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MIDDLE-LATE PROTEROZOIC EXTENSION IN THE CARLSBAD REGION OF SOUTHEASTERN NEW MEXICO AND WEST TEXAS

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Abstract—Extensive bimodal igneous activity occurred in the Middle Proterozoic of North America, affecting areas of Arizona, California, Colorado, Iowa, Kansas, Michigan, Minnesota, Nebraska, New Mexico, Oklahoma, Texas and Wisconsin. We discuss the portion of this activity affecting west Texas and eastern New Mexico. Igneous intrusions formed in west Texas and New Mexico between 1215-1074 Ma. These bodies are exposed or have been penetrated by drilling in the Central Basin platform, Franklin Mountains, Van Horn uplift, Pajarito Mountain and Devils River uplift. Information from previous studies of Precambrian outcrops and wells drilled to the Precambrian are combined with gravity maps to produce a picture of Middle Proterozoic activity in this region. This picture shows that igneous activity occurred in two areas coincident with the Debaca-Swisher terrain and the Delaware aulacogen. The bimodal igneous activity suggests extension. This igneous activity was in part coincident with formation of the Midcontinent rift system and Grenville age tectonic events in Texas. Further geologic and geophysical studies are necessary to understand the Middle Proterozoic of the region and its relationship to Middle Proterozoic tectonics.

INTRODUCTION

The Precambrian geology of west Texas and southeastern New Mexico has been studied by many investigators (Flawn, 1956; Keller et al., 1980, 1989; Denison et al., 1984; Muehlberger and Dickerson, 1989; Bowsher, 1991). Flawn (1956) used wells penetrating Precambrian rocks and their lithologies to map the basement. More recently Denison et al. (1984) refined Flawn's map and reevaluated the Precambrian of west Texas and southeastern New Mexico (Fig. 1). Muehlberger and Dickerson (1989) provide the most recent overview of the Precambrian geology of Trans-Pecos Texas. These studies have focused on definition of basement terrains and not the lithologies of specific bodies. Other authors (Keller et al., 1980, 1989; Bowsher, 1991) have focused on defining specific bodies, Pajarito Mountain and the Central Basin platform respectively.

Our goal is to review the geology and tectonics of the Middle Proterozoic igneous rocks formed between 1215-1074 Ma in the Carlsbad region. We will refer to the time between 1185 and 1010 Ma as Keweenawan, which is used to refer to the period of rifting in the northern Midcontinent. Gravity anomaly maps will be used to constrain and promote synthesis of the geologic data. To accomplish our goal we will combine information from geology, wells penetrating Precambrian rocks, age determinations and gravity data from Texas and New Mexico.

MIDDLE PRECAMBRIAN IGNEOUS ACTIVITY

Igneous activity occurred in several regions of North America during the Middle Proterozoic, including the Midcontinent rift, Colorado, California, Arizona, New Mexico and Texas. The Midcontinent rift system formed between 1185 and 1010 Ma (Weiblen, 1982). Rift related rocks occur in the Precambrian of Oklahoma, Kansas, Nebraska, Iowa, Wisconsin, Minnesota and Michigan, with possible extensions in Ohio, Kentucky, Tennessee and Alabama. In Colorado, the granitic Pikes Peak batholith was intruded between 1030-1060 Ma (Anderson, 1983; Bickford et al., 1989). This batholith's relationship to the tectonics of North America is not well understood. In southern California and Arizona diabase sills intruded in 44 areas between 1069-1120 Ma (Heaman and Grotzinger, 1992). Mild extension may have been driven by the sills (Howard, 1991), which have extensional geochemical affinities (Hammond, 1990). The other area in the West where igneous rocks of Keweenawan age are found is in eastern New Mexico and west Texas (Table 1). Igneous rocks are found in the Central Basin platform (1077-1163 Ma; Keller et al., 1989), Pajarito Mountain (1135-1215 Ma; Bowsher, 1991), Franklin Mountains (1135-1250 Ma; Copeland and Bowring, 1988; Denison and Heatherington, 1969) and the Van Horn uplift (1232-1097 Ma; Soergard, 1992 written communication).

GEOPHYSICAL DATA

The gravity data for this study were obtained from a gravity database maintained by the Department of Geological Sciences at the University of Texas at El Paso. Bouguer anomaly values with a sea level reduction

