

# Magnetostratigraphy of a late Oligocene volcanic sequence, Durango, Sierra Madre Occidental, northern Mexico

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## RESUMEN

Los estudios paleomagnéticos realizados en la secuencia volcánica del Oligoceno tardío de la provincia de la Sierra Madre Occidental, en la región de Durango, permiten delinear la estratigrafía volcánica a partir de las observaciones de cinco reversiones (seis periodos de polaridad) y en los patrones de variación paleosecular del campo geomagnético. Para diecisiete unidades distribuidas en dos diferentes áreas, separadas unos 30 kilómetros, se obtuvieron las direcciones características de magnetización remanente. Los resultados indican que el emplazamiento de algunas de las unidades fué espaciado cercanamente en periodos cortos y que otras unidades están formadas por varios flujos distintos. Los resultados permiten además identificar a una unidad ignimbrítica que no había sido distinguida previamente por los estudios de cartografía geológica y geocronología. Esta unidad está por debajo, y presenta polaridad opuesta, a la unidad más antigua reportada en una de las secciones.

La comparación de la secuencia de polaridades en las dos secciones muestra polaridades diferentes para las unidades por debajo del Miembro Santa María de la formación Río Chico. Este Miembro Santa María es la unidad más antigua que puede ser correlacionada entre las dos secciones. Estas diferencias en la secuencia de polaridades apoyan inferencias previas de correlaciones litológicas e indican que la secuencia pre-Santa María en las dos áreas es producto de diferentes eventos eruptivos.

**PALABRAS CLAVE:** Paleomagnetismo, estratigrafía volcánica, ignimbritas, flujos de cenizas, tobas, provincia volcánica de la Sierra Madre Occidental, norte de México.

## ABSTRACT

Paleomagnetic studies were carried out on a Late Oligocene volcanic sequence exposed in the Sierra Madre Occidental, west of Durango City, Mexico. Volcanic stratigraphy identified five reversals (six polarity periods) of the Earth's magnetic field as well as paleosecular variations recorded in the flows. Characteristic directions of remanent magnetization were obtained at seventeen sites. Emplacement of some units was very closely spaced in time, and other units may be composites of several different flows. An ignimbrite not previously recognized in geologic mapping and geochronological studies was identified below the oldest unit by means of paleomagnetic criteria, as its polarity was opposite to the unit on top.

Comparisons between the paleomagnetic polarity sequences of two sections, sampled some 30 km apart, shows a different polarity for the units below the Santa María Member of the Río Chico Formation, oldest unit correlatable in both areas. This substantiates previous lithologic correlations and suggests that the pre-Santa María sequence in the two areas was produced by different volcanic events.

**KEY WORDS:** Paleomagnetism, volcanic stratigraphy, ignimbrites, ash flow tuffs, Sierra Madre Occidental volcanic province, northern Mexico.

## 1. INTRODUCTION

Stratigraphic correlations in ash-flow tuff volcanic regions are commonly handicapped by a total absence of fossiliferous strata. Physical and lithologic criteria such as thickness, jointing and cooling textures as well as position in the stratigraphic sequence are often used instead. Megascopic and microscopic observations based on the nature and degree of welding and color, total and relative proportions of phenocrysts, and proportion of crystal, lithic and vitric components may also provide supporting evidence.

These criteria may become rather thin when there are continuous outcrops, as similarities in physical appearance and complexity of structures may obscure the stratigraphic relationships between different units. Radiometric dating methods have been successfully applied for defining age relationships; but due to analytical uncer-

tainities, post-emplacement alterations, etc, these often do not provide the required time-resolution in areas of high rates of volcanic activity. It is desirable to obtain a finer definition of the stratigraphy within groups of flows with similar ages. This objective may be successfully approached by studying the paleomagnetic properties of units (e.g., Irving, 1964; Tarling, 1983; Palmer *et al.*, 1991).

The Earth's magnetic field has undergone numerous reversals in polarity throughout geologic time (e.g., Cox, 1969; Jacobs, 1984; Harland *et al.*, 1990). It is possible, as a first approximation, to make broad subdivisions of strata in groups of normal and reversed polarity (e.g., Watkins *et al.*, 1971; Cox and Dalrymple, 1967). Within these groups, further definitions of individual units may be possible by identifying the remanent magnetization directions, which exhibit differences due to secular variations of the geomagnetic field. These variations usually

provide enough distinction between flows as to make them useful as marker horizons (e.g., Hatherton, 1954; Cox, 1971; Best *et al.*, 1973; Mankinen, 1972; Gromme *et al.*, 1972; Tarling, 1983; Palmer *et al.*, 1991; Soler-Arechalde *et al.*, 1991).

This paper describes a magnetostratigraphic survey of a Late Oligocene volcanic sequence exposed to the west of Durango City, Durango State, northern Mexico (Figure 1). The purpose of the study is to provide a paleomagnetic basis for the stratigraphy of the area, to be used, along with other geologic information, for documenting the volcanic evolution of this section of the Sierra Madre Occidental.

