Geofísica Internacional (1995), Vol. 34, Num. 1, pp. 55-66

Paleomagnetic constraints on spatial/temporal volcanic activity in the Santa Catarina - Chalco region, southeastern basin of Mexico

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Received: September 3, 1993; accepted: September 2, 1994.

RESUMEN

Los resultados paleomagnéticos para unidades volcánicas en la región aledaña a la Sierra de Santa Catarina y Lago de Chalco pueden ser separados en tres diferentes grupos. El grupo I (12 sitios) se caracteriza por polaridad reversa, inclinaciones medias someras y variación paleosecular 'normal' (valor cercano a los estimados de modelos globales con dependencia latitudinal). Este grupo comprende unidades basálticas y andesíticas de conos cineríticos y volcanes de tamaño intermedio. Su rango de edad está dentro del cron Matuyama (0.78 a 2.64 Ma). Las unidades muestreadas en Cerro Estrella (polaridad normal e inclinación intermedia) y en Tlapacoya (polaridad reversa e inclinación intermedia) son consideradas dentro del cron Matuyama, como un sub-grupo I-B. El grupo II (7 sitios) está caracterizado por polaridad normal, inclinaciones medias cercanas al valor dipolar y variación paleosecular baja. Este grupo corresponde principalmente a conos cineríticos de composición basáltica. Su edad es considerada dentro del cron Brunhes (0 a 0.78 Ma). El grupo III (4 sitios) presenta polaridad intermedia y comprende a los conos con morfologías jóvenes de la Sierra de Santa Catarina. Probablemente representa un periodo transicional dentro de Brunhes (Pleistoceno tardío?). La actividad freatomagmática se observa en estructuras de Matuyama (Xochiaca) y de Brunhes (Xico y Tetecon), lo que indica la ocurrencia de cuerpos de agua y un nivel freático somero. Las estructuras volcánicas presentan alineaciones preferenciales, lo que está de acuerdo con sugerencias anteriores sobre un control estructural para el emplazamiento de magmas. Varias zonas de fracturamiento pueden ser observadas en las fotografías aéreas e imágenes de satélite. Las direcciones paleomagnéticas, sin embargo, no indican la ocurrencia de rotaciones o desplazamientos significativos. La dirección media para las unidades asignadas al cron Brunhes (grupo II) es similar a la esperada para la zona.

PALABRAS CLAVE: Volcanismo, paleomagnetismo, magnetoestratigrafía, Sierra Santa Catarina, Lago de Chalco, Cuenca de México.

ABSTRACT

Three groups of sites in the Sierra Santa Catarina and Chalco Lake region can be distinguished on the basis of their mean paleomagnetic directions. Group I (12 sites) of reverse polarity, shallow inclination and 'normal' paleosecular variation (i.e., overall VGP angular dispersion in agreement with latitude-dependent global models). This group corresponds to andesitic and basaltic units from cinder cones and medium-size volcanoes and is assigned to the Matuyama Chron (0.78 to 2.64 Ma). Results for Cerro Estrella (normal polarity and intermediate inclination) and Tlapacoya (reverse polarity and intermediate inclination) are also assigned to the Matuyama Chron, as sub-Group I-B. Group II (7 sites) presents normal polarity, mean inclinations close to the dipolar value and low paleosecular variation. This corresponds to mainly cinder cones of basaltic composition and is assigned to the Brunhes Chron (0 to 0.78 Ma). Group III (4 sites) is characterized by intermediate polarity and includes the morphologically young cones of Sierra Santa Catarina. It probably represents a transitional period during the Brunhes Chron (Late Pleistocene?). Phreato-magmatic activity is observed for structures in the Matuyama (e.g., Xochiaca volcano) and Brunhes (e.g., Xico and Tetecon volcanoes) groups, indicating the presence of water bodies and a shallow water table. Volcanic structures show apparent preferred alignments which supports previous interpretations of a structural control for magma emplacement within a dominant stress regime. Several major fractures can be identified from aerial and satellite images. The paleomagnetic directions do not indicate any significant rotations or displacements. The results for the Brunhes volcanic units (group II) have an overall mean direction close to the dipolar direction for the area.

KEY WORDS: Volcanism, paleomagnetism, magnetostratigraphy, Sierra Santa Catarina, Chalco Lake, Basin of Mexico.

1. INTRODUCTION

Volcanism has been the dominant process in the origin and evolution of the Basin of Mexico (Figure 1). Intense and widespread volcanic and tectonic activity has produced a high altitude large basin structure, with volcanic peaks above 5000 m a.s.l. and a lake basin at some 2200 m a.s.l. The conjunction of high topographic relief, volcanic activity and development of an extensive shallow lake system within the tropics has resulted in a rich record of complex environmental and climatic evolution. The basin has been a site for the development of ancient Mesoamerican civilizations. Early human settlement in the Basin has been documented for Tlapacoya, with C-14 dates around 23 000 years B.P. (Lorenzo and Mirambell, 1986). Large urban settlements such as Teotihuacan and Tenochtitlan likely developed because of the favorable conditions and unique location of the basin. Mexico City has become one of the largest metropolitan areas in the world and presently occupies much of the basin.

Volcanic and tectonic processes influenced the conditions for human settlers. Evidence can be found in the archaeological sites of Copilco and Cuicuilco, covered by

