VOLCANIC STRATIGRAPHY OF THE LOS AZUFRES GEOTHERMAL CENTER, MEXICO

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Abstract

The Los Azufres volcanic center, located 200 km northwest of Mexico City, is one of a number of Pleistocene silicic volcanic centers with active geothermal systems that lie north of the axis of the Mexican Neovolcanic Belt. This calc-alkaline suite overlies a thick pile of Miocene to Pliocene volcanic rocks dominated by andesitic lava flows. Three main episodes of volcanism have been documented at the Los Azufres center. Silicic volcanism began approximately 1 m.y. ago with eruption of the Agua Fria rhyodacite to high-silica rhyolite lava domes and flows. They are covered by rhyodacite and dacite lava domes and flows of the San Andres volcano. One of the San Andres dacites has been dated at 0.37 m.y. All these lavas are cut by high-angle normal faults. A north- to northeast-trending set is cut by a younger and more prominent east-trending set that parallels the principal regional structural trend. These faults do not cut the youngest volcanic rocks of the center, the Yerbabuena rhyodacites to high-silica rhyolites. These morphologically well-preserved lava domes are dated at 0.15 m.y. and are probably associated with air-fall tuffs that blanket the western portion of the volcanic center.

Los Azufres is the site of a producing geothermal system. Two episodes of high heat flow suggested by studies of drill-core samples and fluids from the Los Azufres geothermal field may correspond to two different episodes of magma injection to high levels, with the most recent one resulting in eruption of the Yerbabuena lavas 0.15 m.y. ago.

Introduction

The purpose of this short communication is to outline the geology of a silicic volcanic center associated with an important geothermal field for which there is little published information. The Los Azufres area has long been recognized for its thermal manifestations (Waitz, 1906; Maldonado, 1956; Alonso et. al., 1964; Mooser, 1964), but only recently has its geothermal potential prompted further study. Regional mapping and petrologic studies by Demant et al. (1975) and Silva Mora (1979) have been augmented by more detailed investigations of the geothermal area itself under the auspices of Mexico's Comision Federal de Electricidad (CFE) (Garfias and Gonzalez, 1978; Camacho, 1979, de la Cruz et. al., 1982). CFE has drilled over 30 wells to depths of up to 2900 m, providing good subsurface geologic information. Five well-head generators were installed in August of 1982 and are currently producing a total of 23 megawatts of electricity.

Regional Setting of the Los Azufres Volcanic Field

The Los Azufres volcanic center is located along the northern edge of the east-west-trending Mexican Neovolcanic Belt, 45 km east of Morelia, Michoacan (Figure 1). It is one of a number of Pleistocene silicic volcanic centers, including Los Humeros, La Primavera, Huichapan, and Amealco, that lie behind the zone of active andesitic stratovolcanoes (Ferriz and Mahood, in press). The nearest exposures of prevolcanic basement, gently folded shales, sandstones, and conglomerates of Eocene to Oligocene age (Mauvois et al., 1976), lie 35 km southwest of Los Azufres. Extensive Neogene volcanic rocks dominated by basaltic and andesitic lavas unconformably overlie these sediments. Two K-Ar dates of 18 and 13.5 m.y. (Table I) have been obtained on capping andesite flows. Similar Miocene to Pliocene lava flows, comprised primarily of phenocryst-poor andesite, form the local basement for the Los Azufres center. These andesite lavas, with minor intercalated pyroclastic horizons and basalt, porphyritic andesite, and dacite lava flows, have a minimum aggregate thickness of 2900 m as measured in well Az-20 (Garfias and Casarrubias, 1979). A minimum age of 10.2 ± 0.6 m.y. for the oldest volcanic rocks underlying the Los Azufres center is based upon a K-Ar whole-rock date on a drill-core sample from well Az-20 at 2700 m depth. Drill-core samples collected from higher stratigraphic levels yielded K-Ar dates of 5.9, 5.0, and 3.1 m.y. A whole-rock sample from a surface lava flow gave a K-Ar age of 1.35 ± 0.26 m.y. (Table I), thus providing a minimum upper age limit for this dominantly andesitic volcanism.

Volcanic History of the Los Azufres Volcanic Center

Silicic volcanism began shortly after eruption of the last andesites. Three major eruptive groups have been identified at Los Azufres: the Agua Fria rhyolites, the San Andres dacites, and the Yerbabuena rhyolites (Figures 2 and 3). The Agua Fria rhyolites consist of lava domes and stubby flows totalling approximately 10-15 km^3 in volume that cover 35 km^2 in the central part of the Los Azufres center. Outcrops of the lavas are typically blue-gray, flow-banded, and devitrified, with well-developed spherulites. A remnant of pumiceous carapace was observed at Cerro Pizcuaro, one of about seven topographically expressed domes (Figure 2). The domes vary in composition from rhyodacite to high-silica rhyolite, and contain phenocrysts of plagioclase>sanidine=quartz> biotite>Fe-Ti oxides ± hornblende ± orthopyroxene. The principal phenocrysts range in size from 1 to 5 mm and comprise 1-15% of the rock, with the more mafic compositions being more crystal rich. Nonhydrated obsidian samples from Cerro El Gallo and Cerro Chinapo yielded K-Ar dates of 0.85 ± 0.02 and

1.03 ± 0.02 m.y.; these glass dates provide a minimum age range for the Agua Fria volcanics. Three sets of paleomagnetic measurements on lavas gave reversed field orientations, corresponding well with the K-Ar dates. A fourth set of measurements, on the porphyritic Las Humaredas dome dated at 0.94 ± 0.02 m.y. (whole rock), gave a normal field orientation, which corresponds to the Jaramillo subchron of 0.92 - 0.97 m.y. (Tables I and II).

