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Applications of Geophysical and Geological Techniques to Identify Areas for
Detailed Exploration in Black Mesa Basin, Arizona

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1.0 INTRODUCTION

A recent report submitted to the U.S. Department of Energy (DOE) (NIPER/BDM- 0226) discussed in considerable detail, the geology, structure, tectonics, and history of oil production activities in the Black Mesa basin in Arizona. As part of the final phase of wrapping up research in the Black Mesa basin, the results of a few additional geophysical studies conducted on structure, stratigraphy, petrophysical analysis, and oil and gas occurrences in the basin are presented here.

Past exploration in the Black Mesa basin (see Fig. 2-1) has largely been for traps on anticlines. The potential for stratigraphic trap accumulations, such as that occurring in Teec Nos Pos field in the extreme northeastern part of Arizona, remain unevaluated. Drilling in the basin was largely confined to easily accessible areas, such as along the Little Colorado River, or on areas where it is relatively easy to acquire drilling permits¹⁻³. Therefore drilling locations in the past were not always selected on the basis of sound geological information. Compared to the size of the exploratory area involved, there have been very few deep wells for adequate testing of the promising Devonian and the Cambrian sections (see Fig. 2-2) in the basin. In this report, the results of investigations conducted on different aspects of structure, tectonics, and oil and gas occurrences in Black Mesa basin have been synthesized for evaluation of hydrocarbon prospects and delineation of areas for detailed exploration in the basin, preferably with high-resolution seismic data.

A secondary objective of this study is to determine the effectiveness of relatively inexpensive, noninvasive techniques like gravity or magnetics in obtaining information on structure and tectonics in sufficient detail for hydrocarbon exploration, particularly by using the higher resolution satellite data now becoming available to the industry.

2.0 THE STUDY AREA

The study area for this investigation comprises of the structurally deep southwestern part of the Colorado Plateau and includes a large portion of northeast Arizona (see Fig. 2-1). The dominating structural and geomorphological features of the study area is the centrally located Black Mesa basin and the surrounding shelves, benches, and slopes, ringed by a series of structural highs. To facilitate regional investigations, such as regional wireline log cross sections and gravity-magnetic modeling, the study area for this report is best defined as the region enclosed by the Little Colorado River and the boundary lines separating Arizona from Utah and New Mexico (see Fig. 2-1).

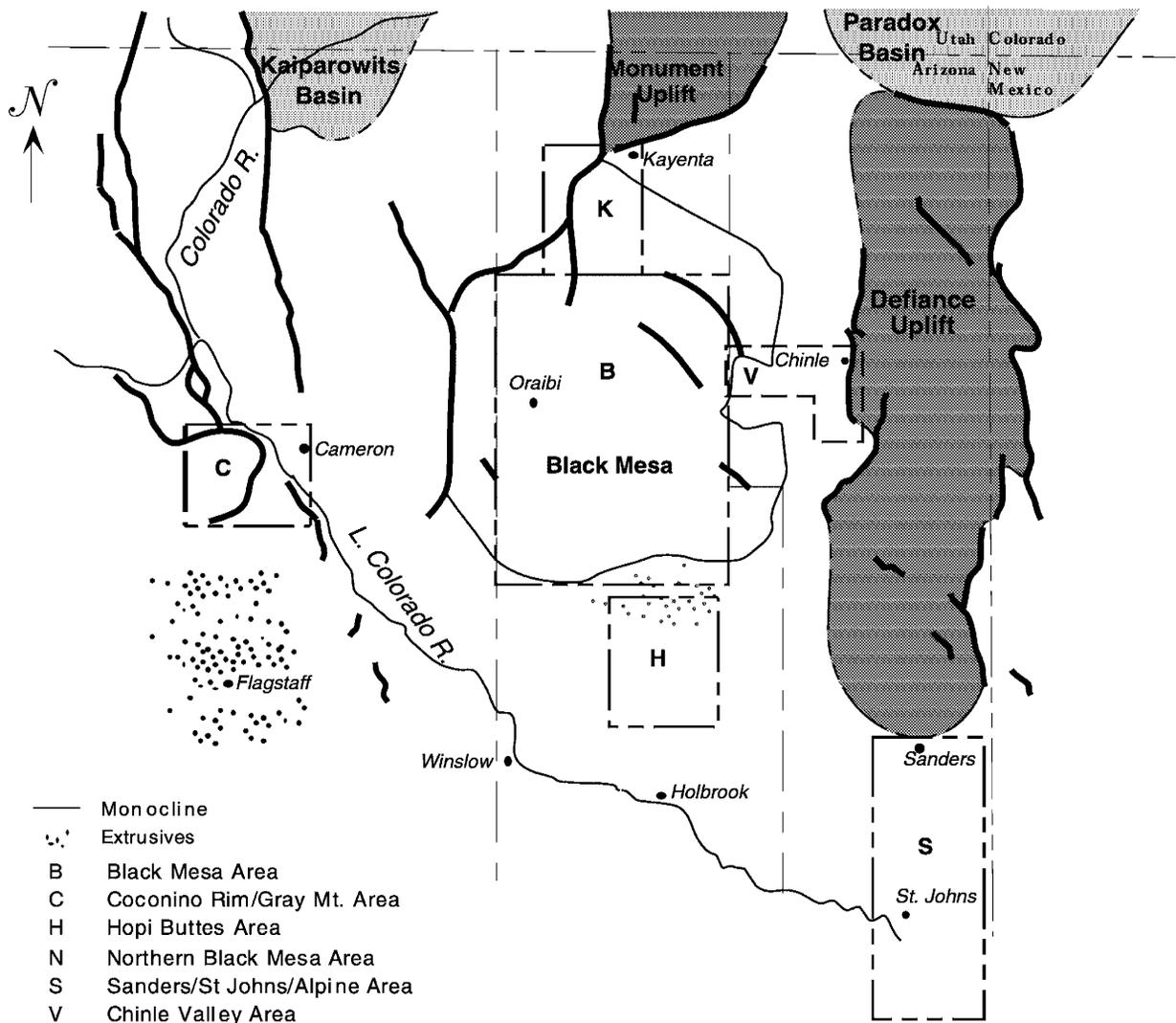
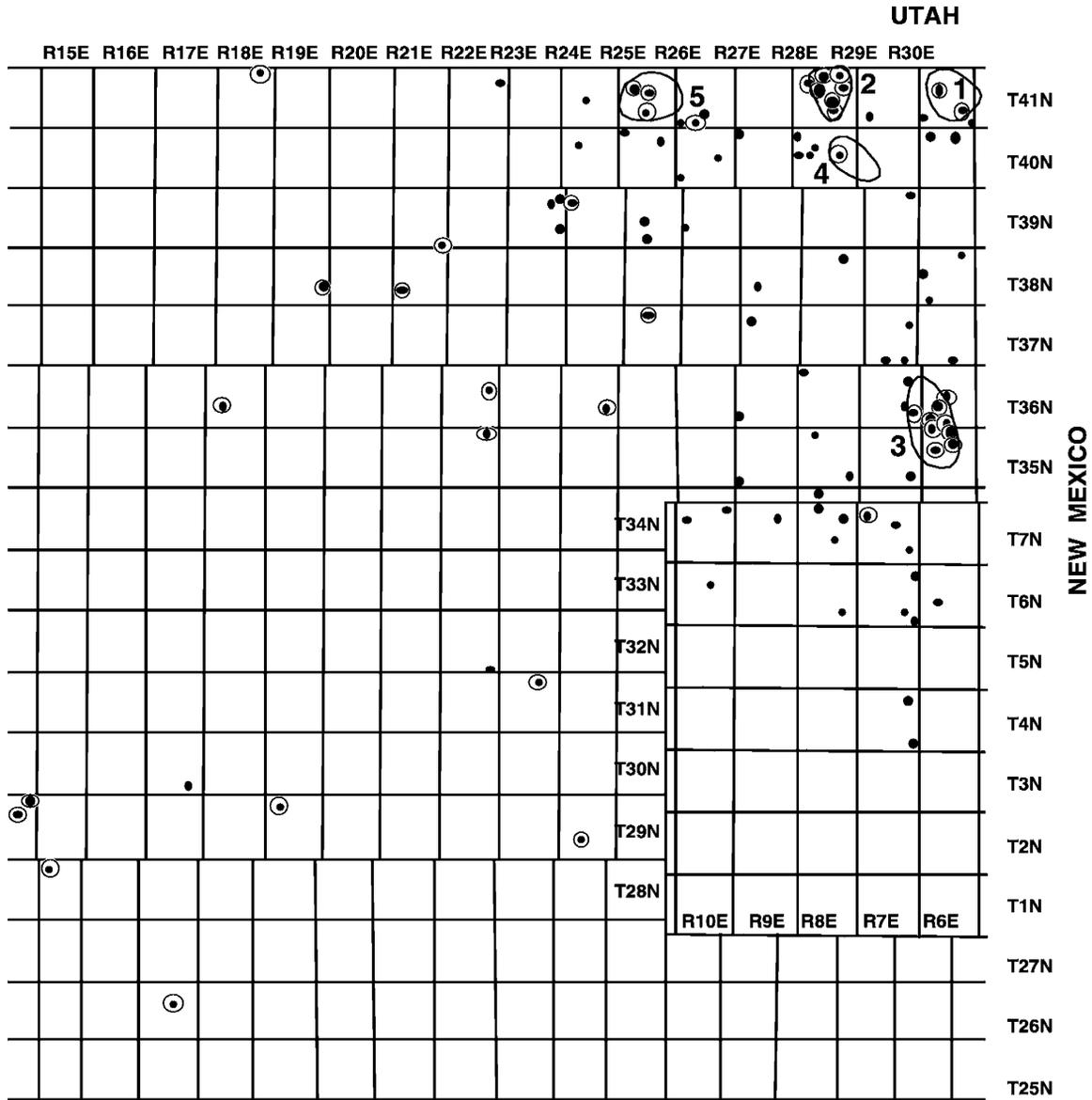


