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Reconnaissance paleomagnetic results from western Cuba

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Abstract

A paleomagnetic study of Mesozoic rocks from the Sierra de Los Organos and Sierra del Rosario fold belts of western Cuba revealed postfolding magnetisation in diabases of the Late Jurassic El Sábalo Formation and carbonates of the middle Cretaceous Pons and the Late Cretaceous Carmita and Moreno formations. Steep components with inclinations of about 70° were isolated from all three formations; at the same time, postfolding shallow components were also found in a few samples of the Pons limestones. We rule out a possibility to account for these results by either horizontal movements or non-dipole field anomaly. Neither very appealing is a hypothesis of a post-remagnetization tilt of the entire region. All the components appear to be confined to a plane perpendicular to the main structural trends; we hypothesize that the remanences might have been distorted or re-aligned during deformation; this assumption, however, is far from being proven. In contrast, well-defined characteristic components were isolated from basalts of the Aptian–Albian Encrucijada ($D/I = 247°/23°$, $K = 14$, $a_{95} = 9.0°$) and the Late Cretaceous Orozco ($D/I = 228°/22°$, $K = 110$, $a_{95} = 4.7$) formations from the Bahia Honda zone in the north of western Cuba; the remanence in the Encrucijada Formation is shown to predate deformation. Mean inclinations in both formations match those in Cretaceous volcanics from central Cuba, and all the results show lower latitudes than expected from the reference data for the North American plate thus implying that volcanic domains of Cuba were displaced northward by about 1000 km prior to the Middle Eocene. Cretaceous declinations in western and central Cuba differ by about the same amount as the major structural trends of these two areas suggesting oroclinal bending of Cuba. At the same time, both areas are rotated counterclockwise with respect to North America thus implying movements on a broader scale.

1. Introduction

The use of paleomagnetism in the study of tectonic movements is clearly vital for our understanding of the Caribbean (Gose, 1985; MacDonald, 1990) but to date the number of studies are few. As for Cuba, it was a paleomagnetic *terra incognita* up to recently, when a short paper was published on Middle Cretaceous paleomagnetic results from the Zaza terrane of central Cuba (Renne et al., 1991). For western Cuba, paleomagnetic data are still limited to those reported in abstracts (Renne et al., 1989; Perez Lazo et al., 1989)

The Cordillera de Guaniguanico of the Pinar del Rio Province of western Cuba (Fig. 1A) can be divided into the Sierra de los Organos and Sierra del

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Rosario belts (Pardo, 1975; Pszczolkowski, 1977; Pszczolkowski, 1978); numerous nappes were recognised in each belt (Rigassi-Studer, 1963; Hatten, 1967; Pszczolkowski, 1977; Piotrowska, 1978). The former belt consists of Jurassic to Lower Eocene rocks (Pszczolkowski, 1978) which were deformed in the Early to Middle Eocene. The Sierra del Rosario belt occupies the northeastern part of the Guaniguanico zone but Jurassic to Paleocene formations of this belt can also be traced to the southwestern end of the zone (Fig. 1A). Thrusting here also occurred in the Early to early Middle Eocene.

The Bahia Honda tectonostratigraphic zone comprises ophiolites and volcanic arc rocks and extends

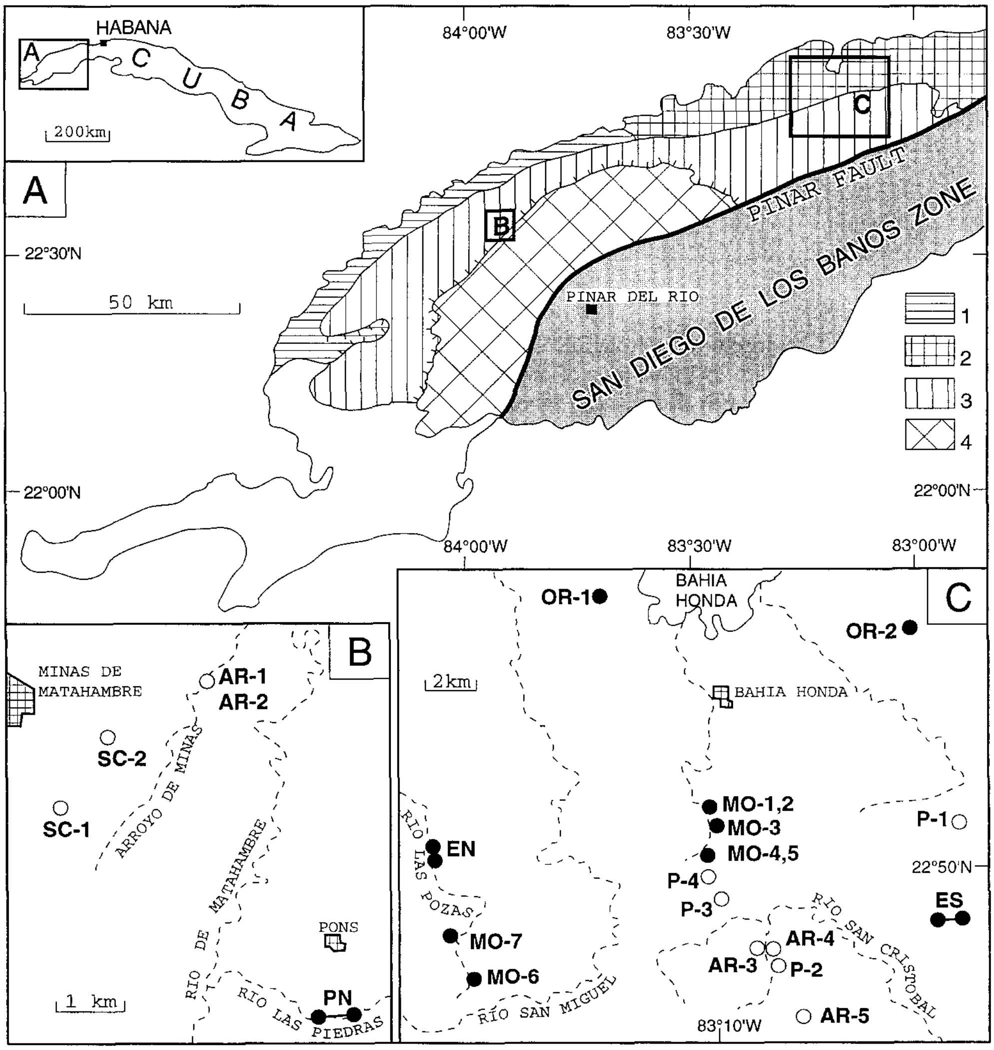


Fig. 1. Tectonostratigraphic zones of western Cuba and sampling sites. (A) Tectonostratigraphic zones of the Pinar del Rio Province: *1* = La Esperanza belt; *2* = Bahia Honda zone; *3* and *4* = Guaniguanico zone, *3* = Sierra del Rosario belt, *4* = Sierra de los Organos belt. (B) Sampled sites and sections in the Minas de Matahambre–Pons area: *PN* = Pons Formation; *AR* = Artemisa Formation; *SC* = San Cayetano Formation. (C) Sampled sites and sections in the Sierra del Rosario belt and Bahia Honda zone: *MO* = Moreno and Carmita formations; *ES* = El Sábalo Formation; *EN* = Encrucijada Formation; *OR* = Orozco Formation; *P* = Polier Formation. In (B) and (C) ● and ○ denote sampling sites from the formation which yielded results (were rejected altogether).

along the northern coast of western Cuba (Fig. 1A). Pillow basalts, radiolarian cherts, pelagic limestones and sometimes volcanoclastics of the Encrucijada Formation up to 900 m thick are regarded as a part of Bahia Honda ophiolites (Fonseca et al., 1984). However, Iturralde-Vinent (1994) interprets the Encrucijada Formation as a rock sequence that belonged to an ocean basin and was juxtaposed to the Guaniguanico margin. The Bahia Honda volcanic arc represented by lavas and tuffs of the Orozco Formation, became extinct in the Campanian as the result of the early Campanian tectonic phase (Pszczolkowski and Flores, 1986). Both the Encrucijada and Orozco volcanics were thrust over the Guaniguanico zone in the Early to Middle Eocene.