The next major eruptive group is the San Andres dacite and rhyodacite lava domes and flows. These lavas cover 70 km^2 east of the Agua Fria rhyolites and comprise an estimated volume of 15-20 km^3. In contrast to the other volcanic edifices of the Los Azufres center, the San Andres lavas form a large vent complex, the 700-m-high Cerro de San Andres. These porphyritic hornblende dacites and rhyodacites are dark gray to blue gray in color and commonly display flow-banding. They consist of 20-40% phenocrysts of plagioclase (1 cm in size), hornblende, clinopyroxene, orthopyroxene and minor biotite and quartz (1-5 mm), and Fe-Ti oxides (<1 mm). Rounded grayish-red aphyric inclusions up to 4 cm in diameter are common, and may be altered andesite from the "basement". Plagioclase from one of the San Andres lavas yielded a K-Ar date of 0.37 ± 0.07 m.y., which agrees with the normal field orientation measured at two sites (Tables I and II).

The Yerbabuena rhyolite forms the youngest major eruptive group of the Los Azufres center. It consists of five biotite-bearing high-silica rhyolite to rhyodacite domes and associated air-fall tuffs. The dome field covers 40 km^2 west of the older Agua Fria rhyolites and has an estimated volume of 8 km^3. The domes are well-preserved with pumiceous carapaces still intact. The lavas are light gray in color, with 5-15%

phenocrysts of plagioclase, quartz, sanidine, biotite, orthopyroxene, Fe-Ti oxides, and minor hornblende set in a glassy pumiceous matrix. The more mafic lavas are richer in phenocrysts. A glass separate from the dome El Carpintero yielded a K-Ar age of 0.15 ± 0.01 m.y., in agreement with its normal field magnetization (Tables I and II). Associated air-fall tuffs are at least 15 m thick near the domes and thin outward. The tuffs have been reworked, forming tuffaceous sediments that crop out south of the domes.

Compositions of Los Azufres Volcanic Rocks

The Los Azufres eruptive products can be classified as calc-alkaline; they fall within the calc-alkalic field of an AFM diagram (Figure 4) and satisfy the major-element and Ba/La-ratio criteria of Gill (1981) for a high-K suite. Possible mafic end-members of the Los Azufres suite are approximated by samples of the youngest "basement" andesites as well as a basaltic andesite from an outlying Pleistocene cinder cone. The relatively high Ti concentrations of the andesites are comparable to those observed elsewhere in the Mexican Neovolcanic Belt (Gunn and Mooser, 1970, Gill, 1981, p. 111). Chemical analyses from selected samples of the Los Azufres center are presented in Table III.

Lack of control on a parental magma for the Los Azufres suite makes modeling very speculative. We simply note that concentrations of Al_2O_3, FeO*, MgO, MnO, CaO, TiO_2, P_2O_5 and V all decrease with increasing SiO_2, while Rb and K increase (Figure 5). Drops in Sr and Ba concentrations after initial increases may reflect the importance of plagioclase and sanidine, respectively, as separating phenocryst phases. Declines in FeO*, TiO_2, and V concentrations are consistent with the presence of Fe-

Ti oxides in all of the Los Azufres volcanic units. Rb is the most incompatible element of those analysed, showing a five-fold increase in concentration with increasing differentiation.

Structural Aspects of the Los Azufres Volcanic Field

The Los Azufres center is structurally bound on the north by a large east-trending graben presently filled by Laguna de Cuitzeo (Figure 6). The orientation and style of faulting at the Los Azufres center are similar to large-scale regional features. East-striking high-angle normal faults cut the Agua Fria rhyolite and the San Andres dacite units, but do not disturb the younger Yerbabuena domes. Thus the last major episode of fault movement occurred between approximately 0.37 and 0.15 m.y. ago. Minimum offsets as determined by scarp heights within the Los Azufres center are on the order of 100 m for the principal faults. Movement is mainly dip-slip; little lateral offset of volcanic units is observed.

The principal faults cut and partially obscure an older set of high-angle normal faults that strike north to northeast. Both sets of faults serve as primary conduits for hydrothermal fluids, as shown by alignments of hot springs and fumaroles (Figure 2).

Comparison of the Los Azufres Volcanic Center with Other Silicic Centers in the Mexican Neovolcanic Belt

The Los Azufres silicic volcanic center differs in both eruptive style and magma compositions erupted from the well-studied Pleistocene silicic centers within the Mexican Neovolcanic Belt, La Primavera and Los Humeros. La Primavera rhyolitic center is located just west of Guadalajara. It is dominated by an 11-km-diameter caldera that formed

95,000 years ago on eruption of 40 km^3 of magma as ash-flow tuffs (Mahood, 1980, 1983). The tuff and succeeding lava domes are all mildly peralkaline, high-silica rhyolites (Mahood, 1981). The Los Humeros system (Yanez and Casique, 1980; Ferriz and Yanez, 1981; Ferriz, 1982; Ferriz and Mahood, in press) is located 180 km east of Mexico City. Three caldera-forming eruptions have occurred, the largest of which produced the 115 km^3 rhyodacite to rhyolite Xaltipan ash-flow tuff 0.50 m.y. ago. Since silicic volcanism began 0.51 m.y. ago, there has been a general trend toward eruption of increasingly mafic magmas as volumetric eruption rates increased with time.

The Los Azufres center is older than these two systems and magma compositions show a different evolution over time. At Los Azufres, approximately 10-15 km^3 of rhyodacite to high-silica rhyolite lavas were erupted between approximately 1.03 and 0.85 m.y. ago, followed by 15-20 km^3 of dacitic to rhyodacitic lavas at about 0.4 m.y., and finally an additional 8 km^3 of rhyodacite to high-silica rhyolite magma were erupted around 0.15 m.y. ago. These estimates of magma volumes are based on areal distribution and thickness of the volcanic units as determined by field mapping and drill-core data (Figures 2 and 3). These calc-alkaline products differ substantially from the slightly peralkaline, high-silica rhyolite products of the Primavera system, and do not span the wide range of compositions that includes significant amounts of mafic lavas at the Los Humeros center.

