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A REGIONAL GEOLOGICAL AND GEOPHYSICAL STUDY OF THE DELAWARE BASIN, NEW MEXICO AND WEST TEXAS

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INTRODUCTION

The Permian Basin (fig. 1) is one of the major hydrocarbon producing regions of North America. In addition, it is a tectonic feature which has played a key role in the geologic history of the southwest. In this study, regional geological and geophysical data have been collected and synthesized in the hope of obtaining a better understanding of the geologic history and deep structure of the Permian Basin area. Our main area of interest was the Delaware Basin and its boundary with the Central Basin Platform.

GEOLOGIC SETTING AND TECTONIC HISTORY

The Permian Basin of West Texas and New Mexico seems to have originated in late Proterozoic time as a low spot on the southwestern edge of the North American craton. At this time, a portion of the province may have been affected by crustal rifting originating in a triple junction spreading center located considerably south of the present basin. The rifting extended northward to northern Lea County, New Mexico and was accompanied by right-lateral faulting along a north-northwest trend. Some vertical movements also may have taken place at this time as the western part of the basin probably formed an aulacogen.

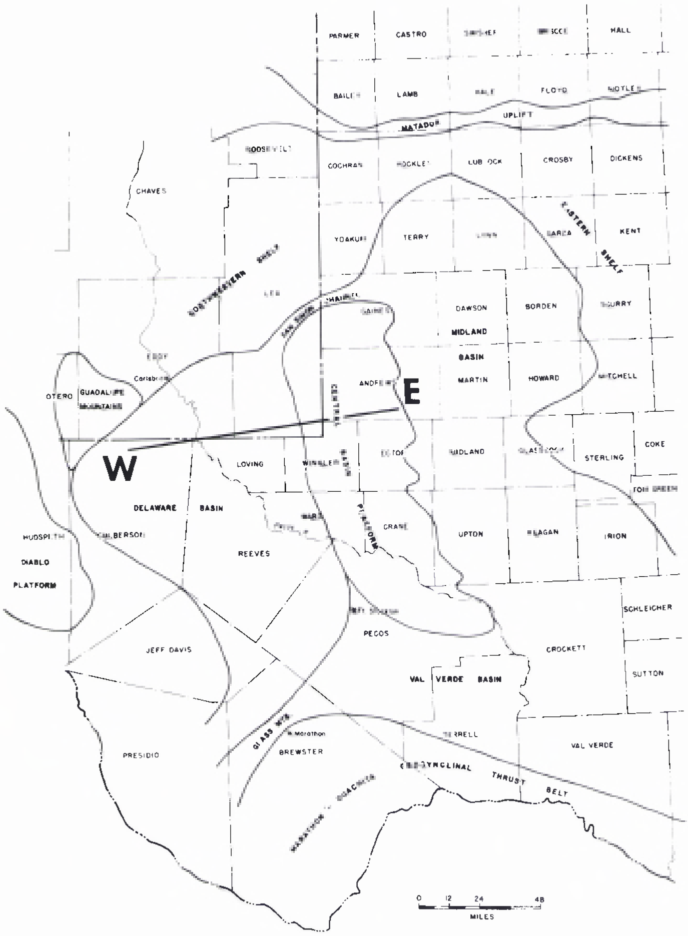

Figure 1. Index map of the study area showing location of the geologic cross-section.

However, most of the history just given is highly speculative. The real evidence is the nearly vertical attitude of many of the deep-seated faults on the west side of the basin pointing to a strike-slip origin, the gravity and magnetic evidence for a major upper crustal anomaly, and the sparse data from well borings to the Precambrian which show extensive volcanic terranes overlying plutonic and metamorphic rocks.

Following a long interval of uplift and erosion during latest Precambrian and Early Cambrian time, a thin veneer of Upper Cambrian and basal Ordovician clastics were deposited in the shallow Tobosa Basin of Galley (1958). Throughout early and middle Paleozoic time, this basin, which covered the study area, was the site of shallow-water deposition, largely limestones and shales. This sedimentation was interrupted frequently by intervals of widespread emergence and subaerial erosion.

In Mississippian time mild tectonic activity began, accompanied by vertical movement along the zones of weakness inherited from late Precambrian lateral faulting. By Middle Pennsylvanian time, these forces had intensified and deformed the central part of the Tobosa Basin into a low folded and faulted mountainous tract. This feature divided the province into two sub-basins, the Delaware on the west and the Midland on the east (fig. 1).

As these basins were forming, broad limestone shelves grew around them. They were cut by stream channels through which fine sands and shales were carried into the basins. By late Early Permian (Wolfcamp) time these limestones had not only covered the shelves but also the eroded roots of the central mountains, thus forming the Central Basin Platform. At the same time, clastic sedimentation continued in the basins on either side of the platform.

