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# Paleomagnetic reconstruction of Coahuila, Mexico: the Late Triassic Acatita intrusives

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## RESUMEN

La serie plutónica de Acatita intrusiona estratos del Paleozoico superior de la secuencia de la cuenca Las Delicias, en la porción sur de la plataforma de Coahuila, en el norte de México. Obtuvimos 96 muestras (15 sitios) de dos intrusivos en localidades en el valle el Sobaco y la Sierra de los Remedios para estudios paleomagnéticos y geocronología de $^{40}Ar$-$^{39}Ar$. Separados de hornblenda (215.9 ±1.9 Ma, nivel de confianza 2σ), biotita (217.3 ±1.2 Ma) y feldespato potásico (205.6 ±1.4 Ma) producen espectros de emisión de argón casi planos, pero ninguno de ellos satisface criterios estrictos de meseta, posiblemente reflejando algo de alteración. Las edades, sin embargo, son interpretadas como registros relativamente precisos de enfriamiento en el Triásico tardío de la serie plutónica, de la que se han reportado edades concordantes en zircones ca. 220 Ma por el método U-Pb. La mayoría de las muestras contienen magnetizaciones dirigidas hacia el norte y con inclinaciones moderadas positivas, similares a la dirección del campo magnético esperada en el Cenozoico tardío. No obstante, las trayectorias de desmagnetización no están dirigidas hacia el origen y en un número reducido de muestras, obtenidas principalmente en enclaves máficos, se obtuvo una dirección característica dirigida hacia el noroeste y de inclinación casi horizontal (hacia el sureste en un sitio interpretado como polaridad reversa). La magnetización se identifica después de aplicar campos alternos de ~30 mT o temperaturas arriba de los 400°C. La dirección media, corregida por el leve basculamiento (~15°) hacia el noreste de estratos del Cretácico que sobreyacen a los intrusivos es de dec=342.7°, inc=+4.2° (k=35.4, α95=9.4°, n=8 sitios) e indica una rotación anti-horaria (14°±8°) con respecto a la dirección esperada utilizando el polo de referencia de Norte América del Triásico tardío (57.5°N/84°E). También indica un pequeño desplazamiento latitudinal (7°±5°). El polo para Acatita se localiza asociado a un grupo de polos del Triásico tardío para África, Sud-América y Norte América rotados en coordenadas para Norte América. Uno de los principales obstáculos para interpretar los datos de terrenos que conforman hoy México es distinguir efectos de deformación local, como basculamiento de los intrusivos después del enfriamiento, de efectos regionales que involucran grandes desplazamientos. Rotaciones de magnitud similar y en el mismo sentido que la observada en Acatita se han observado en magnetizaciones secundarias (de edad Eoceno), sin-plegamiento, en el sector transversal de la Sierra Madre Oriental, así como en direcciones primarias en rocas volcánicas cerca de Chihuahua. Por ello, interpretamos la rotación de la paleoisla de Coahuila como un atributo Cenozoico asociado a la deformación Laramídica que afecta la región. Utilizando los datos paleomagnéticos para Coahuila y datos publicados para la región, proponemos que reconstrucciones paleogeográficas de la región ecuatorial occidental de Pangea deben reconstruir al terreno Coahuiltecano en o cerca de su posición actual con respecto a Norte América.


**PALABRAS CLAVE:** Paleomagnetismo, Coahuila, México, Triásico tardío, Pangea.


## ABSTRACT

The Acatita plutons intrude the upper Paleozoic of Las Delicias, southern Coahuila. We collected 96 samples from 15 sites in two plutons from Valle El Sobaco and Sierra Los Remedios for paleomagnetic and $^{40}Ar$-$^{39}Ar$ analyses. Separates of hornblende (215.9 ±1.9 Ma, 2σ confidence level), biotite (217.3 ±1.2 Ma), and K-feldspar (205.6 ±1.4 Ma) yield nearly flat age spectra although none of the data satisfy strict plateau criteria, possibly reflecting slight alteration. The preferred ages are interpreted as fairly precise records of Late Triassic cooling of the plutonic suite, which has yielded concordant U-Pb Zircon ages ca. 220 Ma. Most samples yield north-directed and steep positive magnetizations similar to the late Cenozoic expected field direction. Some samples, mostly from mafic enclaves, show northwest magnetization of shallow inclination (southeast at one site) with alternating fields above ~30 mT and thermal demagnetization above ~400°C. The overall mean direction, corrected for 15° northeast dip of the overlying lower Cretaceous strata (dec=342.7°, inc=+4.2°; k=35.4, α95=9.4°, n=8 sites) indicates moderate counterclockwise (14°±8°) rotation with respect to the Late Triassic cratonic reference (reference pole: 57.5°N / 84°E), and moderate southward displacement (7°±5°). The Acatita pole falls within a cluster of Late Triassic poles from Africa, South America, and North America as restored in North American coordinates. A major difficulty is distinguishing local, small-scale rotations, such as a gentle tilt of the pluton after magnetization, from regional events involving large-scale displacements. Rotations such as observed at Acatita are suggested by synfolding magnetizations (Eocene in age) in the transverse sector of the Sierra Madre Oriental and by primary magnetizations in Eocene volcanic rocks near Chihuahua. Therefore rotations of Coahuila Island may be a Cenozoic attribute related to late Laramide deformation. Reconstructions of western equatorial Pangea should place the Coahuiltecano terrane at or near its present position with respect to North America.


**KEY WORDS:** Paleomagnetism, Mexico, Coahuila, Late Triassic, Pangea.

## INTRODUCTION

Northeast Mexico is characterized by a predominance of folded upper Mesozoic sedimentary rocks that overlie a Precambrian and Paleozoic basement (López *et al*., 2001). Coahuila island (Figure 1, inset) is a Cretaceous paleogeographic element of northern Mexico that has been interpreted as a block of continental crust accreted to the North America continent during the late Paleozoic Alleghenian-Ouachita orogeny (Handschy *et al*., 1987); Coahuila island is a part of the Coahuiltecano composite terrane of Ortega-Gutiérrez *et al*. (1994). The location of the Gondwana-Laurentia suture and the late Paleozoic front of Alleghenian deformation can be traced southwards from localities in Texas to the Mexican border. After entering northern Mexico, north of Coahuila island, its position remains a subject of speculation. Most workers extend the Ouachita frontal zone from the Marathon region to central Chihuahua, but beyond it may either curve westward into Sonora, or trend southward into central Mexico (Shurbet and Cebull, 1986; Moreno *et al*., 2000). Handschy *et al*. (1987), and more recently Bartolini *et al*. (1999), have postulated that Coahuila - with Nuevo León, Tamaulipas, and parts of San Luis Potosí - formed part of a volcanic arc, comprised of late Paleozoic-earliest Mesozoic igneous and sedimentary rocks of continental arc affinity. The Coahuiltecano terrane, as other Mexican terranes underlain by Precambrian or Paleozoic continental crust, remain difficult to incorporate in reconstructions of western equatorial Pangea, mainly because of insufficient knowledge of the geology.

Most reconstructions of the Gulf of Mexico region restore Mexican terranes to the north and west of their present position, assuming Late Jurassic left-lateral strike-slip segmentation of Mexico along structures similar to the hypothetical Mojave-Sonora megashear (Anderson and Schmidt, 1983). There is an unresolved overlap between northern South America and Mexican terranes. Placing Yucatán (the Maya Block) inside the Gulf, and restoring terranes in northwest South America (Central Cordillera) to the south of their present position, reduces significantly the overlap. Clearly, parts of central and southern Mexico (Oaxaquia, after Ortega-Gutiérrez *et al*., 1995) should be reconstructed west of their present position, but northwest trending structures, such as the hypothetical Mojave-Sonora megashear, are not the only possible mechanism to reconstruct Mexican terranes. Here, we report $^{40}$Ar-$^{39}$Ar and paleomagnetic data of Triassic intrusive rocks in the Coahuila block, and we discuss some paleogeographic implications of these data.

Dickinson and Lawton (2001) examined the tectonic evolution of Mexico, whilst recent reconstructions of the Gulf region include Ross and Scotese (1989) and Pindell (1985). Displacing most of Mexico north and west of its present position is common to most recent reconstructions, as is reconstructing Yucatán in the Gulf interior. Our paleomagnetic evidence suggests that Coahuila may not require such displacement. Similar evidence has been presented for the Caborca block of northwestern Sonora (Molina-Garza and Geissman, 1999).

## REGIONAL GEOLOGIC SETTING

Our knowledge of the Paleozoic geology of Coahuila is derived principally from exposures of Upper Paleozoic marine carbonate and siliciclastic rocks in Las Delicias area (Figure 1) including abundant andesitic volcanic debris that suggest deposition southwards of and adjacent to an active volcanic arc (McKee *et al*., 1988). This interpretation is further supported by isolated exposures of Permian intrusive rocks in Coahuila (McKee *et al*., 1990; Torres *et al*., 1999) and by reports of late Paleozoic intrusions in exploratory wells in Coahuila and Nuevo León (López Ramos, 1979). The paleogeography of this arc and its relationship with the Ouachita collision are not well understood. Such lack of knowledge is in part because of widespread cover by late Mesozoic strata and Cenozoic volcanic rocks, and in part because superimposed events of Late Cretaceous-Early Tertiary folding and thrusting (Padilla y Sánchez, 1986) and Oligo-Miocene extensional deformation (Henry and Aranda, 1992) obscure regional correlations.

