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Paleomagnetic study of Jurassic and Cretaceous rocks from the Mixteca terrane (Mexico)

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Abstract

Three sites from Cretaceous limestone and Jurassic sandstone in northern Oaxaca, Mexico, were studied paleomagnetically. Thermal demagnetization isolated site-mean remanence directions which differ significantly from the recent geomagnetic field. The paleopole for the Albian–Cenomanian Morelos formation is indistinguishable from the corresponding reference pole for stable North America, indicating tectonic stability of the Mixteca terrane since the Cretaceous. Rock magnetic properties and a positive reversal test for the Bajocian Tecomazuchil sandstone suggest that the remanence could be of primary origin, although no fold test could be applied. The Tecomazuchil paleopole is rotated $10^\circ \pm 5^\circ$ clockwise and displaced $24^\circ \pm 5^\circ$ towards the study area, with respect to the reference pole for stable North America. Similar values were found for the Toarcien–Aalenian Rosario Formation, with $35^\circ \pm 6^\circ$ clockwise rotation and $33^\circ \pm 6^\circ$ latitudinal translation. These data support a post-Bajocian southward translation of the Mixteca terrane by around 25°, which was completed in mid-Cretaceous time.

1. Introduction

Southern Mexico is composed of several terranes with contrasting tectonic and stratigraphic histories. To explain these observations, Campa and Coney (1983) proposed a subdivision of Mexico into a number of tectonostratigraphic terranes, most of which have supposedly been accreted to Mexico in Late Cretaceous to early Tertiary time. Apart from explaining the geological diversity, the accretion of terranes after disgregation of Pangea would also remove the overlap between South America and Mexico observed during Permian to Jurassic time (Bullard et al., 1965; Van der Voo and French, 1974; Urrutia-Fucugauchi, 1984).

The Mixteca and Oaxaca terranes are characterized by Precambrian crystalline basement, but much younger basement is also found in southern Mexico, as in the Guerrero or Xolapa terranes (Sedlock et al., 1993). This juxtaposition of old and young basement and their remoteness to the stable craton of North America supports the idea of a possible translation of southern Mexico terranes from unknown positions to their present locations. As paleomagnetic data imply that southern Mexico has been tectonically stable with respect to North America since the Cretaceous (see references in Moran-Zenteno et al., 1988), any displacement should have occurred prior to that era. Therefore, paleomagnetic data from Jurassic and older rocks are of great interest. Unfortunately, the conditions are not very favorable for such studies, as pre-Cretaceous rocks in southern Mexico are often multiply deformed and often the paleohorizontal is indeterminable, or the age is not well constrained. Other potentially useful rocks have been found to be remagnetized, which complicates or impedes a tectonic interpretation (e.g. McCabe et al., 1988; Fang et al., 1989).

In this study, paleomagnetic data are reported from a sedimentary sequence in northern Oaxaca, where Jurassic to Tertiary rocks are exposed. Paleontological and stratigraphical data reasonably restrict the age of the rocks.

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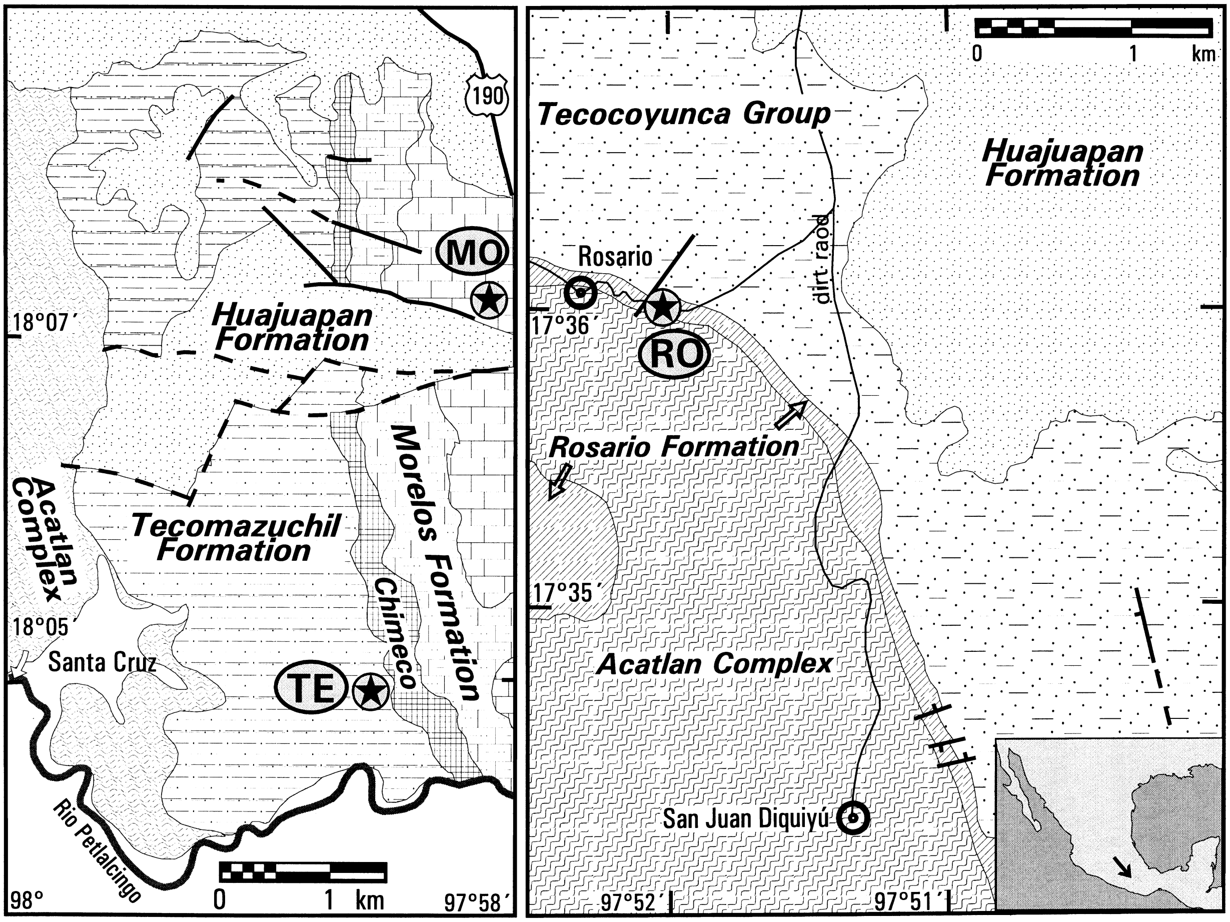

Fig. 1. Simplified geological map of the study area (modified from Perez-Ibarguengoitia et al., 1965; Alencaster de Cserna, 1963). The arrow in the inset map shows the localization in southern Mexico. Paleomagnetic sampling sites are shown by black stars and labeled MO (Morelos limestone), TE (Tecomazuchil sandstone) and RO (Rosario sandstone).

