Geofísica Internacional (1994), Vol. 33, Num. 4, pp. 547-564

Magnetic fabric of a Jurassic clastic sequence from Oaxaca-Puebla, southern Mexico and inferred paleocurrent flow

Cecilia I. Caballero-Miranda
Laboratorio de Paleomagnetismo, Instituto de Geofísica, UNAM, México

Received: May 20, 1993; accepted: April 27, 1994.

RESUMEN

La fábrica magnética de dos secciones de una secuencia continental mesozoica del norte de Oaxaca - sur de Puebla, se interpreta en algunos sitios como de origen primario y en otros secundario. Los criterios de interpretación se basan en (i) el grado de anisotropía y su variación en cada sitio, (ii) la geometría de la fábrica magnética y (iii) la comparación de la fábrica con otros indicadores geológicos. La fábrica magnética se obtuvo a partir de la anisotropía de susceptibilidad magnética (AMS) en campos bajos, de 122 especímenes provenientes de 10 niveles estratigráficos. La interpretación del origen de la fábrica se relaciona con la mineralogía magnética y con los efectos en la AMS (en especímenes piloto) debido a la impartición de una magnetización remanente isotermal (IRM) y, por el posterior calentamiento a pasos en laboratorio a 130°C y 400°C.

La fábrica magnética interpretada como primaria sugiere un sistema de paleocorrientes orientado al NW (270° a 320°) en la sección inferior (Formación Piedra Hueca) y entre el NNE y NW (24° a 310°) para la sección superior (Formación Otlaltepec). La fábrica secundaria se interpreta así en sitios cercanos al contacto entre ambas unidades y está relacionada al intemperismo y a las direcciones de deformación y esfuerzo. La AMS interpretada como primaria muestra fases magnéticas de alta coercitividad y es comparable con otros indicadores de paleocorrientes; tiene grados de anisotropía bajos y muestra características similares con la AMS posterior a la impartición de la IRM y pasos de calentamiento. La AMS interpretada como secundaria tiene alguna fase magnética de baja coercitividad, muestra más altos y variables grados de anisotropía y usualmente presenta una ASM pos-IRM y pos-calentamientos disminuida o con características muy diferentes a la inicial.

La AMS inicial, pos-IRM y pos-calentamientos, fue medida de 3 a 6 veces en cada espécimen con el fin de determinar la precisión de las mediciones. Estas mediciones sucesivas fueron sometidas a análisis estadísticos por espécimen con los que se obtuvo una media por espécimen de las direcciones principales de la AMS y se detectaron algunos especímenes magnéticamente isotrópicos.

PALABRAS CLAVE: Fábrica magnética, anisotropía de susceptibilidad magnética, direcciones de paleocorrientes, areniscas continentales, lechos rojos, Jurásico Medio, terreno Mixteca, Puebla-Oaxaca, sur de México.

ABSTRACT

The magnetic fabric from two sections of a Mesozoic continental sequence from northern Oaxaca-Southern Puebla is interpreted as primary in some sites and secondary in others according to criteria based on (i) the anisotropy degree and its range of variation in each site, (ii) the magnetic fabric geometry and (iii) agreement with other geological indicators. The magnetic fabric was obtained from the low-field anisotropy of magnetic susceptibility (AMS) of 122 specimens from 10 stratigraphical levels. The origin interpretation is related with magnetic mineralogy and with the AMS effects of imparting isothermal remanent magnetization (IRM) and laboratory heating at 130°C and 400°C steps (in pilot specimens).

Primary magnetic fabrics suggest a palaeocurrent system oriented NW (270° to 320°) for the lower section (Piedra Hueca Formation) and NNE to NW (24° to 310°) for the upper section (Otlatepec Formation). Secondary fabrics are interpreted near the contact between both units and are related to weathering and to deformation and strain direction. The AMS interpreted as of primary origin show high-coercivity magnetic phases, compare well with other palaeocurrent indicators, have low anisotropy degrees and show similar or equivalent AMS after IRM and heating steps. The AMS interpreted as of secondary origin have some low or low-intermediate coercivities show the higher and more variable anisotropy degrees, and usually loose or show a very different AMS after IRM and heating steps.

Initial AMS, after IRM AMS and after heating steps AMS was measured 3 to 6 times in each specimen in order to determine measurement precision. Statistical analyses of the repetitive measurements were performed in each specimen obtaining specimen-means of the principal AMS directions and identifying some magnetically isotropic specimens.

KEY WORDS: Magnetic fabric, anisotropy of magnetic susceptibility, paleocurrent flow, continental sandstones, red beds, Middle Jurassic, Mixteca terrane, Puebla-Oaxaca, southern Mexico.

1. INTRODUCTION

The magnetic fabric of rocks is closely related to the petrofabric and potentially useful for geological interpretations. It is defined by the shape and orientation of the ellipsoids that represent the low-field AMS, which has proved to be a potentially useful tool in structural and palaeogeographic applications (Hrouda, 1982; Tarling, 1983; Tarling and Hrouda, 1993). More studies with structural rather than palaeogeographic applications have been carried out (see

Ellwood *et al.*, 1988; Jackson and Tauxe, 1991), because of the low susceptibility values of most sedimentary rocks and the comparatively less effective sedimentary processes for orienting minerals compared with deformational processes.

The primary magnetic fabric of sedimentary rocks reflects the action of currents during deposition which produce an alignment of the magnetic grains. The geometry of this fabric has the minimum axes of the AMS ellipsoids perpendicular to bedding (paleohorizontal), and the maximum and intermediate axes near the bedding plane; one of them may be related to the palaeocurrent flow. The action of weak to moderate currents during deposition may produce parallel orientations of maximum axes of the AMS ellipsoids and the flow direction; while the rolling effect, which is more frequent in stronger currents and in sloping surfaces, may produce an orientation of the maximum axes of AMS perpendicular to flow (King, 1955; Granar, 1958). On the other hand, the shape and orientation of the AMS ellipsoids do not depend only on the sedimentary process but also on the dominant magnetic mineralogy. If magnetite (> 2-3µm diameter) dominates the magnetic mineralogy, then the maximum axis of AMS ellipsoid would correspond to the mean long axis of these grains (shape anisotropy) and magnetic fabric would be prolate or oblate according to the dynamics of the sedimentary process. If the magnetic grains are dominated by hematite or goethite, the alignment of the AMS ellipsoid axes would correspond to the crystallographic axes (crystalline anisotropy). In hematite the maximum and intermediate AMS axes are in the basal crystallographic plane that is usually parallel to bedding, so the magnetic fabric would be mainly oblate. Compaction and diagenetic processes may modify (or even enhance) the original magnetic fabric, and weathering and deformational processes may eventually completely destroy it or overprint a secondary magnetic fabric.

The low magnitude of AMS and the possibility of overprinted fabrics in sedimentary rocks has suggested experiments to enhance the AMS. Experiments on heating the AMS of rocks (> 600°C) have usually enhanced the AMS producing less scatter of the principal AMS directions and changed both the magnitude and shape of AMS (e.g., Abouzahm and Tarling, 1975; Urrutia-Fucugauchi, 1981; Urrutia-Fucugauchi and Tarling, 1983; Schultz-Krutisch and Heller, 1985; Perarnau and Tarling, 1985; Jelenska and Kadzialko, 1990). Nevertheless, the effects of laboratory heating on the AMS may not always be of enhancement (Caballero, 1990), since these effects depend on the rock magnetic composition and such heating does not solve necessarily the problem of interpreting the origin of the AMS. Magnetic treatment as currently applied in palaeomagnetic studies (*e.g.*, thermal or alternating field demagnetization, etc.), in order to evaluate the validity of palaeomagnetic results, has been additionally proposed for a better assessment of the geological significance of AMS data (Rochette *et al.*, 1992), since they can provide criteria based on the rock magnetic content. In order to help distinguish between instrumental noise and isotropic fabrics from low magnitude AMS, repeated and statistically averaged AMS measurements are done in this study.

The aim of this study was to find out the relationship of the magnitude and shape of AMS with magnetic mineralogy, geological structures, precision of measurement; and the effects on AMS of incremental laboratory heating steps and after imparting an IRM. These relationships are useful in order to identify the origin of AMS and to define some interpretation criteria for this identification that may be used elsewhere.

2. GEOLOGIC SETTING

In the Totoltepec-Coyotepec area, southern Mexico (Figure 1 and 2) within the Piedra Hueca and Otlaltepec Formations (Ortega-Guerrero, 1989; Morán-Zenteno *et al.*, 1993), are the sampling sites. Both Formations are very similar clastic units with important fossil flora that indicate a continental origin. They are separated by an angular unconformity and are considered to be of Jurassic age. The more widely known Jurassic continental clastic sequence in the region is the Tecomazúchil Formation (Pérez-Ibargüengoitia *et al.*, 1965), near Petlalcingo. This Formation has a very similar lithology to the Piedra Hueca and Otlaltepec Formations and shows a remarkable angular unconformity near San José Ayuquila (Caballero-Miranda, 1990a; Morán-Zenteno *et al.*, 1993), which divides the formation into a lower and upper part, like the unconformity that separates the Piedra Hueca and Otlaltepec Formations.

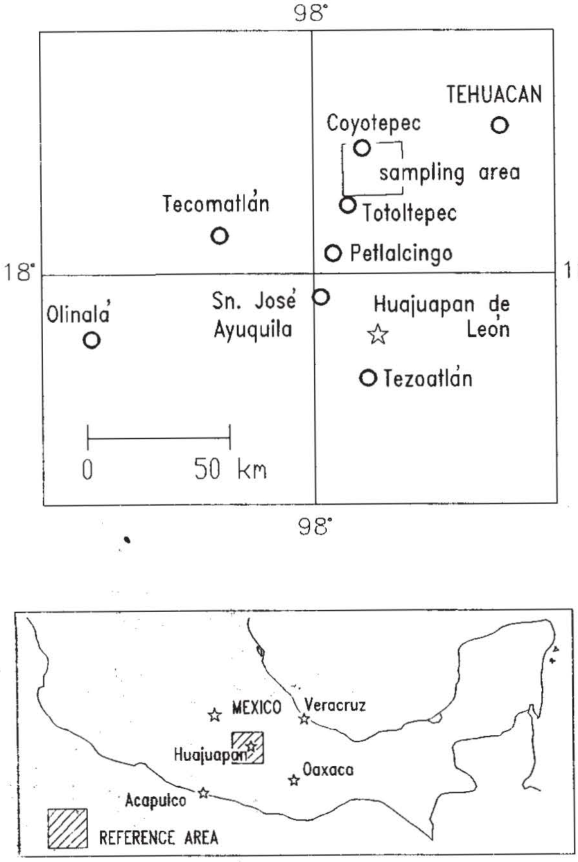

Fig. 1. Schematic maps showing the location of the sampled area. The reference area, enlarged in the upper part, show location of towns referred in text and the sampling area boxed; this area is enlarged in Figure 2. In the lower part the map shows the location of the studied area in southern Mexico.