Figure 2-1 Location Map of Black Mesa Basin Study Area and Surrounding Areas in Northeast Arizona



- Wells penetrated Devonian
- ⊙ Wells with hydrocarbon shows

Important Oil Fields

1. Teec Nos Pos
2. East Boundary Butte
3. Dineh-Bi-Keyan
4. Dry-Mesa/Black Rock
5. Walker Creek

Figure 2-2 Wells Penetrating the Devonian Section, Wells with Hydrocarbon Shows, and Important Oil Fields in Northeast Arizona. (Figure modified from a paper by Kashfi⁵)

2.1 Sources of Data

Geological and geophysical information for the present study were obtained from the following investigations conducted in-house: analysis of gravity and aeromagnetic maps from the study area,^{1,9} results from regional model studies of gravity and magnetic data,⁹ detailed analysis of one seismic line,^{1,9} regional structural and stratigraphic correlations of geologic formations of interest with wireline logs, interpretation of wireline logs of selected wells for distribution of petrophysical properties, results from interpretation of satellite images for fracture analysis,¹ source rock maturity studies,¹ and geological analysis of data published in the literature.⁹ Besides this research, information obtained from sources outside of BDM-Oklahoma consisted of a report published by the Arizona Geological Society¹⁰ that provided information on core descriptions (particularly formation tops) of all the wells drilled in the study area, the geology and the production history of the study area,^{4,10} and several geological and geophysical research publications pertinent to the work presented here.^{5-8,11-14} The present study is a synthesis of the relevant information from these sources for evaluation of hydrocarbon prospects of the study area.

3.0 THE GEOLOGY OF THE STUDY AREA

The geology of the study area has been discussed in great detail by several researchers in the past¹⁻¹⁴. Only the geological characteristics of the region important from the point of hydrocarbon accumulations will be discussed here.

The Black Mesa basin is characterized by low regional dips and the surface elevation in the basin ranges from 6,000 ft above the sea level in the southern edge to 8,000 ft above sea level on the northern edge. The topography has been affected by several low-amplitude folds (monoclines) whose dominant trend is northwest-southeast (see Fig. 2-1).

The prospective study area of the Black Mesa basin is a post-depositional structural depression that developed its present form during the Laramide orogeny. The Black Mesa basin is bordered by the Paradox basin on the north and the Kaiparowits basin of south-central Utah on the northwest. The region of the Black Mesa basin and the surrounding areas were part of the vast, dominantly carbonate eastern shelf of the Cordilleran geosyncline during the Paleozoic. The geosyncline was filled in the Triassic, and the succeeding Rocky Mountain geosynclines formed east of the present plateau. This shelf area existed from the Cambrian to at least the Pennsylvanian and was characterized for the most part by low-relief highlands, which contributed very few terrigenous sediments to the shelf area.⁵

Northeastern Arizona is underlain by sedimentary rocks that range in age from Cambrian to Tertiary. Ordovician, Silurian and Lower and Middle Devonian rocks are not present in most of the region; either they were not deposited or, if they were, they were later eroded.