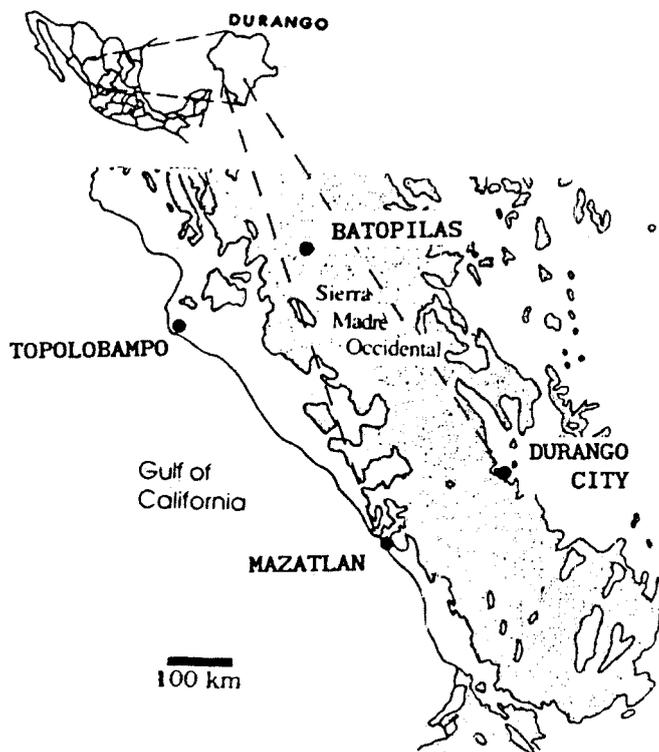


Fig. 1. Schematic map of the Sierra Madre Occidental volcanic province showing location of study sections between Durango and Mazatlán.

## 2. GEOLOGIC SETTING

More than one third of Mexico is covered by volcanic rocks. By far the largest continuous exposure is the Sierra Madre Occidental, a major mountain range paralleling the Pacific Ocean. Flat-lying to gently tilted and faulted Cenozoic volcanic rocks overlie with angular unconformity folded Mesozoic strata and low-grade metamorphic rocks (Clabaugh, 1972). In spite of the size and complexity of the region, geologic work was minimal until the 1960's and even then, limited to general reconnaissance studies. The existence of a thick sequence of mid-Tertiary volcanic rocks was mentioned (King, 1939). The first attempt to differentiate the volcanic units was by Cordoba (1963), who distinguished three units on the basis of major lithologic differences: ignimbrites, air-fall tuffs and rhyolites, grouped into the Río Chico Formation.

Detailed studies were later made (e.g., Clabaugh, 1972; Barrett, 1972; Wahl, 1972, 1973; Waitt, 1970; McDowell and Keizer, 1977; McDowell and Clabaugh, 1979) on a transect along the Durango-Mazatlán highway (Figure 1). On the basis of field mapping and K-Ar dating the existence of two different Tertiary volcanic sequences was documented. The older group, dated 28 to 31 Ma, occurs in the eastern portion of the transect toward Durango City. It is made up of dominantly rhyolitic ash-flow tuffs and ignimbrites with some interbedded basalts, air-fall tuffs and small rhyolitic flow domes throughout the sequence. Basalt flows 9 to 11 Ma old, associated with a later period of normal faulting, are found capping the sequence southwest of Durango. In the western portion of the transect a younger sequence consists of rhyolite flows, basalt flows and poorly to moderately welded ash-flow tuffs. These units yield K-Ar ages which cluster around 23.5 Ma. The inter-relationships of the two sequences are concealed beneath younger basalts (McDowell and Keizer, 1973).

Within the eastern portion, the studies of Waitt (1970) in the Tepalcates-Navios area, and Keizer (1973) and Swanson (1973) in the Durango City area (Figure 1), helped to establish a volcanic stratigraphy. Waitt divided the Río Chico Formation (Cordoba, 1963) in the Tepalcates Navios area, into about 15 separate units. Keizer and Swanson identified, for mapping purposes, 19 members in the same Formation in the Durango City section. Through detailed field mapping these workers identified the regional extent and stratigraphic position of most ignimbritic sheets. The oldest ignimbrite definitely correlated by field mapping in both areas is the Santa María Member of the Durango City area, which is the same as the T-3a unit (Figure 2) in the Tepalcates-Navios area.

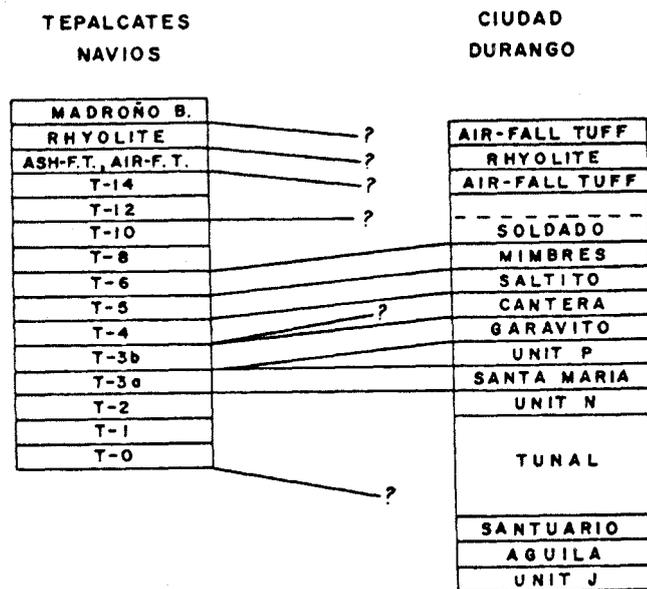


Fig. 2. Lithologic units correlation diagram for the volcanic sequences mapped in the Tepalcates-Navios (Waitt, 1970) and Durango City (Keizer, 1973; Swanson, 1973) areas (taken from Keizer, 1973).

The relationship of the units below the Santa María Member is uncertain and obscured by high-angle faulting, and because the older units in the Tepalcates-Navios area are only exposed at the bottom of deep canyons and on the upthrown side of faults (Waite, 1970). In spite of faulting, the units in both areas are reported as nearly horizontal. Waite (1970) reports a regional dip of only 2 degrees to the west for the Tepalcates-Navios area. In the Durango area, the units are flat-lying where sampled.

