Geofísica Internacional 47 (1), 41-55 (2008)

Paleomagnetic study of Jurassic and Cretaceous rocks north of San Marcos fault, central Coahuila, México.

G. A. González-Naranjo[1]*, R. S. Molina-Garza[2] and G. Chávez-Cabello[3]
[1]Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Querétaro, Mexico.
[2]Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Querétaro, Mexico.
[3]Facultad de Ciencias de la Tierra, Universidad Autónoma de Nuevo León, Linares, Nuevo León, Mexico.

Received: April 1, 2006; accepted: November 13, 2007

Resumen

Capas continentales de edad Jurásico Superior y Cretácico Inferior, en el núcleo del anticlinal de la Sierra de La Fragua en el centro de Coahuila, presentan una magnetización característica de polaridad dual, que interpretamos como una magnetización primaria remanente química. Areniscas eólicas y fluviales del Jurásico Superior que conforman las capas Colorado, presentan una media de D=10.2° I°=28.2° (n=18 sitios, k=22.1, α_{95}=7.5°). Areniscas fluviales del Cretácico Inferior de la Formación San Marcos dan una media combinada de D=358.1°, I=46.4° (n=13 sitios, k=22.7, α_{95}=8.9°), pero los sitios estratigráficamente inferiores en el lado este del anticlinal tienen una dirección sur-suroeste y una magnetización negativa moderadamente alta (D=191.7°, I=-54.9°; k=38.7, α_{95}=9.8, n = 7 sitios), los cuales son estadísticamente diferentes de la magnetización dirigida al noroeste (D=333.6°, I=58.0°; k=28.3, α_{95}=12.8°, n=6 sitios) observada en los sitios estratigráficamente más altos en la parte central-occidental del anticlinal. Interpretamos la diferencia en las inclinaciones en la Formación San Marcos como el resultado de la rotación durante la depositación de esta unidad. La magnetización característica con inclinación somera en los estratos jurásicos es también discordante con respecto a la dirección de referencia para el Jurásico Tardío. Tanto la Formación San Marcos inferior como las capas Colorado indican rotación en sentido horario de 38.5°±8.3° y 30.0°±2.3° respectivamente. Los sitios de muestreo se encuentran localizados dentro de una cuña clástica que registra la actividad de la Falla San Marcos durante el Jurásico Tardío y el Cretácico Temprano. Datos estructurales indican que durante la depositación de las capas Colorado y la Formación San Marcos, la falla se comportó como una falla normal con una pequeña componente lateral-derecha. El area de Potrero Colorado se interpreta como una zona de relevo en la falla San Marcos, la cual acomodó rotación horaria registrada en los estratos Jurásico Superior-Cretácico Inferior.

Palabras clave: Falla San Marcos, Paleomagnetismo, Potrero Colorado, Sierra La Fragua, Coahuila.

Abstract

Upper Jurassic and Lower Cretaceous continental strata at Potrero Colorado, in the core of Sierra La Fragua anticline in central Coahuila, carry dual-polarity characteristic magnetizations that we interpret as near primary chemical remanent magnetizations. Upper Jurassic fluvial and eolian sandstones of the Colorado beds yield a tilt-corrected mean of D=10.2° I=28.2° (n=18 sites, k=22.1, α95=7.5°). A steeper inclination magnetization observed in five sites of the Colorado beds is interpreted as a secondary, post-Laramide folding, magnetization. Lower Cretaceous fluvial sandstones of the San Marcos Formation yield a combined mean of D=358.1°, I=46.4° (n=13 sites, k=22.7, α95=8.9°), but the stratigraphically lower sites on the eastern side of the anticline have south-southwest directed and moderately steep negative magnetizations (mean of D=191.7° I=-54.9°; k=38.7, α95=9.8°, n=7 sites) which are statistically distinct from northwest directed magnetizations (mean of D=333.6° I=58.0°; k=28.3, α95=12.8°, n=6 sites) observed in stratigraphically higher sites in the west-central part of the anticline. We interpret the difference in declinations in the San Marcos Formation as the result of rotation during deposition of this unit. The characteristic shallow-inclination magnetization in Jurassic strata is also discordant with respect to the Late Jurassic reference direction. Both, the lower San Marcos Formation and the Colorado beds indicate clockwise rotations of 38.5°±8.3° and 30.0°±2.3°, respectively. The sampling sites are located within a clastic wedge that records activity of the San Marcos fault during Late Jurassic and Early Cretaceous time. These data indicate that during deposition of the Colorado beds and San Marcos Formation, the fault behaved as a normal fault with a small right-lateral component. The area of Potrero Colorado is interpreted as a zone of relay in the normal San Marcos fault, which accommodated clockwise rotation recorded by Upper Jurassic and Lower Cretaceous strata.

Key words: San Marcos fault, Paleomagnetism, Potrero Colorado, La Fragua Range, Coahuila.

Introduction

The San Marcos fault (SMF) is an important multi-reactivated basement fault in northeast Mexico (McKee *et al*., 1990; Chávez Cabello *et al*., 2005; Aranda-Gómez *et al*., 2005). The fault originated in the Jurassic, and had periods of activity in the Early Cretaceous and Early and Late Tertiary. The fault is the boundary between the Coahuila Block and the Sabinas basin (Fig. 1). The Coahuila block, to the south, is an uplifted late Paleozoic volcanic arc, which remained exposed until mid-Cretaceous time and shed detritus into the Sabinas basin. The Sabinas basin, to the north, contains a thick Jurassic to Cretaceous sedimentary sequence. The stratigraphic record of activity of the fault is a clastic wedge that thins to the north, towards the basin, and is well exposed in the area of Potrero Colorado in the western part of Sierra La Fragua (Fig. 1). Although McKee *et al*. (1990) proposed that the SMF behaved as a left-lateral strike-slip in Jurassic time, recent work by Chávez-Cabello *et al*. (2005) found that the evidence of strike slip movement is less than compelling. These authors suggest that the initial movement along the fault was primarily normal and that the structure was reactivated as a reverse fault during the Laramide orogeny. A significant component of left-lateral slip along the fault would be supported by rotations, particularly at fault bends that may result in transtension or transpression. At Potrero Colorado the SMF changes from an WNW orientation to the east of the area, to a ESE in the area of study, and then again to an WNW orientation to the west of the area (Fig. 1). McKee *et al*. (1990) linked hypothetical left-lateral slip along the SMF to the Mojave-Sonora megashear model for the opening of the Gulf of Mexico (e.g., Anderson and Schmidt, 1983). If the fault had a significant component of left-lateral slip, this geometry would result in a transtensional regime with NW directed extension. We show, however, that Jurassic faults within the Potrero indicate NE directed extension. In this work we present paleomagnetic and structural data, bearing on the interpretation of the kinematics of the San Marcos fault, during Late Jurassic and Early Cretaceous time.