The following formations were sampled during three field excursions (eleven working days in total) in 1988. In the Sierra de los Organos belt, light to dark-grey limestones of the Aptian–Turonian Pons Formation (Hatten, 1957; Pszczolkowski, 1978 and unpublished data) were sampled along a continuous section across both limbs of a fold in a tectonic window (locality PN, Fig. 1B). Limestones and marls of the Cenomanian–Turonian Carmita and Santonian–Campanian Moreno formations (Pszczolkowski, 1984 and unpublished data) were studied at seven sites in the Sierra del Rosario belt (sites MO-1 to MO-7, Fig. 1C). Mafic rocks with sedimentary interbeds of the Jurassic (Pszczolkowski, 1989) El Sábalo Formation were sampled in the east-central part of the same belt (locality ES, Fig. 1C). In the Bahia Honda zone (Fig. 1A), basalts and deposits of the Aptian–Albian (Zalepughin et al., 1982) Encrucijada Formation were sampled at least at fifteen stratigraphic levels along a section in the Las Pozas River valley (locality EN, Fig. 1C). Coniacian–Santonian (Furrazola-Bermudez et al., 1978) probably to early Campanian (Florez Abin, 1983) tuffs and basalts of the Orozco Formation were sampled from two small shallow pits about 10 km apart (sites OR-1 and OR-2, Fig. 1C).

In total, about 140 hand-samples oriented with magnetic compass were taken in the Guaniguanico and Bahia Honda zones. One hand-sample was taken at a stratigraphic level, sampling points being spaced 1–5 m in cross section. Thus, each site or section represents a part of a formation up to 100 m thick. Only the Pons Formation was sampled from two limbs of a fold for a fold test; in the other cases, only smaller structural variations were found.

We also collected about 80 hand-samples from terrigenous rocks of the Early Jurassic–middle Oxfordian San Cayetano Formation at two sites (SC-1 and SC-2), limestones of the Late Jurassic Artemisa Formation at five sites (AR-1 to AR-5) and fine-grained sandstones of the Valanginian–Aptian Polier Formation at four sites (P-1 to P-4, Fig. 1B–C). These rocks yielded no meaningful results due to their weak magnetization and/or large scatter of paleomagnetic data.

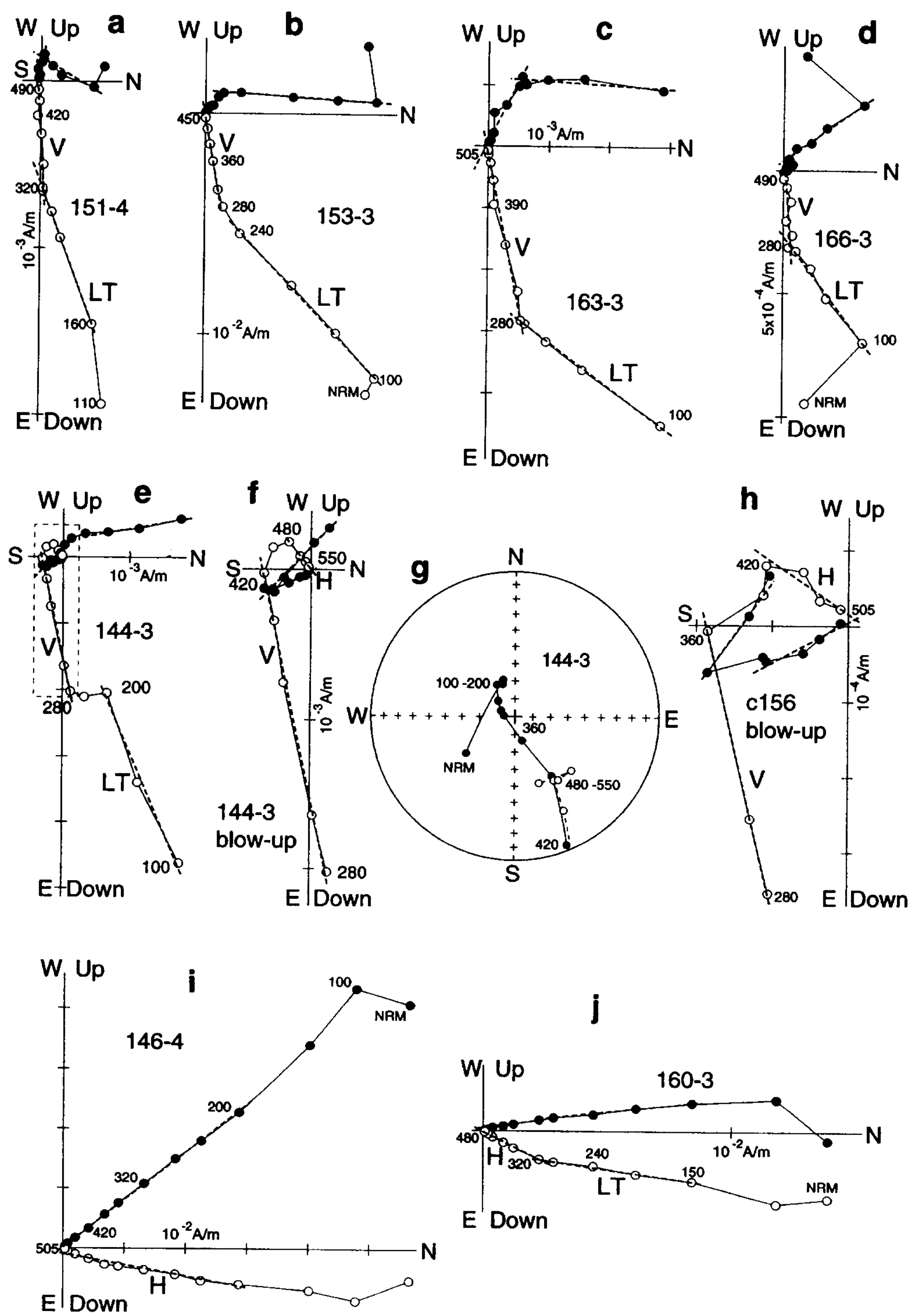
2. Treatments

One or two, sometimes three specimens from each hand-sample were studied. Volcanics of the El Sábalo, Encrucijada and Orozco formations were subjected to stepwise thermal cleaning in a home-made oven and measured on a Czechoslovakian spinner magnetometer JR-4 in the Paleomagnetic Laboratory in Moscow. Sediments of the Pons, Moreno and Carmita formations were thermally demagnetized and measured on a CTF cryogenic magnetometer in the Paleomagnetic Laboratory in Paris. Isolated magnetization components (Kirschvink, 1980) from each specimen were used for computation of sample means, which in turn were used for calculation of formation means. Converging remagnetization circles (Halls, 1976) were used at specimen level.