2. Geological setting

The basement of the area is composed of metamorphic rocks of the Acatlan complex (Yañez et al., 1991), which consists of multiply deformed metasedimentary rocks: schists, granitoids, and eclogites, with crustal residence ages of 1.3–1.6 Ga, comparable to those of the neighboring Oaxaca complex, which might represent the source area for the Acatlan complex. These complexes have been correlated with Appalachian and Grenville rocks. Outcrops of the Acatlan complex are found in the western part of the study area, which is shown in Fig. 1. In the northern part of the study area, the Acatlan complex is overlain with angular unconformity by the Tecomazuchil Formation. Its lower age is not precisely known, but based on Middle Jurassic fossil plants and regional stratigraphic correlations, a Bathonian age has been suggested (Perez-Ibarguengoitia et al., 1965). The rocks are mainly sandstones and siltstones of red, pink and yellow color, and may be interpreted as continental red beds. The Tecomazuchil Formation is conformably overlain by limestones of the Oxfordian Chimeco Formation, where abundant echinoids and pelecypods allow precise dating. This formation is considered to be the basal unit of the Late Jurassic transgressive marine sequence. Following in transitional contact is the Mapache Formation, consisting of argillacous limestones with an ammonite fauna defining a Kimmeridgian to Portlandian age. The abundance of pelecypods and the scarcity of ammonites together with the important content of detritic material indicates a shallow marine deposition environment. The Mapache Formation is discordantly overlain by by the Morelos Formation, a thick sequence of yellowish to dark-grey limestones with foraminifera and rudists, indicative of Albian–Cenomanian age. Covering the sequence are Tertiary conglomerates of the Huajuapan Formation. Folding is very gentle, and strata are dipping around 20° or less towards the east.

In the southern part of the study area continental and marine Jurassic sediments overlay the basement rocks (Erben, 1956; Alencaster de Cserna, 1963). The oldest sediments belong to the Rosario Formation which consists of grey to red-brown sandstone and siltstone. The middle and upper part of the formation contains plants of Toarcien–Aalenian age. The Rosario Formation is overlain by the Tecocoyunca Group, which consists of the Cualac conglomerate, Zorillo, Taberna, Simon, Otatera, and Yucuñuti Formations, which are of marine depositional environment with deltaic influence. On top again the Tertiary Huajuapan Formation is found. Strata here are dipping more steeply (up to 60°), and dip-azimuths vary between NW and NE. The distribution of continental and marine sedimentary rocks in the study area, together with flow direction indicators, has been interpreted in terms of a location of the coastline towards the south or southwest (Caballero-Miranda et al., 1990).

3. Field and laboratory methods

Three formations were sampled for paleomagnetic studies: the Rosario Formation, the lower part of the Jurassic Tecomazuchil, and the Cretaceous Morelos Formation. Locations of the sampling sites are indicated in Fig. 1. The Tecomazuchil Formation was sampled in stratigraphic order over a total height of 13 m in 11 beds, and magnetostratigraphic results have already been published (Urrutia-Fucugauchi et al., 1990). The Morelos Formation was sampled in 8 beds covering a total thickness of 18 m. Roughly 50 km further to the south, the Rosario Formation was sampled in 12 beds with a total thickness of 7 m. Here the overlaying Tecocoyunca Group has been studied as well, but the paleomagnetic results showed strong, unremovable secondary overprints and were therefore of no tectonic relevance (Böhnel, 1985).

The rocks were sampled using a portable gasoline-powered drill with diamond drill bits, and the cores were oriented in situ with an inclinometer and a magnetic compass (Collinson, 1983). Sampling was done in stratigraphic order, taking 3–4 cores per horizon to check for the internal consistency of the magnetic record. In this manner 31 cores from the Morelos limestone were obtained, 38 cores from the Tecomazuchil sandstone, and 35 cores from the Rosario Formation. For laboratory studies cores were later cut into 21 mm long specimens.

Different magnetometers were used to determine the intensity and direction of the natural remanent magnetization (NRM): a Digico fluxgate spinner magnetometer was used for some of the specimens but, due to the rather low NRM-intensites, a SQUID magnetometer was also used. Magnetic susceptibility was measured with a Bison bridge. For demagnetization experiments, a Schonstedt GSD-1 alternating field (AF) equipment and two home-made AF demagnetizers were available, and for thermal demagnetization a Schonstedt TSD-1 oven. Rock magnetic parameters were studied with a pulse magnetizer and a Digico spinner magnetometer with high/low-temperature attachment.

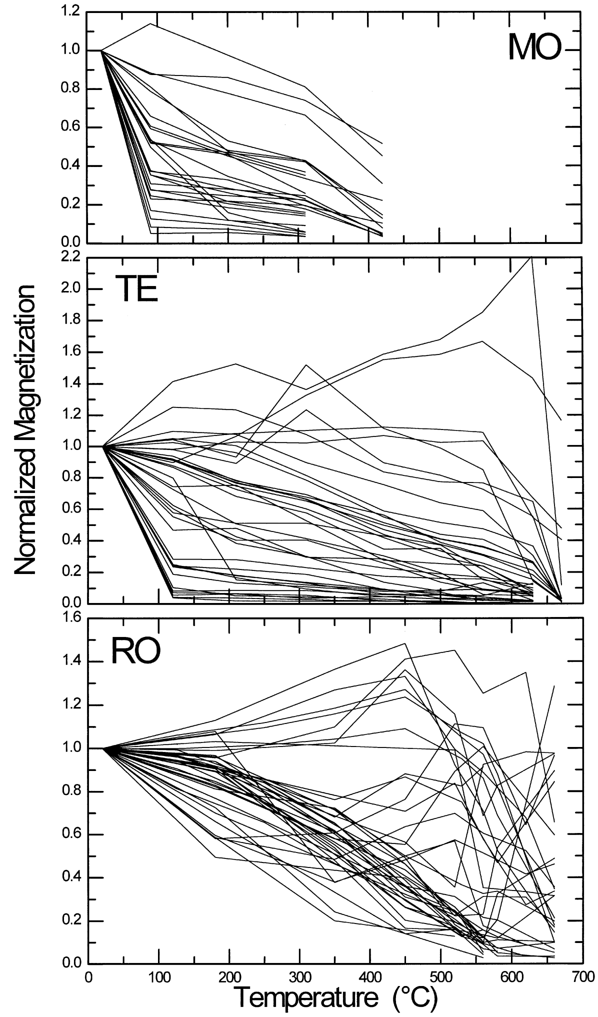

Fig. 2. Normalized intensity of remanent magnetization versus temperature for samples of Morelos limestone (MO), Tecomazuchil sandstone (TE) and Rosario sandstone (RO).

