Palaeomagnetic Investigations of the Tertiary and Quaternary Igneous Rocks: VIII A Palaeomagnetic and Petrologic Study of Volcanics of the Valley of Mexico

By FREDDIE MOOSER, Mexico City, ALAN E. M. NAIRN, Columbia/South Carolina, and JÖRG F. W. NEGENDANK, Trier *)

With 12 figures and 3 tables

Zusammenfassung

Das Becken von Mexiko befindet sich im Zentrum des Transmexikanischen Vulkangürtels, einer Ost-West-Struktur, die den nordamerikanischen Kontinent entlang des 19. Breitengrades durchschneidet.

Paläomagnetische Messungen legen die Vermutung nahe, daß 2 (Guadalupe- und Chichinautzin-Gruppe) der 7 vulkanischen Phasen, die das Becken formten, von wahrscheinlich kurzer Dauer waren. Die Chichinautzin-Gruppe, die das Becken im Süden abschnürte, muß sich grundsätzlich in den letzten 700 000 Jahren gebildet haben.

Die vulkanische Tätigkeit, die im Oligozän begann und sich kontinuierlich bis in die heutige Zeit fortsetzte, förderte nachweislich im wesentlichen andesitische Produkte.

Abstract

The basin of Mexico lies in the center of the Trans-Mexican Volcanic Belt, an east-west structure which dissects the North American Continent along the 19th parallel. Paleomagnetic measurements suggest that two of the seven eruptive phases — Guadalupe Group and Chichinautzin Group — that formed the basin, probably were of short duration; the Chichinautzin Group, which finally closed the basin to the south, must have been formed principally in the last 700,000 years.

The volcanic activity which began in Oligocene time and has continued until the present, has been proved to be essentially andesitic in composition.

Résumé

Le bassin de Mexico se trouve au centre de la ceinture volcanique de Mexico, une structure est-ouest qui recoupe le continent nord-Americain près du 19e parallèle. Les mesures paléomagnétiques conduisent à supposer que deux des sept phases d'activités volcaniques, celles de la Guadaloupe et du Chichinautzin, étaient courtes. Les roches du Groupe de Chichinautzin, fermant le bassin au sud, ont été formées pendant les derniers 700,000 ans.

L'activité volcanique, qui a débuté à l'Oligocène et se continue encore actuellement a une charactère essentiellement andésitique.

---

*) Authors' addresses: Prof. Ing. F. MOOSER, Instituto de Geofisica, Universidad Nacional Autonoma, Torre de Ciencias, Ciudad Universitaria, Mexico 20 D.F. Mexico. — Prof. Dr. A. E. M. NAIRN, Department of Geology, University of South Carolina, Columbia, S.C. 29208, USA. — Dr. J. F. W. NEGENDANK, Abt. Geowissenschaftliches Laboratorium der Fachgruppe Geographie der Universität Trier-Kaiserslautern, D-55 Trier, Schneidershof, W-Germany.

Краткое содержание

Мексиканский бассейн находится в центре трансмексиканского вулканического пояса — некой структуры, которая пересекает северо-американский материк вдоль 19-й параллели с востока на запад.

Палеомагнитные измерения разрешают полагать, что две из семи вулканических фаз, именно группа Guadalupe и Chichinautzin, образовавших этот бассейн, повсей вероятности, были очень непродолжттельными. Группа Chichinautzin, продукты которой составляют границу бассейна на юге, появилась в последние 700 000 лет.

Вулканическая деятельность, начавшаяся в олигоцене и продолжающаяся непрерывно по сегодня, подняла главным образом андезиты.

Contents

Introduction

The volcanoes which so spectacularly bound the Valley of Mexico are parts of a major belt of volcanics, some 20 to 70 km wide, which traverse the country between the 19 th and 21 st parallels (MOOSER & MALDONADO KOERDELL, 1967; MOOSER et al. 1958) from near Puerto Vallarta in the west to the vicinity of Veracruz in the east. Although the belt neither runs parallel to the coast, nor is an obvious island arc as its Central America extension, there has been a persistent belief that it is in some way an oceanrelated structure (MENARD, 1955) since A. VON HUMBOLDT suggested that the Islas Revillagigedo in the Pacific Ocean lay on an oceanward extension of a fracture line along the 19th parallel marked on the continent by the large active volcanoes of Mexico.

The volcanic activity of the belt, apparently beginning at the same time as the Cenozoic flood of ash flows and ignimbrites which blanket most of northwestern and western Mexico and extend into southern Mexico, appears to have lasted longer and thus the belt forms a convenient dividing line between northern and southern Mexico. This line, however, is irregular and MOOSER (1972, Fig. 1) has shown that it follows a zig-zag pattern.

Recent years have witnessed considerable progress in the investigation of the belt, which has now been mapped (based largely on photogeology) over its entire length, on the scale of 1 : 40,000 or 1 : 50,000. Most available data exist at the present moment in the form of internal reports and publications of the Secretaria

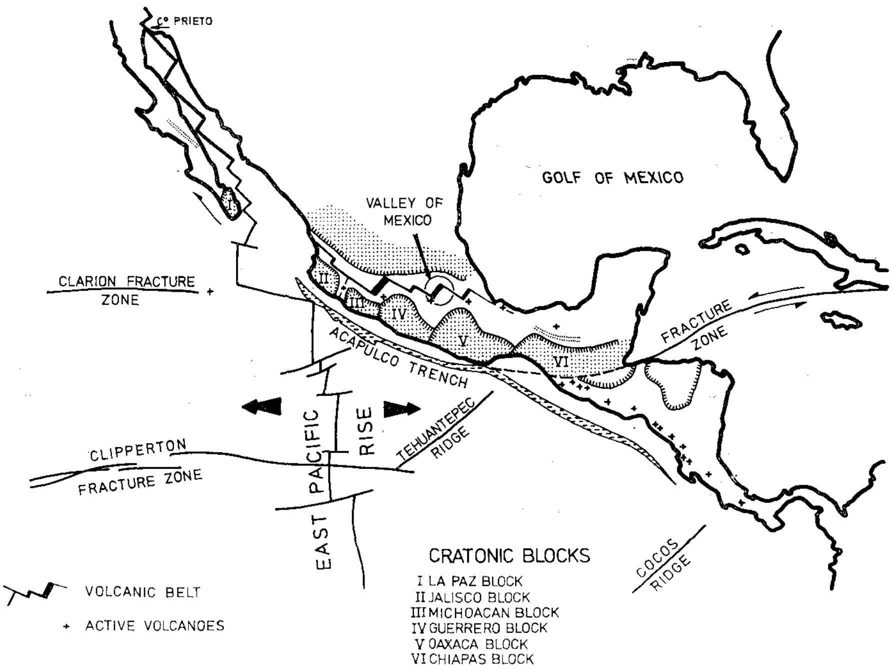

Fig. 1. The Mexican Volcanic Belt and the principal oceanic features. The location of the Valley of Mexico is outlined by a circle (from MOOSER, 1972).

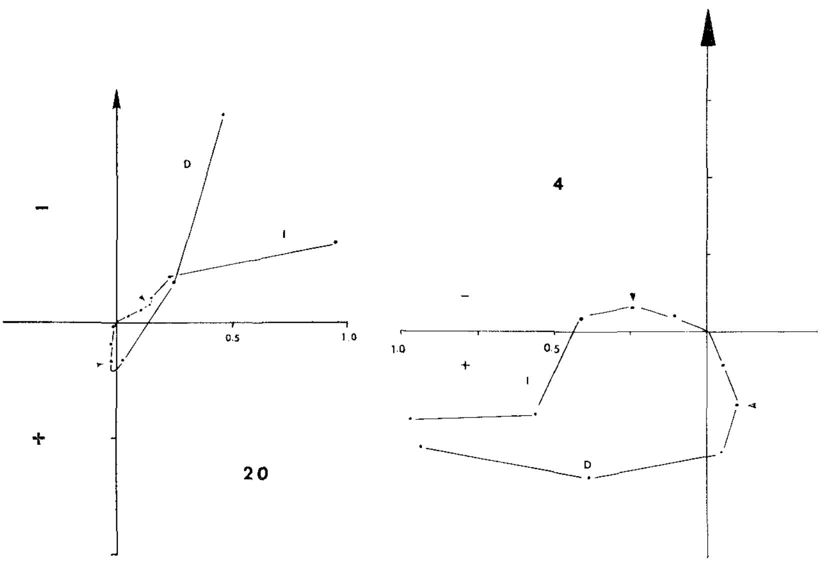

Fig. 2 a

Fig. 2 b

Fig. 2. Diagrams showing the changes in declination (D) and inclination (I) against normalized intensity.

de Recursos Hidraulicos and Comision Federal de Electricidad, as well as vulcanological reports to the IUGG presented by the Institute of Geophysics of the Mexico National University. GUNN & MOOSER (1971) presented a first modern petrographic investigation of the basin and beltrocks, concluding that these may be derived from the Upper Mantle and can be related to subduction of oceanic crust. The Valley of Mexico is the part of the belt, known in greatest detail and it is a paleomagnetic and petrologic study of this region which is described here. However, it is clear that the significance and interpretation of these volcanic rocks cannot be separated from the history of the belt as a whole.

Paleomagnetic and petrologic observations

As the applied paleomagnetic techniques are standard and have been described on numerous occasions, they will be listed here with a minimum of description. At most sites five to ten oriented cores were collected with a portable drill, only at the more inaccessible sites were oriented blocks sampled. Most sites were natural outcrops, relatively few were obtained in quarries or fresh road cuts. Measurements of remanence were made either under a short period astatic magnetometer or using a Foster fluxgate spinner. One specimen per sample (core or block) was used. Two specimens per site were progressively demagnetized in alternating fields up to 1200 oe. During demagnetization specimens were rotated about three axes in near zero field (1008). From plots of declination and inclination against normalized intensity (fig. 2 a, b) stable magnetization is recorded when the successive plot of declination and inclination decreases linearly to the origin with increasing demagnetization. After inspection of these curves, which indicate the minimum field to remove secondary magnetization, the remaining specimens from the site were demagnetized at the stage and the next higher stage. The best representation of the original site magnetization was then chosen from the stage giving the highest value and the smallest circle of confidence. When the N. R. M. value had the lowest circle of confidence the condition was imposed that there should be no significant change of mean direction upon subsequent demagnetization. The initial computations of the FISHER statistics and mean directions of magnetization were carried out on a Univac 1107 using a program written by S. GROMMÉ. Later the program was rewritten to run upon a WANG computer. The principal results are summarized in a series of tables (tables 1 a—e) and stereograms (figure 3 a—e). To further illustrate the applied techniques, normalized demagnetization curves, showing the change in intensity of magnetization with applied field, and a stereogram showing the direction changes during the demagnetization process are given in figures 4 and 5 respectively. Many of the sites had a secondary magnetic component due to lightning; these sites can be recognized in the tabulated results for demagnetizing fields in excess of 300 oe are seldom if ever, required by rocks which are not affected by lightning.

