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Southward migration of volcanic activity in the Sierra de Las Cruces, basin of Mexico? - A preliminary K-Ar dating and palaeomagnetic study

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RESUMEN

En este trabajo se reportan resultados de un estudio combinado de K-Ar y de paleomagnetismo de rocas volcánicas de la Sierra de Las Cruces, Cuenca de México. La Sierra está constituida predominantemente por rocas dacíticas, flujos piroclásticos y lahares. Constituye el límite oeste de la Cuenca y presenta una orientación NNW-SSE. Este estudio preliminar fue diseñado para investigar la estratigrafía volcánica de la Sierra y documentar cuantitativamente una aparente migración espacio-temporal de la actividad volcánica. El muestreo fue realizado a lo largo de un transecto siguiendo la tendencia de la Sierra. Se estudiaron cinco unidades, correspondiendo a cuatro flujos andesíticos y uno basáltico. Los resultados de K-Ar y de polaridad magnética se resumen a continuación:

Unidad	Edad (Ma)	Polaridad	Cron Geomagnético
Ajusco	0.39±0.16	Normal	Brunhes
Ajusco		Intermedia (R)	Brunhes
M. Contreras	1.92±0.13	Reversa	Matuyama
D. Leones	1.79±0.10	Intermedia (N)	Matuyama
Huixquilucan	2.76±0.19	Normal	Gauss
Peñas Cuatas	2.87±0.15		

Los resultados documentan una migración aparente espacio-temporal de norte a sur de la actividad volcánica y sugieren un rango de edad de Plioceno a Pleistoceno predominante para la Sierra de las Cruces. Esta migración se correlaciona con tendencias similares en la Faja Volcánica Mexicana. Sin embargo, se requieren estudios más detallados para establecer el patrón espacio-temporal y sus posibles implicaciones.

PALABRAS CLAVE: Edades K-Ar, paleomagnetismo, Cuenca de México, Sierra de las Cruces, estratigrafía volcánica, migración de volcanismo, Faja Volcánica Mexicana.

ABSTRACT

K-Ar dates and palaeomagnetic data are reported for a suite of volcanic rocks from Sierra de Las Cruces, Basin of Mexico. The NNW-SSE volcanic range is predominantly built of dacitic lavas, pyroclastic units and lahars and constitutes the western limit of the basin. This preliminary study was designed to investigate the volcanic stratigraphy of the Sierra and to document an apparent spatial migration of volcanic activity along the range. The sampling profile followed the trend of the Sierra. The five units selected for the study comprised four andesitic flows and a basaltic flow. Results are summarized below in terms of K-Ar dates and magnetic polarity chrons:

Unit	Date (Ma)	Polarity	Polarity Chron
Ajusco	0.39±0.16	Normal	Brunhes
Ajusco		Intermediate (R)	Brunhes
M. Contreras	1.92±0.13	Reverse	Matuyama
D. Leones	1.79±0.10	Intermediate (N)	Matuyama
Huixquilucan	2.76±0.19	Normal	Gauss
Peñas Cuatas	2.87±0.15		

Results document an apparent southward migration of volcanic activity and suggest an age range of Pliocene to Pleistocene for the formation of the Sierra de las Cruces. This spatial-temporal migration correlates with apparently similar trends of volcanic activity in the Trans-Mexican volcanic belt. Further studies are required to establish any regional characteristics and implications.

KEY WORDS: K-Ar age, palaeomagnetic dating, Basin of Mexico, Sierra de las Cruces, volcanic stratigraphy, migration of volcanic activity, Mexican Volcanic Belt.

INTRODUCTION

Volcanic activity associated with Cocos plate subduction beneath the southern Mexico continental margin is concentrated along an elongated zone known as the Trans-Mexican Volcanic Belt (TMVB), which crosses the country from the Pacific Ocean to the Gulf of Mexico (Figure 1). The TMVB comprises a variety of volcanic structures which feature a characteristic spatial arrangement, the high stratovolcanoes towards the south (along the volcanic arc front) and the large silicic centers to the north (in the back-arc region). Several evolutionary models for the TMVB have been proposed in the past few years, in an at-tempt to explain the features and spatial-temporal distribu-tion of volcanic activity. These models stress the role of subducted plate geometry and dynamics, crustal structure of upper plate, faulting and stress pattern, reactivation of older structures, etc. (e.g. Mooser, 1972; Molnar and Sykes, 1969; Urrutia-Fucugauchi and Del Castillo, 1977; Urrutia-Fucugauchi and Bohnel, 1988; Pasquaré *et al.*, 1988; Johnson and Harrison, 1990).

In this paper we report on a combined K-Ar dating and palaeomagnetic study of the Sierra de las Cruces, a volcanic range which forms the western limit of the Basin of Mexico (Figures 1 and 2a). The preliminary results proved important in the investigation of the spatial-temporal distribution of volcanic activity in the Basin and TMVB, and the plate subduction-magmatic arc relationships in central Mexico.