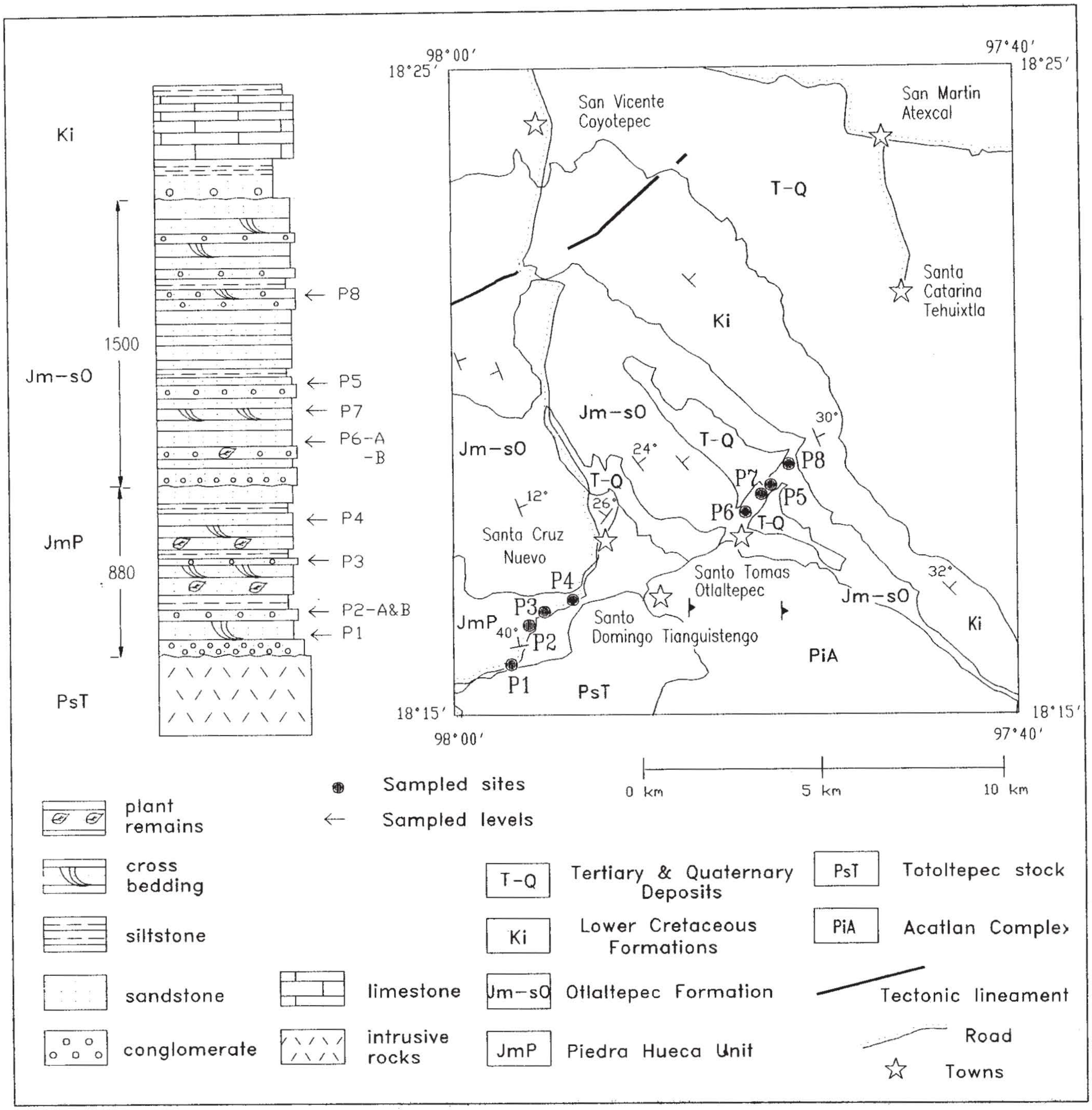

Fig. 2. Geological sketch map and stratigraphic column. The geologic map in the right part shows the distribution of Piedra Hueca and Otlaltepec Formations in the sampling area and location of sampled sites. The stratigraphic column of Piedra Hueca and Otlaltepec Formations in the left part, shows the lithology and stratigraphical position of sampled sites.

The Piedra Hueca and Otlaltepec Formations comprise mainly sandstone and sandy detritic rocks in an non-rhythmic array: conglomeratic lithic arkose with some cross-bedding and cycadophyte plant remains; sandy conglomerate and siltstone and sandy siltstone. The Otlaltepec Formation contains less siltstone and more angular particles than Piedra Hueca. The lithology of the lower and upper Tecomazúchil Formation contains more lithic and less arkosic arenite, more siltstone, similar fossil flora (Silva-Pineda, 1978), and fanglomerate in the lower part. The Piedra Hueca Formation overlies the Totoltepec stock, a quartz rich trondjhemitic intrusive of late Paleozoic age. The Tecomazúchil Formation overlies the Acatlán Complex. The Otlaltepec Formation is unconformably overlain by an Aptian-Albian marine detritic unit (Ortega-Guerrero, 1989) and the Tecomazúchil Formation is locally covered by an Oxfordian marine unit with a gradational contact (Ortega-Gutiérrez, 1978). In most places the upper contact of the Tecomazúchil Formation is an angular unconformity with several Kimmeridgian-Tithonian, Berriasian-Aptian and Albian-Coniacian units (Caballero-Miranda, 1990).

These stratigraphic relationships suggest that the Tecomazúchil and Piedra Hueca-Otlaltepec Formations correlate and are both of Middle Jurassic age, but a more precise age cannot be assigned. They seem to be a northern lateral equivalent of the Tecocoyunca Group (Erben, 1956), which crops out in the Tezoatlán and Olinalá areas (see Figure 1). This Group contains fine-grained continental deposits with plant remains (Wieland, 1914; Silva-Pineda, 1984), coal layers, calcareous beds, limestone, coquinas and ammonites considered of a clear Pacific provenance (Westermann *et al.*, 1984). Accordingly with these correlations and the geometry of outcrops of the Tecocoyunca Group (to the south-southwest) and the continental Tecomazúchil and Piedra Hueca-Otlaltepec Formations (to the north), a general paleoslope towards the SW or SSW can be inferred during the Middle Jurassic (Caballero-Miranda *et al.*, 1990). This conclusion agrees with previous AMS results carried out in the upper Tecomazúchil Formation (Caballero-Miranda, 1990b).

3. SAMPLING

A total of 122 specimens from field drilled cores and laboratory drilled cores from hand samples were obtained. In sites sampled with field drill cores, they come from the same outcrop and the same bed. In sites with more than one hand sample, each one comes from a different bed and a different lithology. The sequences studied in this paper and the location of sampling sites are shown in Figure 2. The sampling is summarized as follows:

Sequence (locality)	sites and specimens	type of sampling field drill cores	hand samples
a) Piedra Hueca Formation (Santa Cruz Nuevo)	4 sites= 62 specimens	P1 P4	P2A, P2B P3
b) Otlaltepec Formation (Santo Tomás Otlaltepec)	4 sites= 60 specimens	P5	P6A, P6B P7 P8

4. EXPERIMENTAL PROCEDURE

The normal remanent magnetization (NRM) and initial AMS were measured for all specimens. In a selected group of pilot specimens the following magnetic treatment and AMS measurements were carried out: Alternating field (AF) demagnetization, forward and backward IRM, AF demagnetization of maximum acquired IRM and AMS measurements; 130°C heating, AMS measurements, IRM and AF demagnetization; 130°C heating, AMS measurements, IRM and AF demagnetization.

The 130°C heating may give information about probable goethite to hematite changes, and the 400°C heating about maghemite to hematite changes. If these changes are detected, then the presence of goethite and/or hematite would indicate that the rocks have been altered or affected by weathering process and that the initial AMS may not correspond to a primary magnetic fabric. On the other hand, magnetic treatment may produce changes that would enhance the AMS of some mineralogical magnetic phase.

Specimens were 2.54 cm in diameter and 2.2 to 2.3 cm in height trying to minimize any possible effects due to sample shape (Noltimier, 1971; Scriba and Heller, 1978). Laboratory measurements were carried out in the paleomagnetic laboratory of the University of Plymouth, UK. The axial susceptibility, AMS and remanent magnetization were measured with Molspin equipment. AF demagnetization and IRM were also done with Molspin equipment. Thermal treatments were carried out in a magnetically shielded furnace. Principal susceptibility directions were field corrected and rotated to the present horizontal. A double structural rotation was made in specimens from the Piedra Hueca Formation. These rotations, the statistical analysis and the magnetic parameters were obtained using a Fortran computer program available at the University of Plymouth. The statistical analysis using the Fisher statistic (Fisher, 1953) is described in a later section.

Principal susceptibility directions are referred as k_1 (maximum), k_2 (medium) and k_3 (minimum).