The petrological character of the volcanic rocks of the Valley of Mexico is much better known as a result of recent petrological (NEGENDANK 1972 and in press) and geochemical (GUNN & MOOSER 1970) studies. As detailed descriptions and analyses of a representative suite of the rocks sampled for paleomagnetic research has already appeared (NEGENDANK 1972), it is only necessary to record

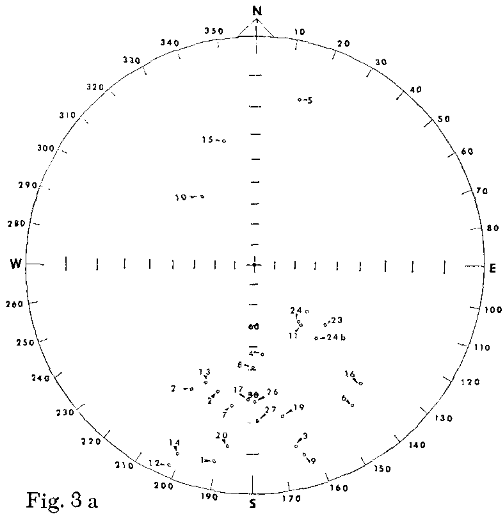

Fig. 3 a

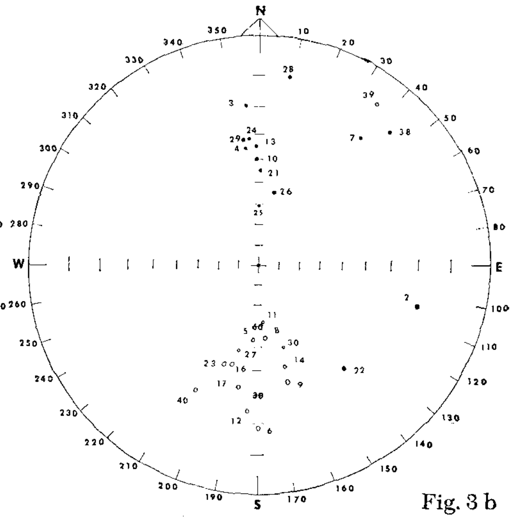

Fig. 3 b

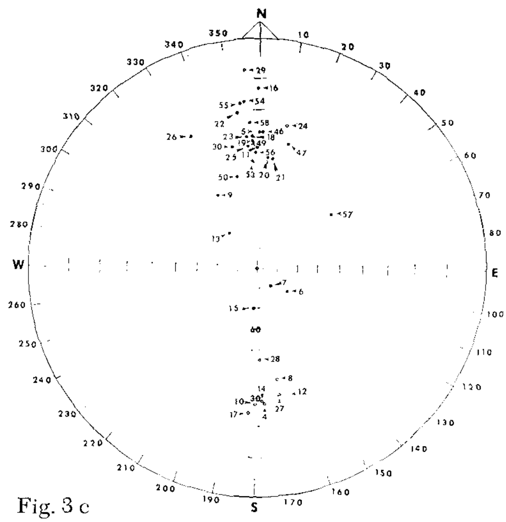

Fig. 3 c

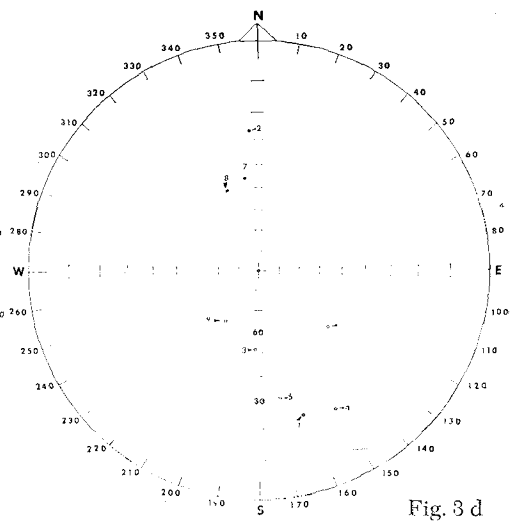

Fig. 3 d

Fig. 3. Site mean directions of magnetization of volcanic rocks after cleaning in alternating magnetic fields. — a) Sierra de Guadalupe, b) Sierra de Las Cruces, c) Sierra de Nevada, d) Vallé, e) Sierra del Chichinautzin. Site numbers correspond to the data tabulated in table 1 a—e.

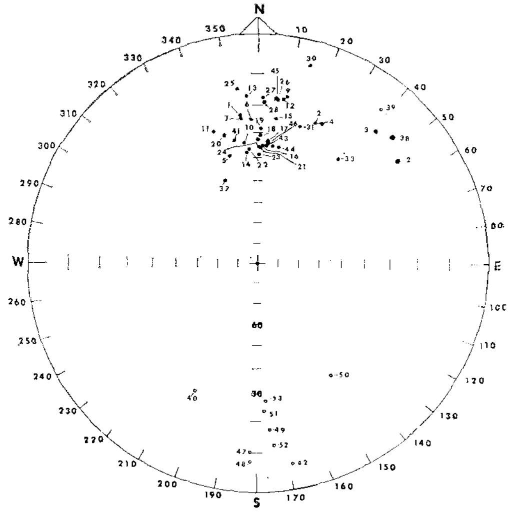

Fig. 3 e

Table 1. Site mean directions of magnetization.

a. Sierra de Guadalupe — b. Sierra de las Cruces — c. Sierra de Nevada and Sierra de Rio Frio — d. Vallé volcanics: south of Mexico; north of Mexico — e. Sierra del Chichinautzin and Sierra de Santa Catarina

The sites are numbered to correspond to the figures of mean direction and various demagnetization curves. Tabulated under sampling a/b — a/ represents the number of samples used in the analysis, b/ represents the number of samples collected. The statistics α_{95}, K and R are defined by Fisher (1953). The alternating demagnetized field used in cleaning is given in the final column.

Table 1a Sierra de Guadalupe

	Site		Declination	Inclination	Sampling a/b	α95	K	R	Field oe
1.	Cuautepec Barrio Alto fresh andesite	late Guadalupe phase	188.2	— 6.9	7/7	45.3*	2	5.446	150
2.	Tianguillo working andesite quarry	Dome phase (post main Guadalupe phase)	195.2	—29.2	6/6	6.6	104	5.952	77
3.	Cerro de Tenayo flow banded andesite	Dome phase (post main Guadalupe phase)	166.1	—10.4	7/7	2.5	608	6.990	150
4.	Cerro de Chiquihuite rhyodacite	Dome phase (post main Guadalupe phase)	174.4	—45.5	5/6	5.7	178	4.978	N.R.M.
5.	Cerro Gordo massive andesite	Dome phase (post main Guadalupe phase)	15.8	+ 15.6	7/7	8.2	55	6.891	N.R.M.
6.	Cerro Ticoman andesite	Dome phase (post main Guadalupe phase)	144.8	—18.6	3/5	12.4	101	2.980	600
7.	Cerro Sta Cecilia andesite	Main Guadalupe phase	188.4	—26.1	5/6	15.9	24	4.834	300
8.	Cerro Sta Cecilia andesite flow breccia	Main Guadalupe phase	179.6	—41.6	4/6	4.8	369	3.992	150
9.	Barrientos andesite flow	Main Guadalupe phase	164.5	— 8.4	6/6	12.0	32	5.844	N.R.M.
10.	Cerro del Panal reddish andesite	Main Guadalupe phase	322.2	+ 48.9	4/7	26.0	13	3.776	150
11.	Cerro del Panal porous reddish andesite	Main Guadalupe phase	146.1	—56.8	5/6	21.5	14	4.706	600
12.	Rambler flow banded andesite	Main Guadalupe phase	201.9	+ 1.0	6/6	12.6	29	5.829	600
13.	Cuauhuis weathered andesite	Main Guadalupe phase	201.3	—31.4	6/6	7.5	80	5.938	300
14.	Cuautepec Barrio Alto road dacite cut	Tezontlalpan phase	200.6	— 6.1	8/8	9.1	38	7.818	77
15.	Cerro Juanalco reddish flow rhyodacite	Main Guadalupe phase	348.0	+ 31.1	4/7	9.2	101	3.970	600
16.	Sta Maria Tulpetlac flow banded andesite	Main Guadalupe phase	138.0	—19.5	6/6	27.7	7	5.266	600
17.	Cerro Risco reddish blue andesite	Main Guadalupe phase	180.6	—27.5	7/7	7.4	68	6.911	77

18.	Cerro Jaguey coarse andesite	Main Guadalupe phase	no result — probably reversed						
19.	Coacalco weathered dacite	Xochitepec phase	171.7	—18.8	10/11	10.0	24	9.630	300
20.	Cuautepec Barrio Bajo	Xochitepec phase	188.3	—11.8	7/7	7.8	61	6.901	300
21.	Cerro Sta Isabel platy andesite	Tezontlalpan phase	no result						
22.	Cerro Sta Isabel quartz latite andesite	Tezontlalpan phase	scattered results — reversely magnetized						
23.	Cerro Sta Isabel platy dacite flow	Tezontlalpan phase	130.0	—44.8	7/7	5.1	141	6.957	77
24a.	Cerro Guerrero lower flow	Tezontlalpan phase	141.9	—51.7	7/7	8.0	57	6.896	77
24b.	Cerro Guerrero upper flow	Tezontlalpan phase	139.2	—44.5	4/6	12.9	52	3.942	150
25.	Cerro de la Cruz platy andesite	Tezontlalpan phase	205.2	—26.9	6/6	18.1	15	5.661	150
26.**	Cerro de la Villita andesite lava	Tezontlalpan phase	178.2	—20.5	6/6	6.6	104	5.952	600
27.*	Cerro de la Villita andesite lava	Tezontlalpan phase	199.1	—26.9	5/6	5.8	175	4.997	150

** Sites are off the southern margin of the map (fig. 8) immediately southwest of Cerro Guerrero.
* Result not regarded as significant.

Table 1b Sierra de Las Cruces

	Site	Declination	Inclination	Sampling	α95	K	R	Field
1.	Calacoaya Oligocene El Tigre complex pheno-andesite	180.0	— 0.5	3/7	34.6*	14	2.85	150
2.	El Fraile dacite dome north of Chiluca	104.7	+ 17.9	3/7	48.3*	5	3.35	150
3.	Chiluca weathered andesite	355.2	+ 20.6	7/7	13,5	21	6.71	300
4.	Helicopter sample probably of Malinche complex	353.2	+ 37.5	3/6	48.0*	8	2.74	150
5.	Helicopter sample probably of Malinche complex	182.8	— 53.3	5/6	40.7*	5	4.11	300
6.	Los Remedios ignimbrite flow	179.5	— 18.1	6/7	9.4	52	5.90	77
7.	Dos Rios, of the Piedra Grande complex	37.8	+ 19.4	6/6	15.5	20	5.75	300
8.	Ignacio Allende, of the La Marquesa complex	173.2	— 53.7	6/6	8.4	64	5.92	300
9.	La Marquesa of the La Marquesa complex quartz andesite	164.6	— 32.9	6/7	21.0	11	5.55	300
10.	Las Cruces of the San Miguel complex	357.7	+ 40.3	7/7	5.8	110	6.960	150
11.	South of the La Venta the San Miguel complex, dacite	174.2	— 61.2	7/7	4.8	157	6.960	N.R.M.
12.	Cerro Judio Oligocene-Miocene complex	184.0	— 24.1	8/8	15.6	14	7.480	300

	Site	Declination	Inclination	Sampling	α_{95}	K	R	Field
13.	Cuatro Dinamos earlier phase exposed in San Miguel complex	5.1	+ 36.1	7/7	4.8	162	6.960	150
14.	Cuatro Dinamos earlier phase exposed in San Miguel complex	164.8	— 39.5	8/8	5.8	94	9.930	150
16.	Monte Allegre of the San Miguel complex	194.3	— 41.0	6/6	6.3	113	5.960	150
17.	Monte Allegre of the San Miguel complex	187.8	— 32.5	5/6	22.4	13	4.680	300
18.	SW of Ajusco of the San Miguel complex	148.2	— 64.8	8/8	8.6	42	7.835	600
19.	SW slope of Ajusco, dome of the Ajusco complex	190.7	— 59.4	4/7	62.7*	3	3.040	150
20.	SE of Ajusco of the San Miguel complex	173.5	— 53.8	6/7	6.0	128	5.691	
21.	Lagunas de Zempoala of the Zempoala complex	360.0	+ 44.8	7/7	13.9	20	6.700	300
22.	5 Km from Lagunas de Zempoala	140.2	+ 28.0	6/6	7.1	90	5.940	150
23.	Cerro Tlalli complex (?)	196.9	— 39.8	7/7	7.4	68	6.910	77
24.	Co. Apaxco, of the Malinche complex	354.6	+ 31.9	7/7	5.7	114	6.947	150
25.	Co. Zacayuca Oligocene-Miocene complex	359.0	+ 61	7/7	21.7	9	6.308	1200
26.	Co. Zacatepetl Oligocene-Miocene complex	11.5	+ 53.8	7/7	5.3	129	6.953	300
27.	Cuatro Dinamos Norte, San Miguel complex	192.3	— 46.7	6/6	6.8	98	5.949	150
28.	Ajusco flow and flow breccia	9.1	+ 10.3	7/7	5.5	120	6.950	300
29.	N. side of Ajusco recent flow	352.0	— 32.2	5/5	32.8*	6	4.374	77
30.	Cuatro Dinamos? San Miguel complex	161.8	— 48.0	4/6	11.9	60	3.950	150
38.	Huitzilac of the Zempoala	46.4	+ 12.2	6/6	8.8	59	5.920	150
39.	SE of Xicalco, Oligocene-Miocene basal complex	37.8	— 7.9	6/6	14.5	22	5.770	77
40.	Ajusco NE Oligocene complex	205.0	— 26.1	3/7	70.3*	3	2.88	600