There are several lines of folding (see Fig. 2-1) in the Black Mesa basin. The major ones have a northwesterly trend, are roughly parallel the Uncompahgre Uplift, and are believed to be of Paleozoic age.⁶ Secondary alignments have a northeast trend, a north-south trend, and a still weaker trend which parallels the edges of the basin. The secondary alignments are believed to be post-Paleozoic (Laramide) in age. The older northwest-trending structures are considered the most favorable for commercial production. Oil and gas producing areas in San Juan basin in New Mexico and in Paradox basin in Utah generally have a dominantly northwesterly trend with local variations.

3.1 Structure and Tectonics

The investigation of structure and tectonics of the study area in northeastern Arizona was conducted from an analysis of available gravity, aeromagnetic, seismic, remote sensing, and wireline log data.

The residual gravity (see Fig. 3-1) and the residual aeromagnetic anomaly (see Fig. 3-2) maps of the study area were modified from a paper by Sumner⁷ and were obtained by removing the regional gravitational and total intensity magnetic field effects from the respective total observed fields. The residual gravity anomaly maps provide information on the structure of the basement rock complex and the overlying sediments, but since the lateral variations in sediment densities is normally insignificant, the basement structure and tectonics normally have the dominant contribution to the gravity anomalies. The aeromagnetic data, on the other hand, provide a means of seeing through an effectively non-magnetic sedimentary rock cover to reveal patterns of magnetization in crystalline basement rocks and any other intrusive or extrusive rock masses that have a significantly higher magnetic susceptibility compared to the overlying sediments.

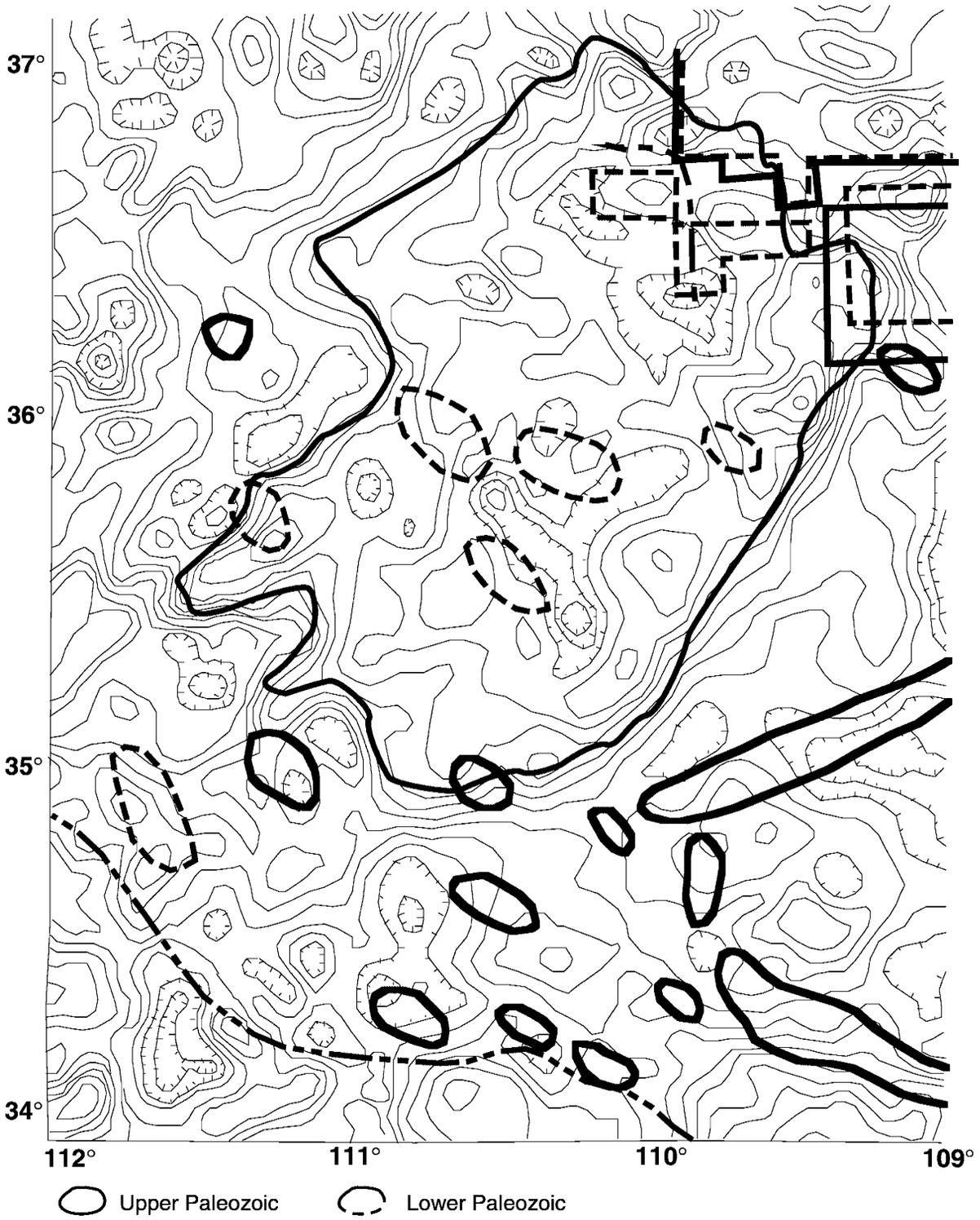


Figure 3-1 Residual Gravity Anomaly Map of the Study Area Modified from a Paper by Sumner⁷ with Upper and Lower Paleozoic Oil Shows

The low residual anomaly values (see Fig. 3-1 and Fig. 3-2) clearly demarcate the structural framework of Black Mesa basin because the low gravity and magnetic values are a reflection of the larger sediment thicknesses compared to that in the surrounding areas. The basement faults may be clearly seen in these figures by the sharp gradients of the gravity and magnetic fields. These faults have been marked in Figures 3-3 and 3-4 from a synthesis of information in these two maps and the satellite imagery data interpreted by Gutman and Heckmann.⁸ The locations of the interpreted basement faults in the two maps are slightly different. This could be due to several factors, such as variations in the density of the sedimentary rocks overlying the basement or from the way the two residual anomaly maps were generated they may not represent the effect of identical geological structures. Nonetheless, the dominant trends of the basement faults in the two maps are quite similar. It may be noted that only the obvious basement faulted zones have been mapped, and there could be many more faults that provide only subtle indications. The locations of the upper and lower Paleozoic oil shows in these two maps is discussed in a later chapter.