Pan-African U-Pb dates for granite clasts in a Jurassic conglomerate suggest that Las Delicias arc was built on continental crust of Gondwanan affinity (López *et al*., 2001). To the south and west of Las Delicias, inherited zircon ages, as well as other evidence suggest the presence of Grenvillean-age crust associated to the Oaxacan subcontinent (Ortega-Gutiérrez *et al*., 1995). Both observations are consistent with proposed continuations of the Ouachita suture near the Chihuahua-Cohuila state border (Figure 1). To the north of Coahuila "island" Jurassic sedimentation is limited to mid-Jurassic (?) to Upper Jurassic marine conglomerates and siliciclastic rocks of the Sabinas basin. Deposition of Jurassic strata was controlled by the San Marcos fault (McKee *et al*., 1990). To the south of Las Delicias arc, Jurassic rocks include volcanic and volcanoclastic rocks of the Nazas Formation.

The Sierra Madre Oriental fold and thrust belt follows the south and western margins of the Coahuila "island" (Figure 1), which experienced less intense deformation than the deep basins on its southern and western margins and the Coahuila fold belt north of it (Padilla y Sánchez, 1986). Sierra Las Delicias and its northward continuation Sierra Los Remedios are a north-south trending range where homoclinal, gently tilted, Lower Cretaceous strata overlie strongly deformed Upper Paleozoic rocks (Figure 2). The Paleozoic rocks were deformed before intrusion of the Late Triassic Acatita (Lindavista) and Cañón la Leona plutons, but appar-

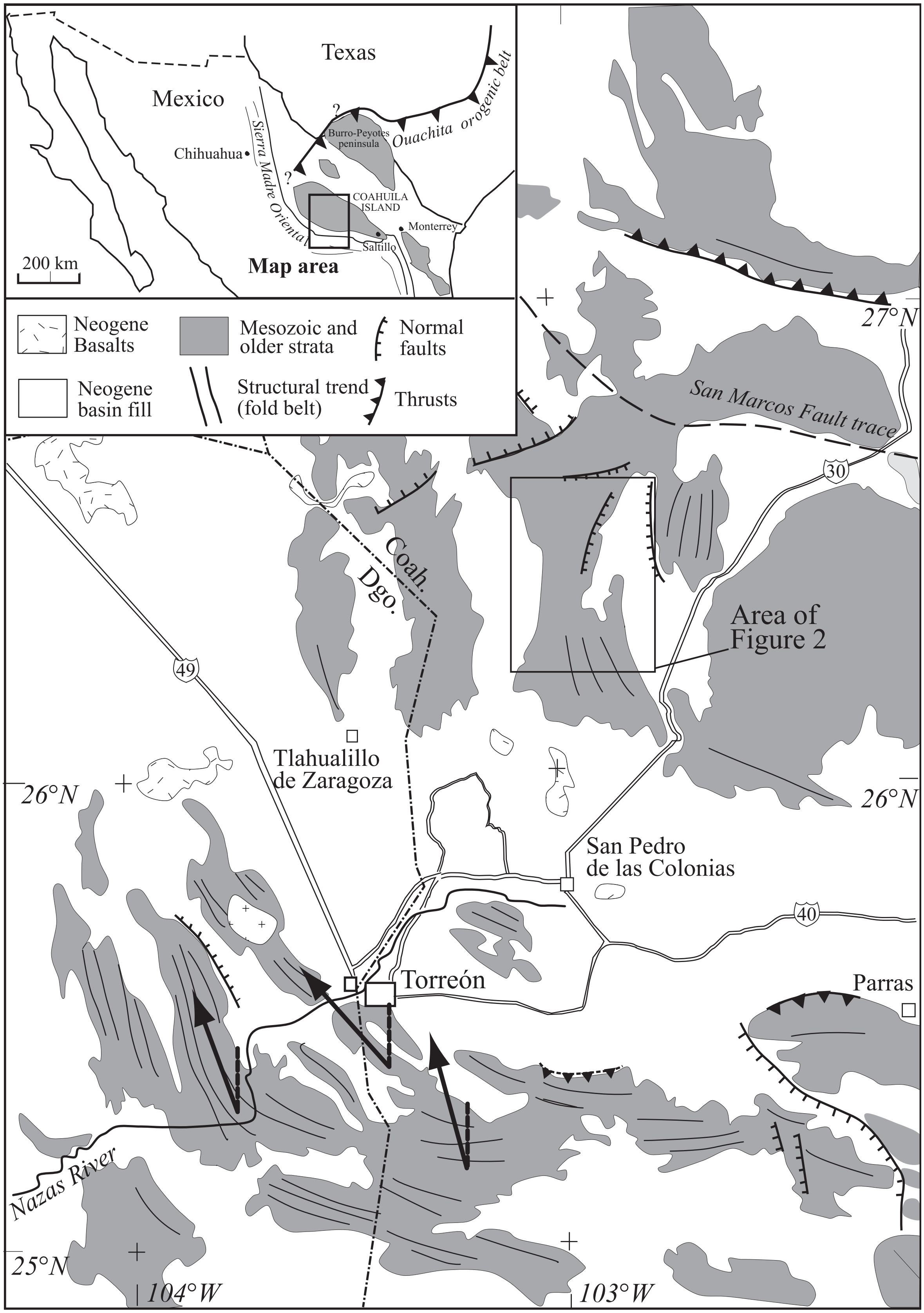


Fig. 1. Schematic tectonic map of the transverse sector of the Sierra Madre Oriental, showing the southern portion of Coahuila island, the fold belt (with main structural trends), and the location of Sierra Las Delicias. Paleomagnetic data (observed and reference declination) for Cretaceous rocks for sites south of Torreón (Nowicki *et al*., 1993) are also illustrated. The box shows the area enlarged in Figure 2.

ently after the Ouachita collision (Jones *et al*., 1995). Rocks of Las Delicias sequence lay to the south of the San Marcos fault (Figure 1), a prominent structural discontinuity along the northern margin of Coahuila "island" active during Early Cretaceous and possibly Late Jurassic time (McKee *et al*., 1990) and separating the island from the Sabinas basin. The late Triassic intrusions have been described as hornblende-biotite tonalites (*e.g*. Jones *et al*., 1995). They contain abundant mafic inclusions small (<10 cm) and subrounded. Contact aureoles are only locally developed producing marginal skarn mineralization.

## SAMPLING AND LABORATORY METHODS

We collected twelve paleomagnetic sites from Late Triassic granitoids, in the Acatita valley, and two from sites in the peculiarly named valley "El Sobaco" (Figure 2). An additional site was collected from Paleozoic carbonate rocks at this second locality. Bulk samples were also collected for $^{40}$Ar-$^{39}$Ar isotopic age determinations. Paleomagnetic samples were drilled in the field using a gas powered portable drill and were oriented *in situ* using magnetic and sun compasses. Differences in orientation using both methods are negligible and non-systematic. In the laboratory, standard (2.1 cm in diameter) paleomagnetic specimens were prepared for measurements of their natural remanence (NRM) and stepwise demagnetization. The attitude of overlying Lower Cretaceous strata was determined at several positions along the western front of the range for a structural correction.

All samples for paleomagnetic analysis were subjected to alternating field (AF) or thermal demagnetization up to inductions of 100 mT or temperatures of 590°C, respectively. Several samples were immersed in liquid nitrogen before AF demagnetization, a procedure that removed a sizeable north directed and moderately positive magnetization. For measurements of the remanent magnetization, a superconducting 2G Enterprises cryogenic magnetometer hosted in a shielded room was utilized. The vectorial composition of the NRM was determined by visual inspection of orthogonal demagnetization diagrams, and magnetization components were determined using standard principal component methods (Butler, 1992).

Mineral separation for $^{40}$Ar/$^{39}$Ar analysis, for samples from sites 8 and 12, a tonalite exposed in the Acatita valley, was done at the New Mexico Bureau of Mineral Resources using standard procedures that involve magnetic and heavy-liquid separation. Final sample selection was made by hand-picking under a binocular microscope. Mineral separates of the intrusive rocks were analyzed using conventional $^{40}$Ar/$^{39}$Ar laser step heating. Experimental and analytical details are described in Hallett *et al*. (1997).

## GEOCHRONOLOGY

Separates of hornblende (215.9 ±1.9 Ma, 2σ confidence level), biotite (217.3 ±1.2 Ma), and K-feldspar (205.6±1.4 Ma) yield nearly flat age spectra (Figure 3), although none of the data satisfy strict plateau criteria and also do not form well-defined isochrones with low MSWD values - possibly reflecting slight alteration. K/Ca ratios suggest that disturbances in the spectra of hornblende (in the low temperature steps) and biotite (at the high temperature steps) are possibly due to impurities such as alteration. The hornblende (closure temperature ~500 °C) and the biotite (closure temperature ~300 °C) give statistically indistinguishable ages near 216 Ma (Figure 3). The feldspar (closure temperature ~250-150 °C) has a slightly climbing spectrum, with a lower temperature flat segment at about 206 Ma, rising to an apparent age 210 Ma. The data are compatible with intrusion of the tonalite into shallow crustal levels (or rapid uplift from deeper crustal levels) at 216 Ma, followed by slower cooling to 150-200°C over the next 6 to 10 million years. The ages are, thereby, interpreted as relatively precise records of cooling of the granite, which has yielded concordant U-Pb Zircon ages ca. 220 Ma (Jones *et al*., 1995). Analytical data are summarized in Table 1.