* Result not regarded as significant

Table 1c Sierra Nevada and Sierra de Rio Frio

	Site	Declination	Inclination	Sampling	$\alpha 95$	K	R	Field
1.	East of Texcoco massive vesicular basalt	200.2	—22.7	6/6	10.6	41	5.877	600
2.	East of Texcoco basalt	177.1	—32.8	8/8	8.6	43	7.836	600
3.	East of Texcoco weathered sample from caldera rim	180.3	—62.3	6/7	7.9	74	5.932	600
4.	Zoquiapan spheroidal weathering basalt	176.7	—27.9	8/8	8.2	47	7.85	1200
5.	Cerro Tezoyo andesite or dacite latite intrusion	0.6	+28.0	7/7	8.3	54	6.89	77
6.	Cerro Ventorrillo	129.2	+70.5	7/7	4.8	162	6.96	600
7.	N.W. of Cerro Ventorrillo	144.5	+78.6	0/6	6.8	98	5.949	600
8.	Rio Frio watershed soft andesite	169.8	—36.7	5/7	48.2*	3	4.62	600
9.	Rio Frio	330.3	+49.6	5/7	57.3*	2	4.09	300
10.	Rio Frio quarry behind village	180.3	—28.3	5/6	25.9	10	4.586	600
11.	Rio Frio flow banded dacite, road crop	359.2	+33.1	3/3	13.8	87	2.975	150
12.	NE of Llano Grande pheno-andesite	165.4	—29.0	6/7	38.5*	3	5.24	300
13.	Llano Grande pheno-andesite	320.2	+67.8	6/7	34.8	5	2.23	300
14.	NE of San Rafael altered andesite below basalt	177.6	—28.5	7/7	4.2	209	6.97	600
15.	NE of San Rafael basalt (120)	183.1	+69.8	3/4	92.4*	2	2.488	77
16.	San Rafael basalt	359.4	+13.0	7/7	4.8	178	6.97	600
17.	San Rafael	183.5	—24.5	7/7	4.5	178	6.97	600
18.	Dome, andesite	356.7	+30.0	7/7	11.4	43	6.86	1200
19.	Dome, red brecciated andesite	356.6	+31.9	7/7	6.8	79	6.92	1200
20.	Flow, same age or younger than 19	3.8	+35.9	7/7	7.6	64	6.91	600
21.	Grey andesite	7.4	+38.1	7/7	7.1	73	6.92	300
22.	Flow top fault scarp N. of Iztaccihuatl	351.8	+21.1	3/6	118.7*	1	2.16	1200

* Result not regarded as significant

	Site	Declination	Inclination	Sampling	α95	K	R	Field
23.	Flow below 25	349.5	+ 29.4	4/7	53.7*	3	3.64	1200
24.	Iztaccihuatl, flank of Cabeza	7.8	+ 21.4	3/7	8.9	192	2.990	300
25.	One of highest flows Cabeza, Iztaccihuatl	354.0	+ 30.0	6/6	7.6	80	5.94	600
26.	Lowest flow from Pecho Iztaccihuatl	331.9	+ 24.4	7/7	11.3	29	6.80	300
27.	San Tomas, Ateingo dacite Xochitepec group	170.2	— 30.1	7/7	5.2	135	6.96	150
28.	San Antonio Tlaltehuacan quartz andesite Chichinautzin group	178.6	— 43.3	7/7	3.7	274		300
29.	Iztaccihuatl Tlal lower flanks west of Pies pheno-andesite	355.5	— 8.0	7/7	7.2	71	6.92	77
30.	Iztaccihuatl south and west of Pies pheno-basalt	347.8	+ 32.0	6/6	26.6	7	5.32	77
47.	Iztaccihuatl south and west of Pies	13.8	+ 31.2	4/7	9.4	96	3.97	600
49.	Iztaccihuatl south and west of Pies (Cerro Venachio)	354.6	+ 33.7	7/7	17.4	13	6.54	600
50.	TV Station Andesite	346.5	+ 44.8	3/6	81.8*	2	2.93	300
53.	TV Station Andesite	356.1	+ 39.8	8/8	4.2	178	7.96	600
54.	Paso de Cortes vesicular basalt	354.3	+ 17.6	7/7	23.6	8	6.20	1200
55.	Nexapa thick flow	352.7	+ 18.0	7/7	7.0	76	6.92	600
56.	Nexapa fairly thin flow of Cerro Toloxochitl	358.3	+ 35.5	7/7	4.9	153	6.96	600
57.	Popocatapetl weathered andesite	54.8	+ 46.4	6/7	37.8*	4	5.28	77
58.	Popocatapetl below repeater station dacite, early Sierra phase?	356.9	+ 24.8	4/7	57.8*	2	3.82	600

Table 1d Vallé volcanics: South of Mexico

	Site	Declination	Inclination	Sampling	α95	K	R	Field oe
1.	Co.Peñon Viejo soft reddish lava	162.2	— 22.9	6/6	23.6	9	5.443	300
2.	Peñon de los Baños	355.9	+ 26.4	6/6	7.4	84	5.940	300
3.	Tlapocoya andesite	182.0	— 52.2	9/9	6.4	65	8.877	600

Table 1d Vallé volcanics: North of Mexico

4.	Atlautenco vesicular basalt	151.0	—20.0	6/7	4.3	248	5.979	600
5.	Cerro Gordo-quartz andesite, snout of flow	170.4	—30.9	6/7	14.1	24	5.787	1200
6.	Pyramides pheno-basalt lava under agglomerate	129.0	—47.8	7/7	43.9*	3	4.892	600
7.	Patlachique pheno-andesitic dome	351.9	+45.2	7/7	3.3	343	6.982	300
8.	Santiago Tepetilan pheno andesite	339.5	+48.6	6/6	4.5	225	5.978	300
9.	Cerro Chapultepec	211.7	—60.7	7/7	6.1	99	6.39	300

* Result not regarded as significant

Table 1e Sierra del Chichinautzin

	Site	Declination	Inclination	Sampling	$\alpha 95$	K	R	Field
1.	Tlalmanalco vesicular quartz andesite	353.3	+24.1	8/8	5.1	118	7.941	300
2.	Tlalteloco basalt flow	21.6	+23.5	3/6	16.1	60	2.967	600
3.	Site east of 2	41.2	+14.0	5/5	43.4	4	4.016	300
4.	Site east of 3	23.8	+21.5	5/6	9.4	67	4.949	300
5.	Atlazalpan vesicular basalt	346.5	+38.3	8/8	5.2	114	7.938	600
6.	Ixtayopan recent quartz andesite	356.6	+25.4	6/6	10.8	39	5.872	600
7.	Ixtayopan vesicular basalt	353.3	+23.7	9/10	8.3	39	8.980	1200
8.	Co. Teutli lower exposed flow	352.0	+23.9	6/6	4.5	219	5.977	600
9.	Milpa Alpa	10.0	+17.3	7/7	10.3	36	6.830	600
10.	San Juan Moyotepec dacite	356.9	+34.9	6/6	7.0	92	5.945	600
11.	San Gregorio Atlapulco pheno-basalt	341.8	+27.3	7/7	13.1	22	6.728	300
12.	Tepetlapa vesicular basalt	9.3	+17.4	4/6	12.2	58	3.950	150
13.	San Mateo Xalpa pheno-basalt	355.7	+17.3	7/7	12.6	24	6.750	300
14.	Pedregal de San Angel, Cuidad Universitaria	6.7	+24.7	7/7	6.0	104	6.942	300
15.	Pedregal de San Angel, Pereferico nr Picacho	354.9	+38.8	8/8	2.7	429	7.980	N.R.M.
16.	Chimalcoyac	3.7	+35.4	3/7	10.1	150	2.987	150

	Site	Declination	Inclination	Sampling	$\alpha 95$	K	R	Field
17.	San Pedro Martir Km 26.8 pheno-basalt	4.1	+ 33.8	6/6	8.65	61	5.920	300
18.	South of San Pedro Martir possibly same flow as 17	1.2	+ 31.2	7/7	3.4	314	6.981	150
19.	Old Cuernavaca road Km 23.9	1.6	+ 29.3	3/9	24.4	27	2.92	1200
20.	Old Cuernavaca road Km 24.9	346.3	+ 30.2	8/8	18.4	10	7.30	600
21.	Old Cuernavaca south esat of Xicalco Km 25.9	1.1	+ 36.1	8/8	6.8	68	7.90	300
22.	West of Xicalco fresh vesicular pheno-basalt	355.2	+ 36.9	6/6	13.8	24	5.80	300
23.	New Cuernavaca highway, flow round old andesite (39)	1.0	+ 38.5	8/8	3.5	259	7.973	300
24.	New Cuernavaca highway, Topilejo vesicular pheno-basalt	0.3	+ 35.9	6/6	8.7	60	5.917	150
25.	New Cuernavaca highway, Topilejo south Km 23 pheno-basalt	352.6	+ 15.4	5/6	7.9	95	4.958	300
26.	New Cuernavaca highway N of Co. Tuxtepec Km 26 andesite	6.7	+ 17.8	6/6	16.4	18	5.717	300
27.	Old Cuernavaca highway El Guarda	1.9	+ 17.6	10/10	9.63	26	9.655	300
28.	New Cuernavaca highway flow from Co. Acopiaxo pheno-basalt	358.5	+ 33.4	7/7	3.8	253	6.976	300
29.	New Cuernavaca S. of Co. Cima pheno-basalt	53.2	+ 14.8	6/6	22.6	10	5.488	N.R.M.
30.	Old Cuernavaca highway flow from Co. Texoyo	14.3	+ 6.1	5/7	11.0	50	4.92	77
31.	Old Cuernavaca highway flow from Co. Tres Marias pheno-basalt	16.2	+ 25.3	8/8	9.2	37	7.81	600
32.	New Cuernavaca highway S of Tres Cumbres dacite	2.0	+ 19.1	7/8	12.4	25	6.756	300
33.	Old Cuernavaca highway due S of Coajomulco	38.3	+ 30.8	5/6	33.3*	6	4.360	1200
34.	New Cuernavaca highway SE of Coajomulco	352.8	+ 41.8	7/7	2.7	489	6.988	150
35.	New Cuernavaca highway ESE of Coajomulco Km 52	8.3	+ 9.8	8/8	7.4	50	7.380	600
36.	New Cuernavaca highway ESE of Coajomulco Km 55	346.6	+ 36.1	7/7	6.0	101	6.941	77
37.	Huitzilac eastern edge of village andesite	338.4	+ 47.8	8/8	10.1	31	7.78	1200
38.	Huitzilac west of village very hard blue andesite	46.4	+ 12.2	6/6	8.8	59	5.92	150
39.	Xicalco SE; old, much altered andesite	37.8	— 7.9	6/6	16.5	22	5.770	77
40.	Ajusco NE Oligocene-Miocene complex	205.0	—26.1	3/7	70.3*	3	2.880	600

* Result not regarded as significant

Table 1e Sierra de Santa Catarina

	Site	Declination	Inclination	Sampling	α95	K	R	Field
41.	La Estrella, Culhuacan vesicular pheno-basalt flow	348.9	+ 32.8	7/8	7.8	61	6.902	1200
42.	Xochiaca fresh vesicular quartz andesite flow	168.7	— 7.7	6/7	9.5	51	5.902	600
43.	Acahuatepec vesicular basalt	2.8	+ 35.2	6/7	11.9	33	5.847	600
44.	Co. Santa Catarina flow	9.7	+ 35.1	8/8	6.4	77	7.909	77
45.	Acatitlan basalt flow breccia	5.9	18.3	5/6	15.6	24	4.839	77
46.	Santiago Acahuatepec vesicular basalt	5.3	+ 34.4	3/6	25.3	25	2.919	300
47.	Co. del Pino, Ayotla fresh pheno-basalt	183.2	—10.6	5/6	7.1	117	4.966	1200
48.	Co. del Pino, Tlalpizhuac fersh pheno-basalt	182.3	— 7.3	6/6	11.6	34	5.854	1200
49.	Co. Los Tecolotes fresh basalt	174.4	—16.9	5/7	20.4	15	4.734	600
50.	Flow south of *Santa Catarina* village	146.7	—28.7	5/6	23.0	12	4.669	600
51.	Cocotitlan vesicular pheno-basalt	176.8	—24.5	8/8	4.9	131	7.946	N.R.M.
52.	Co. Peñon Viejo flow capping cinder cone	175.4	—12.6	7/7	3.4	316	6.981	600
53.	Zoquiapan basalt possibly belonging to Co. Telapon	176.7	—27.9	8/8	8.2	47	7.85	1200

Table 2. Summary of ore-mineralogy data

a. Sierra de Guadalupe — b. Sierra de Las Cruces — c. Sierra de Nevada and Sierra de Rio Frio — d. Vallé volcanics: south of Mexico; north of Mexico — e. Sierra del Chichinautzin and Sierra de Santa Catarina
The sites are numbered as in table 1. Where two samples per site have been examined both results are given as an indication of the variation within the same unit. Two oxidation numbers are given, M the high temperature oxidation classification of titanomagnetit and J the classification of ilmenite alteration. The presence of maghemite (p.) or its absence (a.) is indicated.