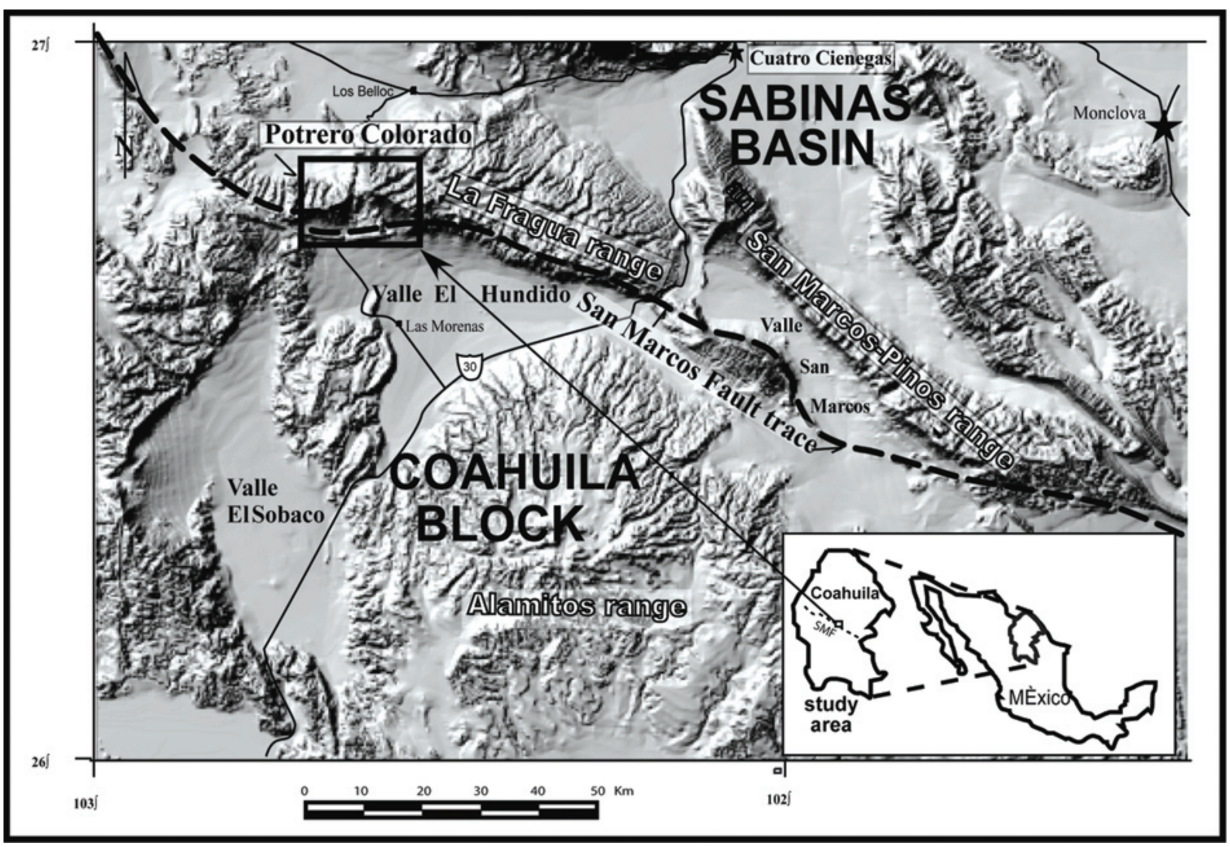

Fig. 1. Digital elevation map of a portion of NE Mexico showing the location of the San Marcos Fault trace and the study area.

Table1

Paleomagnetic data and statitstical parameters for the high-temperature component of the Upper Jurassic Colorado beds at Potrero Colorado, Coahuila.

Site	n/N	West	North	D (°)	I (°)	k	α95(°)	Observations
1	4/6	102°37’21.4”	26°45’ 33.5”	32.0	48.7	22.7	19.7	s-i
2	4/8	102°37’23.5”	26°45’ 38.9”	15.0	8.9	12.1	27.6	s-i
3	4/7	102°37’29.3”	26°45’ 41.8”	17.7	30.3	20.9	20.6	s-i
4	3/8	102°38’03.5”	26°45’ 43.2”	33.1	19.1	29.1	23.3	s-i
4gc	5/8	102°38’03.5”	26°45’ 43.4”	202.1	-28.8	16.7	28.3	s-i
5	6/7	102°37’47.3”	26°46’09.5”	356.9	30.7	14.3	18.3	s-i
6	5/6	102°37’40.1”	26°45’ 41.4”	0.9	13.1	32.0	13.7	s-i
7	3/7	102°37’56.6”	26°46’ 01.6”	321.9	57.2	11.1	38.9	s-i
8	5/7	102°37’15.2”	26°45’ 27.7”	6.7	33.6	28.2	14.7	s-i
8	6/7	102°37’15.2”	26°45’ 27.7”	324.6	48.5	20.2	15.3	h-i
9gc	7/9	102°37’48.7”	26°45’ 56.2”	186.0	-25.6	16.1	20.8	s-i
11	2/11	102°37’57.7”	26°46’ 09.5”	22.7	18.7			X
12	5/11	102°38’ 1.3”	26°46’ 03.4”	354.2	14.3	13.3	21.8	s-i
13	2/7	102°37’17.0”	26°45’ 46.8”	346.8	32.0			X
10-11-13	8/25	102°37’30.6”	26°45’50.8”	154.0	-54.6	25.7	22.6	h-i
14	5/7	102°37’16.7”	26°45’ 55.1”	350.5	12.6	7.2	30.5	s-i
15	5/7	102°37’17.0”	26°45’ 37.4”	359.7	16.2	13.8	26.4	s-i
16	4/7	102°37’29.3”	26°45’ 19.4”	0.7	6.2	8.5	33.8	s-i
17	5/7	102°37’37.7”	26°46’ 03.0”	15.0	31.5	14.7	20.6	s-i
18	5/9	102°37’20.6”	26°46’ 17.0”	20.8	18.0	12.4	22.6	s-i
19	3/7	102°37’43.0”	26°46’ 01.6”	359.3	20.8	21.6	27.2	s-i
20	5/6	102°37’21.4”	26°45’ 43.6”	341.4	23.7	23.8	16.0	s-i
21	4/7	102°37’54.8”	26°45’ 56.2”	173.4	-55.3	93.9	18.0	h-i
23	1/5	102°37’01.2”	26°45’ 58.7”	18.7	38.5			X
24	3//6	102°37’18.1”	26°46’ 04.8”	328.9	17.5	7.1	50.2	X
25	3/7	102°37’35.0”	26°45’ 37.6”	328.9	57.8	28.2	23.6	h-i
26-27	4/8	102°37’47.6”	26°45’44.3”	27.0	8.5	9.0	32.3	s-i
	2/5	102°37’21.0”	26°45’55.1”					
MEAN A magnetization	**18**			**8.4**	**22.3**	**22.1**	**7.5**	
MEAN B magnetization	**5**			**332.4**	**55.2**	**101.3**	**7.6**	

Here: **n** number of samples treated per site; **N** is the number of samples used in the site means calculation; **D** and **I** are the declination and inclination of the remanent magnetization (*in situ* coordinates) *k* and α95 are the statistical paramenters of the Fisher distribution. Sites eliminated = X, and sites we used great circle trajectories are indicated with gc. s-i, shallow inclination; h-i, high-inclination

Geological setting

The study area at Potrero Colorado is a stratigraphic window where Jurassic rocks are exposed in the core of the anticline that conforms Sierra La Fragua (Fig. 2). This mountain range is essentially formed by folded Lower Cretaceous carbonate rocks. The anticline is asymmetric; it oversteeps to the south towards the SMF. Folding is attributed to the Early Tertiary Laramide orogeny, which in this area is characterized by early NE directed compression and later SW directed compression (Chávez-Cabello, 2005). Sierra La Fragua is a complex structure that records both events. The earlier phase formed a fault-bend fold exposed on the eastern part of the range. Chávez-Cabello (2005) has shown that in the later stages of the Laramide orogeny, the originally normal SMF was inverted, and behaved as a high angle reverse fault. The anticline at Sierra La Fragua at Potrero Colorado is thus interpreted as a drape fold related to the second pulse of Laramide deformation.

McKee *et al*. (1990) studied the stratigraphy of Potrero Colorado and adjacent areas where Jurassic and Cretaceous strata record activity of the SMF; the units defined by these authors are described succintly below.

Jurassic rocks.- The oldest strata exposed at Potrero Colorado are red sandstone and siltstone underlying a thick sequence of eolianites, which McKee *et al*. (1990) interpreted the sandstone and siltstone sequence as marine Jurassic strata that they correlate with the Tanque Cuatro Palmas beds of Valle San Marcos about 40 km to the east (Fig. 1). At Valle San Marcos the Tanque Cuatro Palmas beds underlie arkoses of the San Marcos Formation. The rocks we sampled for paleomagnetism are fine to medium grained sandstones, interbedded with red siltstone and mudstone. Common sedimentary structures include climbing ripples, dissecation cracks, rain impacts, trough cross bedding, and parallel bedding. These sedimentary structures, together with observations of petrified wood clasts in conglomerate beds, are not consistent with a marine environment of deposition. We interpret these strata as fluvial deposits. Possibly transitional environment strata are exposed in one isolated small outcrop of red wavy and cross bedded sandstone on the eastern part of Potrero Colorado.

