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The Los Azufres Caldera, Mexico. Comment on the paper by L. Ferrari, V.H. Garduno, G. Pasquaré and A. Tibaldi, or: An attempt to understand the volcanic structure

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Introduction

Recently, Ferrari et al. (1991) stressed the difficulties of knowing the geometry of the collapse area at Los Azufres caldera. They suggest a Late Miocene (~6.1 Ma) subcircular caldera, 27 km in diameter, and reject the previously proposed hypothesis of a smaller and younger collapse affected by Pleistocene resurgence (Pradal and Robin, 1985). New data obtained since 1985 confirm the collapse previously proposed and clarify the Pleistocene evolution of the caldera complex. In this comment, our aim is not to rule out the existence of a Miocene caldera, but to answer the criticism of our work and contribute to the understanding of this rhyolitic complex, the interest in which is augmented by its geothermal field. New field observations reported here should show that the Los Azufres caldera defined by Ferrari et al. should be viewed with caution.

Previous works

From 1975 to 1985, much work has been carried out at Los Azufres by geologists from the Comision Federal de Electricidad and Stanford University (references in Pradal, 1990, and Ferrari et al., 1991). No caldera structure was revealed by this work. After a field reconnaissance, Pradal and Robin (1985) proposed a large collapse in order to explain the large scale siliceous activity in this area. A more detailed paper was submitted to this Journal in 1989. Since one reviewer asked for more data, a geochronological study was undertaken. As a result, the magmatism has been shown to have had long lasting cycles since the Early Pleistocene. Their relationship to the caldera structure and the Pleistocene evolution of a voluminous magma reservoir are described in Pradal (1990) and Robin and Pradal (submitted).

Discussion

In order to clarify the following discussion, the major rhyolitic units recognized at Los Azufres by different studies are listed together in Table 1. Numerous dacitic domes and voluminous andesitic series not reported in this table should also be considered. In our interpretation, these domes and andesites originate mainly from the ring fracture zone and together compose the rhyolitic phases of the long-lived cycles already mentioned.

Miocene ignimbrites

Ferrari et al. relate two earlier ignimbrites (El Terrero and Pucuato ignimbrites, Table 1) to their proposed large collapse. In the field,

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TABLE 1

Rhyolitic units recognized at Los Azufres. In bold: first proposed appelation

Ferrari et al., 1991	Dobson, 1984; Dobson and Mahood, 1985	Pradal, 1990; Robin and Pradal, submitted; Pradal and Robin, 1985	Age (Ma)
El Terrero ignimbrite	not studied	Not studied	~6
Pucuato ignimbrite	not studied	for these authors, not related to Los Azufres (Tepetates ignimbrite of Pradal, 1990)	?
Lake Cuitzeo ignimbrite	not studied	not studied	2.8
Santa Ines ignimbrite	not studied	**Tarandacuao ignimbrite**	< 3, see discussion
Zinapecuaro domes	not studied	**Ucareo ignimbrite and domes**	1.5–1.2
Los Azufres andesite stratocone	not recognized	for these authors, no structure of this type	1 date: 1.02
Summit domes	**Agua Fria Group**	San Pedro Jacuaro ignimbrites and domes	1–0.9
Pueblo viejo pyroclastic flows	not studied	**Pueblo Viejo ignimbrite**	0.8
Recent domes	**La Yerbabuena Group**	Cieneguillas Group	0.3–0.02
(not named and associated with Pueblo Viejo)	not studied	**Acambaro ignimbrite**	0.036

we observed the Pucuato ignimbrite which extends at South over the Sierra Mil Cumbres. This ignimbrite is related to a collapse, 6 km in diameter, observed around the Presa Pucuato, in an area identified by SPOT satellite (Fig. 1). This caldera formed before the major Pliocene subsidence of the Cuitzeo–Maravatio graben and before the collapse of Los Azufres, in such a way that the tuffs are exposed in the La Venta scarp, this latter being the result of both tectonic and volcanotectonic movements (see below). The minimum volume estimated by Ferrari et al. for this unit (4.8 km^3) is compatible with the relatively small diameter of the Pucuato structure and the observed ring scarp. This ignimbrite has been named the Tepetates ignimbrite by Pradal (1990) because of large outcrops at Puerto Tepetates along the La Venta scarp.