Table 2a Sierra de Guadalupe

Site and rock type			Magnetic Sign	Oxidation M	Number J	Mean grain size µ	Maghemite p./a.	Notes
1.	Cuautepec Barrio Alto	quartz latite andesite	R	1.0	1.1	177	p.	
2.	Cerro Tianguillo	pheno-andesite	R	2.4	2.38	129	p.	pseudo-brookite-hematite (myrmekitic intergrowth)
3.	Cerro Tenayo	pheno-andesite	R	6.0	3.0	130	a.	pseudo-brookite-hematite (myrmekitic intergrowth)
4.	Cerro Chiquihiute	rhyo-dacite	R	6.0	3.0	144	a.	pseudo-brookite-hematite (myrmekitic intergrowth)
6.	Cerro Ticoman	pheno-andesite	R	6.0	3.0	95	a.	pseudo-brookite-hematite (myrmekitic intergrowth)
8.	Sta. Cecilia	pheno-andesite	R	6.0	3.0	54	a.	pseudo-brookite-hematite (myrmekitic intergrowth)
11.	Cerro del Panal	pheno-andesite	R	6.0	3.0	76	a.	
12.	Rambler	pheno-andesite	N	3.7	1.66	202	p.	
13.	Cuauhuis	pheno-andesite	R	4.65	2.53	115	p.	titanomagnetite lamellae in ilmenite
14.	Cuautepec Barrio Alto	dacite	R	4.5	1.07	145	p.	pseudo-brookite-hematite (myrmekitic intergrowth)
15.	Co Juanalco	rhyodacite	N	2.95	1.25	135	p.	lamellar titanomagnetite ilmenite
16.	Sta. Marie Tulpetlac	pheno-andesite	R	{ 4.21 1.33	1.69 1.11	40 133	p. p.	
17.	Cerro Risco		R	3.11	1.11	107	p.	lamellar titanomagnetite in ilmenite — ilmenite coating on titanomagnetite

19.	Coacoalco	dacite	R	{ 5.52	2.61	~~152~~	~~p.~~	~~goethite found~~
				1.09	1.05	17	p.	occasionally
21.	Sta. Isabel	pheno basalt	R	1.01	1.0	13	p.	titanomagnetite ilmenite intergrowth granulation present
22.	Cerro Sta. Isabel	quartz latite andesite	—	1.77	1.11	145	p.	
23.	Cerro Sta. Isabel	dacite	R	1.35	1.0	149	a.	ilmenite with titanomagnetite coating
24a.	Cerro Guerrero	dacite	R	2.02	1.15	12	p.	lepidocrocite in biotite
25.	Cerro de la Cruz	pheno-andesite	R	3.77	1.0	145	p.	titanomagnetite-ilmenite intergrowth
27.	La Villita	pheno-andesite	R	4.17	1.72	207	p.	titanomagnetite-ilmenite intergrowth

Table 2b Sierra de las Cruces

1.	Calacoaya	pheno-andesite	R	4.26	1.71	155	p.	
2.	El Fraile	dacite	N	1.0	1.0	158	p.	
9.	La Marquesa	quartz-andesite	R	4.1	1.63	96	p.	ilmenite-titanomagnetite intergrowth
11.	S. of La Venta	dacite	R	4.6	2.58	130	p.	lamellar titanomagnetite in ilmenite

Table 2c Sierra Nevada and Sierra de Rio Frio

5.	Cerro Tezoyo	dacite	N	1.06	1.00	142	p.	
	Rio Frio	pheno-andesite	N	1.14	1.12	8	a.	
11.	Rio Frio	dacite	N	2.46	1.25	57	p.	ilmenite-titanomagnetite intergrowth
12.	NE of Llano Grande	pheno-andesite	R	2.17	1.93	41	p.	lamellar titanomagnetite in ilmenite
13.	Llano Grande	pheno-andesite	N	1.68	1.17	96	a.	ilmenite-titanomagnetite intergrowth
24.	Iztaccihuatl (Cabeza flank)		N	2.9	1.69	222	a.	
27.	San Tomas	dacite	R	1.01	1.0	141	p.	
28.	San Antonio Tlaltehuacan	quartz andesite	R	6.0	3.0	—	a.	red colour

Site and rock type			Magnetic sign	Oxidation M	Number J	Mean grain size μ	Maghemite p./a.	Notes
29.	Iztaccihuatl (west of Pies)	pheno-andesite	R	2.72	1.82	173	a.	granulation present
47.	Iztaccihuatl (south and west of Pies)	pheno-basalt	N	1.21	1.0	3	a.	titanomagnetite-ilmenite intergrowths
	T.V. Station	pheno-andesite	N	1.16	1.0		a.	titanomagnetite-ilmenite intergrowths
54.	Paso de Cortes		N	1.34	1.14	10	p.	
57.	Popocatepetl	pheno-andesite	N	1.01	1.00	143	a.	pyrite, lamellar titano-magnetite in ilmenite
58.	Popocatepetl	dacite	N	1.46	1.15	142	a.	pyrite, chalcopyrite, lamellar titanomagnetite in ilmenite
Table 2d Vallé volcanics: South of Mexico								
1.	Co. Peñon Viejo	olivine-latite andesite	R	4.8	1.7	10	a.	lepidocrocite present
2.	Peñon de Los Baños		N	6.0	3.0	10		
Table 2d Vallé volcanics: North of Mexico								
4.	Atlautenco	pheno-basalt	R	2.56	1.25	16	a.	
6.	Pyramides	pheno-basalt	R	5.55	1.9	31	p.	ilmenite with titanomagnetite coating
7.	Patlachique	pheno-andesite	N	6.0	3.0	75	a.	pseudo-brookite-hematite (myrmekitic intergrowth)
8.	Santiago-Tepetilan	pheno-andesite	N	5.36	2.14	133	a.	hematite, ilmenohematite with rutile
Table 2e Sierra del Chichinautzin Sierra de Santa Catarina								
1.	Tlalmanalco	quartz andesite	N	1.29	1.06	20	a.	
6.	Ixtayopan	quartz andesite	N	1.0	1.0	20	a.	
9.	Milpa Alpa	pheno-basalt	N	2.5	1.31	17	a.	

10.	San Juan Moyotepec	dacite	N	3.3	2.5	16	a.	
11.	San Gregorio Atlapulco	pheno-basalt	N	1.04	1.0	23	a.	
13.	San Mateo Xalpa	pheno-basalt	N	1.0	1.0	15	a.	
14.	Pedregal de San Angel	pheno-andesite	N	6.0	3.0	173	a.	vesicular rock
16.	Chimalcoyac	pheno-basalt	N	1.0	1.0	42–2.5 (needles)	a.	chalcopyrite
17.	San Pedro Martir	pheno-basalt	N	1.0	1.0	5	a.	
18.	San Pedro Martir	pheno-andesite	N	2.17	1.93	41	p.	
22.	West of Xicalco	pheno-basalt	N	1.00	1.0	14	a.	
24.	Topilejo	pheno-basalt	N	4.8	2.8	72	p.	
			N	2.14	1.16	13	a.	
25.	Topilejo (Km 23)	pheno-basalt	N	1.08	1.00	10	a.	
26.	Tuxtepec (Km 26)	andesite	N	1.62	1.19	38–1.8 (needles)	a.	
28.	Co. Acopiaxo	pheno-basalt	N	1.01	1.00	101–1.8 (needles)	a.	ilmenite-titanomagnetite intergrowth
29.	Co. Cima	pheno-basalt	N	1.4	1.00	6	a.	
31.	Co. Tres Marias	pheno-basalt	N	1.37	1.00	11	a.	
32.	Tres Cumbres	dacite	N	1.0	1.0	8	a.	
37.	Huitzilac (east)	andesite	N	1.43	1.00	10	a.	
38.	Huitzilac (west)	andesite	N	1.06	1.00	15	a.	titanomagnetite with ilmenite coating
41.	La Estrella, Culhuacan	pheno-basalt	N	1.14	1.14	31	a.	red colour around highly oxidised grains
42.	Xochiaca	quartz andesite	R	1.10	1.0	38	p.	
44.	Co. Santa Catarina	pheno-basalt	N	1.57	1.05	43	p.	ilmenite-titanomagnetite intergrowth
47.	Co. del Pino Ayotla	pheno-basalt	R	2.41	1.18	14	a.	
48.	Co. del Pino Tlalpizhuac	pheno-basalt	R	1.16	1.01	7	p.	
51.	Cocotitlan	pheno-basalt	R	1.42	1.61	10	a.	ilmenite-titanomagnetite intergrowth

that the volcanic sequence is made up of olivine-andesites, andesites, quartz-andesites, latite-andesites, dacites and rhyodacites and that within each category there is a considerable textural and compositional range. Chemical analyses show that the effect of the large amount of glass normally present shifts the composition towards a more acid composition. In fact there are no real basalts. This particularly is significant in the Sierra del Chichinautzin long regarded as a basalt province but now shown to be essentially andesitic with even occasional dacites.

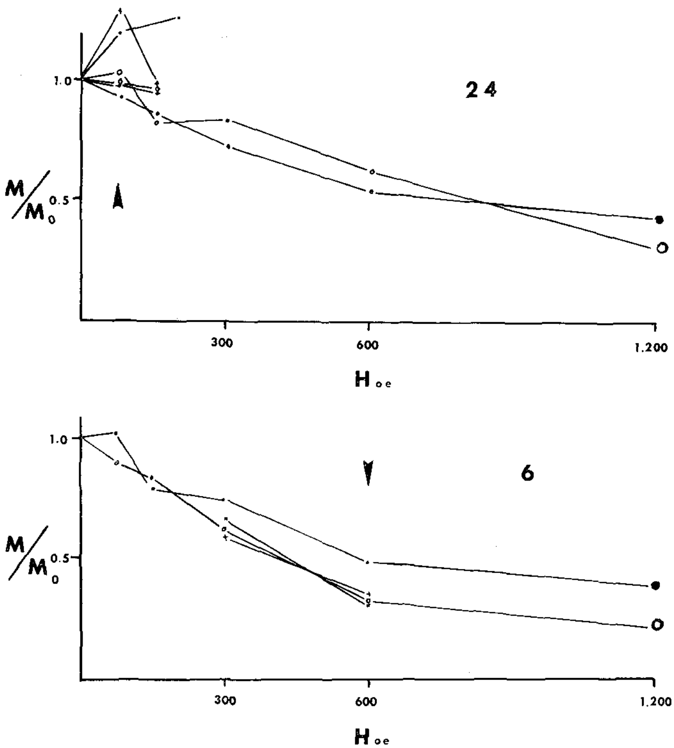

Fig. 4. Alternating field demagnetization curves on rocks from two sites (6, 24) in the Sierra de Guadalupe.

Petrological differences have no significance as stratigraphic markers nor, within the Valley of Mexico, are any regional differences discernable in the andesite-dacite sequence. GUNN & MOOSER (1970) are of the opinion that the volcanics owe their composition to the contamination of a mantle melt with crustal material of granodioritic composition.

The ore-mineralogy and so the oxidation state of the ferromagnetic oxides is of greater importance in the paleomagnetic context. The system of classification of the oxidation state of ilmenite and magnetite used here is that proposed by WILSON, HAGGERTY & WATKINS (1968) and used by ADE-HALL, KHAN, DAGLEY & WILSON (1968) amongst many others. Therefore we use the six classes of high temperature oxidation of titanomagnetite, three classes of high temperature ilmenite oxidation and remarks on low temperature oxidation. Computation of oxidation states was based upon 300 grain counts. The results are summarized in table 2 a—e.