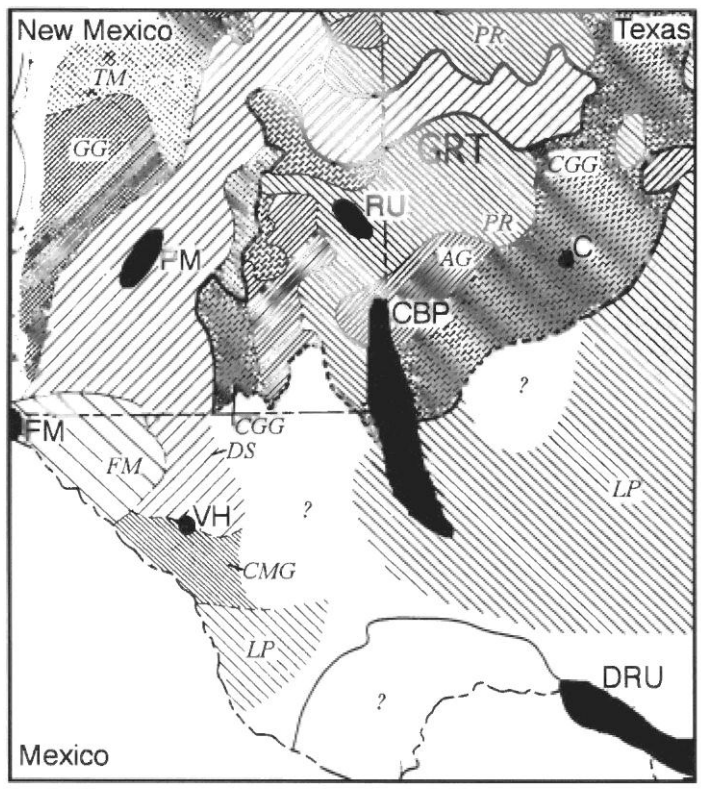

FIGURE 1. Location map showing the positions of bodies of Middle Proterozoic igneous rocks discussed in the text, Central Basin platform (CBP), Devils River uplift (DRU), Roosevelt uplift (RU), Pajarito Mountain (PM), Franklin Mountains (FM), Van Horn uplift (VH) and Crosbyton Geophysical Anomaly (C). Also shown are the basement terrains of Denison et al. (1984); Franklin Mountain (*FM*), Debaca-Swisher terrain (*DS*), Llano Province (*LL*), Panhandle Rhyolite terrain (*PR*), Amarillo Granite terrain (*AG*), Carrizo Mountain group (*CMG*), Chaves Granite gneiss terrain (*CGG*), Granite Gneiss (*GG*) and Torrance metamorphic terrain (*TM*). A heavy line outlines the Granite Rhyolite terrain (GRT). Modified from Denison et al. (1984).

TABLE 1. Summary of Middle Proterozoic igneous rocks in and around the Carlsbad region.

Location	Age (mybp)	Tectonic Setting: Rift	Tectonic Setting: Back-arc	Rock Type	Remarks	Reference
Carrizo Mountains	1,270	X	X	granites-rhyolites	Rare earth element patterns similar to Franklin Mountains.	Rudnick, 1983 Norman et al., 1987
Franklin Mountains	1,064 ± 5	X		granites-rhyolites	Rare earth element patterns similar to Carrizo Mountains.	Norman et al., 1987 Shannon and Barnes, 1992
Hueco Mountains	990 ± 60	X		granites-rhyolites	Petrographically similar to Franklin Mountains.	Denison and Heatherington, 1969
Pump Station Hills	1,064 ± 5	X		granites-rhyolites	Similar to Franklin Mountain igneous rocks and De Baca Terrane rocks (?).	Denison and Heatherington, 1969
Bent Dome	950 (?)	X		granites-rhyolite	Similar to micrographic granites to the south and equivalent to Panhandle Volcanic Terrane rocks of Texas.	Denison and Heatherington, 1969
Sacramento Mountains	1,135-1,215	X		bimodal	Array of syenite, nephline syenite, alkali granite, quartz syenite and gabbro.	Bowsher, 1991
Pedernal Hills	?	X		granite	Alkaline granite with microcline and An_{27-34} plagioclase	Gonzalez and Woodward, 1972
Pajarito Peak	1,190-1,135	X	X	granite-syenite	Riebeckite granite, quartz syenite, syenite	Denison and Heatherington, 1969
Van Horn Mountains	1,238 ± 65			rhyolite	Rhyolite of Carrizo Mountain group, Older than Franklin Mountain granites and rhyolites and metamorphosed.	Denison and Heatherington, 1969
	1,000				Metamorphic event.	
	940	X (?)		rhyolite	Emplacement of rhyolite dikes.	
Nellie Well (Central Basin Platform)	1,163 ± 4	X		gabbro	Gabbroic body that is younger than the surrounding basement rock.	Keller et al., 1989
Devil River Uplift, Texas-Mexico	1,121 ± 244*	X		bimodal	Metarhyolites and metabasalts in area probably affected by Middle Proterozic extension.	F. Moreno, in preparation Nicholas and Rozendal, 1975

(?) The alkaline nature of this rock and age imply an anorogenic setting for the igneous rock. * represents age determination on 4 samples from 4 different depths.

datum using a standard density of 2.67 g/cc were used. The data were projected into Lambert coordinates and gridded at a 4 km interval using a minimum curvature algorithm. A second order best fit polynomial was removed from the grid, producing a residual grid that emphasizes gravity anomalies caused by crustal sources. The residual grid was wavelength filtered and displayed. Three filtered gravity maps were produced from the residual gravity anomaly map in Fig. 2. The filters passed wavelengths of 20-150 km (Fig. 3) and 150-1000 km (Fig. 4).

GEOLOGICAL BACKGROUND

This area's known geological history starts in the Early Proterozoic with formation of the 1600 Ma Torrance metamorphic terrain (Fig. 1; Denison et al., 1984). The next event was formation of the Granite-rhyolite terrain (1340-1410 Ma; Anderson, 1983). This was followed by Grenville age deformation (1232-1116 Ma; Walker, 1992) and the possible Middle Proterozoic extension in Texas (1215-1074 Ma; Table 1). Several Phanerozoic events have also affected this region. These events include the Ouachita-Marathon orogeny, Laramide orogeny and late Cenozoic extension associated with the Rio Grande rift and Basin and Range province.