As regards the earliest volcanic unit, the Terrero ignimbrite, its source is probably in the Los Azufres region, but we have found no evidence allowing us to associate this unit with any obvious collapse.

The Cuitzeo and Tarandacuao (or Santa Ines) ignimbrites: Formation of the Upper Pliocene or Lower Pleistocene Los Azufres caldera

A major ignimbrite sequence north and northeast of Sierra Santa Ines was named the Tarandacuao ignimbrite by Pradal (1990) and the Sant Ines ignimbrite by Ferrari et al. (1991). Two different ages have been obtained on the same unit of welded tuff (4.5 and 3.4 Ma) Pradal (1990) and Robin and Pradal (submitted) stress the difficulty of obtaining the true ages of this ignimbrite, owing to its many xenoliths. Considering that the tuffs overlie Pliocene sediments that fill the Cuitzeo-Maravatio depression, and that no rhyolitic sequence was discovered between the Tarandacuao ignimbrite sequence and the ~1.3–1.5 Ma Ucareo series (thick rhyolite lava flows, ig-

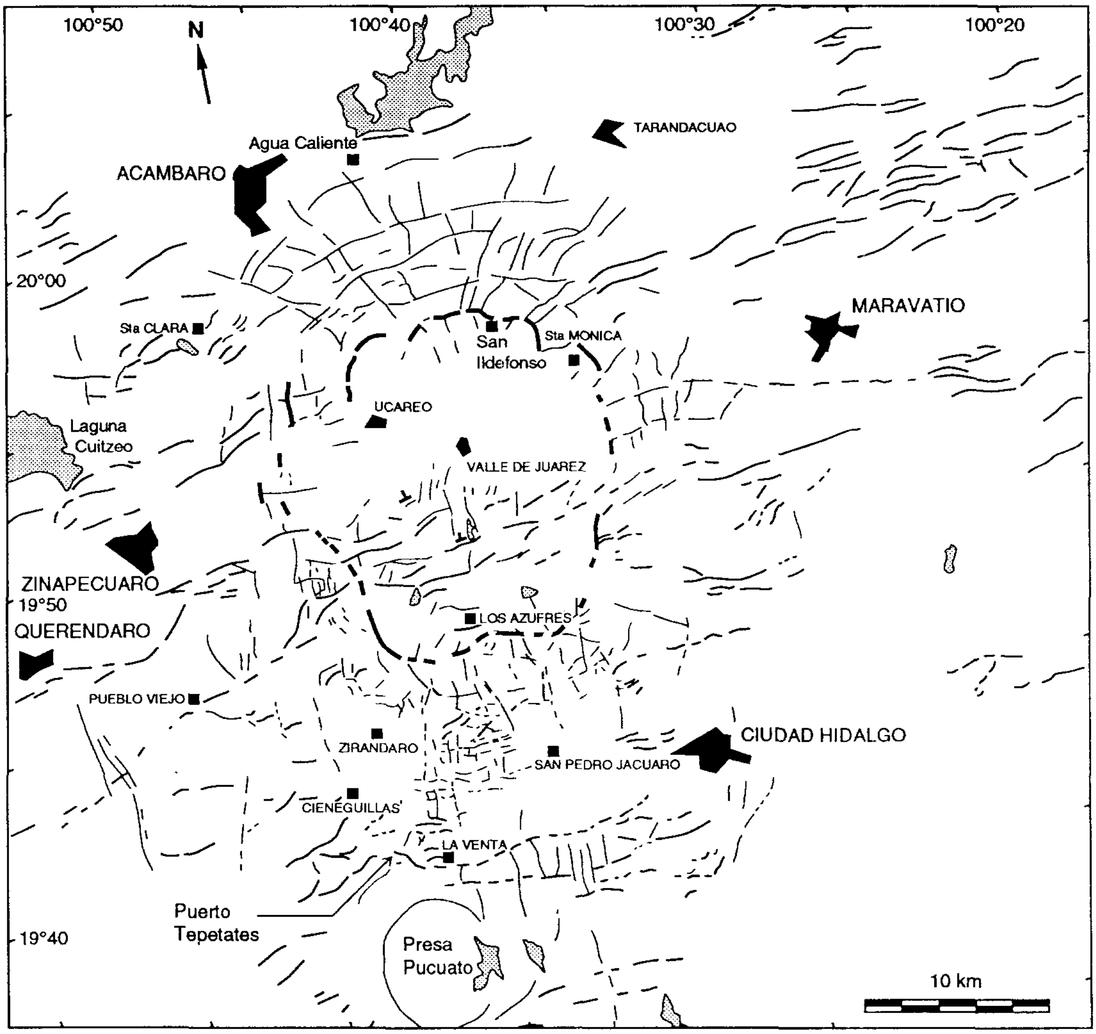

Fig. 1. Structural map of the Los Azufres area, from an interpretation of the SPOT orbital scene (Pradal, 1990; unpublished thesis). Heavy lines: caldera rim.

nimbrites and domes), Pradal (1990) and Robin and Pradal (submitted) proposed a Late Pliocene or Early Pleistocene age for the Tarandacuao sequence. Since the age of the Cuitzeo ignimbrite which extends westwards is about 2.8 Ma (Ferrari et al., 1991), we propose that the Cuitzeo sequence is probably the western equivalent of the Tarandacuao sequence. In view of the wide distribution, original volume (greater than 100 km^3 for both sequences) and the reservations already mentioned about their apparent age, one can suppose that development of the Los Azufres caldera started with the emission of these ignimbrites between 3 and 1.5 Ma.

Geometry of the collapse area

The northern limit along the Sierra Santa Ines in the model of Ferrari et al. agrees with the geometry that we previously proposed. Major differences between the two interpretations concern the eastern and southern rims of the caldera.

Our definition of the collapse area rests on our interpretation of SPOT orbital views (Fig.

