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Crustal structure and location of the Ouachita orogenic belt in northern Mexico

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RESUMEN

La localización en México del margen sur de Laurencia durante el Paleozoico ha sido centro de intenso debate. Dicha localización es necesaria para el análisis de la hipótesis actual consistente en que fragmentos de Norte América fueron transportados hacia Sud América durante la ruptura de Laurencia (Cámbrico Temprano) y de Pangea (Mesozóico Temprano), mientras que enormes movimientos laterales en el norte de México en el Mesozoico ocasionaban el desplazamiento de la faja orogénica Ouachita. Tomando en cuenta afloramientos Paleozoicos, datos de isótopos de plomo y datos de sismicidad y gravimetría regionales, la faja orogénica Ouachita continúa ya sea en dirección sur hacia Coahuila o en dirección sud-sudoeste a partir de la región texana de Big Bend, atravesando Chihuahua y hacia Durango. Con el objeto de evaluar estas dos alternativas, se construyeron modelos de la corteza terrestre a lo largo de tres perfiles en la parte norte de México y oeste de Texas. El número de datos en capas profundas fue insuficiente para limitar el modelo, por lo que se resolvió obtener un modelo para cada una de las dos direcciones consideradas para el seguimiento de la faja orogénica Ouachita. El modelo correspondiente al seguimiento sur sugiere la presencia de dos zonas de valores mínimos de gravimetría, las cuales se encuentran delineando una cuenca de antepaís paleozoica (Mapimí) a lo largo de la frontera entre Chihuahua y Coahuila, y un terreno acretado (terreno Coahuila) en la parte oeste de Coahuila. El modelo sud-sudoeste sugiere a su vez que las zonas de valores mínimos de gravimetría se encuentran delineando terrenos acretados. Nosotros nos inclinamos por el seguimiento sud-sudoeste ya que podemos seguir el rastro de valores máximos de gravimetría asociados con la zona interior Ouachita hasta 300 km al interior de la parte este de Chihuahua y sur hacia Durango en una manera consistente con respecto a datos de isótopos de plomo, muestras de rocas previas al Mesozoico provenientes de pozos y afloramientos en el área, así como litologías y estructuras en la parte oeste de Sonora. Una vez completando el lapso existente entre la faja orogénica de Ouachita postulada aquí con litologías en Sonora, las cuales muestran una tendencia de seguimiento hacia el noreste, nos resulta una imagen del posible margen sur de Laurencia durante el Paleozoico Temprano.

PALABRAS CLAVE: Paleozoico, gravimetría, isótopos de plomo, México, la faja orogénica de Ouachita.

ABSTRACT

The location of the Paleozoic southern margin of Laurentia in Mexico has been much debated. Determining its location is important for the evaluation of hypotheses that suggest large pieces of southwestern North America were translated toward South America during the breakup of Laurentia (early Cambrian) and Pangea (early Mesozoic) and that there were large lateral movements in northern Mexico in Mesozoic time that displaced the Ouachita orogenic belt. Using limited Paleozoic outcrops, lead isotopic data, regional seismic data and regional gravity anomalies, we show that the Ouachita orogenic belt and the Laurentian margin in Mexico trend either directly south into Coahuila or south-southwest across Chihuahua toward Durango from the Big Bend region of west Texas. In order to evaluate these two possibilities, integrated crustal models were constructed along three profiles in northern Mexico and west Texas. Because constraints on deep structure are sparse, each profile could be modeled with either a southward or a south-southwestward extension of the Ouachita orogenic belt. The southward extension model suggests that two regional gravity minima delineate a Paleozoic foreland basin (Mapimi basin) along the Chihuahua/Coahuila border, and an accreted terrane (Coahuila terrane) in western Coahuila. The south-southwestward extension model suggests that these gravity minima both delineate accreted terranes. We favor a south-southwestward extension because we can trace the gravity maximum associated with the known Ouachita interior zone 300 km into eastern Chihuahua and south toward Durango in a way that is consistent with trends in lead isotopic data, pre-Mesozoic geologic data from drill holes and outcrops, and Ouachita-style lithologies and structures found in western Sonora. Spanning the gap between the postulated Ouachita orogenic belt in southern Chihuahua with possible similar lithologies in Sonora with a northwest-trending margin provides a simple way to complete our picture of the southern portion of Laurentia during the early Paleozoic.

KEY WORDS: Paleozoic, gravity anomalies, Pb isotopes, Mexico, Ouachita orogenic belt.

1. INTRODUCTION

Laurentia (paleo-North America) formed as the result of a complex series of accretionary events during the Proterozoic (Hoffman, 1988; Karlstrom and Bowring, 1988; Van Schmus *et al.*, 1996) and then was broken apart by rifting in the Late Proterozoic/Early Cambrian (Stewart, 1976, Dalziel, 1997). The passive margins which formed along the eastern and western portions of Laurentia are well known from exposures in the Appalachian orogenic belt and in the Cordillera of western North America. However, the southern passive margin is known only from scattered outcrops in the Ouachita Mountains of Arkansas and Oklahoma and the Big Bend region of west Texas, the area bounded on the south by a large bend in the course of the Río Grande (Figure 1), and from drilling data (Viele and Thomas, 1989). These outcrops and subcrops are considered to be allochthonous portions of the Ouachita orogenic belt which formed along the southern margin of Laurentia in the late Paleozoic (Flawn *et al.*, 1961). Flawn *et al.* (1961) subdivided the Ouachita orogenic belt in Texas, Oklahoma, and Arkansas into three zones and Thomas (1976) traced these zones in the subsurface to their intersection with the Appalachian orogenic belt. The integration of drilling, seismic, and gravity data provide an approximate location of the Laurentian margin from central Mississippi to west Texas (Kruger and Keller, 1986; Keller *et al.*, 1989a,b; Mickus and Keller, 1992). However, over the past 35+ years, the location of the Ouachita orogenic belt and the related Laurentian margin in northern Mexico has been debated because they are mostly covered by Mesozoic and Cenozoic sedimentary and volcanic rocks, key data are sparse or lacking, and the effects of Mesozoic and Cenozoic tectonic events obscure older features.

Locating the margin of Laurentia in northern Mexico has important implications for efforts to delineate the terranes which form much of Mexico (Campa and Coney, 1983; Sedlock *et al.,* 1993; Ortega-Gutiérrez *et al.,* 1995) and to test theories which suggest large transform movements in northern Mexico during the Mesozoic (Anderson and Schmidt, 1983). This margin's location is also important in efforts to discover and delineate the pieces of Laurentia which were rifted away during the NeoProterozoic/early Cambrian [e.g., the SWEAT (Southwest U.S./East Antarctic) hypothesis (Moores, 1991), or the Argentina Precordillera/Ouachita embayment connection (Thomas and Astini, 1996)].

The Ouachita orogenic belt has been divided into three tectonic zones in west Texas (Flawn *et al.,* 1961): 1) Ouachita foreland, 2) frontal zone, and 3) interior zone (Figure 1). The Ouachita foreland is characterized by early to middle Paleozoic platform rocks that were deformed into basins (e.g., Midland and Delaware) and basement cored uplifts (e.g., Central Basin and Diablo Platforms) during the Paleozoic Ouachita orogeny. The frontal zone is characterized mostly by early Mississippian to early Permian deep water clastic sedimentary rocks. These rocks were subsequently deformed into a fold and thrust belt (exposed in the Marathon and Solitario uplifts) by compressional stresses that originated

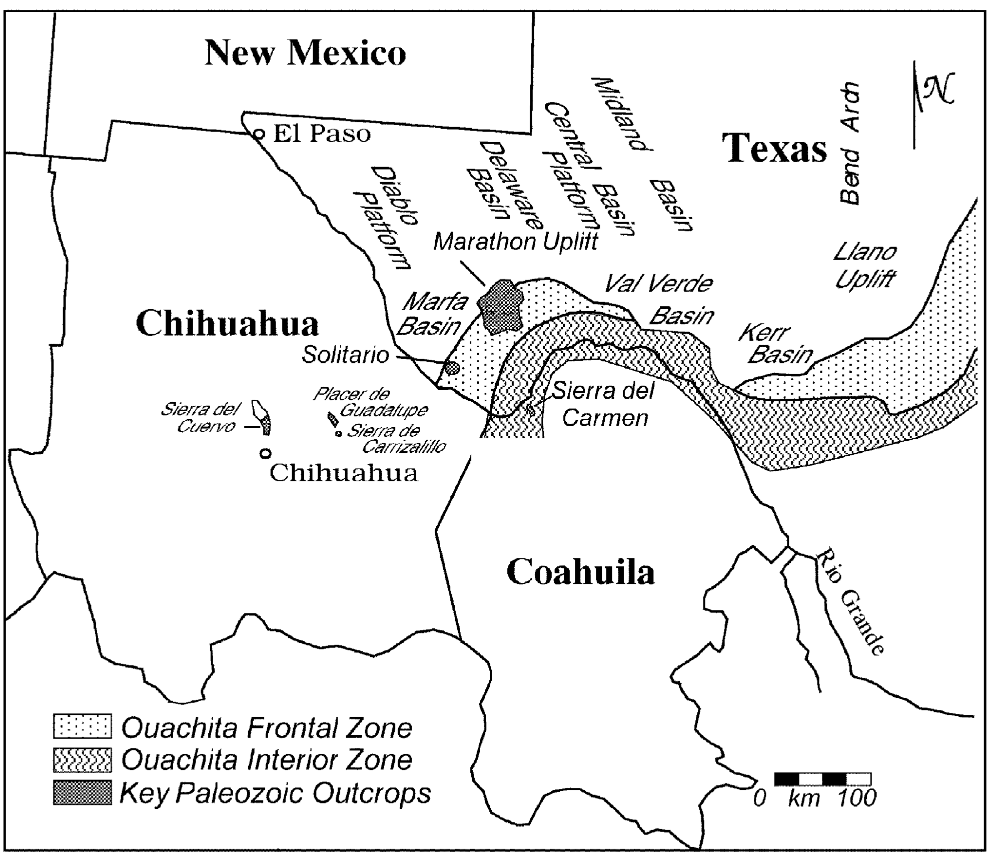


Fig. 1. Tectonic elements of west Texas and northern Mexico as they have been traditionally defined (adapted from Handschy *et al*., 1987).