GEOLOGIC SETTING AND SAMPLING

The Sierra de las Cruces is built of a series of volcanic structures and associated lava flows, pyroclastic and lahar products which form an elongated range roughly oriented NNW-SSE. The range forms the western margin of the graben/horst depression of the Basin of Mexico, which is then separated from the Valley of Toluca. Volcanic sierras constitute the limits of the Basin, such as the Sierras de Tezontlalpan, Pachuca, Río Frío, Nevada, Chichinautzin, Zempoala and de las Cruces (Figure 1). Volcanic activity was also widespread inside the Basin, forming the Sierra de Santa Catarina and many isolated volcanic structures. The southern closing of the Basin is currently associated with the development of the Chichinautzin volcanic field sometime in the past 700 000 years, providing conditions for development of an extensive lake system (Mooser *et al.*, 1974; Urrutia-Fucugauchi *et al.*, 1991).

A detailed volcanic stratigraphy for the Basin has been difficult to establish, mainly because of the lack of radiometric dates, deep drilling and field studies. Mooser *et al.* (1974) discussed the geologic development of the Basin and proposed a stratigraphy for the various Sierras (Figure 2). They considered the Sierra de las Cruces as part of their Lower Sierra and Upper Sierra Groups, with an age range of Miocene to Pliocene.

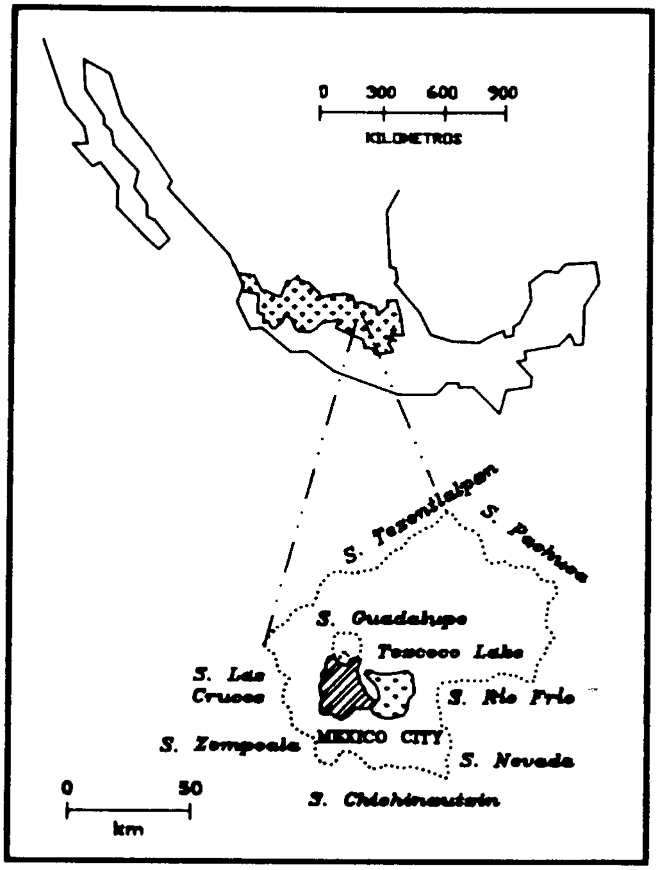


Fig. 1. Location of the Basin of Mexico City in the Trans-Mexican Volcanic Belt (both are dashed). Also location and names of volcanic ranges limiting the Basin of Mexico (taken from Mooser *et al.*, 1974).

Mooser *et al.* (1974) reported a radiometric date for the San Miguel ash flow (the so-called "arenas azules" of the sand mines), which is 9.8±1.0 Ma. He argued that volcanism extended into the Miocene.

Geochemical studies for the Basin volcanics have been reported by Gunn and Mooser (1971) and Richter and Negendank (1976). Volcanic units show calc-alkaline affinities, with an apparent trend from dacitic in the Tertiary towards andesitic in the Quaternary rocks. De Cserna *et al.* (1988) have recently summarized the geological information and discussed the structural and tectonic features of the Sierra de las Cruces. Lugo Hubp (1984) presented geomorphologic studies in the Basin and summarized the evidence for the volcanism being youngest in the south.

For our preliminary study, samples were collected for K-Ar dating and palaeomagnetism along a transect almost along the trend of the range (Figure 2). Samples for palaeomagnetism were drilled in the field with a portable petrol-powered drill with non-magnetic drill bits, and oriented *in situ* with a magnetic compass. The five units selected for the study include four andesites and a basalt. A total of 80 oriented cores from four sites were collected for