Granite-rhyolite terrain

The Granite-rhyolite terrain is located south and southeast of the subcrop of the Torrance metamorphic terrain (Fig. 1). This terrain covers an area extending from Labrador to California with shallow plutonic and rhyolitic material derived from the lower crust (Anderson, 1983). The granitic rocks are also noteworthy because they have undergone only minor metamorphism and deformation after formation (Anderson, 1983). The Granite-rhyolite terrain probably forms a veneer 3-10 km thick on Early Proterozoic crust (Bickford, 1988). Deep seismic reflection profiling by COCORP and the oil industry have revealed extensive layered sequences in the Granite-rhyolite terrain below the Phanerozoic cover (Pratt et al., 1992). The rocks in this terrain can be divided into an eastern terrain (1410-1490 Ma) and western terrain (1340-1410 Ma). The western terrain includes western Missouri, Kansas, Oklahoma, western Texas and eastern New Mexico (Anderson, 1983; Thomas et al., 1984).

Keweenawan age mafic intrusions in the Carlsbad region

As previously mentioned, the Carlsbad region of west Texas and eastern New Mexico was an area of considerable Middle Proterozoic bimodal igneous activity. The area in Fig. 1 is known to have produced igneous rocks during this time: Central Basin platform, Pajarito Mountain, Franklin Mountains, Van Horn uplift and Crosbyton geophysical anomaly, located east of Lubbock, Texas (Adams and Keller, in review).

The Central Basin platform (CBP), located in the Permian Basin, is associated with the largest of these features (Fig. **1).** The CBP is associated with a 220-km-long, north-northwest-trending, 120 mgal gravity anomaly (Fig. 2). Keller et al. (1980) compiled and analyzed the information available on the CBP. A gravity model across the CBP showed that the change in thickness of the sediments from the Delaware Basin to the CBP could not account for 50 mgals of the gravity anomaly. An intra-basement mass, probably a mafic body under the CBP, is required to satisfy the gravity data. Compilation of the drilling information confirms that the entire length of the gravity anomaly (Fig. 3) is associated with mafic igneous rocks (Figs. 1, 5).

In 1984, the North American Royalties Company drilled the #1 Nellie well centered on the southernmost gravity high of the CBP (Keller et al., 1989). This well penetrated 1400 m of Phanerozoic sedimentary rocks and 4460 m of Precambrian rocks, providing a deep penetration of the Precambrian basement. The basement samples from this well are mafic and ultramafic rocks including anorthosite, norite, orthopyroxene and gabbro. Ages for these rocks were obtained by the uranium-lead method on zircon and titanite for three samples from this well. The results provided Keweenawan ages of 1163-1077 Ma (Table 1). Seismic reflection data near the Nellie well and well logs show that the intrusion is heterogeneous and probably layered (Keller et al., 1989).

Pajarito Mountain is a Precambrian outcrop of syenite, syenite gneiss

and gabbro (Kelly, 1971) located in the Sacramento Mountains of southeastern New Mexico (Fig. I) on a northeast and northwest trending, T-shaped, 50 mgal gravity high (Fig. 2). Several oil exploration wells on the gravity high have penetrated gabbro, diabase and monzonite associated with the Debaca-Swisher terrain (Denison et al., 1984). Pajarito Mountain may represent a late intrusion into a layered ultramafic body associated with the gravity high (Bowsher, 1991). This relationship may indicate bimodal volcanism associated with rifting in the period 1135-1215 Ma (Table 1).

The Franklin Mountains provide a Precambrian exposure in west Texas (Fig. 1). The exposed rocks include diabase sills, the Mundy Breccia and the Red Bluff Granite (Harbour, 1960; Denison and Heatherington, 1969). The diabase sills are intruded in the Castner Marble while the Mundy Breccia, a basaltic debris flow, rests unconformably on the Castner Marble (Denison and Heatherington, 1969). The younger Red Bluff Granite has been dated at 1150-1135 Ma and is extensional in nature (Copeland and Bowring, 1988; Shannon and Barnes, 1991).

The Franklin Mountains are associated with a north-south oriented gravity high which extends 50 km from northern Mexico into Texas and New Mexico (Figs. 2, 3). The gravity anomaly extends beyond