from the south. The resulting thrust sheets depressed the crust producing the Val Verde, Marfa and Kerr foreland basins (Hinojosa and Mickus, 1991). The interior zone is defined by a relatively narrow zone of variably sheared early Pennsylvanian to middle Permian metamorphic rocks that have been found only in a few scattered drill holes in west and central Texas (Denison *et al.*, 1977; Marsaglia *et al.*, 1994) and in a small outcrop in Mexico just across the Río Grande at Sierra del Carmen (Flawn *et al.*, 1961; Carpenter, 1997). The interior zone correlates closely with a prominent gravity maximum that connects the scattered locations where drill holes have penetrated interior zone metamorphic rocks (Kruger and Keller, 1986; Keller *et al.*, 1989a). A significant new result comes from a well located east of the Marathon uplift near the apex of the interior zone gravity high (Marsaglia *et al.*, 1994). This well penetrated about 7 km of interior zone rocks whose lithology changed little with depth.

Flawn *et al.* (1961) were among the first workers to try to follow the Ouachita orogenic belt into northern Mexico and suggested that the frontal zone extends westward from the Big Bend region of Texas. Since this first attempt, numerous workers (Bridges, 1964, 1970; King, 1975; Handschy *et al.*, 1987; Shurbet and Cebull, 1987; James and Henry, 1993a) have tried to trace this orogenic belt into Mexico. Recent attempts to constrain the location in Mexico have employed Bouguer gravity anomalies interpreted in conjunction with the scattered drill holes and Paleozoic outcrops (Handschy *et al.*, 1987; Sánchez and Urrutia, 1992) or lead (Pb) isotope data (Cameron *et al.* 1992; James and Henry, 1993a). Recent descriptions of the Paleozoic outcrops and drill holes in northern Mexico of interest here include those provided by Handschy *et al.* (1987), Handschy and Dyer (1987), McKee *et al.* (1988), Sedlock *et al.* (1993), and Hennings (1994). Handschy *et al.* (1987) suggested that the orogenic belt extends from the Big Bend region in west Texas southward into Coahuila at least 100 km whereas Pb isotope based models (Cameron *et al.*, 1992; James and Henry, 1993a) suggest that it trends southwestward into Chihuahua. These two interpretations basically represent the extremes of all the various interpretations and the purpose of this investigation is to reconsider the location of the Laurentian margin in northern Mexico by evaluating all available data. We accomplished this in part by constructing a series of integrated crustal models.

2. PB ISOTOPE RESULTS

Isotopic data are commonly used to help delineate tectonic provinces, and in our study area, we have the advantage of a number of recent Pb isotope analyses (Figure 2), (Cameron *et al.*, 1992; James and Henry; 1993a,b; Carpenter, 1997). James and Henry (1993a) analyzed Eocene to Miocene igneous rocks for their Pb isotopic ratios (^{208}Pb / ^{204}Pb, $^{207}Pb/^{204}Pb$, $^{206}Pb/^{204}Pb$) to delineate the Paleozoic continental margin in west Texas and northern Mexico. They interpreted the Pb isotopic ratios to define three tectonic zones (Figure 2): 1) a northwest zone where Pb isotopic ratios are generally from a mixture of lower crustal and upper mantle sources and represent the North American craton (Laurentia), 2) a southeastern zone where magmas interacted with more radioactive lithospheric sources, which may be sediments accreted during the Ouachita orogeny, and 3) a central zone with Pb isotopic ratios intermediate to zones 1 and 2. Cameron *et al.* (1992) provide similar Pb isotope data for La Olivina (Figure 2).

To illustrate the change in $^{207}Pb/^{204}Pb$ values across the region, two profiles were constructed (Figure 2). The southernmost $^{207}Pb/^{204}Pb$ value on the Ojinaga profile represents an average of all the paragneisses from La Olivina (Cameron *et al.*, 1992). The $^{207}Pb/^{204}Pb$ values on both profiles display a substantial increase from north to south on both profiles and suggest that the area along the Chihuahua/ Coahuila border is well east of the edge of Laurentia. Thus, these data favor a location for the Laurentian margin that is west of the Big Bend region of Texas.

3. GRAVITY DATA AND ANOMALIES

A major part of our effort was the mapping and modeling of gravity anomalies. The gravity data used in this study were compiled from various sources (including the U.S. Defense Mapping Agency, oil industry, U. S. Geological Survey, and University of Texas at Dallas) and were processed to yield Bouguer gravity anomalies. In order to the emphasize larger scale tectonic features (e.g., crustal blocks, foreland basins and uplifts), a variety of low-pass filtered gravity anomaly maps were produced (Moreno, 1993). A filter that passed wavelengths greater than 85 km (Figure 3) showed the clearest correlation with known tectonic features. In west-central Texas, prominent roughly circular gravity maxima are associated with Ouachita foreland structural highs which include the Diablo platform, Central Basin platform, Llano uplift and Bend arch (Figure 1). The gravity maximum associated with the Central Basin platform is mostly caused by at least 5 km of mafic igneous rocks (Keller *et al.*, 1989c; Adams and Keller, 1996). Most of the gravity minima in west Texas are associated with Ouachita foreland basins (e.g., Marfa, Kerr, southern Delaware and Val Verde, Figure 1). The west Texas foreland basins are not as deep as the well known Arkoma basin in Oklahoma and Arkansas (Mickus and Keller, 1992) and produce smaller anomalies. In west Texas and northern Mexico, crustal models derived from gravity and drilling data (Keller *et al.*, 1989a; Moreno *et al.*, 1994) indicate that deeper crustal/mantle features (e.g., mafic intrusions, crustal thinning) produce positive gravity effects which offset some of the negative effects of the foreland basins.

The most prominent gravity anomaly is the maximum that is associated with the Ouachita interior zone and the Laurentian margin in Texas (Kruger and Keller, 1986; Keller