The AMS parameters used in this study for defining the AMS magnitud, are:

- *Mean susceptibility*: $K = (k_1+k_2+k_3)/3$ (Nagata, 1961)
- *Anisotropy degree*: $P_J = \exp\{2[(\eta_1-\eta)^2 + (\eta_2-\eta)^2 + (\eta_3-\eta)^2]\}^{1/2}$ (Jelínek, 1981)

P_J is here frequently expressed in percent in order to enhance the appreciation of this parameter:

$$P_J(\%) = (1 - P_J)\ 100$$

- *Shape of magnetic susceptibility ellipsoid*:
  $T = (2\eta_2-\eta_1-\eta_3) / (\eta_1-\eta_3)$ (Jelínek, 1981)

  where $\eta = (\eta_1+\eta_2+\eta_3) / 3$ and $\eta_i = ln\ (k_i)$

if $T > 0$, the ellipsoid is oblate;
if $T < 0$, the ellipsoid is prolate;
if $T = 1$ or -1 ($\pm$ 0.1 in practice), the ellipsoid is rotational (completely oblate or prolate);
if $T = 0$ ($\pm$ 0.1 in practice) the ellipsoid is neutral

5. MAGNETIC MINERALOGY

The *magnetic mineralogy* can be inferred from the isothermal remanent magnetization (IRM) and the alternating field (AF) demagnetization behavior of specimens from each site and hand sample. A low coercivity mineralogy phase, magnetite, can be recognized by (a) an initial high-slope and later very low-slope IRM curve, which indicates saturation of IRM at low fields (less than 0.2 or 0.3 T), and (b) the important demagnetization during the application of AF (removing around or more than 80% from the original magnetization at 100 mT). High-coercivity mineralogies, corresponding mainly to hematite and/or goethite may be recognized by (a) a constant slope of IRM curves, which indicates that IRM is not saturated in fields of 0.8 T and (b) theirs low to moderate demagnetization (less than 50% from the initial) during the application of AF. These curves, especially the IRM, allowed classification of the samples into 3 main groups (Figure 3):

Group features	Sites and hand samples
1.- High-coercivity	P1, P2B*, P5, P7
2.- Mixed coercivities (high-coercivity and low-coercivities)	P6A, P6B
3.- Low to intermediate coercivity	P2A, P3, P8, P4

* In this hand sample the AF curve suggests a slightly lower coercivity.

6. STATISTICAL ANALYSIS

The axial susceptibility was measured four times for each specimen and averaged and three to six directional AMS measurements were made. A statistical analysis was performed on each specimen in order to (a) determine the precision of the AMS result, using the **α95** and ***kappa*** Fisher parameters, and (b) obtain specimen means of the principal axes of susceptibility, and specimen-average AMS magnitude and shape parameters (P_J and T). A second statistical analysis, using specimen means as input, was done for each site in order to define the magnetic fabric as site means or hand sample means. The Fisher statistic, applicable to vectors, was used for reasons of practicability after adequating it for AMS axes. As the AMS axes can be bipolar, the directions were reversed when necessary to give the lowest **α95** value.

The statistical criterion for accepting or rejecting specimen means was **α95** < 25°, for the mean of the most concentrated axis called specimen-**α95**; and **α95** < 30° for the means of the other two axes. In case of switching of the orientation of axes (20% of all specimens), the three main susceptibility axes were obtained removing the switched axes or using them for obtaining the means. The specimen-**α95** is plotted in graphs P_J *vs.* **α95** and T *vs.* **α95** (Figure 4).

Results from the *specimen analysis* are:

(A) The three main axes were well defined in 68% of the specimens observed: triaxial specimens. Only one axis was well defined and the other two axes were poorly defined in 25% of the specimens: uniaxial specimens.

(B) Most specimen-**α95** were below 20° (84%) and a few were between 20° and 25° (9%). A third of the specimens from P2A, one specimen from P5 and one from P7 (totalling 7%) were magnetically isotropic or had such a low anisotropy that it was not precisely measurable. These rejected specimens show low to very low values of P_J (lower than 8% and most lower than 2%) and of absolute T (lower than |0.25|, and most lower than |0.1|).

(C) Consistent AMS statistics and AMS shape should require k_3 as the best concentrated axis for oblate ellipsoids (T average > 0.1), and k_1 as the best concentrated axis for prolate ellipsoids (T average < 0.1). Yet this was not observed in 36% of the specimens. Some of them are neutral ellipsoids ($|T| < |0.1|$, in 15% of specimens); however, in the others (21% of specimens) this explanation does not apply as the absolute T values are high (up to |0.5|).

(D) An important number of cases (never previously reported) had the k_2 as the best concentrated axis (27% of specimens). In most of these specimens it was barely possible to obtain the k_2 mean: k_2-uniaxial AMS (20%), because the k_1 and k_3 axes were dispersed or showed switched orientations. Most of them show neutral shape ellipsoids ($T \leq |0.1|$ in 15% of specimens). The best documented cases of this situation are sites P2B, P5 and P7. The high-coercivity and the high **K** values of these specimens suggest that their AMS almost certainly resides in hematite.

These observations indicate that the precision of the instrument used was not as good for defining the absolute value of susceptibility for each axis and the shape and magnitude of the AMS as for defining the orientation of the axes. The switched orientation of some axes may be a result of this lack of precision.

A new statistically derived shape parameter is here defined as *Es*, which reflects which of the k_1 or k_3 axes is more concentrated during repetitive AMS measurements of the same specimen :

$$Es = kappa_{(k3)} / kappa_{(k1)},$$

where ***kappa***$_{(k3)}$ is the ***kappa*** Fisher statistic parameter of k_3 axes and ***kappa***$_{(k1)}$ is the ***kappa*** of the k_1 axes.

Thus
if *Es* > 1 the ellipsoid is oblate;
if *Es* < 1 the ellipsoid is prolate; and
if *Es* = 1, the ellipsoid is neutral.

The statistical results indicate that the shape and geometry of the magnetic fabric at any site (or hand sample) may be different than the shape of AMS ellipsoids of their specimens. Thus the oblate AMS ellipsoids (T > 0 and/or *Es* > 1) of the specimens from P1 and P2A define prolate magnetic fabrics at these sites. This may be explained because the shape of the AMS ellipsoids is more directly controlled by the magnetic mineralogy of each specimen,

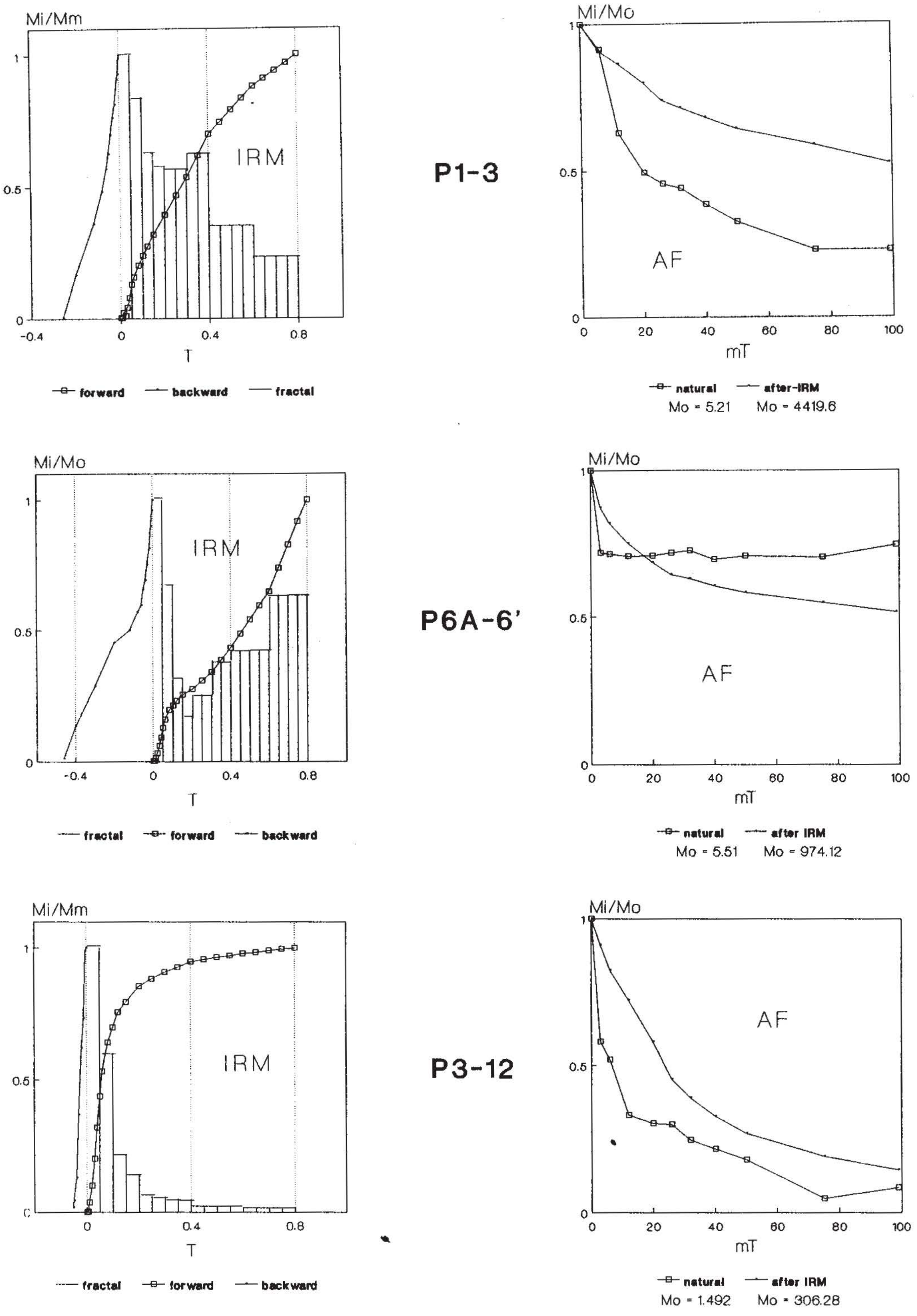

Fig. 3. IRM and AF demagnetization curves for selected specimens. Selected specimens from each of the 3 main groups of magnetic mineralogy detected with IRM (left) and AF curves (right) are shown: Up: specimen 3 from P1 site, belongs to group 1 of high-coercivity magnetic phase. Middle: specimen 6' from P6A hand sample, belongs to group 2 of high and low-coercivity magnetic phase. Down: specimen 12 from P3 site, belongs to group 3 of low to intermediate magnetic phase.

while the fabric of the whole site (or hand sample) is more likely to be related to the dynamics of the geological processes (e.g., the palaeocurrent flow). The *Es* parameter for a site and hand sample is not an average of the *Es* of the repeated measurements of the specimens, but is determined directly from the site (or hand sample) statistical means.