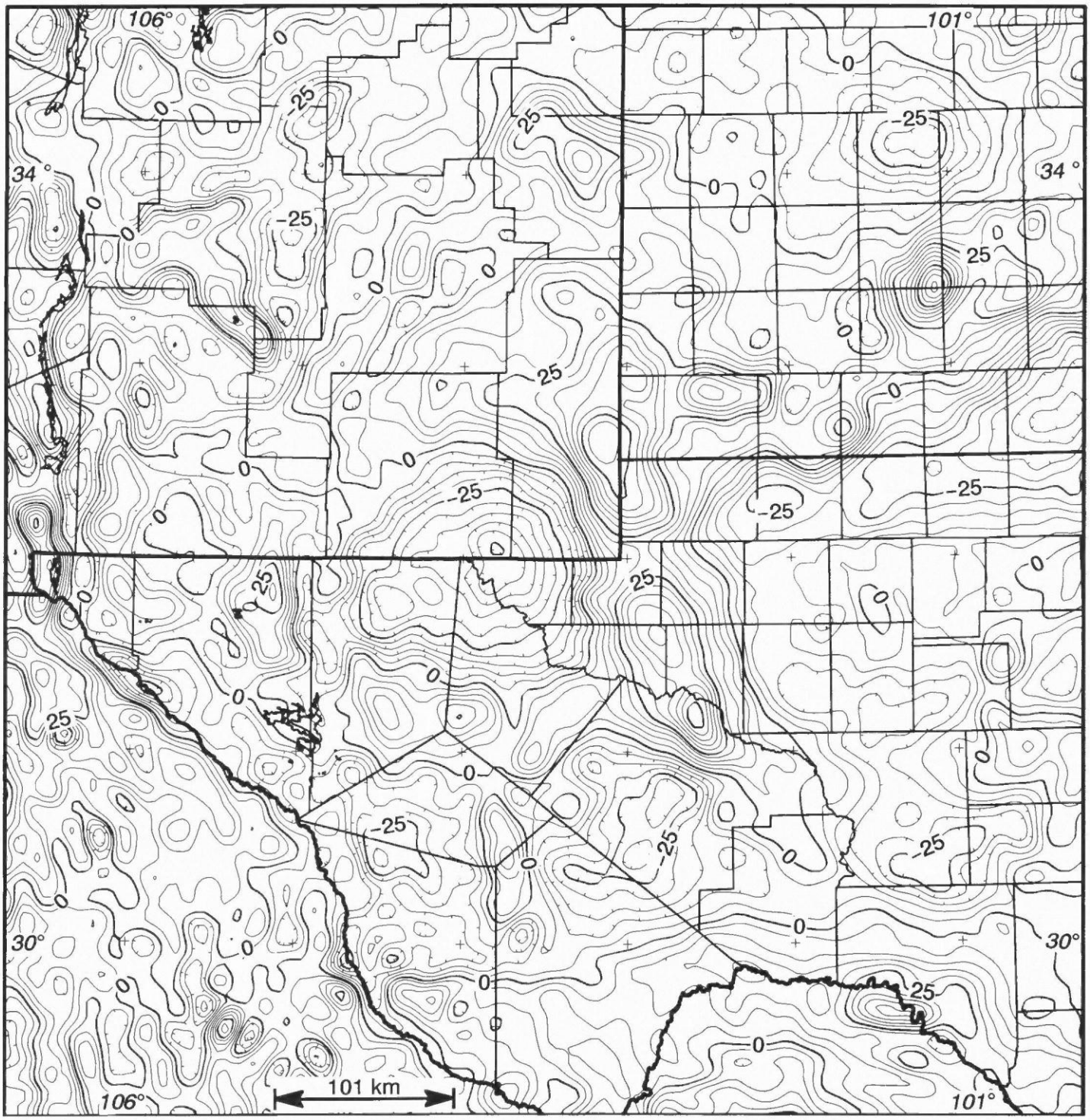

FIGURE 2. Residual gravity anomaly map with Precambrian outcrops in outline. A 5 mgal contour interval was used for the map.

the fault block that forms the Franklin Mountains. This anomaly was interpreted by Hadi (1991, fig. 20) to be associated with a mafic body in the subsurface.

Precambrian outcrops in the Van Horn region of Texas may be associated with mafic activity during this period. The formation names used here are those used by Soergard (1992, written comm.). The "Garren Formation" consists of basalt flows unconformably overlying the Allamoore Formation and overlain by a rhyolite terrain. The Allamoore Formation and rhyolite terrain are dated at 1232 Ma and 1097 Ma, respectively, which suggests that the "Garren Formation" formed at the same time as other mafic rocks in the region. Denison et al. (1984) placed these rocks in the Debaca-Swisher terrain.

The Devils River uplift (DRU) is a complex subsurface basement uplift that formed along a major northwest-southeast trending fault system. It is located in Val Verde and Kinney Counties, Texas and marks the southern limit of the Permian Basin region (Fig. 1). This autochthonous-parautochthonous mass of Precambrian volcanic rock is mantled by Lower and Middle Paleozoic foreland carbonate facies rocks. On the southern flank, the Paleozoic rocks are overridden by highly sheared metamorphic rocks interpreted to belong to the Ouachita facies