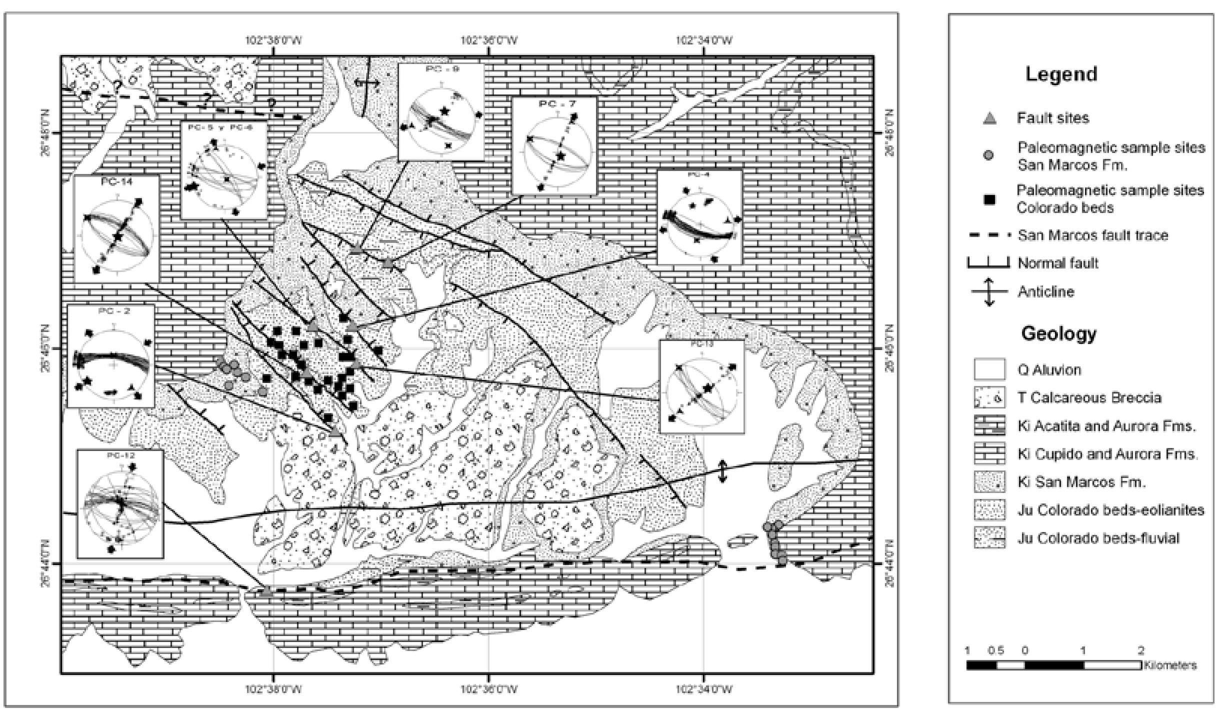

Fig. 2. Simplified geologic map of Potrero Colorado area, showing paleomagnetic sampling sites and stereographic nets of structural data (fault sites).

Table2

Paleomagnetic data and statitstical parameters for the high-temperature component of the Lower Cretaceous San Marcos Formation at Potrero Colorado, Coahuila

East flank (lower San Marcos Formation)

Site	n/N	West	North	D (°)	I (°)	k	α95(°)	Bedding	Tilt Corrected D(°)	Tilt Corrected I (°)	Observations
28	7/7	102°33’18.0”	26°44’21.5”	194.3	-20.0	52.6	12.1	125,29	186.2	-46.5	gc
29	5/5	102°33’19.4”	26°44’20.4”	194.2	-37.5	135.7	24.4		176.4	-3.1	gc
30	5 /7	102°33’18.0”	26°44’21.5”	184.5	-32.2	117.1	15.1		166.5	-5.0	gc
31	4 /6	102°33’22.0”	26°44’19.7”	147.3	-42.8	36.3	27.0		117.8	-6.8	gc X
32	6/9	102°33’24.1”	26°44’20.4”	181.4	-45.1	79.2	14.5	85,10	182.9	-5.1	gc
32n	2/9	102°33’24.1”	26°44’20.4”	333.4	24.2				331.3	33.4	X
33	4 /7	102°33’21.6”	26°44’16.1”	206.9	-42.8	34.0	22.5		213.0	-1.0	gc
34	4 /7	102°33’20.2”	26°44’11.4”	197.8	-43.3	21.6	44.8		202.5	-2.4	gc X
35	6 /8	102°33’19.8”	26°44’ 09.2”	196.7	-53.8	14.3	26.2		203.6	-2.9	gc
36	6 /6	102°33’19.8”	26°44’ 05.3”	205.8	-44.0	43.9	17.4		212.1	-52.3	gc
37	2/2	102°33’16.2”	26°44’ 04.6”	339.1	35.7				336.6	45.3	X
38	2/5	102°33’15.8”	26°44’ 01.7”	357.6	57.5				358.6,	67.5	X
Mean	**7**			**194.6**	**-39.8**	**38.7**	**9.8**		**191.7**	**-54.9**	

West flank (upper San Marcos Formation)

Site	N	West	North	D (°)	I (°)	k	α95(°)	Bedding	Tilt Corrected D(°)	Tilt Corrected I(°)	Observations
42	6/6	102°38’05.6”	26°45’ 35.6”	321.8	47.9	45.6	10.0	60,8	320.2	55.8	
44	6/6	102°38’19.7”	26°45’ 46.4”	1.6	56.8	52.5	8.4		9.7	63.3	
45	5/6	102°38’15.0”	26°45’ 43.9”	346.8	44.8	19.2	15.7		349.6	52.4	
46	2/4	102°38’21.5”	26°45’ 50.8”	335.9	72.7				340.8	80.6	X
47	5/6	102°38’29.0”	26°45’ 51.8”	346.5	55.8	20.7	25.3		350.9	63.4	
48	3/6	102°38’27.2”	26°45’ 49.7”	317.7	33.7	27.5	24.0		316.3	41.5	
50	4 /4	102°38’25.8”	26°45’ 48.2”	218.3	-55.7	74.7	36.3		230.1	- 57.9	gc X
52	3/7	102°38’24.4”	26°45’ 39.2”	312.4	52.7	22.4	26.7		308.3	60.2	
Mean	**6**			**333.0**	**50.0**	**28.3**	**12.8**		**333.6**	**58.0**	

East and West flank (San Marcos Formation)

		In situ				Tilt Corrected			
	N	**D (°)**	**I (°)**	***k***	**α95(°)**	**D (°)**	**I (°)**	***k***	**α95(°)**
Mean	**13**	**358.1**	**46.4**	**15.3**	**10.9**	**355.3**	**57.7**	**22.7**	**8.9**

Here: **n** number of samples treated per site; N is the number of samples used in the site means calculation; **D** and **I** are the declination and inclination of the remanent magnetization; k, R and α95 are the statistical parameters of the Fisher distribution. Sites eliminated = X and sites we used great circle trajectories are indicated with gc.

The sandstone and siltstone sequence is about 100 m thick and its base is not exposed. The top is marked by a 10 m thick polimictic conglomerate. Overlying the conglomerate there is a ~200 m thick package of eolian sandstones. This unit, first described by Charleston (1974), was interpreted by McKee *et al*. (1990) as coastal-dune deposits. Large-scale plannar cross bedding suggests south to southeast wind directions. Sandstones are well-sorted, medium to fine-grained, hematitic, quartz-arenites. Together, the fluvial sandstones, the conglomerate, and the eolianites are included in the Colorado beds of McKee *et al*. (1990).

The Colorado beds and the underlying sequence lack age diagnostic fossils, but they are in the same stratigraphic position as the Tanque Cuatro Palmas beds, directly underlying the San Marcos Formation. The Tanque Cuatro Palmas beds are green olive sandstones with low-angle cross stratification intercalated with fine siliciclastic sediments. McKee *et al*. (1990) report ammonoides from this unit identified as Proniceras and Substeueroceras, and are assigned to the Tithonian (latest Jurassic). A Late Jurassic age has thus been inferred for the Colorado beds, but the correlation is solely based on stratigraphic position.

Cretaceous strata.- The San Marcos Formation overlies the eolianites in what appears to be an erosional unconformity. The San Marcos Formation consists of hematitic coarse conglomeratic sandstone, conglomerate, siltstone and mudstone. Sandstone lenses are interpreted as fluvial channel deposits; they also include basal lag-gravel deposits and cut and fill structures; these beds occasionally present graded bedding. Composition of the sandstones is arkosic to subarkosic. Conglomerates are typically polymictic and coarse, and contain clasts of granite, limestone, and volcanic rocks. At Potrero Colorado the San Marcos Formation is about 400 m in thickness. Sandstones are medium to thick bedded. The San Marcos fines upward towards the contact with the overlying Cupido Formation.

Although the San Marcos Formation also lacks age diagnostic fossils, the age estimated for this unit is Neocomian. The contact with the Cupido Formation is transitional, sandstones near the top of the San Marcos become progressively green and carbonate rich; the age of the Cupido Formation is biostratigraphically established as Aptian (Lehmann *et al*., 1999). The Cupido Formation consists of reefal limestones that bordered a carbonate platform that faces east and south (Lehmann *et al*., 1999). Within the platform, limestones of the Cupido Formation are light-gray thick to medium bedded peritidal facies, but the Coahuila Block remained exposed during much of Cupido deposition. Overlying the Cupido Formation is La Peña Formation, a stratigraphic marker throughout northeast México consisting primarily of fossiliferus shales and shaley limestone. The age of La Peña Formation is Late Aptian, and is overlain by the Acatita Formation. The Acatita Formation are interior platform facies of an Albian age carbonate platform formed on the Coahuila block (Lehmann *et al*., 1999). It consists of wackestones and mudstones intercalated with gypsum beds.

