Palaeomagnetic evidence for local and regional post-Eocene rotations in northern Mexico

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SUMMARY

122 oriented core samples were collected from folded Lower Cretaceous units at four localities in the Sierra Madre Oriental Mountains near Torreon, northeast Mexico. Palaeomagnetic analyses of these samples identify a stable synfolding remanence at three localities that was acquired during the Laramide Orogeny (Eocene). The fourth locality exhibited a post-folding or late-synfolding remanence. Each locality has undergone a regional rotation and at least three localities have undergone local rotations since remanence acquisition. By examining the relationships between the apparent polar wander paths for North America and Mexico, pole positions generated by this study and observed structural trends, it has been possible to evaluate the different contributions of local versus regional rotations and to calculate a least-locally-rotated Eocene pole position for the Torreon region. This pole (Lat. = 69.9°N, Long. = 172.8°E, n = 27, k = 30, α95 = 5.2°) agrees well with a published Mexican Eocene pole position for a locality located 450 km north-northwest of the present study area. On the basis of this information, we conclude that a large fragment of northern Mexico has undergone a 10°-15° post-Eocene counterclockwise rotation with respect to the rest of North America, in agreement with the model proposed by Urrutia-Fucugauchi (1981).

Key words: folding, Mexico, palaeomagnetism.

INTRODUCTION

Geological and geophysical data suggesting major Mesozoic and Cainozoic movements (rotations, translations, deformation, etc.) of all or parts of Mexico with respect to the rest of North America have been presented by several authors (e.g. Filmer & Kirschvink 1989; Longoria 1985; Urrutia-Fucugauchi 1981; Gose, Belcher & Scott 1982; Anderson & Schmidt 1983; and others). The extend and timing of these movements play a critical role in any comprehensive model for the tectonic development of the Gulf of Mexico, the western United States, central America and the Caribbean Sea. It is therefore important to carefully and accurately document these motions in order to constrain such models. In the case of northern Mexico, the evidence for Cainozoic movements has not been as compelling as that for Mesozoic movements and consequently there is still considerable debate over the amount and timing of any post-Cretaceous movement. Much of the evidence for large scale, early Mesozoic movements in northern Mexico comes from palaeomagnetic studies (e.g. Gose et al. 1982). The major difficulties involved in interpreting such data lie in distinguishing regional events involving large scale (i.e. hundreds of kilometres) crustal blocks from local, small-scale rotations, and in placing reliable age constraints upon the timing of remanence acquisition. The detailed study of the Cupido Limestone in Arteaga Canyon (Kleist, Hall & Evans 1984), for example, convincingly demonstrated that a major fraction of observed declination anomalies may be related to local scale deformation. On the other hand, Urrutia-Fucugauchi (1981) presented palaeomagnetic evidence interpreted to indicate a post-Eocene tectonic rotation of major parts of northern Mexico with respect to North America. It therefore appears likely that many of the rotations reported by various authors include both local and regional components of motion.

To distinguish regional from local movements and to determine the timing of such movements, we have undertaken a detailed palaeomagnetic study of localities in the Sierra Madre Oriental near Torreon. The localities were selected to lie on structural trends with different orientations so as to provide a means with which to test for local-only or local-plus-regional movements. Localities geographically...
separated from one another by significant distances (4–60 km) were used to identify rotations common to all localities that could be attributed to regional events. Additionally at all localities, we were able to carry out a fold test to help constrain the timing of acquisition of stable remanence.

GEOLOGIC AND TECTONIC SETTING

The Sierra Madre Oriental has been described by Wall, Murray & Diaz (1961) as a tectonic belt trending in a north–northwesterly direction from the Isthmus of Tehuantepec to the City of Monterrey in Nuevo Leon. At Monterrey, the fold belt bends sharply to the west making an almost right angle turn and continues along a westerly trend until it reaches the vicinity of Torreon where it turns again to the north–northwest (see Fig. 1a). While some authors believe that the Sierra Madre Oriental dies out a short distance northwest of Torreon (Weidie, Wolleben & McBride 1970), others suggest that it continues in a north–northwesterly direction to the Rio Grande (Wall et al. 1961).

As described by Humphrey (1956) the structural patterns and types in northeast Mexico are largely the product of the early Tertiary (post-Palaeocene–pre-upper Eocene) Laramide Orogeny. During the strongest phases of the orogeny, the Mesozoic units of northeast Mexico were variously deformed according to the position of their depositional areas with respect to the previously existing early upper Jurassic palaeogeographical elements (Fig. 1a). Variations in the trend of the Sierra Madre Oriental fold belt can therefore be attributed to the shape of the Coahuila and Tamaulipas Peninsulas against which the Mesozoic strata of the Mexican Sea were buttressed by Laramide compressive forces acting from the southwest (Charleston 1981).