3.1. Rock magnetic properties

3.1.1. Laboratory unblocking temperatures of NRM

The magnetic mineralogy of the rocks was already apparent from the unblocking temperature spectra obtained from the stepwise thermal demagnetization experiments (see next section). Fig. 2 shows the variation of the normalized remanent magnetization with temperature. The Morelos limestone contained a considerable amount of goethite, since many samples lost more than 60% of the NRM-intensity between 20 and 90°C. Most other samples contained goethite as well but in lower concentration than the magnetically domi-

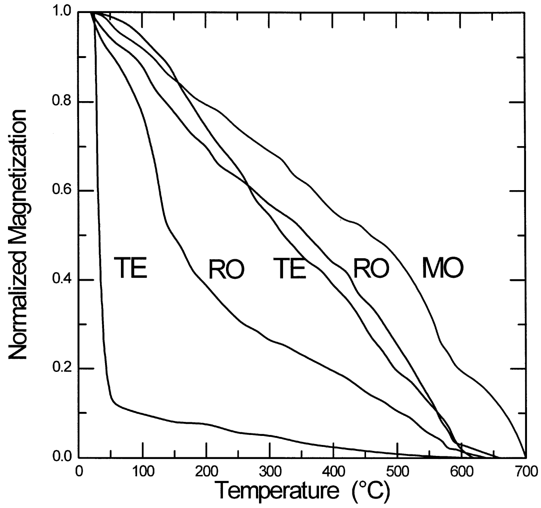

Fig. 3. Variation of normalized strong-field induced isothermal remanent magnetization (IRM) during heating. MO, Morelos limestone; TE, Tecomazuchil sandstone, RO, Rosario sandstone.

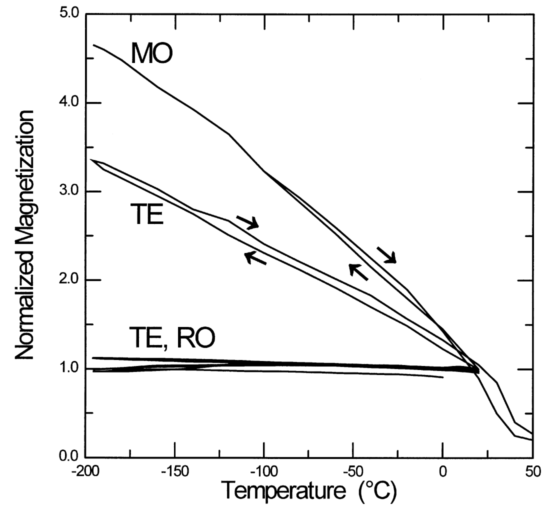

Fig. 4. Variation of normalized strong-field induced isothermal remanent magnetization (IRM) during low-temperature cycling. Arrows indicate cooling and warming curves. MO, Morelos limestone; TE, Tecomazuchil sandstone, RO, Rosario sandstone.

nant minerals. At 420°C the demagnetization was stopped, because the remaining remanence was approaching the noise-level even of the cryogenic magnetometer. At this temperature, the remanence had dropped in most samples to < 30% of the NRM, which, together with the curvature of the curves in Fig. 2, suggests that magnetite was the main magnetic carrier. It was not possible to unequivocally distinguish the unblocking temperature of magnetite and hematite from the thermal demagnetization experiments alone.

In the Tecomazuchil sandstone, unblocking temperatures were much more variable. A fraction of the samples was again dominated by goethite, visible from the strong drop of remanent magnetization below 120°C. In other samples a more continuous unblocking temperature spectrum was observed, which extended clearly above 600°C. These samples possibly contained hematite pigment, while other samples with discrete unblocking temperature spectra above 600°C contained hematite in the form of specularite (Collinson, 1980). Finally, a number of samples also showed unblocking temperatures typical for magnetite, often together with a high-temperature component (specularite). We may conclude that the Tecomazuchil sandstone contains all magnetic minerals typically encountered in red beds. The magnetite could indicate the presence of primary magnetic minerals in these rocks, and the magnetic record may therefore be related to the primary deposition of the sediment.

Rocks from the Rosario Formation resembled those from Tecomazuchil, with the difference that less goethite seemed to be present, as the NRM intensity drop below 200°C was much smaller. Furthermore, more samples seemed to be dominated by magnetite, as remanence often dropped below 580°C. In both TE and RO samples, the remanence components residing in magnetite and hematite often exhibited the same directions (see Fig. 6), which supports the idea of a primary origin of NRM (see below).

3.1.2. Laboratory unblocking temperatures of IRM

Thermal demagnetization of high-field induced isothermal remanent magnetizations (IRM) supports the above interpretations (Fig. 3). The Morelos limestone showed a large decrease of IRM below 600°C, which is attributed to the presence of magnetite. A minor hematite fraction unblocked just below 700°C. Some of the Tecomazuchil and Rosario samples were dominated by magnetite, as remanence completely disappeared below 600°C. Other samples were clearly dominated by goethite, shown by a remanence drop below 20–40% of the initial IRM at less than 150°C. The remaining remanence was unblocked below about 600°C, thus again suggesting magnetite.

3.1.3. Low-temperature variation of IRM

Variation of IRM was also studied at temperatures down to −196°C. The presence of goethite is very clearly seen in Fig. 4 for two samples from limestone and sandstone: remanence increased largely towards lower temperatures, reaching several times the initial IRM. On upwarming this effect was almost reversible, and heating just to 50°C destroyed a considerable part of the initial IRM. Other samples of limestone and sandstone showed almost no variation with temperature, probably indicating that single domain magnetite dominated the magnetic properties. In these samples hematite could be excluded, as no drop of IRM