At Potrero Colorado the SMF has a general E-W orientation, with subtle changes in orientation. Fault stations throughout the area (Fig. 2, Table3), for which we inverted the fault data using the INVD program of Angelier (1990) document minor right-lateral slip parallel to the SMF at stations PC-2 and PC-4 (Fig. 2) and NW-SE oriented normal faults such as at stations PC-7, PC-9, PC-13 and PC-14 (Fig. 3). These structures only affect the Colorado beds and they are buried by the Cupido Formation, thir age is syn to pre-Neocomian. Laramide strain was documented at station PC-12.

Table 3

Ubication of fault sites

Site	West	North
Pc-2	102° 37’ 16.3”	26° 45’ 1.5”
Pc-4	102° 37’ 19.9”	26° 46’ 8.4”
Pc5-6	102° 37’ 41.2”	26° 46’ 11.0”
Pc-7	102° 36’ 55.9”	26° 46’ 48.1”
Pc-9	102° 37’ 12.0”	26° 46’ 56.7”
Pc-12	102° 38’ 3.4”	26° 43’ 45.3”
Pc-13	102° 37’ 14.1”	26° 45’ 50.9”
Pc-14	102° 37’ 39.6”	26° 45’ 47.3”

Sampling and laboratory methods

We collected samples from two units for paleomagnetic study. In ascending stratigraphic order this include the basal sandstone and siltstone sequence and the eolianites of the Colorado beds, and the sandstone and conglomerates of the San Marcos Formation. We also sampled red sandstone clasts in the San Marcos Formation which are interpreted as derived from the underlying eolianites. In the Jurassic Colorado beds we collected 30 sites in both eolianites and the underlying fluvial sandstones. The sites were mostly collected in the core of the anticline of Sierra la Fragua, where they dip gently (~6°) to the south (Fig. 2). In the San Marcos Formation we collected a total of 20 sites, 11 of them on the eastern part of the Potrero Colorado, where they dip gently to the southeast (~6 to 10°), and 9 in the central area of the fold.

The rocks were collected in the field with a gas powered portable drill cooled with water using a diamond impregnated stainless steel drill bit. Five to ten samples were collected from each site (=one bed). The cores were oriented *in-situ* with magnetic and sun compasses and an inclinometer, and marked with indelible ink. In the laboratory, one or two specimens were cut from each sample with a saw blade.

The intensity and direction of the natural remanent magnetization (NRM) was determined with a JR-5 spinner magnetometer from *AGICO*. All samples were subjected to either alternating field (AF) or thermal demagnetization. For AF demagnetization we used a *LDA-3a* AF demagnetizer from AGICO, and for thermal demagnetization we used an ASC Scientific TD-48 S thermal demagnetizer.

Pilot specimens were demagnetized in about 15 steps up to 680° C; an abbreviated demagnetization sequence was used for the rest of the collection. Magnetic susceptibility was monitored throughout the process using a Kappabridge. Progressive AF demagnetization was applied up to peak inductions of 100 mT. The vectorial component of the NRM was determined from visual inspection of orthogonal demagnetization diagrams (Zijderveld, 1967), and the direction of the components identified was determined using principal component analysis techniques (Kirschvink, 1980).

Site mean directions were determined assuming the directions are well described by a Fisher distribution. Demagnetization experiments show that occasionally the components that make the NRM have overlapping unblocking temperature spectra; we therefore also used great circle trajectories combined with stable end-point directions in order to determine some of the site means. For this we used the algorithm of Bailey and Halls (1984). Rotations and/or latitudinal displacement was determined comparing the observed mean direction with the reference direction calculated from the North American craton apparent polar wander path, following Butler (1992).

Paleomagnetic results

Colorado beds. The NRM intensities of samples of this unit are moderate (e.g. 1.5 to 6.0 mA/m). Progressive AF demagnetization fails to remove a significant fraction of the NRM, we thus employed thermal demagnetization to separate the components that make the NRM (Fig. 3). Most samples contain two magnetizations, a low unblocking temperature component which is north directed and moderately steep (~ 50°), and a high unblocking temperature component (Fig. 3a). Maximum unblocking temperatures of the low temperature component are typically of the order of 600°C, but are occasionally higher (~ 650°C). In some samples this is the only component present (Fig. 3b). Maximum unblocking temperatures of the high temperature component exceed 680° (Fig. 3c). It thus appears that both components reside in hematite. The mean direction of the low temperature component is of D=358.57° and I=51.1° (k = 34.6; α_{95}=5.0º).

The high temperature component is considered the characteristic magnetization (ChRM), but there are two groups of directions. In the first group the ChRM is northwest directed and moderately steep positive (Fig. 3d), or south-southeast directed and moderately steep negative (reverse polarity). We refer to this component as the high inclination or B magnetization. The second group of directions is northeast directed and moderately shallow positive (inclinations of 6 to 34º; Fig. 3e), or southwest directed and shallow negative. We refer to this as the shallow inclination or A magnetization. In few samples both magnetizations are evident, but more often than not one of them is dominant within a site. The high inclination magnetization was observed in five sites; whilst at 18 sites the ChRM is of shallow inclination.

In several samples, (e.g. samples from sites PAN4, 9, 10, 11 and 13), unblocking temperature spectra of the magnetization components present overlap evident by curved demagnetization trajectories, and there is no clear separation between the low and the high temperature magnetizations. This occurs more often when the characteristic magnetization is of reverse polarity (Fig. 3f). For these sites, poles to great circles were determined, and the site mean was calculated combining stable end-point directions with poles to great circles. Only samples with well defined great circle trajectories (with MAD values less than 12º) were used in these calculations. Site mean directions and statistical parameters are listed in Table 1 and plotted in Fig. 4. Site means are defined with some uncertainty, with precision parameter values between about 8.5 and 32. High within-site dispersion has been observed in eolianites because the timing of chemical remanence acquisition is relatively long (e.g., Molina-Garza *et al*., 2003).

Between site dispersion of site mean directions is moderate; the in-situ overall mean of the shallow inclination A magnetization is of D=8.4°, I=22.3° (Table 1). For the high inclination B magnetization in-situ the mean is of D=332.4°, I=55.2° (Table 1). The attitude of the Jurassic beds exposed is uniform; a fold test is thus impossible. Sites with cross-stratification have similar directions than sites with planar bedding, suggesting that the remanence is chemical and not depositional in origin.