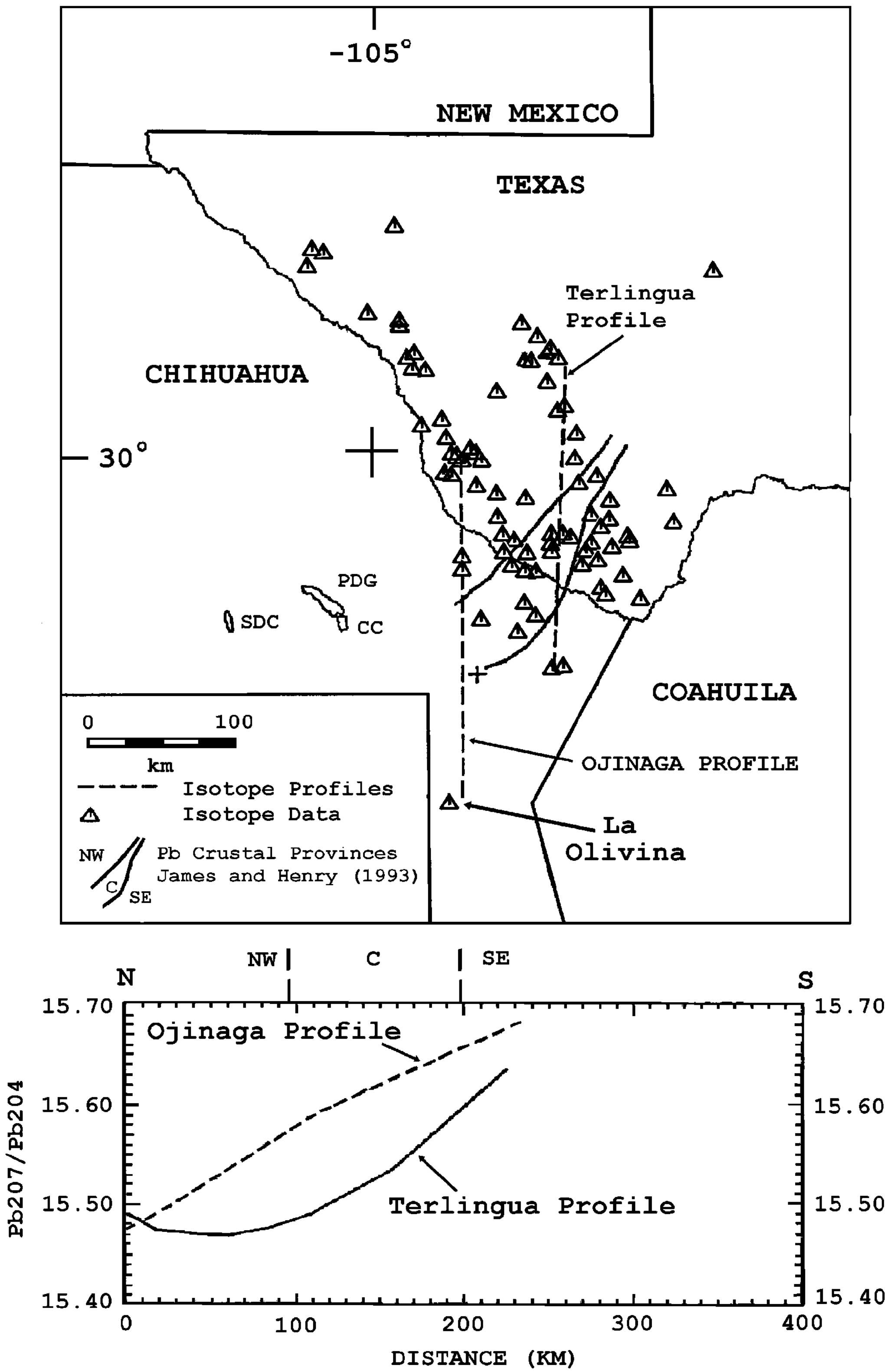


Fig. 2. Locations of Pb isotope data used in this study (Cameron *et al.,* 1992; James and Henry, 1993a,b; Carpenter, 1997). The Terlingua and Ojinaga profiles illustrate the variations of $^{207}Pb/^{204}Pb$ values across the Ouachita orogenic belt. Also shown are the boundaries (solid, bolded lines) of the tectonic provinces (NW, C, and SE) determined by James and Henry (1993a) using the Pb isotope data. SDC-Sierra del Cuervo, CC-Sierra el Carrizalillo, PDG-Placer de Guadalupe.

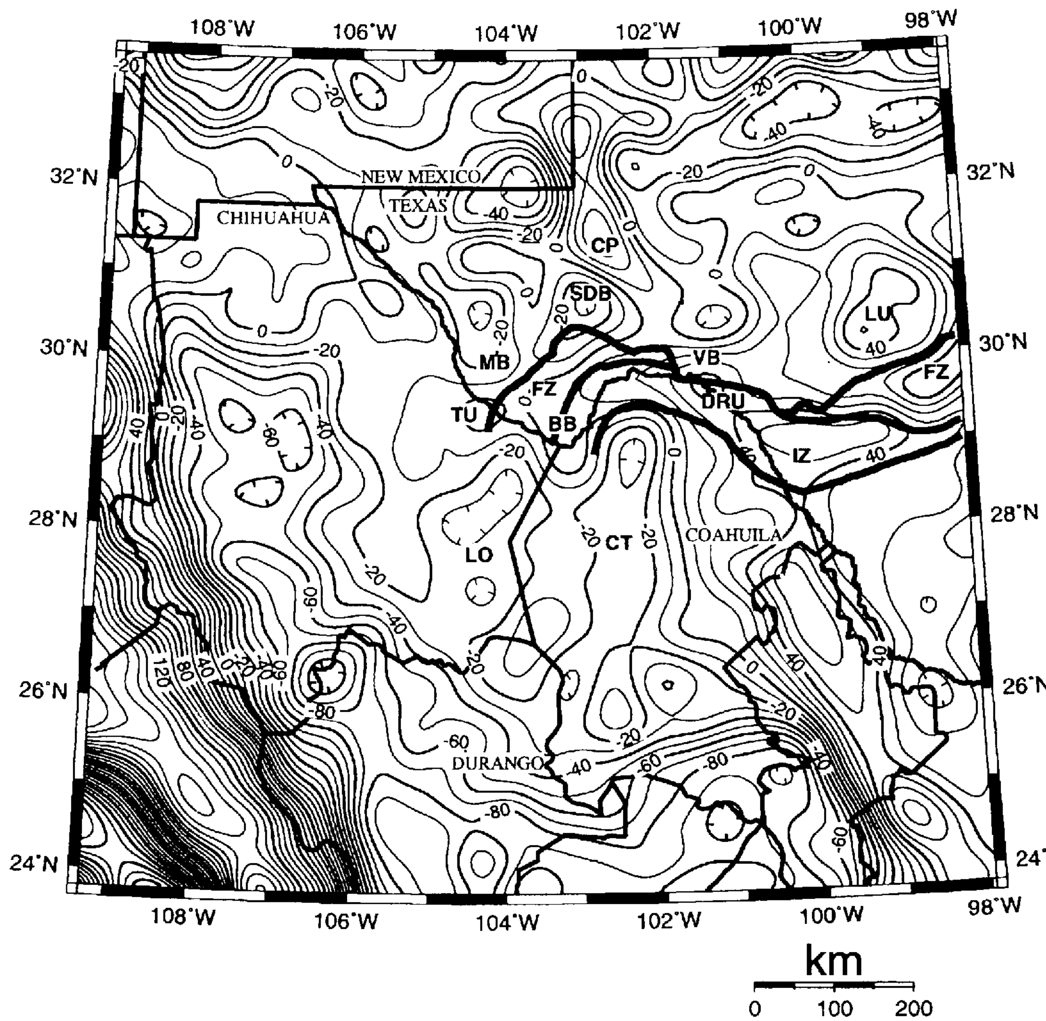


Fig. 3. Low-pass filtered gravity anomaly map of the study area in which wavelengths greater than 85 km were passed. The dark, thick lines show the known boundaries in west Texas of the Ouachita frontal zone (FZ) and the Ouachita interior zone (IZ) (Handschy *et al.*, 1987). Also shown are the Ouachita foreland tectonic elements of the Marfa Basin (MB) and Val Verde Basin (VB). CT is centered on the suspected Coahuila Terrane (Handschy *et al.*, 1987), BB-Big Bend region, TU- Tascotal uplift, LO-La Olivina, CP-Central Basin Platform, LU-Llano Uplift, DRU-Devil's River Uplfit, SDB-southern Delaware Basin. The contour interval is 10 mGal.

et al., 1989b). The location of this anomaly is a key part of our analysis. Handschy *et al.* (1987) suggested that it can be traced about 100 km southward from the Big Bend region into Coahuila beyond which it is obscured by anomalies caused by younger tectonic events or cut off by the Mojave-Sonora megashear (Anderson and Schmidt, 1983) and transported toward the southeast. The gravity maximum trending west from the Big Bend region (Figure 3) provides an alternative to this interpretation. This anomaly follows the Tascotal uplift and then turns south-southwestward extending across east-central Chihuahua (see -20 mGal contour). We will discuss this anomaly in more detail below.

Not all the gravity anomalies on Figure 3 can be correlated with known tectonic features. This is especially true in northern Mexico where outcrops containing Ouachita facies rocks, drill holes and seismic reflection/refraction data are limited. Handschy *et al.* (1987) interpreted the large gravity minimum south of the Big Bend region (28°N, 104°W) as the possible signature of a Ouachita foreland basin because it lies west of their interpreted position of the Ouachita orogenic belt. However, if the alternate western location of the interior zone gravity is correct, this gravity minimum could not be a foreland basin. In this case, the name Mapimi terrane was proposed by Moreno *et al.* (1994) for the region defined by the gravity minimum.

4. CRUSTAL MODELS AND INTERPRETATIONS

Gravity modeling along three profiles was used as the framework whereby we constructed integrated crustal models. The locations of these profiles are shown in Figure 4,