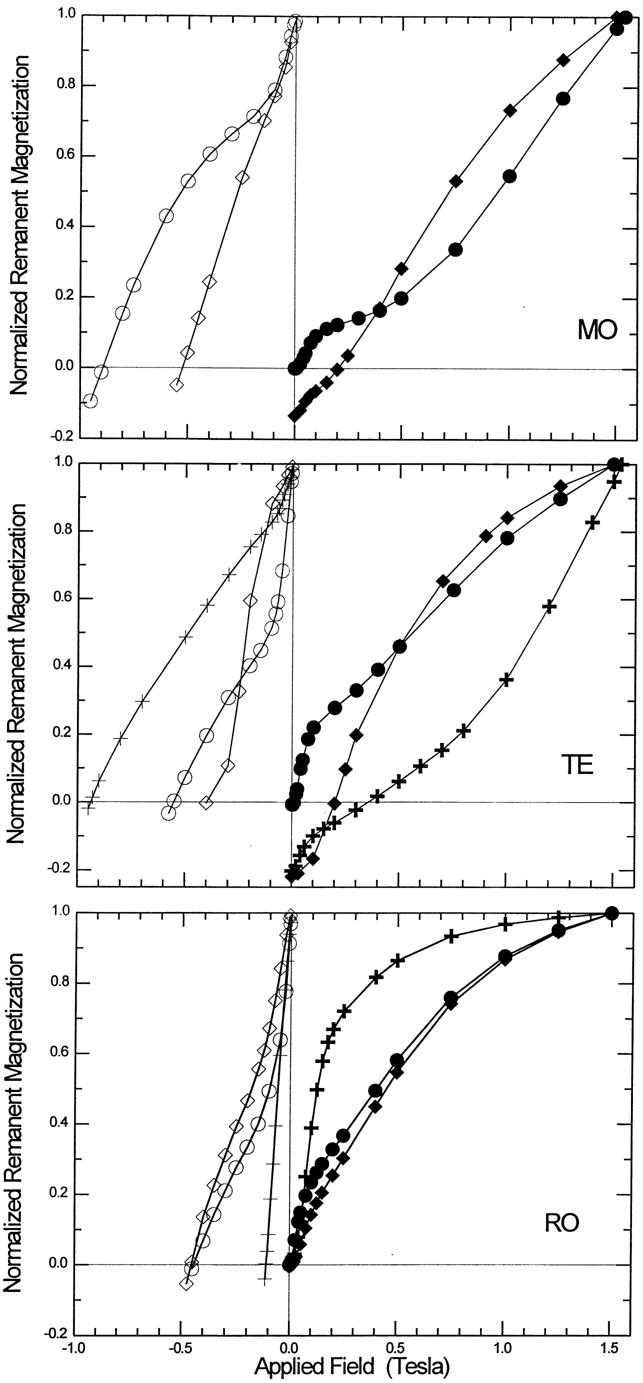

Fig. 5. Acquisition of isothermal remanent magnetization (IRM) in magnetic fields (solid symbols) and back-field demagnetization (open symbols) of the maximum IRM. MO, Morelos limestone; TE, Tecomazuchil sandstone, RO, Rosario sandstone.

occurred around −15°C, the temperature of the Morin transition.

3.1.4. IRM acquisition

IRM acquisition and back-field demagnetization curves are shown in Fig. 5. None of the samples was saturated by the maximum available field of 1.5 T. This was due to the presence of highly coercive magnetic minerals like goethite or hematite, as suggested above. The inflection of the IRM acquisition and back-field demagnetization curves at fields <200 mT again indicated the presence of magnetite.

3.1.5. Conclusion of rock magnetic experiments

The remanent magnetization of the Morelos limestone was carried by goethite and magnetite in variable proportions, with minor hematite. The Tecomazuchil and Rosario sandstones contained the same minerals, but hematite in the form of pigment and specularite was present in larger concentrations in many samples. In both of these formations, the magnetic mineralogy was fairly constant within each bed, and changes occurred predominantly between different beds. This may be the result of varying conditions during the deposition of the sediments, but also of local differences of recent weathering of the rock which produced more or less goethite.

3.2. Paleomagnetic results

To study the composition of the NRM, all samples were demagnetized mainly by means of the stepwise thermal method. This was done up to 420°C for the Morelos limestones, as at this temperature, the NRM had dropped to a level comparable to the noise of the SQUID-magnetometer. Nevertheless, up to that temperature the directional variation of remanence was mainly uni-vectorial and the demagnetization curves tended towards the origin of the diagram [Fig. 6(a)]. It was therefore straightforward to determine characteristic remanence (ChRM) directions for 27 out of 31 samples.

Vector plots for the Tecomazuchil sandstone were pretty varied: many samples showed uni-vectorial NRM [Fig. 6(c)]. This was always the case for samples containing magnetite and hematite (specularite), which supports the idea that both minerals carried the same, possibly primary, remanence. Other samples contained at least two remanence components [Fig. 6(b),(d)], and sometimes the demagnetization process did not isolate a stable endpoint ChRM [Fig. 6(b)]. This happened more often in samples where goethite dominated the magnetic properties. Finally, a few samples showed stable endpoint ChRM, but of intermediate direction. All in all, a total of 11 samples from the Tecomazuchil sandstone had to be rejected for further interpretations. Samples demagnetized by the AF method in most cases did not reach a stable endpoint direction, because of the presence of high-coercive minerals, and were not considered for further interpretation.

Samples from the Rosario Formation behaved similarly in general terms. Most ChRM directions were of reversed polarity, and often a normal overprint was