3. Results

3.1. The Pons Formation

Natural remanent magnetization (NRM) varies from 0.1 to more than 10 mA/m. During thermal cleaning, an unstable component (LT) was isolated in many samples from 100 to 200 or 300°C (Fig. 2a–e, j). This component is rather scattered, and its in-situ mean direction (Table 1) is close to the present-day dipole field, PDF, at the locality ($I = 40°$). After removal of the LT component which may be of viscous origin, other components (V, H) were found in most samples (Fig. 2a–e, h). The V compo-



a
151-4
W Up
S
N
490
420
V
320
10^{-3}A/m
LT
160
110
E Down
b
153-3
W Up
450
N
V
360
280
240
LT
10^{-2}A/m
NRM
100
E Down
c
163-3
W Up
10^{-3}A/m
505
N
390
V
280
LT
100
E Down
d
166-3
W Up
N
490
V
280
LT
$5x10^{-4}$A/m
100
NRM
E Down
e
144-3
W Up
S
N
10^{-3}A/m
V
200
280
LT
100
E Down
f
144-3 blow-up
W Up
480
S
550
N
420
H
V
10^{-3}A/m
280
E Down
g
144-3
N
W
E
S
100 -200
NRM
360
480 -550
420
h
c156 blow-up
W Up
420
H
S
505
360
10^{-4}A/m
V
280
E Down
i
146-4
W Up
100
NRM
200
320
420
10^{-2}A/m
505
N
H
E Down
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160-3
W Up
480
N
H
320
240
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150
LT
NRM
E Down

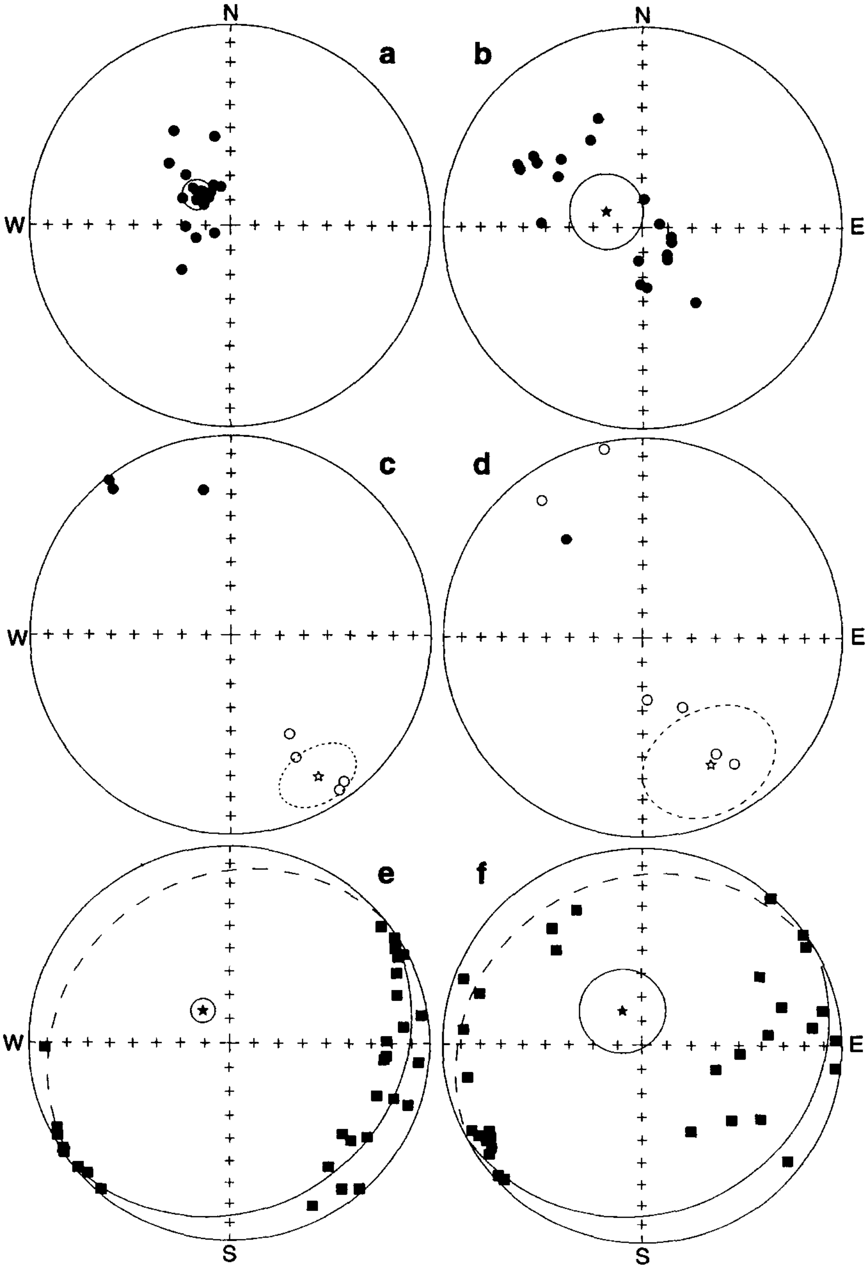

Fig. 3. Equal-area stereoplots of component V (a–b), component H (c–d) and normals to remagnetization circles (e–f) from the Pons Formation. Dots and squares are paleomagnetic vectors and normals to remagnetization circles, respectively, stars are mean directions. Closed/open symbols and solid/dashed lines are projected onto the lower/upper hemisphere. Left/right column is in situ/tilt-corrected data.

Fig. 2. Representative demagnetization plots (a–f, h–j) and stereoplot (g) from the Pons Formation. Dashed lines show the adjustment of linear segments (LT = low temperature component; V = subvertical component; H = flat component; see text for explanations). All data are in situ. Closed/open symbols are projections onto the horizontal/vertical plane. Temperatures are in degrees Celsius.

nent has always the normal polarity and is much better grouped in situ than after tilt correction (Fig. 3a, b); the fold test (McFadden and Jones, 1981) unambiguously points to its postfolding age (Table 1). Usually, component V shows rectilinear decay to the origin (Fig. 2a–d). In five samples, however, still another component could be recognized (Fig. 2e–h). The third component (H) accounts for just a few percents of the NRM intensity and has a shallow inclination with two polarities (Fig. 3c, d). Surprisingly enough, only a shallow component was found in two samples where it accounts for a larger part of the NRM intensity (Fig. 2i, j). These seven shallow directions are better grouped in geographic coordinates, and the fold test (McElhinny, 1964) points to a postfolding origin of component H (Table 1).

Table 1
Paleomagnetic results on different formations from the Sierra de Los Organos and Sierra del Rosario belts

S	C	*N*	*B*	In situ				Tilt corrected			
				D (°)	*I* (°)	*K*	a_{95} (°)	*D* (°)	*I* (°)	*K*	a_{95} (°)
Pons Formation											
Mean [a]	LT	29/21		352	46	11	10.1	350	48	5	15.4
P1	V	15/10	136/29	305	73	26	8.8	148	77	31	8.0
P2	V	14/9	301/26	315	69	39	7.5	304	42	27	9.0
Mean [a]	V	29/19		311	71	31	5.7	293	74	6	13.3
$F_{(2, 34)} = 3.3$				$f = 0.6$				$f = 70.0$			
P1	H	15/5	136/29	326	18	22	13.3	329	43	18	14.9
P2	H	14/2	301/26	335	15	–	–	336	−10	–	–
Mean [a]	H	29/7		328	18	20	11.8	332	28	7	20.2
$F_{(12, 12)} = 2.7$				$K_{is}/K_{tc} = 2.9$							
CRC		(33)		321	73	–	4.9	331	74	–	17.5
Moreno Formation											
Mean [a]	LT	44/24		3	29	24	6.1	359	−14	12	8.8
GR1	A	8/8	339/84	252	76	24	10.2	325	6	27	9.6
GR2	A	13/8	324/70	151	83	21	10.8	323	28	20	11.3
GR3	A	9/6	338/50	173	84	13	15.9	337	45	10	18.1
GR$	A	8/8	321/40	10	74	33	8.7	335	36	34	8.5
Mean [a]	A	38/30		282	88	16	6.4	329	28	13	7.2
Mean [b]				327	70	18	6.0				
$F_{(6, 52)} = 2.3$				$f = 4.2$				$f = 6.3$			
MO-4	B	5/4	329/72	149	46	20	21.3	333	61	45	13.9
CRC		(30)		318	82		10.1	325	23		13.2
El Sabalo Formation											
Mean [a]	HT	20/15	356/34	233	62	4	17.9	305	61	5	16.8
CRC		(28)		302	73	–	11.0	337	48	–	10.8

S represents sites as in the text and Fig. 1 or groups of samples (GR) with similar bedding attitudes for the Moreno Formation; CRC represents the results obtained with converging remagnetization circles (Halls, 1976); C is the component (see text for details and component labels); *N* is the number of samples studied/accepted (in brackets, the number of remagnetization circles); *B* is the azimuth of dip/dip angle; *D* is the declination; *I* is the inclination (all the data are inverted to normal polarity); *K* is the precision parameter (Fisher, 1953); a_{95} is the radius of the 95% circle of confidence.