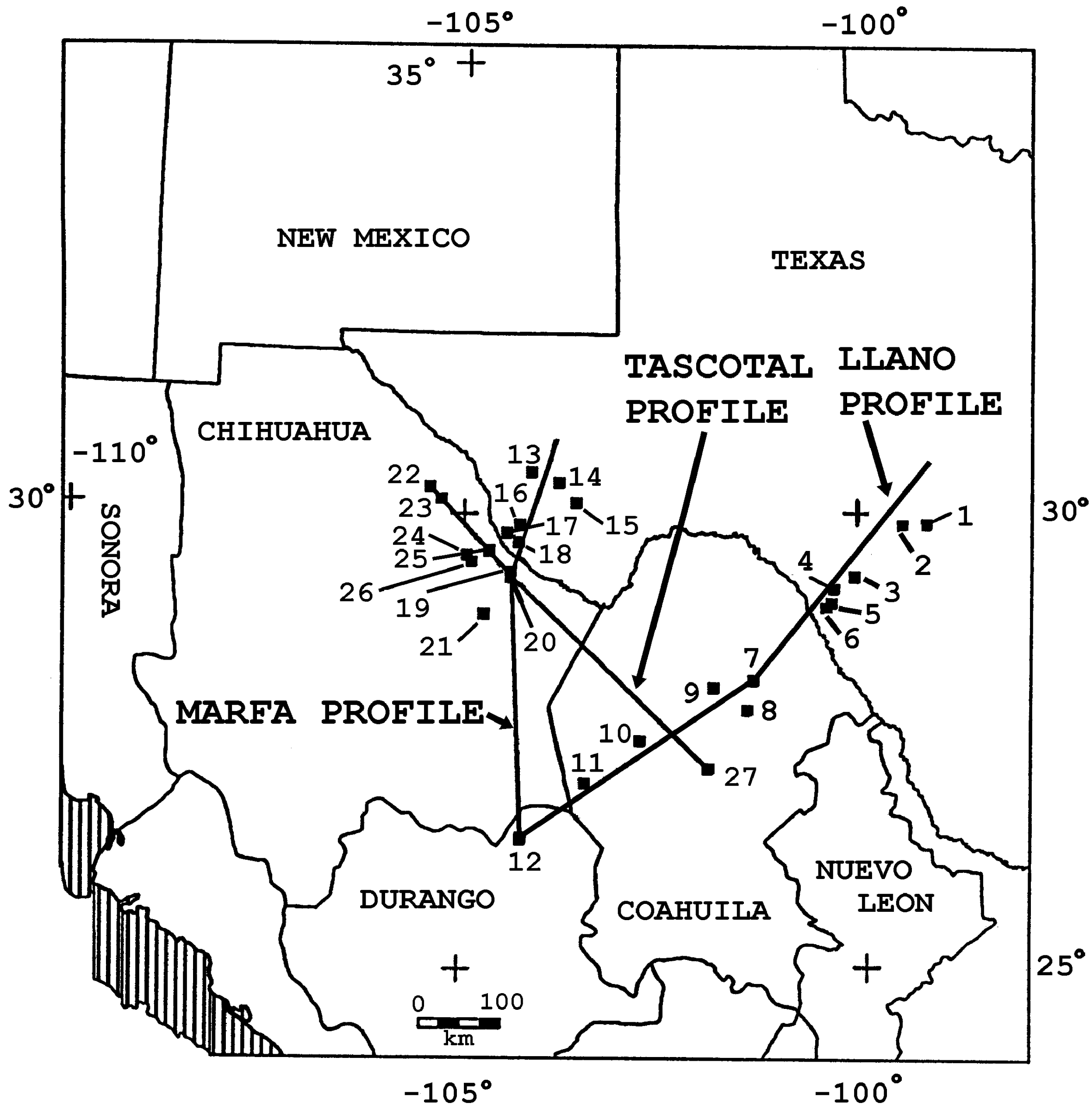


Fig. 4. Location of the three gravity profiles that were modeled. Also shown are the locations (squares) and numbers of the wells that were used to constrain the gravity models.

and their locations were chosen so as to cross key tectonic features and to take advantage of constraining data. The constraints we used include drill hole data (including density and velocity logs), seismic data (reflection, refraction, and surface wave results), and geological mapping. Figure 4 also shows the locations of the drill holes which were used in constructing the gravity models, and Table 1 lists pertinent well information. Crustal thicknesses are constrained by seismic surface wave studies by Gomberg *et al.* (1988), Prewitt (1969), Pinkerton (1978), and a widely-spaced seismic refraction study by Meyer *et al.* (1961). These studies were conducted along the fringes of our study area but indicate that the regional crustal thickness is about 40 km. Seismic reflection data in Texas (Nicholas, 1983; Reed and Strickler, 1990; Culotta *et al.,* 1992) provide a general picture of the geometry of the thrust belt in Texas. The seismic refraction and gravity model of the Laurentian margin in Arkansas constructed by Keller *et al.* (1989b) and Mickus and Keller (1992) was used as a starting point for the modeling. This approach represents considerable extrapolation spatially but was necessary due to the lack of more nearby results and is justified by the strong geologic correlations (Flawn *et al.*, 1961) and previous geophysical studies (Keller *et al.*, 1989a) along the Ouachita orogenic belt. In our model, the Laurentian margin and Ouachita interior zone are nearly coincident, and the crustal thinning associated with the margin, igneous intrusions, and dense interior zone metamorphic rocks together produce the distinctive interior zone gravity high (Mickus

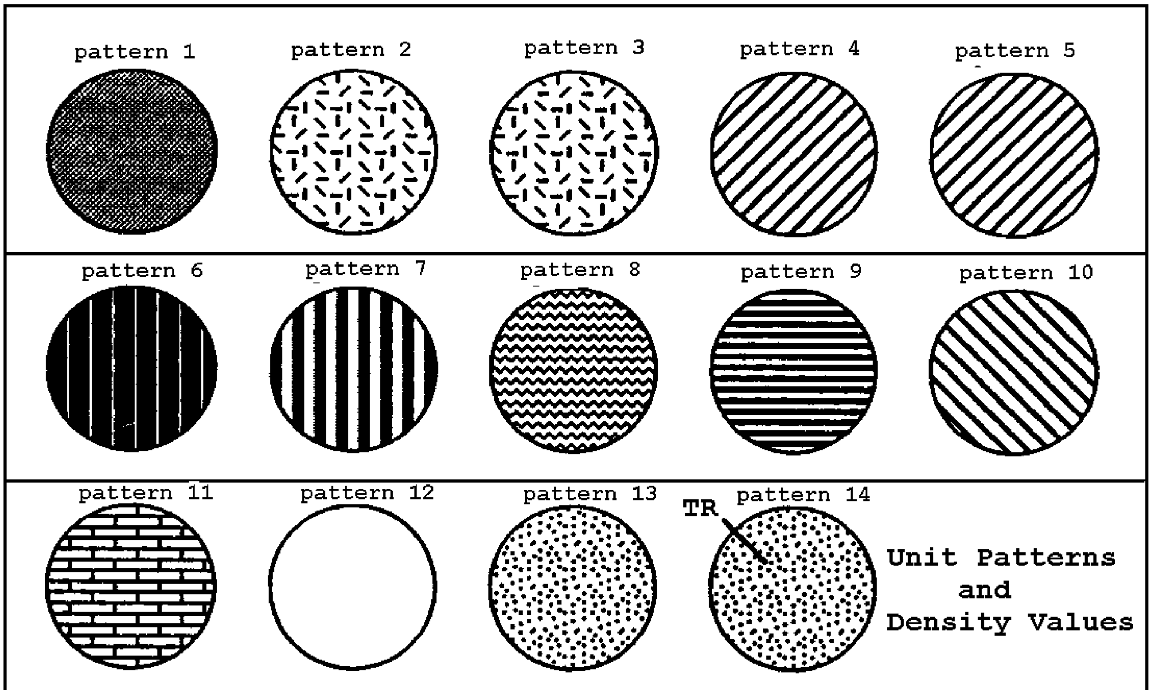
Table 1

Drill holes used in the modeling of the three profiles. Data from Flawn *et al.* (1961), Ammon (1977), Luff (1981), Nicholas and Waddell (1989) and Marsaglia *et al.* (1994)

PROFILE	WELL NAME	WELL NAME (on model)	TOTAL DEPTH (M)	FORMATION-GROUP UNIT/AGE AT TOTAL DEPTH
Llano	Walters #2	1	1852.0	Ellenberger/Ordovician
	Petty O.S. Etux	2	1960.0	Ellenberger/Ordovician
	Harris B #1	3	1830.0	Ellenberger/Ordovician
	W.C. Hedrick	4	2420.0	Pennsylvanian
	Dunbar Fee #1	5	2210.0	Hosston/L. Cretaceous
	Bandera Co. #1	6	4227.6	Metamorphic
	Leono #1	7	1910.0	Basement
	Palau #1	8	2950.0	Barril Viejo/L Cretaceous
	Inca #1	9	2750.0	Hosston/L. Cretaceous
	Sierra Del Fuste	10	2350.0	La Virgen/L. Cretaceous
	Tarahumara	11	2998.0	Andesite (272 +/- 22 Ma)
	Mapimi #1	12	3580.0	Aurora/L. Cretaceous
Marfa	Beer #1	13	2048.0	Cambrian
	Gulf #1	14	3079.0	Ellenberger/Ordovician
	T&P #1	15	1341.0	L. Guadalupe-Ochoan/Permian
	F. Birdsell #1	16	1829.0	Simpson/Ordovician
	West & Cockburn #1	17	2713.0	Ellenberger/Ordovician
	West #1	18	3749.0	Woodford/Devonian
	Ojinaga #1	19	3997.0	Precambrian
	Chapo #1	20	3199.3	Cuchillo/L. Cretaceous
	Apache #1	21	5700.0	Pastor/Permian-Pennsylvanian
	Mapimi #1	12	3580.0	Aurora/L. Cretaceous
Tascotal	Menonita #1	22	7060.0	Rara/Permian
	Hueso #1	23	4918.0	Rhyolite
	Cuchillo Parado #1	24	2600.0	Permian
	Cuchillo Parado #2	25	2600.0	Permian
	Chapo #2	26	3989.8	Paleozoic
	Ojinaga #1	19	3997.0	Precambrian
	Chapo #1	20	3199.3	Cuchillo/L. Cretaceous
	Sierra Del Fuste	10	2350.0	La Virgen/L. Cretaceous
	Menchaca #1	27	2950.0	Igneous

and Keller, 1992). Our model also shows that the Ouachita orogeny did not produce much crustal-scale deformation so that the associated suturing preserved the structure of the original continental margin. In west Texas and northern Mexico, the lack of data precludes the level of detail in the model of Mickus and Keller (1992). Thus, we employed a minor amount of crustal thinning and increased density in the main crustal layers (Figure 5) to model the two possible locations for the interior zone gravity high (Figure 3). We use the term *suture zone* in the models discussed below to refer to the Laurentian margin- Ouachita orogenic belt complex. However, our knowledge of crustal structure and geophysical anomalies suggests that these sutures are not zones of significant crustal scale deformation and thickening such as are observed in the case of major continent-continent collision zones (Thomas and Gibb, 1977).