### 3. SAMPLING AND METHODOLOGY

Ten to fifteen cores, 2.54 cm in diameter and about 8 cm long, were drilled at each of seventeen sites with a portable gasoline-powered drill (Helsley, 1967). They were oriented while still attached to the outcrop. Most of the sites were located in two stratigraphic sections. The lower unit of the Durango section was sampled at Guadalupe Victoria water reservoir, about 13 km southwest of Durango City. Younger units were sampled about 9 km south of Durango City on the road to the town of La Ferrería, at 104.6 E, 23.9 N. The other section was located at km 51 of the Durango-Mazatlán highway in the Tepalcates-Navios areas, at 105.1 E, 23.9 N. Whenever possible, sampling was done vertically throughout the sections and also horizontally spaced.

In the laboratory, the cores were sliced into 2.54 cm long cylinders and the natural remanent magnetization (NRM) of the bottom specimens was measured on a Princeton Applied Research (PAR) spinner magnetometer. Based on field observations and lithologic variations, at least one specimen from each flow was selected for a pilot set, on which detailed step-wise progressive alternating field (AF) demagnetization was performed at up to 140 milliTesla (mT). The AF demagnetization tests were performed using 420-cycle equipment described by Helsley (1969). During the tests all samples were tumbled about three axes in a region of low direct field, generally less than 200 nanoTesla (nT).

Thermal demagnetization studies were made on a few specimens in increasing temperature steps up to 650°C. Heating was performed in a non-inductively wound eighteen-sample capacity furnace, and cooling was accomplished in a region in which the residual field was less than 10 nT. All demagnetization experiments were performed in a mu-metal shielded room in a maximum field of about 200 mT, in order to minimize viscous magnetization effects during the demagnetization and measurement procedures.

In order to define the demagnetization stage at which unwanted secondary magnetization was removed, vector rotation criteria were used (Zijderveld, 1967). The results of the progressive demagnetization steps for each specimen of the pilot set were plotted on orthogonal vector demagnetization diagrams (Figure 3). The sample was assumed to be within the range of stable magnetization when no further rotation of the directional vector occurred, the only change being a decrease in intensity toward the origin. It is implied that at this point the low

stability components have been removed and that the characteristic magnetization has been isolated. Within this range of stability, a set of four AF demagnetization steps was selected and applied to the remaining the specimens from the same unit. From Figure 3 it can be seen that once stability of direction was reached, the variations in declination and inclination were usually less than one degree in the following demagnetization steps. These stable results were averaged to obtain the characteristic direction of each specimen.

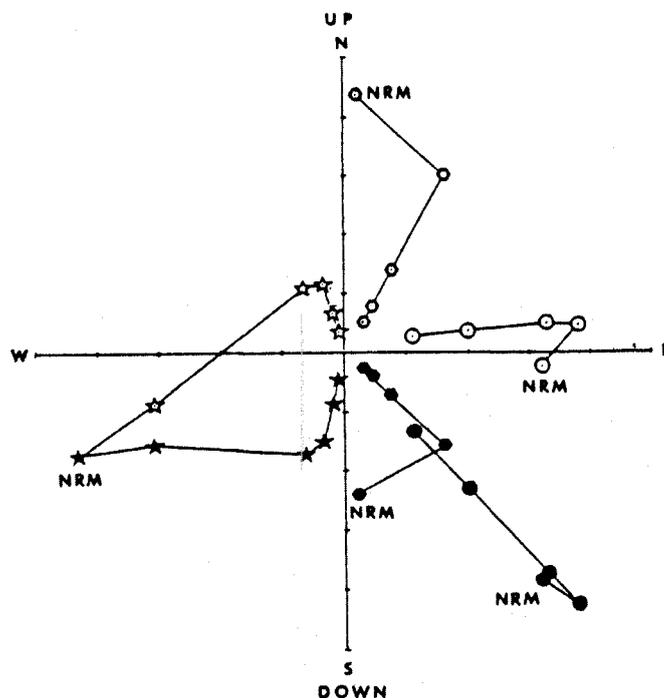


Fig. 3. Vector demagnetization diagrams for three samples that illustrate the range of directional stability with AF demagnetization measured in this study. Open symbols indicate the horizontal component and solid symbols indicate the vertical component. The initial step is marked by the letters NRM, for each example.

### 4. PALEOMAGNETIC RESULTS

The magnetic behavior varied from site to site. For some units the NRM directions initially exhibited a large scatter, which greatly diminished upon AF demagnetization (Figure 4). For some other units the directions remained tightly grouped and little change occurred upon demagnetization. Most of the units attained a stable direction upon AF demagnetization at 17.5 mT. Some samples did not respond to AF or thermal demagnetization; their directions remained widely separated ( $> 20^\circ$ ) from the mean direction of the unit, indicating that some unwanted secondary magnetization was still present or was produced during the field or laboratory work. These samples were deleted for the final statistical analysis of the data (Table 1).