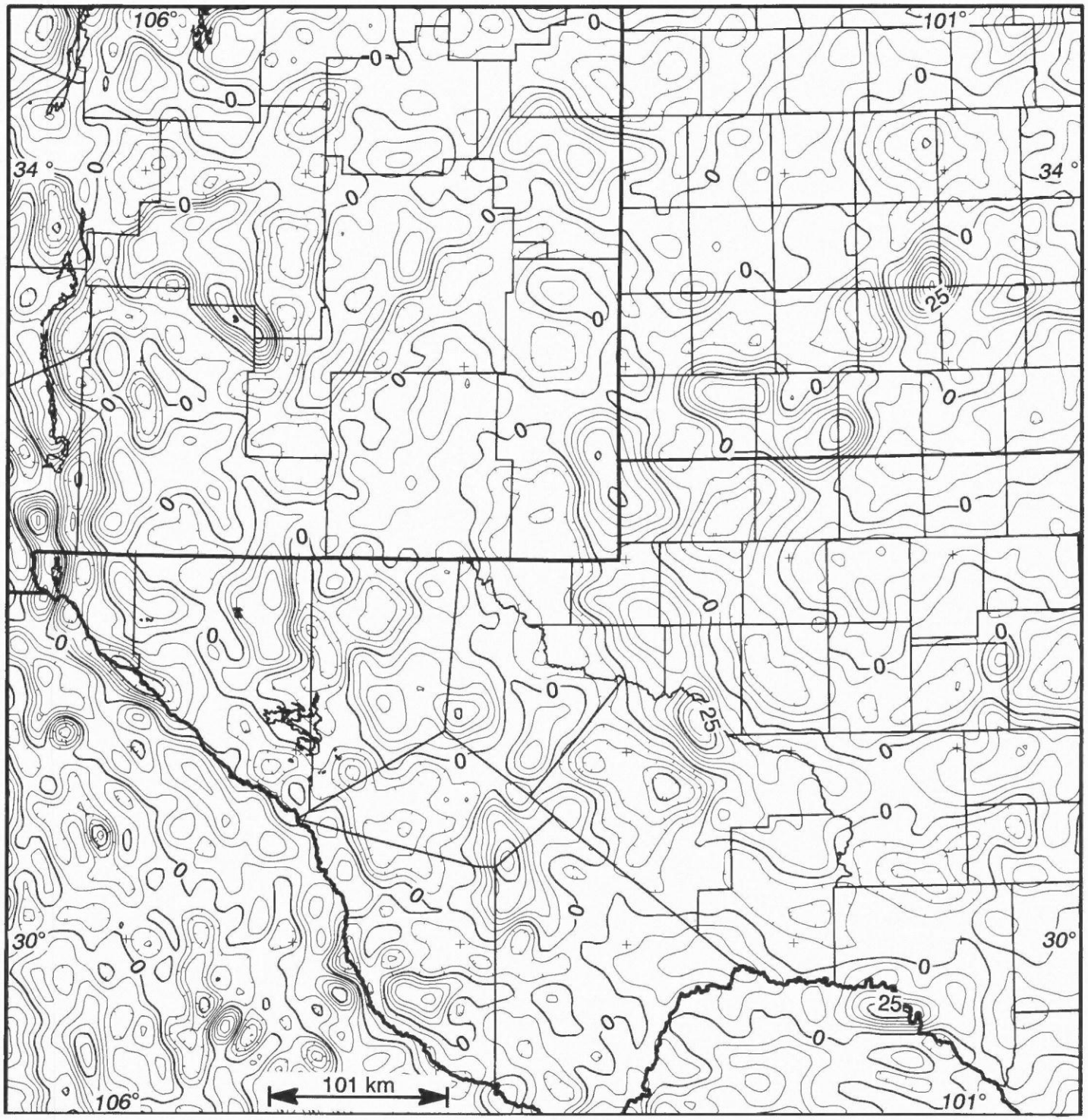

FIGURE 3. High pass (20–150 km) filtered gravity anomaly map. This map enhances the gravity anomalies caused by upper crustal structures. Precambrian outcrops are shown in outline. A 5 mgal contour interval was used for the map.

rocks of the interior zone (Flawn et al., 1961; Nicholas and Rozendal, 1975).

Several wells in the DRU region have penetrated Precambrian rocks and the allochthonous Ouachita interior zone. They provide information on the age and tectonic environment of the DRU (Fig. 5). The Shell Stewart well penetrated metaigneous and metasedimentary rocks dated by Rb-Sr methods at 1121 ±244 Ma and 529 ± 31 Ma, respectively (Nicholas and Rozendal, 1975; Table 1). Denison et al. (1977) reported that the oldest rocks for the Shell Stewart well were massive plutonic rocks of granitic composition. The two sets of dates reported by Nicholas and Rozendal (1975) may represent two magmatic episodes in the region. The younger Precambrian rocks of the DRU region have been interpreted as being deposited during the time of initial continental rifting in the Late Precambrian similar to the southern Oklahoma aulacogen (Webster, 1977). Walper (1977) included the DRU with the CBP in the Delaware aulacogen. The Shell #1 Gillis and the Husky #1 Rose-Robertson wells also penetrated metamorphic rocks reported to be derived from a basaltic protolith (Denison et al., 1977). These wells represent the oldest basement rocks on the DRU and are associated with the isolated 25 mgal gravity high (Fig. 3). The metaigneous rocks