For the most part, the Sierra Madre Oriental comprises deformed Mesozoic units, with a majority of the topographic high ground being formed by massive Cretaceous limestones (de Cserna 1956). The generalized stratigraphic column for the Cretaceous in the vicinity of Torreon (Fig. 2) shows the three units sampled in the present study. The Barremian–Aptian Cupido Limestone (Wilson 1977) was sampled at two locations, while the Albian Aurora Limestone (Young 1977) and the medial Albian–early Cenomanian Cuesta del Curá Limestone (Ice & McNulty 1980) were sampled at one location each.

All four sampling localities were situated south or southwest of Torreon (Fig. 1b) in an area where the structural trend of the orogenic belt changes from essentially east–west to predominantly north–northwesterly. Since mesoscopic anticlines were exposed at localities 1, 2 and 4, the opposing limbs at these localities were sampled at stratigraphic horizons which were approximately equivalent. Locality 3 was mapped as an overturned anticline (de Cserna 1956) but could not be directly observed as such in the outcrop. Consequently, the degree of precision with which stratigraphic equivalence could be determined in the opposing limbs of locality 3 was substantially less than for the other three localities. With the exception of locality 4, the amount of plunge observable at the sampling localities did not exceed 4°. Therefore, only at locality 4 was plunge considered to be a significant factor in making geometric reconstructions. Table 1 provides additional information about each of the sampling localities.

Since the primary goal of the study was the solution of structural problems, the major consideration in the selection of the spacing between consecutive samples was to allow for the sampling of a sufficient overall age interval to average out the effect of secular variation. After considering the potential range of limestone depositional rates a sampling interval of between 0.3 and 1.0 m was considered satisfactory. Consequently, samples were collected approximately 0.5 m apart with minor variations as needed to avoid severely fractured or weathered intervals. For each locality, sampling was conducted at one site on either limb of the anticline.

RESULTS

Initial analysis involved the progressive demagnetization of groups of pilot specimens from all four localities in small increments using standard thermal and alternating field procedures. Based on the results of this initial analysis and subsequent experimentation, it was determined that a combination of thermal (to 200°C) and alternating field (to 300 Oe) demagnetization was the most effective method of isolating the various components of NRM present in the remaining samples from localities 1 and 2. Thermal
demagnetization alone was judged to be the most effective method for the remaining samples from localities 3 and 4. A summary of laboratory methods used and the results obtained is provided by Table 2. Demagnetization response to optimum demagnetization procedures is illustrated in Fig. 3.

Examination of the demagnetization data indicated that the magnetizations identifiable for the western limb of locality 2 and for both limbs of locality 1 were effectively isolated by certain discrete demagnetization steps. The characteristic remanent magnetization for samples obtained from these localities was therefore defined by the magnetization measured after optimum demagnetization. In contrast, the range of stability of the identifiable components for the eastern limb of locality 2 and both limbs of localities 3 and 4 were more distributed and could only be isolated over ranges of demagnetization steps which varied to some extent from specimen to specimen. As a consequence, demagnetization data from the eastern limb of locality 2 and both limbs of localities 3 and 4 were examined with principal component analysis (Kirschvink 1980) in order to more precisely determine remanent directions.

Magnetizations were identified in samples from all four localities which exhibited stability of a range of demagnetization steps. These magnetizations may have been acquired at any time since deposition in the Early Cretaceous, i.e. prior to, during or subsequent to deformation of the rocks. To place greater constraints on the possible age of remanence, the stable directions were computed with and without a tectonic tilt correction. A mean magnetization direction was calculated for each limb of the fold at each of the different localities and the effect on this direction of untilting the limb about the local strike and dip direction was determined. It is clear from this exercise that the mean directions from each limb of localities 1, 2 and 3 do not coincide either in situ or when fully untilted. Rather the directions display a ‘cross-over’ relationship in which they coincide with one another at some intermediate position where the limbs retain some degree of opposing tilt (Fig. 4). In the case of locality 4, the cross-over relationship