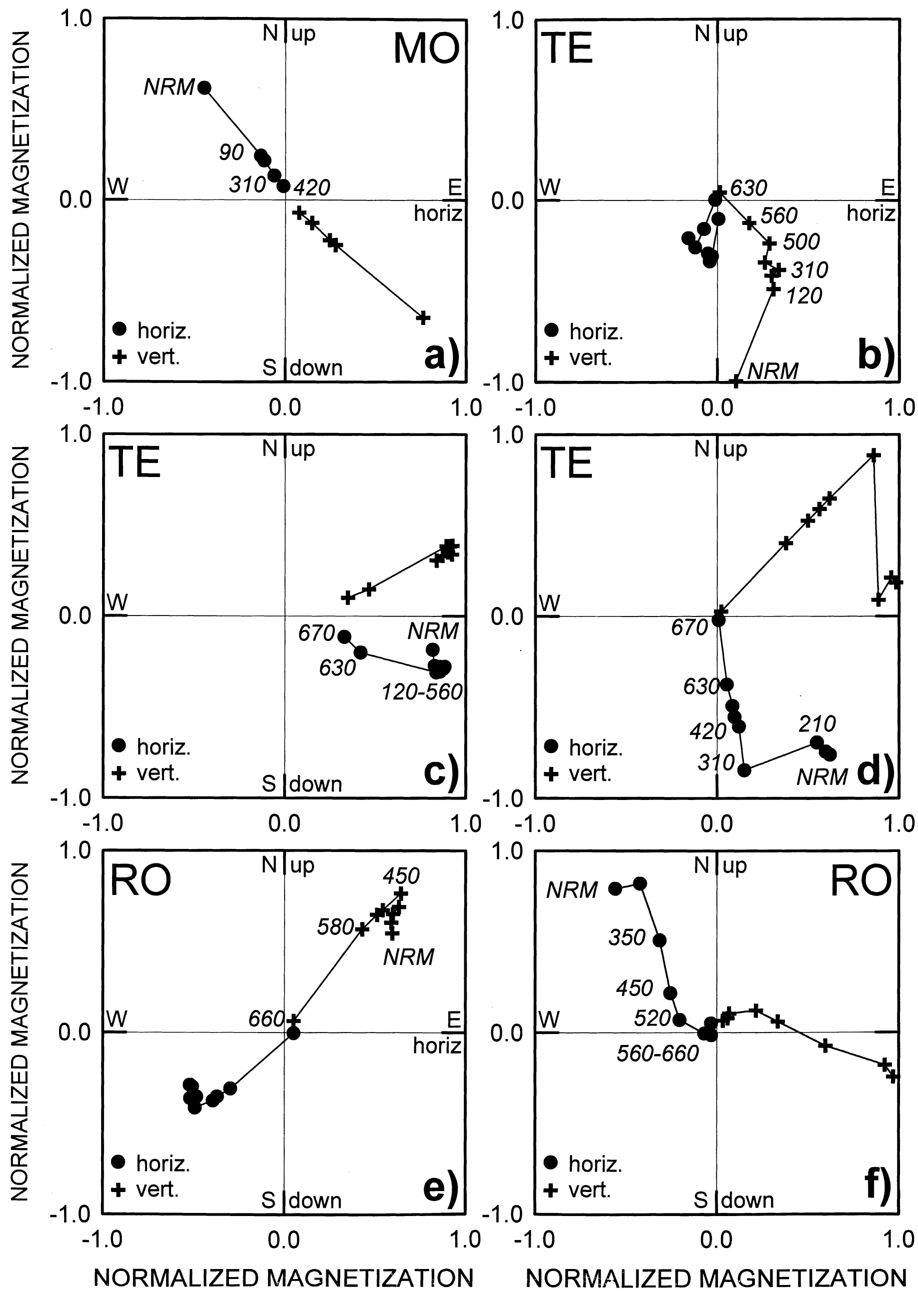

Fig. 6. Modified Zijderveld diagrams for stepwise thermally demagnetized samples from the Morelos limestone (MO), Tecomazuchil (TE) and Rosario (RO) sandstone. Demagnetizing temperatures are shown as labels along curves.

removed at intermediate [Fig. 6(e)] to higher [Fig. 6(f)] temperatures. Sometimes the remanence remained of normal polarity, and it is suspected that this corresponds to a recent overprint.

The ChRM directions obtained for the Morelos limestone are plotted without tilt correction in an equal area projection [Fig. 7(a)]. In agreement with the age which falls in the Cretaceous Normal Superchron, the Morelos limestone exhibited only normal polarity of remanence. Fig. 7(b) shows the ChRM directions for the Tecomazuchil sandstone before and after tilt correction. Here polarities are mixed, with 16 normal and 13 reversed ChRM directions. Applying Fisher-statistics (Fisher, 1953) site-mean directions were calculated for both cases (Table 1). For that purpose, the reversed directions from the Tecomazuchil sandstone were inverted and combined with the normal directions. Data from the Rosario Formation [Fig. 7(c)] again resemble those of the Tecomazuchil, with ChRM direction mainly of reversed polarity. The few normal polarity directions here show high dispersion and were not antipodal to the reversed directions and were dis-

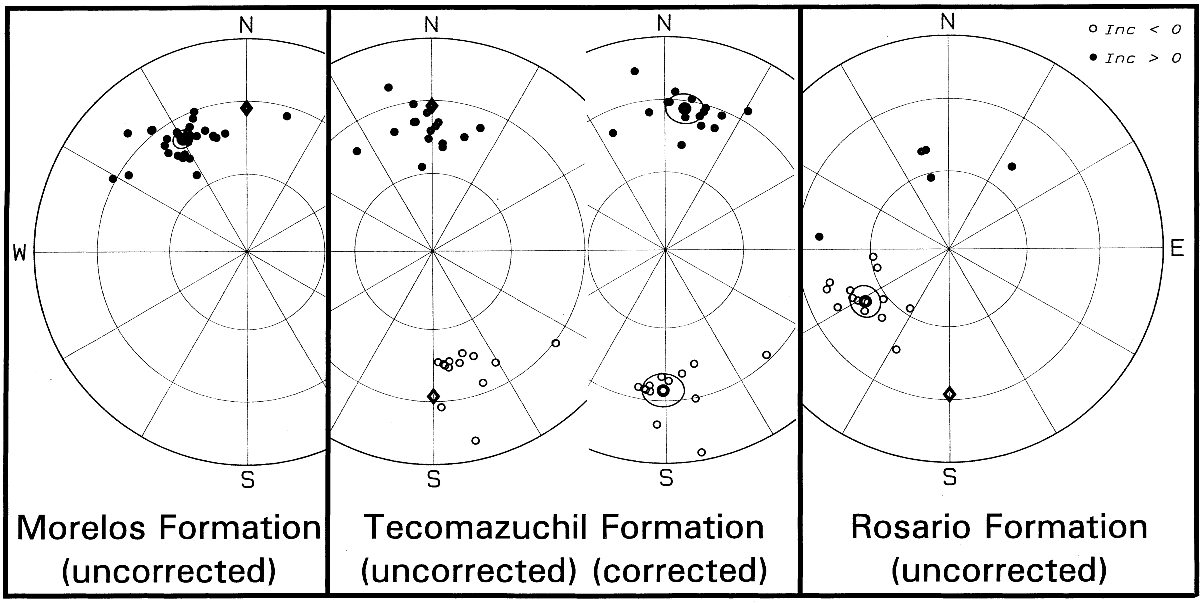

Fig. 7. Characteristic remanent magnetization directions for the Morelos limestone (MO), and the Tecomazuchil (TE) and Rosario (RO) sandstone. Mean directions are given with 95% confidence circles. Rhombi show directions of the axial geocentric dipole field for the study area.

carded. These samples were probably affected by a magnetic overprint which has not been completely removed by the demagnetization experiments.

3.2.1. Stability tests

Although the rock magnetic properties suggest that the NRM may be of primary origin, I shall evaluate other criteria to infer the origin of the observed remanence. First of all, because of the rather invariant bedding attitude over the sampling sites, we were not able to perform affirmative fold-tests. This is seen from the data in Table 1, where the site-mean directions for the Tecomazuchil Formation are listed with and without tilt correction. There is no significant difference in the dispersion, as the precision parameter k remains almost unchanged after correction. For the Rosario and Morelos Formation no variation at all was observed for the bedding attitude of the sampled strata.

In situ site-mean directions differed significantly from the direction of the axial geocentric dipole (Fig. 7) and therfore exclude a recent magnetic overprint. Finally, in the case of the Tecomazuchil Formation we observed different polarities of remanent magnetization. The polarity varied in stratigraphic order, which was already used for a magnetostratigraphic interpretation (Urrutia-Fucugauchi et al., 1990). If we compare the mean of the inverted reversed and the normal polarity directions, no significant difference is observed (Fig. 7; Table 1). The means are indistinguishable at

Table 1
Mean directions and palepoles for the study area and reference poles for stable North America with statistical parameters[a]

Site or tectonic plate	Label	n	r	R	k	α_{95} (°)	Dec (°E)	Inc (°)	Lat (°)	Long (°E)	$R \pm R$ (°)	$P \pm P$ (°)	Ref (Ma)
MO, NSC	MO	27	2	26.56939	60.4	3.6	330.4	38.9	62.0	184.9			
MO, SC	MO	27	4	26.56939	60.4	3.6	345.5	39.5	75.7	192.0	2 ± 6	1 ± 5	100
TE, normal polarity, SC		16	0	15.55628	33.8	6.4	8.5	33.8	81.9	347.8			
TE, reversed polarity, SC		11	2	10.85971	71.3	5.4	181.4	−35.5	−88.0	122.7			
TE, combined polarity, NSC	TE	27	2	26.45384	47.6	4.1	354.0	42.3	81.5	211.7			
TE, combined polarity, SC	TE	27	2	26.44031	46.5	4.3	5.6	34.6	84.6	341.2	10 ± 5	−24 ± 5	177–195
RO, reversed polarity, NSC	RO	15	4	14.673.11	42.8	5.9	231.6	−51.9	−41.4	143.9			
RO, reversed polarity, SC	RO	15	4	14.67311	42.8	5.9	210.4	−46.2	−60.3	147.1	35 ± 6	−33 ± 6	177–195
North America, 100 Ma	100					5.7			74.1	192.5			
North America, 177–195 Ma	177–195					4.3			67.0	93.0			

[a] SC, NSC, structurally corrected/not corrected sites-mean direction and paleopole. *n, r*, number of samples used/rejected for calculation of mean direction; *k*, α_{95}, statistical parameters; Dec, Inc, site-mean direction and inclination; Lat, Long, virtual geomagnetic pole; *R, P*, apparent rotation and poleward displacement; Ref, Reference pole used to calculate*R* and *P*. Labels also refer to Fig. 9.