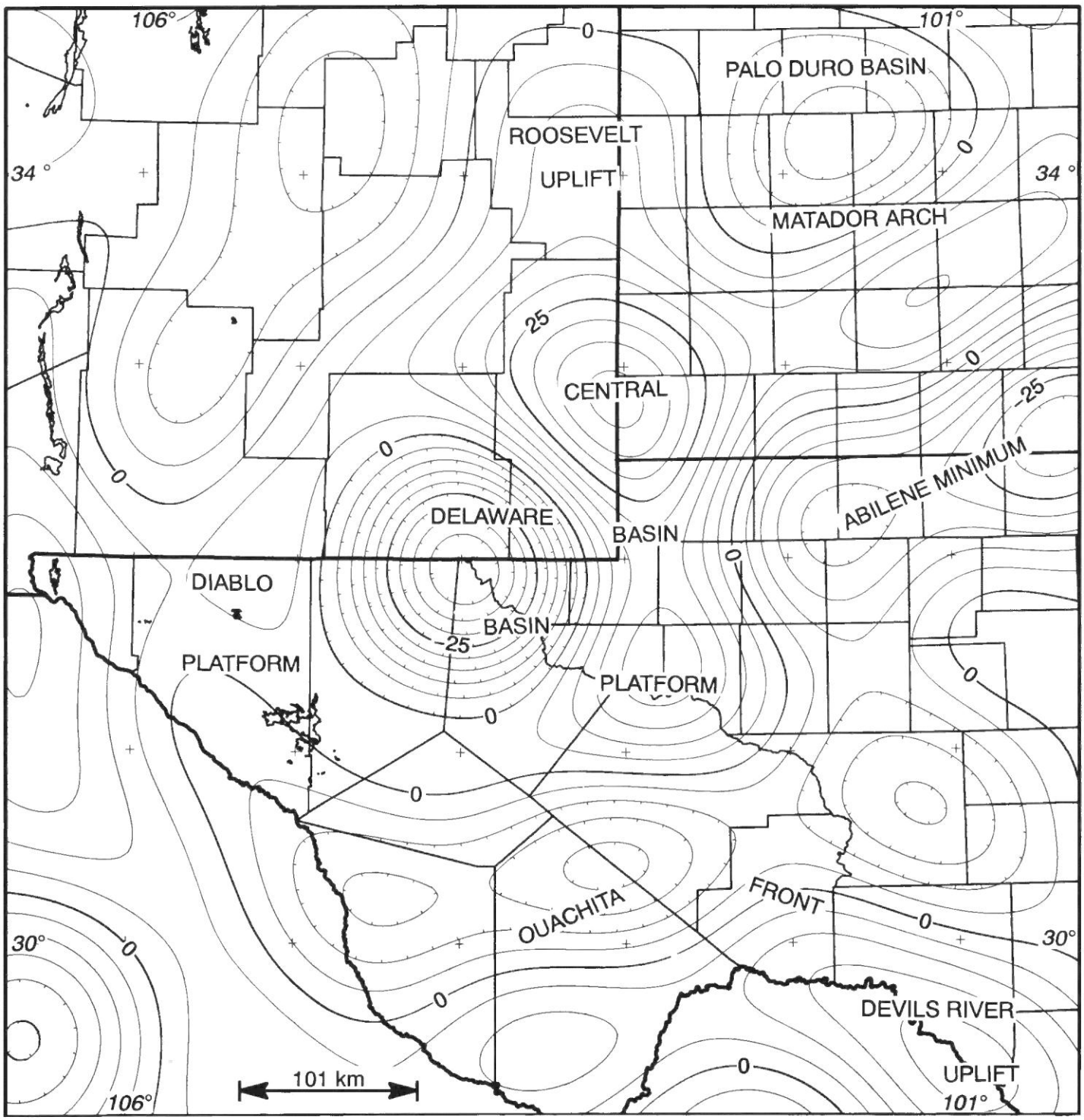

FIGURE 4. Low pass (150–1000 km) filtered gravity anomaly map. This map enhances gravity anomalies caused by large or deep crustal structures. Precambrian outcrops are shown in outline. A 5 mgal contour interval was used for the map.

may represent a portion of ocean crust, welded to the southern edge of the Texas margin during a Late Proterozoic orogenic event (Calhoun and Webster, 1983). Several wells have encountered Precambrian metarhyolites, similar to the Shell Stewart and to outcrops northwest of the Van Horn area (Flawn et al. 1961). These wells are associated with a 10 mgal gravity low on the DRU (Fig. 3). The DRU is associated with a northwest trending gravity high that is parallel to the gravity maximum associated with the Ouachita interior zone (Figs. 1, 4, 5).

The Crosbyton geophysical anomaly is located at the corner of Crosby, Garza, Dickens and Kent Counties in the Texas Panhandle (Fig. 1). The magnetic anomaly is offset 13 km northwest of the gravity high. This anomaly would be offset to the southeast if it were induced by the Earth's field and not remanently magnetized. Shurbet et al. (1976) used the isolation of this anomaly from other anomalies to produce simultaneous three-dimensional models of the gravity and magnetic fields. These models were used to determine the direction of the remnant