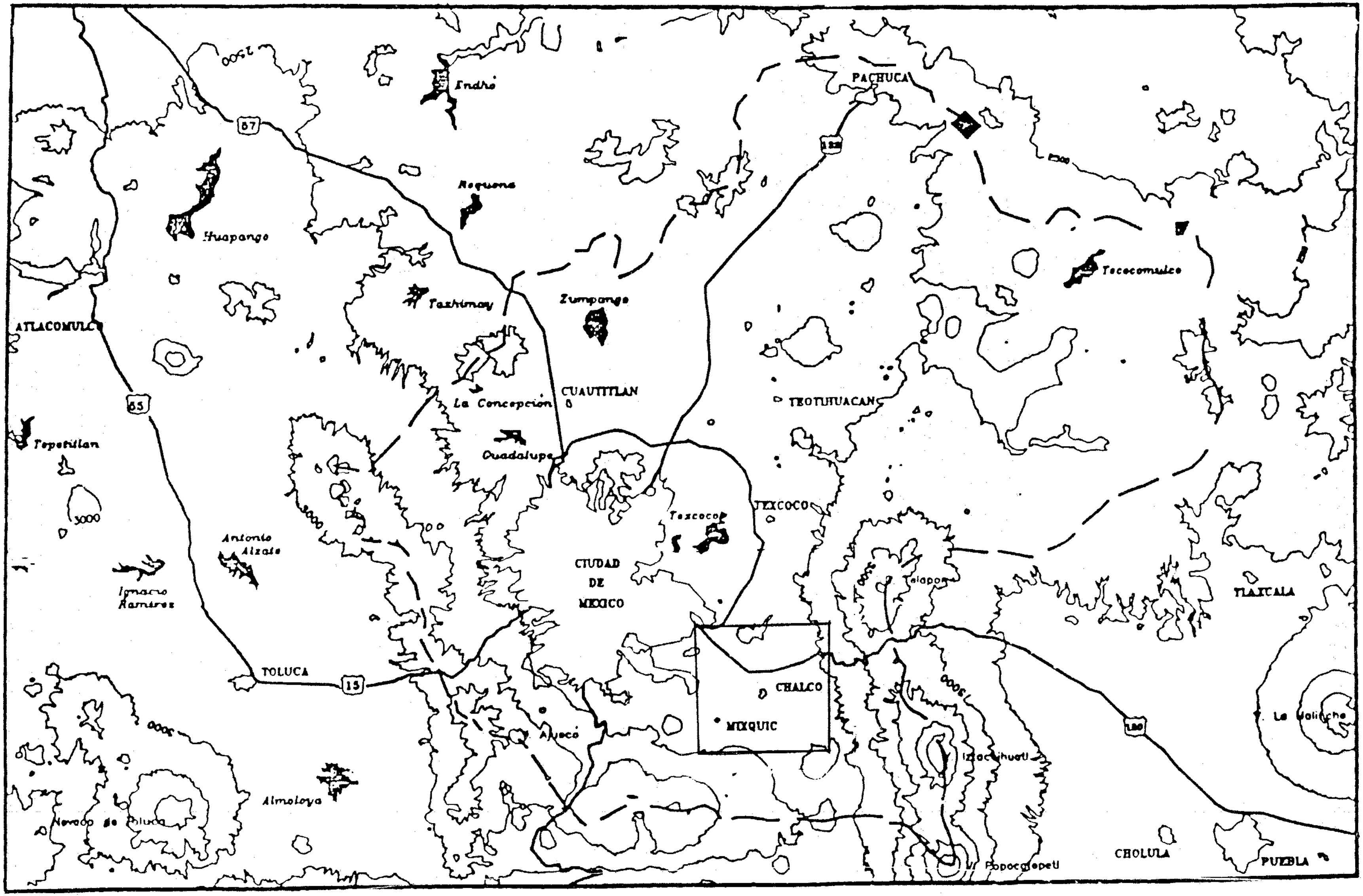

Fig. 1. Simplified map of the Basin of Mexico (dashed line marks the approximate boundaries). The study area, in the southeastern sector, is indicated by the rectangle.

lava flows, to recent destruction during the September 18-19, 1985 earthquakes. Yet little is known about the volcanic and tectonic evolution of most parts of the basin. Some important research has been acomplished (e.g., Mooser, 1963, 1970, 1975, 1978; Mooser *et al.*, 1974; de Cserna *et al.*, 1988), but knowledge of volcanic structures within City limits remains limited. This is also true of climatic change and environmental modifications of the basin which are linked to volcanic and tectonic processes.

Paleomagnetic data have been used to provide temporal constraints on the volcanic activity in the Basin of Mexico (Mooser *et al.*, 1974; Mora-Alvarez *et al.*, 1991; Urrutia-Fucugauchi and Martin del Pozzo, 1993). However, conclusions concerning the onset and duration of volcanic activity and environmental implications are not always accurate. An example is the assumption that activity in Chichinautzin began 700 000 years ago and that it marked the closure of the basin and development of the lake system (discussion in Urrutia-Fucugauchi and Martin del Pozzo, 1993).

In this paper preliminary results are reported for a magneto-stratigraphic and paleomagnetic study of volcanic structures in the Sierra Santa Catarina, Chalco Lake and southern Texcoco Lake, in the southeastern sector of the Basin of Mexico (Figures 1 and 2).

2. GEOLOGIC SETTING AND SAMPLING

The Basin of Mexico is a high altitude volcanic structure that is bounded by the Sierras Nevada and Rio Frio in the east, the Sierra de las Cruces to the west, the Sierras Tezontlalpan and Pachuca to the north and the Sierra Chichinautzin to the south (Figure 1). The Basin contains a thick volcano-sedimentary sequence, including lake sediments. Within the Basin, there are several volcanic structures, notably the Sierra Santa Catarina and the volcanoes La Estrella, Peño Viejo, Chimaluacán, Xico, etc (Figure 1). This study focuses on the Sierra Santa Catarina and volcanic structures in the Chalco and southern Texcoco lakes (Figure 2 and 3). The region is now extensively covered by urban development and agriculture (Figure 2). Some volcanic structures are being quarried for construction materials and the area provides part of the groundwater supply for Mexico City.

Mooser *et al.* (1974) found reverse polarity in 10 sites (Figure 3), and normal polarity in 12 sites (Figure 3) and concluded that activity in Santa Catarina started during the Matuyama Chron and has continued into the Brunhes Chron (see Table 1). They contrasted Santa Catarina with the Sierra Chichinautzin field that forms the southern sector of the Basin (Figure 1). All volcanic units studied in Chichinautzin have normal polarity, so they proposed that the activity in the Santa Catarina area covered a longer period than that represented by Chichinautzin alone. Structures in the Sierra Santa Catarina show a young morphology (Lugo-Hubp *et al.*, in press) and had been assigned to the Late Pleistocene.

Table 1

Age range of polarity chrons and sub-chrons for the last 3.6 Ma based on Ar/ Ar dating (after Baksi, 1993).