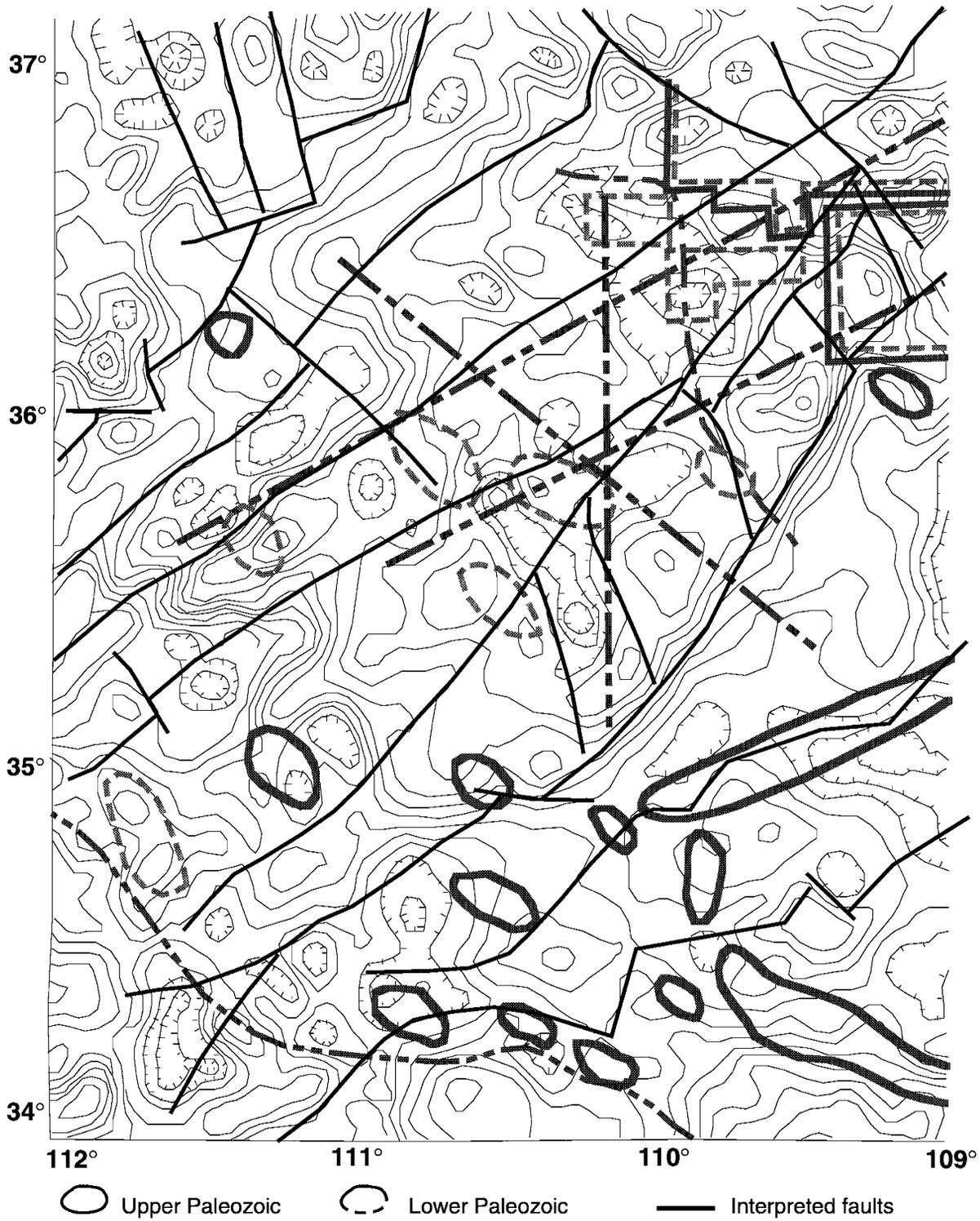


Figure 3-3 Residual Gravity Anomaly Map of Study Area with Interpreted Major Basement Faults and Oil and Gas Shows in the Upper and Lower Paleozoic Formations