Figure 1. (b) Location of sampling localities in relation to local and regional structural trends within the study area. Since the area shown lies within the Sierra Madre Oriental Fold Belt, local structural trends are defined by the orientation of individual anticlinal axes while regional trends are defined by the general orientation of the fold belt. Deformation within the fold belt is the result of Laramide compressive forces which acted from the southwest to the northeast (Charleston 1981). Although thrust faults were observed in the field and reported in the literature (de Cserna 1956; Kellum 1936), the limbs of the folds sampled were not fault separated. Modified after McIeroy & Clemons (1965).
is also present, however, optimum agreement occurs with only a small amount of tilt correction and this optimum agreement is only slightly better than the in situ case. A number of possible mechanisms that can produce such a cross-over geometry have recently been discussed by Hudson, Reynolds & Fishman (1989). These mechanisms include situations where the magnetizations on either limb differ in age (i.e. pre, post and synfolding components), where there has been structural modification of the rock material including the effects of pressure solution, and/or the mechanical rotation of individual magnetized grains, and where the magnetization of both limbs is acquired at the same time during folding (i.e. simple synfolding). A careful analysis of folding geometry and structural style was carried out in order to determine which of these possible mechanisms is the most likely cause of the observed cross-over relationship.

If one limb of a fold was magnetized prior to folding, then the tilt-corrected magnetization direction should correspond to a position on the apparent polar wander path (APWP) for North America (or Mexico) that lies between the age of deposition (Early Cretaceous) and the initiation of folding in the region in the early Tertiary (Palaeocene/Eocene). On the other hand, if the magnetization of one limb was acquired after folding was complete, then the in situ directions should correspond to pole positions subsequent to deformation at the locality (i.e. late Eocene to the present). We have examined both in situ and tilt-corrected pole positions for each limb of the folds at localities 1, 2 and 3 and find that none of these pole positions coincides with either APWP for the time intervals involved. A possible explanation for this lack of correspondence may be that, during deformation, the folds have undergone rotations about a vertical axis. Accordingly we have calculated the amounts of rotation necessary to bring the individual limb directions (both pre- and post-folding) into coincidence with the appropriate parts of the APWPs. In several cases, because of the paleolatitudes involved, no amount of rotation about a vertical axis will produce correspondence between locality poles and the APWPs. In others, the amount of rotation required is large (up to maximum of 78°) and is commonly in opposite senses for each limb of an individual fold, a situation that can only be explained in terms of multiple, sequenced clockwise and counterclockwise rotations. Finally, restoring the azimuth of the fold axis at each locality using such rotations produces a series of folds with trends that are radically different from one

Table 1. Summary of sampling localities.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Location</th>
<th>Unit Sampled/Age</th>
<th>Lithology</th>
<th>Structure</th>
<th>Plunge</th>
<th>Strike</th>
<th>Dip</th>
<th>Samples Drilled</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sierra Graceros - 50 km SW of Torreon - 103°46'W, 23°16'N.</td>
<td>Cupido/Barremian - Aptian (Wilson, 1977).</td>
<td>Thick to massive beds (1-5 m) of bioclastic micrite separated by thin shales and shaley bioclastic micrites. Total thickness - 620 m.</td>
<td>Anticline - axis trends N4⁰E.</td>
<td>3°NE</td>
<td>East Limb</td>
<td>N2⁰E</td>
<td>2⁰E</td>
</tr>
<tr>
<td>2</td>
<td>Sierra Melato (Rosario) - 50 km SW of Torreon, 4 km E of locality 1 - 103°46'W, 23°16'N.</td>
<td>Cupido/Barremian - Aptian (Wilson, 1977).</td>
<td>Thick to massive beds (1-5 m) of bioclastic micrite separated by thin shales and shaley bioclastic micrites. Total thickness - 620 m.</td>
<td>Anticline - axis trends N15°W.</td>
<td>0°</td>
<td>East Limb</td>
<td>N15°W</td>
<td>5°E</td>
</tr>
<tr>
<td>3</td>
<td>Sierra Espana - 25 km S of Torreon, 30 km ENE of localities 1 &amp; 2 - 103°30'W, 23°18'N.</td>
<td>Aurora/Aptian - Aptian (Young, 1977).</td>
<td>Thick to massive bedded (1-3 m) resistant dolomitized bioclastic micrites and wackestones with a large amount of nodular chert. Total thickness - 21 to 46 m.</td>
<td>Overturned anticline - axis trends N34°W.</td>
<td>4°SE</td>
<td>Northeast Limb</td>
<td>N25°W</td>
<td>30°SW</td>
</tr>
<tr>
<td>4</td>
<td>Sierra Piedra Blanca - 65 km SSE of Torreon, 60 km ESE of localities 1 &amp; 2, 45 km SSE of locality 3 - 103°15'W, 24°39'N.</td>
<td>Cuesta del Cura/Medial Albion - Early Cenomanian (Ice and McPInley, 1980).</td>
<td>This to medium beds (15-75 cm) of bioclastic packstones and wackestones with thin shale interbeds. Total thickness 62 to 150 m.</td>
<td>Anticline - axis trends N8⁰E.</td>
<td>13°NE</td>
<td>North Limb</td>
<td>N8°PE</td>
<td>23°N</td>
</tr>
</tbody>
</table>