The density values used in our models were based on work by Smith (1986), Schellhorn (1987) and Keller *et al.* (1989a,b). For all our models, the various lithologic units were grouped into geophysically significant units. For example, the upper Cambrian through lower Pennsylvanian



DENSITY (gm/cc)	ROCK UNIT	PATTERN #
3.33	Upper mantle	1
3.00	Lower continental crust	2
2.70	Upper crust (Precambrian rocks)	3
2.69	Upper transitional crust	4
2.98	Lower oceanic/transitional crust	5
3.00	Mafic intrusive rocks	6
2.75	Upper Cambrian though Lower Pennsylvanian; consisting of carbonate metasedimentary and volcanic rocks	7
2.67	Paleozoic Ouachita facies rocks	8
2.67	Upper Cambrian through Lower Pennsylvanian and post Arbuckle rocks	9
2.60	Post Arbuckle Group, predominantly Mississippian through Permian Flysch	10
2.50	Cretaceous and Cenozoic sedimentary rocks	11
2.40	Tertiary volcanic rocks	12
2.00	Tertiary and Quaternary sedimentary rocks	13
2.47	Triassic graben fill sediments	14

Figure 5. Fill patterns and their associated densities that were used to represent the various units/bodies in the gravity models.

platform strata were grouped together and assigned a density of 2.75 gm/cc. Figure 5 lists the lithologic groupings and their densities.

4.1 Llano Model

The Llano profile extends southwestward from the Llano uplift which is part of Laurentia and crosses the known location of the Ouachita orogenic belt (the northern suture in Figure 6) just south of the Devil's River uplift in west Texas (Nicholas, 1983) (Figure 4). This is our best constrained model (Figure 6). The Kerr foreland basin accounts for the gravity minimum at a distance of 130 km along the model, and the gravity minimum over the southern margin of this suture (270 km) is modeled as a Triassic rift graben similar to one shown by Mickus and Keller (1992) in southern Ar-

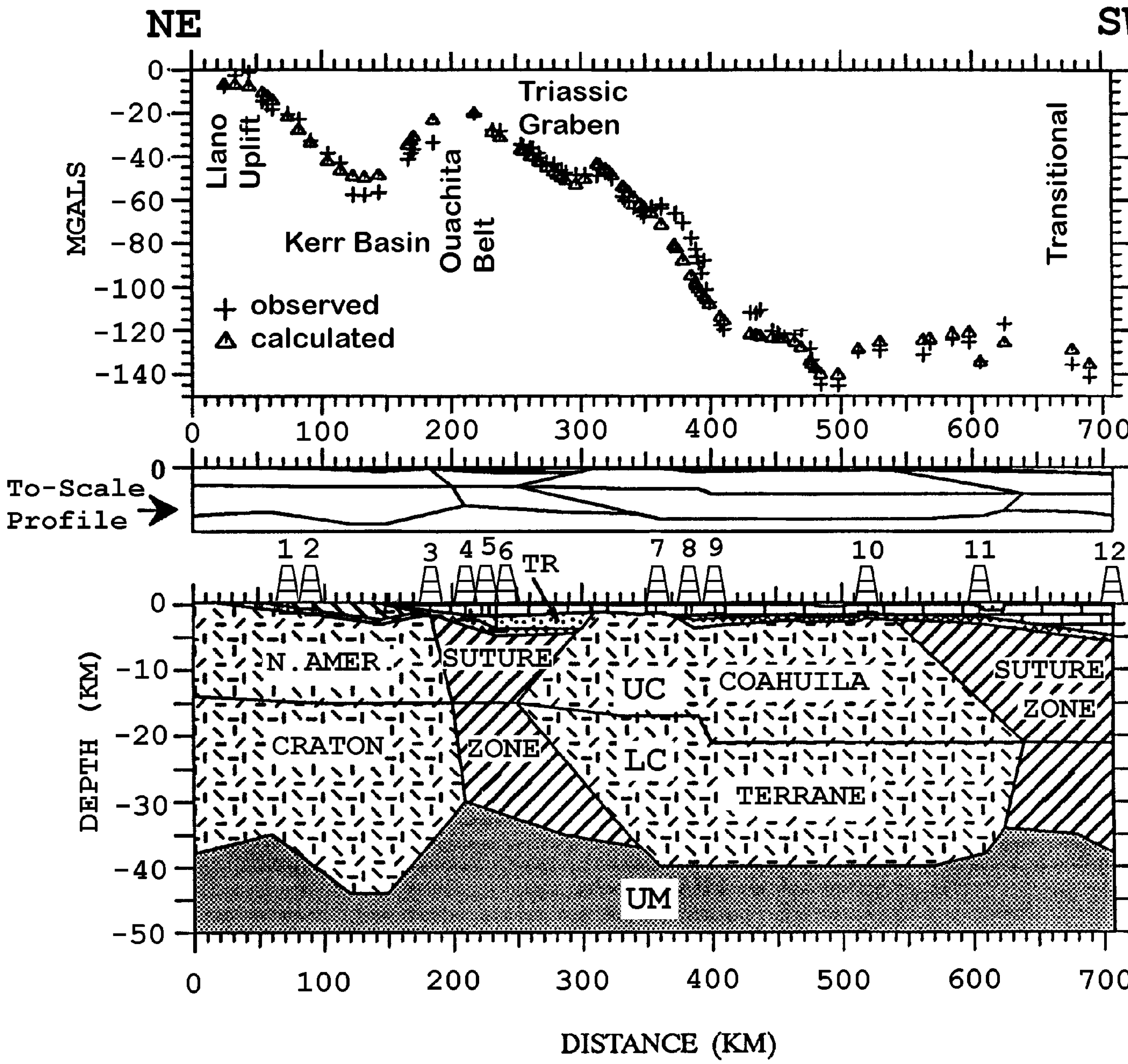


Fig. 6. Integrated crustal model of the Llano gravity profile. The well locations are shown in Figure 4. The densities of the various bodies are shown in Figure 5. Tr represents Triassic strata.

kansas. Evidence for this graben are the Triassic red beds encountered in a drill hole (Bandera Co. #1, no. 6 in Table 1). This basin would then be part of a series of Triassic (Jurassic? in Mexico) rift basins that follow the Ouachita trend from southern Arkansas and east Texas (Milliken, 1990) to eastern Mexico (Salvador, 1987) and are associated with the opening of the Gulf of Mexico. A second suture zone is crossed at the southern end of the model (650 km). This suture represents either the southerly extension of the Ouachita orogenic belt as interpreted by Handschy *et al.* (1987) or the suture between two accreted terranes (Mapimi and Coahuila) if the western location of the Laurentian margin (Figure 3) is correct.

4.2 Marfa Model

The Marfa profile (Figure 4) does not cross a known location of the Ouachita orogenic belt, but it crosses the gravity high which extends westward along the Tascotal uplift (Figure 3) and shows a possible western location for the Laurentian margin. On the north, the profile begins near the Diablo platform and then crosses the Marfa foreland basin. The gravity high at the Tascotal uplift (150 km) is either due to a mafic core for this uplift (Figure 7) or the Ouachita suture (Figure 8). In the model shown in Figure 7, the gravity minimum is interpreted as a foreland basin that extends from 210 km southward to the end of the profile. By analogy, this