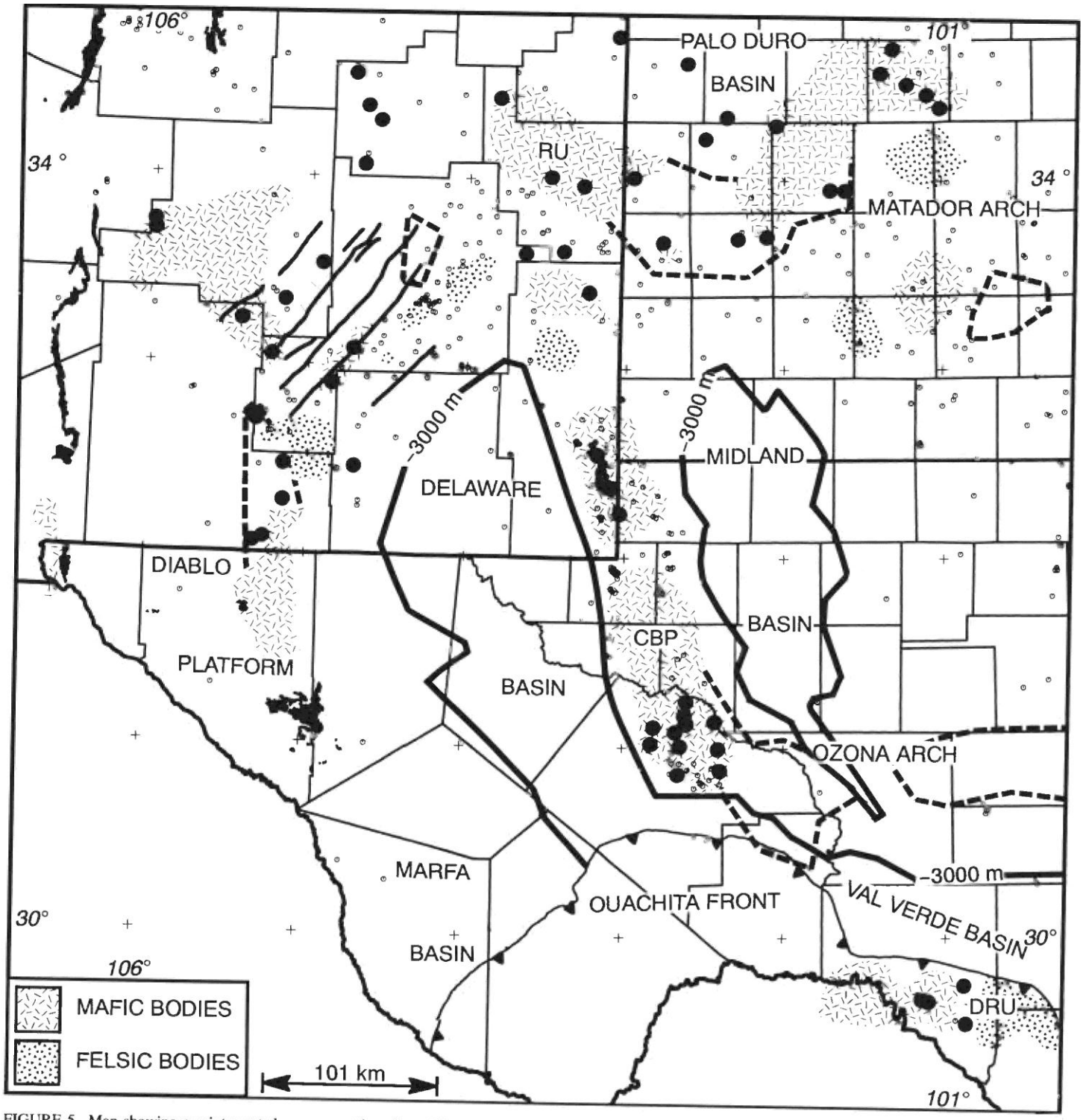

FIGURE 5. Map showing our interpreted upper crustal geology. The stippled areas represent gravity highs associated with mafic rocks or gravity lows associated with felsic rocks. The dashed lines show possible extensions of the mafic bodies. The large dots are the locations of drill holes penetrating mafic igneous rocks. Small dots are associated with other wells penetrating the Precambrian. The outlines of Precambrian outcrops and the –3000 m contour on the Precambrian in the Delaware, Midland and Val Verde Basins are shown.

magnetic vector that corresponds to an apparent pole position of 24°N and 169°E (Shurbet et al., 1976). When this pole is plotted on the apparent polar wander curve of Symons (1992) for the Midcontinent rift system it corresponds to 1074 Ma. This anomaly is thought to be caused by mafic igneous rocks (Shurbet et al., 1976).

WELL INFORMATION

Mapping the wells that penetrate Precambrian rocks enhances our ability to interpret the gravity data. Well data for this paper were obtained from Flawn (1956), Flawn et al. (1961), Denison and Heatherington (1969), Muehlberger et al. (1966), Foster and Stipp (1961), Muehlberger and Denison (1964), Foster (1959), Keller et al., (1989) and the University of Texas at El Paso Well Database. The data were combined with published age determinations from Denison and Heatherington (1969), Muehlberger et al. (1966), Denison et al. (1970), Wasserburg et al. (1962), Copeland and Bowring (1988) and Keller et al., (1989). A subset of the database consisting of 53 wells penetrating mafic rocks, was used in this study. The locations of the wells penetrating mafic rocks, are shown in Fig. 5. When these locations are compared with the gravity maps (Fig. 2) the mafic rocks are associated gravity highs.