## DEMAGNETIZATION RESULTS AND ROCK MAGNETISM

Most samples of the Acatita intrusions yield north-directed and steep positive magnetizations, similar to the recent dipole or the Late Cenozoic field directions. This magnetization is likely of viscous origin (Figure 4a) and, as mentioned above, is partly removed by cooling the samples to liquid nitrogen temperatures. The viscous overprint is removed with inductions of ~25 mT or temperatures of ~400 °C, and demagnetization trajectories reveal a magnetization of shallow inclination. So widespread and prominent is the overprinting component that it was not possible to isolate a characteristic magnetization (ChRM) in the majority of the samples analyzed. However, a few samples, collected mostly from mafic enclaves, contain a well-defined north-northwest and shallow ChRM that is isolated with alternating fields above about 30 mT and thermal demagnetization above about 400°C (Figure 4b and 4d). Site means were thus calculated combining stable directions from mafic enclaves and available great circle trajectories from other samples. Maximum unblocking temperatures of 590°C and intermediate coercivity values indicate that the remanence carrier is most likely magnetite. A site near Cerro el Venado contains a ChRM that is southeast directed and of negative shallow inclination (Figure 4e). The ChRM magnetization in the plutons is interpreted as a TRM (thermal remanent magnetization) acquired upon cooling.

Specimens collected in Paleozoic strata carry (*in situ*) shallow north to northwest directed magnetizations nearly

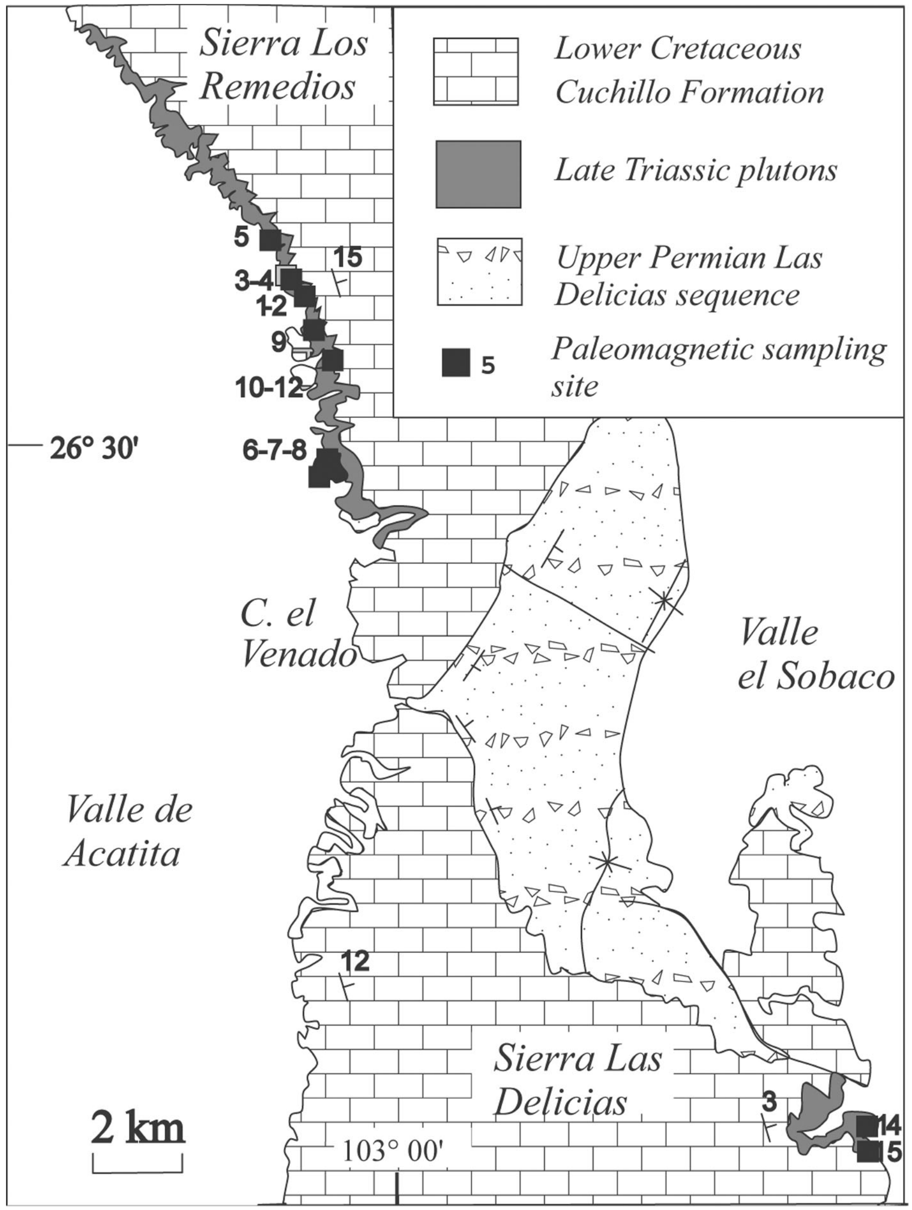


Fig. 2. Schematic geologic map of part of Sierra Las Delicias and Sierra Los Remedios, southwestern Coahuila, showing paleomagnetic and geochronologic sampling, after McKee *et al*. (1988).

identical to those in the Triassic granitoides (Figure 4f). This magnetization is interpreted as a thermal overprint associated with the Late Triassic intrusions and provides support for a primary magnetization in the plutons. Permian rocks were collected from a single site a few tens of meters from site 14 in the pluton (Figure 2). Cooling ages and distributed laboratory unblocking temperatures between 400 and 590°C suggest that the remanence in the plutons and the host-rock was locked-in between about 205 and 215 Ma.

Within site dispersion is variable with k values ranging between a low discarded site with a k value of 4.5 and a high of 89.8. Only sites with k greater than 10 were included in the overall mean. Between site scatter is relatively high, with an angular standard deviation of 15.3°, and suggests adequate averaging of paleo-secular variation over prolonged cooling of the plutons. This prolonged cooling history is also supported by the presence of magnetizations of reverse polarity.

Hysteresis curves for representative samples are shown in Figure 5. The samples are dominated by contributions from multi-domain (MD) particles, which are less marked in samples from mafic enclaves. IRM acquisition curves are also consistent with a cubic phase such as magnetite as the

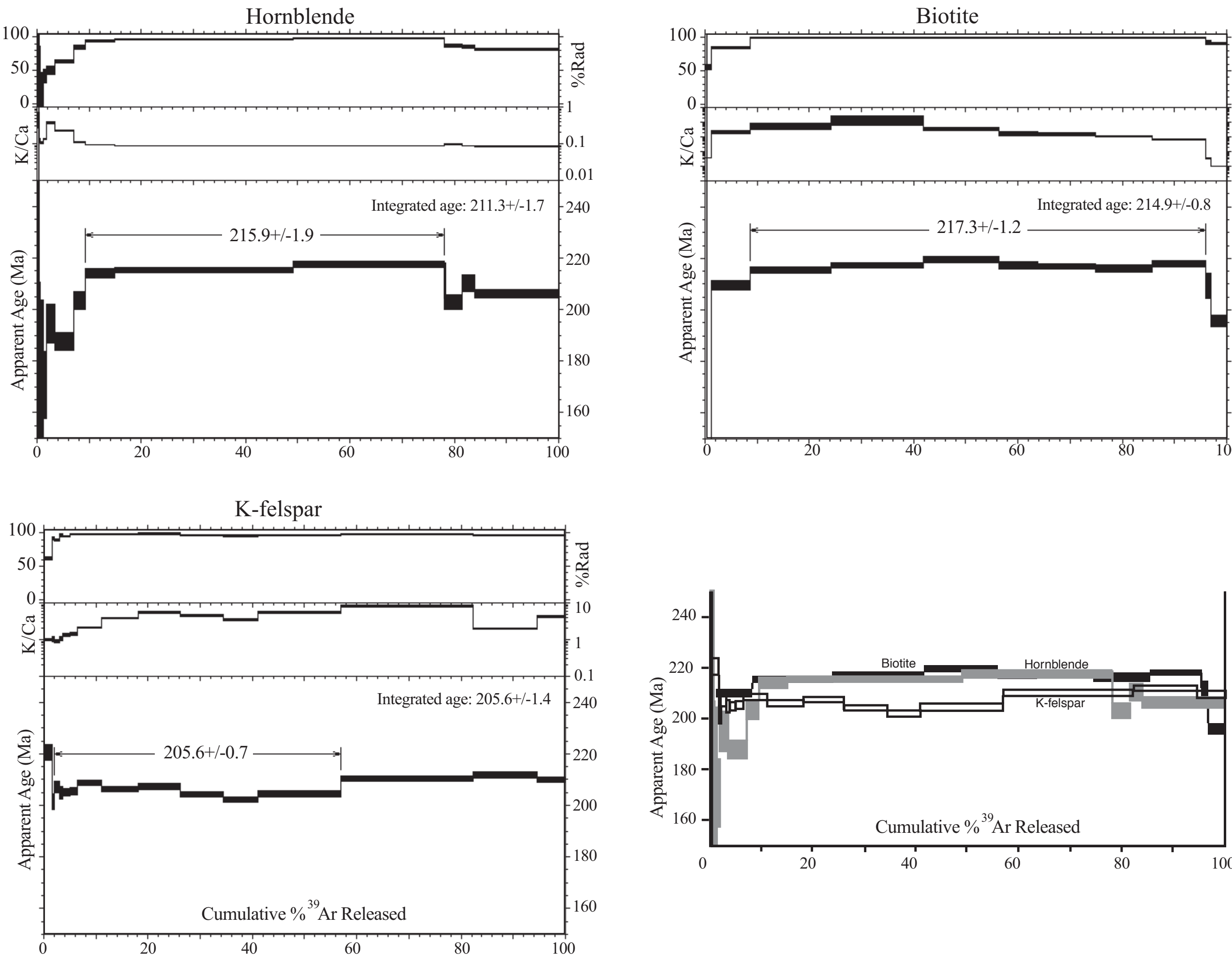


Fig. 3. $^{40}Ar/^{39}Ar$ apparent age spectra for biotite (a), hornblende (b), and K-feldspar (c) for a sample from the Acatita tonalite. Width of the horizontal bar on each diagram represents analytical error (1σ). The interval selected for age calculation is shown in each diagram.

principal remanence carrier. A relatively small population of smaller gains in the PSD (pseudo-single domain) or perhaps SD range is the likely carrier of the ChRM, whereas MD grains probably carry the prominent viscous remanence.