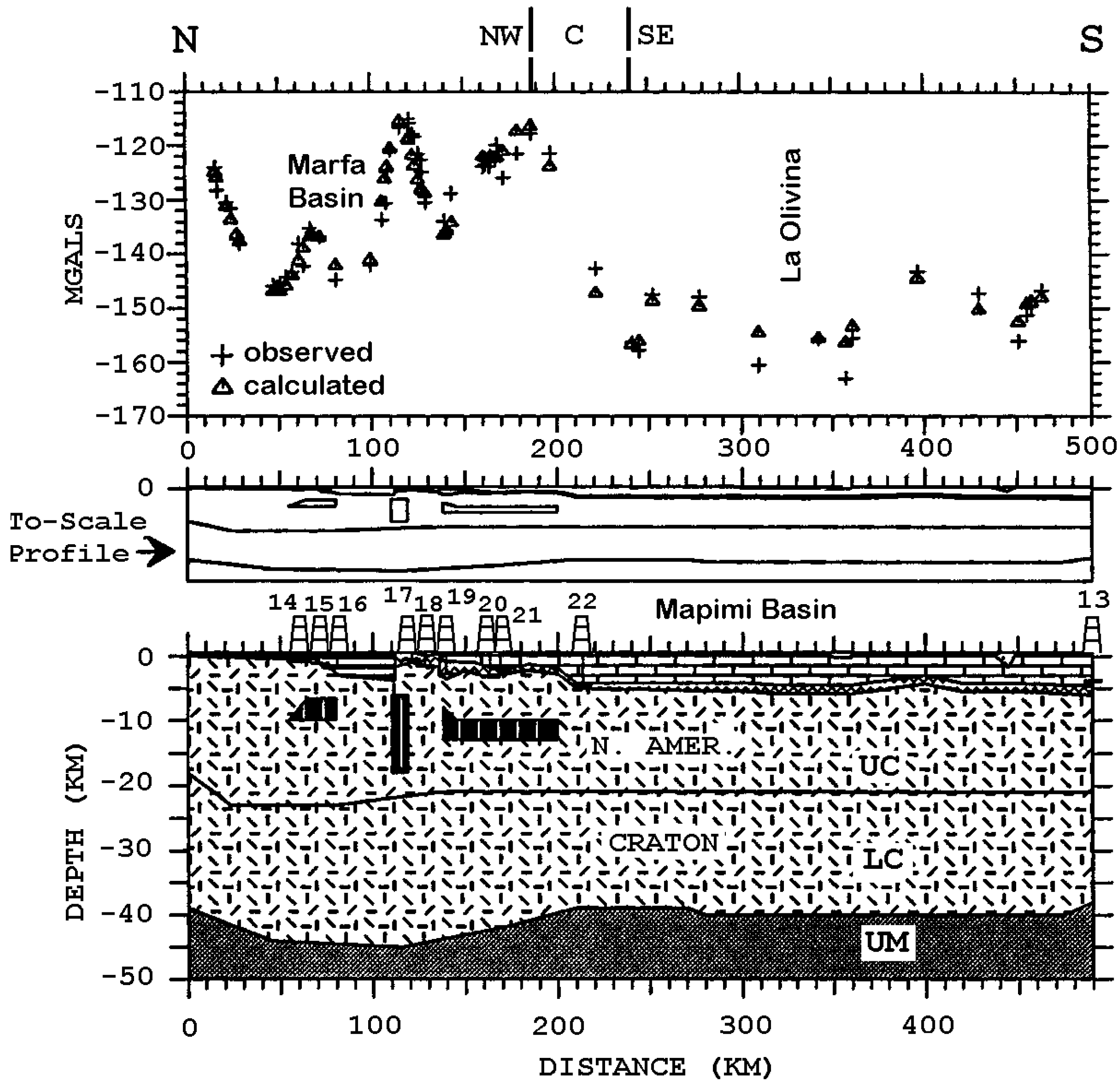


Fig. 7. Integrated crustal model of the Marfa gravity profile representing a southern extension of the Ouachita orogenic belt into Mexico. The well locations are shown in Figure 4. The densities of the various bodies are shown in Figure 5.

basin would be similar to other Ouachita foreland basins (e.g., Marfa) and is located on Laurentia whose margin would be east of the profile. In the model shown in Figure 8, the Ouachita orogenic belt extends south-southwestward from the Big Bend region, and this gravity minimum would be due to the relatively thick crust of the Mapimi terrane, an accreted microcontinent/arc. The Mapimi terrane would be similar in size to some of the smaller terranes in southern Mexico (Coney and Campa, 1987; Sedlock *et al.*, 1993).

4.3 Tascotal Model

The Tascotal profile (Figure 4) lies entirely in Chihuahua and Coahuila and crosses the proposed locations of the Laurentian margin and Ouachita suture. The northern portion of the profile is on Laurentian crust and includes a gravity minimum associated with the Marfa basin (50 km). The gravity maximum representing the extension of the Tascotal uplift anomaly extends from about 100 to 200 km (Figures 9 and 10). The width of this profile is the result of crossing the anomaly at a gentle angle where it is wide and turns south (Figure 3). The model representing a southward extension of the Ouachita suture from the Big Bend region is shown in Figure 9. As in the Marfa profile model shown in Figure 7, the gravity minimum south of the Tascotal uplift (220 km) is interpreted as being due to a Paleozoic foreland basin. The Ouachita suture accounts for the gravity maximum at approximately 280 km on Figure 9. The model representing a

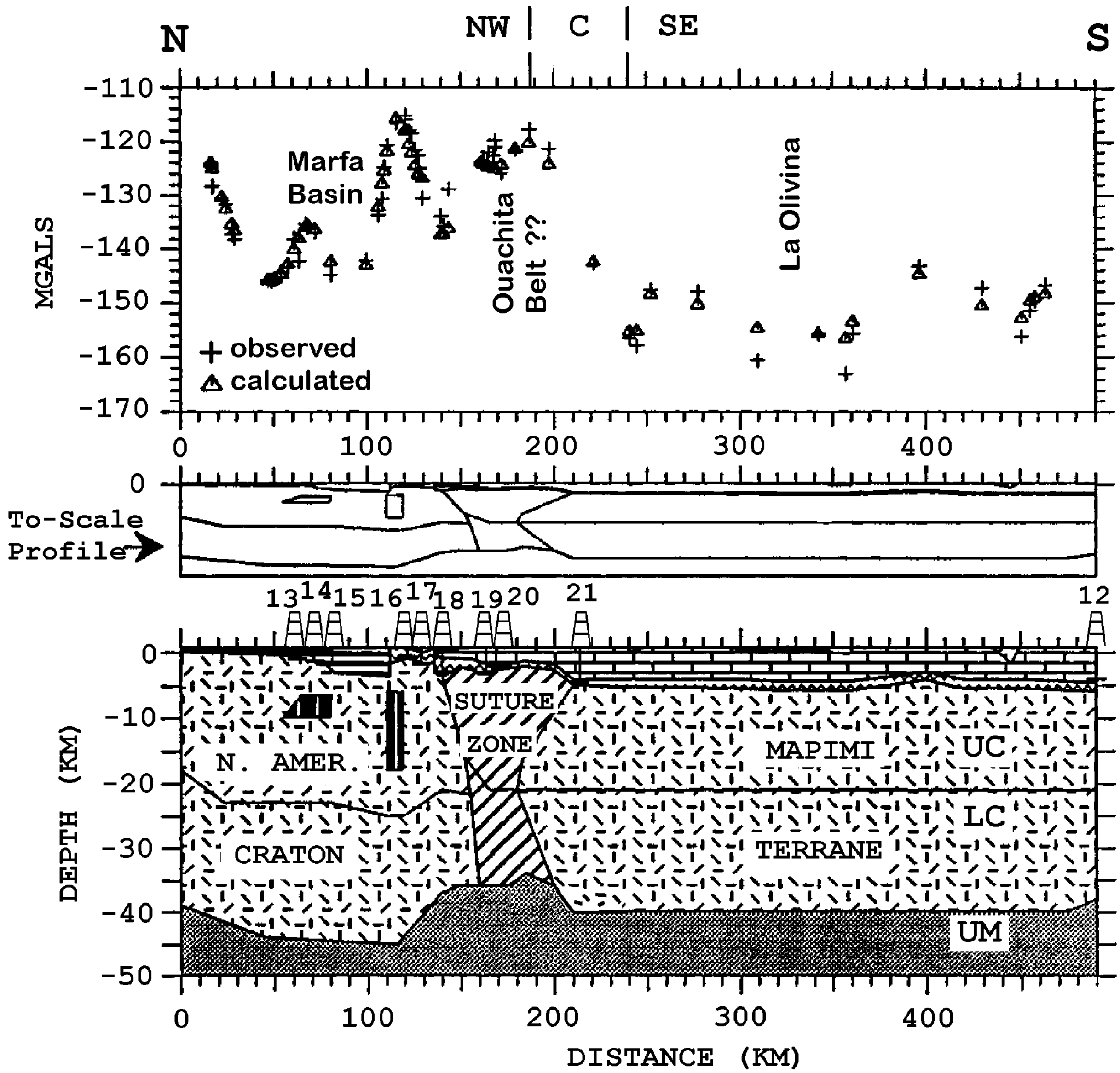


Fig. 8. Integrated crustal model of the Marfa gravity profile representing a south-southwestern extension of the Ouachita orogenic belt into Mexico. The well locations are shown in Figure 4. The densities of the various bodies are shown in Figure 5.

south-southwestward extension of the Ouachita suture from the Big Bend region is shown in Figure 10 where the gravity maximum extending from 100-200 km is interpreted as a suture manifested by possible Ouachita-style lithologies. As in the model shown in Figure 8, the gravity minimum at 220 km on Figure 10 is called the Mapimi terrane and the gravity maximum at 270 km is interpreted as a suture between the Mapimi and Coahuila terranes.