The coercivity spectrum also varied from site to site and even within one site. Normalized demagnetization curves show different behavior with increasing AF de-

Table 1

Summary of paleomagnetic data for the Late Oligocene Durango volcanics, Mexico

## A. Mean direction of NRM for each unit, after demagnetization

	D	I	N	R	K	$\alpha_{95}$	Plong	Plat	dp	dm
1) Madroño b.	5.1	24.1	6	5.99	1466.9	1.76	50.6	77.7	1.0	1.9
2) Mimbres (T-6)	157.6	-18.0	10	9.91	147.4	4.99	134.2	64.1	2.1	4.1
3) Cantera (T-4)	356.3	48.4	13	12.99	1688.9	1.01	224.5	83.6	0.9	1.3
4) T-2	307.7	41.5	6	5.98	246.9	4.27	176.1	42.5	3.2	5.2
5) T-1	312.5	37.6	8	7.99	800.3	1.96	171.0	46.2	1.4	2.3
6) T-0	316.9	39.7	10	9.98	492.3	2.18	171.9	50.5	1.6	2.6
7) T-00	154.2	1.3	8	7.98	634.8	2.20	124.1	54.9	1.1	2.2
8) Mimbres (T-6)	153.5	-15.0	9	8.98	415.5	2.53	136.6	59.9	1.3	2.6
9) Soldado	140.7	-25.4	9	8.99	813.2	1.81	156.3	51.4	1.0	1.9
10) Mimbres (T-6)	148.7	-8.2	8	7.99	899.5	1.85	136.5	53.9	0.9	1.9
11) Cantera (T-4)	353.2	44.7	9	8.99	1240.9	1.46	172.2	83.4	1.2	1.8
12) Caravito	186.1	-48.2	5	4.99	908.2	2.54	299.4	82.4	2.2	3.3
13) Unit P	156.3	-54.4	12	11.95	247.5	2.76	199.1	66.7	2.7	3.9
14) Santa María	163.3	-13.8	5	4.99	751.8	2.79	121.6	66.7	1.5	2.8
15) Unit N	180.2	-50.1	15	14.97	564.5	1.61	256.7	83.0	1.4	2.1
16) Tunel	176.1	-37.5	7	6.99	691.8	2.30	127.1	85.4	1.6	2.7
17) Santuario	184.4	-49.5	10	9.97	414.2	2.38	285.8	82.5	2.1	3.1

## B. All units combined except the Madroño basalt

	D	I	N	R	K	$\alpha_{95}$	Plong	Plat	dp	dm
	337.5	34.48	16	14.86	13.2	10.56	155.9	68.5	6.9	12.1

In part A.: Number close to the name of the unit identifies its VGP on Fig. 5 a; D= mean declination eastward; I=mean inclination (positive downward); N=number of specimens; R= vector resultant length of N unit vectors; K= precision parameter (Fisher, 1953);  $\alpha_{95}$ = semi-angle of cone of 95 percent confidence of mean; Plong. Plat = longitude east and latitude north of VGP's (all calculated for the upper hemisphere); dp and dm= angular length of semi-axes of 95 percent oval of confidence. In Part B.: N= in part B is the number of unit.

magnetization (Figure 5a). Some samples exhibited a stable magnetization with little decrease in intensity in fields up to 140 mT. These high coercivities, and the behavior of some samples with increasing thermal demagnetization steps (Figure 5b), suggest that magnetic carriers are, in some cases, hematite. The remanent magnetization directions of all sampled units (Figure 6; Table 1) are discussed separately for the two areas.

#### 4.1. Tepalcates-Navios Section

Most of the samples from this area were taken from Waitt's (1970) TN-1 section near km 51 on the highway between Durango and Mazatlán, in order to ensure better stratigraphic control. Waitt used a letter and number system for naming the different units. Sampling started at the bottom of the canyon on Waitt's oldest unit, T-O, and continued upwards to unit T-4. Upon measuring the NRM and after AF demagnetization, it was found that T-O is underlain by another unit. This unit had reversed polarity, while T-O polarity was normal. This was not unexpected since, as Waitt (1970, p.47) states, T-O and T-1 are the oldest ignimbrites mapped yet do not represent the basal members of the ignimbrite sequence. The reversed unit may be another ignimbrite from a different unit, or it may be the lower portion of T-O which may be

a composite unit. The magnetic data may indicate two cooling units when the petrographic criteria only indicates one unit. In any case, there are two different ignimbritic bodies emplaced at different times. Noble *et al.* (1968) found the Thirsty Canyon Tuff, in southern Nevada, to consist of two different ash flow sheets of opposite polarity.

Units T-O and T-2 have normal polarity (Figure 6, Table 1). As their directions of magnetization do not differ significantly (McFadden and Lowes, 1981), these three units may have been emplaced in rapid succession so that little time elapsed between each successive deposit. This pattern is believed to be real and not the product of structural uncertainties due to widely separated sampling localities, since the units were sampled in the same section where they overlie each other. A larger interval must have elapsed between the emplacement of the newly identified ignimbrite (here informally called T-OO) and the unit above, T-O, because of the different polarities and the time it takes for the field to reverse direction (e.g., Opdyke *et al.*, 1973; McElhinny, 1973; Tarling, 1983; Jacobs, 1984).

Some samples from the upper part of unit T-2 showed a very small change in direction and intensity

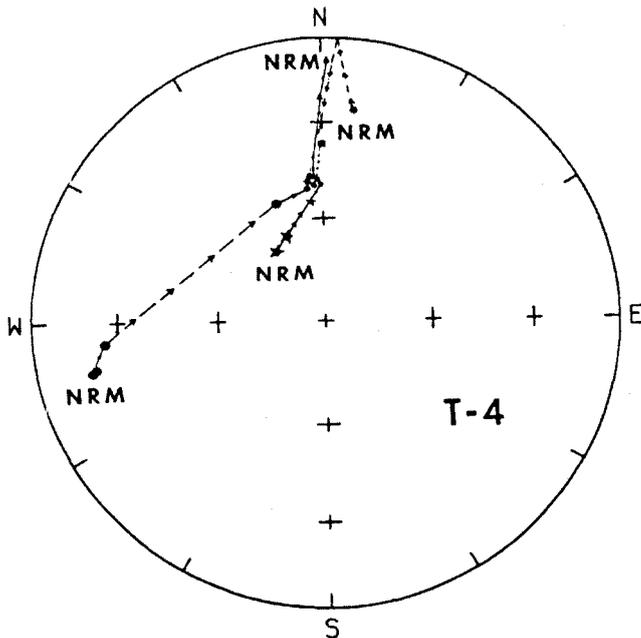


Fig. 4. Equal area plot showing the typical behaviour of three samples from one of the units (T-4) with AF demagnetization. The initial direction is indicated by NRM and the following directions after AF demagnetization are connected by broken curves and the arrows. Note the initial scatter in NRM directions and the clustering of directions after (17.5 mT and subsequent steps) demagnetization.