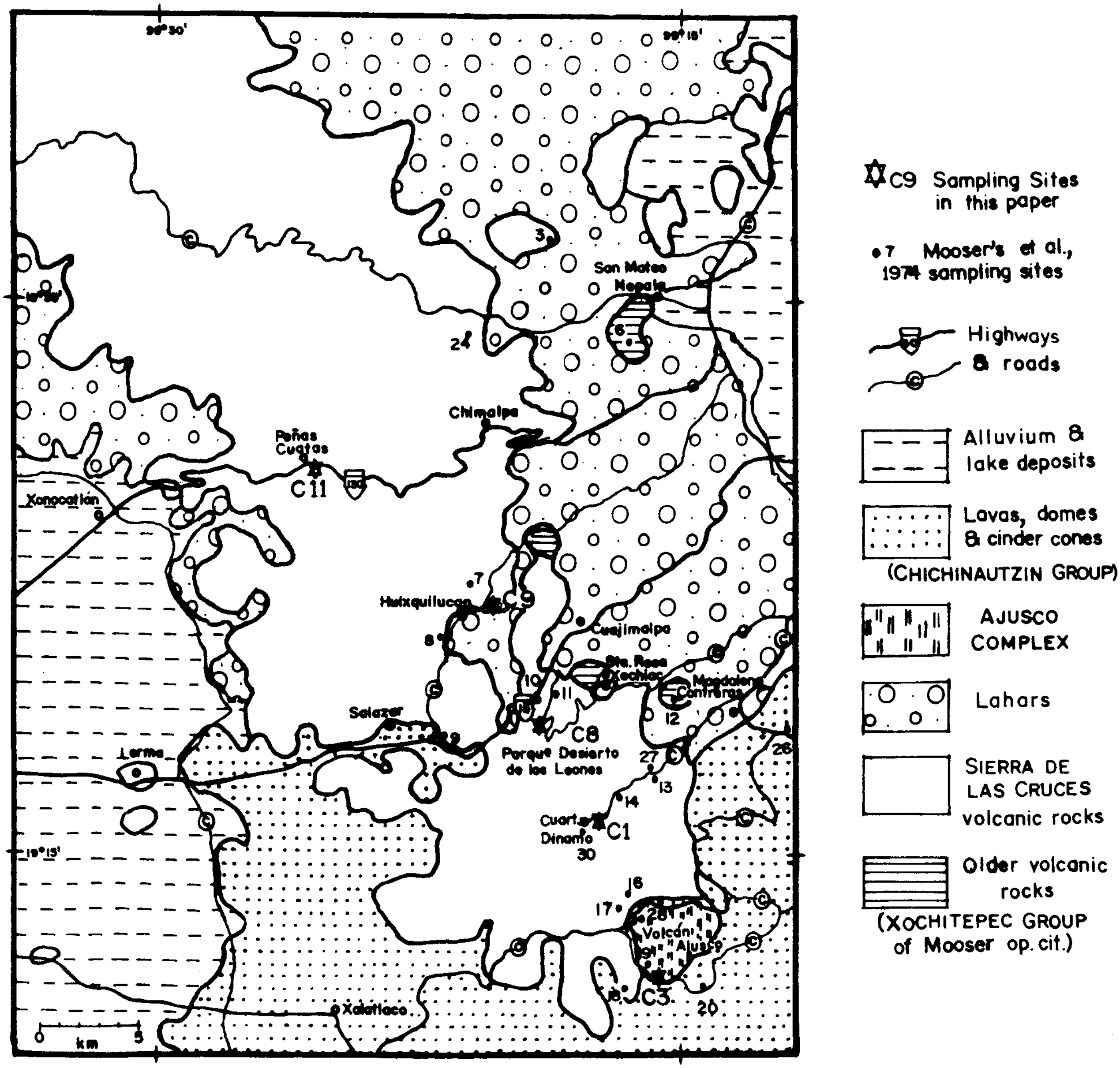


Fig. 2. Geological sketch (simplified from Mooser *et al.*, 1974 and Carta Geológica E14-2 of Dirección General de Geografía, 1986) and location of sites studied in this paper (stars C-numbered sites), as well as previously studied sites (Mooser *et al.*, 1974).

palaeomagnetism and several fresh hand samples from the same sites were chosen for K-Ar. The sampling strategy for the pilot survey was designed in order to investigate an apparent spatial N-S migration of volcanic activity, which was suggested mainly by the morphology of volcanoes and general erosional characteristics of the Sierra. The most eroded volcanoes are found in the northern sector of the range.

3. METHODOLOGY AND RESULTS

The intensity and direction of natural remanent magnetization (NRM) of all samples were measured in a Molspin spinner magnetometer. Examples of the angular distributions of remanence directions are given in Figure 3. The vectorial composition and magnetic stability of NRM were investigated with both thermal and alternating field (AF) demagnetizations. Thermal demagnetization was carried out in 7 steps from room temperature to 500° C in a Schonstedt TSD-1 non-inductive furnace. Low-field magnetic susceptibility was measured with a susceptibility bridge; for the thermally demagnetized samples, measurements were taken after every heating step. AF demagnetization was carried out in 14 steps up to maximum fields of 100 mT in a reversing triaxial thumbler Schonstedt demagnetizer. Typical examples of AF and thermal behaviour are shown in Figure 4. Samples showed mainly univectorial behaviour, where low coercitivity and low blocking temperature components are present.

Magnetic carriers likely correspond to members of the titanomagnetite series, with unblocking temperatures of