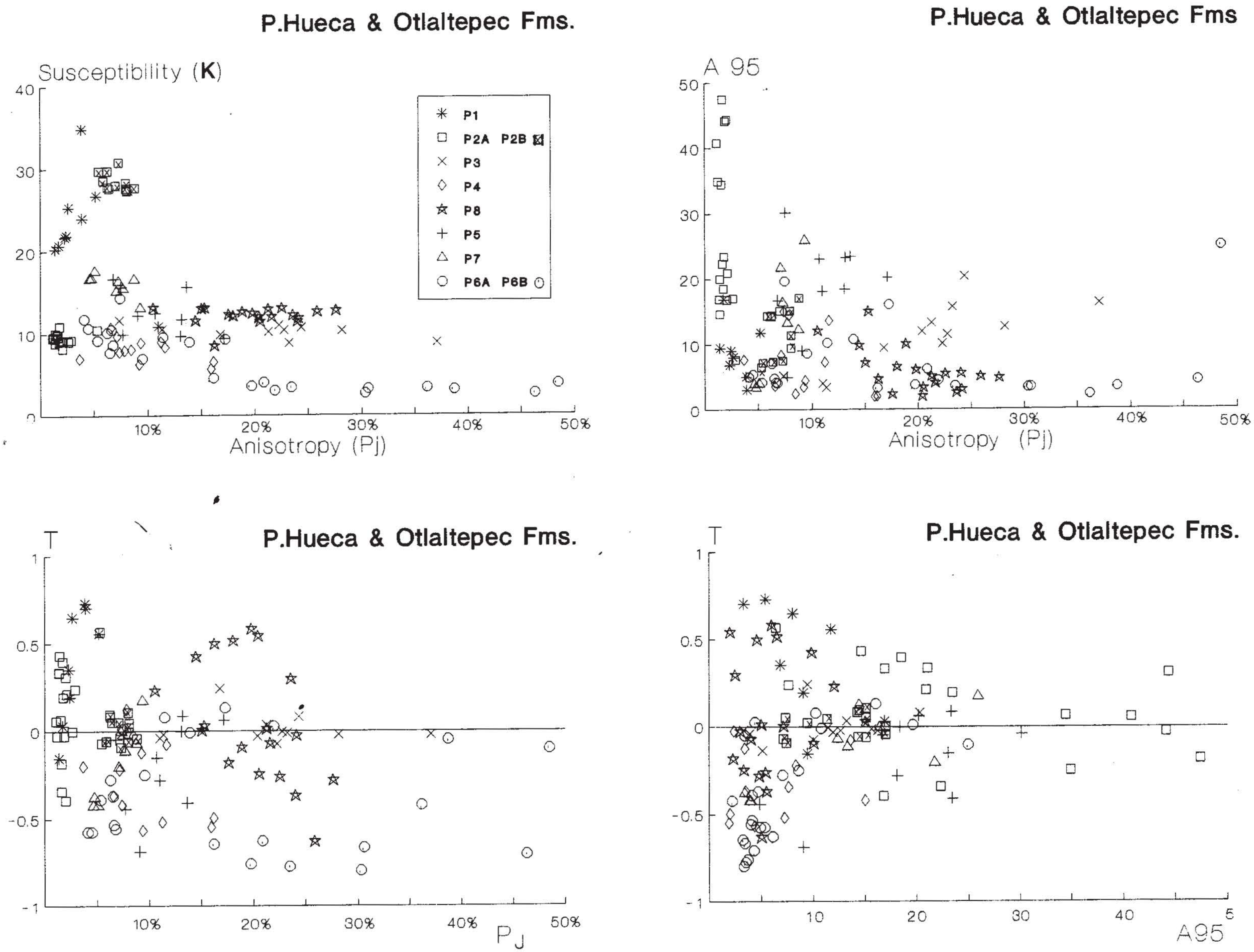

Fig. 4. AMS magnitud (P_J and K) and shape (T) parameters of studied specimens. Left: P_J *vs* K (K is in SI (x 10^{-5}) units) and P_J *vs* T graphs. Positive T values are oblate ellipsoids and negative are prolate. Notice the constant internal K values in almost all cases and the high and variable values of P_J in P3 and P6B. Right:. Precision of P_J (anisotropy degree) and T (susceptibility ellipsoid shape) parameters according with the specimen-α95 obtained from specimen-statistical analysis (see text). Up: P_J *vs* specimen-α95; down: specimen-α95 *vs* T. (the specimen-α95 corresponds to the mean of the most concentrated principal AMS direction). Note that high α95 values correspond to some low P_J and T values.

7. CRITERIA OF AMS INTERPRETATION

Distinguishing between primary and secondary magnetic fabrics of rocks and determining their geological meaning is always difficult and may be subjective. This is especially true when dealing with sandstones, due to the variability of their magnetic mineralogy and possible post-depositional processes. The criteria of interpretation used in this study were:

(i) An $\alpha 95 < 25°$ for the mean of the most concentrated AMS ellipsoid axis during repeated measurements in specimens is essential for consider the AMS to have a reliable direction.

(ii) High P_J values (particularly higher than 20%), are more likely to be found in secondary fabrics, where the processes of orienting minerals or grains are more effective than the primary process of sedimentation. However, low P_J values may also be present in secondary fabrics, e.g., associated with the initial steps of the deformational process, and low primary P_J values may be increased by compaction.

(iii) High to low values of P_J at any given site and hand sample may be attributed to an irregular secondary process that has modified the original magnetic fabric (lower P_J values). Apparently isotropic specimens or disordered magnetic fabrics may also correspond to cases in which it is very difficult to distinguish between both fabrics.

(iv) The shape (prolate or oblate), geometry and orientation of the AMS axes in the paleohorizontal or field corrected coordinates should be compared with ideal primary or secondary fabrics. These can then be used to select the most likely origin of the AMS. For example, a primary fabric may be oblate or prolate but should have subvertical k_3 and/or subhorizontal k_1 axes in paleohorizontal coordinates.

(v) The agreement of the AMS ellipsoids with other primary or secondary geological structures is the best way to identify the AMS origin, especially when the structures and the specimens for the AMS study come from the same outcrop.

8. AMS RESULTS AND INTERPRETATION

8.1. Magnitude of AMS

AMS parameters of magnitude and shape of specimens are shown in graphs of P_J *vs.* **K** and P_J *vs.* T (Figure 4). The following features may be observed:

The **K** (mean susceptibility) is nearly constant at each site or hand sample (usually less than 19 x 10^{-5} SI), which suggests that the magnetic mineralogy is homogeneous.

The P_J (anisotropy degree) is constant at some sites or hand samples, but is rather variable at others (*e.g.*, P3, P4, P6B). These variations may be related to secondary processes that partially changed the original magnetic fabric. Specimens with low P_J values usually show the highest **K** values (P1, P2B, P7 and some P5).

The AMS shape (according to the T parameter) of most sites and hand samples is mainly prolate (P4, P5, P6A, P6B, P7). One site is mainly oblate (P1); two are mainly neutral (P2B, P3); and one ranges from prolate to oblate (P2A, P8). The ellipsoid shape (T) does not show a correlation with P_J or **K**.

8.2 AMS directions and magnetic fabric of sites

The *main susceptibility mean directions* and average of AMS parameters for each site are shown in Tables 1 and 2. The *geometry* of the magnetic fabric in each site or hand sample and the interpretation of its origin are summarized in Tables 3 and 4, with some of the parameters used as main criteria for the interpretation. The geometry is described as: (a) prolate, oblate or neutral, according to the most concentrated axis-mean (lowest $\alpha 95$) and the *Es* parameter of the site; and (b) uniaxial or triaxial, depending on the number of concentrated axis means. The mean AMS ellipsoid for most sites (or hand samples) is mainly prolate (uniaxial or triaxial). Only in one case (P8) it is uniaxial oblate. Three cases (P2B, P7 and P5) stand out because of their neutral geometry with k_2 axes as the best concentrated axes; and there is one case (P3) with apparently two superimposed geometric fabric patterns.

The proposed criteria for AMS interpretation suggest that all sites and hand samples from Otlaltepec Formation have a reliable AMS that may be useful for geological inferences. The Otlaltepec Formation contains only 3 sites or hand samples that can be accepted as reliable. Hand sample P2A may be accepted as reliable if only some specimens are considered; but sample P3 is definitely not accepted for directional geologic interpretations.

Piedra Hueca Formation (Figure 5).
Descriptions in stratigraphical order (from bottom to top)

P1.- Uniaxial prolate fabric (defined by triaxial oblate specimens), with k_1 mean at 2° from the paleohorizontal. A primary fabric is interpreted. The bipolar inclinations of the k_1 axes do not clearly reflect the flow direction and may suggest a weak current or rolling in a stronger current. This seems more likely to agree with the lack of a well-defined foliation. In this case the distribution of k_3 axes in an E-W oriented vertical plane, would reflect a westward flow direction. The oblate ellipsoids, high **K** values and high-coercivity magnetic phase suggest a high hematite content.

P2-A.- Triaxial prolate fabric with k_1 mean at 17° from the paleohorizontal. Geometry and low P_J values suggest a primary fabric where the inclinations of k_1 axes may correspond to an imbricated structure reflecting a NW flow direction. One third of specimens have high $\alpha 95$ values, which might reflect a loss of their very low P_J due to weathering or diagenetic processes.