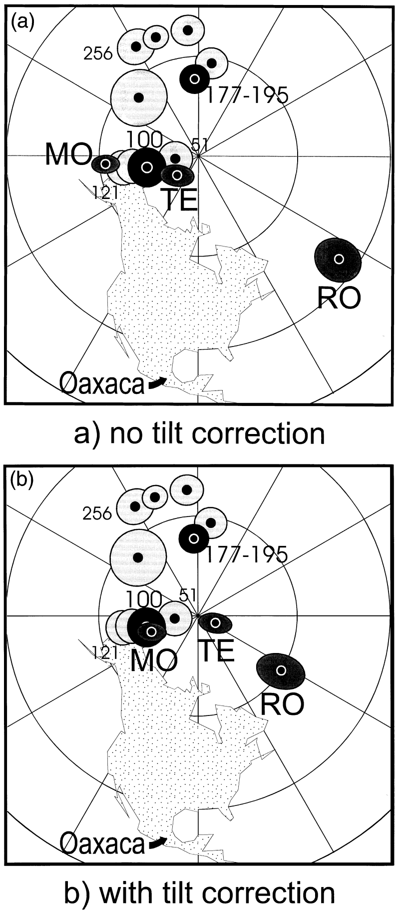

Fig. 8. Paleopoles for the study area (dark gray shading) and reference poles for stable North America with 95% confidence limits (light gray shading, Van der Voo, 1990), (a) without tilt correction, (b) with tilt correction. The mean age or an age range is shown close to some of the reference poles; reference poles with solid shading and larger labels correspond in age to the studied rocks. Labels correspond to Table 1.

the 95% probability level (McFadden and Lowes, 1981), and the Tecomazuchil Formation thus passes the reversal test. We conclude from the rock magnetic properties and from the ChRM directions that the magnetic record is possibly primary, although a remagnetization over a prolonged period covering several polarity chrons of the Earth's magnetic field may not completely be excluded. A recent remagnetization of the rocks is excluded because of the observed mean directions and the polarity changes.

3.2.2. Paleopoles

Table 1 lists paleopoles calculated from the site-mean directions, and two reference poles for stable North America. The 100 Ma reference pole (Globerman and Irving, 1988) corresponds well with the age of the Morelos limestone. Alternative reference poles for this time are given by McEnroe (1986) but they differ only slightly. The selection of Jurassic paleopoles is more difficult due to the poorly defined and controversial data from the North America craton (e.g. Van Fossen and Kent, 1990; Van der Voo, 1992; Hagstrum, 1993; Courtillot et al., 1994). In this work a paleopole for the interval 177-195 Ma (Lower-Middle Jurassic; Van der Voo, 1990) was chosen, located at 67°N, 93°E, with a confidence limit of $A_{95}=4.3°$. This reference pole is based on 8 paleopoles with quality factor Q3 (Van der Voo, 1990) and represents a conservative approach, which seems justified in view of the controversy over "correct" Jurassic reference poles for North America. As the present work is not focused on resolving the question of detailed small scale and/or high time-resolution tectonic processes, but rather on large scale movements of the study area, minor differences between the chosen and alternative reference poles will not significantly change the tectonic interpretation presented below. The age range for the chosen reference pole brackets the age of the Bathonian Tecomazuchil and Toarcien–Aalenian Rosario Formations.

The Morelos (MO) paleopole is indistinguishable from the 100 Ma reference pole for stable North America [Fig. 8(b)], indicating no relative movement between these regions since that time. The Tecomazuchil (TE) and Rosario (RO) paleopoles are rotated clockwise and situated considerably closer to the study area than the reference poles [Fig. 8(b)]. Fig. 8(a) shows the paleopoles without tilt correction, and the MO and RO poles are displaced away from any younger reference poles, probably indicating there was no later remagnetization of these rocks. The Tecomazuchil pole roughly coincides with the 51 Ma reference pole and therefore a post-folding remagnetization of this rock could not be excluded, based on the position of the tectonically uncorrected paleopole alone. As discussed above, the mixed polarity of remanence in these rocks and the positive reversal test argue against such a relatively recent remagnetization. It is further noted that after the tilt correction the TE and RO paleopoles are located much closer to each other than before the correction, which supports the idea of a pre-folding acquisition of remanence.

Apparent rotation (R) and poleward translation (P) were determined numerically (Beck, 1980; Demarest, 1983), resulting in values of $R = 10° \pm 5°$ and $P=-24° \pm 5°$ for Tecomazuchil and $R = 35° \pm 6°$ and $P = -33° \pm 6°$ for Rosario, respectively (Table 1). The good correspondence between the TE and RO data suggests that the Rosario rocks may have undergone a similar tectonic and/or magnetic evolution. This also lends confidence to my interpretation of the remanence being of primary origin, as the studied sites are separated by about 50 km.

If the apparent movements were due to tectonic processes, these had ceased by the mid-Cretaceous. Other