after AF demagnetization at 140 mT. These samples were then thermally demagnetized in steps of 250°, 350°, 450°, 500°, 550°, 600° and 650°C and the results compared with samples from the more indurated vitric phase that attained stability at 17.5 mT AF demagnetization. The intensity and direction of the thermally demagnetized samples underwent no change after heating to 600°C, but a drastic drop in intensity occurred at 650°C. (Figure 5b). The directions are very similar to those of the AF demagnetized samples and the behavior upon thermal demagnetization seems to indicate that hematite with a narrow blocking temperature range may be the carrier of the remanent magnetization in these samples. This ilmeno-hematite appears to be the product of deuteric alteration, since no significant difference in direction (McFadden and Lowes, 1981) is noticed between these sample directions and the magnetite-bearing samples from the same unit. Thus there is essentially no difference in the time of acquisition of magnetization between the two oxidation phases of the same unit.

The next unit upwards, T-3, which Waitt subdivides into two members, yielded inconsistent results. Upon AF demagnetization at 35 mT, the directions of magnetization showed no rotation but a continuous decrease in intensity; however, the directions were scattered over 20 degrees. Further demagnetization up to 140 mT barely reduced the dispersion of directions, and no significance can be attached to the mean results. Abnormally high intensities were associated with the NRM of these samples.

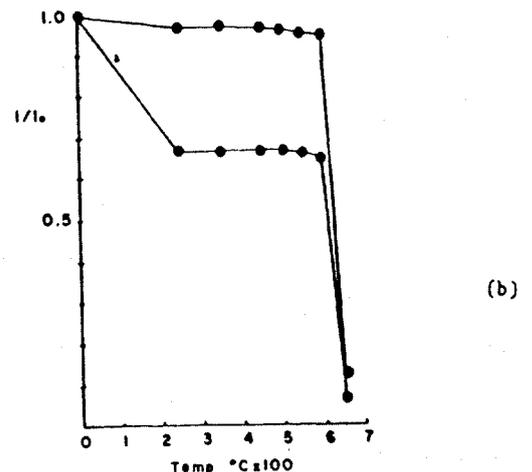
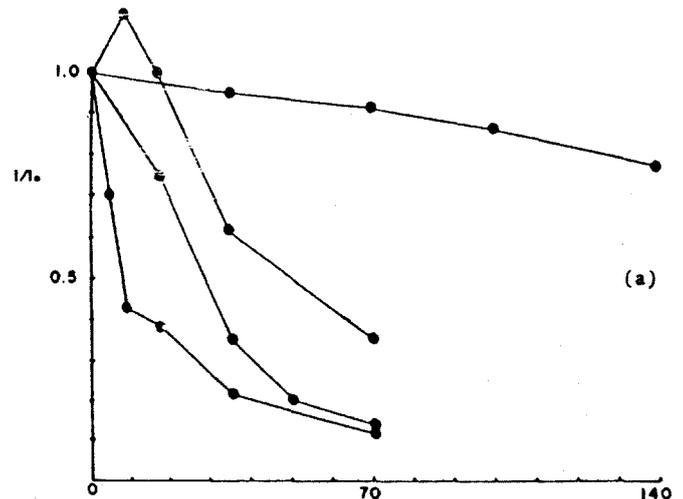


Fig. 5. Examples of normalized intensity diagrams as a function of AF field or temperature for some selected samples. (a) AF demagnetization (in mT). (b) Thermal demagnetization (in C).

Lightning may be responsible, in part, for this behavior, though the samples were taken several meters apart to minimize this possibility (Graham, 1961; Cox, 1961). Another explanation may be that the deformation associated with the development of spherulites formed by in-situ devitrification (Waitt, 1970) has in some way altered the magnetization. Similar scatter of directions was reported by Gose (1970) from the Swett ignimbrite in Nevada. T-3 is the oldest unit in the Tepalcates-Navios area that is correlatable, by field mapping, with the ignimbrites of the Durango area (Keizer, 1973).

T-4, a vitric tuff with a purple welded phase that forms a very prominent cliff, has a normal polarity (Figure 6). Its direction of magnetization is separate from the others (McFadden and Lowes, 1981), which makes it easily distinguishable. This unit is correlated (Keizer, 1973) with the Cantera Member of the Durango area, where it is known to consist of two to five ignimbrites. Eight kilometers west of this section, in the neighbor-