5. DISCUSSION

The integrated crustal models presented above show that the available data are consistent with two general scenarios for the location of the Ouachita suture and Laurentian margin in northern Mexico: 1) a southward extension from the Big Bend region along the Coahuila/Chihuahua border (called the eastern margin model) and 2) a south-southwestward extension across east-central Chihuahua toward Durango (called the western margin model). Below, we will discuss these interpretations. Ouachita interior zone rocks occur at Sierra del Carmen (Carpenter, 1997) just south of the Big Bend region (Figure 11), but these outcrops are far enough north to be consistent with either interpretation. The position of the Laurentian margin in northern Mexico is constrained by exposures of cratonic rocks at Cerro Carrizalillo/ Placer de Guadalupe and Sierra del Cuervo (Figures 1 and 11). Futhermore, Blount *et al.* (1988) and Ruiz *et al.* (1988) showed that the crystalline rocks exposed at Sierra del Cuervo

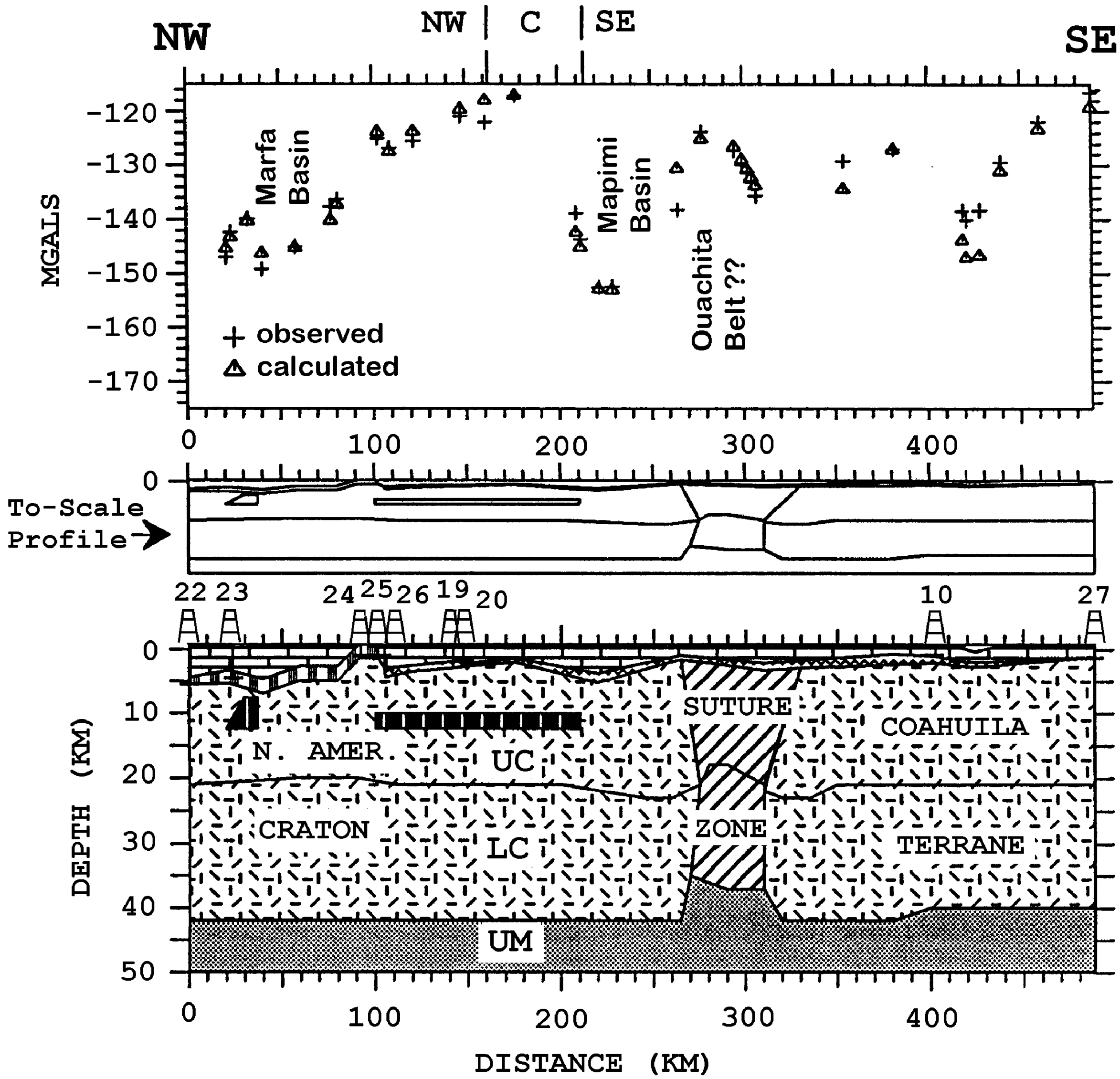


Fig. 9. Integrated crustal model of the Tascotal gravity profile representing a southern extension of the Ouachita orogenic belt into Mexico. The well locations are shown in Figure 4. The densities of the various bodies are shown in Figure 5.

are Precambrian in age and are Laurentian in origin. Handschy and Dyer (1987) showed that the Permian strata exposed there are probably related to uplift of the Sierra del Nido block (Figure 11) which served as the sedimentary source.

Connections with Paleozoic strata exposed in northwestern and southeastern Mexico are an issue in either interpretation of the location of the Ouachita orogenic belt we have discussed. The geologic data of Stewart (1988) and Stewart *et al.* (1990) showed that there are scattered outcrops in Sonora that contain Ordovician to Permian carbonate and siliciclastic rocks that were deformed in the late Mississippian and the late Permian to middle Triassic. These authors suggest that some of these rocks are related to the Cordilleran Paleozoic continental margin, but some may be part of the craton fringing strata which may have extended toward the Marathon uplift (Figure 1). Stewart *et al.* (1990) conclude that some of the rocks in Sonora and the Marathon regions may have been continuous, but due to the lack of outcrops in western and central Chihuahua, a definitive conclusion could not be reached. Additional evidence of a connection between the Sonora and Marathon lithologies comes from Pattison (1992), who described a sedimentary sequence at San Francisco del Oro in south-central Chihuahua. This sequence is in a position to be along a connection between Sonora and eastern Chihuahua. These strata are similar lithologically to exposures in the Big Bend region, but the lack of paleontological work puts the age of these rocks in question.

Flawn *et al.* (1961) and Carrillo-Bravo (1961) correlated strata in the Big Bend region with Precambrian and lower

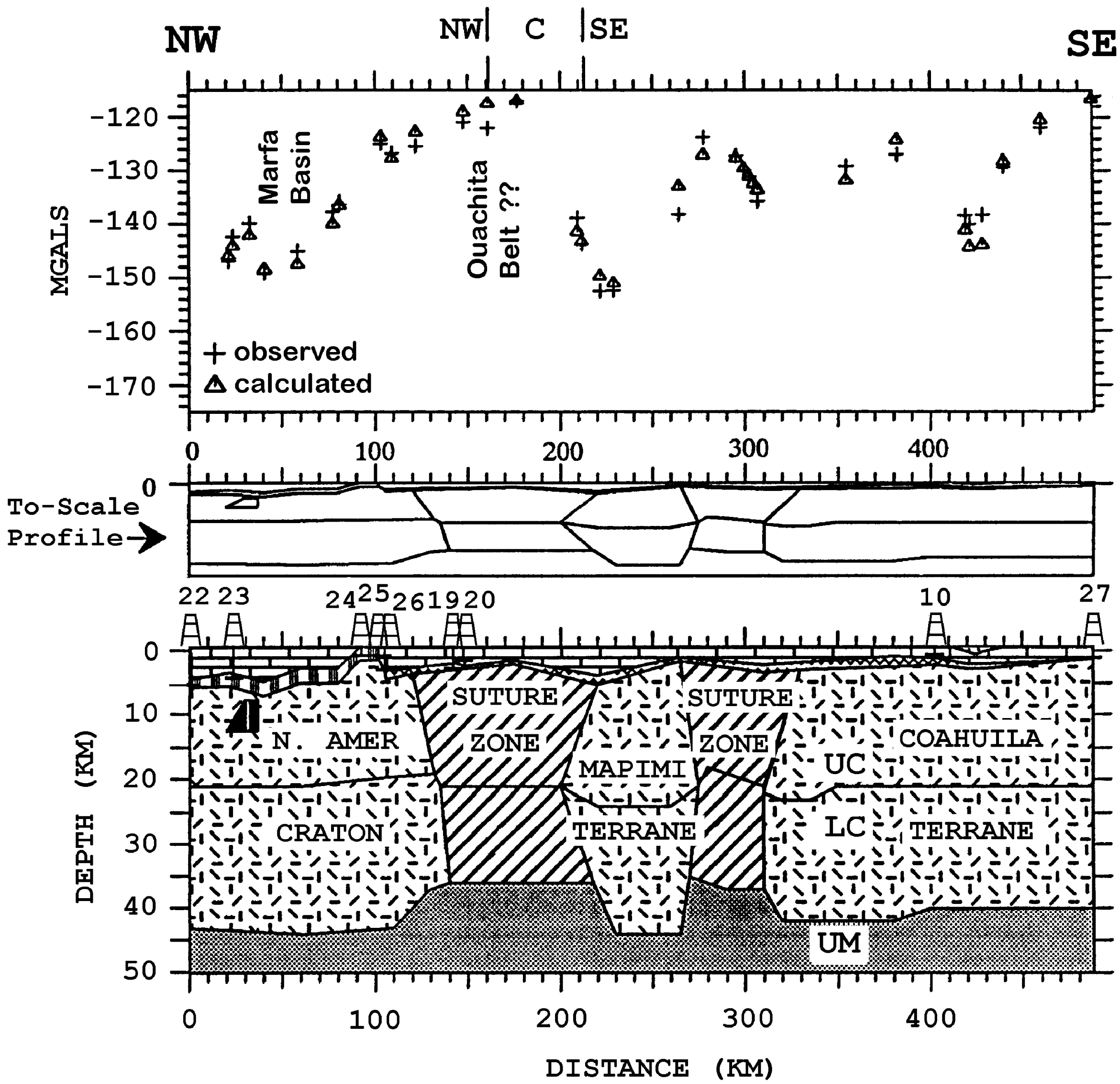


Fig. 10. Integrated crustal model of the Tascotal gravity profile representing a south-southwestern extension of the Ouachita orogenic belt into Mexico. The well locations are shown in Figure 4. The densities of the various bodies are shown in Figure 5.