* Plunge could not be directly measured in the field. Plunge indicated was calculated from strike and dip measurements assuming cylindrical folding.
** Plunge directly measured in the field.
Table 2. Summary of laboratory methods and results.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Thermal Demag</th>
<th>AF Demag</th>
<th>RM Rem</th>
<th>Thermal-Magnetic Analysis</th>
<th>Magnetic Components/Magnetic Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locality 1</td>
<td>A distinct component was removed by low temperature demagnetization (10°C to 25°C). A total loss of directionality and NRM intensity occurred at 250°C.</td>
<td>Demagnetization in low fields (10°C to 100°C) effectively removed a distinct component. Stable decay was observed between 150°C and 999°C.</td>
<td>All specimens showed a rapid intensity increase between 0 and 150°C followed by a gradual increase from 150°C to 25°C.</td>
<td>Increase in demagnetization observed at 450°C. Increased in remagnetization intensity at 250°C to 400°C and at 500°C to 550°C.</td>
<td>Recent overprinting carried by goethite (Neel Temperature 100°C - 120°C, alters to hematite at 200°C to 400°C). Stable syngenic component carried by hematite whose blocking temperature spectrum has an upper limit of 500°C to 550°C.</td>
</tr>
<tr>
<td>Locality 2</td>
<td>A distinct component was removed by low temperature demagnetization (150°C to 250°C). A total loss of directionality and NRM intensity occurred at 600°C.</td>
<td>Stable decay of NRM intensity from 0 to 999°C with little directional change.</td>
<td>All specimens responded the same as those for locality 2 except specimens 15E which showed a continual intensity increase to max field.</td>
<td>Specimens 15E maintained significant intensity through demagnetization step 700°C and had remagnetization intensity changes at 130°C, 350°C, and 650°C. All other specimens experienced remagnetization intensity increases at 200°C.</td>
<td>Complex magnetic mineralogy in which goethite, hematite and, in some specimens, magnetite probably contributed to NRM. Recent overprinting carried predominantly by goethite, stable syngenic component probably carried by hematite which has a blocking temperature spectrum with an upper limit between 550°C and 600°C. Hematite may also have contributed to the NRM of a small number of samples.</td>
</tr>
<tr>
<td>Locality 3</td>
<td>A distinct component was removed by thermal demagnetization at temperatures generally between 135°C and 400°C. Most specimens that exhibited a stable demag behavior lost stability between 550°C and 600°C.</td>
<td>Half the pilot specimens exhibited either no directional change or unstable decay of NRM. In the remaining specimens, a distinct component was removed by cleaning in low fields (100 to 200°C) and a stable decay was observed from 200°C to 999°C.</td>
<td>Two specimens exhibited rapid intensity increase to 1000°C followed by more gradual increases to max field.</td>
<td>Demagnetization curves of all specimens were characterized by gradual but continual intensity decrease to 650°C or 700°C. Remagnetization intensity increases were observed at 130°C to 250°C and at 650°C.</td>
<td>Recent overprinting carried by goethite. Stable syngenic component carried by hematite which has a blocking temperature spectrum which largely overlaps that of the syngenic component was recognized in a few specimens but is considered poorly defined.</td>
</tr>
<tr>
<td>Locality 4</td>
<td>A distinct component was removed by low temperature demagnetization (150°C to 200°C). Most specimens which exhibited stable demag behavior maintained that stability to between 655°C and 660°C. Two specimens became unstable after the 375°C heating step and one specimen (3L 5A) became unstable at 500°C.</td>
<td>All specimens subjected to AF cleaning were either unaltered by the process or exhibited unstable demag response.</td>
<td>All specimens exhibited gradual increase through max field.</td>
<td>Significant intensity was maintained in all specimens through demag steps 600°C. A rapid intensity loss occurred between 600°C and 700°C in all specimens. Remag intensity increases were observed at 150°C.</td>
<td>Recent overprinting carried by hematite. Stable post-folding or late remanence carried by hematite which blocking temperature spectrum had an upper limit of 635°C to 660°C.</td>
</tr>
</tbody>
</table>