During the course of this reconnaissance field study, no caldera was identified. Ash-flow tuff does, however, crop out in the vicinity of the Los Azufres center. We were not successful in dating the phenocryst-poor, pumiceous ash-flow tuffs. Chemical analyses of samples from two outcrops located north and west of the center (A-80-5 and A-80-7 in Table III) indicate that the ash-flow tuffs are more evolved than any of the Los Azufres rhyolites sampled, having higher Rb and lower Ba, Cu, and Zr concentrations than either the Agua Fria or the Yerbabuena rhyolites. Ash-flow tuffs are commonly more evolved than cogenetic domes (e.g. Smith, 1979), thereby making Los Azufres a chemically plausible source. Significant accumulations of ash-flow tuff are not seen at the surface within the Los Azufres area proper and have not been identified in drill holes. Although an unusual thickness (>1000 m) of rhyolite was cut by well Az-23 (Figure 3), thin sections from drill core samples do not exhibit the vitroclastic textures, lithic inclusions, or broken phenocrysts typical of densely welded ash-flow tuffs. We interpret it as a feeder for the Cerro La Providencia dome.

One important feature shared by these three centers is the presence of an associated active geothermal system. The fact that all three centers have undergone significant silicic volcanism within the last 150,000 yrs. emphasizes that high-level silicic magma chambers are important as heat sources for the corresponding geothermal systems (Smith and Shaw, 1975). The reservoirs for all three of these geothermal systems are hosted by andesitic rocks that are capped by younger, altered, silicic volcanic rocks which act as a seal for the geothermal system (Ferriz, 1982, Mahood et al., 1983). The centers have fracture-controlled permeability, a feature demonstrated by the localization of hot springs and fumaroles along major faults, and by the close correlation of resistivity anomalies with principal structural features (Palma, 1982; Ferriz, 1982; Templos, 1982). The deep fluids of all of these systems are boron-rich chloride waters. Measured downhole temperatures of approximately 300°C in the Los Azufres system (Dobson and Janik, in prep.) are comparable to the deep water conditions of La Primavera (Mahood et al., 1983, Dominguez and Lippmann, 1983) and Los Humeros (Ferriz, 1982).

Links between Geothermal Activity and Volcanism at Los Azufres

The active geothermal field currently being exploited by the Comision Federal de Electricidad is centered within the highly fractured Agua Fria rhyolites and their underlying andesitic basement rocks. Hydrothermal activity is noticeably absent from the zone of most recent silicic volcanism, the Yerbabuena rhyolites.

Gutierrez and Aumento (1982) found that most alteration minerals in drill-core samples form two or more distinct zones that are spatially subparallel. They take this as evidence for two periods of hydrothermal activity which they attribute to two magmatic cycles. Oxygen isotope data on secondary quartz and calcite in drill-core samples supports an earlier stage of hydrothermal activity at Los Azufres (Janik and Dobson, 1983, Dobson and Janik, in prep.). These hydrothermal minerals are significantly out of isotopic equilibrium with present-day geothermal fluids at all but the lowest stratigraphic levels. Equilibration probably took place with an isotopically heavier fluid and at lower temperatures than are presently observed.

Abundant Pleistocene basaltic cinder cones that surround the Los Azufres center but do not occur within it are suggestive of a shadow effect within the Los Azufres center, implying that a high-level silicic magma chamber is currently present. A new influx of silicic magma to high levels between 0.4 and 0.15 m.y. could have rejuvenated the hydrothermal system and and culminated in eruption of the Yerbabuena rhyolite domes. Faulting appears to be a prerequisite for the movement of hydrothermal fluids. This may explain the absence of geothermal activity in the zone of the unfaulted younger domes.

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ABLE 1

ummary of K-Ar dates for the Los Azufres region

uptive unit	Locality[1]	Material	Sample wt.(g)	K_2O%	$^{40}Ar^*$ (10^{-13} mol/g)	$^{40}Ar^{atm}$ (%)	age(m.y)
asement" rocks	near Querendaro, Michoacan	--	--	--	--	--	18[2]
	19°39' 100°57'	WR(?)	--	1.722	--	66.0	13.8 ± 0.7[3]
	19°45'23" 100°41'10" (2700 m)	WR	--	1.648	--	87.5	10.2 ± 0.6[4]
	unknown drill hole (? m)	WR	--	2.129	--	95.2	5.9 ± 0.4[4]
	19°46'47" 100°40'00" (900 m)	WR	--	2.167	--	87.7	5.0 ± 0.4[4]
	19°45'23" 100°41'10" (720-1000 m)	WR	--	4.260	--	93.7	3.1 ± 0.2[4]
	19°49'48" 100°38'11"	WR	2.6500	2.790	52.3	86.8	1.35 ± 0.26[5]
ua Fria yolites	unknown	WR	--	4.401	--	94.6	1.2 ± 0.4[4]
	19°46'21" 100°39'26"	glass	4.1217	4.69	69.5	46.6	1.03 ± 0.02[5,6]
	19°46'58" 100°39'46"	WR	6.6280	4.5	60.7	87.0	0.94 ± 0.02[5]
	19°48'46" 100°40'22"	glass	4.1003	4.68	57.0	49.1	0.85 ± 0.02[5]
n Andres acites	19°46'38" 100°37'30"	plagioclase	9.9638	1.8395	9.83	95.0	0.37 ± 0.07[5]
babuena olites	19°48'05" 100°43'15"	glass	6.4385	4.725	10.1	80.9	0.15 ± 0.01[5]

lue in parentheses gives depth below surface for drill-core samples.

macho, 1979 (old decay constants). Dash indicates data not reported.

mant et al., 1975 (old decay constants).

mento and Guteirrez, 1980. Dates recalculated using new decay constants.

is study. Decay constants are: $\lambda_\varepsilon = 0.581 \times 10^{-10} yr^{-1}$

$$\lambda_\beta = 4.962 \times 10^{-10} yr^{-1}$$

$$^{40}K/K = 1.161 \times 10^{-4} \text{ atom/atom}$$

· 82-50 (Table III).