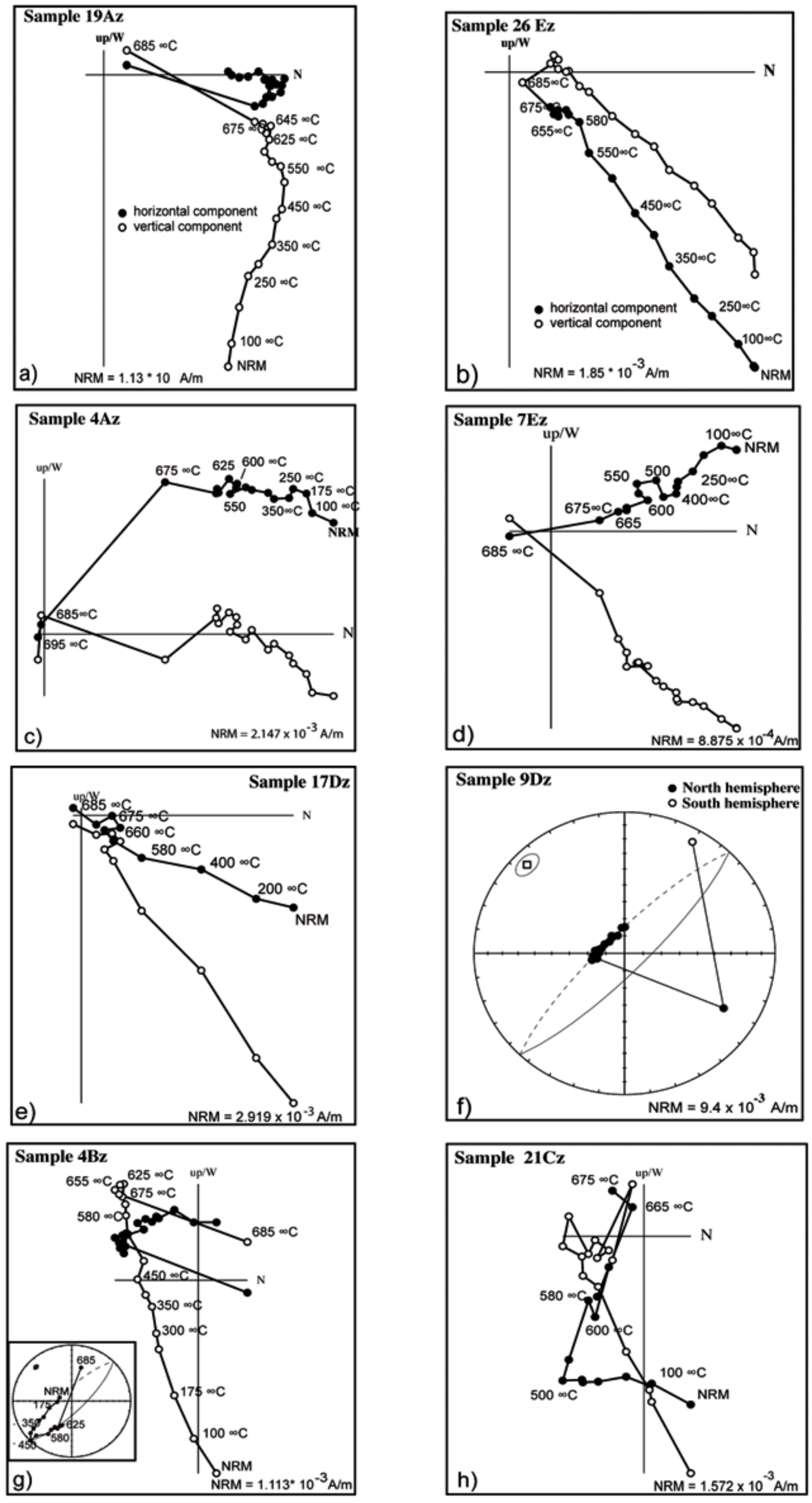

Fig. 3. Orthogonal demagnetization diagrams for selected samples of the Colorado beds. Open (closed) symbols are projections on the vertical (horizontal) plane. The capital letter after the number of the sample (*e. g.* A, B, C, D) indicates the sample in the site, and the lower letter after it (*e. g.* z) indicates the specimen of the specific core.

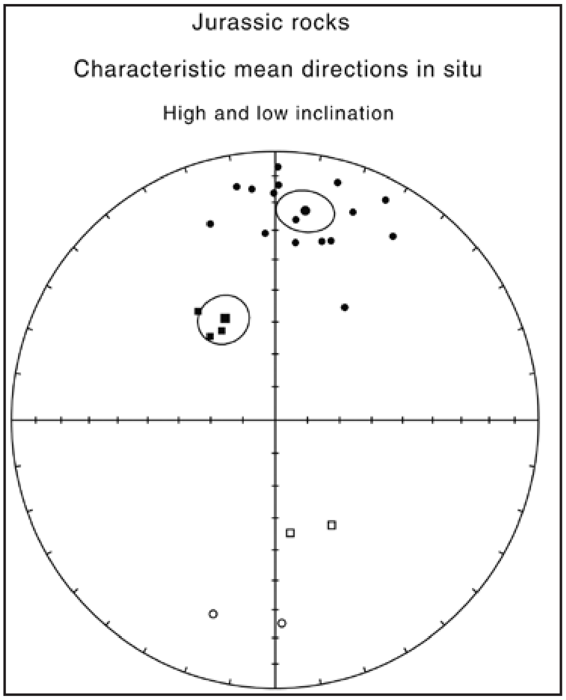

Fig. 4. Stereographic plot of the site mean directions observed in Jurassic strata at Potrero Colorado. Open (closed) are projections on the upper (lower) hemisphere circles correspond to shallow inclination component, boxes correspond to high inclination component. Big circle/box represents the media of the shallow/high inclination component.

A conglomerate test was carried out sampling sandstone clasts incorporated in deposits of the San Marcos Formation. The magnetization of the clasts is also composed of a low unblocking temperature component and a high unblocking temperature component (Fig. 5a). The magnetizations are well defined, but they are both randomly distributed, suggesting that the magnetizations were acquired before the clasts were incorporated in the deposit (Fig. 5b). Duplicate specimens from the same clast suggest that magnetizations within the clasts are homogeneous. The conglomerate test is thus positive, suggesting that even if the ChRM is of chemical origin, it was acquired soon after deposition.

San Marcos Formation. The intensity of the NRM in the San Marcos Formation is also of moderate values (e.g. 10 to 2.5 mA/m). The NRM is also made of two magnetization components. A low-unblocking temperature component with maximum unblocking temperatures between 580° and 600° C, is north directed and of moderate positive inclination. It overprints a dual-polarity high unblocking temperature magnetization with maximum unblocking temperatures of 670° C to 680° C (Fig. 6). The magnetizations of low and high temperature are both of high coercitivity, they are not affected during AF demagnetization; they thus reside in hematite.

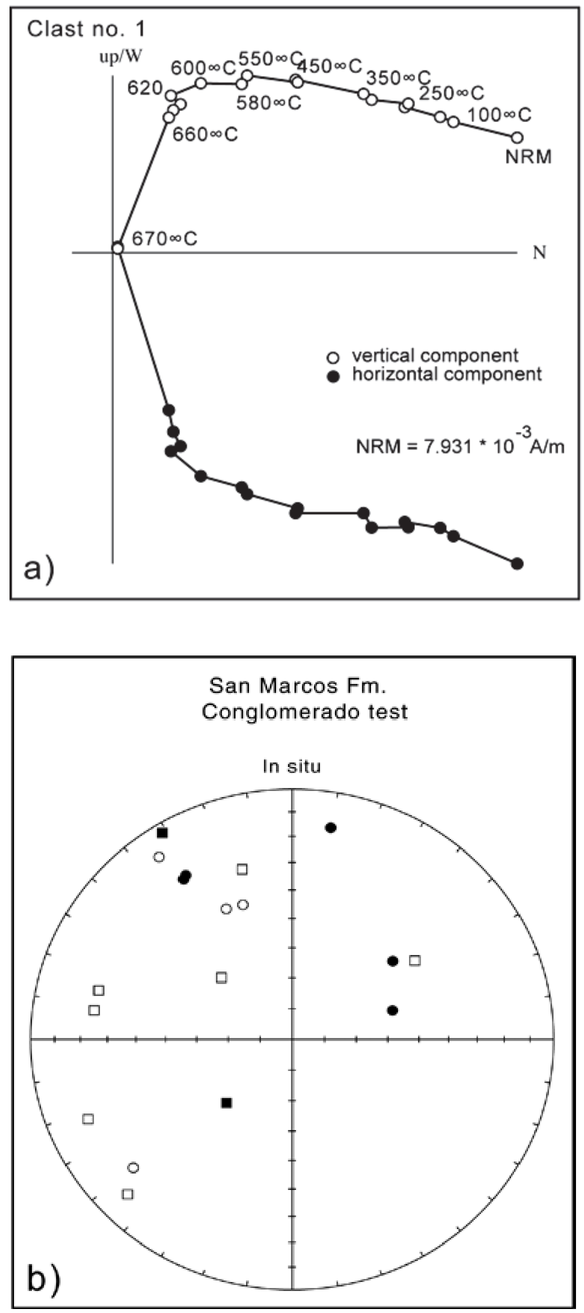

Fig. 5. Results of a conglomerate test on Jurassic sandstone clasts incorporated in the San Marcos Formation. (a) Example of a demagnetization diagram in the conglomerate clasts; (b) stereographic projection of directions observed in conglomerate clasts, indicating that the test is positive.