Chron	Sub-chron	Age Range (Ma)	Polarity
Brunhes		Present-0.78	Normal
Matuyama		0.78 - 2.64	Reverse
	Jaramillo	0.99 - 1.05	Normal
	Olduvai	1.78 - 2.02	Normal
	Reunion	2.14	Normal
Gauss		2.64 - 3.61	Normal
		3.10 - 3.17	Reverse
		3.27 - 3.38	Reverse

The trend of eruptive activity suggests a structural control, notably for the young Santa Catarina cones. Shifting patterns of activity include changes in ejecta volume and composition. The presence of lakes or a shallow water table is indicated by phreato-magmatic activity. Some of the younger structures developed in association with the lake system, e.g., Xico cinder cone in Chalco lake (Figures 2 and 3). Alternation of magmatic and phreato-magmatic activity can also be documented in some of the Santa Catarina cones (e.g., Tetecon). Earlier phases of phreato-magmatic activity are represented by the Xochiaca double structure in Texcoco lake (Figures 2 and 3) (Urrutia-Fucugauchi and Uribe-Cifuentes, in preparation).

Volcanic products in the area belong to the calc-alkaline series and include mainly olivine basalts, andesites, dacites and basaltic andesites (Gunn and Mooser, 1971). Pino, Estrella, Peñón and Cocotitlan are dominantly andesites. Tlapacoya is of dacitic composition.

The present study discusses the spatial-temporal distribution of volcanic activity in the region. The early stage did not include the young structures in the Sierra Santa Catarina or some of the young structures in Chalco such as the Xico (Figure 3). Twelve additional sites were later collected in Santa Catarina, Xaltepec (sites 22-23), Tetecon (sites 8 and 13), Tecuautzi (sites 9-10) and Santa Catarina (sites 20-21) and Chalco areas, Xico (site 12) and Tlapacoya (site 14) (Figure 3). Site 24 is on a thick flow at the base of the Teutli along the road to Milpa Alta. Site 25 is in the basaltic volcanic dome of Morro Moyotepec.

3. METHODOLOGY

The intensity and direction of natural remanent magnetization (NRM) of each specimen were measured with a Princeton Applied Research (PAR) magnetometer or a Molspin fluxgate magnetometer. The stability and vectorial composition of NRM were investigated by stepwise alternating field (AF) demagnetization in 8-10 steps up to maximum fields of 60 or 100 mT, by using either a home-made AF demagnetizer or a Schonstedt reverse tumbling AF demagnetizer. The characteristic NRM (chNRM) component was estimated from the vector plots and from principal component analysis (PCA).

Fig. 2. Landsat thematic mapper image of the study area in the southeastern sector of the Basin of Mexico.

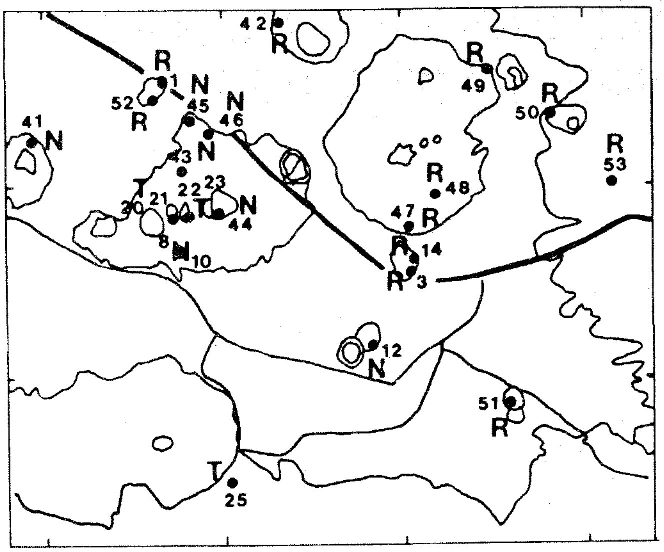

Fig. 3. Sketch of the study area showing location of sampling sites (adapted from De Cserna *et al.*, 1988). The polarity of the units is indicated by "N", normal and "R", reverse. Numbers refer to site identification (data in Table 2).

Vector means for each site were obtained by giving unit weight to sample chNRM directions (Fisher, 1953). Some outliers were rejected (McFadden and Jones, 1981). Virtual geomagnetic pole (VGP) positions were calculated for each site by assuming an axial geocentric dipole field. Magnetic polarity was simply estimated in terms of VGP latitudinal distribution, with normal polarity corresponding to 90°N to 45°N and reverse polarity for 90°S to 45°S. VGP latitudes between 45°N and 45°S were considered as intermediate or transitional states. For the stratigraphic dating, the magnetic polarities are assigned to the geomagnetic polarity time scale of Baksi (1993) (Table 1) which is based on recent Ar/Ar plateau dating of selected reversal boundaries and gives ages considerably older (5-7 %) than for K-Ar methods (Mankinen and Dalrymple, 1979). The Brunhes/Matuyama boundary lies at 0.78 Ma instead of the earlier assignment at 0.73 Ma. These revisions bring into agreement the astronomical calibrated scales (Shackleton *et al.*, 1990; Hilgen, 1991a,b) and the 'conventional' geomagnetic time scales. For the structural interpretations, the reference pole for the Quaternary was the geographic pole and for the Pliocene, the mean paleomagnetic pole for northern Mexico (from Urrutia-Fucugauchi, 1984).

The Landsat TM image for the southern sector of the Basin of Mexico (Figure 2) corresponds to a combination of spectral bands 3 (0.63-0.69 μm), 4 (0.76-0.90 μm) and 7 (2.08-2.35 μm). Band 3 corresponds to the chlorophyll absorption band which allows for vegetation discrimination. Ban 4 permits delineation of water bodies and estimation of biomass content. Band 7 is useful for lithological identification, particularly for day minerals and mapping of hydrothermal alteration. Fault scarps, structural and volcanic features can be examined in the combination of spectral bands (Figure 2). Image processing, which includes contrast, color, edge and multi-image enhancement procedures, has been discussed by Harrison and Johnson (1988).

4. RESULTS

Secondary NRM components in young volcanics may arise from viscous effects, lightning, weathering and hydrothermal activity and other sources. Many of these effects produce a vector in the direction of the present-day or dipole fields and obscure any record of tectonic effects by re-orienting the resultant magnetizations towards the dipolar direction. Secondary components also affect the estimation of angular dispersion for evaluating paleosecular variation.