Vertical movement continued along the faulted Precambrian line of weakness which now formed the eastern side of the rapidly deepening Delaware Basin. Similar deepening occurred on a lesser scale in the Midland Basin. By Middle Permian time the growth of shelf-edge carbonates and a slight eustatic lowering of sea level led to the formation of back-reef evaporites. This process continued throughout the Permian with increased intensity, interrupted only by a marine flood in San Andres time.

By Late Permian time, carbonate deposition was limited to a narrow band around the Delaware Basin formed by the high barrier of the Capitan reef complex. The central part of the basin continued to receive limited amounts of fine clastic material which was deposited in a reducing environment. By the end of the period, continuing retreat of the seas resulted in deposition of evaporites and continental red beds over the entire basin. During Middle and Late Permian time, tectonic activity was minimal, being limited to gradual deepening of the Delaware Basin with slight tilting to the east.

After an interval, continental deposition resumed in the Late Triassic in much the same location as in the Permian. However, following a hiatus representing Jurassic time, Cretaceous deposition began on a different pattern, with shallow seas advancing from the southeast and depositing marine sandstones and limestones over the area. The Cretaceous beds which have survived erosion are largely all of Comanchean age.

The Laramide orogeny seems to have strongly affected only the western edge of the basin where Permian shelf-edge carbonates and adjacent basinal rocks were uplifted. Downfaulting, both contemporaneous and later, formed the Salt Basin graben. These movements tilted the Delaware Basin even more strongly to the east and formed the Guadalupe and Delaware Mountains. An important side effect of this renewed tilting was the opening of joints about the zone of weakness along the eastern side of the Delaware Basin. This greatly facilitated the solution of large amounts of Permian salt during the Pliocene and Pleistocene.

Late Cenozoic sediments in the basin are generally thin except for those filling the Salt Basin graben, solution trenches along the Pecos River, and the east side of the Delaware Basin. Tectonic movement during this time has been minimal although slight seismic activity continues.

GEOLOGICAL STUDIES

The Permian Basin area has been the focus of geological investigation since G. G. Shumard first collected Permian fossils at the base of El Capitan nearly 130 years ago. The discovery of oil in the basin in the 1920's intensified the interest in the geology of the province and led to the drilling of thousands of wells in the basin. Records have been kept of most of these borings and each has contributed something to our knowledge of the rocks beneath the surface.

In the present investigation we have utilized the logs of some of these wells and the earlier work of many geologists to construct a stratigraphic column (fig. 2) and to divide it into density units as explained in the next section. A cross-section was then constructed across the central and western parts of the basin showing the stratigraphic and structural relations of these units (fig. 3).

The basement rocks of the region are of Precambrian age. These rocks have been reached in numerous wells on the Central Basin Platform and more recently in many very deep wells in the Delaware Basin. Information from these wells has enabled us to map the elevation of the top of the Precambrian (fig. 4). Unfortunately, penetration of the Precambrian rocks has rarely exceeded a few meters. Good cuttings or cores of this small interval are even rarer. Thus, our knowledge is confined to widely scattered samples of the upper skin of the basement. Nevertheless, extensive knowledge of the overlying sedimentary rocks enable us to make interpretations of crustal geophysical data that have a much greater plausibility than those made without this detailed subsurface information.

GEOPHYSICAL STUDIES

Although sedimentary strata in the Permian Basin have been studied extensively in the search for hydrocarbons, few geophysical data are published, and the deep structure of the area is poorly known. The basement rock studies of Flawn (1956) and Muehlberger and others (1966) provide a general picture of the distribution of basement lithologies, but the depths to which these lithologies extend are unknown. In this study, gravity and magnetic data have been combined with deep drilling data to produce an integrated interpretation of the deep structure of the Delaware Basin and adjacent areas.

System	Series	Delaware Basin Gr./Fm	Density Unit	Density Value	Central Basin Pltfm. Gr./Fm	Density Unit	Density Value
QUATERNARY	Holocene	Holocene Sand			Holocene Sand		
TERTIARY	Pliocene	Ogallala			Ogallala		
CRETACEOUS	Gulfian Comanchean		VIII	2.55		VII	2.55
JURASSIC	Absent						
TRIASSIC		Dockum			Dockum		
PERMIAN	Ochoa	Dewey Lake			Dewey Lake		
		Rustler			Rustler		
		Salado	VII	2.4	Salado		
		Castile	VI	2.77		VI	2.77
	Guadalupe	Delaware Mt. Gr.: Bell Canyon			Artesia Gr.: Tansill		
		Delaware Mt. Gr.: Cherry Canyon			Artesia Gr.: Yates		
					Artesia Gr.: Seven Rivers	V	2.69
		Delaware Mt. Gr.: Brushy Canyon			Artesia Gr.: Queen		
					Artesia Gr.: Grayburg		
		Victoria Peak	V	2.55	San Andres		
					Glorieta Ss.		
	Leonard	Bone Spring Ls.			Yeso: Clear Fork		
					Yeso: Wichita-Abo	IV	2.73
	Wolfcamp	Wolfcamp	IV	2.58	Wolfcamp		
PENNSYLVANIAN	Virgil	Cisco					
	Missouri	Canyon					
	Des Moines	Strawn			Strawn		
	Atoka	Atoka			Atoka		
	Morrow	Morrow	III	2.52	Morrow	III	2.52
MISSISSIPPIAN	Chester	Barnett					
	Meramec	Mississippian Ls.			Osage - Meramec		
	Osage						
	Kinderhook				Kinderhook		
DEVONIAN	Upper	Woodford			Woodford		
	Middle	Lower Devonian			Lower Devonian		
SILURIAN	Middle	Silurian Sh.			Silurian Sh.		
		Fusselman	II	2.70	Fusselman	II	2.70
ORDOVICIAN	Upper	Montoya			Montoya		
	Middle	Simpson			Simpson		
	Lower	Ellenburger	I	2.81	Ellenburger	I	2.81
CAMBRIAN	Upper	Cambrian			Cambrian Ss.		
PRE-CAMBRIAN		Pre-Cambrian			Pre-Cambrian		