Procedures:
- **Thermal Demag.** For all localities thermal demagnetization was performed on pilot specimens with heating steps of 15°C (100°C for locality 1), 200°C, and 250°C - 700°C in 50°C increments. The main suite of specimens for locality 3 (heating steps - 150°C: 250°C; 300°C: 660°C in 25°C increments) and locality 4 (heating steps - 150°C - 500°C in 50°C increments; 500°C - 600°C in 35°C increments; 615°C; 630°C, 645°C, 650°C, 655°C, 660°C) was also thermally demagnetized.
- **AF Demag.** For all localities AF demagnetization was performed on pilot specimens with cleaning steps of 10°C, 25°C, 50°C, 100°C, 150°C, 200°C to 100°C increments, and 999°C.
- **RM Rem.** For specimens from each locality were subjected to a magnetic field of known strength and then measured in the magnetometer. The procedure was repeated for progressively stronger magnetic fields to the maximum available field of 6925 Oe.
- **Thermal-Magnetic Analysis.** Four specimens from each locality were magnetized in the strongest available field (6925 Oe), measured, thermally demagnetized, measured, and remagnetized. The procedure was repeated for heating steps of 100°C, 150°C, and 200°C - 700°C in 50°C increments.

another—a situation rarely observed in fold belts. It is clear from these results that it is extremely unlikely that the cross-over geometries observed at localities 1, 2 and 3 are the result of magnetizations acquired pre- and post-folding.

In order for our cross-over magnetization to be the result of pressure solution effects or the mechanical rotation of grains, rocks within the study area would have to have been subjected to a relatively intense deformation. The structural style of the Sierra Madre Oriental in general and the study area in particular is characterized by open folds and overturned anticlines which are suggestive of deformation of an intensity which is not nearly sufficient to produce such effects. We conclude therefore, that the observed cross-over geometry is the result of simple synfolding magnetization in the case of localities 1, 2 and 3 and postfolding or late synfolding magnetization in the case of locality 4. We now proceed to examine the various ways in which the folding may have taken place.

To determine the fold correction required for each limb, two models, consistent with the style of folding present in the study area, were used to progressively 'unfold' the asymmetric anticlines. For each model, a palaeomagnetic pole and associated k value was calculated for each progressive unfolding step. The unfolding step yielding the maximum k value was considered to signify, for each model, the position of the limbs of the fold at the time of remanence acquisition.

The first model assumes that the more steeply dipping limb of the anticline was continuously folded at a higher rate than the more gently dipping limb. As a consequence, this model unfolded each limb in progressive steps which represented percentages of the total folding correction. The second model assumes that both limbs of the anticline were folded at the same rate until the more gently dipping limb reached its total displacement from the horizontal. The model then assumes that the limb with the steeper dip remained unchanged. Progressive unfolding in accordance with the second model was performed by correcting only the more steeply dipping limb until both limbs were symmetrical. At this point, both limbs were progressively unfolded to the horizontal in equal amounts.
Figure 3. Vector demagnetization/intensity plots for representative specimens. (a) Locality-1 west specimen XB; (b) locality-2 west specimen 16A; (c) locality-3 NE specimen 4A; (d) locality-4 north specimen 6A.
Although both models yielded the same maximum $k$ value for each individual locality, when the results from all localities were analysed as a group, the second model produced inconsistencies not present in the results of the first model. These inconsistencies are briefly described as follows:

(1) Assuming that northern Mexico has not rotated with respect to North America since the Laramide (Eocene—Humphrey 1956) deformation, the poles for localities 1 and 2 calculated using the second unfolding model can only be brought into coincidence with the Eocene pole for North America by rotating locality 1 counterclockwise and locality 2 clockwise about vertical axes. Since these two localities are separated by just 4 km, it is difficult to understand how one could be rotated clockwise and the other counterclockwise.

(2) Assuming that northern Mexico was rotated relative to North America subsequent to the Eocene as suggested by Urrutia-Fucugauchi (1981), poles calculated for the second unfolding model would require large rotations about vertical axes for localities 1 and 2 and little or no rotation of locality 3. Locality 3 occupies a transitional position between major north–south and east–west trends of the fold belt and has been subjected to more intense folding (eastern limb overturned) than any of the other localities. Thus, locality 3 is much more likely to have undergone a large local rotation than locality 1 or locality 2.