Table 1

AMS results of Piedra Hueca Formation

SITE - - hand block		MAIN SUSCEPTIBILITY DIRECTIONS (k1 = maxim; k2 = interm; k3 = minim)							AMS MAGNITUDE			
			palaeohorizontal		*field corrected*		Fisher statis.		mean Susceptib.	Anisotropy Degree	Ellipsoid shape	Statistic shape
	n (nt)		Dec	Inc	Dec	Inc	α95	*kappa*	K	Pj (%)	T	Es
P4	12 (12)	k1	156	51	*123*	*35*	13	13	8.0	9.5	-0.289	0.67
		k2	286	32	*298*	*59*	13	12				
		k3	31	27	*30*	*8*	15	9			p	p
P3		k1					---	---	10.2	25.3	-0.015	1.00
k2 con-	7 (12)	k2	82	38	*76*	*10*	18	13				
centrated spec.		k3					---	---			p	n
prolate	5 (12)	k1	17	61	*31*	*42*	16	23	10.5	13.5	0.014	0.42
specimens		k2	180	31	*157*	*32*	28.9	9				
		k3	274	5	*280*	*30*	26	10			o	p
P2-B	5 (12)	k1	142	49			17	21				1.00
	12 (12)	k2	345	36			5	79	28.5	7.1	0.009	
	5 (12	k3	245	11			17	21			o	n
P2-A	16 (17)	k1	145	22			7	15	9.4	2.0	0.141	0.56
using all	11 (17)	k2	31	30			19	7				
specimens	13 (17)	k3	261	57			15	9			o	p
only sta-	9 (17)	k1	142	17			11	22	9.3	2.2	0.195	0.36
tistically accepted		k2	30	31			22	7				
specimens		k3	262	48			19	8			o	p
P1	8 (8)	k1	352	2			18	11	24.4	2.4	0.381	0.45
		k2	76	75			34	4				
		k3	271	16			29	5			o	p

n = number of specimens considered

nt = total number of specimens

K is in 10 (-5) SI units

o = oblate

p = prolate

P2-B.- Specimens with neutral ellipsoids and some triaxial ellipsoids, defining a neutral fabric in which the k_2 axes are the best concentrated ones in a mean at 36° from the paleohorizontal. The geometry, low P_J values and large contents of hematite (indicated by high **K** and the high-coercivity magnetic phase) suggest a primary crystalline anisotropy, with secondary effects. The concentration of k_2 axes may have been originally related to paleocurrents and later enhanced by deformational processes that might have switched the orientations of k_1 and k_3 axes. Alternatively, a secondary hematite growth along preferential axes of previous minerals may explain the concentration of the k_2 axes.

P3.- A poorly ordered fabric with low **K** and low coercivity mineralogy, apparently composed of two patterns: (a) a dominant neutral fabric with k_2 axes concentrated and higher P_J; and (b) a triaxial prolate fabric with k_1 axes concentrated and lower P_J. The geometry of the fabric and the very variable P_J values suggest two superimposed fabrics related to a secondary origin. The first pattern may be the previous fabric and/or be constituted by low coercivity minerals (magnetite). The second seems to be the overprinted fabric, and/or show the effects of paramagnetic minerals. The k_2 axes of the first and second fabrics form two elongated clusters that apparently lie in the same plane.

P4.- Triaxial prolate fabric with k_1 mean as the best concentrated one at 50° from the paleohorizontal; k_3 and k_2 are in a plane angling 30° with the paleohorizontal. A secondary magnetic fabric is interpreted based on its geometry and the variable and high P_J values in specimens from this site. The subhorizontal k_3 mean (in present coordinates) is close to the maximum deformational shortening of Cretaceous rocks. The low **K**, low-coercivity and high P_J may suggest additionally the effects of paramagnetic minerals.

Otlaltepec Formation (Figure 6).

P6A.- Uniaxial to triaxial-prolate fabric with its k_1 mean at 39° from paleohorizontal; k_3 axes are around the paleohorizontal and k_2 axes have the highest angles from paleohorizontal. The high angle of k_1 from palaeohorizontal disallows a primary fabric interpretation. Hence the fabric

Table 2

AMS results of Otlaltepec Formation

SITE - - hand block			MAIN SUSCEPTIBILITY DIRECTIONS (k1 = maxim; k2 = interm; k3 = minim)						AMS MAGNITUDE			
			palaeohorizontal		*field corrected*		Fisher statis.		mean Susceptib.	Anisotropy Degree	Ellipsoid shape	Statistic shape
	n (nt)		Dec	Inc	Dec	Inc	α95	*kappa*	K	Pj (%)	T	Es
P8	**19 (19)**	k1	24	1			17	5	12.1	19.8	0.048	11.00
		k2	115	0			16	5				
		k3	**230**	**89**			**5**	**55**			o	o
P5		k1	---	---			---	---	12.8	11.6	-0.099	1.00
	8 (10)	**k2**	**336**	**30**	*324*	*45*	**14**	**19**				
		k3	---	---			---	---			p	n
P7	4 (8)	k1	80	22			26	13				1.46
	7 (8)	**k2**	**177**	**5**			**18**	**12**	16.1	6.5	-0.232	
	4 (8)	k3	229	72			22	19			p	o
P6-B	**10 (11)**	**k1**	132	36	***146***	***18***	**13**	**14**	3.0	25.8	-0.495	1.21
	6 (11)	k2	47	8	*55*	*34*	14	18				
	6 (11)	k3	309	53	*264*	*54*	17	17			p	o
P6-A	**9 (12)**	**k1**	247	39	***235***	***17***	**9**	**35**	9.4	7.0	-0.396	0.20
		k2	65	51	*113*	*61*	21	7				
		k3	156	3	*334*	*20*	21	7			p	p

n = number of specimens considered
nt = total number of specimens
K is in 10 (-5) SI units
o = oblate
p = prolate

Table 3

Main features of magnetic fabric of Piedra Hueca Formation and its interpretation

Site-hand block	Mineralogy Group (see text)	K average	Best Concentrated Axes (α95)	Symmetry	Pj (%) average (maximum value)	Origin Interpre-tation
P4	1	8	k1 (13)	tPr	9.5 (16.1)	S
P3	3	10.2 10.5	k2 (18) & k1 (16)	N & tPr	20.4 (36.2)	2 S fabrics overprinted
P2B	1	28.5	k2 (5)	uN (tN)	7.1 (8.8)	P + S
P2A	3	9.3	k1 (11)	uPr-tPr	1.96 (5.3)	P + S
P1	1	24.4	k1 (18)	uPr	2.4 (5.2)	P

Pr=prolate, Ob=oblate, N=neutral; u=uniaxial, t=triaxial
P=primary, S=secondary.
K is in 10 (-5) SI units

is interpreted as secondary. The k_1 and k_3 means are near horizontal in present coordinates, k_2 is subvertical and the k_3 and k_2 axes define a subvertical plane parallel to the general trend of bedding. The subhorizontal k_3 mean in present coordinates, is subperpendicular to the maximum deformational shortening of Cretaceous rocks. This relation may reflect early effects of deformational processes.

P6B.- Triaxial to uniaxial prolate fabric with the k_1 mean at 36° from local bedding; the k_2 axes lie nearly in the bedding plane and k_3 mean is at 37° from local bedding pole. The high angles from bedding of k_1 and the high and variable P_J values suggest secondary effects. But, as the k_1 and k_2 axes are subparallel to the general bedding plane, a primary origin cannot be ruled out. In present coordinates the k_1 mean is subhorizontal and the k_3 axes are 56° from the horizontal, without a clear relation to geometric elements of deformation.

P7.- Neutral to triaxial oblate fabric (specimens with prolate and neutral ellipsoids) with the k_2 mean as the best concentrated one in the paleohorizontal plane; most k_3 are subvertical and k_1 subhorizontal. This is interpreted as a primary fabric, in which the k_2 axes are oriented parallel to

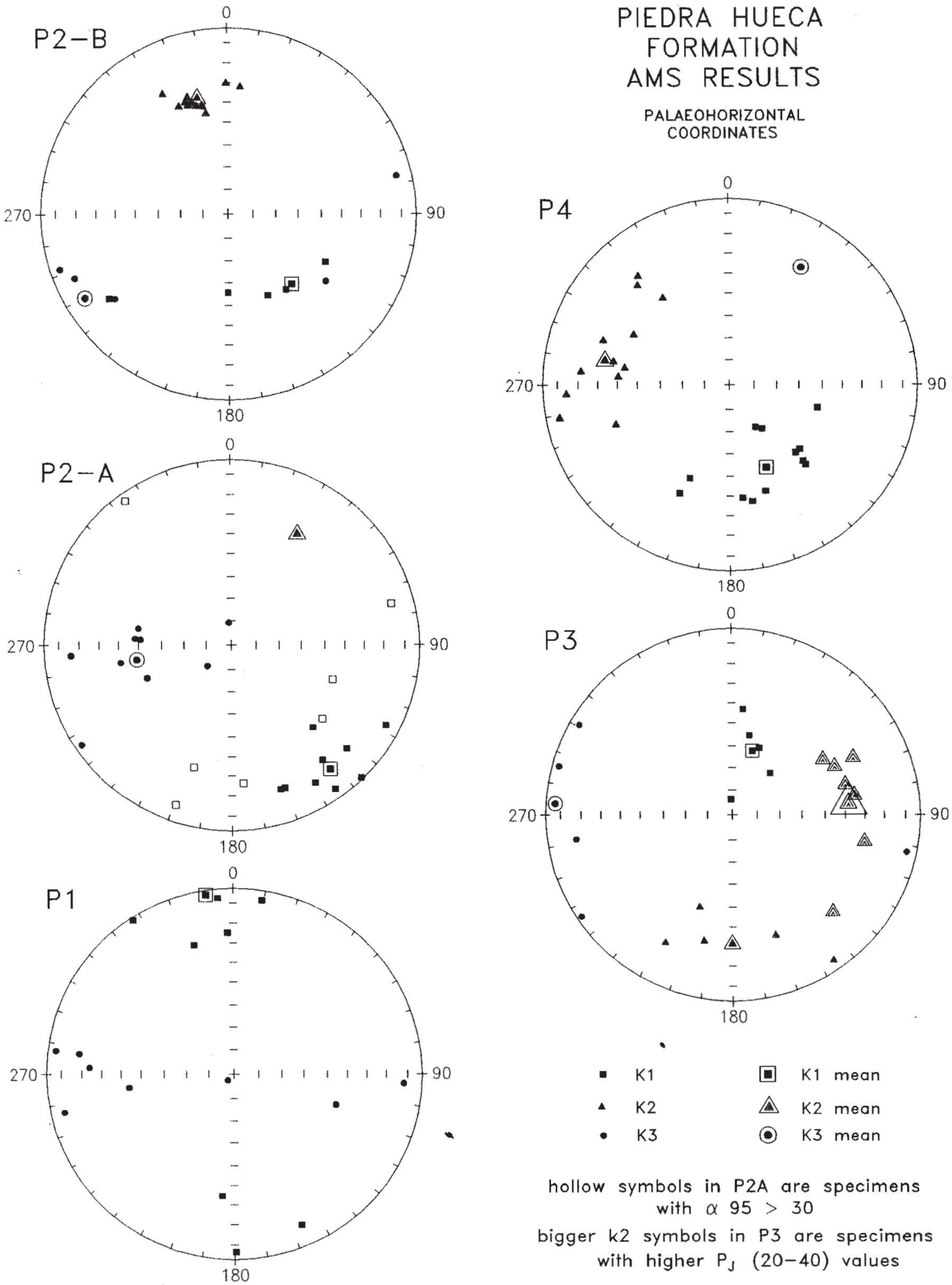

Fig. 5. Piedra Hueca Formation AMS results. Plots are in equal-area polar projection of upper hemisphere. Each plot is a specimen axis mean with $\alpha95< 25°$ or 30° (see text). Left: results interpreted as having primary AMS in palaeohorizontal coordinates and stratigraphical order. Right: results interpreted as having secondary AMS in present geographical coordinates and stratigraphical order.