Figure 2. Generalized stratigraphic column of West Texas and southeastern New Mexico. After T. J. Jones (1965) and J. M. Hills (1972).

In interpreting the geophysical data, extensive well data were used in order to obtain as accurate as possible representation of the sedimentary strata present. The cross-section of Figure 3 was used in computer modeling of a gravity profile by assigning densities to groupings of stratigraphic units which displayed regionally consistent density values.

For the purposes of this study, the sedimentary section was divided into 8 density units for the Delaware Basin and into 7 units for the Central Basin Platform by analyzing compensated formation density logs (fig. 2). As only general variations in density were of interest, visual smoothing of the logs was employed along with a method of weighted averages.

Density unit 1 is represented by the Lower Ordovician Ellenburger dolomite. Often this formation has a basal sandstone resting on Precambrian basement. A density of 2.8 gm/cc was determined for this unit.

Density unit 2 is composed of rocks whose ages range from Middle Ordovician to Lower Devonian. The lowest subunit represents the Simpson (Middle Ordovician) which consists of shaly limestone with sandstone interbeds. The overlying Montoya (Upper Ordovician) is crystalline cherty and dolomitic limestone. The Fusselman crystalline dolomitic limestone (Silurian) and related shales are overlain unconformably by Lower Devonian limestones. The density calculated for this unit was 2.70 gm/cc.

Density unit 3 is composed of Upper Devonian, Mississippian and Pennsylvanian strata. The Woodford Formation consists of black organic and highly radioactive shale. The overlying Meramec