Mooser *et al.* (1974) included only two vector plots without reference to any particular site or sierra. Their two examples clearly show the presence of secondary components; one with components of opposite polarities (sample 4 in their Figure 2). They only used four demagnetization steps, so the directions are not well defined. Their method for identifying and isolating the characteristic magnetizations involved selection of an optimum AF field in a pilot specimen and then demagnetization of the rest of samples from the site to that selected field. If the two examples reported are representative of the NRM records, then it is likely that secondary components may contaminate the site mean directions obtained for some units. In our samples, the coercivity spectra for the various NRM components varied widely for any given site. Thus no single AF field or range was found suitable for 'blanket' demagnetization or successful component separation. Examples of vector plots, showing various coercitivity spectra and vectorial compositions, are given in Figure 4.

Site mean chNRM directions for the sites are summarized in Table 2. Four sites have normal polarity, four sites intermediate or transitional polarity and one site shows reversed polarity. Directions from two sites (9 and 13) show a large scatter. No characteristic directions could be isolated and none are listed in the table. The magnetic polarity data are then referred to the geomagnetic time scale (Table 1). The temporal interpretation is included in Figure 3 and is further discussed below. Also added in Figure 3 are the site-mean declinations and the corresponding expected declination for the structural/tectonic interpretation.

5. DISCUSSION

Mooser *et al.* (1974) reported normal and reverse polarities for Sierra Santa Catarina and proposed that activity covered a long interval during the Quaternary. They contrasted the results with those for the Sierra Chichinautzin for which only normal polarity was found. Yet, some of the structures in the Sierra Santa Catarina have a youthful appearance with little or no erosion and little established vegetation cover (Lugo-Hubp *et al.*, in press). Geomorphological indications would disagree with those derived from paleomagnetism. Actually, our paleomagnetic polarity distribution shows a simple consistent pattern (Figure 3). Our new results for the young cones Xaltepec, Tetecon, Santa Catarina and Tecuautzi of Sierra Santa Catarina and Xico (and Xico Viejo) indicate normal and intermediate polarity, in agreement with geomorphological observations (Lugo-Hupb *et al.*, in press). The reverse polarity sites come

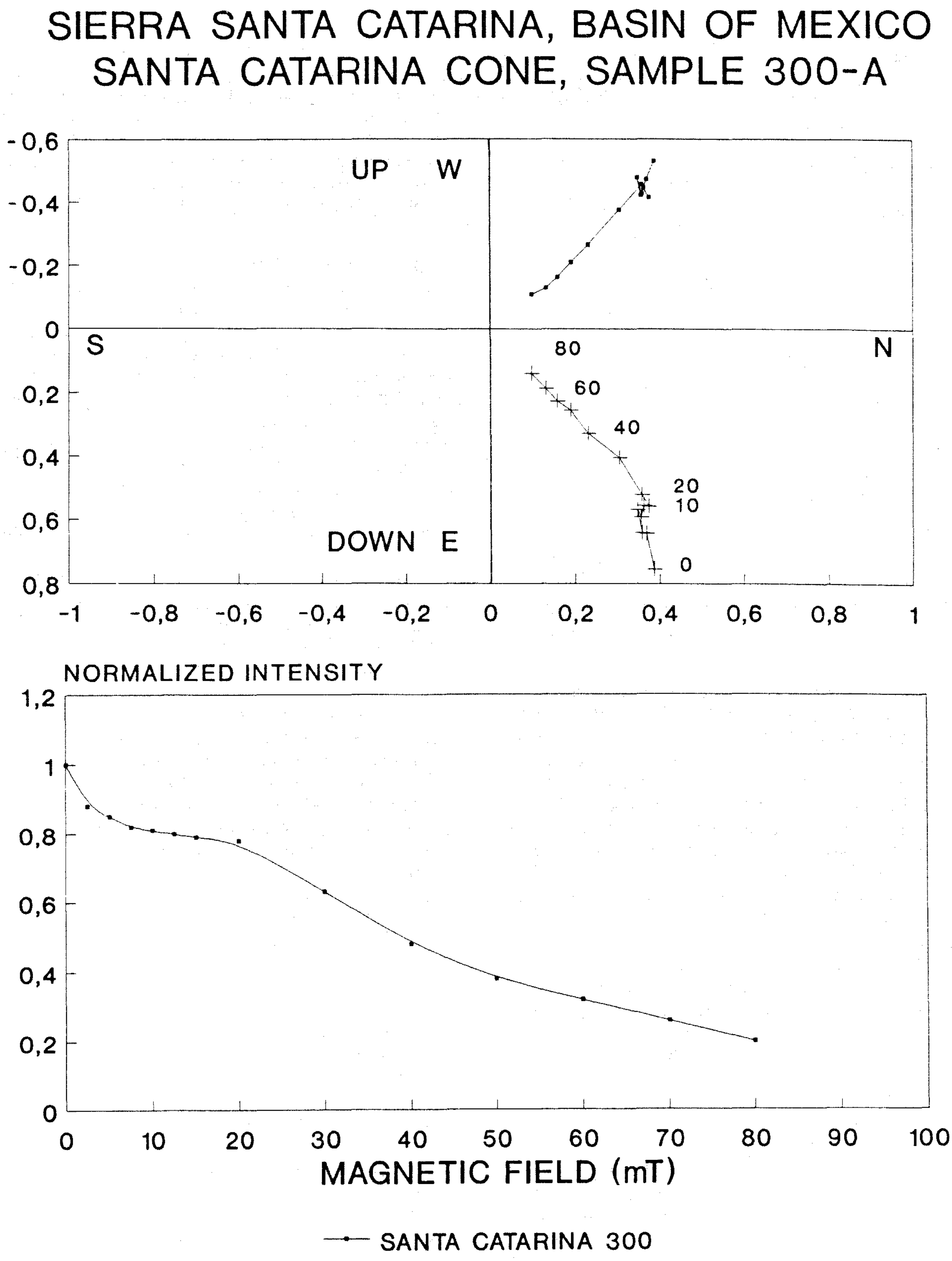

Fig. 4. Examples of AF demagnetization data (vector plots above and normalized intensity diagrams below) for four samples from the Sierra Santa Catarina. The characteristic magnetization (chNRM) was calculated by principal component analysis. It corresponds to the last linear segments going through the origin in the vector plots. Note that two or more magnetization components are present in the samples. The horizontal component is given by dots and the vertical component is represented by crosses in the four examples.