TABLE II

Results of flux-gate magnetometry measurements

Eruptive Unit	Location	# Samples	Field Orientation	Interpreted Polarity Chron/Subchron
"Basement" rocks	19°45'49" 100°41'43"	5	reversed	unknown
	19°45'51" 100°41'32"	5	reversed	unknown
Agua Fria Rhyolites	19°47'16" 100°37'47"	5	reversed	Matuyama
	19°48'33" 100°38'55"	5	reversed	Matuyama
	19°48'06' 100°40'44"	6	reversed[1]	Matuyama
	19°46'58" 100°39'46"	5	normal	Matuyama/Jaramillo
San Andres Dacites	19°44'49" 100°33'14"	5	normal[1]	Brunhes
	19°47'37" 100°36'09"	6	normal	Brunhes
	19°48'23" 100°36'23"	6	normal	Brunhes
Yerbabuena Rhyolites	19°47'41" 100°42'27"	5	normal	Brunhes

[1] Additional samples were measured using alternating field demagnetization. The measured inclinations correspond with the flux-gate deflections observed in the field.

TABLE III

Chemical analyses of Los Azufres volcanic rocks[1]

	Outlying andesite	"Basement" andesites		San Andres lavas				Agua Fria domes		
	PDLA 82-29	PDLA 82-37	386	PDLA 82-24	PDLA 82-34	943	968	PDLA 82-38	PDLA 82-40	PDLA 82-50
	19°42'09" 100°34'01"	19°48'25" 100°31'46"	19°45'21" 100°41'15"	19°46'02" 100°37'18"	19°47'32" 100°36'18"	19°42'10" 100°35'58"	19°52'10" 100°37'00"	19°48'33" 100°38'55"	19°46'16" 100°38'53"	19°46'21" 100°39'26"
SiO_2	54.4	58.0	56.6	69.4	67.0	65.8	66.1	76.2	71.2	73.5
TiO_2	1.77	0.92	1.38	0.43	0.45	0.79	0.67	0.05	0.22	0.06
Al_2O_3	16.7	17.0	17.7	14.9	15.5	14.5	15.2	12.7	14.1	13.3
Fe_2O_3*	9.17	6.27	1.50	3.33	3.44	1.50	1.50	1.01	2.24	1.60
FeO	---	---	5.47	---	---	2.57	2.47	---	---	---
MnO	0.17	0.13	0.14	0.07	0.07	0.07	0.06	0.03	0.05	0.05
MgO	3.98	4.51	3.46	0.76	1.09	1.97	1.47	0.10	0.40	0.10
CaO	7.56	6.73	6.17	2.39	2.80	3.97	3.48	0.34	1.31	0.54
Na_2O	3.47	3.68	4.22	3.97	3.71	4.12	4.29	3.62	3.86	4.39
K_2O	1.63	1.74	2.03	3.59	3.43	3.01	2.95	4.55	4.22	4.61
P_2O_5	0.32	0.24	0.33	0.11	0.13	0.17	0.16	0.03	0.07	0.03
LOI	0.66	0.14	---	0.35	1.91	---	---	0.39	1.11	0.25
H_2O^+	---	---	0.93	---	---	0.93	0.48	---	---	---
H_2O^-	---	---	0.07	---	---	0.13	0.33	---	---	---
Total	99.80	99.33	100.03	99.28	99.51	99.50	99.14	99.53	98.77	98.65
V	209	120	140	30	39	75	65	10	11	10
Rb	43	46	54	119	100	75	78	169	140	136
Sr	456	651	500	241	327	569	459	12	141	23
Y	32	22	---	30	26	---	---	28	34	41
Zr	203	194	---	191	192	---	---	120	197	267
Nb	14	10	---	13	13	---	---	21	17	22
Ba	450	490	385	750	660	468	---	20	820	560
La	36	20	---	31	30	---	---	20	31	37

	Agua Fria domes		Yerbabuena domes				Air-fall tuff	Ash-flow tuff	
	PDLA 82-64	PDLA 82-70	PDLA 82-52	PDLA 82-74	389	447	PDLA 82-19a	A-80-5	A-80-7
	19°47'07" 100°39'36"	19°47'13" 100°39'52"	19°47'41" 100°42'27"	19°43'13" 100°42'47"	19°47'06" 100°41'16"	19°43'21" 100°43'03"	19°44'43" 100°40'20"	19°39'05" 100°44'37"	19°42'54" 100°44'57"
SiO_2	70.1	71.5	72.9	74.3	73.7	74.7	71.1	72.8	74.6
TiO_2	0.36	0.16	0.07	0.08	0.12	0.30	0.15	0.05	0.09
Al_2O_3	14.6	13.7	12.4	12.5	12.7	12.9	12.8	12.2	11.8
Fe_2O_3*	3.02	0.95	1.25	1.17	0.35	0.19	1.63	1.02	1.17
FeO	---	---	---	---	1.15	0.97	---	---	---
MnO	0.08	0.04	0.04	0.04	0.06	0.04	0.05	0.04	0.04
MgO	0.35	0.10	0.15	0.13	0.59	0.33	0.25	0.10	0.12
CaO	1.09	0.57	0.53	0.52	0.01	0.66	0.72	0.38	0.50
Na_2O	3.61	3.14	3.32	3.44	3.80	3.97	2.60	2.07	3.29
K_2O	4.21	4.66	4.29	4.74	4.68	4.89	4.48	5.93	4.87
P_2O_5	0.05	0.05	0.05	0.05	0.03	0.01	0.05	0.05	0.05
LOI	1.74	4.55	4.07	2.03	---	---	4.66	4.87	2.23
H_2O^+	---	---	---	---	2.55	1.66	---	---	---
H_2O^-	---	---	---	---	0.20	0.14	---	---	---
Total	99.41	99.40	99.05	99.37	99.93	100.70	98.59	99.49	98.91
V	21	10	10	10	---	14	10	10	10
Rb	134	147	185	219	---	254	186	215	236
Sr	130	42	31	27	---	10	24	19	26
Y	38	35	34	37	---	---	30	45	37
Zr	254	208	174	132	---	---	148	110	122
Nb	19	20	18	21	---	---	14	22	19
Ba	800	890	140	120	---	155	510	58	100
La	42	52	29	22	---	---	29	22	23

[1] Major elements, Rb, Sr, Y, Zr, and Nb determined by XRF. V, Ba, and La determined by emission spectrographic analysis. Analyses (with exception of 386, 943, 968, 389, and 447 from Silva Mora (1979)) performed by U.S.G.S. and P. Dobson (Mn, Rb, Sr, Y, Zr, and Nb). Dash indicates lack of data.