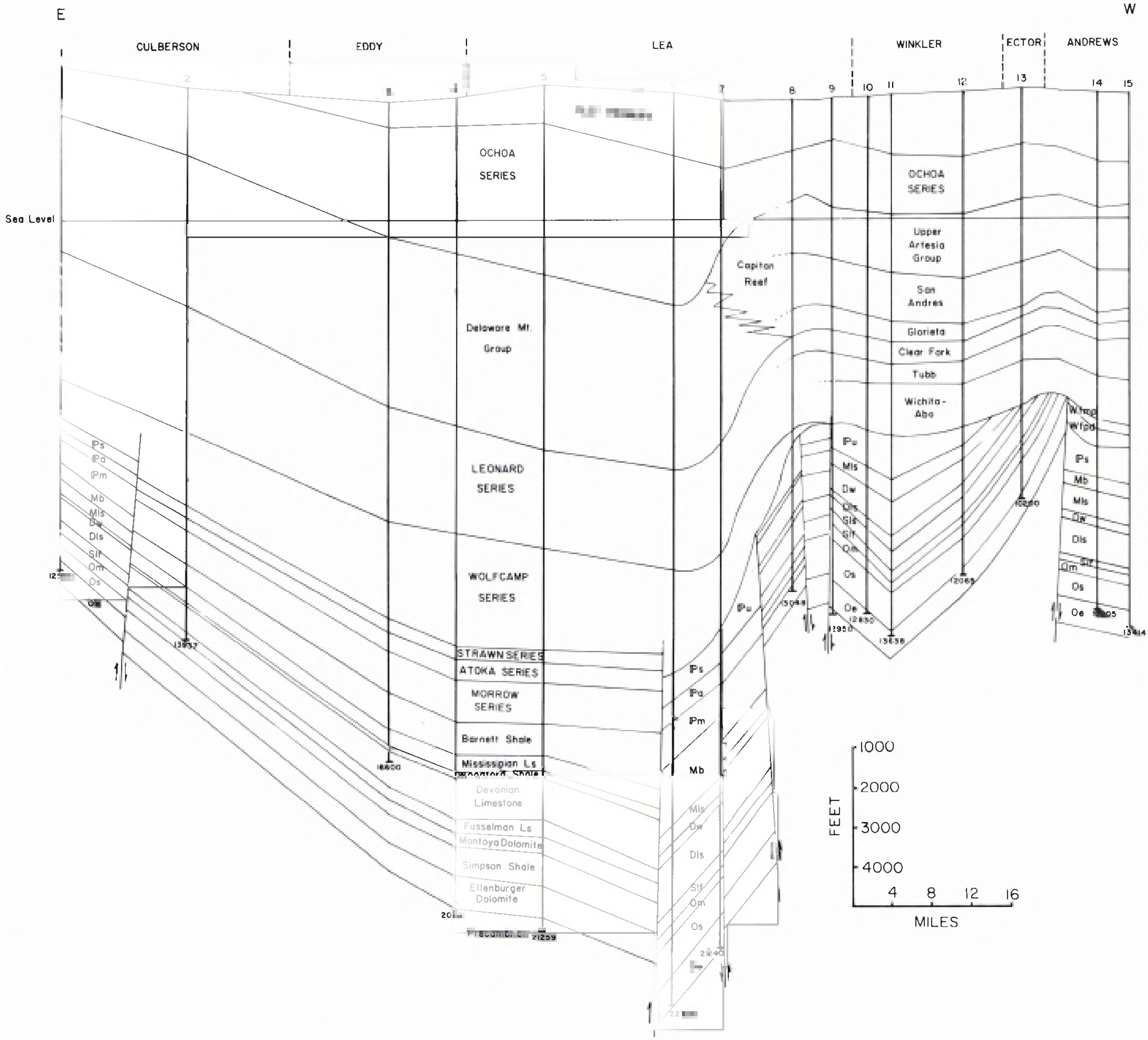

Figure 3. Geologic cross-section. Numbers refer to wells listed in Table 1.

and Osage limestones (Mississippian) underlie the Barnett black fissile shale (Chesterian) which is generally absent from the Central Basin Platform. The Morrow Series (Lower Pennsylvanian) is composed of deltaic sandstone and shales while the overlying Atoka Series is composed of interbedded limestone, shale and sandstone. The Strawn Series of the Middle Pennsylvanian consists of thin beds of limestone. The Canyon and Cisco Series (Upper Pennsylvanian) are very thin or absent. A density of 2.52 gm/cc was determined for unit 3.

Density unit 4 (Delaware Basin) is composed of the Wolfcamp Series of the Permian System which is about 4256 m (14,000 ft) thick in the deepest part of the Delaware Basin. The Wolfcamp Series is thin-bedded limestones and shales and sandstones in the Delaware Basin but thick beds of limestone on the Central Basin Platform. The density determined for this unit was 2.58 gm/cc.

Density Unit 5 (Central Basin Platform) comprises the Wolfcamp and the lower Leonard Series, which are composed of fine crystalline dolomite with calcareous sandstones and sandy shales. A density of 2.73 gm/cc was determined for this unit.

The upper Leonard and Guadalupe Series constitute density unit 5 of the Delaware Basin. The Leonard Series is composed of thick beds of limestone with interbeds of shale. The Guadalupe Series (Delaware Mountain Group) consists of the Brushy Canyon, Cherry Canyon and Bell Canyon sandstones, silts, and thin limestones. The density determined for this unit was 2.55 gm/cc.

Density unit 6 (Central Basin Platform) is composed of the Glorieta Sandstone, the San Andres Dolomite and the Artesia Group with the exception of the Tansill. The formations of the Artesia Group are lagoonal (back-reef) sandstones, anhydrites, and dolomite equivalent to the Capitan reef limestone. The density determined for this unit was 2.69 gm/cc.

The uppermost series of the Permian System is the Ochoa Series.

Table 1. Wells used to construct stratigraphic cross-section.

Well Name	Company	Location	County
E. E. Pokorny #1	Continental Oil Co.	61, 18	Culberson, TX
Black River Federal #1	Coquina Oil Corp.	28-26-25	Eddy, NM*
U. V. Industries, #1	American Quasar	59, 42	Culberson, TX
Damsite Unit Well #1	Texaco, Inc.	56, 9	Loving, TX
Kyle #1-10	HNG Oil Co.	55, 10	Loving, TX
Red Hills Unit #1	Pure Oil Co.	32-25-33	Lea, NM*
New Mexico Federal #1	Skelly Oil Co.	21-26-35	Lea, NM*
South Lea Deep Unit #1	HOR Co.	17-26-36	Lea, NM*
Eagle Draw Federal #1	HNG Oil Co.	8-26-36	Lea, NM*
Denton #17	Phillips Pet. Co.	11-15-37	Lea, NM*
Federal Leonard #1	Stanolind Oil & Gas Co.	11-26-37	Lea, NM*
Federal Lowe #1	Forest Oil Corp.	7-26-38	Lea, NM*
Tennie Cowden	HOR Co.	56, 24	Winkler, TX
Evans R. & #1	HOR Co.	56, 2	Winkler, TX
Cowden #1	Maquire, Russell	73, 40	Winkler, TX
Jessie May Williams #1	Stanolind Oil & Gas Co.	45, 8	Ector, TX
R. B. Cowden C #1	HOR Co.	45, 3	Ector, TX
Barbara Cowden #1	Sinclair Oil & Gas Co.	45, 2	Andrews, TX
Frank Cowden #1	Pan American Pet. Co.	44, 10	Ector, TX
W. F. Cowden A #13	Pan American Pet. Co.	43, 12	Andrews, TX
Nobbles #1	Phillips Pet. Co.	44, 7	Ector, TX
R. B. Cowden C #1	HOR Co.	45, 3	Ector, TX
Barbara Cowden #1	Beal, Carlton Assoc.	45, 12	Andrews, TX
Emblar B #6	Phillips Pet. Co.	44, 8	Andrews, TX