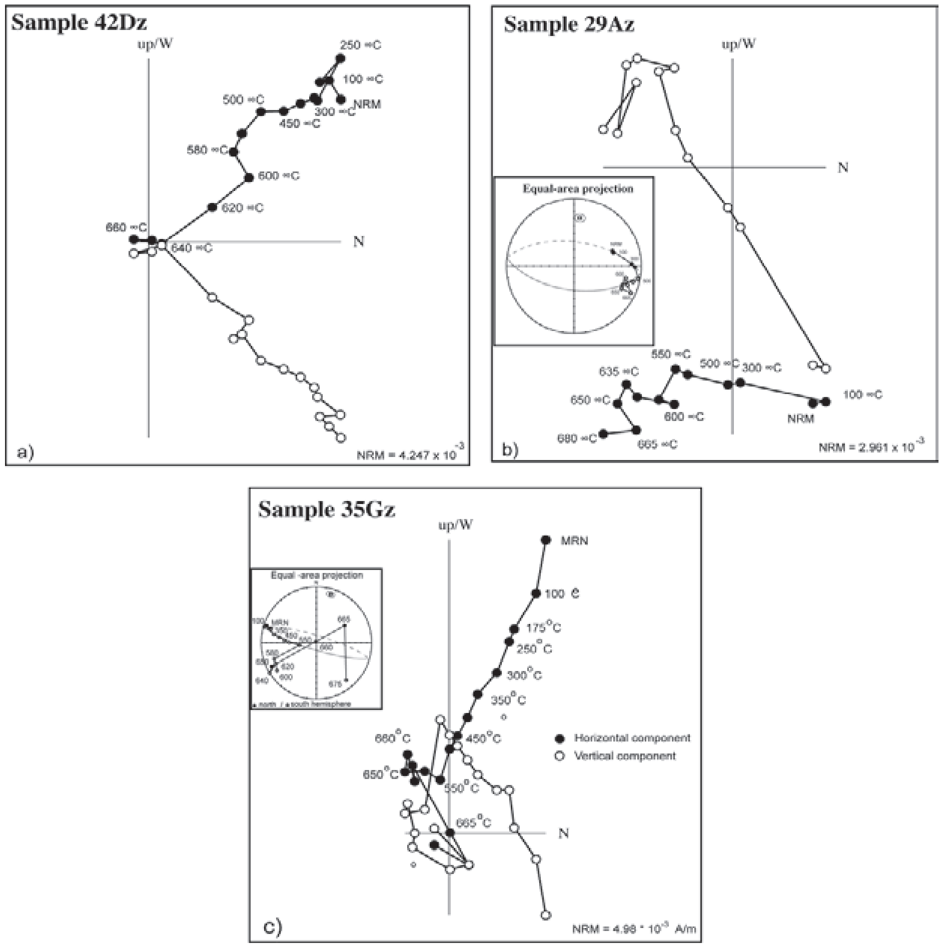

Fig. 6. Orthogonal demagnetization diagrams for selected samples of the San Marcos Formation. Open (closed) symbols are projections on the vertical (horizontal) plane.

Most of the samples on the eastern side of the sampling area are of reverse polarity, that is south directed magnetizations of negative inclination. These magnetizations are defined by great circle trajectories, because demagnetization behavior is unstable above about 550°C, and this temperature is not always sufficient to completely remove the north directed overprint (Fig. 6). Nonetheless, great circle trajectories define the site means with good precision (k values range between a minimum of 14 and a maximum of 135; Table 2).

Sites in the central part of the sampling area are predominantly of normal polarity (northwest directed and moderately steep positive). Because dip directions are slightly different in the eastern and central areas of the anticline we attempted a fold test, to establish the timing of remanence acquisition relative to folding. *In situ*, the precision parameter k of the combined data set is of 15.3, whereas the tilt corrected value is of 22.7 (Table 2). The precision parameter increases, but the fold test is not statistically significant. Nonetheless, the presence of both polarities suggests that the magnetization is near primary, and we assume that the magnetization was acquired prior to Laramide folding. Also, the in-situ mean is shallower than expected for Cretaceous time. The sites means are reasonably well defined, with precision parameter values between about 14 and 130. We notice that the tilt corrected mean of the sites in the eastern side of the sampling area, and stratigraphically low in the San Marcos section, are of D=191.7°, I=-54.9° (Table 2), whilst sites on the west-central side of the structure and stratigraphically high in the section are of D=333.6°, I=58.0° (Table 2). A summary of the data for the San Marcos Formation is shown in Table 2, and plotted in Fig. 7.

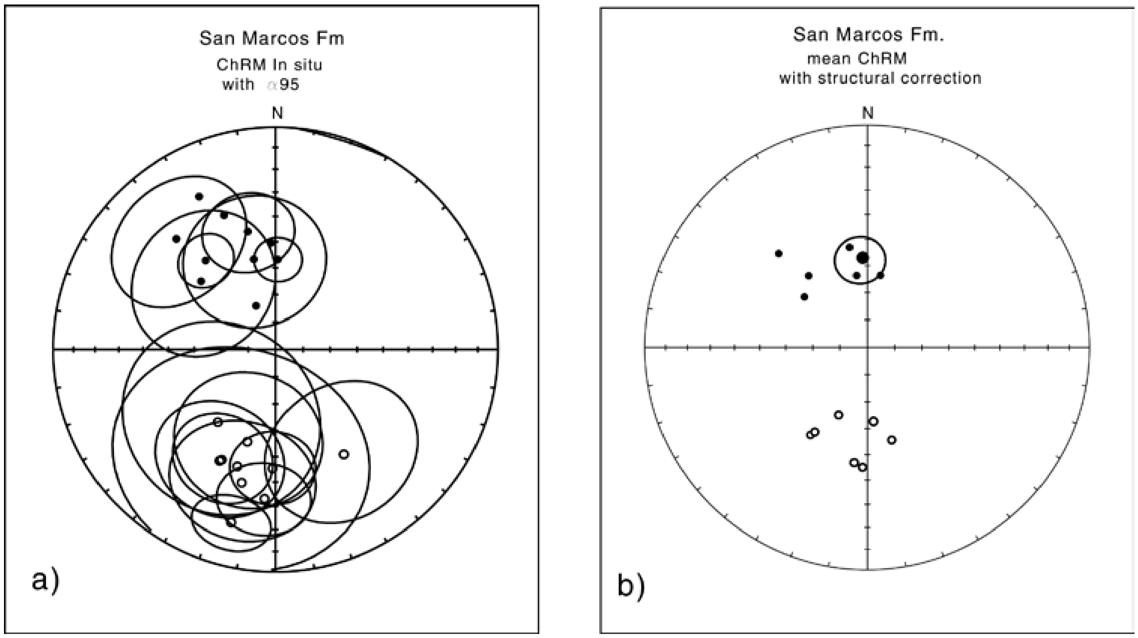

Fig. 7. (a) Stereographic plots of the site mean directions observed in the San Marcos Formation at Potrero Colorado. (b) overall site mean in the San Marcos Fm. Open (closed) are projections on the upper (lower) hemisphere.

Discussion

Sites in the Jurassic rocks of the Colorado beds have two magnetizations, one of shallow-inclination and one of high-inclination. A positive conglomerate test indicates that the characteristic A magnetization is Jurassic in age, but the *in-situ* magnetization of high-inclination gives a paleomagnetic pole that falls on the Cenozoic segment of the North American apparent polar wander path (APWP). The pole we calculated is 64.9° N, 195.1° E. In contrast, the A magnetization (its inclination is moderately shallow in both in-situ and tilt-corrected) in tilt corrected coordinates gives a pole at 72.9° N, 48.3° E; the pole falls off the North America APWP. We thus interpret the A magnetization as an ancient magnetization of Jurassic age, and the high inclination B magnetization as a secondary yet ancient magnetization. This secondary magnetization is considered in *in-situ* coordinates, and was probably acquired after or during the Early Tertiary Laramide orogeny. We base this interpretation on the criteria of Van der Voo (1990), a pole that resembles that of a younger unit is suspect of remagnetization. The B magnetization will not be considered further, but suggests that no rotation occurred after the Laramide orogeny.

Both the presence of dual-polarity magnetizations and between-site dispersion for the A magnetization suggest that sampling is sufficient to average paleosecular variation. In turn, the overall mean can be used to make tectonic interpretations. For this, we compare the mean direction with the expected direction calculated from the reference pole for the North America craton. The reference pole for the Late Jurassic is based on results for the Morrison Formation of the Colorado plateau (Steiner and Helsley, 1975; Bazard and Butler, 1994) and coeval strata in the eastern plains of the craton, in New Mexico (Steiner et al., 1995). But relative rotation between the Colorado plateau and the craton (Steiner, 1988; Bryan and Gordon., 1990; Molina-Garza *et al*., 1998) requires that plateau poles are restored to the same reference frame than the craton before a reference mean can be calculated.