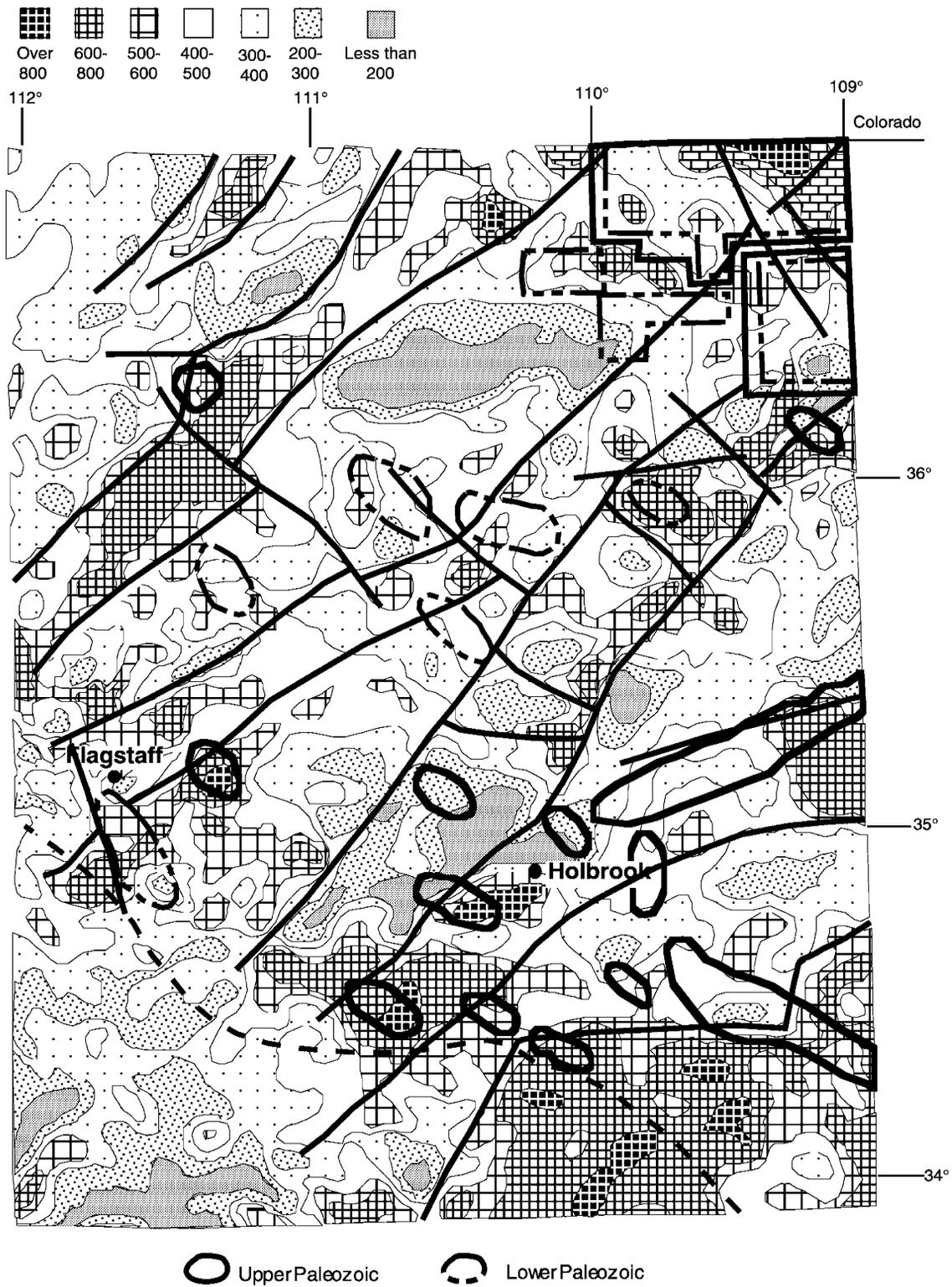


Figure 3-4 Residual Aeromagnetic Anomaly Map of Study Area with Interpreted Major Basement Faults and Oil and Gas Shows in the Upper and Lower Paleozoic Formations

3.1.1 Gravity and Magnetic Model Studies

Figure 3-5 shows the locations of profiles AB, CD, EF, and GH, along which gravity and magnetic model studies were conducted, and seismic line 5, which was interpreted. The observed gravity data over these profiles and the geological models over which the computed gravity gave a good match with the observed anomaly are shown in Figures 3-6 through 3-9. The details of modeling techniques and the assumptions made have already been discussed,¹ but the important conclusions drawn from these studies were that they could provide reliable estimates of the thickness of the sedimentary rocks overlying the crystalline basement, the structure and configuration of the basement surface, and major faults affecting the basement and the overlying sediments. When integrated with other sources of information (such as wireline log and seismic data), the gravity and magnetic modeling can also provide information on anomalous conditions within the sedimentary cover that are potentially favorable for entrapment of hydrocarbons.

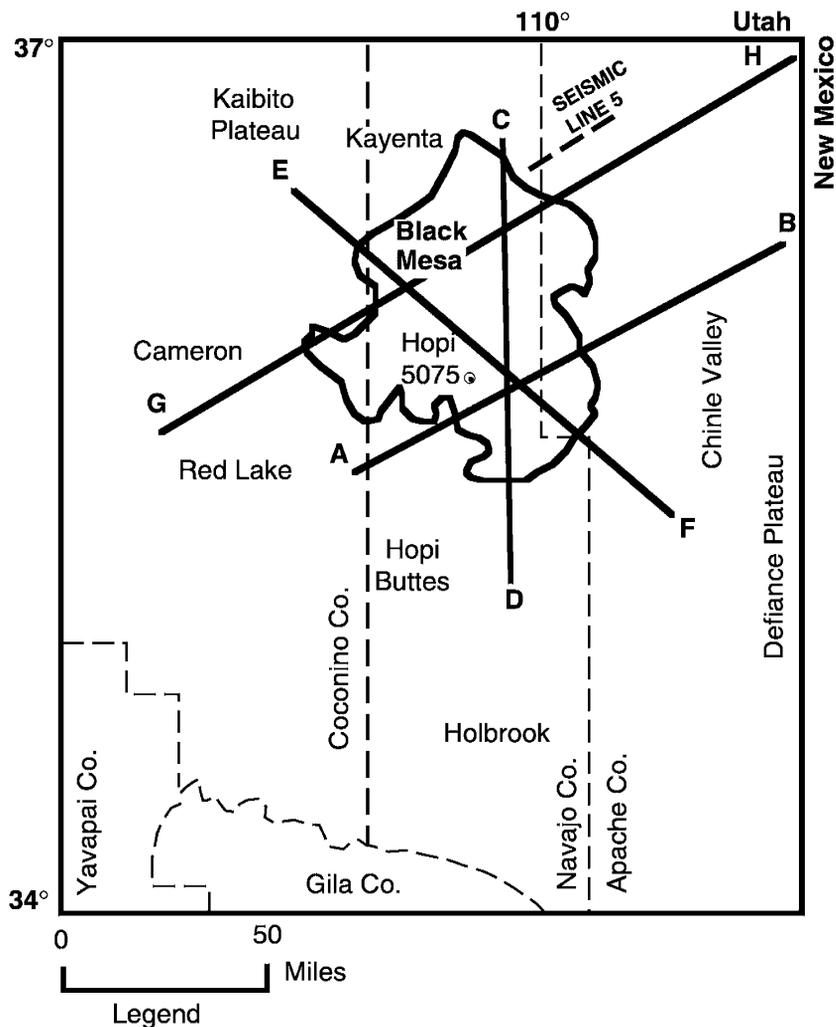


Figure 3-5 Locations of Profiles AB, CD, EF, and GH along which Gravity and Magnetic Model Studies were Conducted, and Interpreted Seismic Line 5