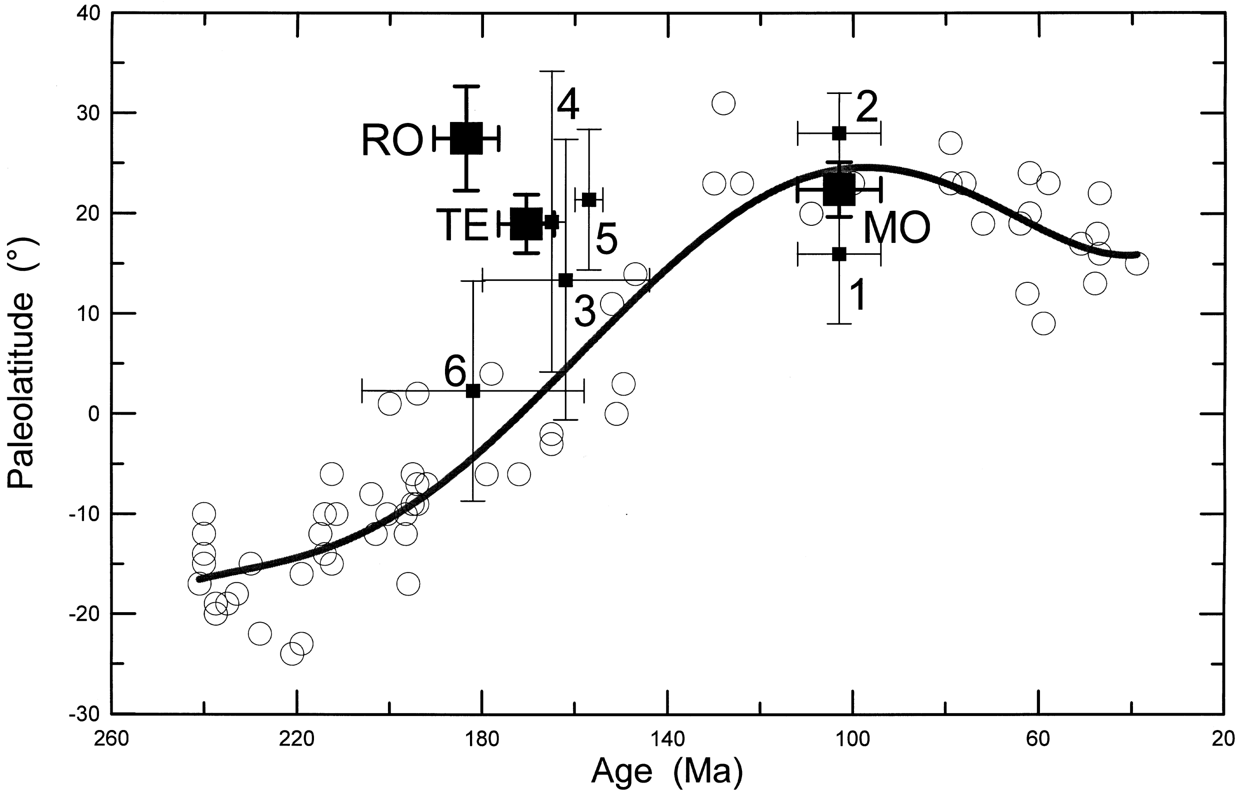

Fig. 9. Jurassic and Cretaceous paleolatitudes for the Mixteca terrane (squares) in comparison with paleolatitudes for the study area as derived from reference poles (Van der Voo, 1990; see text) for the stable North America craton (circles). Labels: TE, MO, RO, paleopoles from this study; 1, Oaxaca limestone (Urrutia-Fucugauchi, 1981); 2, Morelos formation (Urrutia-Fucugauchi, 1988); 3, Otlatepec red beds, and 6, Piedra Hueca red beds (Ortega-Guerrero and Urrutia-Fucugauchi, 1993); 4, Caliza con Cidaris, and 5, Yucuñuti formation (Caballero-Miranda et al., 1990).

paleomagnetic data from southern Mexico (Moran-Zenteno et al., 1986; Caballero-Miranda et al., 1990) suggested similar clockwise rotations and southward displacements for the area of northern Oaxaca. Such tectonic movements could be related to lateral displacements of southern Mexico along regional fault systems (megashear zones) which have been proposed for Mexico (e.g. Murray, 1956; Silver and Anderson, 1974; De Cserna, 1976; Anderson and Schmidt, 1983). In such a scenario, the study area would have arrived from a more northerly position. During the Cenozoic, relative motion between oceanic plates in the Pacific basin and the North American plate had predominantly a right-lateral component, and accretion and coastwise translations therefore occurred towards the north (e.g. Debiche et al., 1987). This tectonic regime led to the northward transport and clockwise rotation of Cordilleran terranes. Nevertheless, for times prior to 120 Ma, a left-lateral displacement component has been proposed for the southern margin of North America (Debiche et al., 1987), and the study area could have been transported coastwise from a position more to the north to its present location, in a manner similar to that proposed by Sedlock et al. (1993). In this scenario, however, the displacement along a left lateral shear zone would have resulted in a counter-clockwise rotation of blocks, and the observed paleopoles would then require large counter-clockwise rotations of about 330°.

A position of Oaxaca originally along the eastern margin of the North America craton and a later displacement along a right lateral shear system would have resulted in a clockwise rotation, as suggested by the paleomagnetic data. Such a position has been proposed earlier on the basis of isotopic studies, which allow a correlation of the Oaxaca basement rocks with the Grenville orogen (Ruiz et al., 1988). In that case the displacement of the study area must be related to the breakup of Pangea and the separation of North and South America. Repositioning the Mixteca terrane about 25° or 2500 km towards the north would place it close to the Grenville complex in Canada. This value correlates well with the northwest-southeast displacement of about 3000 km between the two cratons, which occurred since the Jurassic (Sedlock et al., 1993). Although there is no clear evidence for transform systems along the eastern margin of Mexico, Sedlock et al. (1993) proposed a right lateral fault along the eastern margin of Mexico, which was connected tentatively with the (proto-) Gulf of Mexico. Such a shear system may have facilitated the displacement of terranes along the eastern margin of North America towards the south during the Jurassic–Cretaceous.

An alternative interpretation is to consider a southern hemisphere paleolatitude, similar to those of some of the terranes in western North America (e.g. Hillhouse, 1977; Stone et al., 1982). The Bajocian–early Callovian ammonite fauna found in Oaxaca correlates well with fossils from the Central Andes in South America (Westermann et al., 1984), although it is not incompatible with a northern hemisphere position. Such a position at about 20–30°S during deposition of the Tecomazuchil and Rosario Formations would require high displacement velocities of the study area towards the north, to arrive at its present relative position before the Albian. Furthermore, it would require a large counter-clockwise rotation of about 150°. Finally, no plate tectonic model has been proposed which could provide such a northward transport during Jurassic–Cretaceous. Therefore, this alternative is considered to be less probable.

Fang et al. (1989) studied Paleozoic rocks from the Mixteca terrane just north of our sampling area. These rocks were remagnetized, maybe by the large Totoltepec intrusion (which was itself metamorphosed at an unknown age), and the age of the observed remanence was suggested to be in the Carboniferous to Jurassic range. Paleopoles were found to be rotated clockwise with respect to the apparent polar wander path for stable North America, and this rotation was interpreted to have occurred during Jurassic or Early Cretaceous. No conclusive evidence has been found for north–south displacements due to the large scatter in mean directions and the uncertainty of remanence ages. Anyway, the proposed rotations correlate well with the data presented here.

McCabe et al. (1988) reported data from Paleozoic rocks in the neighboring Oaxaca terrane, which were also remagnetized. These authors interpreted remagnetization to have occurred between Late Permian and Early Cretaceous. The remagnetized paleopole indicated a counter clockwise rotation of up to 28°, depending on the age assignment, and would thus require a different tectonic history as compared to the Mixteca terrane.