*Location by Section, Township, Range; all others by Block, Section

The two chief divisions of this series are the Castile Anhydrite and the Salado Salt. As there is a large density contrast between the Salado (2.4 gm/cc) and the Castile (2.77 gm/cc) Formations, separate density units (6 and 7) were attributed to each of these formations within the Delaware Basin. The Salado and the underlying Tansill dolomite are combined into density unit 6 on the Central Basin Platform with a determined density of 2.77 gm/cc.

The Triassic System is represented by the Dockum red shales. Cretaceous limestones and sands may also be present. Tertiary and Quaternary deposits are sands, gravels, clays, and silts. These post-Permian rocks constitute density unit 8 for the Delaware Basin and density unit 7 for the Central Basin Platform and both have a density of 2.5 gm/cc.

Prior to computer modeling along the geologic cross-section a regional Bouguer anomaly map was constructed, by combining over 6,000 gravity readings obtained from the Department of Defense gravity library, Mr. Hart Brown, and a gravity survey conducted as part of this study (fig. 5). Standard corrections (Dobrin, 1976) were applied to these data to reduce them to Bouguer anomaly values which were referenced to IGSN-71 (Morelli, 1976) base station values. Details on the reduction process and principal facts for the gravity readings are on open file at the University of Texas at El Paso.

The Bouguer anomalies shown on the regional map correlate well with the principal geological features of the region. The Central Basin Platform coincides with a positive Bouguer gravity anomaly, and the adjacent Delaware and Midland Basins coincide with negative Bouguer anomalies. The gravity minimum generally corresponds to the deepest portion of the Delaware Basin (fig. 4). The West Platform fault zone, separating the Central Basin Platform from the Delaware Basin, correlates with a steep gravity gradient. An east-west trending saddle in the gravity readings extends across the Central Basin Platform and must be due to some deep intra-basement structure because it does not correlate with basement topography.

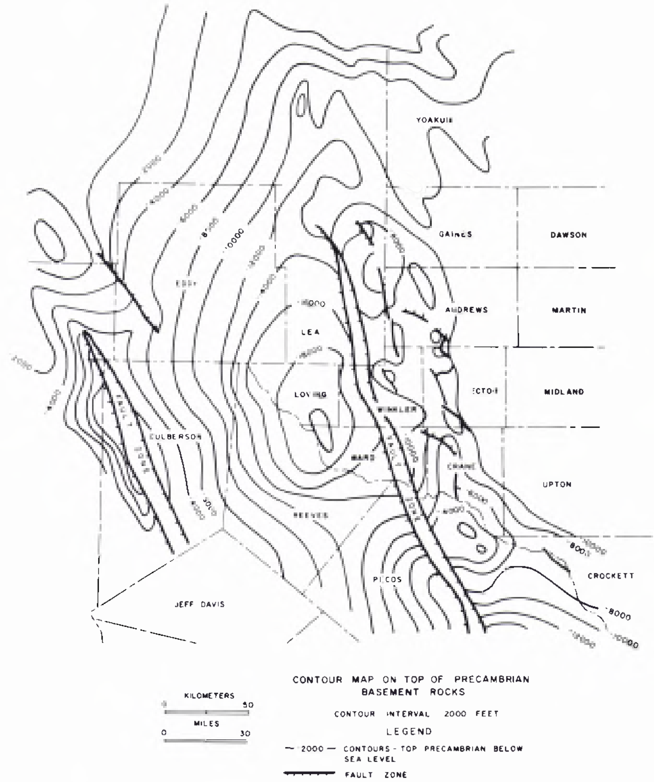

Figure 4. Structure contour map on top of Precambrian basement.