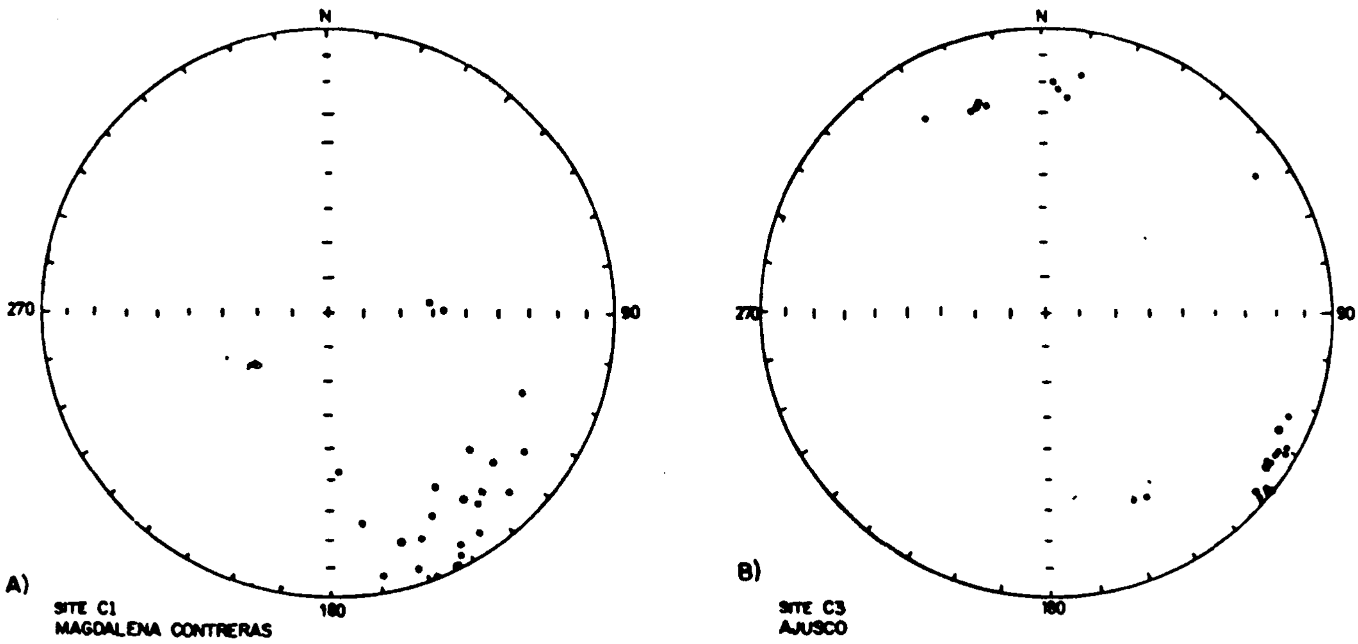


Fig. 3. Examples of equal-area polar projection of remanence directions of A) site C1 in Magdalena Contreras and B) site C3 in El Ajusco. Solid circles are lower hemisphere and open are upper hemisphere projection.

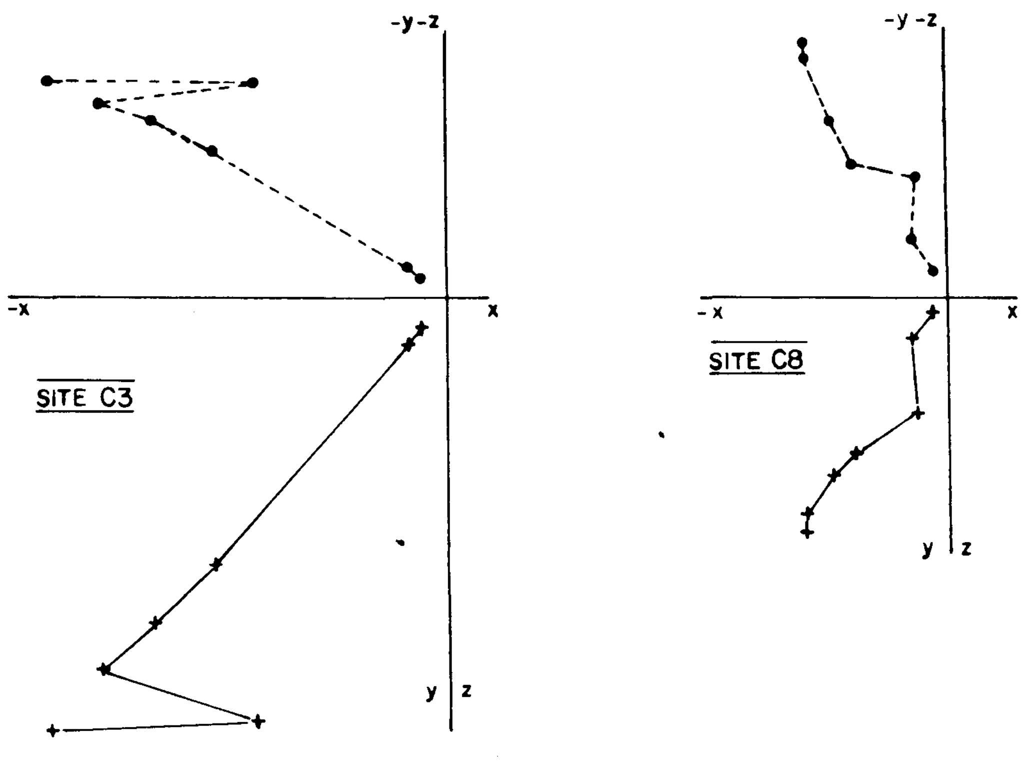


Fig. 4. Examples of vectorial diagrams showing thermal behaviour of A) site C3 in El Ajusco and B) site C8 in Desierto de los Leones. Crosses and solid line are in the horizontal plane (-x - y); points and dotted line are in the vertical plane (-x - -z).