Table 4

Main features of magnetic fabric of Otlaltepec Formation and its interpretation

Site-hand block	Mineralogy Group (see text)	K average	Best Concentrated Axes ($\alpha95$)	Symmetry	Pj(%) average (maximum value)	Origin Interpretation
P8	3	12.1	k3 (5)	uOb (tOb)	19.8 (25.8)	P
P5	1	12.8	k2 (14)	uN	11.6 (17.1)	P + S
P7	1	16.1	k2 (18)	tN (tOb)	6.8 (9.3)	P
P6B	2	3	k1 (13)	tPr-uPr	30 (48)	P + S
P6A	2	9.4	k1 (9)	uPr-tPr	8 (14.9)	S

Pr=prolate, Ob=oblate, N=neutral; u=uniaxial, t=triaxial

P=primary, S=secondary.

K is in 10 (-5) SI units

the palaeocurrent direction as inferred from cross-bedding. The cross-bedding dip and the plunge of the k_2 axes in relation to cross-bedding indicate a northward paleocurrent direction. The concentration of k_2 axes may correspond to hematite crystalline anisotropy, in agreement with the high **K** values and high-coercivity magnetic phase.

P5.- Neutral fabric with k_2 axes as the only ones oriented with a mean 30° from the paleohorizontal. A primary fabric may be interpreted, in which the k_2 mean would be the result of a hematite crystalline anisotropy (high **K** values and high-coercivity magnetic phase) and the k_2 inclinations correspond to an imbricated structure that suggest a paleocurrent direction toward the southeast. Alternative possibilities are: secondary replacement of hematite along preferential axes of previous minerals and/or concentration of k_2 axes enhanced due to deformation such that the k_2 axes acted as a hinge for switching k_1 and k_3 axes. The k_2 mean direction is 45° from the present horizontal and close to the general trend of bedding of the formation.

P8.- Uniaxial oblate to triaxial oblate fabric with the k_3 mean subvertical and the k_1 and k_2 axes around the paleohorizontal plane. This fabric is interpreted as primary because of its geometry and agreement of most k_1 axes with the cross-bedding dip. Alignment of k_1 axes is not very sharp and their inclinations are not imbricated, which may be due to a very gentle paleoslope and/or a palaeocurrent that was not strong enough to produce alignment. High P_J values might be due to paramagnetic mineral effects (low **K** and high-coercivity) and a compaction process might have produced dispersion of k_1 and k_2 axes and increased the P_J values.

9. MAGNETIC TREATMENT EFFECTS

The magnitude and shape parameters (P_J, K, T) and the measurement precision (**α95**) during IRM and heating steps are given in Table 5. The following features are observed:

Magnetic treatment in all cases decreased the anisotropy degree (P_J) values. This is especially noticeable in P3, P6B and P8.

There are no important changes in mean susceptibility (**K**) during treatment, with only a slight tendency to decrease. One specimen of P3 that showed a large increase of **K** after IRM, probably due to magnetic domain changes (from multiple to single domain).

The T-shape parameter shows irregular and different changes during treatment. Two main tendencies may be identified: (a) Alternating increase and decrease of T (even repetitive changes from positive to negative) after each treatment. (b) A tendency of either increase or decrease, in which specimen shapes became more oblate or more prolate (*e.g.*, P1, P2B, P8, P5).

The specimen-**α95** during the magnetic treatment (a) decreases in P1, P5 and P8 (the initial AMS is enhanced); (b) remains "reliable" in P2B, P4 and P7; or (c) increases in P2A, P3, P6A, P6B (the AMS practically disappears). The increment is more important after IRM, which suggests that it is mainly related to magnetic domain changes. After heating the **α95** values do not increase so steeply, and in some cases they even decrease.

The AMS *principal directions* of specimens changed in most cases during treatment. Sometimes the before-and after-treatment AMS geometry is similar, or shows switched axes positions: P1, P8; P7, P5 and P2B. This similarity is more noticeable in the first two cases, suggesting that the AMS of these samples is more reliable. In some of the previous cases it seems that a different but complementary AMS was enhanced with respect to initial AMS. This may indicate that the treatment has enhanced a different element of the same fabric.

In one case (P4) the magnetic treatment resulted in a completely different AMS, that seems unrelated to the initial one. In the remaining cases (P2A, P2B, P3, P6A and P6B) the magnetic treatment has practically destroyed the initial AMS.

The *magnetic mineralogy*, based on the IRM curves, does not change at the 130°C heating step, which suggest that goethite is not present or is not changing at this tem

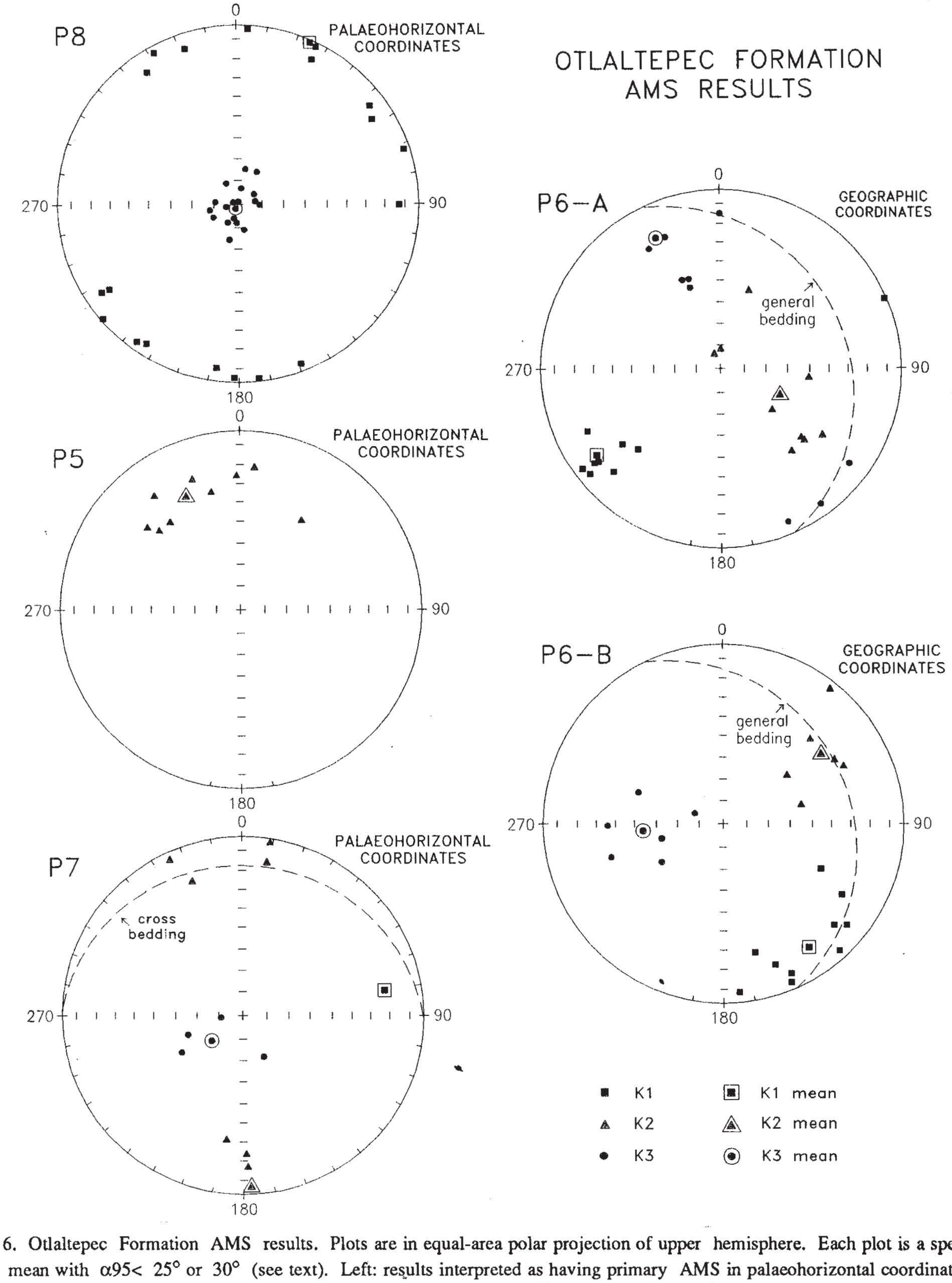

Fig. 6. Otlaltepec Formation AMS results. Plots are in equal-area polar projection of upper hemisphere. Each plot is a specimen axis mean with α95< 25° or 30° (see text). Left: results interpreted as having primary AMS in palaeohorizontal coordinates and stratigraphical order. Right: results interpreted as having secondary AMS in geographical or field corrected coordinates and stratigraphical order.