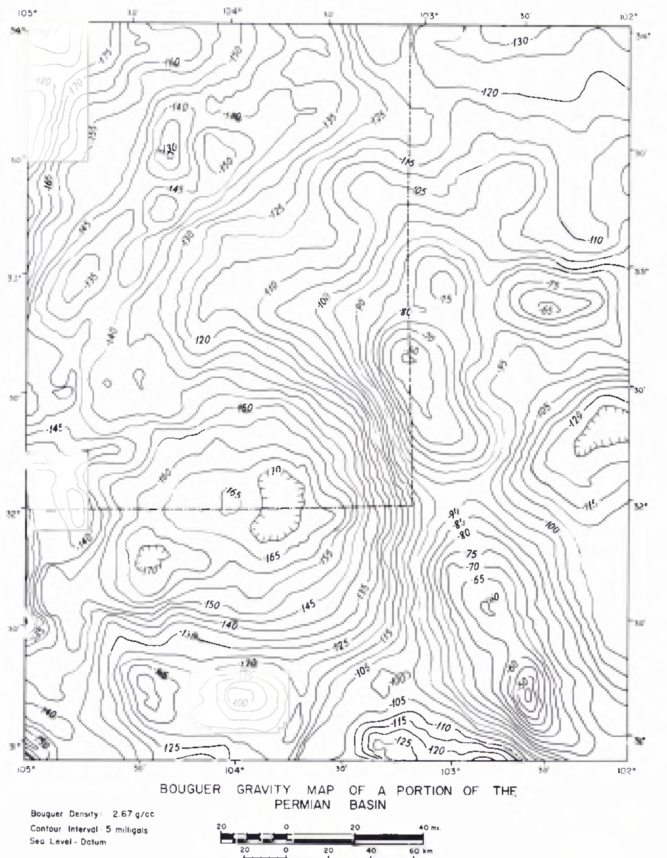

Figure 5. Bouguer gravity map of a portion of the Permian Basin, New Mexico and Texas.

In the northern portion of the map area, the North Basin Platform and the Matador Arch are reflected by positive gravity anomalies. A northeast gravity trend with a series of small gravity highs and lows coincides with the northwestern shelf and the existence of a negative Bouguer anomaly in the far northwest corner of the map area is due mostly to the higher elevation of the region. The Guadalupe and Delaware Mountains are associated with a small north-trending positive anomaly. The adjacent Salt Basin graben is reflected by a negative anomaly (Veldhuis and Keller, this guidebook). The large east-west trending gravity high in the southwest portion of the Delaware Basin does not correlate with the deep drilling data and must be due to an intrabasement structure.

Although the aim of this study was not the search for the hydrocarbons, it is interesting to note the correlation between some oil fields and gravity anomalies. The Artesia-Vacuum oil field trend which is located in the northern part of the Delaware Basin coincides very well with a positive gravity nose plunging northwest from the Central Basin Platform. Other fields such as the Wasson and Slaughter are also associated with gravity highs.

Preliminary aeromagnetic maps of the Pecos and Van Horn quadrangles (1:250,000) were available as part of the National Uranium Resource Evaluation (NURE) program and were obtained through Oak Ridge National Laboratories. These surveys were flown along east-west flight lines at an elevation of 152 m (500 ft) above the ground. The flight-line spacing was 5 km (3 mi). Portions of these maps were combined to produce Figure 6.

The correlation between gravity and magnetic anomalies is good in general, but, as expected, the magnetic map is more complicated to interpret than the gravity map. The magnetic anomalies reflect the principal geological features, but they are complex and often offset spatially. However, the Central Basin Platform is indicated by a magnetic high while the adjacent Delaware and Midland Basins are reflected by magnetic lows. As in the gravity map, an east-west trending saddle in the magnetic data extends across the central part of the Central Basin Platform, and the West Platform fault zone correlates with a steep magnetic gradient.

As one of the main goals of this study was to obtain a true subsurface picture of the basement underlying the Delaware Basin and the Central Basin Platform, an earth model was constructed along a gravity profile corresponding to the geologic cross-section. The technique of Talwani and others (1959) was used to accomplish the computer modeling. This technique is used to compute the vertical component of the gravitational attraction due to any two-dimensional body. Because of the large amount of well data available, the attraction of the sedimentary layers could be calculated with considerable accuracy (a few percent). The infor-