In general high oxidation states characterize both titanomagnetite and ilmenite grains, and with increasing oxidation a reddening of the silicate phases progressively becomes more evident. Low temperature oxidation evinced by the occurrence of maghemite was observed in about half of the 85 sections examined, but granulation was seen in only two.

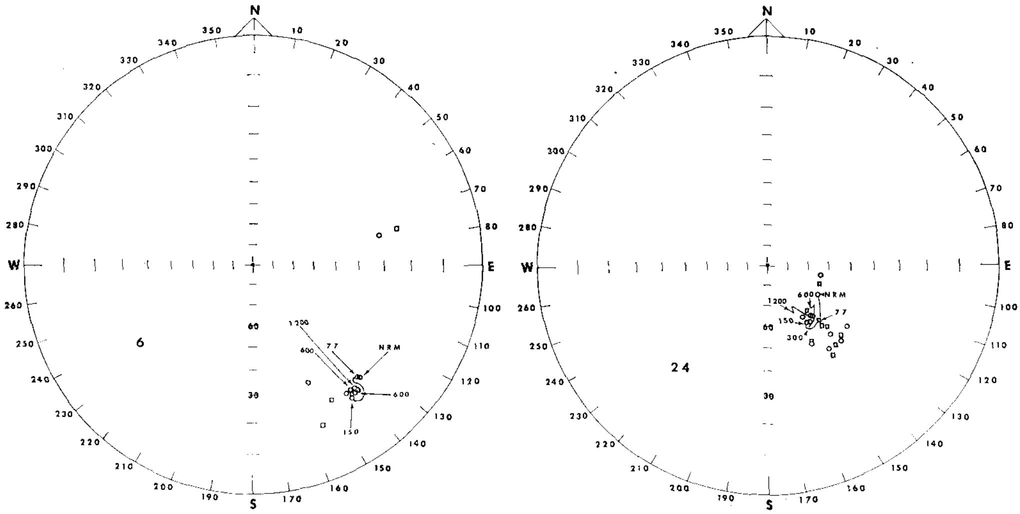

Fig. 5. Illustration of the direction changes during demagnetization of sites (6, 24). NRM direction represented by and cleaned result by 0. The step demagnetization in fields up to 1200 oe shown for only one sample per site.

General geology of the Valley of Mexico

The attempt to review the Cenozoic geology of the Valley of Mexico is handicapped by a surprising lack of published information. The principle source is MOOSER (1963, 1969, 1972) and unpublished data provided by MOOSER.

Although commonly referred to as the Valley of Mexico, structurally the region has the form of a basin entirely hemmed in by volcanic rocks (fig. 6, 7). Its mountain boundaries are the Sierra de Nevada (with the northern Sierra de Rio Frio) to the east, the Sierra del Chichinautzin to the south; to the west lies the Sierra de Las Cruces (with the southern Zempoala complex), and to the north the Sierras de Tezontlalpan (fig. 7) and Pachuca. Lake Texcoco lies in the southern-part of the Valley, with Mexico City extending on its western margin. The east-west dimension of the basin is about 60 km, its north-south dimension 110 km.

A single borehole east of Mexico City, Pozo Texcoco (fig. 11) (MOOSER 1970) penetrates the entire volcanic pile, and after traversing 2,060 m of predominantly volcanic material bottoms in a continental breccia containing blocks of Cretaceous limestone. As folded pelagic Cretaceous beds are found near Tula in the north and Puebla in the east, and Cretaceous inliers occur south and east of Cuernavaca (fig. 7), it is a reasonable inference that rocks of Cretaceous age underlie the Valley of Mexico, though downfaulted by a major NE-SW trending graben (fig. 6) of Upper Oligocene-Lower Miocene age (MOOSER 1972). It also follows that the present elevation of Mexico City is almost entirely due to the accumulation of Neogene volcanic products.

The date of the onset of volcanicity is not clearly defined, for the oldest dated volcanic rocks (30.4 my, 31.1 my ADAMS; in MOOSER 1970) are located some 500 m above the base of the volcanic sequence. The onset however appears to be coeval with that of the flood of ash flows and ignimbrites which blanket much of western Mexico. We distinguish now seven principal phases of activity, (table 3) the earliest being the basal volcanics (here called the Tezontlalpan group) followed by the Xochitepec group (GUNN & MOOSER, 1970) of Upper Oligocene-Lower Miocene age, which was succeeded by a period of quiescence marked by strong erosion and weathering of the extant volcanoes. The following Miocene-Pliocene Sierra-Phase is divided into the Lower- and Upper Sierra-Phase with a further short phase of activity at around 15 my whose products are named the Guadalupe group interfingering the products of the two Sierra-Phases.

The volcanoes of the last phase of activity, from Upper Pliocene-Pleistocene to recent times, are here referred to as the Chichinautzin group from their development in the southern part of the valley.

Preceding is the so called Transition-group concerning the products of the Tlalli-Zempoala-Nexpayantla- and the younger Ajusco-complexes.

Table 3 Sequence of Volcanic Activity in the Valley of Mexico

Chichinautzin group	*Upper Pliocene-Pleistocene to recent*	
Upper Sierra group	Miocene-Upper Pliocene	14—4 my.
Guadalupe group	*Upper Miocene approx.*	15 *my.*
Lower Sierra group	Miocene	
Xochitepec group	Upper Oligocene-Lower Miocene	30 my.—27 my.
Tezontlalpan group	Upper Oligocene	> 30 my.

With only a few dates available the time limits of the groups cannot be closely defined. (See also the stratigraphic column of the Valley of Mexico, fig. 7a.).

The distribution of volcanoes shows a very close association with underlying fracture patterns, although few fractures are clearly exposed because of the recent sedimentary lake fill. The early phases (Tezontlalpan and Xochitepec) were associated with WNW-ESE fractures although the influence of the SW-NE striking faults is apparent too (MOOSER, 1972). From the point of view of the shaping of the Valley of Mexico the controlling events were the development of the fracture patterns associated with the extrusion of the Sierra groups of volcanics which form the high boundary ranges to the east and west along poorly defined (SSE-NNW) lineaments whose origin is as yet poorly understood. During Quaternary times the dominance of extrusions of the Chichinautzin group, related to the development, or reactivation of an east-west fracture pattern (MOOSER 1963) sealed the valley to the south. One may suspect that both the Sierra Nevada (Popocatepetl and Iztaccihuatl) and the Sierra Zempoala belong to this newly appearing fracture pattern (fig. 6), which is very much concealed by recent effusions.

Although topographically the Valley is dominated by Pliocene or younger volcanic rocks, in the foothills of the Las Cruces, Sierra Nevada and Rïo Frio ranges, and within the basin itself, isolated and eroded relicts occur surrounded by lake sediments or younger volcanics. The most important of these is the Sierra

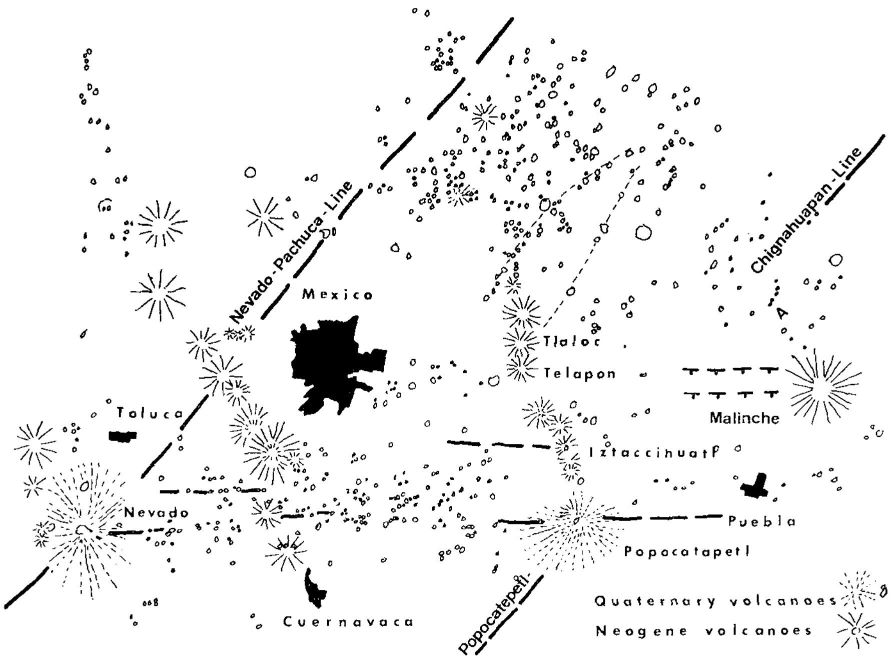

Fig. 6. The principal Quaternary and Neogene volcanoes in the vicinity of Mexico city. Smaller cones, mostly cinder cones, are shown by open circles.

de Guadalupe, for it provides the key to the early volcanic history in the Valley of Mexico, when taken in conjunction with the results from the Texcoco bore.

In order to discuss the geology of the Valley of Mexico further on it is convenient to divide arbitrarily the Valley into a number of geological-geographic regions. These do not completely define the Valley for in the northeastern segment relatively little work has been done prior to 1970. The regions are described in terms of volcanic stratigraphy marked by the super-position of single flows or flow units from different vents. The handicaps are that where there is no superposition of units, the relative ages of different vents are unknown, and exposures are such that the stratigraphy of individual volcanic units from a given vent may not be known. As there are only a handful of radiometric dates available, it is clear that while the history of a single volcano may be known in some detail, regional correlation is hazardous.

A. Sierra de Guadalupe. The Sierra de Guadalupe lies north of Mexico City in the fork formed by the diverging highways to Teotihuacan and Queretaro. It rises some 700 metres above the valley floor and is 20 kilometers in diameter. The near circular outline is delineated by an encircling secondary road which strings together the villages around its base. The only road to penetrate the complex approaches the village of Cuautepec from the southwest. The village lies in a graben (LOZANO 1968) whose southern continuation underlies part of Me-

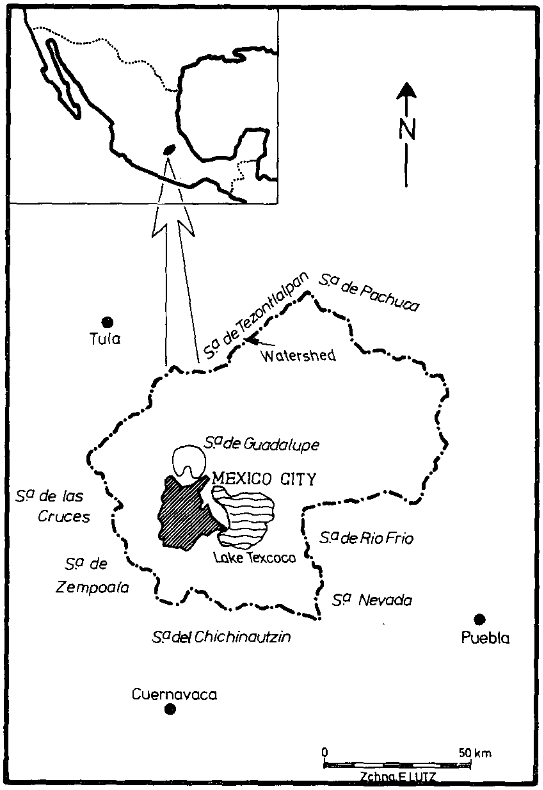

Fig. 7. Location and names of the ranges bounding the Valley of Mexico as used in this article.

xico City, whose northern extension however is buried by the products of the last phase of activity of Sierra de Guadalupe.

The Sierra de Guadalupe is a complex of large, viscous extrusive domes and medium sized stratovolcanoes built up of andesitic and dacitic lavas and pyroclastic rocks. Only on the northeastern flank of the complex is a young "basaltic" cinder cone found interfingering with lake sediments. The complex has been sufficiently eroded so that some indication of the internal structure may be obtained (Geological map, figure 8). The village of Cuautepec lies close to the center of the complex and it is in this region where hydrothermal alteration has resulted in some kaolinization. The hydrothermal solutions appear to have followed channels formed by the intersection of the graben faults with the pre-existing WNW-ESE fractures.