Fig. 9 summarizes Jurassic and Cretaceous paleolatitudes obtained so far for the Mixteca terrane, as calculated from paleo- and reference poles. Also shown are paleolatitudes from the Mixteca terrane for the case of a tectonic stability relative to the craton of North America, as deduced from 64 Mesozoic paleopoles listed by Van der Voo (1990) for North America with quality factors Q3. The paleolatitudes are modeled by a polynomial which averages out some of the dispersion present in these data and is used here for easier comparison. As stated above, the Mixteca terrane apparently was already attached to North America in Late Cretaceous times, as indicated by the coinciding paleolatitudes of the data points 1, 2 and MO (this study) with the reference curve for stable North America (Fig. 9). Entry 2, although from southern Mexico, corresponds to the neighboring Guerrero terrane, thus indicating that most of southern Mexico was already in place when the Morelos formation was deposited (Böhnel, 1985; Urrutia-Fucugauchi, 1988).

Most Jurassic data are less well defined and thus have rather large confidence limits: not only are they not significantly different from the reference curve, but most of them are also similar to the data from the Tecomazuchil and Rosario redbeds. In view of the rock magnetic properties of these red beds and of the stability tests passed by the data, I propose that from all data the TE and in second term the RO paleopoles probably best represent the paleolatitude of the Mixteca terrane in mid-Jurassic. Accordingly, the Mixteca terrane moved 20–30° southward with respect to North America during the Jurassic–Early Cretaceous and was attached to its present position before the Albian.

4. Conclusions

The rocks of the Morelos, Tecomazuchil and Rosario formations probably contain primary remanent magnetizations which reside in magnetite, in the case of the limestone, and in hematite and magnetite, in the case of the sandstone. In both rocks, goethite was present in many samples which obscured the primary remanence, especially in the red beds. The site-mean directions before and after tectonic correction deviate significantly from the direction of the geocentric axial dipole field in the study area, which excludes a recent remagnetization. Mixed polarity of remanence was observed in the Tecomazuchil and Rosario red beds, with antipodal ChRM directions passing a reversal test in the former.

While the Cretaceous Morelos paleopole coincides with the reference pole for North America, the Jurassic Tecomazuchil and Rosario paleopoles are rotated clockwise by ~30° and situated 25°–33° closer to the study area than the reference pole. Therefore, the study area was probably displaced from a more northerly position to its present position. This southward shift must have been completed in mid-Cretaceous, when the Morelos limestone was deposited. Based on paleomagnetic studies of Paleozoic rocks, similar rotations have been proposed for nearby

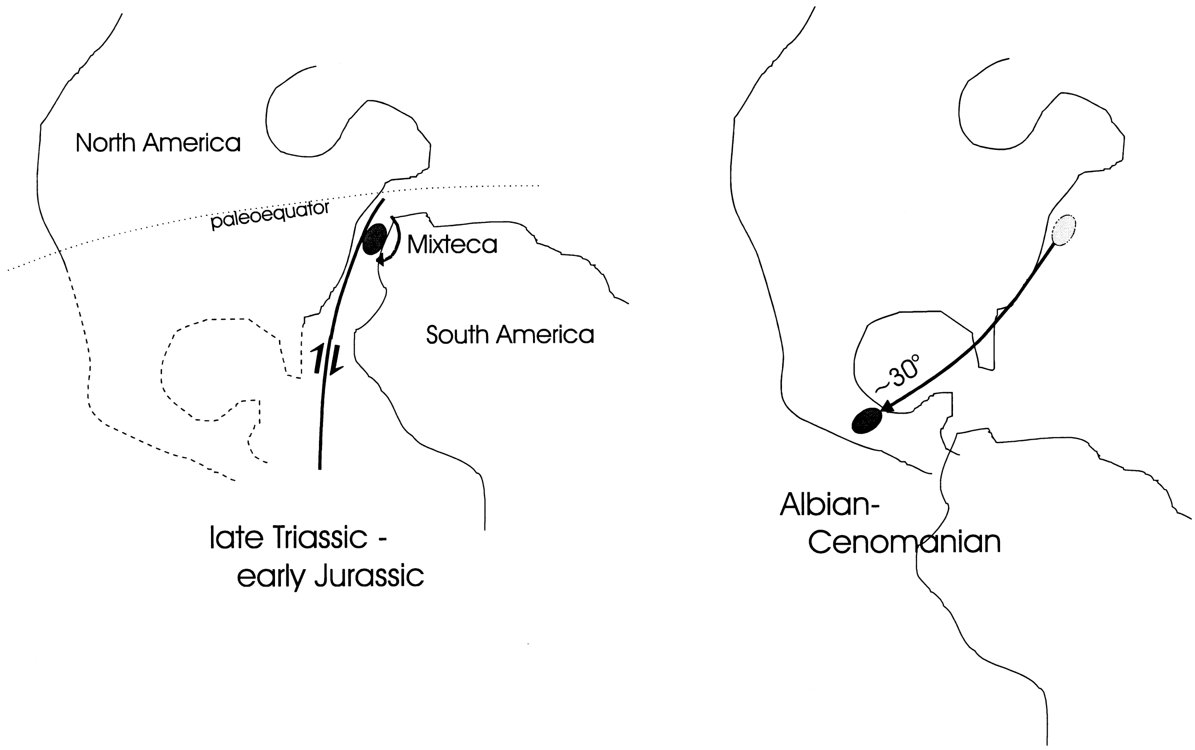

Fig. 10. Schematic model for a position of the Mixteca terrane along the eastern border of North America during Late Triassic-early Jurassic time and its displacement together with South America along a right lateral shear zone towards its present position, where it was fixed in Albian–Cenomanian time. The paleoequator is shown for Late Triassic–early Jurassic, and the southern margin of North America is shown as a stippled line as in its actual form.

sites of the Acatlan complex, but there was no conclusive evidence for southward displacements (Fang et al., 1989). Other Jurassic data from the Mixteca terrane are similar in paleolatitude but have much larger confidence limits, which results in a more ambiguous paleogeographical interpretation. The Mixteca terrane may have been displaced to its present position along a left lateral shear zone from the western margin of North America, although this would require a very large counter-clockwise rotation of ~330°. Such a displacement could have occurred due to oblique convergence between Pacific plates and North America, which had a left lateral component during part of the Jurassic and Cretaceous. An original position along the eastern margin of the North America craton, close to the Grenville complex, would require a right lateral shear system and only 30° of clockwise rotation (Fig. 10). This shear zone would be related to the separation of North and South America during the Jurassic and Cretaceous. Such a paleoposition corresponds in general terms with the interpretation of Ortega (1981) and Sedlock et al. (1993) that the Mixteca terrane is of Appalachian affinity. In such a scenario, the Mixteca terrane would have traveled southward together with South America and was left behind in southern Mexico at some time before the Albian. Additional paleomagnetic studies are required to test these hypotheses and to decipher in detail the provenance and displacement of the Mixteca terrane.

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