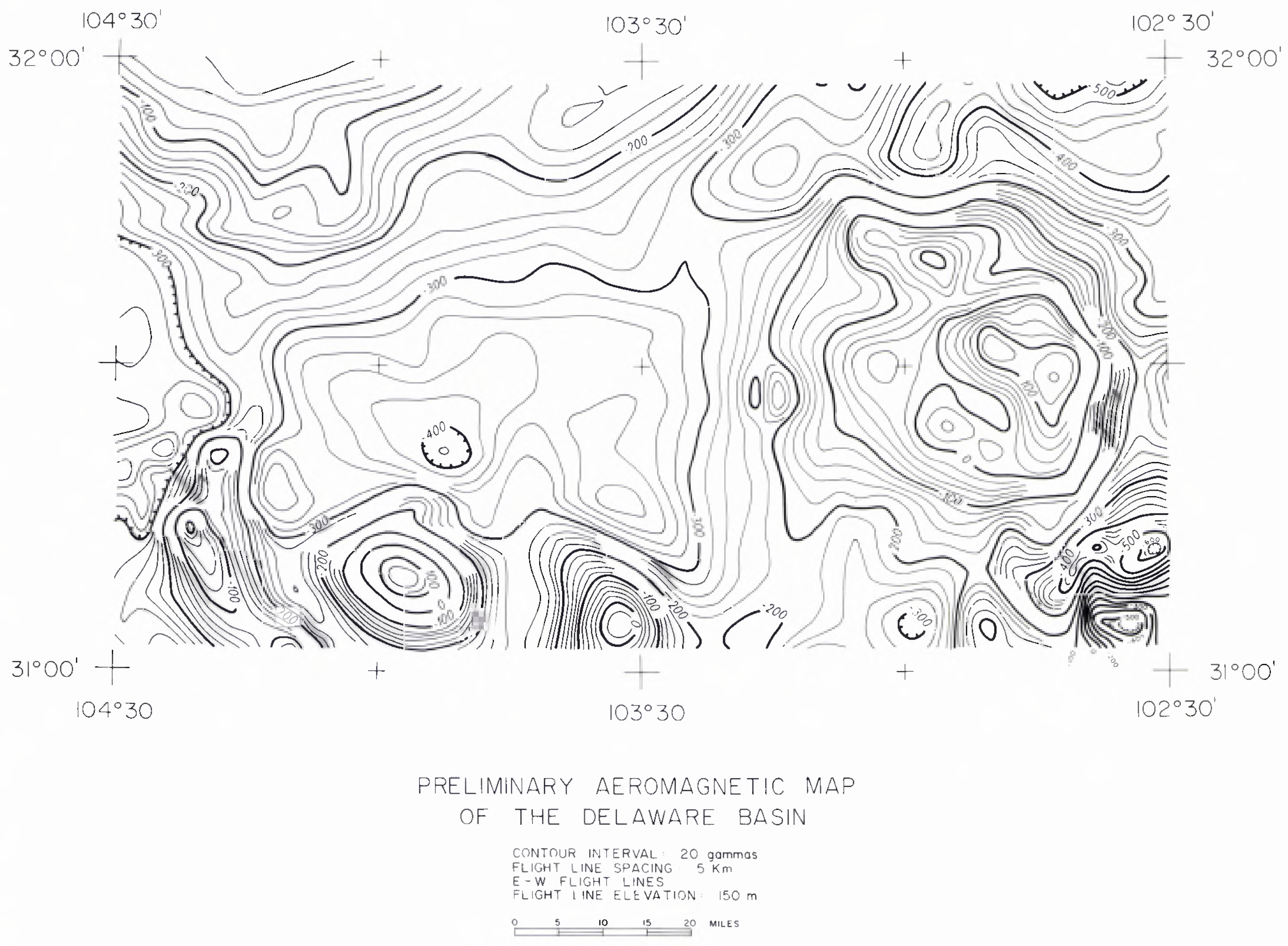

Figure 6. Preliminary aeromagnetic map of the study area. These data were provided by Oak Ridge National Laboratories as part of the National Uranium Resource Assessment program (Bendix Field Engineering Corporation, Grand Junction, Colorado).

mation derived from the geologic cross-section was a major constraint in the computer modeling process, which was in reality a trial-and-error procedure in which the earth model is altered until a fit between the observed and the theoretical values was obtained. During the modeling process the density of the sedimentary density units was held constant because of the control provided by the density logs. Thus, major modifications were confined to the basement.

An initial earth model using uniform basement for both the Delaware Basin and the Central Basin Platform produced a large (~50 mgal) discrepancy between the observed and theoretical gravity values. This difference is far too great to be due to inaccuracies in our ability to model the sedimentary layers. Thus, there must be either an excess of mass beneath the Central Basin platform or a mass deficiency beneath the Delaware Basin. The wavelength of the gravity anomalies indicates that the causative masses are in the upper crust and two alternative models (fig. 7) were produced which depict the general classes of models which will satisfy these data. The model with the mass excess beneath the Central Basin Platform (fig. 7a) seems most plausible from a geological viewpoint and produces a structure very similar to those obtained by Pruatt (1975) for the southern Oklahoma aulacogen.

DISCUSSION AND CONCLUSIONS

The gravity and magnetic maps presented demonstrate that the gravity and magnetic anomalies present correlate well with the known subsurface geology of the region. The Delaware and Midland Basins originated from the Tobosa Basin (Galley, 1958) in late Paleozoic time and were completely formed at the end of the Permian. This study shows that these basins are reflected by strong negative gravity and magnetic anomalies, especially the Delaware Basin. The Central Basin Platform is associated with a strong positive Bouguer anomaly. The maximum gravity relief from the Central Basin Platform to the Delaware Basin is about 120 mgals. The West Platform fault zone which separates the Central Basin Platform from the Delaware Basin is reflected by a steep gravity gradient. The stratigraphic cross-section constructed shows that the West Platform fault zone is characterized by several fault blocks downthrown both to the west and to the east. The western faults of this zone dip to the west while those on the eastern side of the zone seem to dip to the east (fig. 3).