*Total iron reported as Fe_2O_3 where FeO not given.

Figure Captions

Figure 1 - Regional location map.

Stippled pattern: Mexican Neovolcanic Belt (modified from Demant and Robin, 1975; Demant, 1978); Quaternary calderas: La Primavera (LP), Amealco (A), Huichapan (H) and Los Humeros (LH); M: Mexico City. Box gives location of Fig. 5.

Figure 2 - Geologic map of the Los Azufres volcanic center.

Heavy lines with hachures indicate high-angle normal faults. Cerro El Gallo (EG), Cerro El Chino (CEC), Cerro Pizcuaro (CP), Cerro La Providencia (CLP), Cerro Las Humaredas (LH), Cerro El Jilguero (CEJ), and Cerro Chinapo (CCH) are Agua Fria rhyolite domes. Mesa El Carpintero (MEC), Mesa El Bosque (MEB), Mesa El Rosario (MER) and Cerro El Guangoche (CEG) are Yerbabuena rhyolite domes. Cerro de San Andres (CSA) is a vent complex for the San Andres dacites. Stars mark hot springs and fumaroles. A, B, C, D and E, F mark cross section locations.

Figure 3 - Geologic cross sections of the Los Azufres center. No vertical exageration. Vertical scale in meters above sea level. Symbols as in Fig. 2. Numbers mark well locations; data from Garfias (1981), Garfias and Casarrubias (1979a, b, c), Garfias and Gonzalez (1978), Garfias and Rivera (1980a, b, c), Izaguirre and Garfias (1981), and Rodriguez and Garfias (1981).

Figure 4 - AFM diagram.

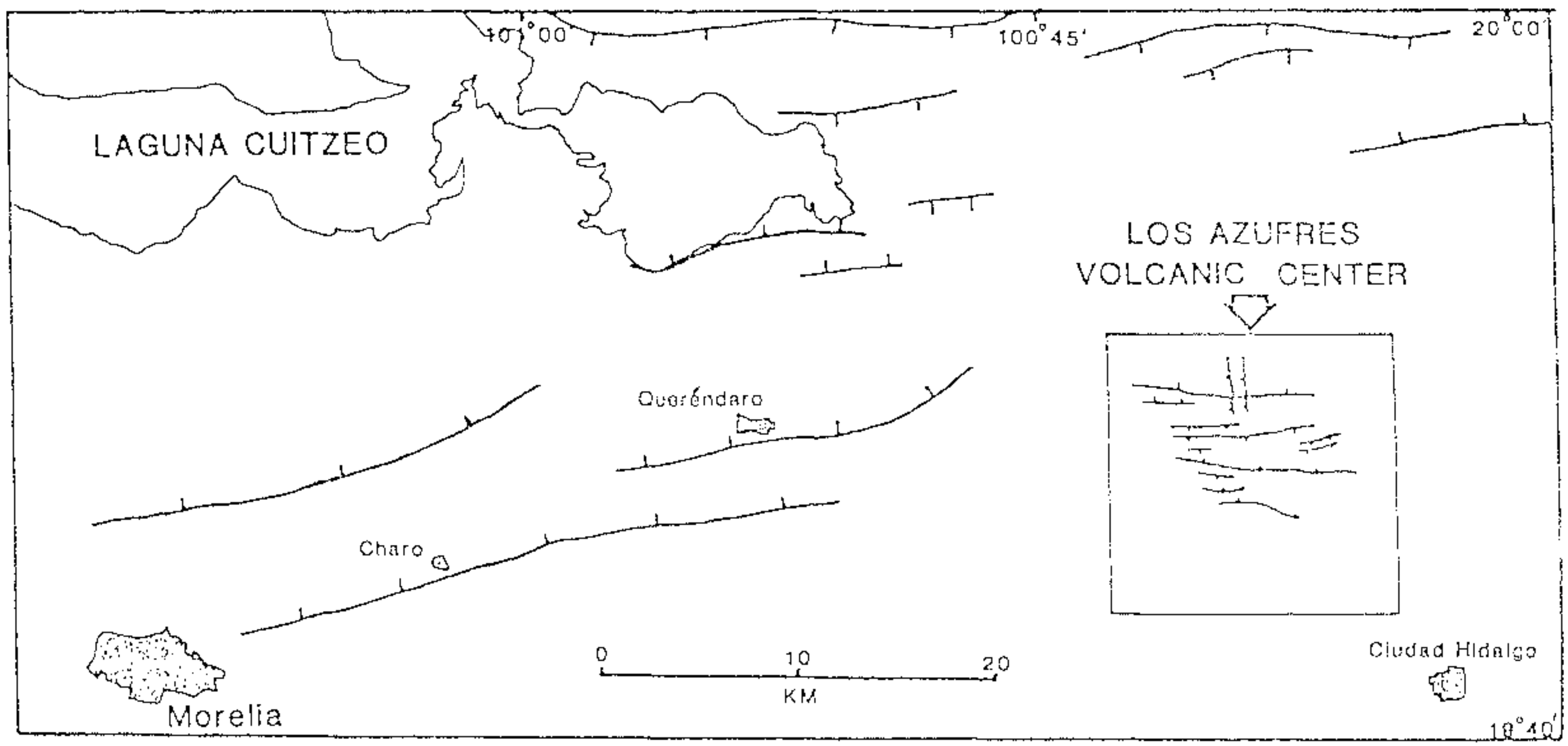
Dashed line marks boundary between calc-alkaline and tholeiitic fields of Irvine and Barager (1971). Squares: basaltic andesite and andesites; circles: Los Azufres volcanics; triangles: outlying ash-flow tuffs. Analyses from Table III recalculated to 100% anhydrous.