Polished sections of selected samples were inspected under a reflected light microscope (Figure 6). Oxide phases are readily identifiable as large magnetite grains (several hundred microns), with oxy-exsolution textures (ilmenite or hematite lamellae). Mottled ilmenite or rutile occurs as an irregular mantle on some grains; the large grains also contain silicate inclusions (Figure 6a). These grains are too large to carry a stable remanence, and possibly carry the prominent viscous overprint. Smaller grains (tens of microns in size) show thin to coarse lamellae. The smallest visible grains (Figure 6c) are rod-shaped grains about one micron in length. Some may be in the PSD or SD size range.

## DISCUSSION

The overall mean direction, corrected by the gentle (~15°) northeast dip of nonconformably overlying Lower Cretaceous strata of the Cuchillo Formation (except for sites in El Sobaco valley, where the tilt of Cretaceous strata is insignificant) is D=342.7°, 4.2° (k=35.4, $\alpha_{95}$=9.4°, n=8 sites). The tilt correction results in a small increase in the precision parameter k, suggesting that no relative tilt or rotation occurred between both sampling localities prior to Early Cretaceous time. The tilt axis is nearly parallel to the remanence declination, and the tilt correction affects only slightly the overall direction. One could criticize the inability to correct structurally paleomagnetic data from plutonic rocks. Although this criticism is valid, the fact that data for plutons on opposite sides of Sierra Los Remedios yield indistinguishable data (sites 1 through 6 versus sites 11 to 15) strongly suggests that relative rotation or tilt between these locations has not occurred. Further, the sampling localities are not

**Table 1**

| ID | Temp (°C) | $^{40}Ar/^{39}Ar$ | $^{37}Ar/^{39}Ar$ | $^{36}Ar/^{39}Ar$ (x 10-3) | $^{39}ArK$ (x 10-15 mol) | K/Ca | $^{40}Ar^*$ (%) | $^{39}Ar$ (%) | Age (Ma) | ±2σ (Ma) |
|---|---|---|---|---|---|---|---|---|---|---|
| Acatita-1, J13:47, 1.26 mg biot., J=0.000790112±0.09%, NM-47, Lab#=6421-01 | | | | | | | | | | |
| A | 650 | 782.4 | 17.12 | 2474.8 | 0.005 | 0.03 | 6.7 | 0.1 | 74 | 262.3 |
| B | 750 | 186.3 | 1.351 | 277.9 | 0.073 | 0.38 | 56.0 | 1.3 | 143 | 5.6 |
| C | 850 | 184 | 0.0246 | 95.57 | 0.455 | 20.7 | 84.7 | 8.7 | 209.5 | 1.8 |
| D | 920 | 162 | 0.0094 | 5.174 | 0.950 | 54.6 | 99.1 | 24.2 | 215.4 | 1.2 |
| E | 1000 | 162.5 | 0.004 | 1.628 | 1.090 | 127.1 | 99.7 | 42.0 | 217.4 | 1.1 |
| F | 1075 | 164.8 | 0.015 | 3.421 | 0.881 | 33.9 | 99.4 | 56.3 | 219.5 | 1.2 |
| G | 1110 | 163.4 | 0.032 | 4.461 | 0.461 | 15.9 | 99.2 | 63.8 | 217.5 | 1.4 |
| H | 1180 | 163.1 | 0.0337 | 4.897 | 0.673 | 15.1 | 99.1 | 74.8 | 216.9 | 1.2 |
| I | 1210 | 161.7 | 0.0469 | 2.554 | 0.673 | 10.9 | 99.5 | 85.8 | 215.9 | 1.3 |
| J | 1250 | 163.5 | 0.0763 | 2.999 | 0.633 | 6.7 | 99.5 | 96.1 | 218 | 1.2 |
| K | 1300 | 168.5 | 1.456 | 44.09 | 0.059 | 0.35 | 92.3 | 97.0 | 209.3 | 4.7 |
| L | 1650 | 159.5 | 4.919 | 51.86 | 0.182 | 0.1 | 90.6 | 100.0 | 195.7 | 2.3 |
| Total gas age | | | n=12 | | 6.14 | 42.2 | | | 214.9 | 1.6 |
| Plateau | | | n=7 | steps D-J | 5.36 | 46.5 | | 87.4 | 217.3 | 1.2 |
| Acatita-1, J14:47, 9.57 mg hbl, J=0.0007902272±0.09%, NM-47, Lab#=6422-01 | | | | | | | | | | |
| A | 675 | 2637.6 | 1.386 | 8514.8 | 0.009 | 0.37 | 4.6 | 0.2 | 165.7 | 436.7 |
| B | 725 | 1121.3 | 1.027 | 3361.8 | 0.009 | 0.50 | 11.4 | 0.4 | 173.9 | 176.8 |
| C | 775 | 756.3 | 4.128 | 2292 | 0.009 | 0.12 | 10.5 | 0.6 | 110 | 100.7 |
| D | 825 | 614.9 | 4.670 | 1661.7 | 0.024 | 0.11 | 20.2 | 1.1 | 169.5 | 34.4 |
| E | 875 | 304.3 | 3.830 | 606.7 | 0.032 | 0.13 | 41.2 | 1.9 | 170.8 | 13.1 |
| F | 950 | 288.8 | 1.340 | 490.3 | 0.071 | 0.38 | 49.9 | 3.5 | 194.6 | 7.5 |
| G | 1050 | 217.9 | 2.280 | 269 | 0.156 | 0.22 | 63.6 | 7.0 | 187.7 | 3.5 |
| H | 1080 | 178.2 | 4.636 | 95.06 | 0.099 | 0.11 | 84.4 | 9.2 | 203.3 | 3.4 |
| I | 1110 | 169.7 | 5.410 | 38.29 | 0.257 | 0.094 | 93.6 | 15.0 | 214.1 | 1.9 |
| J | 1140 | 165.7 | 5.876 | 21.86 | 1.520 | 0.087 | 96.4 | 19.2 | 215.3 | 1 |
| K | 1170 | 164.9 | 5.782 | 13.49 | 1.290 | 0.088 | 97.9 | 78.1 | 217.4 | 1.2 |
| L | 1200 | 172.3 | 5.312 | 76.83 | 0.146 | 0.096 | 87.1 | 81.4 | 202.9 | 2.8 |
| M | 1230 | 182.3 | 5.855 | 91.42 | 0.115 | 0.087 | 85.4 | 84.0 | 210.3 | 3.3 |
| N | 1650 | 186.5 | 5.991 | 116.7 | 0.711 | 0.085 | 81.8 | 100.0 | 206.1 | 1.6 |
| Total gas age | | | n=14 | | 4.45 | 0.100 | | | 211.3 | 3.3 |
| Plateau | | | n=3 | steps I-K | 3.07 | 0.088 | | 69.0 | 215.9 | 1.9 |
| Acatita-1 kspar A16:56, 7.80 mg, kspar, 7.80 mg, J=0.00077679±0.09%, nm-56, Lab#=7114-01 | | | | | | | | | | |
| A | 690 | 271.3 | 0.5188 | 352.3 | 0.421 | 0.98 | 61.6 | 1.6 | 220.4 | 3.1 |
| B | 690 | 166.1 | 0.4852 | 47.78 | 0.116 | 1.1 | 91.5 | 2 | 201.4 | 2.9 |
| C | 740 | 176.3 | 0.5658 | 67.11 | 0.255 | 0.9 | 88.8 | 3 | 207.1 | 2.1 |
| D | 740 | 161 | 0.4837 | 21.09 | 0.159 | 1.1 | 96.2 | 3.6 | 205 | 2.4 |
| E | 790 | 163 | 0.3763 | 27.74 | 0.376 | 1.4 | 95 | 5 | 204.9 | 1.4 |
| F | 790 | 158.3 | 0.349 | 10.32 | 0.363 | 1.5 | 98.1 | 6.4 | 205.6 | 1.4 |
| G | 890 | 160.9 | 0.2385 | 10.55 | 1.23 | 2.1 | 98.1 | 11 | 208.66 | 0.96 |
| H | 990 | 158.8 | 0.1319 | 9.853 | 1.87 | 3.9 | 98.2 | 18 | 206.3 | 0.93 |
| I | 1090 | 159.2 | 0.0929 | 8.028 | 2.16 | 5.5 | 98.5 | 26.1 | 207.4 | 1.2 |
| J | 1190 | 159.6 | 0.1104 | 17.9 | 2.19 | 4.6 | 96.7 | 34.4 | 204.31 | 0.98 |
| K | 1240 | 159.8 | 0.1494 | 23.77 | 1.78 | 3.4 | 95.6 | 41.1 | 202.4 | 1 |
| L | 1290 | 159.4 | 0.0921 | 16.67 | 4.2 | 5.5 | 96.9 | 56.9 | 204.5 | 1.1 |
| M | 1340 | 162.8 | 0.063 | 12.09 | 6.78 | 8.1 | 97.8 | 82.4 | 210.5 | 1 |
| N | 1490 | 165.8 | 0.2545 | 18.61 | 3.25 | 2 | 96.7 | 94.6 | 211.8 | 1.3 |
| O | 1750 | 164.7 | 0.1209 | 20.15 | 1.44 | 4.2 | 96.4 | 100 | 209.8 | 1 |
| Total gas age | | | n=15 | | 26.6 | 4.9 | | | 207.9 | 1.1 |
| Plateau | | | n=10 | steps C-L | 14.6 | 4.3 | | 54.8 | 205.6 | 1.4 |

Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, not corrected for interferring reactions.
Individual analyses show analytical error only; mean age errors also include error in J and irradiation parameters.
Correction factors:
(39Ar/37Ar)Ca = 0.00070±0.00005
(36Ar/37Ar)Ca = 0.00026±0.00002
(38Ar/39Ar)K = 0.0119
(40Ar/39Ar)K = 0.0002±0.0003

within the Laramide fold belt, but within Coahuila island. This area experienced much less deformation than the fold belt, and carbonate rocks of the Cuchillo formation attest to this milder deformation. They dip gently throughout most of the range providing reasonably good structural control for interpretation of paleomagnetic data. In Figure 1 we included two strike and dip readings to show the monoclinal character of the range.

Data and statistical parameters are summarized in Table 2. Six sites did not yield useful data and one site was excluded from the overall mean because its site mean is poorly defined. Site means have relatively large confidence intervals because they are defined by few samples. There is significant between-site scatter (Figure 7), which may indicate incomplete removal of the recent overprint in some sites, but a reversal test is positive and directions are not streaked in a trend towards the recent field direction. The hypothesis that the reverse polarity site mean was derived from the same distribution than the remaining sites cannot be rejected with a 95% confidence using the isolated observation test of McFadden and McElhinny (1990). The fact that both polarities were observed suggest adequate averaging of paleo-secular variation, which in turn suggests that the overall mean can be used to evaluate relative plate motions. This evaluation should consider, though, that gentle tilt of the pluton after remanence acquisition but prior to deposition of the Cretaceous Cuchillo Formation could not be detected. The relative stability of the platform during Mesozoic time argues against such tilt but no other data are available.

Previous paleomagnetic work in this area is limited. It includes a study of Lower Cretaceous strata near Torreón (Nowicki *et al.*, 1993), a study Late Triassic-Jurassic (?) volcanic rocks and redbeds of the Nazas Formation, also near Torreón (Nairn, 1976), and, in abstract form, a study of Paleozoic rocks of Las Delicias (Torres *et al.*, 1986). Paleomagnetic data are also available for the Upper Cretaceous Difunta Group (Nairn, 1976), for localities on the Coahuila platform near Saltillo. The Torreón localities are located

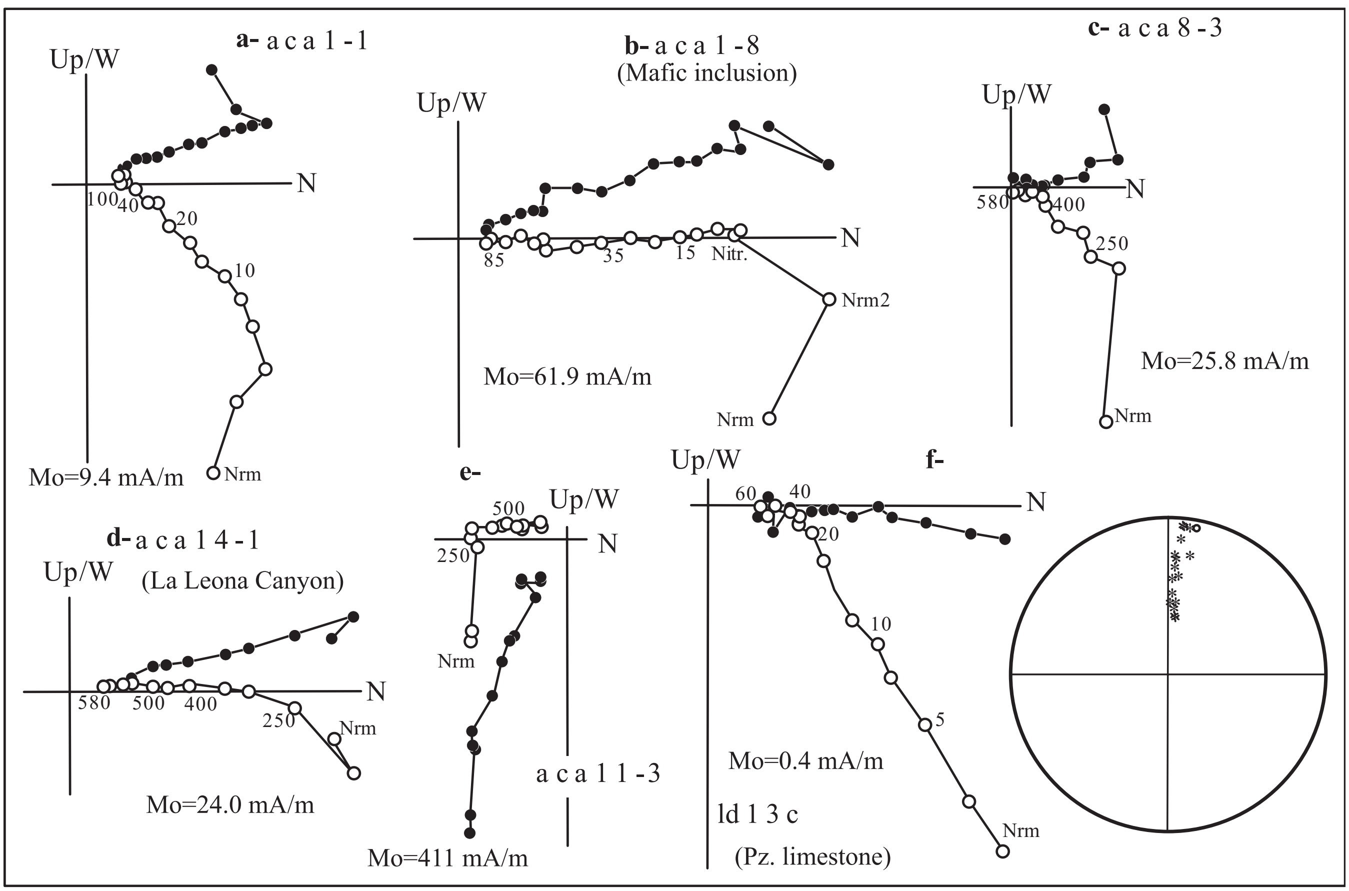


Fig. 4. (a-e) Orthogonal demagnetization diagrams of representative samples of the Acatita intrusions. Open (closed) symbols are projections on the vertical (horizontal) plane. (f) orthogonal demagnetization diagram and stereographic projection of demagnetization trajectory of a sample of the Upper Paleozoic sequence from Las Delicias. Samples such as a, c, and f yield only great circle trajectories that were combined with stable end point data.