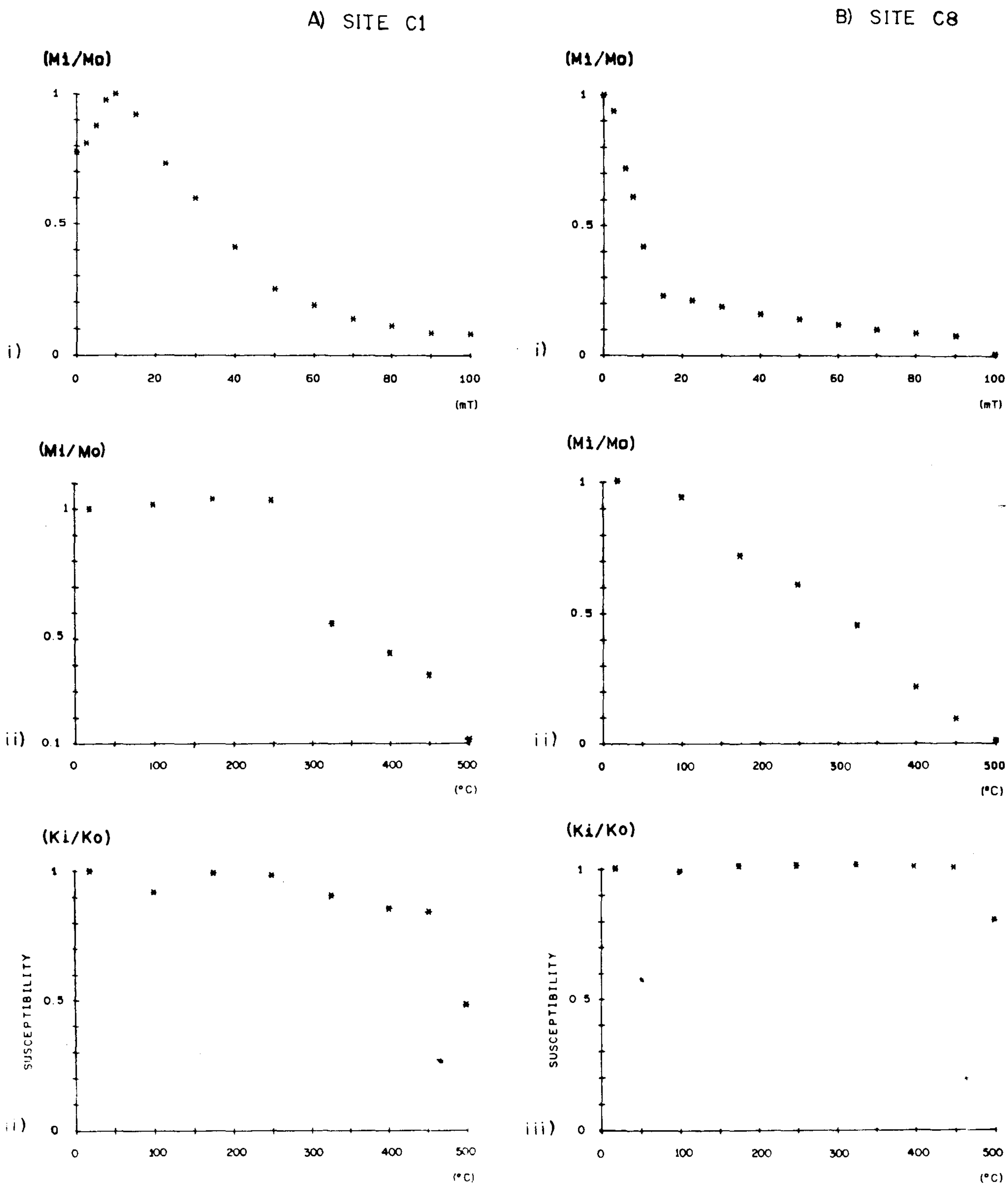
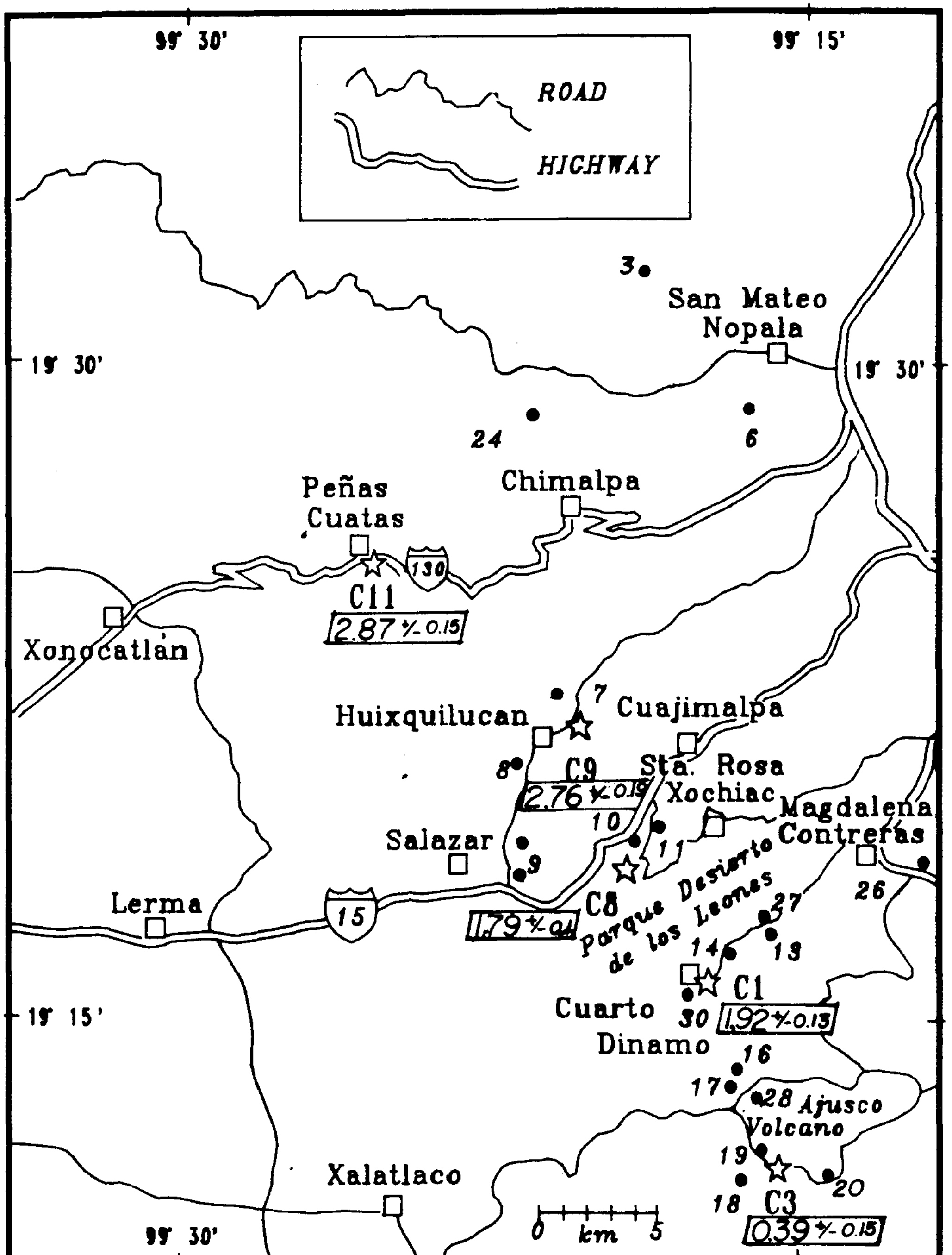