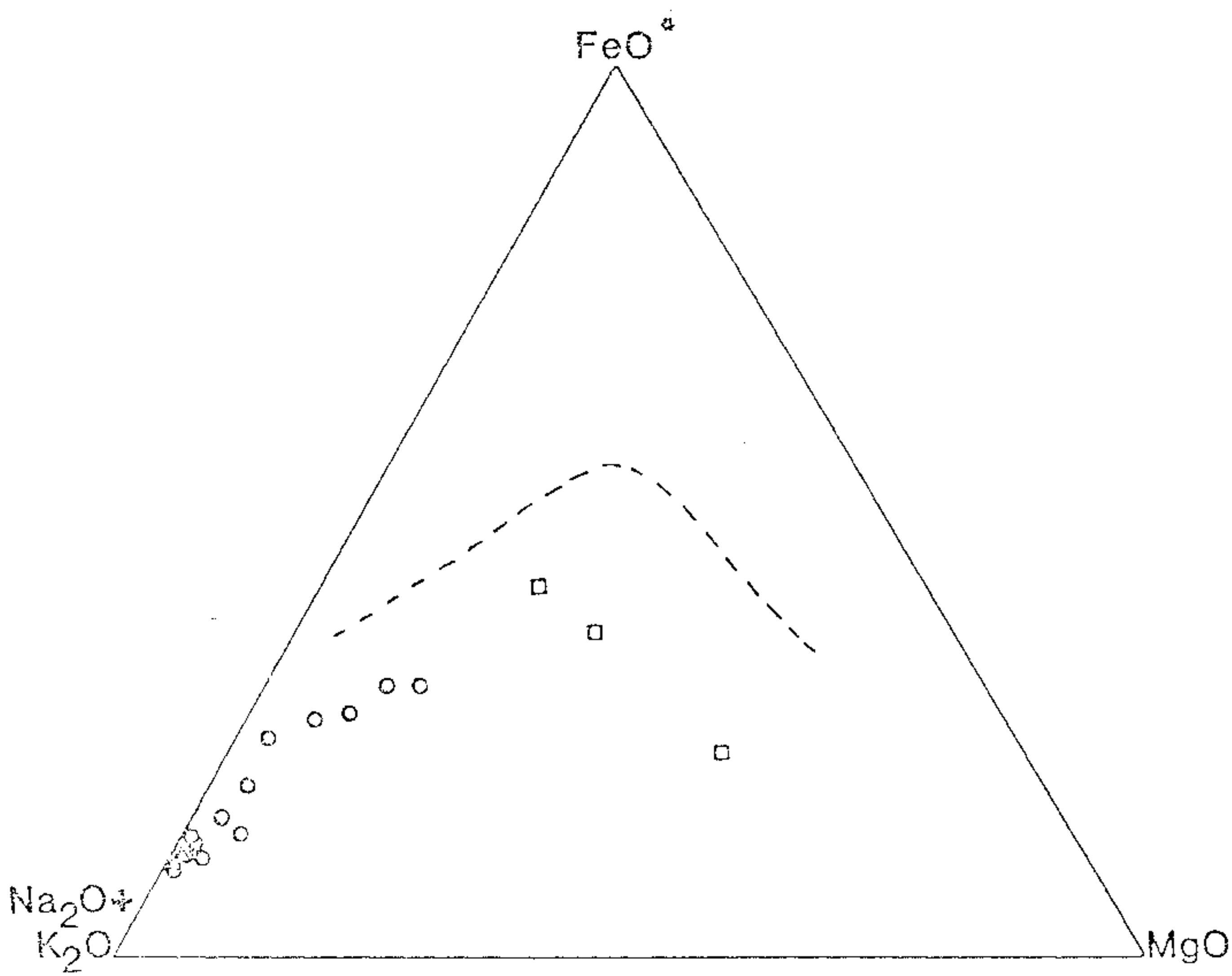
Figure 5 - Harker diagrams.