With one exception near Cuautepec the oldest volcanic elements ascribed to the Tezontlalpan group are found to the southeast of the Guadalupe complex (Sta. Isabel, Guerrero) as well as to the west. The isolated hill on the northern

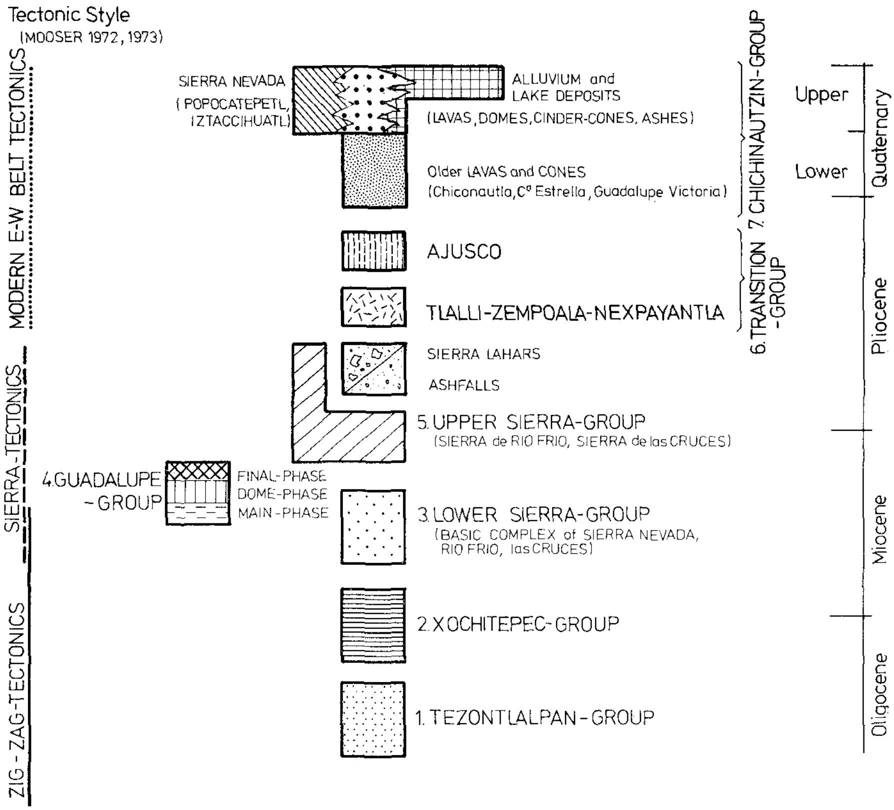

Fig. 7 a. Stratigraphic column of the Valley of Mexico (Explaination of the fig. 8—12).

foot of the complex is thought to belong to the Xochitepec group which developed in the lower Miocene.

The Guadalupe activity in a strict sense began with a series of andesitic, dacitic and latitic flows (main phase). Subsequently the NE-SW trending Cuautepec graben developed. Viscous extrusive domes ascended along the graben faults before fault movement was completed and as a result are truncated by them. Where the graben faults intersect fractures of the NW-SE running trend, hydrothermal solutions have caused some kaolinzation, as mentioned above. The final series were restricted principally to the northern part of the complex where volcanic products completely obscure the continuation of the graben in the region of the highest peak. A young flow (site 1, fig. 8) belonging to the final series

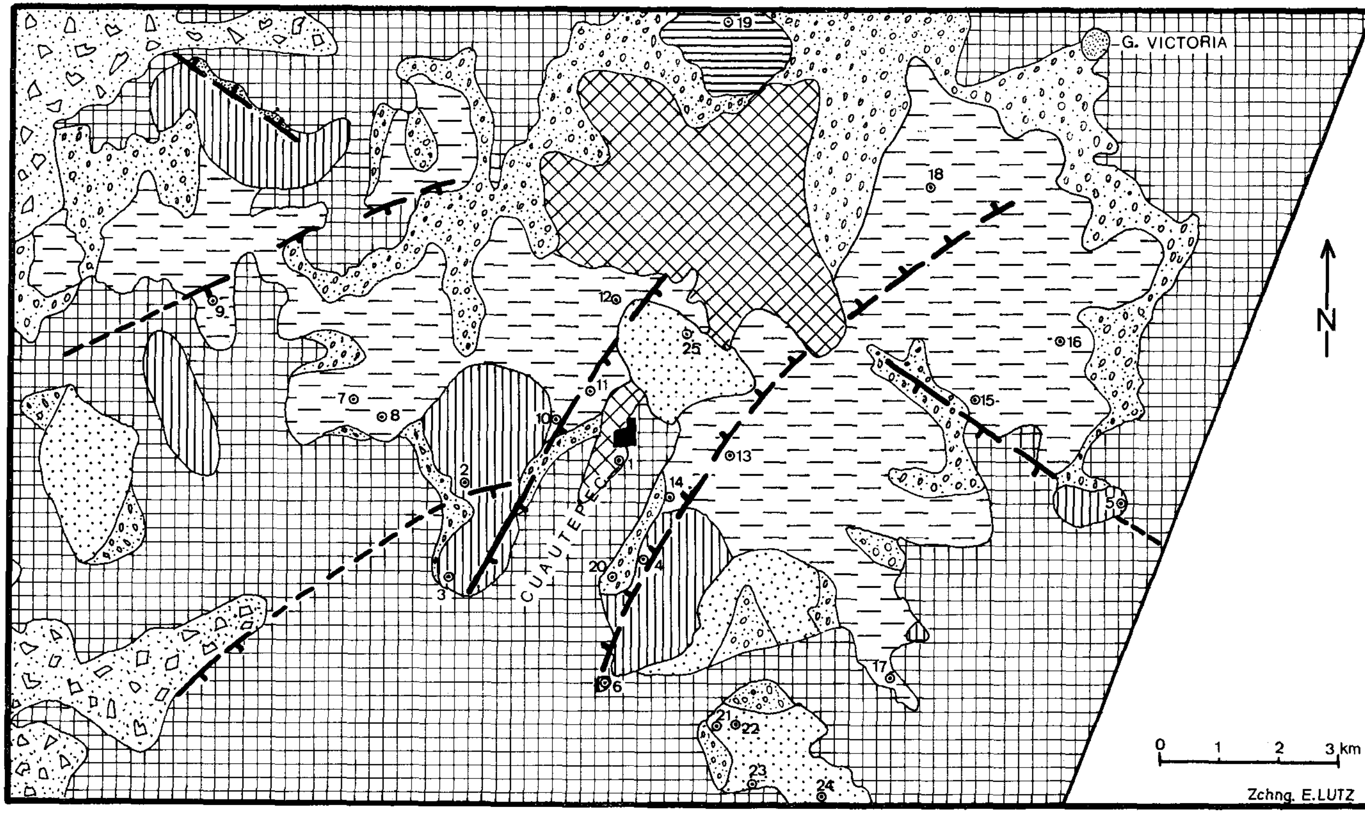

Fig. 8. Geological sketch map of the Sierra de Guadalupe. The numbered sites indicate the location of rocks sampled for paleomagnetic work and correspond to the data tabulation (table 1 a) and as shown in fig. 3 a. Map modified from LOZANO (1968) and PALACIOS (unpubl.) (see fig. 7 a).

of activity has been dated at 14.2 + 0.7 my, not significantly different in age from the main series of activity where an andesitic flow (site 9, fig. 8) yielded a date of 15.0 ± 0.8 my.

The graben faults were inactive in Pliocene times for they are covered by ashfalls of the younger Sierra phase.

The subsequent history is one of erosion and the encroaching of the western Sierra de Guadalupe by lahars and occasional ignimbrites originating in the high Sierra de las Cruces. The geological history of the complex is brought up to date by the deposition of Quaternary alluvial and lake deposits which surround it and into which the cinder cone of Guadalupe Victoria is intercalated.

The sites from which samples were drilled for paleomagnetic investigation are shown in figure 8. While the sampling of more sites would have been an advantage, the results from the twentyseven sites reported here are adequate due to their wide distribution over the Sierra de Guadalupe. Of these twenty-seven sites only four possessed normal magnetization (table 1 a, figure 3 a) of which one site (site 5) was a dome lying on a ESE fault; this structure is separated from the domes lining the graben. This underrepresentation of normally magnetized rocks could either be an artifact of the sampling or as we believe more likely a reflection of the rapidity with which the main part of the complex formed. The close spacing of the two radiometric dates available tends to support the latter conclusion.

B. Sierra de Las Cruces. The Sierra de Las Cruces parallels the Sierra de Rio Frio and forms part of the western margin of the Valley of Mexico. Although the range stretches NNW-SSE, it is not reflected in the observed pattern of faulting.

The Sierra de Las Cruces is built of an alignment of volcanoes of which the oldest and most eroded appear to be in the north. The higher parts of the volcanoes are formed of lava and breccia while the lomas or foothill regions are built up of volcanic fan material including abundant lahars and a few ignimbrites. It is this fan material which laps around the Sierra de Guadalupe in the west and hence sets a minimum age for the end of the "Guadalupe phase", the formation of the Sierra de Guadalupe complex. A few deeply weathered and eroded remnants which have been assigned to the earliest exposed (Xochitepec) phase of activity known in the Valley of Mexico are still exposed along the eastern flanks of the Sierra de Las Cruces (e. g. fig. 9 Cerros del Judio, Totoltepec). The main mass of the Sierra de Las Cruces is envisioned as formed by consecutive episodes of faulting and formation of stratovolcanoes, which were progressively displaced southwards. The evidence for this is the overlap of volcanic units, of which seven are recognized (see map fig. 9), if we include the Tlalli and Zempoala cones. Accompanying the development of each stratovolcano were ash flows and lahars. Ash from the San Miguel ash flow ("arenas azules" of the sand mines) yielded an age of 9.8 ± 1.0 my (MOOSER 1970).

The five lower units all show normal and reversed magnetization (see table 1 b and fig. 3 b) despite the low sampling density. If therefore the geological interpretation is valid, it is clear that volcanic activity must extend back into the Upper Miocene, and have been fairly continuous. In the absence of more K/Ar dates the interpretation of the measurements cannot be further refined. As in the Sierra de Guadalupe, the oldest exposed volcanics are reversely magnetized. Anomalous directions of magnetization of two ages, one in the youngest unit (Zem-

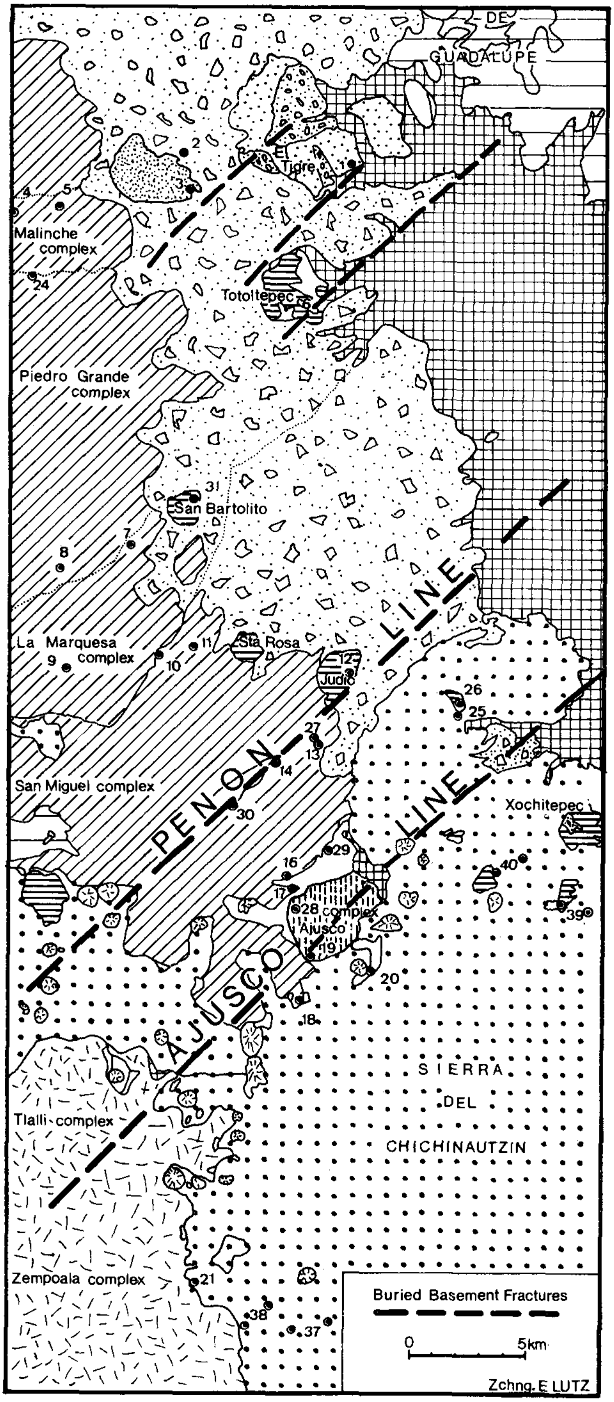

Fig. 9. Geological sketch map of the Sierra de las Cruces. The numbered sites indicate the location of rocks sampled for paleomagnetism and correspond to the tabulated results (table 1 b) and shown in fig. 3 b. The lavas of the Sierra group can be divided into a number of complexes as shown (see fig. 7 a).

poala) and one on Mt. Ajusco, may reflect intermediate directions associated with the process of field reversal, although the N.R.M. intensity was not significantly lower than that at other sites. (= Transition-Group).