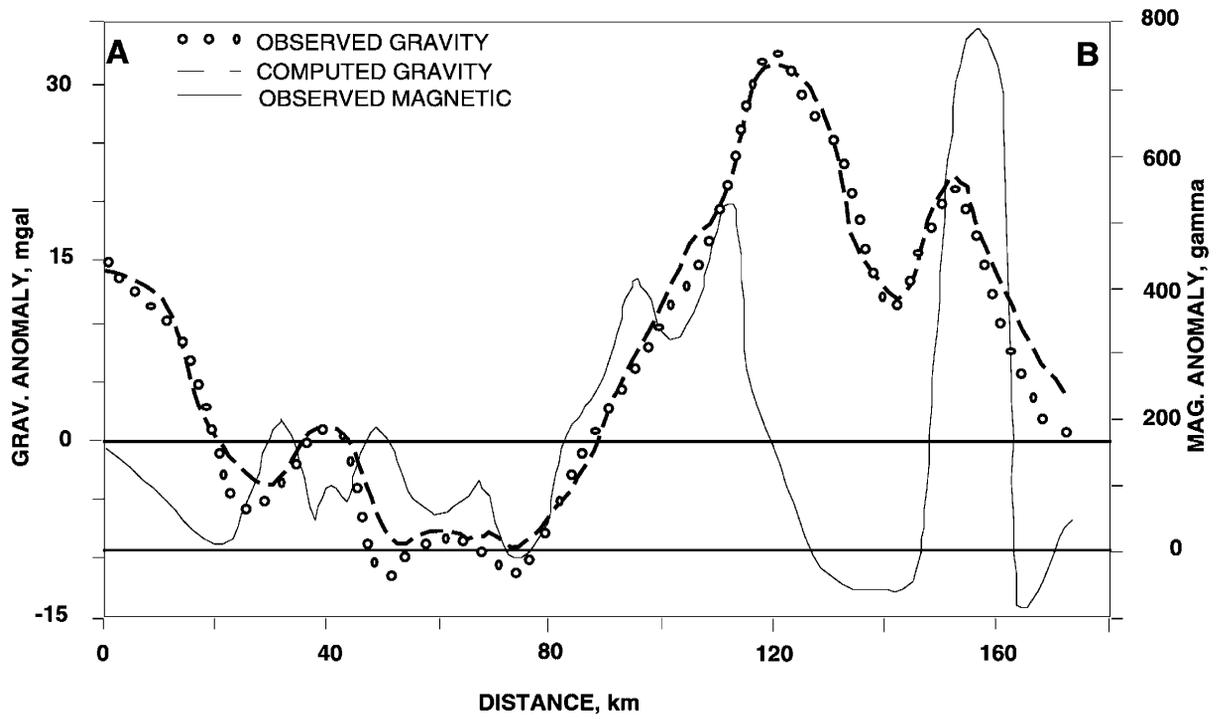


Figure 3-6 Gravity-Magnetic Model Studies along Profile AB

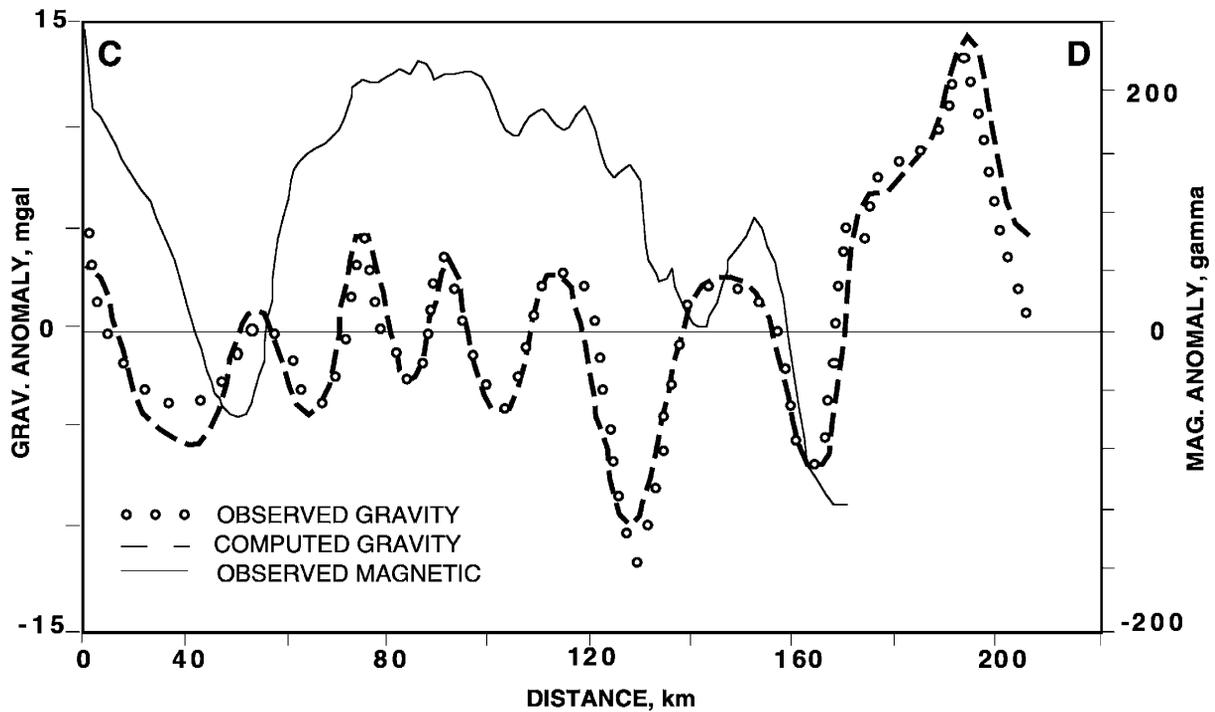


Figure 3-7 Gravity-Magnetic Model Studies along Profile CD

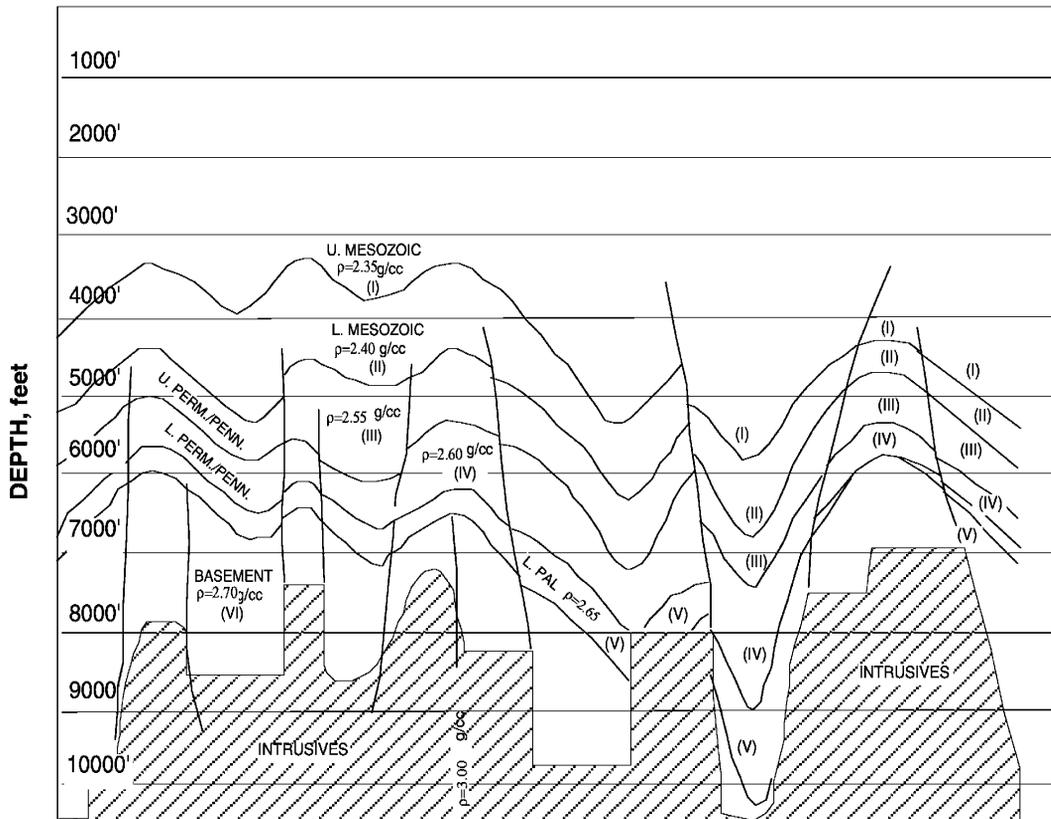
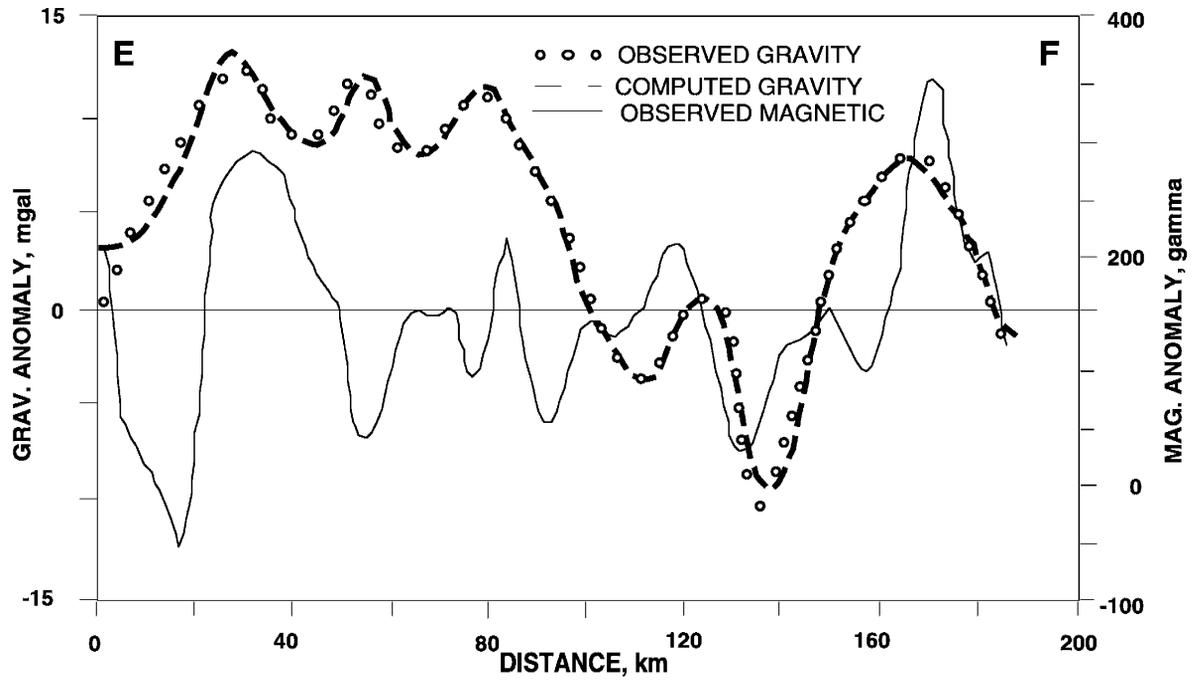


Figure 3-8 Gravity-Magnetic Model Studies along Profile EF

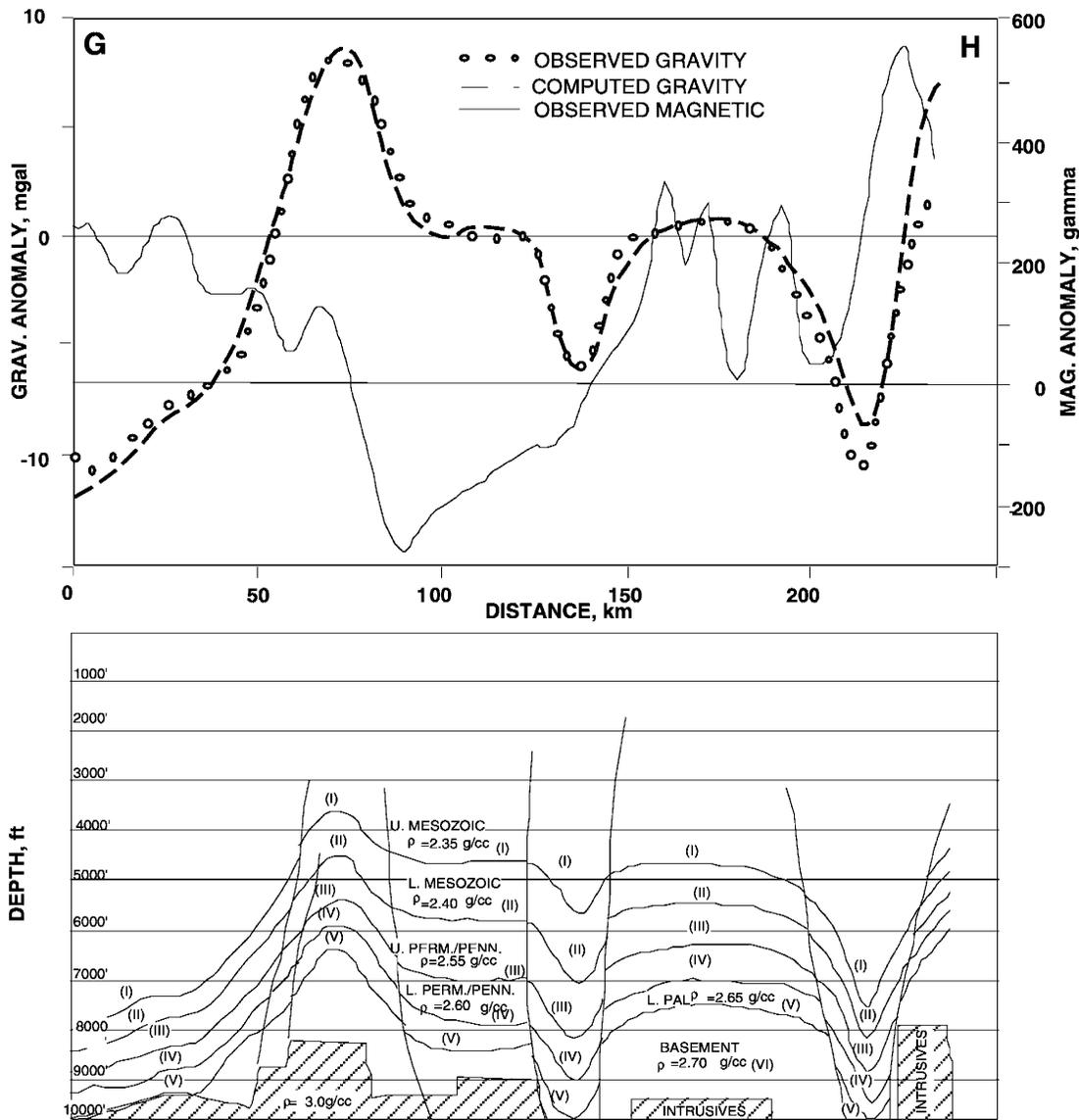


Figure 3-9 Gravity-Magnetic Model Studies along Profile GH

Interpretation of gravity and magnetic data has particular relevance in the study area of northeastern Arizona because some of the important exploration targets identified are in the lower Paleozoic formations which are in close proximity to the basement. As analysis of seismic line 5 indicates,⁹ the structure of the Devonian section (one of the prime exploration targets) could be strongly affected by the basement structure. The residual gravity anomaly map of the study area (see Fig. 3-1), which is a good reflection of the basement structure, shows, except for a small lateral shift, a striking resemblance with the Devonian isopach map (see Fig. 3-10) obtained from drilling information and published by the Arizona Bureau of Mines.⁴ Figure 3-10 also shows the locations of wells that were analyzed for construction of the structural and stratigraphic sections discussed in this report.