Paleozoic units found far to the southeast in Tamaulipas (Figure 11) and also reported Devonian novaculites at the same locality. Thus, they thought that the Ouachita orogenic belt might extend into northeastern Mexico. However, more recent data suggest that this correlation is not valid (Gursky and Ramírez, 1986; Stewart, 1988; Ruiz *et al.* 1988; Sedlock *et al.*, 1993; Stewart *et al.*, 1993). For example, Stewart *et al.* (1993) reported that the Paleozoic sediments at Huizachal-Peregrina in Tamaulipas contain fossils that originated in Argentina.

5.1 Western Margin Model

The crustal models, and a tectonic map which propose the Laurentian margin and Ouachita suture extending across east-central Chihuahua and south toward Durango are shown in Figures 8, 10, and 11. In this interpretation, the margin and related gravity maximum (Figure 3) extends across eastern Chihuahua toward Durango before it either turns northwestward to connect with possible Ouachita-related outcrops in Sonora (Stewart, 1988; Stewart *et al.*, 1990), is truncated by the postulated Mojave-Sonora megashear (Anderson and Schmidt, 1983), or is obscured by Mesozoic and younger rocks and tectonic events. Evidence favoring this interpretation is presented in isotopic studies by Rudnick and Cameron (1991), Cameron *et al.* (1992) and James and Henry (1993a,b) which imply that the Laurentian margin lies in the northwestern portion of the Big Bend region and somewhat to the northwest of La Olivina (Figure 11). In this interpretation, La Olivina is located within the Mapimi terrane and was underlain by relatively thick crust in the late Paleozoic (Cameron *et al.*, 1992).

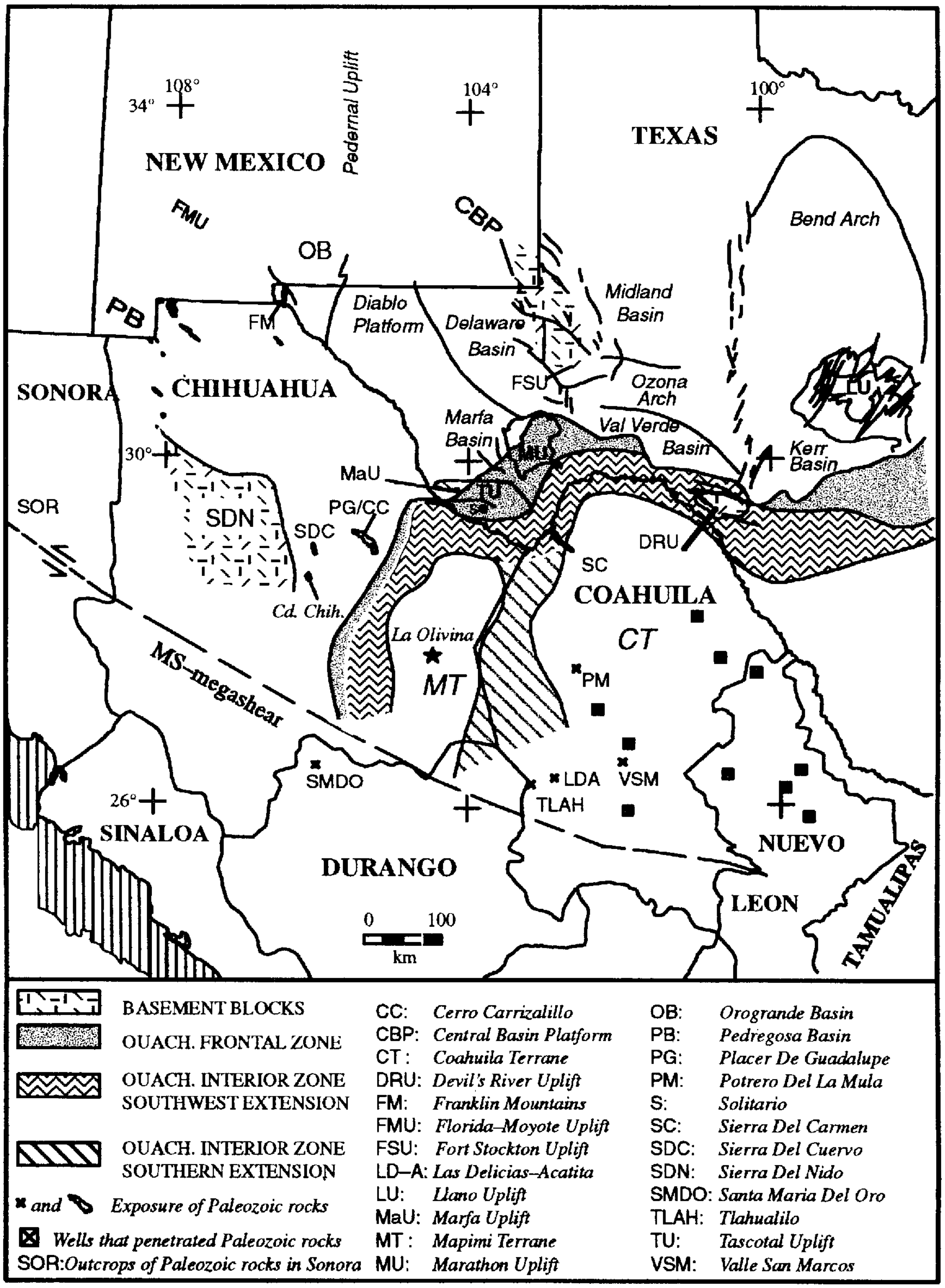


Fig. 11. Summary tectonic interpretation of the extension of the Ouachita orogenic belt into Mexico. Based on the integrated results presented here, we prefer the south-southwest extension (eastern margin model) shown.

The evidence against the above model for the location of the Laurentian margin is simply that there are no drill penetrations or outcrop data to directly support this interpretation. It is consistent with the available data, but they are sparse. Its advantage is that it best satisfies the combination of gravity and Pb isotopic data.

5.2 Eastern Margin Model

Figure 11 also depicts a possible southward extension of the Laurentian margin and Ouachita suture zone, which occurs south and east of the Big Bend region. In this case, the south trending gravity maximum would be the signature of a Laurentian foreland structure of unknown origin. The crustal models illustrating a southward extension of the Ouachita orogenic belt are shown in Figures 7 and 9. Besides gravity anomalies (Handschy *et al.*, 1987), the main arguments for a southward extension are based on various Paleozoic outcrops in northern Mexico. However, these arguments are also consistent with the western margin model. The arc-related outcrops at Las Delicias/Acatita, Valle San Marcos and Potrero de la Mula and wells containing arc-related rocks south and east of Potrero de la Mula (Handschy *et al.* 1987; McKee *et al.*, 1988) do make a better case for the presence of the Coahuila terrane and its boundaries than can be presently made for the presence of the Mapimi terrane. We interpret the southward trending gravity anomaly in Figure 3 as delineating a suture and trace it further south than Handschy *et al.* (1987).

6. CONCLUSIONS

Analysis of regional gravity anomalies coupled with the integration of all available geological, drill hole, Pb isotopic and geophysical data to construct of a series of crustal models reduces the number of interpretations of how the Laurentian margin and Ouachita orogenic belt extend into northern Mexico to two: An eastern margin model which has a southern extension from the Big Bend region of west Texas into Coahuila for approximately 250 km and a western margin model, which postulates a parallel extension of about 300 km in length, but lying to the west. Gravity, drill hole and geologic data cannot distinguish between these models, but Pb isotope data suggest that the western margin should be preferred. Connecting the western margin with correlative outcrops in Sonora (Stewart, 1988; Stewart *et al.*, 1990) places the Laurentian margin trending northwest between southern Chihuahua and Sonora and provides a complete and potentially simple picture of this margin which requires no large lateral movements after its formation. The tectonic features in Mexico inferred from the eastern margin model include the Mapimi foreland basin and the Coahuila terrane to the east; whereas the western margin model suggests that two accreted terranes, the Mapimi and Coahuila, are present. Additional mapping to locate Paleozoic and Precambrian outcrops, drilling, and seismic profiling will be required to differentiate between these two models.

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