Table 5

AMS magnitude and precision changes during magnetic treatment (pilot specimens)

Site-block		PIEDRA HUECA FORMATION						OTLALTEPEC FORMATION			
/specimen		initial	IRM	130 C	400 C			initial	IRM	130 C	400 C
P1/3						**P6-B/14**					
	Pj	1.73	1.79	1.74			Pj	30.27	5.29	11.1	
	K	20.71	20.48	19.97			K	2.64	2.45	2.44	
	T	0.028	-0.55	-0.43			T	-0.8	-0.382	0.035	
specimen-	α95	16.9	14.1	16.3		specimen-	α95	3.3	15.4	88.1	
P2-A/9						**P6-A/6'**					
	Pj	2.87	1.84	4.35			Pj	6.6	1.63	3.52	2.05
	K	9.22	9.52	9.42			K	10.46	10.31	10.65	6.97
	T	0.24	-0.142	0.124			T	-0.536	-0.18	0.241	-0.064
specimen-	α95	7.6	49.8	37.8		specimen-	α95	4	82.5	29	23.6
P2-B/14						**P7/3**					
	Pj	6.21	1.88	1.63	1.04		Pj	4.61	1.79	3.8	
	K	29.68	29.92	29.03	26.14		K	16.66	16.51	16.2	
	T	0.094	0.261	0.246	0.363		T	-0.424	0.34	0.378	
specimen-	α95	14.4	23.6	8	14.8	specimen-	α95	3.9	8.7	11.2	
P3/6						**P5/3'**					
	Pj	22.7	0.79	2.4	1.67		Pj	10.66	2.11	3.15	2.08
	K	10.29	41.9	10.6	8.55		K	11.42	12.19	11.93	9.68
	T	-0.007	0.04	-0.116	0.074		T	-0.152	0.304	-0.08	0.317
specimen-	α95	11.5	47.8	56.4	29.6	specimen-	α95	23	10.1	18.1	13.3
P3/12						**P8/7''**					
	Pj	7.33	2.29	2.04			Pj	24	11.61	10.7	9.82
	K	11.59	11.56	11.21			K	11.61	10.67	10.59	11.08
	T	-0.139	0.212	0.076			T	-0.372	-0.621	-0.725	-0.858
specimen-	α95	5.1	53.7	51.5		specimen-	α95	5.5	2.8	5.1	2.1
P4/4											
	Pj	7.94	3.4	3.1	4.1						
	K	8.07	7.91	7.87	13.8						
	T	-0.405	0.141	0.082	0.15						
specimen-	α95	15.4	17.4	26.8	9.6						

perature. At the 400°C heating step, three changes in the magnetic mineralogy occur in some samples (Figure 7):

(a) A development of lower coercivity magnetic phases in P6A and P5, that may correspond to a direct change of goethite to magnetite.

(b) A development of a higher coercivity magnetic phase in P4 and P3, that may correspond to a change of maghemite to hematite. In both cases the initial AMS would not correspond to a primary fabric. The interpretation of maghemite in the initial magnetic mineralogy of these two sites agrees with the fact that their specimens are the most weathered. The P4 site, the strongest weathering, shows the highest coercivity magnetic phase after 400°C. The poorly-ordered magnetic fabric of P3 could also be explained by the presence of maghemite.

(c) The development of a final higher intensity of IRM in P8 with a similar low-coercivity phase, may indicate a development of more magnetic minerals in the same initial proportion of low and high-coercivities, and/or a change to single magnetic domain structures. In any case, the post-treatment geometry of the AMS principal directions is not altered and is nearly the same as the initial one.

10. DISCUSSION AND CONCLUSIONS.

The statistic analysis of repeated measurements showed that 93 % of the specimens have at least one AMS mean axis with α95 < 25°. Hence they are considered acceptable and reliable for geologic interpretations. The rejected specimens (mainly one-third of P2A) are considered magnetically isotropic. The precision of the equipment is better for measuring AMS directions than for measuring intensities

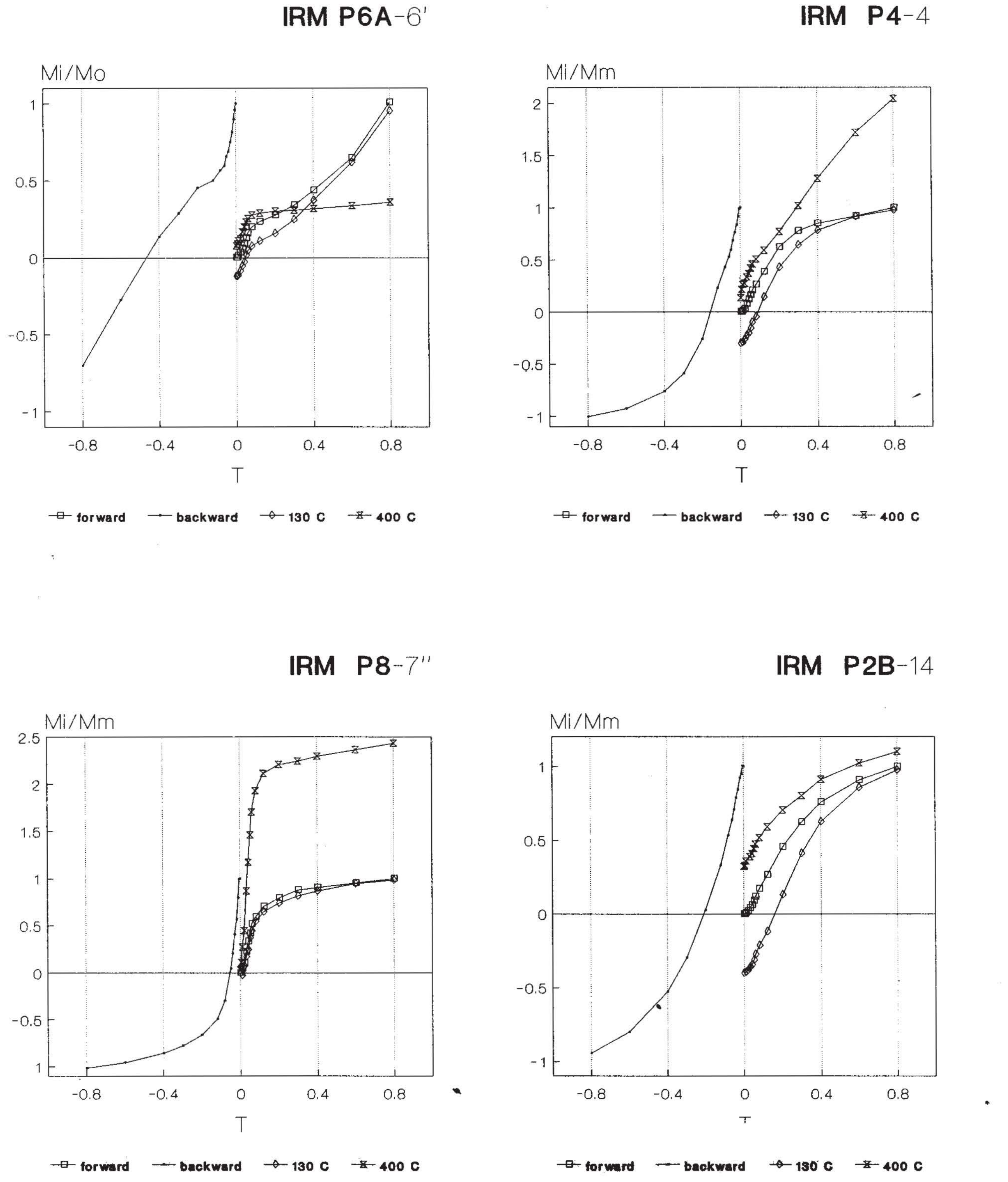

Fig. 7. Examples of magnetic mineralogy changes after heatings as detected with IRM curves. Curves are normalized with maximum saturation value of the first IRM performed. Up: note the change to a higher coercivity phase in P4 and to a lower in P6 after the 400°C heating. Down-left: the change to a higher saturation value of a similar low-coercivity magnetic phase in P8. Down-right: the case of practically no important magnetic change in P2B .

of susceptibility and thus for evaluating the shape of the AMS. These results suggest that Molspin equipment can be used for AMS studies of sedimentary rocks of low susceptibility and/or low anisotropy. Statistical analysis of repeated measurements may be useful for a better evaluation of AMS shape and is a definitive test to identify magnetically isotropic specimens.

The criteria proposed for evaluating the usefulness of AMS for geological inferences (such as statistics of repeated measurements, P_J values, magnetic fabric geometry and agreement with other indicators) indicate that some 85% of the specimens can be useful for directional geological interpretation (at least 50% for palaeocurrent inferences). Magnetically isotropic specimens (7%, mainly one third of P2A specimens) and specimens with apparent complex overprinted fabrics (9%, P3 specimens), in which it is difficult to identify nature and origin of their fabrics, are not useful.

AMS results suggest a primary magnetic fabric at P1, P7 and P8; the last two sites have elements of their magnetic fabrics that agree with cross-bedding. A primary magnetic fabric with probable secondary effects is recognized at P2A, P2B, P5 and P6B. At P2B and P5 the secondary processes might have enhanced the concentration of k_2 axes. At P2A and P6B these processes might have tilted the magnetic foliation in relation to the local bedding planes. A fairly clear secondary fabric is identified at P3, P4 and P6A, mainly due to their high P_J and subvertical foliations. The low-coercivity and low **K** of the last three sites (plus P6B), may additionally suggest effects of paramagnetic minerals and /or of simple domain structures in the AMS.

Magnetic treatment does not enhance the AMS, but is very useful for identifying the magnetic mineralogy through relations of before-and after-treatment changes of coercivity and AMS. The relationship among these changes and the statistical results suggested the following conclusions:

(i) Secondary minerals such as goethite and maghemite may be present in some sites. Goethite may be present at P5 and P6A, as indicated by the development of lower coercivity phases at 400°C. These phases may be due to hematite, derived from goethite. Maghemite is suggested at P4 and P3 (the most weathered sites), as suggested by the development of higher coercivity phases at 400°C. These phases might correspond to a change of maghemite to magnetite. These secondary minerals strengthen the interpretation for a secondary fabric and for secondary effects at these sites. Some fabrics may be additionally related to weathering processes, e.g., at P3.