The high-pass filtered map in Fig. 3 emphasizes upper crustal structure and density variation. Aside from the major bodies, several areas where mafic rocks have been penetrated are associated with gravity highs. For example between the Central Basin platform and the Roosevelt uplift there is a pair of gravity highs. A gravity high is also associated with the Texas Panhandle portion of the Debaca-Swisher terrain of Denison et al. (1984; Fig. 1). This map also isolates a gravity high on the eastern margin of the Diablo platform. Two wells near the northwestern margin of this anomaly have penetrated mafic rocks. The gravity anomaly is interpreted to represent a southeast extension of the mafic rocks east of the Pump Station hills (Figs. 3, 5; Veldhuis and Keller, 1980). The gravity high associated with the Ozona arch may be caused by another mafic body (Fig. 5). The Phillips, #1 Callan well in Schleicher County, east of the study area, penetrated mafic rocks associated with the gravity high (Figs. 3, 5).

Gravity lows are associated with the deepest parts of the Delaware, Midland and Val Verde Basins (Fig. 3). The anomalies resemble the shape of the basins outlined by the —3000 m basement elevation contour in Fig. 5. The general gravity signature of the Midland and Delaware Basins (Fig. 2), is more complex than the structural contour of the basins would suggest (Fig. 5). This complexity may indicate structural or lithological variation in the Precambrian basement.

LOW PASS FILTERED GRAVITY MAP

To better examine the deep or large structures of the area a low pass filtered map was produced (Fig. 4). The filter passed wavelengths between 150-1000 km. There are several prominent features in this map. A north-south trending gravity high is associated with the Central Basin platform and Roosevelt uplift. A northeast-southwest trending gravity high branches out from the high between the Matador arch and Abilene minimum. A gravity low is associated with the Palo Duro asin north of the Matador arch and another circular 40 mgal gravity low is located under the Delaware Basin. The low does not seem to be completely related to the Delaware Basin structure. It may originally have been part of the Abilene gravity minimum, which is an east-northeast trending 400 km long gravity feature in Texas extending from southern Oklahoma to the CBP. The Abilene minimum represents a fundamental crustal structure (Van Schmus et al., 1987). The Ouachita front is associated with a pair of east-west trending high and low gravity anomalies. The gravity low is located on the north side of the Ouachita front and the gravity high is located south of the front in the interior zone. A portion of the gravity high is represented by the Devils River uplift in Fig. 4.

DISCUSSION

Fig. 5 shows our interpretation of the gravity anomalies, well and outcrop data. The mafic bodies appear to form two groups of the same age. The first group is composed of bodies in the Debaca-Swisher terrain of Denison et al. (1984) and the second group is located along the trend of the Delaware aulacogen. Other areas have not been interpreted, in this paper, due to the sparseness of well control. The gravity anomalies of the Permian Basin only partly match the Phanerozoic structures present and may indicate additional Proterozoic structures in west Texas and eastern New Mexico.

Many studies have looked at the Precambrian outcrops and wells in west Texas and southeastern New Mexico (Denison and Heatherington, 1969; Gonzales and Woodward, 1972; Rudnick, 1983; Norman et al., 1987; Keller et al., 1989; Bowsher, 1991; Shannon and Barnes, 1991). The igneous activity of the Middle Proterozoic here is reported to have an origin of continental extension (Table 1). It is common to use the alkalinity of the igneous rocks as a guide to distinguish tectonic relationships. Several of these studies have used additional criteria such as trace elements, mineral chemistry and consideration of the igneous rock source region to distinguish the tectonic setting (Rudnick, 1983; Norman et al., 1987; Shannon and Barnes, 1991). Anorogenic granites, also called A-type granites, are formed in continental regions but not along plate margins or areas with active subduction. They are generally associated with continental rifts and back-arcs and are emplaced soon after rifting has occurred. The designation of A-type granite, or other type of granite, is difficult and often misleading without additional analytical data to support it.

A summary of investigations of Middle Proterozoic igneous rocks in this area (Table 1) compares the age, tectonic setting as reported by the investigator(s), rock types and general remarks concerning each occurrence. During this period magmatic activity was bimodal. Bimodal volcanic activity was active in eastern New Mexico and west Texas from 1215-1074 Ma. This igneous activity was in part coincident with formation of the Midcontinent rift system (1185-1010 Ma) in the Lake Superior region and Grenville age tectonic events as recorded in the Llano uplift in Texas (1116-1232 Ma; Walker, 1992).

CONCLUSIONS

Correlation of well and outcrop data with gravity anomalies allows us to determine the extent of Middle Proterozoic igneous activity in the Carlsbad region. The study area is underlain by an extensive region of bimodal igneous rocks formed between 1074-1215 Ma. This includes the five areas discussed in this paper, namely the Franklin Mountains, Van Horn uplift, Central Basin platform, Pajarito Mountain and the Crosbyton geophysical anomaly. Fig. 5 shows our interpretation of the gravity anomalies, well and outcrop data. The igneous bodies form two groups of the same age. The first group is composed of bodies in the Debaca-Swisher terrain of Denison et al. (1984) and the second group is located along the trend of the Delaware aulacogen. The presence of bimodal igneous rocks and alkaline felsic rocks indicates that an extensional event occurred here in the Middle Proterozoic. The Middle Proterozoic igneous activity in New Mexico and Texas is age correlative with both Midcontinent rifting (1185-1010 Ma) and Grenville age tectonic events in Texas (1232-1116 Ma).

Additional geological and geophysical studies are necessary to better understand the tectonic setting of this area in the Middle Proterozoic. These additional studies may also help to understand the role of Proterozoic structure in the Marathon-Ouachita Orogeny and its bearing on petroleum geology of this region.

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