1), field observations and a diagrammatic representation of andesite topography under the rhyolites in Sierra Los Azufres, based on drilling data (Pradal, 1990). The arcuate distribution of the domes and andesitic vents (Pradal and Robin, 1985; figs. 2 and 3 in Robin and Pradal, submitted) is also a strong argument for the delineation of the ring structure. Since the domes were extruded 4.5–5 Ma after the proposed Miocene collapse, the model of Ferrari et al. suggests that the rhyolitic domes are independent of the caldera development. In their model, most domes, andesitic vents and basaltic vents are located within the 27-km-wide collapse area. In our model, the domes are mainly on the ring fracture, the other ones lying outside the collapse on outer fractures, concentric to the caldera edge, and only scarce basalts were emitted within the caldera.

Concerning the eastern rim, we emphasize the existence of pyroclastic flows underlying the la Calabaza andesites. Both rhyolitic and andesitic rocks are seen to have flowed eastward, i.e. over the outer flank of our proposed structure. By their location, the thick La Calabaza lava flows ($\sim$0.6 Ma) compare to the lava series that originated at the southern edge of the Los Humeros caldera (Demant, 1981; Ferriz and Mahood, 1984). In the interpretation of Ferrari et al., the vents should be about 4 km inside the caldera and these series would dip towards the wall. We consider this illogical.

In the south, Ferrari et al. argue that epiclastic fluviolacustrine sediments are present in the sector Huajumbaro–La Venta and suggest that the La Venta depression bears evidence of the Los Azufres caldera system and subsequent refilling. Thus, they associate these sediments (the main sequence of which is located near Cieneguillas Village and has been described by Pradal, 1990) to the sediments that fill the Valle de Juarez depression near San Ildefonso. The latter, located at 2450 m altitude have horizontal or gentle dips toward the center of the Valle de Juarez depression and may be considered intra-caldera lacustrine deposits (description in Pradal, 1990).