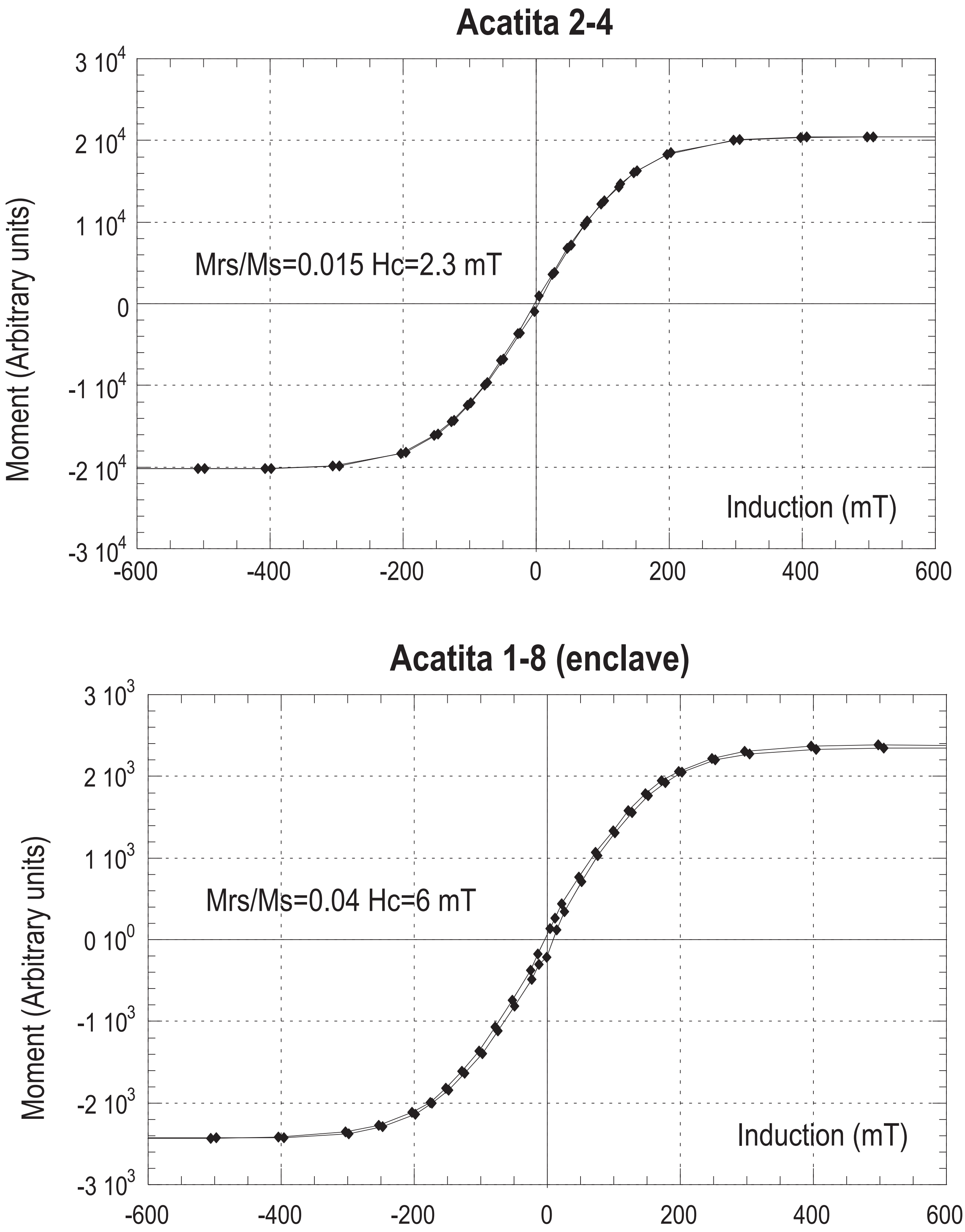


Fig. 5. Hysteresis curves for representative samples of the Acatita intrusions. Sample 1-8 is representative of the behavior observed in mafic enclaves, which generally have larger Mrs/Ms ratios than homogenous tonalite samples.

within the fold belt. There, Lower Cretaceous strata yield syn- or post-folding magnetizations interpreted to indicate moderate counterclockwise rotation of the sampling area (Nowicki *et al.*, 1993). *In situ*, magnetizations in the Nazas Formation are indistinguishable from those observed in Cretaceous strata, and may be secondary in origin. Their tectonic significance is uncertain. Of the Upper Cretaceous Difunta Group data, only a set of thirteen sites collected north of Saltillo (at Sierra Guijardo) are considered reliable and relevant to our discussion, statistical uncertainties are too large at the other two localities sampled by Nairn (1976) and no sufficient demagnetization details were published to evaluate the reliability of these data.

The Acatita plutons yield a paleomagnetic pole of relatively high quality as it is based on fully demagnetized samples, from a statistically sufficient number of samples, for a well dated rock unit, in an unambiguous structural setting, and dual polarity magnetizations are observed. An indirect field test is also available, as the magnetizations of Permian carbonate rocks has been reset by intrusion of the plutons (Figure 4). The paleomagnetic pole for the Acatita intrusions is first compared with the North American apparent polar wander path in Figure 8. The pole obtained falls at 60.5°N-114.1°E. The mean direction of the Acatita pluton is moderately rotated counterclockwise (13.9°±8.1°) with respect to the North America cratonic reference of the Late

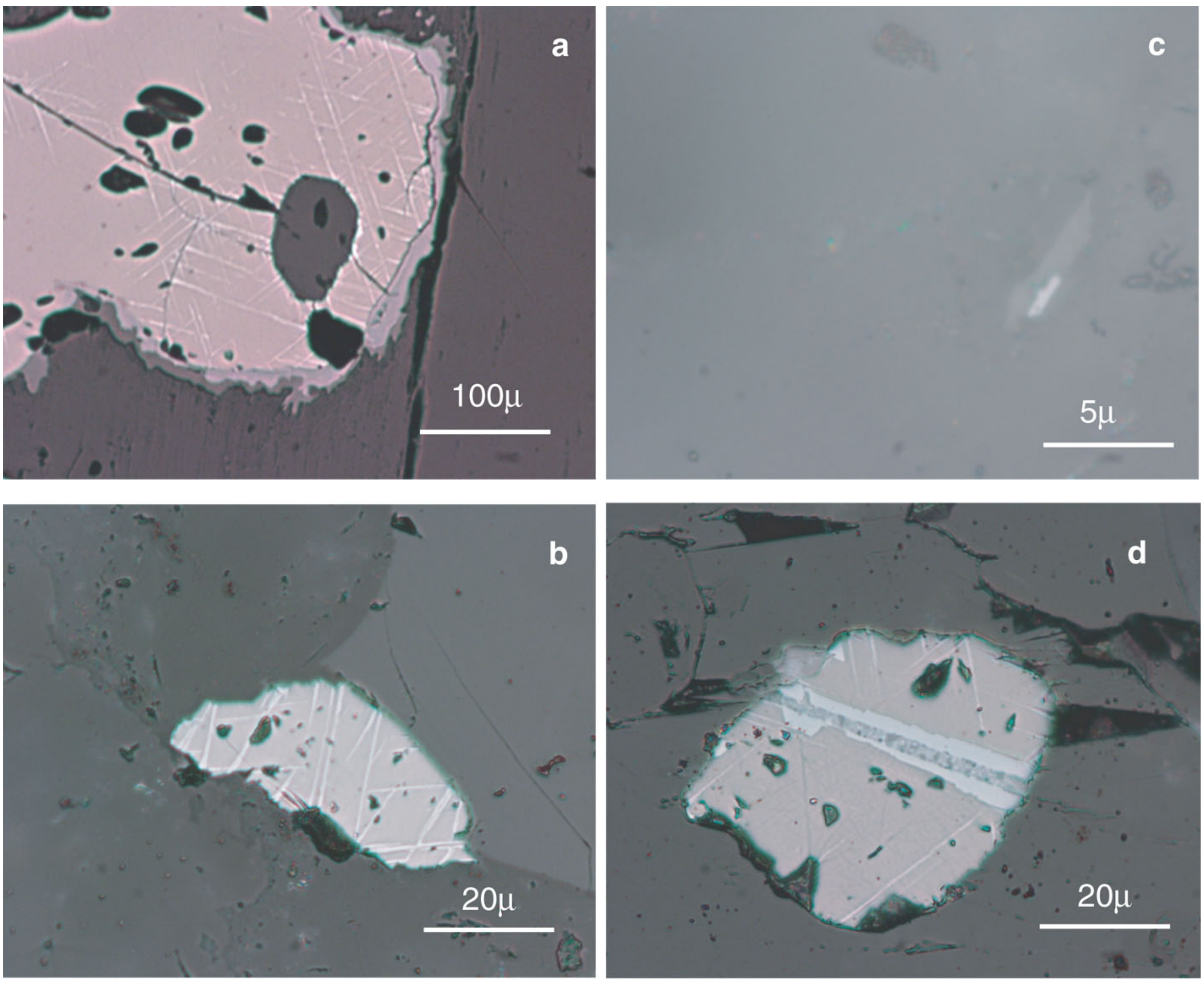


Fig. 6. Reflected light photomicrographs of typical samples of the Acatita intrusion. Notice the large to medium size grains with oxy-exsolution textures (lamellae), mantled grains (a), and composite grains (c). All host grains are magnetite, with hematite (white), ilmenite (gray), or rutile (darker gray). Grain shown in (a) contains silicate inclusions. Notice higher density of lamellae near inclusions, grain boundaries, and fractures. Grain in (c) shows earlier ilmenite and later hematite lamellae. The small grain (d) is representative of homogenous discrete crystals of magnetite, typically elongated (possible stable remanence carriers).

**Table 2**

Paleomagnetic data and statistical parameters, Acatita plutons

| Site | n\nd | dec (°) | inc (°) | k | α95 | R |
|---|---|---|---|---|---|---|
| 1 | 4\8 | 350.6 | -5.4 | 57.9 | 12.2 | 3.948 |
| 2 | 4\5 | 326.7 | 8.9 | 17.3 | 22.7 | 3.827 |
| 3 | 4\5 | 339.7 | 1.2 | 14.7 | 24.8 | 3.796 |
| 6 | 4\6 | 355.0 | 15.1 | 63.1 | 11.7 | 3.952 |
| 5* | 3\6 | 327.9 | 12.5 | 4.5 | 66.9 | 2.553 |
| 11 | 5\8 | 142.8 | -12.3 | 16.7 | 19.3 | 4.761 |
| 12 | 4\5 | 348.3 | 10.0 | 14.1 | 25.3 | 3.788 |
| 14 | 5\8 | 345.2 | 5.1 | 38.4 | 12.5 | 4.896 |
| 15 | 4\8 | 339.5 | -16.7 | 89.8 | 9.7 | 3.967 |
| Mean i.s. | 8\9 | 341 | 3.9 | 27.9 | 10.7 | 7.7493 |
| Mean t.c. | 8\9 | 342.7 | 4.2 | 35.4 | 9.4 | 7.802 |

Here, n (nd) is the number of samples used (demagnetized) in the site mean calculation, dec and inc are the declination and inclination, and k and $\alpha_{95}$ are Fisher's statistical parameters. Site 5 was excluded from the overall mean.