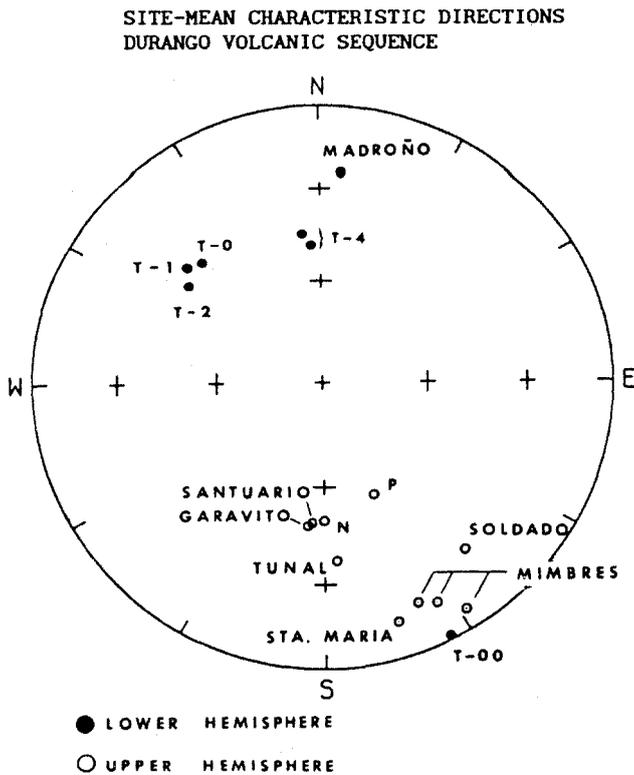


Fig. 6. Equal area plot of characteristic mean directions for the units studied in the Tepalcates-Navios and Durango City volcanic sequences. Solid symbols correspond to positive (downward) inclination and open symbols correspond to negative (upward) inclination. For explanation of the abbreviations for the units consult Fig. 2.

hood of the town of Navios, several samples were taken at a site which is also supposed to be T-4. The directions of magnetization were very similar to those of T-4 (Cantera) in Waitt's TN-1 section, and it is believed to represent another ignimbrite of the Cantera (T-4) Member.

Some samples were taken from the pink vitric, cliff-forming ignimbrite exposed on the north side of the highway, at km 51, on the hill side opposite Waitt's TN-1 section. He named this unit T-6 and its polarity was found to be reversed. Two more sites were sampled between this locality and Rio Mimbres about 4 km east, toward Durango City; in both sites the polarity was also found to be reversed (Table 1). It seems that this unit, which is correlated with the Mimbres Member at the Durango area (Keizer, 1973) is composed of several ignimbrites, as shown by the three close but different remanent magnetization directions (Figure 6).

At km 46 on the highway, several samples from the Soldado Member were obtained. This member is reported by Keizer (1973) as being formed by two ignimbrites, but in some places the upper ignimbrite has been eroded away. Keizer (1973) correlates the Soldado Member with Waitt's (1970) units T-8 through T-14. The paleomagnetic results obtained from this member yield a reversed remanent magnetization direction. Further west, at Mesa

del Madroño, the Madroño basalt which is 9 Ma old (McDowell and Keizer, 1977) exhibits normal polarity (Figure 6, Table 1).

#### 4.2. Durango City Section

Six units were sampled in the vicinity of Durango City. They are (from older to younger) Santuario, Tunal, Unit N, Santa María (correlative with T-3a), Unit P, and Garavito (correlative with T-3b). All have reversed polarity. The change of secular variation imprinted in these flows shows an erratic pattern for consecutive units when compared with that of the Tepalcates-Navios area. Distinctive directions are shown by the Santa María, Tunal, and P Members which are clearly different from each other as well as from the rest of units. A different situation is observed for Member N and for the Santuario and Garavito Members. Their remanent magnetization directions are so similar that almost no distinction can be made between them, particularly between the Santuario and Garavito Members. These units, as observed in the field and explained above, were not emplaced one after another; rather, Santuario and Garavito are the oldest and youngest, respectively, of the six units sampled in this section. Between them and Member N other ignimbrites were emplaced with markedly different magnetic directions so that the argument for rapid successive emplacement cannot be applied here.

#### 5. DISCUSSION AND CONCLUSIONS

The paleomagnetic studies of the Durango ignimbritic sequences provide further insight into the volcanic history of the region (McDowell and Keizer, 1977). At least five reversals (six polarity periods) can be identified in a composite magnetostratigraphic section of the two areas of Tepalcates-Navios and Durango City (Figure 7). The units at the Tepalcates-Navios and Durango City areas are not correlatable and belong to a different volcanic event. This is supported by the observation that the polarities are opposite for the next older units at both localities and the directions of remanent magnetization are different due to sampling of different portions of the paleosecular variation curve. Thus any correlation is ruled out.

An ignimbrite not previously reported was identified by means of paleomagnetic criteria below the oldest reported unit (T-O) in the Tepalcates-Navios area. It is informally named T-00, following the system of Waitt (1970). The lithology of T-00 is very similar to the Garavito (T-3b) Member. Swanson (written communication), who kindly studied the thin-sections of the new unit, suggests that the samples may come from a down-faulted block of this member. This is not supported by the paleomagnetic results. The sampling was initiated at the base of Waitt's TN-1 section where no fault was apparent, although some faults are known to exist nearby. A tilt of about 55 degrees would be required to bring the remanent magnetization direction of the Garavito Member into agreement with T-00 (Figure 6). No tilting of this magnitude has been documented in the area. Thus T-00 is believed to be a separate cooling unit. The po