In the southern area (La Venta), the floor of the depression is at 2050 to 2100 m, 400 m lower than the altitude of San Ildefonso. The sediments near Cieneguillas (marl, diatomites, and flinty siltstones) are faulted and perched on blocks of the extensive margin of the Sierra Mil Cumbres. Moreover, they are tilted 15–25° to the south, i.e. toward the caldera wall if we accept the model presented by the authors. Another perched sequence with layers of rounded blocks occurs 4 km west of Ciudad Hidalgo, 130 m above the la Venta–Ciudad Hidalgo depression. Many similar sequences can be observed at various altitudes from 2000 m to 2600 m (see sections fig. 5, Robin and Pradal, submitted and Pradal, 1990) in the north and east up to 30 km from the Los Azufres volcanic complex. Thus, no argument allows us to dismiss the hypothesis of deposition during the long-lasting subsidence of the Cuitzeo–Maravatio depression. At Cieneguillas, the faulting of the sediments as well as the arcuate form of the La Venta scarp are the consequence of the overlapping in this region of Pliocene graben subsidence and an outer fracture zone related to the Upper Pliocene or Lower Pleistocene caldera as we defined it. The southward dip of the sediments in the La Venta depression, first produced by tilting of blocks during the extensional tectonism may have been accentuated by regional doming related to emplacement of a magma body before the emission of the Tarandacuao and Cuitzeo ignimbrites, as also suggested by northward dips observed in diatomites near Agua Caliente, on the northern flank of the complex.

Pleistocene development. On the existence of the "Los Azufres stratocone" and discussion of resurgent doming

Ferrari et al. refute our interpretation of the Sierra Los Azufres as the result of resurgent doming. In order to explain this volcanic chain, they propose a Pleistocene andesitic volcano built within the 27-km-wide caldera, then covered by summit eruptions of rhyolitic and dacitic domes. The existence of such a stratocone is based on the dating of one andesitic lava flow (1.03 My; Dobson and Mahood, 1985), unpublished data on an unknown number of measurements, and apparent opposite dips of the lavas towards the north and the south. Such a model rules out the possibility that the andesites of the sierra could be vestiges of ancient uplifted volcanic rocks similar to the Mil cumbres or Santa Ines volcanics. Ferrari et al. estimate the thickness of the "Los Azufres stratocone" to the 700–800 m.

The following arguments raise questions about the existence of such an edifice and favor instead an elevated andesitic basement:

(1) On the northern side of the sierra Los Azufres, the andesites crop out up to 3200 m whereas on the southern side they are at elevations of less than 2800 m, below the rhyolites. Thus, if it exists, the Los Azufres stratocone is asymmetrical. It is worth noting that the caldera we proposed (Pradal and Robin, 1985 and fig. 1) separates the two parts of this "stratocone", the highest (i.e. the resurgent zone in our interpretation) being *inside* the caldera.

(2) Ages from 3 to 6 My have been measured on andesites from wells, below the rhyolites at depths ranging from 700 to 900 m (Aumento and Gutierrez, 1980). For example, if one considers that the thickness of the rhyolites in hole A7, located at the centre of the sierra, is 500 m and that an andesite dated 5.9 ± 0.4 Ma has been encountered at a depth of 700 in the hole, the thickness of the Pleistocene Los Azufres stratocone at its centre is very reduced.

(3) On the southern side of the sierra, between 2550 m and 2900 m, as well as on the northern side, several ash and pumice-flow deposits of the San Pedro Jacuaro series ($\sim$0.9–1 Ma) and interbedded fluvioclastic deposits overlie the andesites. These deposits have average dips outwards of 12 to 15° and locally 20° or more. Such values are unlikely for original deposits of these materials and we must conclude that there has been a general uplift of the center of the Sierra during the Late Pleistocene.