Triassic (Norian) and indicates a small to negligible amount of latitudinal displacement (7°±5°). Discordance parameters were calculated after Butler (1992). A major difficulty in interpreting these data is distinguishing local, small-scale, rotations, from regional event involving large-scale displacement. Counterclockwise rotation has been observed in other regions of Coahuila island, the fold belt, and localities on its western margin (Urrutia-Fucugauchi, 1981). We thus believe that before comparison with the North America reference pole, the Acatita pole needs to be restored clockwise by about 12 to 15°. This rotation of Coahuila Island may be similar to rotation of the Colorado plateau during the Laramide orogeny (Hamilton, 1981), since regions of more intense deformation and large crustal discontinuities similarly surround it. The rotated pole (using 15° and a local rotation pole) is located at 65.3°N-87.3°E (Figure 8).

The small latitudinal displacement implied by the observed inclination may not reflect tectonic motion. This interpretation is based on the good agreement between the African, North American and South American reference poles with the (restored) Coahuila datum (Figure 8). The South America pole was modified from Van der Voo (1993). It falls at 75.1°N-88.4°E, and was restored into North American coordinates closing the Atlantic ocean using the parameters of Rabinowitz and La Brecque (1979) and Lottes and Rowley

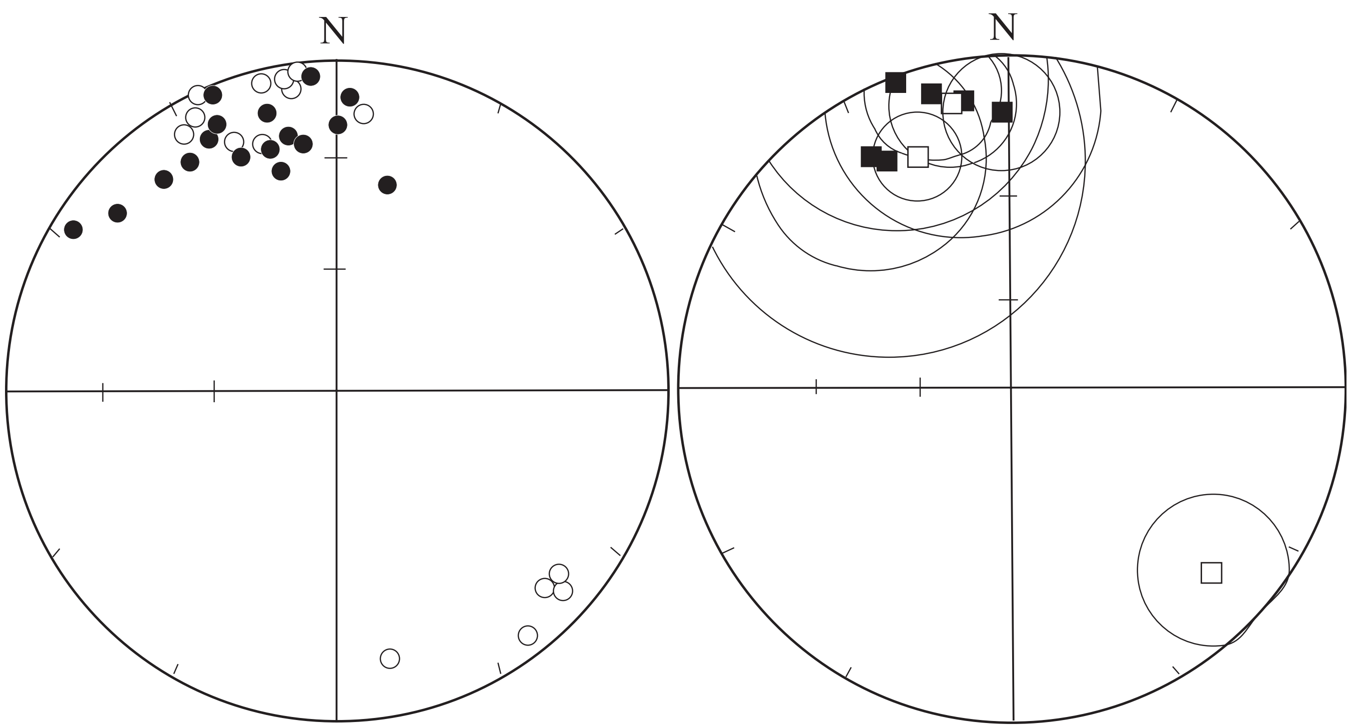


Fig. 7. Equal area stereographic projections of sample directions (a) and site means (b) or samples of the Acatita intrusive. All directions in *in situ* coordinates. Notice the relatively large between site scatter.

(1990). The rotated South American Late Triassic pole is located at 61.5°N and 96.1°E. Two African poles were obtained from Van der Voo (1993), and represent the Late Triassic (216-232) and Late-Triassic-Early Jurassic (196-215). Few poles are available for Africa in this interval. It is evident from Figure 8 that the cluster of Late Triassic poles for the continental masses, is indistinguishable from the Acatita pole.

## TECTONIC IMPLICATIONS

Paleogeographic reconstruction of western equatorial Pangea assume that must of Mexico is allochthonous (*e.g.*, Pindell and Dewey, 1982). Some fragments of continental crust in Mexican terranes may have a western Cordilleran provenance as suggested by the Mojave-Sonora megashear model, whilst others were displaced from positions near the Ouachita suture. Here we propose that reconstructions of western Pangea do not require displacing the Cohuiltecano terrane, as indicated by paleomagnetic data for the Acatita plutons. This claim is supported by paleomagnetic data for South America, North America, and Africa, restored in a reconstruction that uses the rotation parameters of Lottes and Rowley (1990). The stability of northern Mexico, including Sonora (Molina-Garza and Geissman, 1999) and Coahuila (this study) is supported by additional geochemical and geological data. Based on radiogenic isotope systematics, McDowell *et al.* (1995) and López *et al.* (2001) have inferred that the lithosphere below the axis of the SMO in west-central Chihuahua resembles that of eastern Chihuahua and

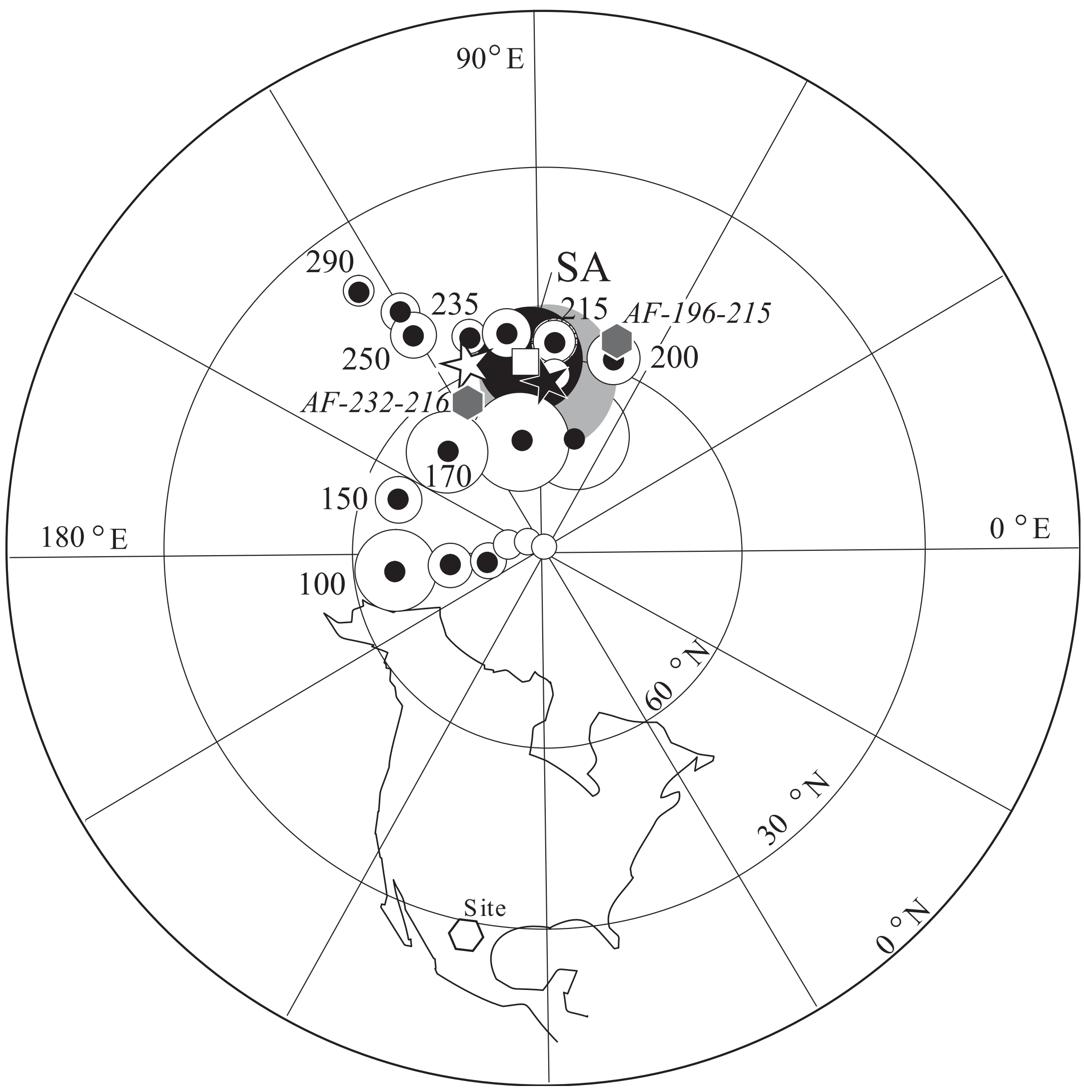


Fig. 8. Paleomagnetic poles for the Acatita plutons (closed star) compared with Paleozoic to Cenozoic paleomagnetic poles for North America (small circles; modified from Van der Voo, 1993) with the Late Triassic paleomagnetic poles for South America (open square) and Africa (hexagons) reconstructed to North American coordinates. The unrotated paleomagnetic pole for South America is located at 75.1°N – 88.4°E, and is based on five poles ranging in age from 220 to 200 Ma obtained from the global paleomagnetic database (Lock and McElhinny, 1993). The open star corresponds to the Acatita pole uncorrected for the assumed Tertiary rotation as explained in the text.