In addition to this, the Morrison Formation has produced two poles, one for the lower member, the Salt Wash Member, and one for the upper member, the Brushy Basin Member. The poles for both members are statistically different, as they record rapid movement of the North American plate during deposition of this unit. The age of the Brushy Basin Member is based on ^{40}Ar-^{39}Ar dating of intercalated ash layers, which give ages between 147.82 ± 0.63 and 150.33 ± 0.27 Ma, whilst the age of the lower Morrison is based on ash layers dated at about 154.87 ± 0.52 Ma (Kowallis *et al*., 1998). The age of both units is established with good precision; the best estimate of the age of the lower Morrison pole is latest Oxfordian, whereas the age of the upper Morrison pole is Kimmeridgian to early Tithonian (Kowallis *et al*., 1998). On the eastern plains of the craton the lower member of the Morrison Formation is called the Romeroville member, whilst the upper member is called the Trujillo Hill Formation. Only the pole for the Trujillo Hill is of sufficient reliability and was combined with results for the Brushy Basin Member.

Because the Colorado beds are believed to be correlative with the Tanque Cuatro Palmas beds, of Tithonian age as explained above, we use the poles of the upper Morrison Formation to calculate the reference direction. We have corrected the poles from the Colorado plateau using the rotation parameters of Molina-Garza *et al*. (1998). Three poles for the upper Morrison give a mean pole at 63.7°N-162.0°E (A_{95}=2.8°). From this pole we calculate the expected direction for a site at Potrero Colorado (26.75°N-102.6°W); the expected direction is of D=331.7 and I=38.2°.

Similarly, dual-polarity magnetizations and moderate between site dispersion for sites collected from the San Marcos Formation suggest that secular variation is adequately averaged, and that the overall mean can be interpreted in terms of tectonic rotation and/or displacement. The sites on the east side of the sampling area are stratigraphically lower than sites in the central part of the anticline. The stratigraphically lower sites form, however, a group of directions slightly more northerly (southerly) than the stratigraphically higher sites in the center of the sampling area, which yield northwest directed magnetizations (Fig. 7; Table 2). The difference between directions at both localities is mostly in declination, inclinations are statistically indistinguishable. Although this could be attributed to structural complexity within the area, we interpret the declination difference in terms of tectonic rotation during deposition of these rocks; this interpretation is explained below. For the interpretation of the paleomagnetic data for the San Marcos Formation we compare its mean direction with the expected direction calculated from the Cretaceous stand-still pole as defined by McElhinny and McFadden (2000). The reference pole falls at 72.7°N-197.2°E, and the expected direction for a locality at Potrero Colorado is of D=341.2° and I= 51.8°.

Tectonic implications and structural interpretation

The paleomagnetic poles for A and B magnetization in the Colorado beds and San Marcos Fm. are plotted in Fig. 8. From the observed tilt corrected mean D=10.2° and I=28.2° at Potrero Colorado we calculated a rotation R=+38.5 ± 8.3 and a flattening value F=10.4° ± 9.4°. This result indicates that the sampling area has rotated in a clockwise sense with respect to the North American craton. Given the combined uncertainties in the reference pole position for the Late Jurassic and the age of the Colorado beds we believe that latitudinal displacement is small to negligible. Similarly the mean for the lower San Marcos Formation compared with the reference direction (Fig. 9b) yields rotation and flattening values of R=+30.5° ± 12.3° and F=3.1° ± 13.3. In contrast, the upper San Marcos Formation yields a concordant direction R=-7.6° ± 16.7° and F=6.2° ± 16.9°.

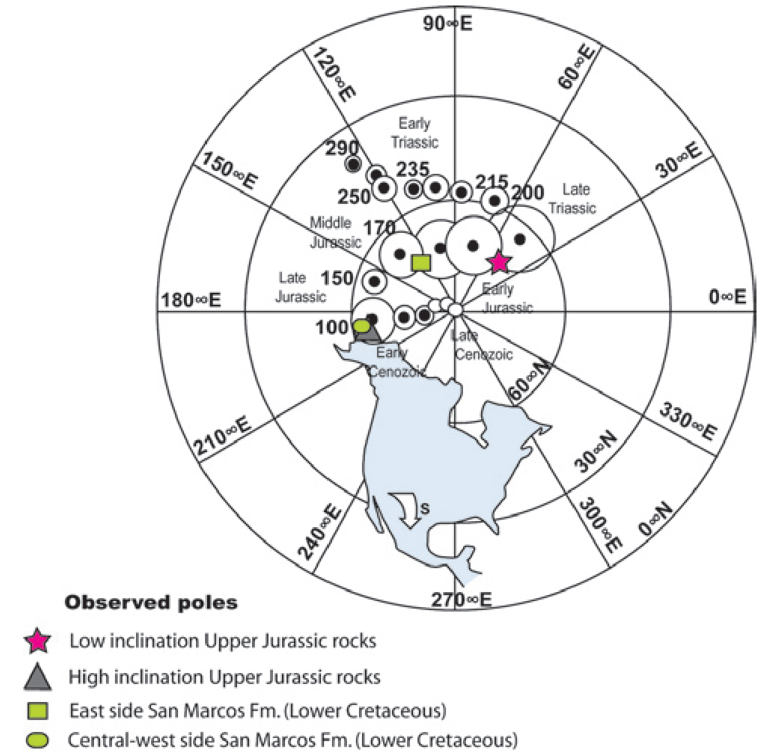

Fig. 8. Comparison of observed and expected directions for the Upper Jurassic and Cretaceous time. The expected directions were calculated from the reference pole for a central locality at Potrero Colorado.

In both of the units studied rotations are clockwise, but the amount of rotation is greater for the Jurassic rocks. It is likely, therefore, that Jurassic rocks accumulated a Jurassic rotation of about 8° prior to deposition of the lower San Marcos Formation and rotation of about 30° after that. Field relations indicate that normal faulting at Potrero Colorado predates the Early Cretaceous Cupido Formation, and is characterized by NE directed extension (Fig. 2). As we mentioned earlier this geometry is inconsistent with transtension in a left-lateral strike slip system, but this should not be a surprise as structural evidence of left-lateral slip is lacking. In fact, there is overwhelming evidence of normal faulting (Chávez-Cabello *et al*., 2005) and subordinate right lateral slip. In support of the interpretation of the San Marcos Formation as syn-tectonic with respect to activity on the San Marcos fault, we illustrate in Fig. 9 an intraformational angular unconformity.

As an alternative to Jurassic strike-slip, we interpret the fault geometry at Potrero Colorado as a relay ramp between two segments of a major normal fault. Given the ESE-WSW orientation of the SMF, oblique NW trending normal faulting, and a small component of right-lateral slip, the kinematics are consistent with a geometry that produces clockwise rotation within the region of the relay ramp (Fig. 10). This model reproduces the clockwise rotation determined paleomagnetically in this study and the measured fault data.

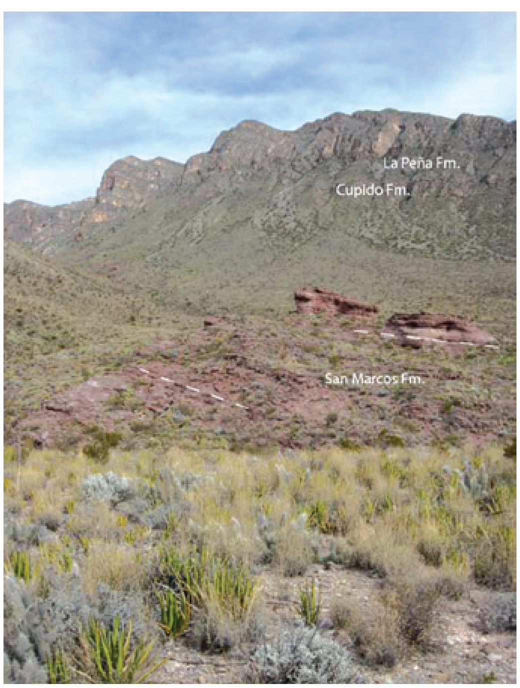

Fig. 9. Intraformational angular unconformity in the San Marcos Formation at Potrero Colorado.

In support of the interpretation of rotations at Potrero Colorado as a local rotation, results for stratigraphically equivalent strata are available for the core of La Gavia anticline, about 120 km to the east (Nairn, 1976). These author reports a concordant mean direction of D=330.4 and I=28.9 (n=27 samples, k=22, α_{95}=5.9°) for a unit he refers to as the "Huizachal beds at La Muralla". Correlation of the section at La Muralla with the lower Jurassic Huizachal Formation of the Sierra Madre Oriental (Mixon *et al*., 1959) is equivocal. The units considered by Nairn (1976) as Huizachal lie in the same stratigraphic position as strata assigned to the Colorado beds, they are more likely La Casita and Tanque Cuatro Palmas equivalent (Upper Jurassic). The paleomagnetic data for rocks at La Muralla do not indicate significant rotation, we thus believe that rotations observed at Potrero Colorado are of local origin.