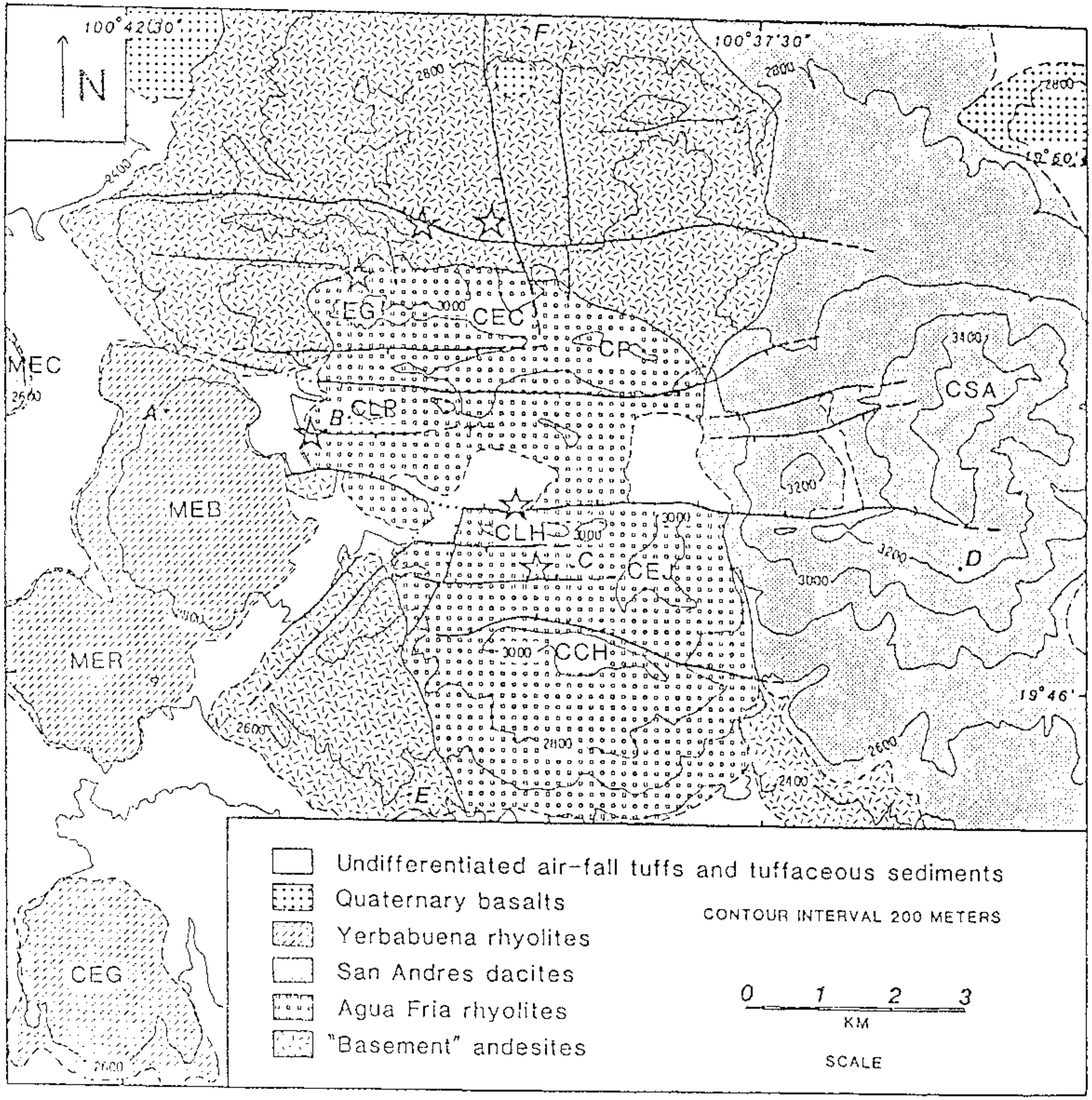
Analyses from Table III recalculated to 100% anhydrous (with Fe_2O_3* recalculated to FeO and Fe_2O_3 assuming $Fe^{2+}/(Fe^{2+} + Fe^{3+}) = 0.8$ for samples for which FeO was not determined). Symbols as in Fig. 3.

Figure 6 - Regional structural map.

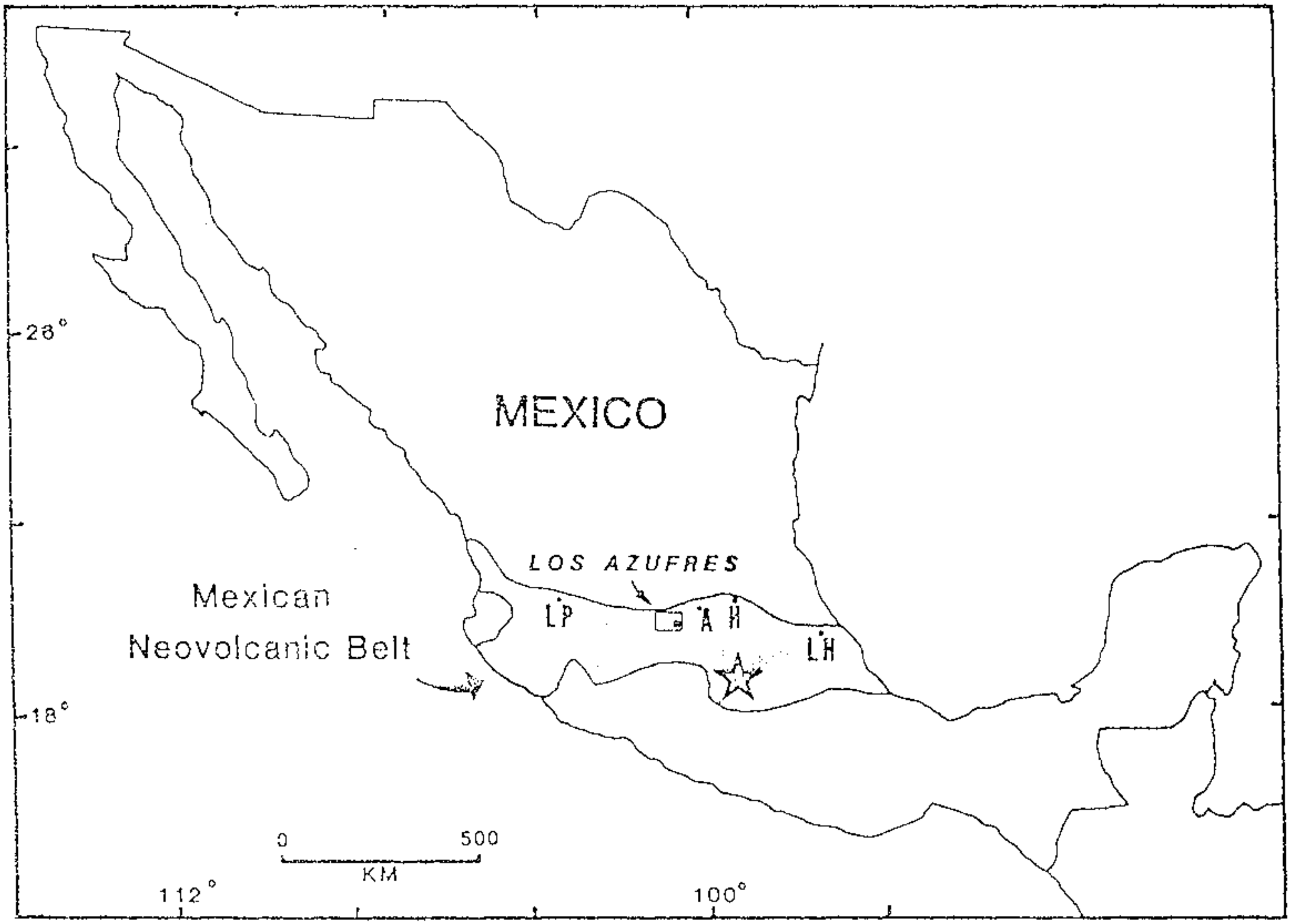
Heavy lines with hachures indicate high-angle normal faults. Stippled areas show locations of towns. Box gives location of Fig. 2.