[a] Statistics on the sample level.

[b] The result after 30% unfolding.

Vector end-points during cleaning move along great circles (Fig. 2g) which converge much better in situ than after tilt correction (Fig. 3e, f); the direction of the least-dispersed component (Halls, 1976) is very similar to that of component V as deduced from component analysis (Table 1). Similar very steep directions have already been reported from the Pons Formation (Renne et al., 1989).

3.2. The Moreno and Carmita formations

The data on six samples of the Carmita Formation were pooled with those from the Moreno Formation. In most samples, an unstable component (LT) isolated from 100 to 200, sometimes to 280°C (Fig. 4a–e), is better grouped in situ and its mean direction is close to, though slightly shallower than, the

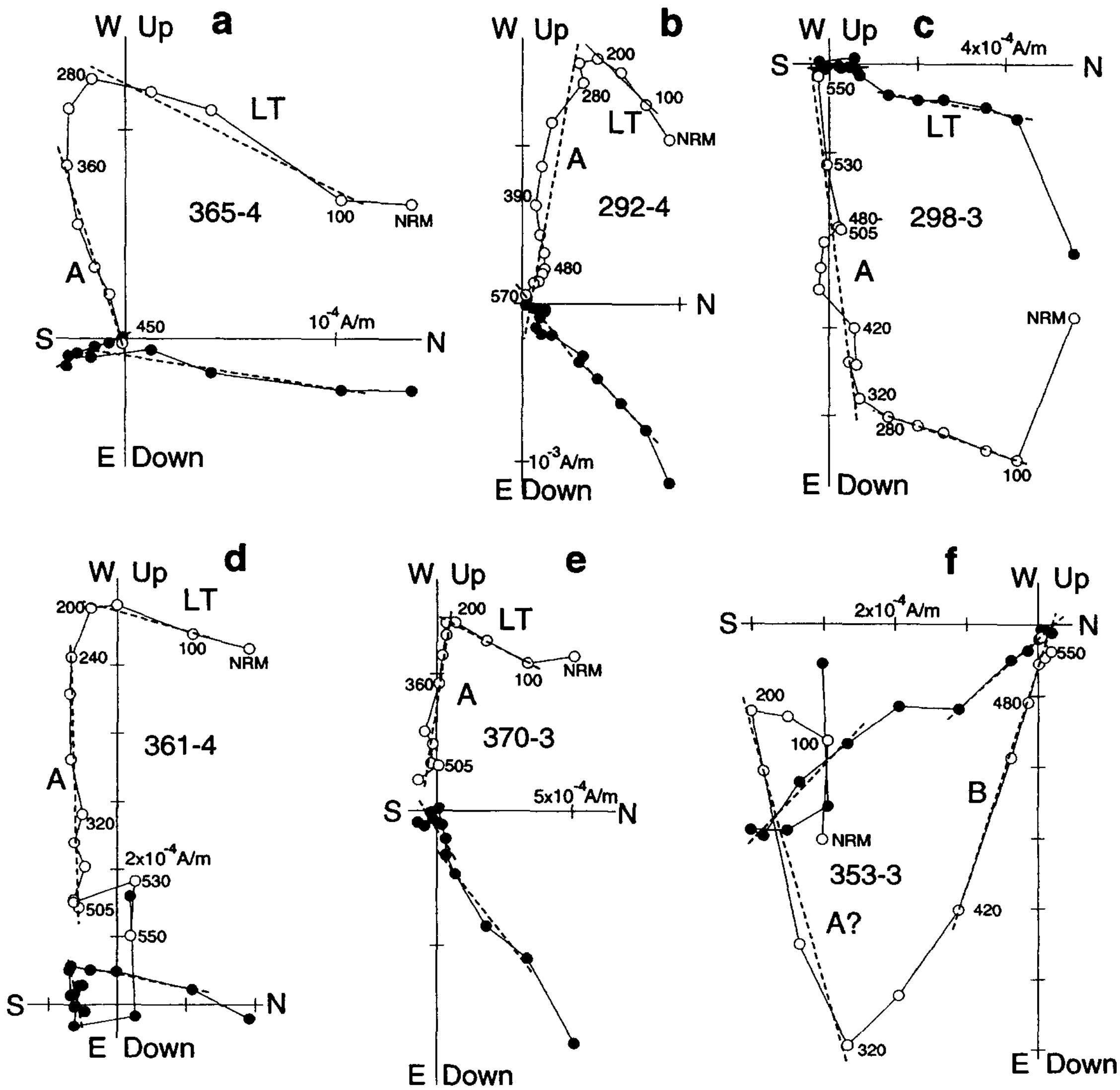

Fig. 4. Representative demagnetization plots from the Moreno and Carmita formations. Dashed lines show the adjustment of linear segments (see text for component labels and explanations). Other notation as in Fig. 2.

PDF direction for the area (Table 1); this component is probably of viscous origin. After removal of component LT, another component (A) was isolated from most samples from sites MO-1–3, -5 and -6. In some cases, it decays to the origin (Fig. 4a, b); usually, however, it does not (Fig. 4c–e), thus implying that