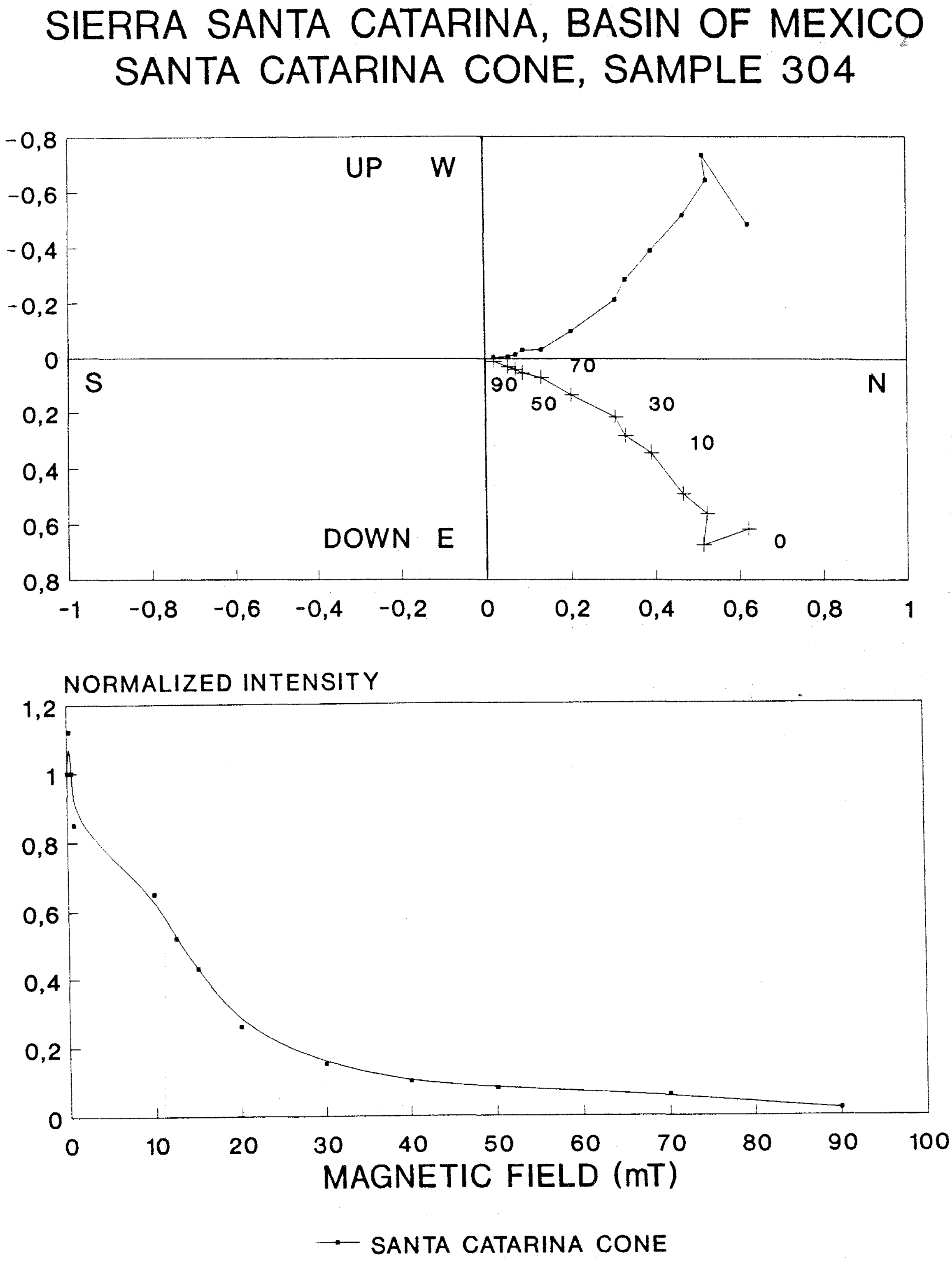
SIERRA SANTA CATARINA, BASIN OF MEXICO
SANTA CATARINA CONE, SAMPLE 304
UP W
DOWN E
S
N
-0,8
-0,6
-0,4
-0,2
0
0,2
0,4
0,6
0,8
-1
-0,8
-0,6
-0,4
-0,2
0
0,2
0,4
0,6
0,8
1
70
90
50
30
10
0
NORMALIZED INTENSITY
1,2
1
0,8
0,6
0,4
0,2
0
0
10
20
30
40
50
60
70
80
90
100
MAGNETIC FIELD (mT)
SANTA CATARINA CONE

Fig. 4. (Cont.)