## MAGNETOSTRATIGRAPHY - LATE OLIGOCENE DURANGO VOLCANIC SEQUENCE

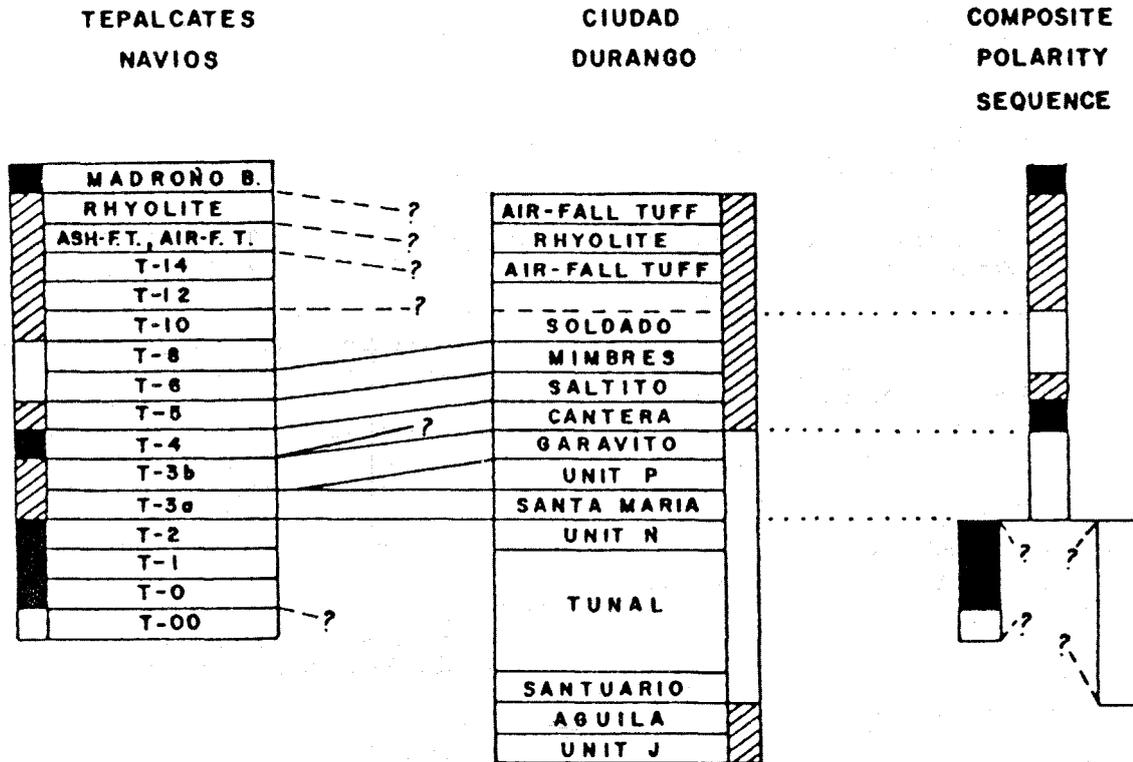


Fig. 7. Summary of magnetostatigraphic results for the Durango volcanic sequence. The composite polarity sequence is based on the lithologic correlation diagram of Keizer (1973) and the paleomagnetic results. The magnetic polarity is indicated by the shading: normal polarity is black, reverse polarity is white. The diagonal pattern indicates that no paleomagnetic result is available. The proposed correlation between the sequences of Tepalcates-Navios and Durango City areas is indicated by the discontinuous and continuous lines (uncertainty is emphasized by the question marks). Below the Santa María (T-3a) member the relative position of units is undetermined. Dotted lines refer the composite polarity column (right) with the lithologic columns.

larity and characteristic directions of magnetization obtained for the several units and groups of units (Figure 7), provide a pattern against which paleomagnetic measurements can be compared in future studies of the volcanic units in the Sierra Madre Occidental volcanic province.

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## BIBLIOGRAPHY

- BARRET, T. W., 1972. Geología entre los kilómetros 125 y 152 a lo largo de la carretera Durango-Mazatlán, México: Soc. Geol. Mexicana, II a Conv. Nal. Mem., Mazatlán, Sinaloa, p. 127-129.
- BEST, M. G., R. T. SHUEY, C. F. CASKEY and S. K. GRANT, 1973. Stratigraphic relations of members of

the Needles Range Formation at type localities in southwestern Utah. *Geol. Soc. Am. Bull.*, 84, 3269-3278.

- CLABAUGH, S. E., 1972. Geologic road log Durango-Mazatlán: Soc. Geol. Mexicana, II Conv. Nal. Mem., Mazatlán, Sinaloa, p. 80-96.
- CORDOBA, D.A., 1963. Geología de la región entre Río Chico y Llano Grande, Municipio de Durango, Estado de Durango. *Bol. Inst. Geol., UNAM*, 71, pt. 1.
- COX, A., 1961. Anomalous remanent magnetization of basalt. *U.S. Geol. Surv. Bull.* 1083 - E, p. 131-160.
- COX, A., 1969. Geomagnetic reversals. *Science*, 163, 237-245.
- COX, A., 1971. Remanent magnetization and susceptibility of late rocks from New Zealand. *New Zealand J. Geol. Geophys.*, 14, 192-207.