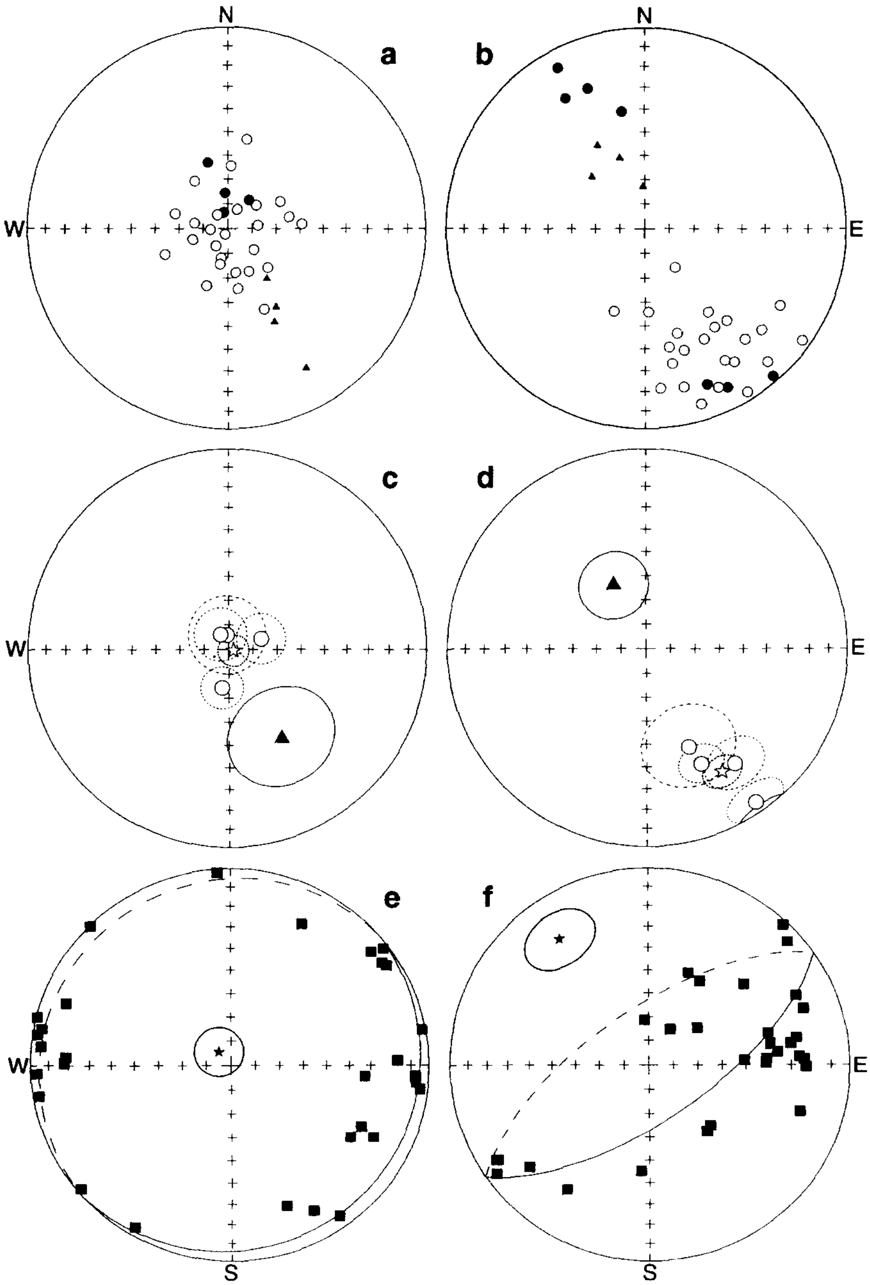

Fig. 5. Equal-area stereoplots of intermediate- to high-temperature components (a–d) and normals to remagnetization circles (e–f) from the Moreno and Carmita formations. (a–b) Sample mean from all sites (○, ●) and component B from site MO-4 (▲). (c–d) Group-mean directions of component A (○) site mean of component B (▲). (e–f) Normals to remagnetization circles. Other notation as in Fig. 3.

still another component may be present. Unfortunately, the measurements often become erratic above 500°C (Fig. 4d) thus preventing further demagnetization.

A somewhat different demagnetization pattern was found at sites MO-4 and MO-7. At the latter, consistent results were obtained for component LT only, whereas components isolated at higher temperatures were chaotic and therefore excluded from further analysis. In contrast, two consistent components were recognized at site MO-4. A component isolated from 200 to 320°C (Fig. 4f), sometimes to 350°C, however, is quite different from the LT directions from other sites but very similar to those of component A from the other sites. Still another component (B) was resolved at this site above 400° (Fig. 4f).

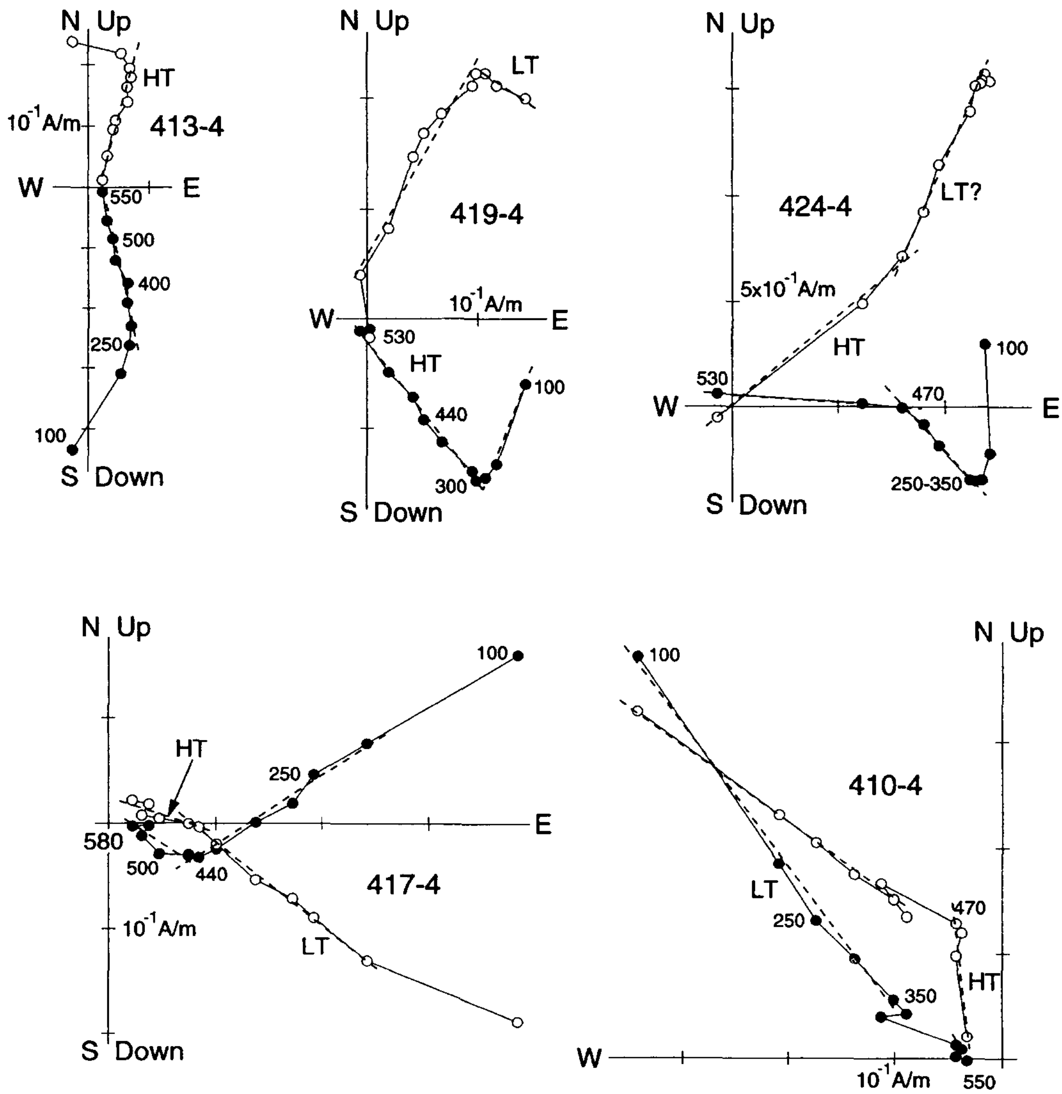

Fig. 6. Representative demagnetization plots of diabases from the El Sábalo Formation. All data are tilt corrected. Other notation as in Fig. 2.

When directions of component A from sites MO-1–3, -5 and -6 and both components from site MO-4 were plotted on the stereonet, most in-situ vectors proved to gravitate to the stereonet pole with the exception of high-temperature component B from site MO-4 (Fig. 5a, b). The intersection of remagnetization circles defines a direction of the least-dispersed component which is close to overall mean of subvertical component (Table 1).

The grouping of the subvertical directions is slightly, but not significantly better in situ than after tilt correction. Bedding attitudes differ considerably within each site, and the fold test (McFadden and Jones, 1981) could not be performed directly. So, all bedding measurements were pooled and then divided into four more compact groups, and the corresponding group means were calculated (Fig. 4c, d; Bazhenov and Shipunov, 1991). Even after this, the calculated statistics are larger than the critical ones thus precluding a definite conclusion on the remanence age. The best data grouping is achieved at 30% unfolding (Table 1), but the improvement of clustering is significant at the 90% level only with respect to the tilt-corrected data. At this stage of analysis, the only conclusion is that the subvertical component A in the Moreno sediments was acquired at the final stages of deformation; to the same effect speaks a better clustering of normals to remagnetization circles in situ than after tilt correction (Fig. 5e, f). This component is reversed in most samples but a few normal directions appear to be almost perfectly antipodal (Fig. 5a). The age of component B cannot be reliably established; it is worth noting, however, that the tilt-corrected directions of component B are close to in-situ directions of component A.