Because of these and additional inconsistencies involving the analysis of the pole calculated for locality 4, the second unfolding model was rejected. Consequently, only results derived from the simple percentage unfolding (Figs 4 and 5) are considered further.

Specimens from all 30 samples collected at locality 4 were subjected to thermal demagnetization with progressive...
Figure 5. Equal-area projections showing magnetic directions (optimum demagnetization) in geographic coordinates and with optimum-fold correction (i.e. $k$ maximized). (a) Locality 1. (b) Locality 2. (c) Locality 3. (d) Locality 4.
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Figure 5. (Continued)
segments as small as 5 °C. Despite this cautious approach, a stable remanence was observed in only 11 specimens. Of these 11, seven gave a well-grouped normal polarity direction, three gave a reversed polarity direction nearly antipodal to the normal direction, and one gave a reversed value appearing to belong to an altogether different population (this specimen, southern limb specimen 5A, had a different demagnetization path and a substantially lower blocking temperature than the other 10 results). Although the presence of antipodal normal and reversed magnetizations is sometimes interpreted as evidence of primary magnetization, progressive fold correction of the antipodal locality four directions resulted in only minor k values increases with small amounts of unfolding (10 per cent) followed by progressively lower k values as the antcline was further unfolded (Fig. 4d). We interpret these data to indicate that the locality 4 remanence was not acquired during deposition but was, at the earliest, acquired during the later stages of folding.

DISCUSSION

Illustrated in Fig. 6 are synfolding poles for localities 1, 2 and 3, the pole for the locality 4 in situ data, the Aptian to Paleocene segment of the APWP for North America, and the Late Jurassic–Early Cretaceous to Paleocene segment of the APWP for Mexico. Although the two APWPs show considerable divergence for poles earlier than the Eocene, it should be noted that the Mexican poles are based on only a small number of palaeomagnetic studies. Consequently, it is not yet clear whether this divergence is entirely the result of folding.

Figure 6. Palaeomagnetic poles (shown in boxes) for the synfolding magnetization at localities 1, 2 and 3, calculated using percentage unfolding (model 1) and the locality-4 in situ magnetization. Changes in pole position in response to the rotation of locality 1 (counterclockwise) and locality 3 (clockwise) about vertical axes are represented by open circles. Change in the locality-4 pole in response to the rotation of locality 4 about a horizontal axis perpendicular to observed plunge is represented by solid circles. (Each successive circle represents a rotation of 5°.) North American APWP—Albian (100 Ma): Globerman & Irving (1988); other poles: Piper (1987). Mexican APWP—Eocene: Urrutia-Fucugauchi (1981); other poles: Urrutia-Fucugauchi (1979).

As mentioned previously, poles obtained for localities 1, 2 and 3 are associated with a synfolding magnetization while the pole for locality 4 represents a post-folding or late synfolding magnetization. Deformation observed in the study area is confined to the post-Paleocene to pre-upper Eocene (an interval of approximately 15–20 Ma.) (Humphrey 1956). More recently, Tardy (1980) indicates the age of deformation to be Thanetian–Ypresian (an interval of approximately 8–10 Ma). The three synfolding poles can therefore be assigned a latest Paleocene or Eocene age, while the age of the locality 4 pole must be Eocene or younger (Table 3).

Considering first the synfolding poles, Fig. 6 shows that the locality 1 pole lies close to the Paleocene–Eocene segment of the North American APWP while the locality 2 pole agrees well with the Eocene–Oligocene segment of the Mexican APWP. Changes in the position of the locality 1 pole in response to counterclockwise rotation of locality 1 about a vertical axis is represented in Fig. 6 by a series of small open circles (each circle represents a rotation of 5°). Because the track of open circles defining the locality-1 rotation passes through the locality-2 pole, the discrepancy between the locality-1 and locality-2 poles can be completely accounted for by either a counterclockwise rotation of locality 1 with respect to locality 2 or a clockwise rotation of locality 2 with respect to locality 1 of 10°–15°. As the locality-2 anticlinal axis is offset some 19° to the west of that of locality 1, the rotations necessary to make the two poles coincident are consistent with both the magnitude and sense of the relative divergence of the two anticlinal axes.

The pole for locality 3 plots considerably south and east of the poles for localities 1 and 2 and the North American and Mexican APWPs. By rotating locality 3 clockwise about a vertical axis (small open circles, Fig. 6) some 30°–35°, the locality-3 pole can be brought to a position where its 95 per cent confidence cone shows considerable overlap with that of locality 2. Further clockwise rotation of locality 3 by approximately 10°–15° will bring the locality-3 pole to a position where its 95 per cent confidence cone considerably overlaps that of locality 1. Once again, these rotations agree well with both the magnitude and sense of the relative divergence of antclinal axes.