Fig. 5. i) Alternating field (in mT) and ii) thermal demagnetization (in C and iii) susceptibility behaviour during demagnetization of samples. A) Cl in Magdalena Contreras and B) C8 in Desierto de los Leones. Note that coercitivities are below 100 mT and unblocking temperatures are below 500°C.



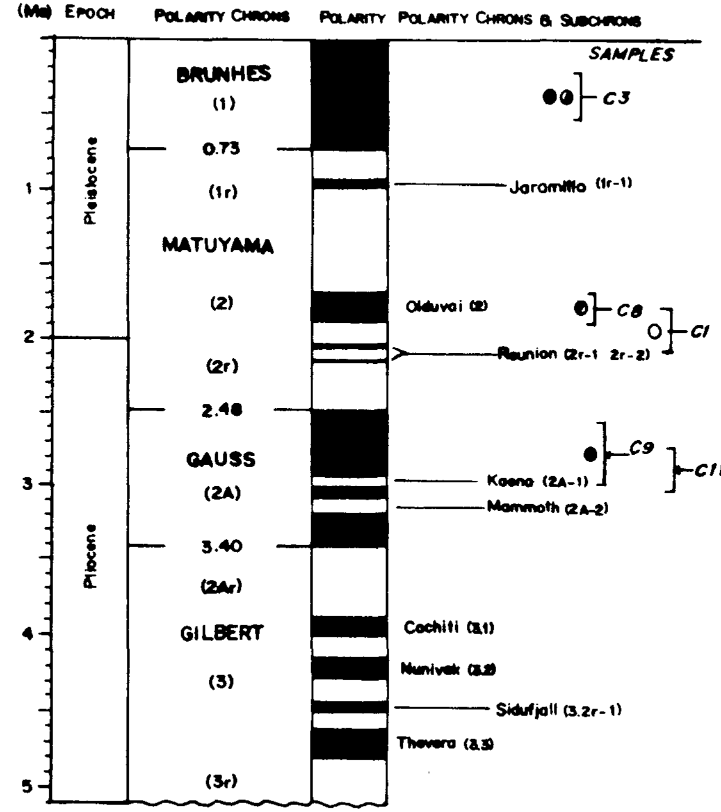


Fig. 6. A) Sketch showing apparent spatial migration of volcanic activity in the Sierra de Las Cruces, sites are indicated by stars and number of sites; boxed italic numbers give the K-Ar date estimated in this study. Closed circles are previously studied sites (Mooser *et al.*, 1974). B) The polarity time scale from late Pliocene-Pleistocene (after Harland *et al.*, 1982) showing the position of samples studied according to their K-Ar dates. Polarity results of samples are represented with closed circles as normal polarity, open circles as reverse polarity and intermediate polarities are half closed-half open circles.