- COX, A. and G.B. DALRYMPLE, 1967. Statistical analysis of geomagnetic reversal data and the precision of potassium-argon dating. *J. Geophys. Res.*, 72, 2603-2614.
- DALRYMPLE, G. B., A. COX and R. R. DOELL, 1965. Potassium-argon age and paleomagnetism of the Bishop Tuff, California. *Geol. Soc. Am. Bull.*, 76, 665-673.
- FISHER, R. A., 1953. Dispersion on a sphere: Proc. R. Soc. London, Ser. A. v. 217, p. 295-305.
- GOSE, W. A., 1970. Paleomagnetic studies of Miocene ignimbrites from Nevada. *Geophys. J. R. Astr. Soc.*, 20, 241-252.
- GRAHAM, K. W. T., 1961. The re-magnetization of a surface outcrop by lightning current. *Geophys. J. R. Astr. Soc.*, 6, 85-102.
- GROMME, C.S., E.H. MCKEE and M.C. BLAKE, 1972. Paleomagnetic correlations and potassium-argon dating of middle Tertiary ash-flow sheets in the eastern Great Basin, Nevada and Utah. *Geol. Soc. Am. Bull.*, 83, 1619-1638.
- HARLAND, B. *et al.*, 1990. A geologic time scale 1989. Cambridge Univ. Press, UK.
- HATHERTON, T. 1954. The magnetic properties of the Whakamaru ignimbrites. *New Zealand J. Sci. Tech.*, Ser. B, 35, 421-432.
- HELSEY, C. E., 1967. Advantages of field-drilling of samples for palaeomagnetic studies. *In*: Collinson, D. W., K. M. Creer, and S. K. Runcorn, (Eds.) *Methods in Palaeomagnetism*, Elsevier Publ. Co., p. 26-30.
- HELSEY, C.E., 1969. Magnetic reversal stratigraphy of the Lower Triassic Moenkopi Formation of western Colorado. *Geol. Soc. Am. Bull.*, 80, 2431-2450.
- IRVING, E. T., 1964. *Paleomagnetism and its Application to Geological and Geophysical Problems*. John Wiley and Sons, Inc. 339 p.
- JACOBS, J.A., 1984. *Reversals of the Earth's Magnetic Field*. Adam Hilger Ltd., UK.
- KEIZER, R. P. 1973. Volcanic stratigraphy, structural geology and K-Ar geochronology of the Durango, Mexico area: M. A. Thesis, Univ. Texas at Austin, Texas.
- KING, R. E., 1939. Geological reconnaissance in northern Sierra Madre Occidental of Mexico. *Geol. Soc. Am. Bull.*, 50, 1625-1722.
- MANKINEN, E.A., 1972. Paleomagnetism and potassium-argon ages of the Sonoma volcanics, California: *Geol. Soc. Am. Bull.*, 83, 2063-2072.
- McDOWELL, F. W. and S. E. CLABAUGH, 1979. Ignimbrites of the Sierra Madre Occidental and their relation to the tectonic history of western Mexico. *Geol. Soc. Am. Sp. Paper*, 180, 113-124.
- McDOWELL, F.W. and R.P. KEIZER, 1977. Timing of mid Tertiary volcanism in the Sierra Madre Occidental between Durango City and Mazatlán, Mexico: *Geol. Soc. Am. Bull.*, 88, 1479-1487.
- McELHINNY, M. W., 1973. *Palaeomagnetism and Plate Tectonics*: Cambridge Univ. Press, UK, 350 p.
- McFADDEN, P.L. and F.J. LOWES, 1981. The discrimination of mean directions drawn from Fisher distribution. *Geophys. J. R. Astr. Soc.*, 67, 19-33.
- NOBLE, D.C., G.D. BATH, R.L. CHRISTIANSEN and P.P. ORKILD, 1968. Zonal relations and paleomagnetism of the Spear Head and Rocket Wash members of the Thirsty Canyon Tuff, southern Nevada. *U. S. Geol. Surv. Prof. Paper* 600-C. C 61-C 65.
- OPDYKE, N. D., D. V. KENT and W. LOWRIE, 1973. Details of magnetic polarity transitions recorded in an high deposition rate deep-sea core. *Earth Planet. Sci. Lett.*, 20, 315-324.
- PALMER, H.C., W.D. McDONALD and A. HAYATSU, 1991. Magnetic, structural, and geochronologic evidence bearing on volcanic sources and Oligocene deformation of ash flow tuffs, northeast Nevada. *J. Geophys. Res.*, 96, 2185-2202.
- SOLER-ARECHALDE, A. M., J. URRUTIA-FUCUGAUCHI and G. AGUIRRE-DIAZ, 1991. Characterization and stratigraphy of large ignimbrites of central Mexico from paleomagnetism and K-Ar dating. *Terra Abstr. Suppl. Terra Nova*, 5, 80.
- SWANSON, E., 1973. *Volcanic stratigraphy of the Durango Area, Durango: Mexico: M. A. Thesis, Univ. Texas at Austin, Texas.*
- TARLING, D. H., 1983. *Palaeomagnetism*. Chapman and Hall, UK, 202 p.
- WAHL, D. E., Jr., 1972. *Geología de la región de El Salto, Durango, México: Soc. Geol. Mexicana, II a Conv. Nac., Mazatlán, Sinaloa, Mem.*, p.245-247.
- WAHL, D. E., Jr., 1973. *Geology of the El Salto Strip, Durango, Mexico: M.A. Thesis, Univ. Texas at Austin, Texas*, 112 p.
- WAITT, R. B., 1970. Ignimbrites of the Sierra Madre Occidental between Durango and Mazatlán, Mexico: M.A. Thesis, Univ. Texas at Austin, Texas, 91 p.

WATKINS, N.D., B.M. GUNN, A.L. BAKSI, D. YORK and J. ADE-HALL, 1971. Paleomagnetism, geochemistry, and potassium-argon ages of the Río Grande de Santiago volcanics, central Mexico. *Geol. Soc. Am. Bull.*, 82, 1955-1968.

WILSON, R. L., 1970. Paleomagnetic stratigraphy of Tertiary lavas from northern Ireland. *Geophys. J. R. Astr. Soc.*, 20, 1-9.

ZIJDERVERELD, J. D. A., 1967. A. C. Demagnetization of rocks: Analysis of results. *In*: Collinson, D. W., K. M. Creer and S. K. Runcorn, (Eds.), *Methods in Palaeomagnetism*, Elsevier Publ. Co., p. 254-286.

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