C. Sierra Nevada (Sensu lato). The eastern limit of the Valley of Mexico is formed by the Sierra Nevada and Sierra de Rio Frio, together loosely referred to as the Sierra Nevada (sensu lato). The divide between the two ranges approximates the line of the Puebla highway. The Sierra Nevada (sensu stricto) comprises Popocatepetl und Iztaccihuatl (see fig. 10). The Sierra Nevada (sensu lato) has the general aspect of a block. Its presumed horst nature has recently been disproved (MOOSER 1972). The effects of east-west trending faults which form a double graben in the Puebla valley (only its northern half being visible) can be traced through the range. As in the case of the Sierra de Las Cruces, along the flanks of the range denuded and weathered remnants of the older volcanic elements are exposed south and west of Iztaccihuatl. There is uncertainty as to their correlation with the described groups; for the effects of this paper we unite them in the Basic complex of the Sierra Nevada. Most of the upper slopes of Iztaccihuatl and Popocatepetl are formed by andesites of a younger phase upon which rests the superstructure of the modern volcanoes which probably began forming in Upper Pliocene times. Young flows are found in the col between the two volcanoes known as Paso de Cortes and to the north in the vicinity of Rio Frio along the Puebla highway.

In general, the Sierra de Rio Frio is assumed to have been active since Upper Miocene times, just as its counterpart, the Sierra de Las Cruces. Cerros Telapon and Tlaloc, which crown the northern Sierra, were surely active in Upper Pliocene times, the latter displaying clear SW-NE fracturing at its summit. We correlate this fracturing with the Apan trend, calling it the Tlaloc-Apan line (fig. 10). Between older and younger volcanoes there are other strato-volcanoes whose stratigraphic position is uncertain. North of the Sierra de Rio Frio lies the Plio-Pleistocene series of Apan. Reaching down into the Valley of Mexico there is a series of overlapping fans built up of lahars, ash flows and occasional ignimbrites of different ages paralleling the development in the Las Cruces range.

The Sierra Nevada (s. l.) is affected by the east-west graben faults in the Puebla Valley. The divide between the Sierra de Rio Frio and the Sierra Nevada (s. s.) coincides with the western extension of the Tlaxcala fault forming the northern shoulder of the graben. A parallel fault to the south, which extends under the Malinche Volcano, reaches to the west under a small caldera lying on the northern Slopes of Iztaccihuatl. Mt. Popocatepetl seems to lie over the extension of the southern Puebla graben fault on its intersection with a deep-seated SW-NE trending fault. The further westerly prolongation of the first mentioned fault is buried under the Sierra del Chichinautzin range; within this range there are many cone alignments suggesting the existence of fractures with the same trend (fig. 6). The Sierra Nevada range, however, does not show any clear evidence of SW-NE tectonism, indicating the greater age of these fractures.

The locations of the sites sampled for paleomagnetic work are shown in figure 10. Site mean directions are listed in table 1 c and figured in figure 3 c. As in the case of the Sierra de Guadalupe, the predominance of a single magnetic sign is found on the higher slopes of Iztaccihuatl. In one unit above the tree-line flow by flow sampling (STEELE 1971) failed to disclose any sign change. We therefore

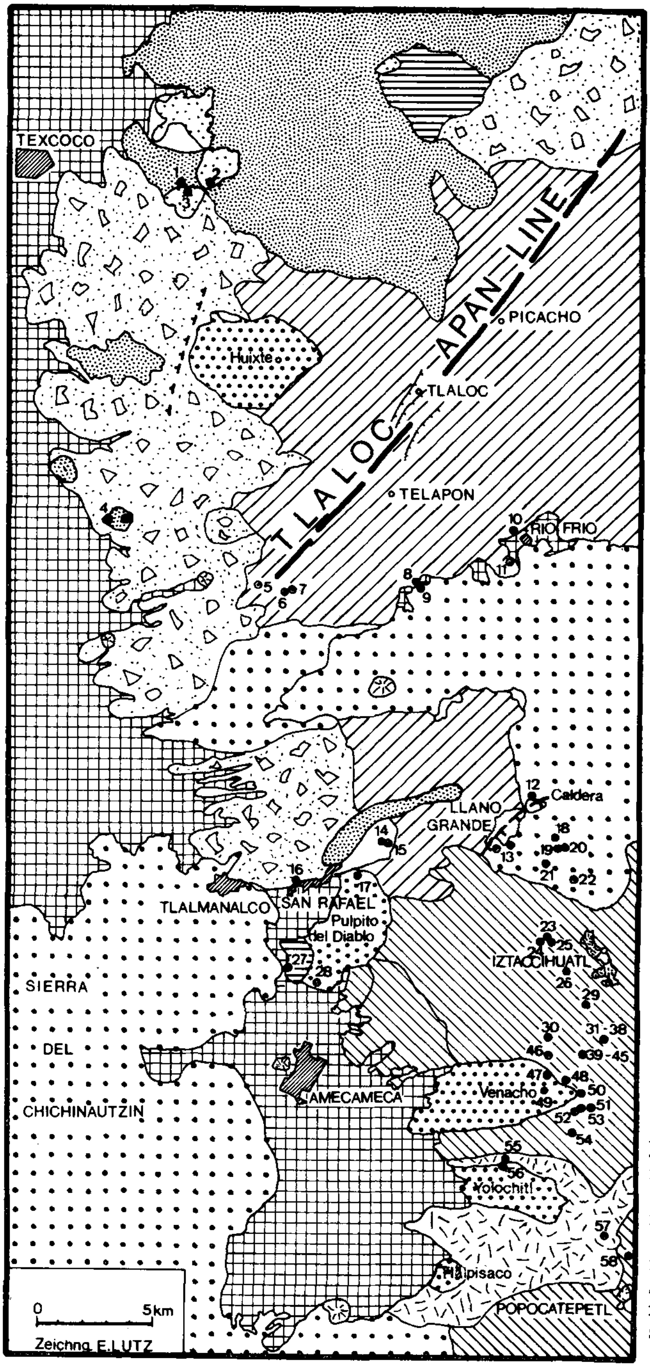

Fig. 10. Geological sketch map of the Sierra Nevada. The numbered sites indicate the location of rocks sampled for paleomagnetism and correspond to the tabulated results (table 1 c) and shown in fig. 3 c (see fig. 7 a).

believe that the paleomagnetic results support the idea of very rapid growth of individual volcanoes or volcanic units. The number and distribution of normally and reversely magnetized sites may again be paralleled with the situation in the Las Cruces range, and regarded as supporting short periods of very rapid volcan-

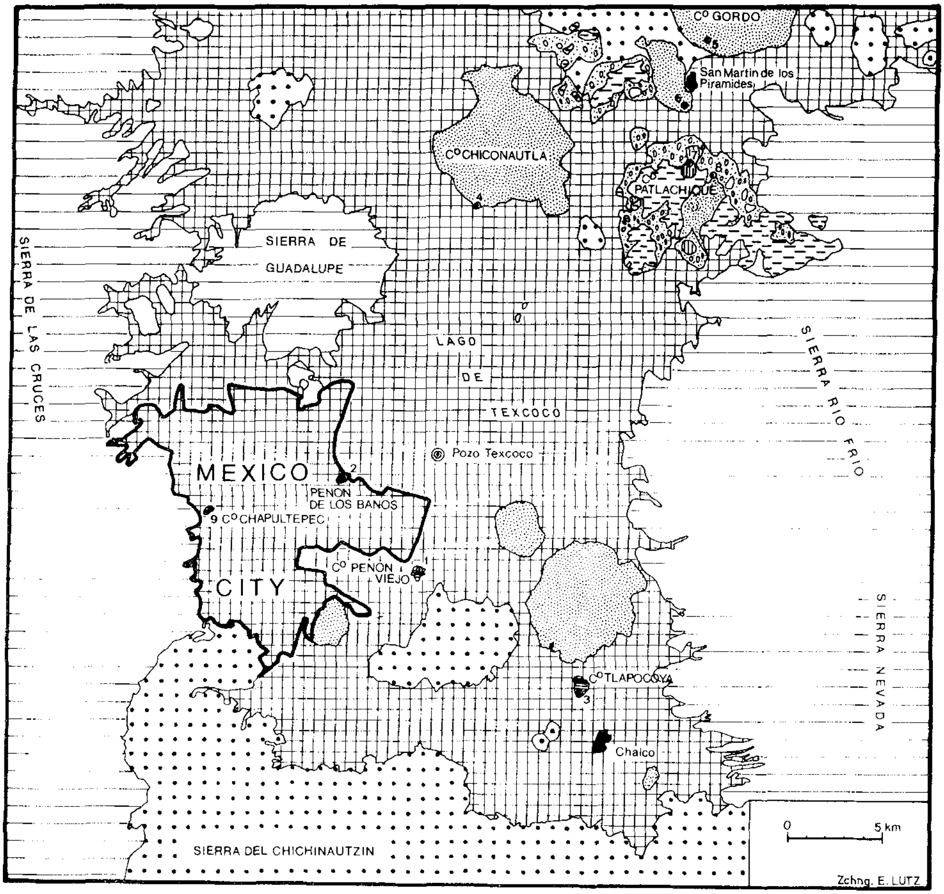

Fig. 11. Geological sketch map of the Vallé volcanics. The numbered sites indicate the location of rocks sampled for paleomagnetism and correspond to the tabulated results (table 1 d) and shown in fig. 3 d (see fig. 7 a).

ic activity at a given centre with activity extending over a considerable period of time.

Both normal and reversed directions of magnetization were found in sites in the oldest volcanic units exposed in the foothills of the chain.