Since the three synfolding poles are all of the same age, the differences between these poles must be the result of localized rotation(s). The ‘true’ Mexican Eocene pole would then be most closely represented by the synfolding pole for the locality which has been subjected to the least amount of local rotation. Locality 3 lies in a transitional position between major trends of the Sierra Madre Oriental and has been subjected to more intense folding than localities 1 or 2. Consequently, locality 3 would appear to be the least likely choice for the non-rotated or least-rotated locality. This conclusion appears to be confirmed by the position of the locality-3 pole which is substantially displaced from the APWPs of both Mexico and North America (Fig. 6).

Although localities 1 and 2 have clearly not been subjected to the large local rotation(s) that locality 3 has experienced, the difference in their poles indicates that there has been a relative localized rotation between the two localities. Since the locality-1 pole is in close agreement with
the Eocene pole for North America and the locality-2 pole is in close agreement with the Eocene pole for Mexico (Fig. 6), it is of great importance to determine which of these two localities is the non-rotated or least rotated.

Kleist *et al.* (1984) suggest that certain local rotations within the Sierra Madre Oriental are evidenced by the relative orientations of structural axes. Since the differences between the three synfolding poles can be accounted for by rotations about vertical axes which are consistent with variations in anticlinal axis trend, such a relationship also appears to hold for local rotations within the current study area. Therefore, one means of determining whether locality 1 or locality 2 has undergone the lesser amount of local rotation may be through an examination of the deviation of the anticlinal axis of each locality with respect to the predominant structural trend in the area. Since locality 2 is more consistent with this predominant trend while locality 1 appears to represent more of a localized anomaly (Fig. 1b), this line of reasoning supports the contention that locality 2 represents the least rotated of the areas studied.

More convincing support for this view is derived from an analysis of the pole calculated for locality 4. Although the results of the fold test demonstrated that this pole must be Eocene or younger, it lies considerably to the south of the Eocene and later segments of both the Mexican and North American APWPs. This suggests that locality 4 was also subjected to some type of rotation subsequent to remanence acquisition.

Since there is no significant variation between the orientation of the locality-4 anticline and the dominant structural trend in the area (Fig. 1b), a rotation about a vertical axis similar to those of the localities giving synfolding poles does not appear to be a likely explanation for the position of the locality-4 pole. However, a different type of rotation is suggested by the 13°, N84°E plunge which was measured at locality 4 (Table 1). The series of small solid circles in Fig. 6 illustrates the change in the position of the locality-4 pole with rotation of locality 4 about a horizontal axis perpendicular to the observed plunge. The track of these solid circles brings the locality-4 pole toward Eocene and younger segments of both APWPs. We thus interpret the locality-4 remanence to have been acquired prior to plunging. Its age, like that of the synfolding poles, can therefore be more confidently estimated as Eocene.

Since the remanence at locality 4 was acquired post-folding (or late synfolding) but pre-plunge during the Eocene, correcting the locality-4 pole for the observed plunge should provide another reliable estimate of the Eocene pole for the study area. Rotating locality 4 by 13° in a direction opposite to observed plunge moves the locality-4 pole into good agreement with the locality-2 pole (Fig. 6). In contrast, a rotation of greater than 15° is necessary just to effect an overlap of the 95 per cent confidence cones of the locality-4 and locality-1 poles and a rotation corresponding to a plunge greater than 25° is necessary to bring the locality-4 pole into near coincidence with the locality-1 pole. This analysis of the effect of plunge on the position of the locality-4 pole therefore provides strong additional support for the selection of locality 2 as the least--locally rotated locality and the selection of the locality-2 pole as the most representative Eocene pole for the study area.

The synfolding pole for locality 2 agrees quite well (95 per cent confidence limits of the locality-2 pole includes the Urrutia--Fucugauchi (1981) pole and vice versa (Tauxe, Besse & La Brecque 1983) with the Eocene pole for Mexico (Mexican Eocene pole) which was calculated by Urrutia--Fucugauchi (1981) from igneous rocks some 450 km to the north--northwest of the current study area. Both poles are determined with sufficient precision to make them resolvable from the Eocene pole of the North American APWP (Fig. 6). Since the Mexican Eocene pole and the locality-2 pole were calculated from sampling areas located such a great distance apart, it is difficult to attribute the difference between these two poles and the North American Eocene pole to movements of local fault blocks. Rather, the fact that samples from widespread locations gave Eocene poles with nearly the same displacement with respect to the North American Eocene pole further supports Urrutia--Fucugauchi's (1981) contention that all or most of northern Mexico has undergone a counterclockwise rotation of some 10--15° with respect to North America since the Eocene. Although Urrutia--Fucugauchi believed that this rotation took place in response to motion along the Texas Lineament, other structural features have been identified which may also be related to the observed Eocene declination anomaly in northern Mexico (Fig. 7). At present, we consider the available palaeomagnetic data to be too sparse to allow for a more detailed picture of how the regional rotation(s) has/have developed.