Table 1

Sierra de Las Cruces palaeomagnetic data

Site number	Dec	Inc	sampling	α95	K	R	FIELD	pola-rity
This paper (from north to south)								
C9 HUIXQUILUCAN	340.9	+16.91	2/2	9.4	708	1.99	NRM	N
C8 D. LOS LEONES	70.4	-20.4	25/25	3.2	82	24.71	NRM	I (N)
C1 M. CONTRERAS	144.5	+18.2	23/23	11.0	9	20.45	NRM	R
C3-A EL AJUSCO	124.1	+ 0.4	14/16	3.8	111	13.88	NRM	I (R)
C3-B EL AJUSCO	0.3	+17.1	13/14	9.9	18	12.35	NRM	N
Mooser *et al.*, 1974 (sites out of the map of Fig. 1 and with α95 > 30 and K < 9 are not included)								
3. Chiluca	355.2	+20.6	7/7	13.5	21	6.71	300	N
6. Los Remedios	179.5	-18.1	6/7	9.4	52	5.9	77	R
7. Dos Rios	37.8	+19.4	6/6	15.4	20	5.75	300	N
8. Ignacio Allende	173.2	-53.7	6/6	8.4	64	5.92	300	R
9. La Marquesa	164.6	-32.9	6/7	21.0	11	5.55	300	R
10. Las Cruces	357.7	+40.3	7/7	5.8	110	6.96	150	N
11. S of La Venta	174.2	-61.2	7/7	4.8	157	6.96	NRM	R
12. Cerro Judio	184.0	-24.1	8/8	15.6	14	7.48	300	R
13. M. Contreras	5.1	+36.1	7/7	4.8	162	6.96	150	N
14. M. Contreras	164.8	-39.5	8/8	5.8	94		150	R
16. Monte Alegre	194.3	-41.0	6/6	6.3	113	5.96	150	R
17. Monte Alegre	187.8	-32.5	5/6	22.4	13	4.68	300	R
18. SW of Ajusco	148.2	-64.8	8/8	8.6	42	7.84	600	R
20. SE of Ajusco	173.5	-53.8	6/7	6.0	128	5.69		R
24. C. Apaxco	354.6	+31.9	7/7	5.7	114	6.96	150	N
26. C. Zacatepetl	11.5	+53.8	7/7	5.3	129	6.95	300	N
27. M. Contreras	192.3	-46.7	6/6	6.8	98	5.96	150	R
28. El Ajusco	9.1	+10.3	7/7	5.5	120	6.95	300	N
30. M. Contreras	161.8	-48.0	4/6	11.9	60	3.95	150	R

around 500° C and coercitivities below 100 mT (Figure 5). Magnetic susceptibility did not change with the thermal treatment, indicating absence of significant alterations of the magnetic mineralogy as a result of laboratory heating.

The unit from Huixquilucan presents northwesterly declinations and downward positive inclinations and has therefore a normal polarity. The unit of the Desierto de los Leones presents an intermediate direction with westerly declinations and upward negative inclinations. The polarity is interpreted here as reverse. The westward declination will be discussed later. The unit from Magdalena Contreras presents southerly declinations and upward negative inclinations indicating a reverse polarity (Figure 3a). The unit from Ajusco volcano presents an interesting case in which northward declinations and downward inclinations as well as southeasterly declinations and upward inclinations are observed (Figure 3b). A previous study at different localities of lava flows from this volcano showed reverse and normal polarities and a relatively high directional scatter. The two apparently reliable sites showed one normal and the other reverse polarity (Mooser *et al.*, 1974; Bremer-Bremer and Urrutia-Fucugauchi, 1985). Available palaeomagnetic data for the Sierra de Las Cruces are summarized in Table 1. The palaeomagnetic results are discussed together with the K-Ar dates in the next section.

The main objective of this study was the estimation of magnetic polarities for the volcanic units. Directional results will be further analyzed in terms of vector means and pole positions in the second phase of the study, which will involve a larger sample collection and will be aimed at documenting the tectonic features and potential control on the volcanic activity. Therefore, further discussion of palaeomagnetic results is reserved for a treatment of the magnetostratigraphic implications.

The K-Ar dating study was completed in the Geochronological Laboratories of the Geological Survey of Japan at Tsukuba. Fresh portions were selected from the sample collection. Analyzed samples were prepared for whole-rock analysis using standard potassium and argon

Table 2

Sierra de Las Cruces K - Ar data

Site sample	Latitud & Longitud	K_2O (%)	^{40}Ar rad ($\times 10^{-6}$ mlSTP/g)	^{40}Ar atm (%)	Age	Polarity Chron
C11 PEÑAS CUATAS	19°25'40"N 99°25'29"W	1.702 - 1.719	0.158	43.4	2.87 ± 0.15	
C9 HUIX-QUILUCAN	19°22'28"N 99°20'08"W	2.417 - 2.477	0.218	67.8	2.76 ± 0.19	Gauss
C8 D. LOS LEONES	19°18'29"N 99°19'00"W	1.675 - 1.695	0.0973	36.1	1.79 ± 0.10	Matuyama
C1 MAGD. CONTRERAS	19°16'00"N 99°17'15"W	1.954 - 1.984	0.1219	44.76	1.92 ± 0.13	Matuyama
C3 AJUSCO	19°11'45"N 99°15'38"W	0.9512 - 0.9507	0.0121	79.0	0.394 ± 0.155	Brunhes

procedures. In some cases, hand picking during sample preparation (crushing and sieving) was done to remove oxidized material. K_2O content was determined by atomic absorption analysis. Argon was released by fusion without flux using a radiofrequency induction heater; it was purified with a titanium sponge and copper oxide furnance in a high vacuum pyrex system. Argon isotopic ratios were determined in a Nier-type mass spectrometer which was operated in the static mode. The constants used in age calculation are: 1β = 4.962 x $10^{-10/y}$, 1e = 0.581 x $10^{-10/y}$, $^{40}K/^{38}K$ = 0.01167 atom %. All quoted ages in the paper are recalculated with these values. Duplicate measurements for both potassium and argon were done for each sample.