D. Volcanics of the Valley of Mexico. This is a heterogeneous grouping of various isolated volcanic remnants still exposed despite the thick fluvial and lake fill in the Valley of Mexico. For convenience the younger volcanics south of Mexico City are deferred to the final section under the name of the Sier-

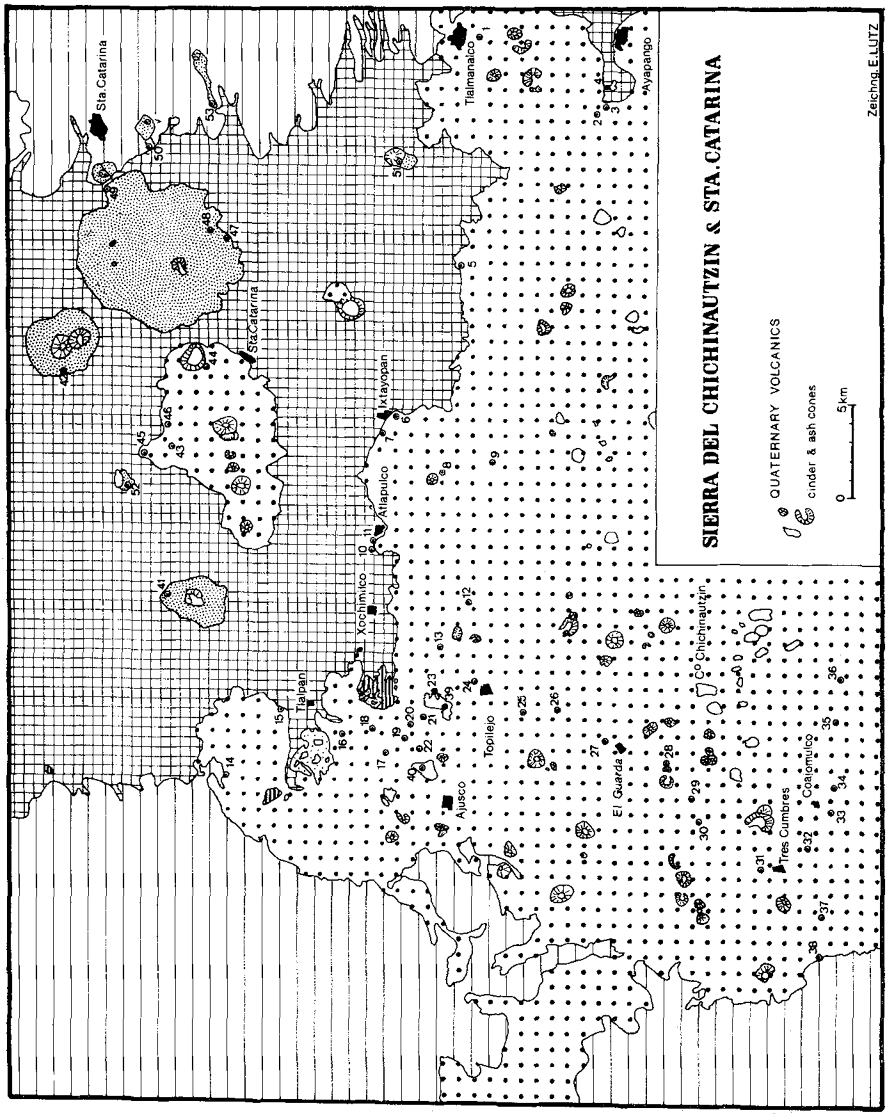

Fig. 12. Geological sketch map of the Sierra del Chichinautzin and Sierra de Sta. Catarina. The numbered sites indicate the location of rocks sampled for paleomagnetism and correspond to the tabulated results (table 1 e and shown in fig. 3 e). The principal cinder and ash cones are outlined (see fig. 7 a).

ra de Santa Catarina. We have examined two isolated units southeast of Mexico City, two within the city limits and a group of five in the vicinity of Teotihuacan (figure 11).

The rocks from the exposures in Mexico City and to the southeast are regarded as belonging to the second phase of vulcanicity (Xochitepec group). The ages on two units, which have not been examined paleomagnetically, are 22.5 to 25.7my. (Adams; in Mooser 1970). Both normal and reversed directions of magnetization are found.

Northeast of Mexico City lies the Quaternary volcano of Chiconautla. Given a Quaternary age for the volcano, the reversed magnetization at the site sampled suggests an age in excess of 0.69 my. for on geological grounds the site cannot represent the LASCHAMPS event. Cerro Gordo, also regarded as Quaternary, is also reversely magnetized. Only a few sites were collected on the Patlachique volcanic complex. This complex, not yet studied in detail, appears to bear many resemblances to the Sierra de Guadalupe, in that Upper-Tertiary andesitic and dacitic rocks probably equivalent in age to the Guadalupe phase crop out from under a cover of Plio-Pleistocene volcanic products. Samples from the younger units are normally magnetized and may thus represent extrusion as late as the GILBERT or even BRUNHES normal epochs. However no firm conclusions are possible.

E. Sierra del Chichinautzin and Sierra de Santa Catarina. This grouping covers the products of the youngest phase of volcanic activity of Upper Pliocene to Holocene age, which products formed the thick blanket that finally sealed of the Valley of Mexico to the south and permitted the formation of Lake Texcoco (fig. 12). Two bands can be discerned, the broad southerly band which includes Cerro Chichinautzin, and a secondary discontinuous belt to the north, here called the Sierra de Santa Catarina. The two are separated by the Chalco basin, the main Texcoco basin lying north of the Santa Catarina range.

Close to the northern margin of the Sierra del Chichinautzin relicts of older eroded andesitic rocks are found. No radiometric dates are available. The Chichinautzin range itself is over-whelmingly formed by younger cinder cones and lava flows, morphologically very fresh and all assigned to the younger Quaternary. As they are without exception normally magnetized, it is reasonable to assign to them an age of less than 0.69 my.

In the northern belt of Santa Catarina both normal and reversely magnetized directions are found. The reversed directions (sites 47—50, 42, 51) imply that the onset of Quaternary volcanic activity was earlier and persisted longer than in the southern belt, that is, it began at first at the MATUYAMA reversed epoch (0.69—2.50 my.) and continued during the BRUNHES normal epoch. Some of the flows are so young that vegetation has not yet become firmly established upon them.

Discussion

If we consider the results of our palaeomagnetic and petrologic work we can conclude that there is no obvious correlation between magnetic sign and oxidation state; we find both high and low oxidation associated with rocks of both polarities. There are more normally magnetized rocks with low oxidation state, this however appears to reflect the lower oxidation state which is more common in the youngest volcanics of the Chichinautzin range. Rocks seem to be either in a very high or a low oxidation state.

We believe that the reversals recorded represent true geomagnetic field reversals. However, detailed paleomagnetic stratigraphy is impossible for flow by flow sequences are the exception, and there is but a handful of absolute age determinations. The frequency of Cenozoic reversals however may be used to gauge the history of individual volcanoes. The high incidence of reversed magnetizations found in the Sierra de Guadalupe despite a well distributed sampling pattern suggests that the complex developed very rapidly. This is consistent with the only two K/Ar dates available from the complex. In a flow by flow sampling of a single volcanic unit on Iztaccihuatl STEELE (1971) did not find a single sign change. The total absence of reversed magnetization from the younger volcanics of the Chichinautzin range is most easily interpretated in terms of the youthfulness of its development within the BRUNHES normal epoch. In the Sierra de St. Catarina however we see a somewhat long history extending back we believe into the MATUYAMA interval. In marked contrast to the Sierra de Guadalupe there are approximately equal numbers of normal and reversed sites in both the Sierra Nevada (s. 1.) and Sierra de Las Cruces. If we accept the suggested geological interpretation, there is in both ranges evidence of activity extending back into Miocene times. The sporadic nature of the outcrops of the oldest volcanics which provide both normal and reversed magnetization preclude further interpretation.

The search for a cause for this vulcanicity can only be sought in terms of the Mexican volcanic belt as a whole. An explanation for the changing fracture patterns and source of magma along its irregular zig-zag course must be found in a complex tectonic history. The belt might be the result of deep-seated extension (STEWART 1971) of the product of a palaeoshear (LE PICHON & FOX 1971), or even a reactivated geosuture (MOOSER 1969); whether this belt is associated with an underthrust northward dipping plate or even if it represents a ridge-like structure, there is little concrete information available. The "underthrust plate hypothesis", however, accounts for three significant facts related to or characteristic of the Trans-Mexican Volcanic Belt: 1) the subduction of the Cocos plate explains the shallow seismisity in the Acapulco Trench; 2) the overwhelmingly andesitic composition of the Belt volcanics finds its explanation in subduction of the same plate under the southern Mexican crust; 3) the distribution of the metalliferous deposits north and south of the belt follows lines perpendicular to the trend of the Belt, SW-NE faults providing the principal control.

Nevertheless the absence of deep seismicity and the localization of the belt which does not run parallel to the Acapulco-Trench and at quite a distance from it are not yet readily explained. It is possible that the clue may lie in the ascent of volcanics along pre-existing lines of weakness. In this context we should mention the second hypothesis of petrogenesis considering the main part of the volcanic products as partial melting products of the lower crust (NEGENDANK 1972, 1973). This would explain the contrast with the Guatemalan volcanic belt.

Acknowledgements

The research was made possible by the support of N.S.F. Grant GF-246 under the U.S. — Japan cooperative research, and by a Cleveland Foundation grant which provided some of the equipment. To our Japanese colleagues Prof. N. KAWAI, Dr. K. HIROOKA and Dr. K. YASKAWA go our warmest thanks for their help particularly in the early stages of research. W. K. STEELE assisted throughout this general survey and subsequently studied parts of the Iztaccihuatl Volcano in detail. We must also express our thanks to Prof. I. HERRERA and Dr. M. MALDONADO of the Institute of Geophysics UNAM for useful discussions at the beginning of the work and their continuing interest.

A very great debt of gratitude is due to those Mexican geologists who assisted in the field with unfailing good humour, particularly Ing. DE LA PEÑA and Ing. PUENTE CRUZ. We also wish to thank Mrs. I. MIZOUCHI for her help with the routine measurements.

Further thanks is given to Mr. E. LUTZ, Trier, for drawing some maps, and Mrs. E. KNAPP, Trier, for retyping the manuscript after the incorporation of the newest available data done in June 1973 in Mexico City.

The Deutsche Forschungsgemeinschaft supported these investigations by a grant for oremineralogical equipment.

Bibliography

ADE-HALL, J. M., KHAN, M. A., DAGLEY, P., & WILSON, R. L.: A Detailed Opaque Petrological and Magnetic Investigation of a Single Tertiary Lava Flow from Skye, Scotland — I. Iron-Titanium Oxide Petrology. — Geophys. J. R. astr. Soc., **16**, 375—388, 1968.

GUNN, B. M., & MOOSER, F.: Geochemistry of the Volcanics of Central Mexico. — Bull. Volc., **XXXIV**, 2, 577—616, Neapel 1971.

LE PICHON, X., & FOX, P. J.: Marginal offsets, fracture zones, and the early opening of the North Atlantic. — J. Geophys. Res., **76**, 6294—6308, 1971.

LOZANO, L.: Geologia de la Sierra de Guadalupe, Mexico D. F. thesis. — Inst. Poly. Noc. Mexico, pp. 118, 1968.

MENARD, H. W.: Deformation of the northeastern Pacific Basin and the West Coast of North America. — Bull. Geol. Soc. America, **66**, 1149—1198, New York 1955.

MOOSER, F.: Historia tectonica de la Cuenca de Mexico. — Bol. Assoc. Mex. Geol. Petrol., **15**, 239—245, 1963.

—: The Mexican Volcanic Belt-Structure and Development. Formation of Fractures by Differential Crustal Heating. — *Pan American Symposium on the Upper* Mantle, **II**, 15—22, Mexico 1969.

—: Condiciones geologicas aceria del Pozo Texcoco PP I, V. — Reunion Nac. Mex. de Suelos, **2**, 143—161, 1970.

—: Bases geologicas y geo-hidrologicas paro et approrechamiento de las aguas subterraneas del Norte del Valle de Mexico. — Informe A.T.E.C., Sec. Rec. Hidrolicos, Mexico D.F. 1972.

—: The Mexican Volcanic Belt. Structure and Tectonics. Geofisica Internacional (in press).

MOOSER, F., & MOLDONADO-KOERDELL, M.: Mexican National Report on Volcanology. An. del Inst. de Geofisica, **12**, 99—106, Mexico 1967.

MOOSER, F., MEYER-ABICH, H., & MCBIRNEY, A. R.: Catalogue of the active volcanoes of the World, VI Central America, I.V.A. Naples pp. 146, 1958.

NEGENDANK, J. F. W.: Volcanics of the Valley of Mexico, Part I: Petrography of the volcanics. — N. Jb. Miner. Abh., **116**, 3, 308—320, Stuttgart 1972.

—: Volcanics of the Valley of Mexico, Part II: The Opaque Mineralogy. — N. Jb. Miner. Abh., **117**, 2, 183—195, Stuttgart 1972.

—: Zur Geologie des Tales von Mexiko. — Münster. Forsch. Geol. Paläont., H. 31/32, Münster 1973.

—: Some aspects of volcanic rocks of the Valley of Mexico. Proceedings of the Mexican Symposium on Geodynamics. — (In press.)

—: Some aspects of volkanic rocks of the Valley of Mexico (in press). — Bull. Volc., **37**, 3, Neapel 1973.

STEELE, W. K.: Palaeomagnetic directions from the Iztaccihuatl Volcano, Mexico. — Earth Planet. Sci. Letters, **11**, 211—218, 1971.

STEWART, J. H.: Basin and Range Structure: A system of horsts and grabens produced by deep-seated extension. — Bull. Geol. Soc. America, **82**, 1019—1044, 1971.

WILSON, R. L., HAGGERTY, S. E., & WATKINS, N. D.: Variation of Palaeomagnetic Stability and Other Parameters in a Vertical Traverse of a Single Icelandic Lava. — Geophys. J. R. astr. Soc., **16**, 79—96, 1968.