101°00'
100°45'
20°00'
LAGUNA CUITZEO
LOS AZUFRES
VOLCANIC CENTER
Queréndaro
Charo
0
10
20
KM
Ciudad Hidalgo
Morelia
19°40'

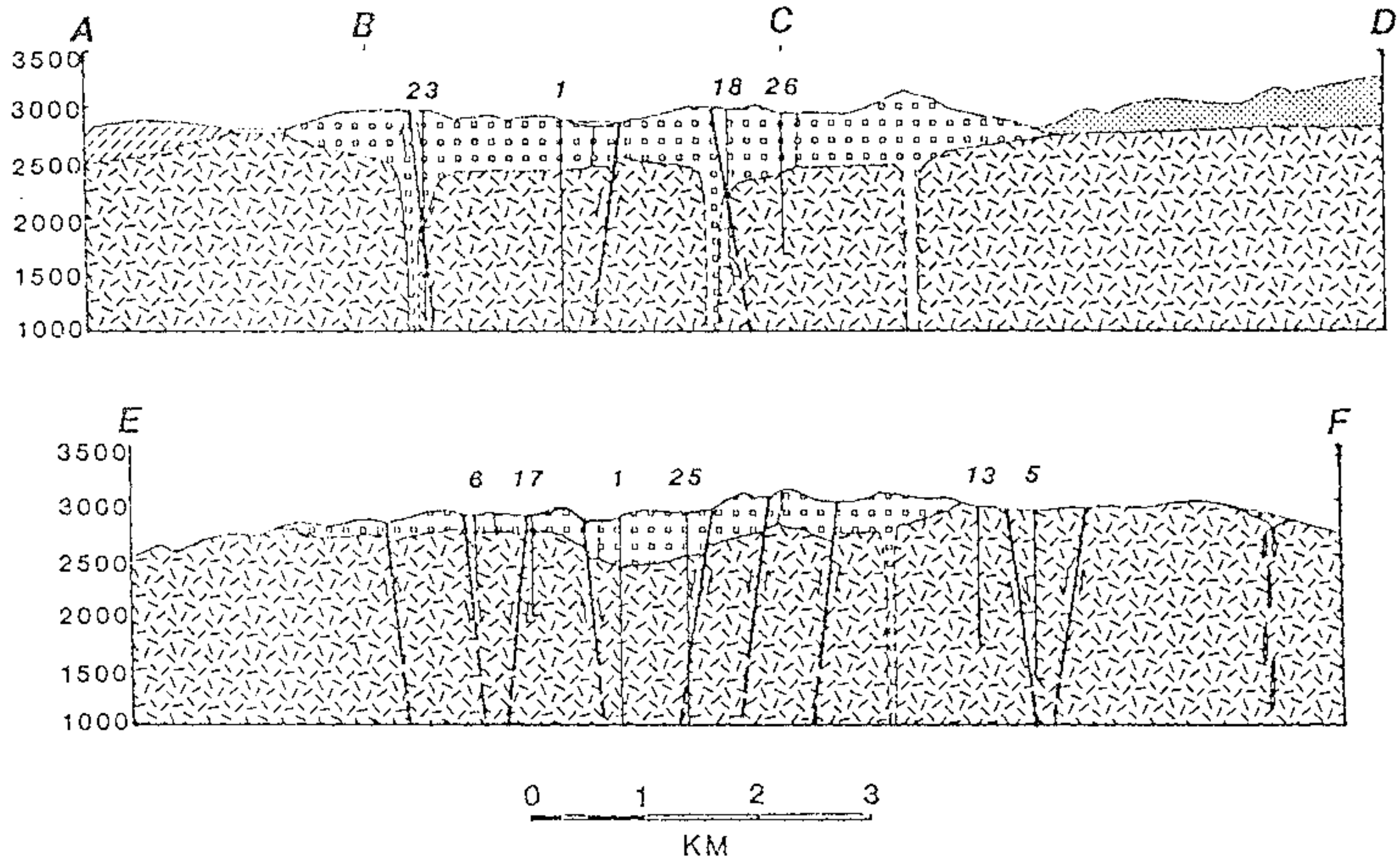

FeO*
Na2O+
K2O
MgO



N
100°42'30"
100°37'30"
F
2800
2400
19°50'
EG
3000
CEC
CP
MEC
2600
A
B
CLB
CSA
3400
3200
MEB
CLH
3000
C
CEJ
D
3200
3000
2800
MER
CCH
19°46'
2600
2800
2400
E
CEG
2600
Undifferentiated air-fall tuffs and tuffaceous sediments
Quaternary basalts
Yerbabuena rhyolites
San Andres dacites
Agua Fria rhyolites
"Basement" andesites
CONTOUR INTERVAL 200 METERS
0 1 2 3
KM
SCALE



MEXICO
LOS AZUFRES
Mexican
Neovolcanic Belt
LP
A
H
LH
28°
18°
112°
100°
0
500
KM


A
B
C
D
3500
3000
2500
2000
1500
1000
23
1
18
26
E
F
6
17
25
13
5
0
2
3
KM