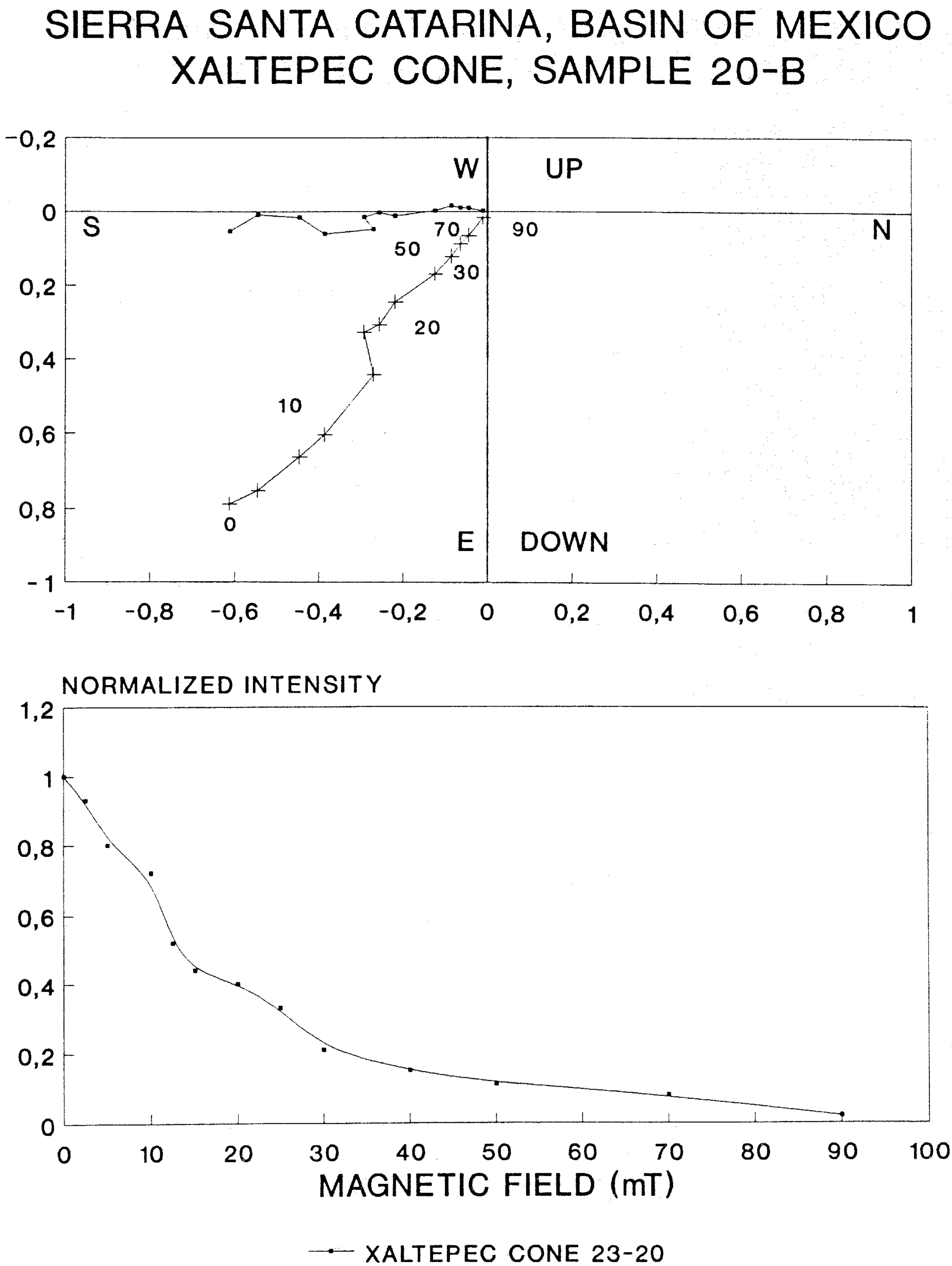
SIERRA SANTA CATARINA, BASIN OF MEXICO
XALTEPEC CONE, SAMPLE 20-B
W
UP
S
N
E
DOWN
0
10
20
30
50
70
90
-0,2
0
0,2
0,4
0,6
0,8
-1
-1
-0,8
-0,6
-0,4
-0,2
0
0,2
0,4
0,6
0,8
1
NORMALIZED INTENSITY
1,2
1
0,8
0,6
0,4
0,2
0
0
10
20
30
40
50
60
70
80
90
100
MAGNETIC FIELD (mT)
XALTEPEC CONE 23-20

Fig. 4. (Cont.)

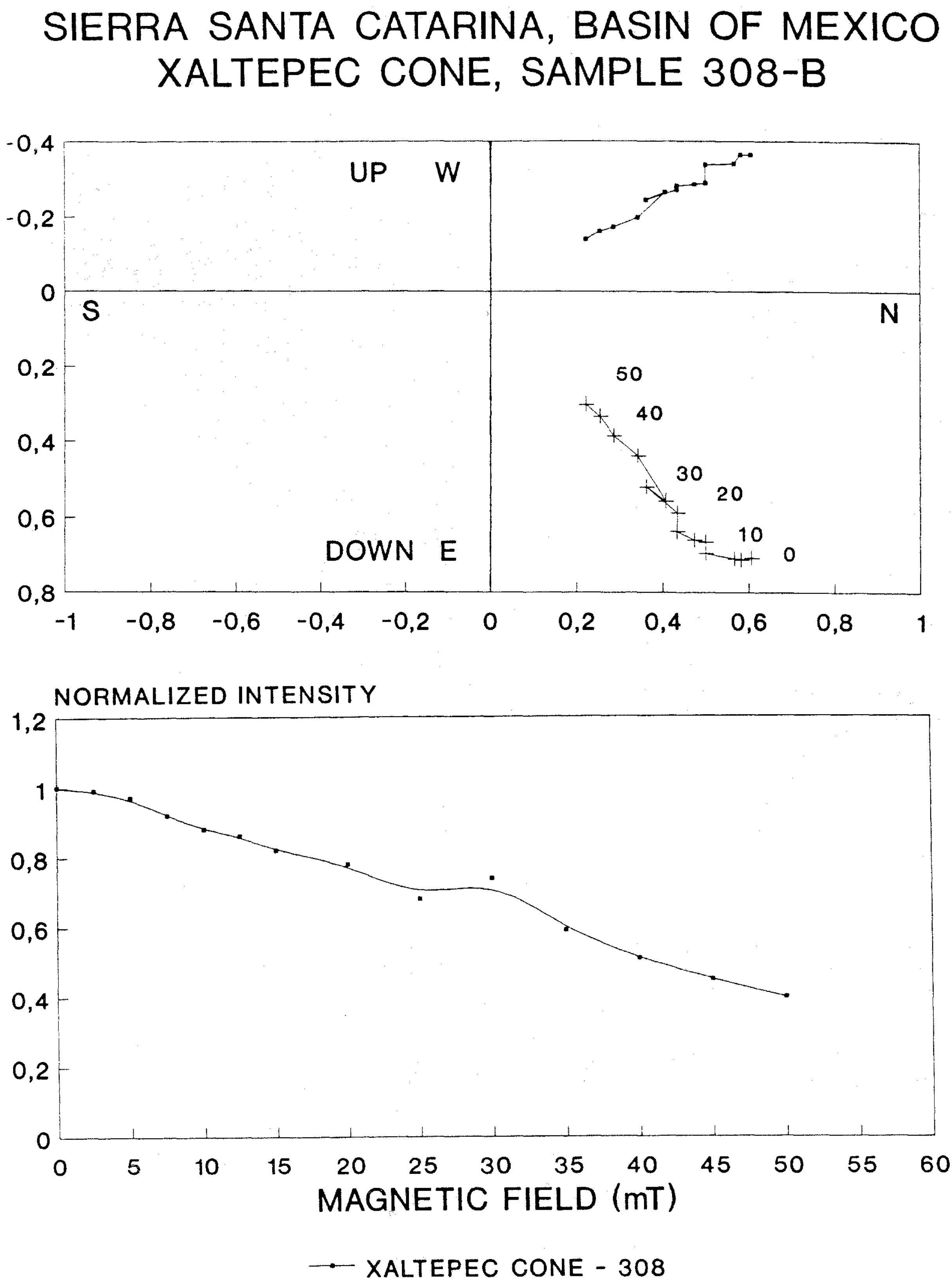
SIERRA SANTA CATARINA, BASIN OF MEXICO
XALTEPEC CONE, SAMPLE 308-B
UP W
S
N
DOWN E
50
40
30
20
10
0
-0,4
-0,2
0
0,2
0,4
0,6
0,8
-1
-0,8
-0,6
-0,4
-0,2
0
0,2
0,4
0,6
0,8
1
NORMALIZED INTENSITY
1,2
1
0,8
0,6
0,4
0,2
0
0
5
10
15
20
25
30
35
40
45
50
55
60
MAGNETIC FIELD (mT)
XALTEPEC CONE - 308