3.3. The El Sábalo Formation

No meaningful results were derived from sediments of this formation because of the NRM erratic behaviour during cleaning. In diabases, NRM intensity decreased several fold after heating to 100°; after that, one or often two components can be isolated in most samples (Fig. 6). With a few exceptions, component directions are consistent at the within-sample level. The scatter, however, is very high at the between-sample level: the LTC component is nearly chaotic with a precision parameter less than 2 both in situ and after tilt correction. The HTC component, though slightly better grouped (Table 1), is also very scattered and can hardly be used for interpretation.

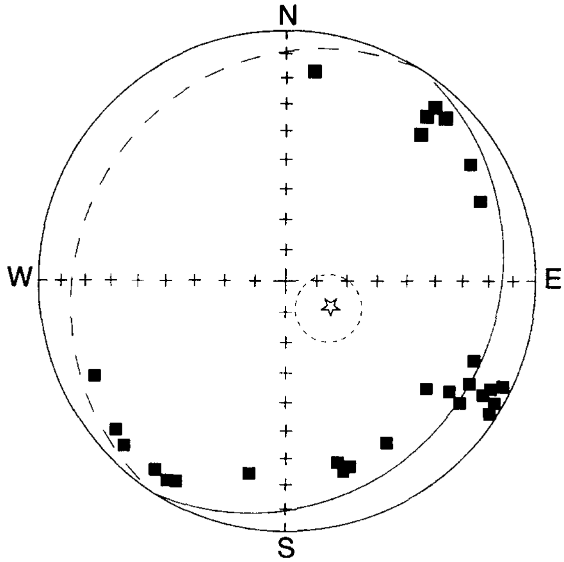

Fig. 7. Equal-area stereoplot of normals to remagnetization circles from the El Sábalo Formation. All data are in situ. Other notation as in Fig. 3.

During thermal cleaning, paleomagnetic directions from 28 specimens from twelve diabase samples out of sixteen studied shifted along remagnetization circles. Surprisingly, the normals to remagnetization circles outline a well-defined planar distribution, thus allowing to determine the direction of the least-dispersed component both in geographic and stratigraphic coordinates (Fig. 7). Due to limited variation of the bedding poles (concentration parameter of bedding poles is 34), the distribution of normals to remagnetization circles remains essentially the same in the both coordinates, and the direction of the least-dispersed component in situ is close to that in stratigraphic coordinates after correction for the mean bedding attitude. Thus we think that the same component was determined in both coordinates. Judging by directions of shift of endpoints along remagnetization circles during treatment, the HT component as indicated in Fig. 6 is of reversed polarity.

We believe that just two components are actually present in the El Sábalo diabases, and at least one of

them has rather well clustered directions as evidenced by converging remagnetization circles (Fig. 7), whereas the other is probably chaotic. The unblocking spectra of these two components, however, are strongly overlapping and very variable. It may be due to strong weathering and lateritization; indeed, the pillow-lava structure could be observed in completely lateritized outcrops of this formation.

3.4. The Encrucijada Formation

No interpretable results were derived from sediments because of weak magnetization and unstable

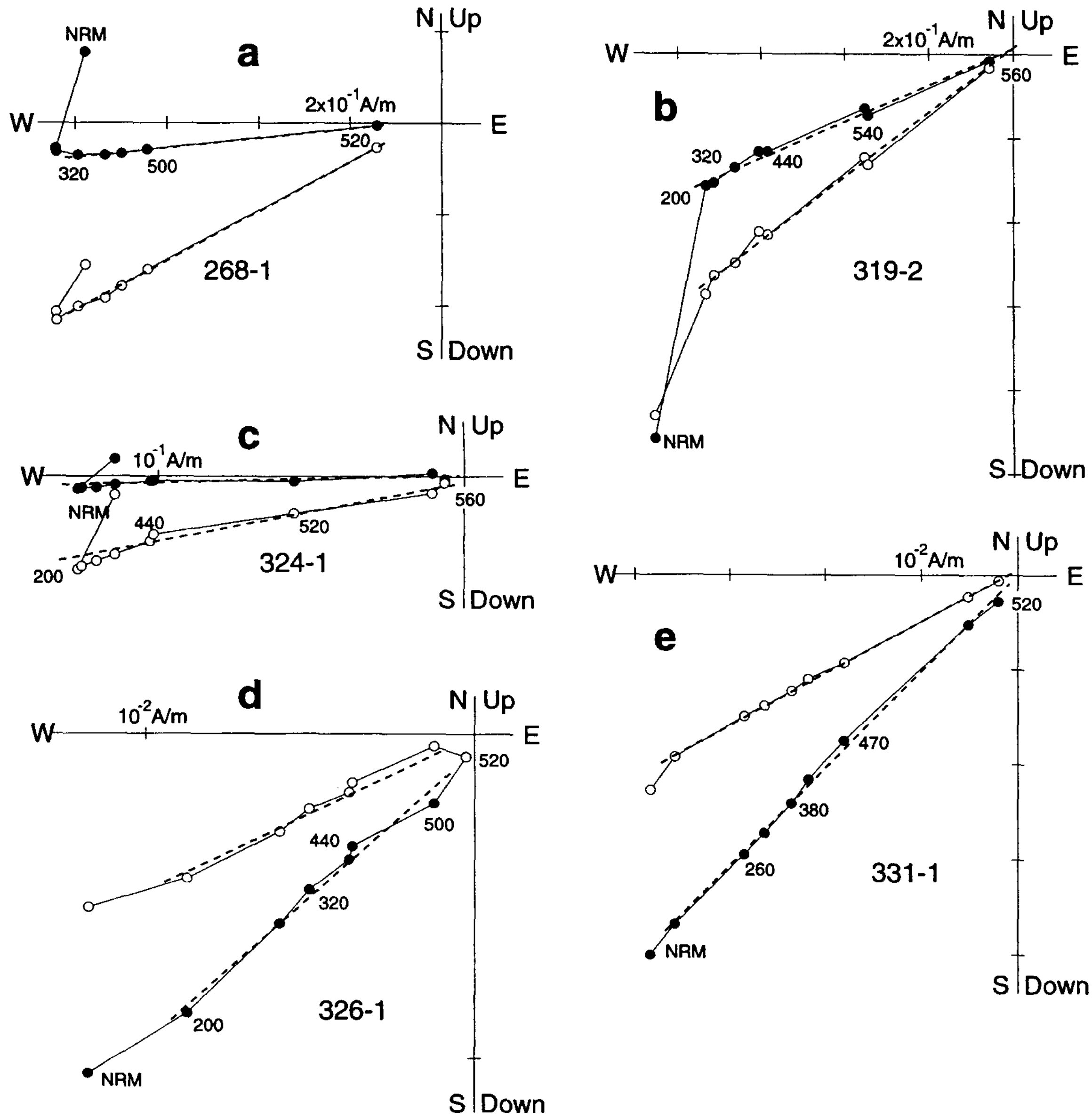

Fig. 8. Representative demagnetization plots of volcanics from the Encrucijada (a–c) and Orozco formations (d–e). All data are tilt corrected. Other notation as in Fig. 2.