the Coahuila platform. They infer that crustal fragments of Paleozoic or older age may underlie this area, which may represent the buried continuation of the Ouachita interior. Also, abundant zircon grains of 250-280 Ma in sandstones of the Triassic Barranca Group of eastern Sonora (Gehrels and Stewart, 1998), suggest a link between the Caborca block and the Las Delicias arc of Chihuahua and Coahuila. Not enough reliable paleomagnetic data from southern Mexico are yet available to evaluate the paleogeography of other Grenvillean basement terranes in Mexico, although existing data for Oaxaca (McCabe *et al*., 1988) also indicate stability with respect to the craton. Other data for Jurassic rocks in Oaxaca have been interpreted to indicate more northern latitudes for southern Mexico (Böhnel, 1999), but these data can be also interpreted as Late Cretaceous-Early Tertiary remagnetizations (Molina-Garza and Böhnel, 2003).

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## BIBLIOGRAPHY

ANDERSON, T. H. and V. A. SCHMIDT, 1983. The evolution of Middle America and the Gulf of Mexico-Caribbean Sea region during Mesozoic time. *Geol. Soc. Am. Bull., 94,* 941-966.

BALLARD, M. M., R. VAN DER VOO and J. URRUTIA-FUCUGAUCHI, 1989. Paleomagnetic results from Grenvillian-aged rocks from Oaxaca, Mexico; evidence for a displaced terrane. *Precambrian Research, 42,* 343-352.

BARTOLINI, C., H. LANG and W. STINNESBECK, 1999. Volcanic rock outcrops in Nuevo León, Tamaulipas, and San Luis Potosí, Mexico: Remnants of the Permian-Early Triassic magmatic arc?, *Geol. Soc. Am. Spec. Pap., 340,* 347-356.

BÖHNEL, H., 1999, Paleomagnetic study of Jurassic and Cretaceous rocks from the Mixteca terrane (Mexico). *J. South Am. Earth Sci., 12*, 545-556.

BUTLER, R., 1992. Paleomagnetism; magnetic domains to geologic terranes, 319pp., Blackwell Sci. Publ., Boston, MA.

GEHRELS, G. E. and J. H. STEWART, 1998. Detrital zircon U-Pb geochronology of Cambrian to Triassic miogeoclinal and eugeoclinal strata of Sonora, Mexico, *J. Geophys. Res., B, Solid Earth and Planets, 103, 2,* 2471-2487.

HALLETT, B. R., P. R. KYLE and W. C. MCINTOSH, 1997. Paleomagnetism and $^{40}Ar/^{39}Ar$ age constraints on the chronologic evolution of the Río Puerco volcanic necks and Mesa Prieta, west-central New Mexico: Implications for transition zone magmatism. *Geol. Soc. Am. Bull., 109,* 95-105.

HAMILTON, W., 1981. Plate-tectonic mechanism of Laramide deformation. *In:* Rocky Mountain Foreland basement tectonicsm, Boyd, D.W., Lillegraven, J. A., eds., Contributions to Geology, 19, 87-92, University of Wyoming, Laramie.

HANDSCHY, J. W., G. R. KELLER and K. J. SMITH, 1987. The Ouachita system in northern Mexico. *Tectonics 6*, 323-330.

HENRY, C. R. and J. J. ARANDA-GÓMEZ, 1992. The real southern Basin and Range; mid- to late Cenozoic extension in Mexico. *Geology, 20*, 701-704.

LÓPEZ-RAMOS, J., 1979. Geología de México, Tomo II, Tesis Rezendis, México, D. F.

LÓPEZ, R., K. L. CAMERON and N. W. JONES, 2001. Evidence of Paleoproterozoic, Grenvillean, and Pan African age Gondwanan crust beneath northeastern Mexico. *Precambrian Research, 107*, 195.214.

JONES, N. W., R. LÓPEZ and K. L. CAMERON, 1995. Linda Vista plutón and latest Permian-Late Triassic orogeny, Las Delicias area, Coahuila, México. *Geol. Soc. Am. Abstr. Prog., 27*, 6, 388.

LOTTES A. L. and D. B. ROWLEY, 1990. Early and Late Permian reconstructions of Pangaea. *In:* Palaeozoic palaeogeography and biogeography, Memoir Geological Society of London 12, p. 383-395.

MCCABE, C., R. VAN DER VOO and J. URRUTIA-FUCUGAUCHI, 1988. Late Paleozoic or early Mesozoic magnetizations in remagnetized Paleozoic rocks, State of Oaxaca, Mexico. *Earth Planet. Sci. Lett., 91,* 205-213.

MCDOWELL, F. W., T. B. HOUSH and D. A. WARK, 1995. The crustal lithosphere beneath the Sierra Madre Occidental volcanic field as inferred from radiogenic isotopes in rocks from the Tomochic volcanic center, western Chihuahua, Mexico. Geol. Soc. Am. Abstr. Prog., 27, 187.

MCFADDEN, P. L. and M. MCELHINNY, 1990. Classification of the reversal test in Paleomagnetism. *Geophys. J. Int., 103*, 725-729.

MCKEE, J. W., N. W. JONES and T. H. ANDERSON, 1988. Las Delicias basin: A record of late Paleozoic volcanism in northern Mexico. *Geology, 16*, 37-40.

MCKEE, J.W., N. W. JONES and L. E. LONG, 1990. Stratigraphy and provenance of strata along the San Marcos fault, central Coahuila, Mexico. *Geol. Soc. Am. Bull., 102*, 593-614.

MOLINA GARZA, R. S. and H. BÖHNEL, 2003. Paleomagnetism of the Cretaceous Morelos and Mezcala Formations, Southern Mexico. *Tectonophysics, 361/3-4,* 301-317.

MOLINA GARZA, R. S., R. VAN DER VOO and J. URRUTIA-FUCUGAUCHI, 1992. Paleomagnetism of the Chiapas massif, southern Mexico: evidence for rotation of the Maya Block and implications for the opening of the Gulf of Mexico. *Bull. Geol. Soc. Amer., 104,* 1156 1168.

MORENO, F. A., K. L. MICKUS and G. R. KELLER, 2000. Crustal structure and location of the Ouachita orogenic belt in northern Mexico. *Geofís. Int., 39,* 229-246.

NAIRN, A. E. M., 1976. A paleomagnetic study of certain Mesozoic formations in northern Mexico. *Phys. Earth Planet. Int., 13,* 46-56.

NOWICKI, M. J., S. A. HALL and I. EVANS, 1993. Palaeomagnetic evidence for local and regional post-Eocene rotations in northern Mexico. *Geophys. J. Int., 114,* 63-75.

PINDELL, J. and J. F. DEWEY, 1982. Permo-Triassic reconstruction of western Pangea and the evolution of the Gulf of Mexico/Caribbean region. *Tectonics, 1, 2,* 179-211.

ORTEGA-GUTIÉRREZ, F., R. L. SEDLOCK and R. C. SPEED, 1994. Phanerozoic tectonic evolution of Mexico. *In:* Speed, R.C., Phanerozoic Evolution of North American Continent-Ocean Transitions, Boulder Colorado. Geol. Soc. Amer., DNAG Continent-Ocean Transect Volume, 265-306.

ORTEGA-GUTIÉRREZ, F., J. RUIZ and E. CENTENO-GARCÍA, 1995. Oaxaquia, a Proterozoic microcontinent accreted to North America during the late Paleozoic. *Geology, 23,* 1127-1130.

PADILLA Y SÁNCHEZ, R. J., 1986. Post-Paleozoic tectonics of northeast Mexico and its role in the evolution of the Gulf of Mexico. *Geofís. Int., 25,* 157-206.

RABINOWITZ, P. and J. LABRECQUE, 1979. Am. Ass. Petr. Geol., Map sheet Gondwana.

SHURBET, D. H., and S. E. CEBULL, 1986. Tectonic interpretation of the westernmost part of the Ouachita-Marathon (Hercynian) orogenic belt, west Texas-Mexico. *Geology, 15,* 458-461.

TORRES, V., R. VAN DER VOO and J. URRUTIA-FUCUGAUCHI, 1986. Remagnetization of Permian rocks from Las Delicias, México. Eos Trans. Amer. Geophys. Union, 67, 267.

TORRES, R., J. RUIZ, P. J. PATCHETT and M. GRAJALES, 1999. Permo-Triassic continental arc in eastern Mexico; tectonic implications for reconstructions of southern North America. *In:* Mesozoic sedimentary and tectonic history of north-central Mexico. *Geol. Soc. Amer. Spec. Pap., 340*, 191-196.

URRUTIA-FUCUGAUCHI, J., 1981. Paleomagnetic evidence for tectonic rotation of northern Mexico and the continuity of the Cordilleran orogenic belt between Nevada and Mexico. *Geology, 9,* 179-183.

VAN DER VOO, R., 1993, Paleomagnetism of the Atlantic, Tethys and Iapetus oceans, 411 p., Cambridge Univ. Press, United Kingdom.

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