Fig. 4. (Cont.)

Table 2

Summary of paleomagnetic data for Santa Catarina, Chalco and Texcoco, southeastern Basin of Mexico.

Site	N	Dec	Inc	k	α95	R	Plat	Plong	Pol	Group	Ref
1	6/6	162.2	-22.9	9	23.6	5.443	71.3	170.2	R	I-A	1
3	9/9	182.0	-52.2	65	6.4	8.877	76.4	268.2	R	I-B	1
41	7/8	348.9	32.8	61	7.8	6.902	79.4	164.8	N	I-B	1
42	6/7	168.7	-7.7	51	9.5	5.902	71.0	117.9	R	I-A	1
43	6/7	2.8	35.2	33	11.9	5.847	87.4	349.0	N	II	1
44	8/8	9.7	35.1	77	6.4	7.909	80.8	349.4	N	II	1
45	5/6	5.9	18.3	24	15.6	4.839	78.5	50.4	N	II	1
46	3/6	5.3	34.4	25	25.3	2.919	85.0	355.3	N	II	1
47	5/6	183.2	-10.6	117	7.1	4.966	75.7	68.1	R	I-A	1
48	6/6	182.3	-7.3	34	11.6	5.854	74.2	72.6	R	I-A	1
49	5/7	174.4	-16.9	15	20.4	4.734	78.0	108.7	R	I-A	1
50	5/6	146.7	-28.7	12	23.0	4.669	58.0	169.1	R	I-A	1
51	8/8	176.8	-24.5	131	4.9	7.946	82.8	106.8	R	I-A	1
52	7/7	175.4	-12.6	316	3.4	6.981	76.3	100.7	R	I-A	1
53	8/8	176.7	-27.9	47	8.2	7.850	84.5	116.4	R	I-A	1
8	5/6	2.0	37.4	278	4.6	4.986	87.6	310.8	N	II	2
10	3/5	316.5	47.4	375	6.4	2.995	49.4	192.6	N	II	2
12	4/6	354.6	36.0	351	4.9	3.992	84.9	179.9	N	II	2
14	5/6	184.8	-47.1	173	5.8	4.977	80.0	286.0	R	I-B	2
20	3/6	303.1	47.0	57	16.4	2.965	37.7	192.1	T	III	2
21	3/6	233.4	37.4	611	5.0	2.997	24.0	25.9	T	III	2
22	6/6	17.9	63.9	71	8.0	5.929	60.1	286.6	N	III	2
23	3/6	190.2	54.8	2986	2.3	2.999	34.3	70.9	T	III	2
24	5/5	358.2	22.4	95	7.9	4.958	82.2	94.1	N	-	2
25	3/5	49.8	12.2	41	12.2	2.951	39.9	0.6	T	-	2
Group Mean directions and statistics											
I-A	9	172.2	-18.0	36	8.7	8.776					
I	12	173.3	-24.5	22	9.5	11.494					
II	7	358.3	35.9	25	12.2	6.763					
II	6	3.5	32.8	96	6.9	5.948					

Note: N, number of samples used/samples collected; Dec, Inc, declination and inclination of characteristic magnetization; k, α95, Fisher parameters R, vector resultant; Plat, Plong, latitude and longitude of VGP; Pol, polarity; Ref, reference: 1 Mooser *et al.* (1974), 2 this work.

from the Cerro Pino basal structure, the Tlapacoya and Cocotitlan volcanoes in the Chalco area, and Xochiaca and Peño Viejo in the Texcoco area. The Zoquiapan basalt of Telapon and southern Santa Catarina flow (in the eastern section at the base of the Sierra Nevada) are also reversed. The sites with intermediate polarity come from cones in the Sierra Santa Catarina, in Xaltepec and Santa Catarina.

These results may be interpreted in terms of at least two volcanic phases rather than a single long-lived period. Reverse polarity units represent older volcanism of andesites and basalts characterized by shallow site-mean inclinations are distributed through the region and include the Peñón Viejo and Xochiaca in Texcoco, Cerro Pino and Telapon, and the Cocotitlan and Tlapacoya in Chalco. The young structures are represented by basaltic cinder cones of youthful morphology and dipolar site-mean inclinations. The angular difference in site-mean inclinations suggests that magnetizations at each site were acquired at different paleomagnetic periods. This does not rule out the possibility of a long-activity period during the Matuyama and Brunhes Chrons, but it seems more consistent with the morphological evidence.