Table 2
Mean directions of the characteristic components from volcanics of the Bahia Honda zone

S	N	B	In situ				Tilt-corrected			
			D (°)	I (°)	K	a_{95} (°)	D (°)	I (°)	K	a_{95} (°)
Encrucijada Formation										
EN-1 [a]	6/4	304/56	204	32	11	21.6	237	25	11	21.6
EN-2 [a]	10/9	328/67	226	18	21	10.3	250	17	21	10.3
EN-3 [a]	4/4	310/47	199	40	6	28.9	251	36	12	20.8
Mean	20/17		216	27	10	11.0	247	23	14	9.0
$F_{(4,28)} = 2.7$			$f = 2.9$				$f = 1.4$			
Orozco Formation										
OR-2 [b]	10/8	24/28	226	−4	110	4.7	228	22	110	4.7

Other notation is the same as in Table 1.
[a] The entire set of bedding attitudes was divided into three groups.
[b] Two samples of tuffs were rejected.

behaviour during cleaning. NRM intensities in pillow lavas range from 1 to 40×10^{-2} A/m, about 10×10^{-2} A/m on average, and a characteristic component (ChRM) was reliably isolated from the basalts above 200–300°C (Fig. 8a–c). The formation mean is based on basalt samples from seventeen stratigraphic levels combined into three groups with similar bedding attitudes (Table 2; Fig. 9). The fold test after McElhinny (1964) is inconclusive, but the test after McFadden and Jones (1981) points to prefolding nature of the ChRM in basalts (Table 2). The age of deformation is not well constrained but it is probably post-Santonian and certainly pre-Middle Eocene, since all the younger formations in western Cuba are nearly undeformed. All ChRM directions are of normal polarity which agrees with the Aptian–Albian age of the formation.

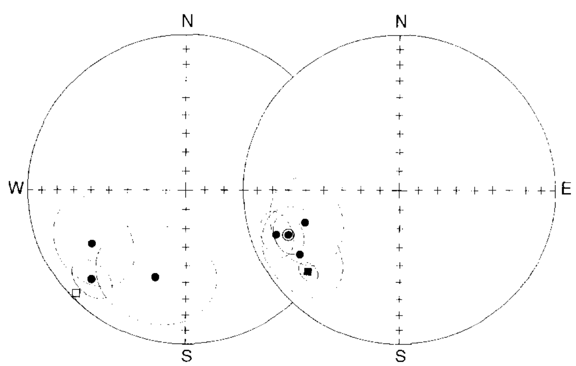

Fig. 9. Equal-area stereoplots of group-mean directions together with confidence circles from the Encrucijada (●) and Orozco (■) formations before (left) and after tilt correction (right). Overall mean for the Encrucijada Formation is shown as encircled dot. Other notation as in Fig. 3.

3.5. The Orozco Formation

Tuffs from site OR-1 proved to be unstable. In contrast, a characteristic component clearly decaying to the origin was isolated from basalts from site OR-2 (Table 2; Fig. 8d, e). The tight clustering of ChRM directions as well as the limited thickness sampled here imply that secular variations were not averaged out (Coe et al., 1985); besides, no field test could be applied. In spite of the small confidence limits associated with the OR mean vector (Fig. 9), the reliability of this result is low.

4. The results from the Sierra de Los Organos and Sierra del Rosario belts: a discussion

When all the data from these belts are considered together, a good agreement of the in-situ mean directions of component V from the Pons limestones, the HT (great circle determination) component in the El Sábalo volcanics and component A from the Moreno rocks is evident (Fig. 10). The agreement becomes even better if one considers the Moreno mean after 30% unfolding. This pattern presumably implies that all three remanences had been acquired either at the

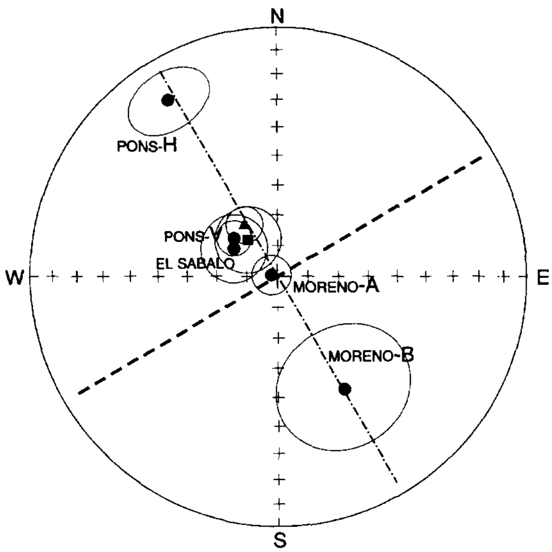

Fig. 10. Mean directions of different components from the Sierra de los Organos and Sierra del Rosario belts. ● are in situ data, ▲ is the mean Moreno-A direction after 30% unfolding, ■ is the Moreno-B mean after 80% unfolding (see text for details). Thick dashed line is the mean strike of structures in western Cuba, whereas the thinner dash-pointed line denotes a plane where compression and extension axes should lay. All data are projected onto lower hemisphere.

final stages of deformation or after it. Component H in the Pons limestones also postdates folding. The acquisition of all components encompassed a considerable time interval as evidenced by the presence of both polarities in the Pons (component H) and Moreno (component A) formations. The Moreno component B data also fit into the pattern if one assumes that this remanence was acquired at an initial stage of deformation; indeed, its mean precisely fits the other data at 80 to 90% unfolding (solid square in Fig. 10).

The main deformation in western Cuba took place in the Eocene; since then, Cuba is regarded as a part of the North American plate. Because the postfolding acquisition was demonstrated or inferred for all the above remanences, the same or a slightly younger age was assumed for these data. For the studied area, the apparent polar wander paths for North America (Van der Voo, 1990; Besse and Courtillot, 1991) predict an inclination of about 40° for the entire Cenozoic. It is immediately clear without computation that neither of the remanences fits the reference data. Unreasonably steep inclinations—that would place western Cuba at the latitude of Greenland or Antarctic Peninsula—as well as the coexistence of flat and steep components in the Pons limestones allows us to rule out any possibility of large-scale movements of western Cuba after the acquisition of the above remanences.

Also extremely unlikely is to attribute the observed pattern to the non-dipole field. A non-dipole contribution should be at least about 50% of the dipole field to account for the observed steep inclination; it also cannot account for the coexistence of two different components in the Pons Formation. Such an anomaly is difficult to match with the almost perfect antipodality of normal and reversed paleomagnetic directions (Fig. 3c and Fig. 4a). Finally, a non-dipole anomaly, being connected with the Earth core, should have dimensions comparable to the depth of the outer core. No reliable data have so far been reported on Paleogene rocks of Cuba, but the results of the same age from Haiti (Van Fossen and Channell, 1988) and Puerto Rico (Van Fossen et al., 1989) did not reveal any inclination anomaly.

The rejection of the two above explanations means that the observed paleomagnetic vectors in situ do not correspond directly to any direction of the ancient geomagnetic field. There appears to be a relation between all the components from the Sierra de Los Organos and Sierra del Rosario belts. Indeed, all paleomagnetic directions seem to be confined to a plane perpendicular to the strikes of the studied structures (Fig. 10). This may imply that remanence acquisition was somehow controlled by deformation, for the directions of maximal compression and extension should also be confined to the plane perpendicular to the trend of structures. If this is the case, the subvertical vectors appear to have been either acquired or re-aligned along the vertical extension axis; component H in the Pons limestones is close to the axis of compression, whereas component B in a few samples of the Moreno rocks is in an intermediate position between these two principal axes. Otherwise, it might be acquired at an early stage of deformation parallel to the other sub-vertical components. On the other hand, a coexistence of different paleomagnetic directions may reflect different orien-

tation of the stress ellipsoid axes at different stages of deformation.

Such a pattern, however, has never been observed either in the field or laboratory experiments (Kligfield et al., 1983; Cogne and Perroud, 1987). The strain hypothesis, however, infers strong internal deformation, but neither cleavage nor other types of internal deformation were observed in either formation. Besides, any internal deformation could hardly be so uniform as to result in close agreement of paleomagnetic directions from the sections about 100 km apart. Anisotropy of magnetic susceptibility might have been of help for testing the strain hypothesis; unfortunately, these sediments are very weakly magnetized, and AMS measurements could not be performed. Nevertheless, the hypothesis that observed pattern of paleomagnetic directions is related to the deformational process cannot now be discarded.