In the development of the interpretation described above we have utilized only rotations which are (1) simple in nature and (2) are consistent with observed structural features. While we acknowledge that the actual mechanisms by which folds are magnetized and deformed may be very complicated, we found no evidence to suggest such complexities in the folds we studied. Therefore, despite the

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**Table 3. Summary of results.**

<table>
<thead>
<tr>
<th>Pole</th>
<th>Age of Remanence</th>
<th>Mean Dec</th>
<th>Mean Inc</th>
<th>Lat</th>
<th>Long.</th>
<th>n/n₀</th>
<th>k</th>
<th>αₙ₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locality 1 Synfolding</td>
<td>Eocene</td>
<td>350.4</td>
<td>44.3</td>
<td>81.4° N</td>
<td>173.2° E</td>
<td>18/30</td>
<td>104.7</td>
<td>3.4°</td>
</tr>
<tr>
<td>Locality 2 Synfolding</td>
<td>Eocene</td>
<td>337.6</td>
<td>44.1</td>
<td>69.9° N</td>
<td>172.8° E</td>
<td>27/32</td>
<td>29.8</td>
<td>5.2°</td>
</tr>
<tr>
<td>Locality 3 Synfolding</td>
<td>Eocene</td>
<td>305.5</td>
<td>56.0</td>
<td>42.6° N</td>
<td>194.0° E</td>
<td>20/25</td>
<td>9.3</td>
<td>11.3°</td>
</tr>
<tr>
<td>Locality 4 In-Situ</td>
<td>Eocene</td>
<td>327.0</td>
<td>37.8</td>
<td>59.5° N</td>
<td>166.4° E</td>
<td>10/30</td>
<td>47.5</td>
<td>7.1°</td>
</tr>
<tr>
<td>Locality 4 Synfolding</td>
<td>Eocene</td>
<td>327.0</td>
<td>38.6</td>
<td>59.4° N</td>
<td>167.7° E</td>
<td>10/30</td>
<td>51.6</td>
<td>6.8°</td>
</tr>
</tbody>
</table>

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Fucugauchi (1981) from igneous rocks some 450 km to the north--northwest of the current study area.
fact that alternative interpretations could be developed by considering rotations about inclined axes, multiple rotations about various horizontal axes or some combination of these, such interpretations appear to us to be unwarranted in light of an adequate explanation assuming a more simple structural history.

CONCLUSIONS

Palaeomagnetic data from Cretaceous limestones in the vicinity of Torreon suggest a number of significant factors concerning the remanent magnetization and tectonic history of the study area. To varying degrees the importance of these factors can be extended to all or at least a major part of northern Mexico.

At three of our sampling locations the oldest resolvable remanent component was demonstrated, quite convincingly, to have been acquired during folding. At the fourth locality the oldest component was either post-folding or late-synfolding. This absence of pre-folding remanent magnetizations underscores the need to support the recognition of pre-Eocene remanence for Sierra Madre Oriental localities with highly precise data and with field tests which constrain the age of magnetization.

Although remanence acquisition for all four of our localities is either contemporaneous with our subsequent to folding, evidence has been presented to suggest that localized movements subsequent to remanence acquisition are common within the study area. Where these movements can be described by rotation of the sampling localities about vertical axes, there appears to be a correlation between the magnitude and sense of the rotations and localized departures from regional structural trends. Such localized movements must be considered before regional rotations can be reliably determined.

Finally, by examining the relationship between palaeomagnetic pole positions and observed structural features, an Eocene pole has been calculated for the study area (Lat. = 69.9°N, Long. = 172.8°E, n = 27, k = 30, α95 = 5.2°). This pole agrees well with Eocene results for a location some 450 km to the north-northwest. From this we conclude that our results support the tectonic model presented by Urrutia-Fucugauchi (1981) in which a 10–15° post-Eocene counterclockwise rotation of northern Mexico with respect to North America has taken place.

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