In Group I (old phase) there are 9 sites with reverse-polarity magnetizations and shallow inclinations (sites 1, 42, 47- 53; Figure 3 and Table 2). They are referred to as Group I-A and their mean direction is Dec=172.2°, Inc= -18.0° (n = 9, k=36, α95=8.7). Three additional sites form sub-Group I-B; Cerro Estrella (site 41, normal polarity) and Tlapacoya (sites 3 and 14, reversed polarity). These two sites have mean inclinations close to the dipolar value that varies from 34.9° to 35.2° in the area. Combining all Group I sites yields a mean direction of Dec=173.3°, Inc= -24.5° (n=12, k=21.7, α95=9.5). The young group (Group II) includes seven sites (43, 44, 46, 8, 10, 12) of normal polarity and mean inclinations around the dipolar value. The overall mean direction is Dec=358.3°, Inc=35.9° (n=7, k=25, α95 = 12.2). The overall mean data for Groups I and II is summarized in Table 3. The sites with intermediate polarity are included in Group III; they come from the cinder cones of Sierra Santa Catarina. They are morphologically young (Lugo-Hubp *et al.*, in press). Two sites come from a lava flow to the south of Santa Catarina (20-21) and two further sites come from a lava flow of cone Xaltepec (22-23). One site on the Acatitlan basalt flow (site 45) has a shallow inclination. One site from Xaltepec has normal polarity with a steep inclination. These results seem consistent and may represent magnetizations acquired during a transitional geomagnetic field. A possible alternative interpretation as a large counterclockwise rotation is not supported by the rest of the data (Group II overall mean is close to dipolar direction). Hence a transitional geomagnetic field interpretation is preferred. The results from a flow at the base of Teutli and from the volcanic dome of Morro Moyotepec (sites 24 and 25; Table 2) are not included in the overall mean calculations because of their geographic location near Xochimilco and the Chichinautzin Sierra. The site 25 mean direction has a shallow inclination and an intermediate polarity. Site 24 has a normal polarity.

Table 3

Summary of mean paleomagnetic data - Santa Catarina, Chalco and Texcoco, southeastern Basin of Mexico. Paleosecular variation data

GROUP	B	DEC	INC	K	A95	Plat	Plong	ST	SW	SB	SF
I	12	173.3	-24.5	33.2	7.6	81.8	133.3	14.1	13.9	13.0	12.9
II	6	3.5	32.8	158	5.3	86.5	12.2	6.4	11.6	3.9	3.7

Note: B, number of sites; K and A95, statistical parameters (Fisher, 1953); Plat, Plong, latitude and longitude of mean pole position; ST, SW, SB, SF, angular dispersion parameters for total, within-site, between- site, and geomagnetic field estimations. For the two groups, calculations are without outlying VGPs. Group I corresponds to Matuyama chron. Group II corresponds to Brunhes chron (see text for explanation).

In an attempt to investigate if the secular variation of the geomagnetic field can be averaged out, the angular dispersion of site-mean virtual geomagnetic poles was calculated. The methodology has been explained earlier (Böhnel *et al.*, 1990). It is based on two-tier and shape analyses of VGP distributions. The results for Groups I and II are summarized in Table 3. Group I is characterized by a value of SF of 12.9° which is relatively close to the estimate for the area from global latitudinal dependent models (e.g., Model G of McFadden *et al.*, 1988). Group II, however, has a low value for SF of 3.7°. It seems that the time span represented by the data is small compared with characteristic times for paleosecular variation. However, the number of sites is relatively small for paleosecular variation studies. Sierra Chichinautzin reports a value of SF = 11. 7° (Böhnel *et al.*, 1990), which is smaller than estimated from global models. A stalagmite sample from San Luis Potosí shows only a small angular dispersion, SF = 9.5°. The stalagmite is some 1200 years old and the record is short compared with secular variation periods. Volcanic units in the eastern sector of the volcanic belt yield an estimate SF of 14.8° but this also reflects the occurrence of tectonic rotations (Böhnel *et al.*, 1990). It has been suggested that a low paleosecular variation may have characterized central Mexico during the Brunhes chron (Böhnel *et al.*, 1990).

The young volcanic phase in the Sierra Santa Catarina follows a north-east trend, around N 70-80° E (Figure 3). The flow sampled in Santa Catarina seems younger than flows from Tecuautzi and Xaltepec. Xaltepec seems younger than Yuhualixqui. The young activity phase may include the cinder cones on top of Cerro Pino which follows a trend around N 60-70°E. The lineament of the Santa Catarina and Pino is roughly parallel to the Estrella-Peñon-Xochiaca trend to the north. Fries (1960) examined alignments in the Sierra Chichinautzin and reported a trend of around N 80-85° E associated with shallow fractures over deep en-echelon fractures due to N 45° E regional compression. Mooser (1963, 1975) also discussed major lineaments and fault systems in the Basin. De Cserna *et al.* (1988) described alignments of cinder cones in the Sierra Chichinautzin and the Tezontepec field. They report a dominant trend of about N 55-75° E for Chichinautzin and N 35-45° E for Tezontepec. They also provide data for the Sierra Santa Catarina and structures in the adjacent areas. Lozano-García *et al.* (1993) documented a normal fault east of the Xico double structure, which is contemporaneous with the recent lacustrine sedimentation. Gravity studies indicate a major discontinuity between the western and eastern sectors of Chalco lake; the eastern sector has a thicker sedimentary sequence (Urrutia-Fucugauchi and Chavez-Segura, 1991). Preferred alignments of cinder cones in the region may permit estimation of stress state and magma emplacement characteristics in the region (Nakamura, 1977; Shaw, 1980). Further study of the volcanic stratigraphy in the various volcanic fields is required to resolve the temporal-spatial sequence of tectonic activity in central Mexico.

ACKNOWLEDGMENTS

Useful critical comments by J. Lugo-Hubp, Don H. Tarling and Vincenzo Constanzo are gratefully acknowledged. An early sampling campaign in the Sierra Santa Catarina was carried out with the participation of F. Mooser, D.A. Valencio and S.P. Verma. Assistance with measurements on the initial samples was provided by R. Ponce and J. Sosa. The TM image was provided by C. Johnson. Most of the study was supported by UNAM DGAPA Projects IN-103589 and IN-103292, and by the Ricardo J. Zevada Scientific Foundation.

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