(ii) IRM destroyed or changed the AMS (according with statistical criteria of repeated measurements) in around 40% of the samples: P6B, P6A, P3 and P2A (in which one third of its specimens was rejected). In another 10%, the IRM completely changed the AMS: P4. Almost all these samples are the same that are interpreted of secondary origin: All have some low-coercivity phase in the initial magnetic mineralogy (groups 2: high and low and 3: low-intermediate coercivities). This fact suggests that the changes in the magnetic domain arrangement were produced by IRM, resulting in a loss of AMS in rocks with low-coercivity magnetic phases. If a similar change in magnetic domain occurred in nature, the AMS would not be useful or reliable for geological interpretations. This may be the case for the magnetically isotropic specimens from P2A.

On the other hand, the presence of some low-coercivity phase in most rocks with secondary AMS could due to this phase being more easily affected by secondary processes due to probable smaller grain sizes and/or because it was developed during secondary processes.At P3 and P4 the presence of maghemite may explain the low-coercivity phase; in both cases weathering is apparently a very important secondary process. At P6A and P6B the secondary process seems to be tectonic: deformation or strain, depending on the geometry of AMS.

(iii) The AMS of sites in which the reliability of AMS remained acceptable after IRM and heating, show similar geometry than the initial AMS. These sites are mainly interpreted of primary origin (P1, P7, P8) or primary with some secondary effects (P2B, P5). Most of these sites (except P8) have a high-coercivity magnetic mineralogy, which indicates that primary AMS resides in the high-coercivity magnetic phases. Among this group of samples, P1 and P8 stand out because their statistical parameters get more precise values after magnetic treatment and their geometry keeps the same pattern before and after-treatment. This stresses the reliability and usefulness of AMS at these sites.

The magnetic fabrics interpreted as primary suggest a palaeocurrent system flowing to the NW (270° to 320°) for two sites in the lower part of the Piedra Hueca Formation (P1 and P2A) and to the NNE to NW (24° to 310°) for three sites from the Otlaltepec Formation: P7 and P8 (360° to 24°) with cross-bedding indicators, and P6B (310°). These current directions do not fit the general SSW paleoslope direction inferred from the geometry of outcrops of Middle Jurassic units, suggesting the presence of some local positive paleogeographic element(s). At two places with apparently secondary effects in the magnetic fabric (P2B and P5), the flow seems to have been to the SE. These changes in current direction may be normal in some fluvial systems, due to very local conditions of depositation; on the other hand, they may be a result of secondary effects. Most of the secondary fabrics (or secondary effects) have subvertical magnetic foliation related to the maximum shortening of the deformation of the Mesozoic sequence. Secondary magnetic fabrics in sites from the upper part of Piedra Hueca Formation (P4 and P3) may have been additionally furthered by weathering processes that took place before the deposit of the Otlaltepec Formation; such processes should have lasted long enough to account for the angular unconformity between these two Formations.

ACKNOWLEDGMENTS

This research was supported by grants from the Programa de Apoyo a las Divisiones de Estudios de Posgrado, a program for supporting graduate studies of the National

University of Mexico, and by a fellowship for laboratory work at Plymouth University awarded by the British Council. The field assistance of Teodoro Hernández and Gilberto Silva is gratefully acknowledged, as well as the hospitality of Onésima Gil Machado in Santo Domingo Tianguistengo. Special thanks are due to Jaime Urrutia, Donald Tarling, Dante Morán and Cinna Lomnitz for their helpful comments and critical reviews of the manuscript.

BIBLIOGRAPHY

ABOUZAHM, A. G. and D. H. TARLING, 1975. Magnetic anisotropy and susceptibility of Late Precambrian tillites from north-western Scotland. *J. Geol. Soc., London, 131*, 647-652.

CABALLERO-MIRANDA, C., 1990a. Geología y Anisotropía magnética del Jurásico Continental del área Huajuapan de León-Petlalcingo, Estados de Oaxaca y Puebla. Unpublished Master Thesis, UNAM, Fac. de Ciencias. 142 p.

CABALLERO-MIRANDA, C., 1990b. Efectos de los tratamientos de desmagnetización térmica en la anisotropía de susceptibilidad magnética. Inst. Geofísica, México. *Comunicaciones Técnicas, Serie Investigación 120*, 27 p.

CABALLERO-MIRANDA, C., D. J. MORAN-ZENTENO, J. URRUTIA-FUCUGAUCHI, H. BÖHNEL, Z. JURADO-CHICHAY, E. CABRAL-CANO and G. SILVA-ROMO, 1990. Paleogeography of the northern portion of the Mixteca Terrane, Southern Mexico during the Middle Jurassic. *J. South American Earth Sciences, 3*, 4, 195-211.

CAMPA, M. F. and P. J. CONEY, 1983. Tectono-stratigraphic terranes and mineral resource distributions in Mexico. *Can. J. Earth Sci., 26*, 1040-1051.

ELLWOOD, B. B., F. HROUDA and J. J. WAGNER, 1988. Symposia on magnetic fabrics. *Phys. Earth Planet. Ints.*, 51, 249-389.

ERBEN, H. K., 1956. El Jurásico Medio y el Calloviano de México. XX Congr. Geol. Internal., México, 139 p.

FISHER, R. A. 1953. Dispertion on a sphere, *Proc. R. Soc. London*, A217, 295-305.

GRANAR, L., 1958. Magnetic measurements on Swedish varved sediments. *Arkiv. f. Geofysik, 3*, 1-40.

HROUDA, F., 1982. Magnetic Anisotropy of Rocks and its application in Geology and Geophysics.

JACKSON, M and L. TAUXE, 1991. Anisotropy of Magnetic Susceptibility and Remanence: Developments in the characterization of tectonic, sedimentary and igneous fabric. *Rev. of Geophys.*, supplement, 371-376.

JELENSKA, M. and M. KADZIALKO-HOFMOKL, 1990. Dependence of anisotropy of magnetic susceptibility of rocks on temperature. *Phys. Earth Planet. Int., 62*, 19-31.

JELINEK, V., 1981. Characterization of Magnetic Fabric of Rocks. *Tectonophysics 79*, 563-567.

KING, R. F., The remanent magnetism of artificially deposited sediments. *Mon. Not. R. Astr. Soc., 7*, 115-134.

MORAN-ZENTENO, D., C. CABALLERO-MIRANDA, G. SILVA-ROMO, B. ORTEGA-GUERRERO and E. GONZALEZ-TORRES, 1993. Jurassic-Cretaceous paleogeographic evolution of Northern Mixteca terrane, southern Mexico. *Geofís. Int. 32*, 3, 453-473.

NAGATA, T., 1961. Rock Magnetism. Maruzen, Tokio.

NOLTIMIER, H. C., 1971. Magnetic rock cylinders with negligible shape anisotropy. *J. Geophys. Res.*, 75, 4035-4037.

ORTEGA-GUERRERO, B., 1989. Paleomagnetismo y Geología de las unidades clásticas mesozoicas del área Totoltepec-Ixcaquixtla, Estados de Puebla y Oaxaca, Unpublished Master Thesis, UNAM., Fac. Ciencias.

ORTEGA-GUTIERREZ, F., 1978. Notas sobre la Geología del área entre Santa Cruz y Ayuquila, Edos. de Puebla y Oaxaca, UNAM, Inst. Geol., *Paleont. Mexicana 44*, 17-26, 2 figs.

ORTEGA-GUTIERREZ, F., 1981. Metamorphic belts of southern Mexico and their tectonic significance. *Geofís. Int., 20*, 3, 177-202.

PEREZ-IBARGÜENGOITIA, J. M., A. HOKUTO-CASTILLO and Z. DE CSERNA, 1965. Estratigrafía y paleontología del Jurásico Superior de la parte centro-meridional del Estado de Puebla, UNAM, Inst. Geol. *Paleont. Mexicana 21*, 5-22.

PERARNAU, A. and D. H. TARLING, 1985. Thermal enhancement of magnetic fabric in Cretaceous sandstone. *J. Geol. Soc. Lond., 142*, 1029-1034.

ROCHETTE, P., M. JACKSON and C. AUBOURG, 1992. Rock magnetism and the interpretation of anisotropy of magnetic susceptibility. *Reviews of Geophysics, 30*, 209-226.

SCHULTZ-KRUTISCH, T. and F. HELLER, 1985. Measurement of magnetic susceptibility anisotropy in Buntsandstein deposits from southern Germany. *J. Geophys., 56*, 51-58.

SCRIBA H. and F. HELLER, 1978. Measurements of anisotropy of magnetic susceptibility using inductive magnetometers. *J. Geophys.*, *44*, 341-352

SILVA-PINEDA, A. 1984. Revisión Taxonómica y Tipificación de las Plantas Jurásicas Colectadas y Estudiadas por Wieland (1914) en la Región de El Consuelo, Oaxaca. UNAM *Paleont. Mexicana, 49,* 103 p., 31 láms.

SILVA-PINEDA, A. 1978. Paleobotánica del Jurásico de México, UNAM, Inst. Geol. *Paleont. Mexicana, 44,* 1-16.

TARLING, D. and F. HROUDA, 1993; The Magnetic Anisotropy of Rocks. Chapman and Hall, London.

TARLING, D. 1983. Palaeomagnetism. Chapman and Hall, London, 379 p.

URRUTIA-FUCUGAUCHI, J. 1981. Preliminary Results on the Effects of Heating on the Magnetic Susceptibility Anisotropy of Rocks. *Jour. Geomag. Geoelectr.*, *33*, 411-419.

URRUTIA-FUCUGAUCHI and D. TARLING, 1983. Palaeomagnetic properties of Eocambrian sediments in northwestern Scotland: Implications for world-wide glaciation in the Late Precambrian. *Palaeogeog., Palaeoclim., Palaeoecol.*, *41*, 325-344.

WESTERMAN, G. E. G., R. CORONA and R. CARRASCO, 1984. The andean Mid-Jurassic *Neuqueniceras* amonite assemblage of Cualac, Mexico. *In:* Westerman, G.E.G. (Ed), Jurassic-Cretaceous biochronology and paleogeography of North America, *Geol. Assoc. Canada, Sp. Paper 27*, 99-112.

WIELAND, G. R., 1914. La flora liásica de la Mixteca Alta, Inst. Geol. México, *Bol. 31*, 165 p.

Cecilia I. Caballero-Miranda
Laboratorio de Paleomagnetismo,
Instituto de Geofísica, UNAM,
04510, México D. F. México.