Results are summarized in Table 2. Analytical errors quoted for the K-Ar dates correspond to standard error propagation estimates by considering 2% error for the potassium analyses, 1% and 2% for the $^{40}Ar/^{38}Ar$ and $^{36}Ar/^{38}Ar$ ratios, and 2% for the spike calibration.

Potassium varies from 0.95% in the Ajusco flow to 2.45% in the Huixquilucan flow, corresponding to low-K and high-K lavas. Potassium contents for the three other flows are about 1.69-1.97%.

4. DISCUSSION

The K-Ar dates and magnetostratigraphic results are summarized in Tables 1 and 2 and illustrated in Figure 6. The range of radiometric K-Ar dates is 400 000 years to 2.9 Ma. The dates display an age progression, becoming younger from north to south. The magnetic polarities are assigned to the corresponding geomagnetic chrons (Harland *et al.*, 1984), covering the Brunhes, Matuyama and Gauss chrons. The results agree with geomorphological observations in terms of distribution of volcanic structures; the older and most eroded volcanoes appear to be located to the north of the range.

The dual magnetic polarity observed in the lava from Ajusco volcano is not readily understood from the demagnetization data. It may correspond to acquisition during a short polarity event or excursion during the Brunhes chron (i.e. lava emplacement at that time). Alternatively, it may reflect a secondary magnetization acquired during an earlier polarity event or excursion. The former is considered more likely in view of earlier results which show reverse polarity or high directional scatter (Table 1).

For a quantitative reference for assignment of magnetic polarity, virtual geomagnetic poles (VGP) and angular differences were calculated for each site of Table 1. Polarity assigned according to the following convention: normal sites with VGP located between 0 and 45 degrees away from palaeomagnetic pole; intermediate (normal), sites with VGP located between 45 and 90 degrees away from palaeomagnetic pole; intermediate (reverse), sites with VGP located between 90 and 135 degrees away from palaeomagnetic pole; and reverse, sites with PGV located between 135 and 180 degrees away from palaeomagnetic pole.

There is a predominance of reverse polarities, more than 50%, in the Sierra de Las Cruces. This suggests that volcanic activity spanned the Matuyama reverse chron. Normal polarities observed may correspond to the Gauss and Brunhes chrons.

The results constrain the age range for the Sierra de Las Cruces to predominantly Pliocene and Pleistocene. They further document a spatial north - south migration of volcanic activity along the volcanic range.

Further studies are required in order to establish the characteristics of this apparent pattern and its regional implications. Distribution of volcanic activity may likely present a more complex pattern. In the northern sector of the Sierra, pumitic units of Late Pleistocene to Holocene ages are present in the Cerro de San Miguel (Pantoja-Alor, written communication, 1991). Some of the problems currently associated with dating of young volcanic sequences may be tackled by means of combined studies, which could include geomorphology, detailed field studies (K-Ar, Ar-Ar, fission-tracks, thermoluminescence, etc.) radiometric dating and magnetostratigraphy.

A peculiar characteristic of volcanic activity in the TMVB is the apparent spatial north-south migration shown by some of the active stratovolcanoes like the Volcán de Colima. Popocatépetl and Pico de Orizaba, and in the Michoacán-Guanajuato cinder cone field (e.g. Robin, 1981). The active stratovolcanoes lie at the southern end of elongated volcanic ranges which show a N-S age progression. Colima volcano lies at the end of the Cántaro and Nevado de Colima range, the Popocatépetl lies at the southern end of the Sierra Nevada - Iztaccíhuatl range, and Pico de Orizaba forms the southern extension of the Cofre de Perote and Sierra Negra ranges. In the Michoa-cán-Guanajuato cinder cone field, younger and active volcanism occurs preferentially in the southern sector. This is not, however, the only rule governing distribution of activity. In the Chichinautzin cinder cone field, Basin of Mexico, historic volcanism has apparently occurred in the northern sector, including the historic Xitle eruptions. Also, the migration pattern is clearly not present in many other volcanic structures and fields. Stratigraphic and radiometric studies of volcanism are needed to properly document apparent trends of spatial migration; for instance, the case for the Sierra Nevada, Iztaccíhuatl and Popocatépetl requires more data. Spatial-temporal trends in the Michoacán-Guanajuato volcanic field are better documented and support a southward progression of volcanic activity (Ban *et al.*, 1991). Detailed studies of the temporal spatial distribution of volcanic activity are important for a number of reasons, including those related to faulting and stress patterns and to plate subduction - magmatic arc models (e.g., Urrutia-Fucugauchi, 1986). A southward migration of volcanism could be related to dip-angle steepening of the subducted plate, with the corresponding implications for the Cocos - North America plate convergence and plate kinematics in the region.

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