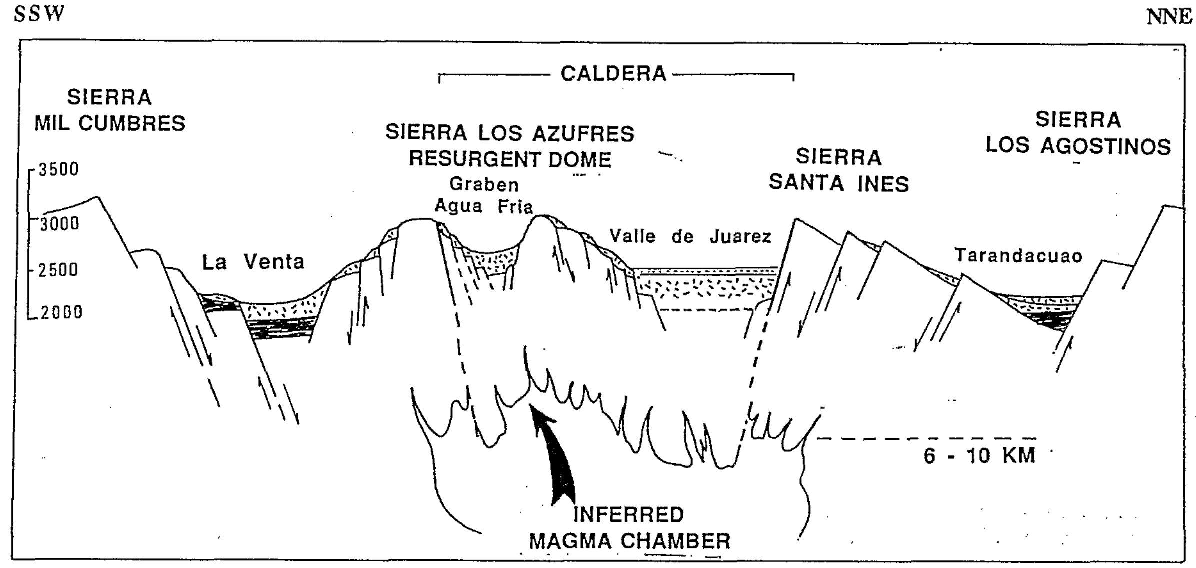

Fig. 6. Interpretative diagram of the Los Azufres caldera in a SSW–NNE section showing the relationships with the extensional tectonics and the resurgent doming (arrow). *1*=andesitic basement; *2*=Plio-Pleistocene sediments; *3*=ignimbrites; *4*=intracaldera sediments.

pumice flows; and (3) a series of horsts and grabens through the sierra. It is difficult to date the beginning of this uplift: relations between faulting and chronology of the volcanic units lying on the sierra (Pradal, 1990) suggest that the main phase of the uplift may be related to the replenishment of the magmatic reservoir occurring just before the eruption of La Calabaza and Llano Grande andesites ~0.6 Ma ago. Thus, this uplift would represent resurgent doming in the system. Because the dacitic extrusions of Cerro San Andres (0.33±0.07 Ma) are also cut by the E–W fractures (Dobson and Mahood, 1985), which localized the uplift, we think that several successive resurgent pulses might have occurred. The age of the CI rhyolites and their emission along the ring fracture zone close to the uplifted basement of Sierra Los Azufres, are consistent with such a model. This model points out a persistent, voluminous rising body of differentiated magma, probably at shallow depth under the SSW side of the volcanic complex (Fig. 6). Such results form a starting point for further studies, and may consequently influence future evaluation of the geothermal potential as well as volcanic forecasting in the Los Azufres region.

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