(4) A stratigraphic reference for definitive evidence of uplift is the Pucuato (or Tepetates) ignimbrite at the top of the Sierra Los Azufres near Laguna Alhaïta (2900 m altitude, sample AZ 145 in Pradal, 1990, equivalent to sample AZ 50 from Puerto Tepetates at 2400 m altitude). Thus, even in the Ferrari et al. model, the Sierra would represent either a resurgent zone or a horst that have not participated to the collapse. This is difficult to imagine.

Ferrari et al. agree with the estimated 10–5 km^3 (Dobson and Mahood, 1985) of Late Pleistocene rhyolites that constitute the "summit domes" of the Los Azufres volcanic volcano. Pradal (1990) estimates the volume of the Late Pleistocene rhyolites around Los Azufres at $\sim 16\ m^3$ (ca. 6 and 10 km^3 for the San Pedro Jacuaro and the Cieneguillas series, respectively). As for the acidic products of the Sierra Los Azufres, the volume of the San Andres complex of dacitic domes — at least 5 km^3 — should be added to these rhyolites. Since they have a genetic relationship with andesites (Pradal, 1990), such a volume of differentiated materials should belong to a much more voluminous cone than the "Los Azufres volcano", as this latter is defined by the authors, and should also be related to a large caldera in the summit area of that stratocone. On the contrary, the whole caldera complex (including the Pleistocene Zapote Alto and La Calabaza andesites) is more likely to produce such a volume of differentiated products. As mentioned earlier, the Pleistocene development of the volcanism of Los Azufres follows cycles with alternating felsic and mafic products. One of these cycles started with the eruption of the Ucareo rhyolites at 1.3–1.4 Ma and ended with emission of andesites and basalts on the western caldera edge at about 1 Ma. Probably, the andesite dated at 1.03 Ma in the Sierra Los Azufres and the other aphanitic lavas mentioned by Ferrari et al. belong to a vent from the end of this cycle, and located near the fracture zone.

Thus, one can reasonably conclude that resurgent doming occurred. By comparison of the elevations of the Pucuato ignimbrite at Puerto Tepetates and Laguna Alhaita the resurgence can be estimated to have been about 500 m. A major resurgent phase occurred between 0.8 and 0.3 Ma (Pradal, 1990), probably as a result of refilling the magma chamber during the last magmatic cycle at about 0.6 Ma (Robin and Pradal, subm.). On the contrary, no serious evidence supports a large stratovolcano in the Sierra Los Azufres. The main part of the andesites from Sierra Los Azufres (elevated by resurgent doming), the voluminous lava series in Sierra Santa Ines, the 12-Ma andesites from the eastern caldera wall near Santa Monica and overlain by the La Calabaza andesites (Pradal, 1990), and those from many inliers within the graben, are remains of an ancient volcanic province that covered the region before the graben was formed. These andesites, from 12 My or more to ~3 My, constitute the basement of the Late Pliocene and Pleistocene Los Azufres calderic complex.

Conclusion

The reconnaissance and description of the Lake Cuitzeo ignimbrite by Ferrari et al. (1991) are an important contribution to the understanding of the Los Azufres rhyolitic center. The beginning of the still persistent acid volcanism 3 to 1.5 My ago is now well supported. It is difficult, however, to associate the Pucuato ignimbrite and the earliest Terrero ignimbrite will the Los Azufres caldera. Such a conclusion does not preclude the existence in this region of a former Miocene caldera that could be related to the Terrero ignimbrite, but no longer discernible.

As regards the southern geometry of the caldera, further investigations are needed of the Pleistocene evolution of the caldera complex and the definition in time and space of resurgence. Nevertheless, in the light of the present discussion, our results offer a better working basis for further studies than the model proposed by Ferrari et al. Although some points of our short 1985 contribution were not well founded, we do not believe they deserve the criticisms of Ferrari et al.

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