Computer modeling shows that the gravity relief associated with the Central Basin Platform and the Delaware Basin cannot be attributed solely to the thick 6900 m (23,000 ft) sedimentary section of the Delaware Basin but must be due to intrabasement density variations. These variations can take the form of two general models. In the first a strong positive gravity anomaly is associated with the Central Basin Platform and is caused by a large mafic type body in its basement. In the second model a gravity low is associated with the Delaware Basin which is due to a large volume of anomalously low density basement rocks beneath the Delaware Basin.

As the first model is especially suggestive of models for the southern Oklahoma aulacogen (Pruatt, 1975) and as the geological similarities between the southern Oklahoma aulacogen and Permian Basin area have been noted previously (Walper, 1977), the aulacogen concept is worth additional discussion. This is particularly true because the southern Oklahoma aulacogen is probably the best known example of an aulacogen in the North American continent (Burke and Dewey, 1973; Hoffman and others, 1974; Pruatt, 1975).

The southern Oklahoma aulacogen originated as a trough which developed as a graben underlain by Precambrian granitic basement. This trough was filled by 5000 m (16,400 ft) of clastics and volcanics in Early and Middle Cambrian time. From Late Cambrian to Devonian time the trough became a broad downwarp which was then compressed and broken by a system of faults with both vertical and transcurrent movements (Hoffman and others, 1974). The result was the formation of the Wichita–Amarillo and Red River uplifts and the Anadarko and Hollis Basins in the Wichita province (southwestern Oklahoma) with the Arbuckle and Muenster uplifts and Ardmore and the Marietta Basins in the Arbuckle province (southeastern Oklahoma).

In similar fashion, the Permian Basin was a broad downwarp from Late Cambrian to Mississippian time and was affected by a late Paleozoic orogeny which originated a series of basins and uplifts. Available evidence suggests that the Permian Basin like the southern Oklahoma aulacogen can be characterized by thick sediment fill, thick crust (~50 km; Stewart and Pakiser, 1962; Mitchell and Landisman, 1971), an evolution from a trough to a broad downwarp, and relation to periods of major continental break-up. Both the Permian Basin and the southern Oklahoma aulacogen are linear features that strike at a high angle to the early Paleozoic continental margin and are associated with re-entrants of the Ouachita orogenic belt. The Bouguer gravity anomalies and the arrangement of basins and uplifts are also similar.

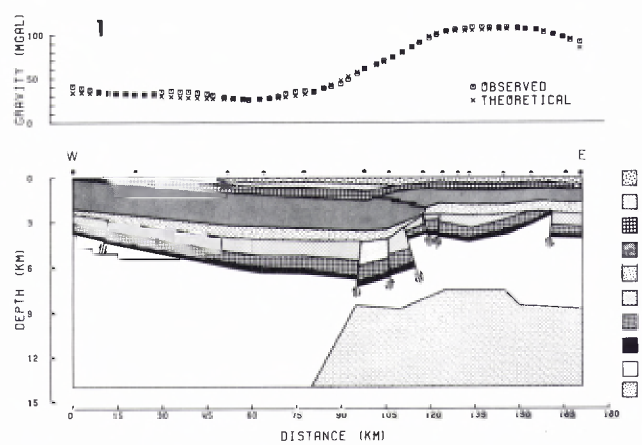

Figure 7a. Computer model (Model 1) of gravity data along the geologic cross-section of Figure 3.

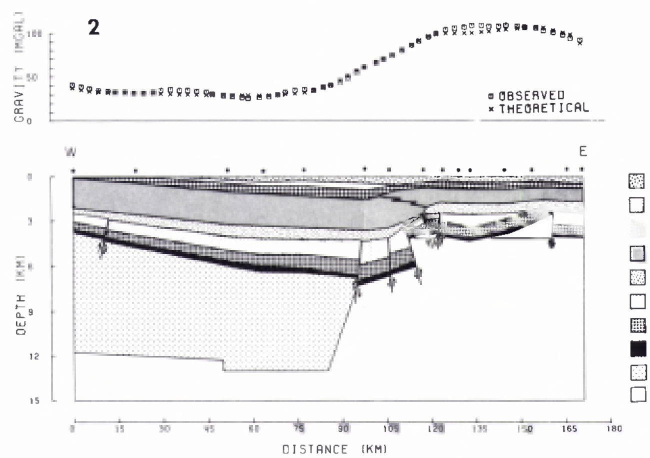

Figure 7b. Alternative computer model (Model 2).

It seems likely that the late Paleozoic basins and uplifts which characterize the Permian Basin developed along pre-existing structural features (Hills, 1970), which correlate well with major mass anomalies probably located in the upper crust. The integrated analysis of the geological and geophysical data suggests that these features are inherited from a Late Precambrian aulacogen. If the aulacogen model is correct, the major difference between the Permian Basin and the southern Oklahoma aulacogen is that the Permian Basin is entirely covered by late Paleozoic and younger sediments while the southern Oklahoma aulacogen is partially exposed.

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Texas antelope squirrel, *Ammospermophilus interpres.*

Bush muhly plant and spikelet, *Muhlenbergia porteri*.