In principle, it is possible that the studied formations were tilted after thrusting and folding and acquisition of remanence because the precise position of a rock mass with respect to the paleohorizontal is unknown for a postfolding component. Actually, tilt correction does shift the Moreno and El Sábalo remanences to more "reasonable" intermediate inclinations (about 40°). Moreover, it does not contradict the above conclusion on the postfolding age of magnetization, because minor variations in the bedding of the Moreno Formation may in fact be older than the general northward tilt, whereas the El Sábalo volcanics are essentially monoclinal. The magnitude of the required tilt is about 30° northward. Some geological data also favour post-remagnetization tilt (e.g., stronger uplift of the Sierra de los Organos belt compared to the Sierra del Rosario belt, and the continuing compression during the post-Middle Eocene uplift of the cordillera (Pszczolkowski, 1994).

It is more difficult, however, to fit the Pons data into this pattern. First, this formation is exposed on two gentle-dipping limbs of a fold with NE–SW-striking horizontal fold axis. A large tilt after folding and remagnetization would have resulted in a structure more complex before this tilt than after it, which is unlikely. Second, the component H data remain unaccounted for. Nevertheless, at this time, we cannot definitely either prove or rule out the post-remagnetization tilt hypothesis.

5. Tectonic implications of the data from the Bahia Honda zone

The results from the Encrucijada (EN) and Orozco (OR) formations from the Bahia Honda zone appear to be mutually consistent (Fig. 9): the tightly clustered OR vectors fall within the more diffuse EN data, though the corresponding means are significantly different in declination. The ChRM in the Encrucijada volcanics is shown to predate deformation. The EN and OR means before and after tilt correction are far away from either the present-day field or the previously discussed postfolding components from the zones to the south. The normal polarity of the observed ChRM's agrees with the age of these rocks and the ChRM acquisition during the Cretaceous quiet interval. Therefore, the ChRM's in the Encrucijada and Orozco formations are at least pre-Middle Eocene in age and probably primary.

We compared our data with the apparent polar wander path for the North American plate (Van der Voo, 1990; Besse and Courtillot, 1991) and computed flattening, F, rotation, R, and their confidence limits as suggested by Demarest (1983). The EN and OR mean inclinations are shallower than the reference inclinations, although the confidence interval of the former slightly overlaps that of the reference curve (Fig. 11). Also shown here is the Late Cretaceous result from the island-arc Zaza terrane of central Cuba (Renne et al., 1991; Chauvin et al., 1994) which is consistent with our data and also shallower than the reference data. Because of difference in ages of these three results, it is difficult to precisely calculate the F value and its confidence limits. As an approximation, the F value is about 15–20°.

This observed pattern is important in two relations. First, it is robust with respect to remanence ages: even assuming an Eocene age for the remanence in these Cretaceous rocks leaves the inclinations shallower than the reference ones, though the F value diminishes. Second, it cannot result from erroneous tilt corrections, since the in-situ inclinations from western (Table 2) and central (Chauvin et al., 1994) Cuba are close to or shallower than the tilt-corrected ones.

Thus we come to the conclusion that the calculated F value represents a northward transport of the

volcanic domains of Cuba by about 1000 km (the main domains are shown in Fig. 12). Since western and central Cuba was almost inactive tectonically except for vertical and strike-slip movements since the Middle Eocene (Iturralde-Vinent, 1977; Hatten et al., 1989), the movement can not be younger. The convergence and collision of the volcanic domains with the northern zones of Cuba, which are commonly regarded as a North American passive margin, is the cause of the Eocene tectonism (e.g., Hatten et al., 1989).

Paleomagnetic declinations in western and central Cuba are strongly deflected westward with respect to the reference data (Fig. 11), the R values being $89 \pm 12°$ and $108 \pm 8°$ for the Encrucijada and Orozco results, respectively. This counterclockwise rotation is not local since similar results are from two localities about 20 km apart. The Late Cretaceous mean direction from central Cuba (Renne et al., 1991; Chauvin et al., 1994) represents a counterclockwise rotation of $37 \pm 11°$ for the island-arc Zaza terrane. The difference between the more reliable EN mean declination and that from the Zaza terrane is $52 \pm 12°$. Tectonic trends measured as the strikes of major faults differ by 50–60° between central and western Cuba (Fig. 12). The close fit of both the senses and values of structural and declination differences strongly implies an oroclinal bending of Cuba. Since the Eocene, the boundary between the Caribbean and North American plates has moved to the south of the island and thus a younger age of bending is unlikely; however, it may be older.

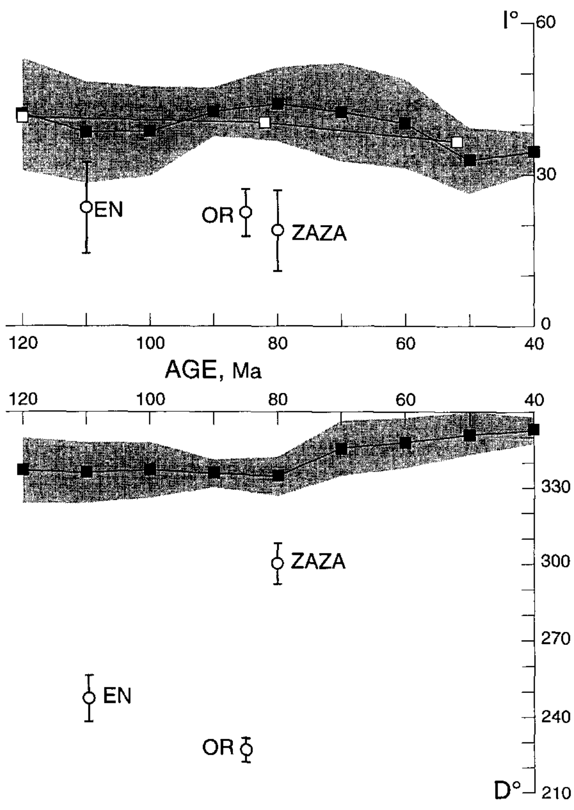

Fig. 11. Plots of inclination I (°) (top) and declination D (°) (bottom) versus age for the results from Cuba and reference data. ○ = paleomagnetic results with associated error bars— EN = Encrucijada Formation, OR = Orozco Formation, ZAZA = mean direction on volcanics from central Cuba (Chauvin et al., 1994); ■ = reference data recalculated from Besse and Courtillot (1991) with the confidence region as shaded area; □ = reference inclinations recalculated from Van der Voo (1990).

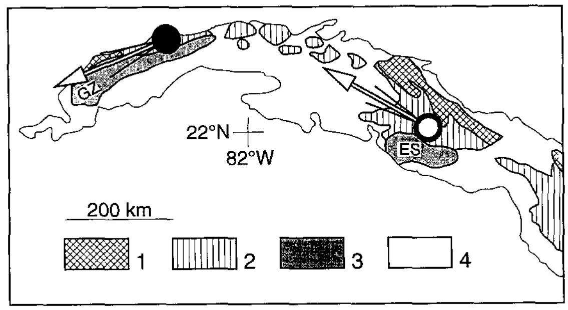

Fig. 12. Tectonic scheme of western and central Cuba with mean declinations from the Encrucijada Formation of the Bahia Honda zone (●) and Cretaceous volcanics from the Zaza terrane (○). 1 = northern sedimentary domain; 2 = central volcanic domain; 3 = southern sedimentary and metamorphic domain (GZ = Guaniguanico zone, ES = Escambray massif); 4 = post-Eocene cover.

Our few paleomagnetic results are clearly insufficient, and much more data are needed to better understand the tectonic evolution of Cuba and the entire Caribbean region. We just hope that this description of our numerous failures and few successes (?) may be of a help in the future.

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