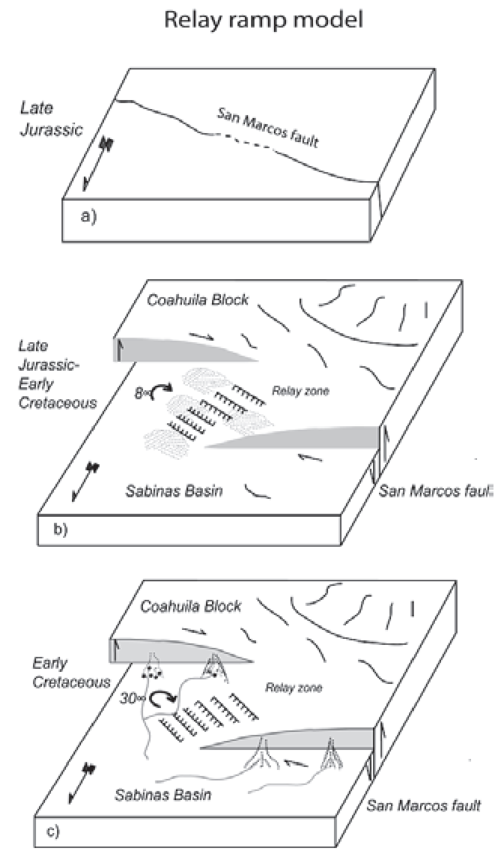

Fig. 10. Schematic diagram of a model that explains clockwise rotations at Potrero Colorado, invoking the formation of a relay ramp between two segments of the dominantly normal Late Jurassic San Marcos Fault. A small component of right lateral slip, as observed in fault slip data, is necessary to explain the observed rotations in the paleomagnetic data. In b) a dune patron shown the Capas colorado, and in c) an alluvial patron shows the San Marcos Formation deposits.

Acknowledgements

This research was supported by grant IN2002 from the PAPIIT-UNAM program to RSMG and by grant 47071 from CONACyT to Jorge Aranda Gómez and collaborators, and a Master Degree scholarship to the first author by CONACYT. We thank Iriving Arvizu Gutiérrez, Tomás Cossío Torres and Jorge Velasco for their assistance in the field and Gabriel Origel Guitiérrez for his assistance in the map edition. We also thank three anonymous reviewers for their comments to the original manuscript.

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, *Geological Society of American Bulletin, V. 94*, 941-966.

Angelier, J., 1990. Inversion of field data in fault tectonics to obtain the regional stress. III. A new rapid direct inversion method by analytical means. *Geophysical Journal International*. In Hancock, P.L. (Ed), Continental Deformation. Pergamon Press, Oxford, 53-100.

Aranda-Gómez, J. J., T. B. Housh, J. F. Luhr, C. D. Henry, T. Becker and G. Chávez-Cabello, 2005a: Reactivation of the San Marcos fault during mid- to late- Tertiary extention, Chihuahua, México. In: Anderson, T., The Jurassic Mojave-Sonora Megashear, Southwest North America: Evidence, Assessment, and Alternatives. Geological Sociaty of America Special Paper 393 p.

Bailey, R. C. and H. C. Halls, 1984, Estimate of confidence in paleomagnetic directions derived from mixed remagnetization circle and direct observational data, *Journal of Geophysics,54*, 174-182.

Bazard, D.R. and R. F. Butler, 1994. Paleomagnetism of the Brushy Basin Member of the Morrison Formation; implications for Jurassic apparent polar wander, *Journal of Geophysical Research, 99*, 6695-6710.

Bryan, P. and R. G. Gordon. 1990. Rotation of the Colorado Plateau; an updated analysis of paleomagnetic poles, Geophysical Research Letters, 17, 1501-1504.

Butler, R.F., 1992. Paleomagnetism: Magnetic domains to geologic terranes, Blackwell Scientific Publications, Cambridge, Massachusetts, 319 p.

Charleston, S., 1974. Stratigraphy, tectonics and hydrocarbon potential of the Lower Cretaceous, Coahuila series, Coahuila, Mexico: University of Michigan, Ph. D. dissertation, 268 p.

Chávez-Cabello, G., J. J. Aranda-Gómez, R. S. Molina-Garza, T. Cossío-Torres, I. R. Arvizu-Gutiérrez and G. A. González-Naranjo, 2005. La Falla San Marcos: Una estructura Jurásica de basamento multireactivada del noreste de México.en: Alaniz-Álvarez, S.A., Las Grandes Fronteras Tectónicas de México. *Boletín de la Sociedad Geológica Mexicana*, 27-52.

Kowallis B., J., E. H. Christiensen, A. L. Deino, F. Peterson, C. H. E. Turner, M. J. Kunk, J. D. Obradovich , 1998. The Age of the Morrison Formation; *Modern Geology 22*, 235-260.

Kirschvink, J. L., 1980. The least-squares line and plane and the analysis of paleomagnetic data: examples from Siberia and Morroco, Geophys. *J. Roy. Astron. Soc., 62*, 699-718.

Lehmann, C., D. A. Osleger, I. P. Montanez, W. V. Sliter, A. Arnaud-Vanneau and J. L. Banner, 1999. Evolution of Cupido and Coahuila carbonate platforms, Early Cretaceous, northeastern Mexico, *Geological Society of America Bulletin, 111*, 1010-1029.

McElhinny, M. W. and P. L. MacFadden, 2000. Paleomagnetism; continents and oceans, Academic Press, San Diego, United States, 386 p.

McKee, J. W., N. W. Jones and L. E. Long, 1990. Stratigraphy and provenance of strata along the San Marcos fault, central Coahuila, Mexico, GSA Bulletin, 102, 593-614.

Mixon, Robert B., E. Murray Grover, T. E. Diaz-Gonzalez, 1959. Age and correlation of Huizachal group (Mesozoic), State of Tamaulipas, Mexico, *Bulletin of the American Association of Petroleum Geologists, 43*, 757-771.

Molina Garza, R. S., G. D. Acton and J. W. Geissman, 1998. Carboniferous through Jurassic paleomagnetic data and their bearing on rotation of the Colorado Plateau, *Journal of Geophysical Research, 103*, 24,179-24,188.

Molina-Garza, R.S., J. W. Geissman and S. G. Lucas, 2003. Paleomagnetism and magnetostratigraphy of the lower Glen Canyon and upper Chinle Groups, Jurassic-Triassic of northern Arizona and northeast Utah, USA, *Journal Geophys. Research.*, 108 p.

Nairn, A. E. M., 1976. A paleomagnetic study of certain Mesozoic formations in northern Mexico, *Physics of the Earth and Planetary Interiors, 13*, 47-56.

Steiner, M. B., 1988. Paleomagnetism of the Late Pennsylvanian and Permian; a test of the rotation of the Colorado Plateau, *Journal of Geophysical Research, 93*, 2201-2215

Steiner, M. B. and C. E. Helsley, 1975. Reversal pattern and apparent polar wander for the Late Jurassic, Geol. *Soc. Am. Bull., 86*, 1537-1543.

Steiner M. B., S. G. Lucas and E. M. Shoemaker, 1995. Correlation and age of the Upper Jurassic Morrison Formation from magnetostratigraphic analysis, in: Mesozoic systems of the Rocky Mountain Region, USA, Capauto, M.V., Paterson J.A., and Franczyk, K.J. (editors), 315-330.

Van der Voo, R., 1990. Phanerozoic Paleomagnetic Poles from Europe and North America and comparison with continental reconstructions. *Rev. Geophys., 28*, 167-206.

Zijderveld, J. D. A., 1967. A.C. demagnetization of rocks: Analysis of results, in: Methods in Rock Magnetism and Paleomagnetism, edited by D.W. Collinson, K.M. Creer, and S.K. Runcorn, Elsevier, Amsterdam, 254-286.

Gildardo A. González-Naranjo[1]*, Roberto S. Molina-Garza[2], Gabriel Chávez-Cabello[3]
[1]Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Querétaro, Mexico City, Mexico.
[2]Centro de Geociencias, Universidad Nacional Autónoma de México, Campus Juriquilla, Querétaro, Mexico City, Mexico.
[3]Facultad de Ciencias de la Tierra, Universidad Autónoma de Nuevo León, Linares, Nuevo León, Mexico.
**Corresponding author: gildardogonzalez323@hotmail.com*