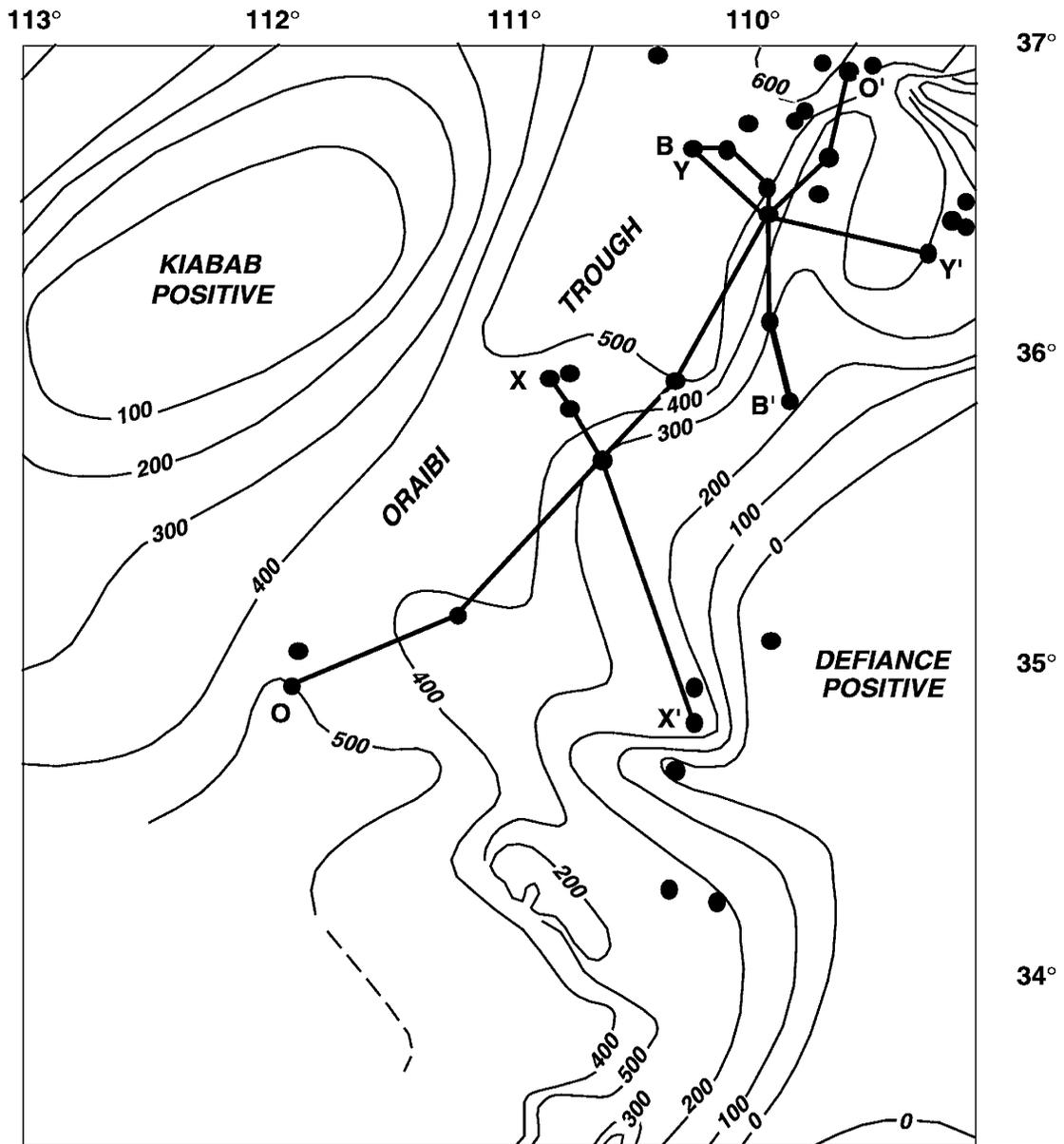


Figure 3-10 Map Showing Locations of Wells with Wireline Logs that were Interpreted for Lithology, Petrophysical Properties, and Construction of Stratigraphic Cross Sections OO', XX', YY', and BB'. The Upper Devonian isopach (contour interval = 100 ft) has been superimposed on the location map.

Although the magnetic susceptibilities of different rock types show considerable overlap, the average magnetic susceptibility of common sedimentary rocks is usually very low and is in the range 0 to 50×10^{-6} cgs units, compared to the susceptibility of common acidic igneous rocks like granite ($1,000 \times 10^{-6}$ cgs units) and of basic igneous rocks like diorite or diabase ($15,000 \times 10^{-6}$ cgs units).¹⁵ In general, therefore, it may be assumed that the observed magnetic anomaly in the study area is entirely a contribution from the magnetic basement and intrusive or extrusive magnetic rocks.

3.1.2 Gravity Modeling Results

The results of gravity magnetic model studies along the four profiles have been integrated with the residual gravity and magnetic maps of the study area obtained from a report by Gutmann and Heckmann⁸ to generate a map of the basement structure (see Fig. 3-11). This map identifies the dominant basement highs (marked "H" on Fig. 3-11) and basement lows (marked "L" on Fig. 3-11) in the study area. The locations of all the wells drilled within the Black Mesa basin and a few deep wells drilled at structurally strategic locations (see Table 1 below) outside of the structural Black Mesa basin are also shown in Figure 3-11. Fifteen wells have penetrated the basement surface; just below the well numbers, the basement depths in these wells are indicated. Several wells stopped in the Cambrian section. A comparison of actual depths with the highs and lows in Figure 3-11 indicate that the residual anomalies follow the actual depths quite accurately. For precise depth estimation from the residual anomalies, however, model studies will have to be performed.

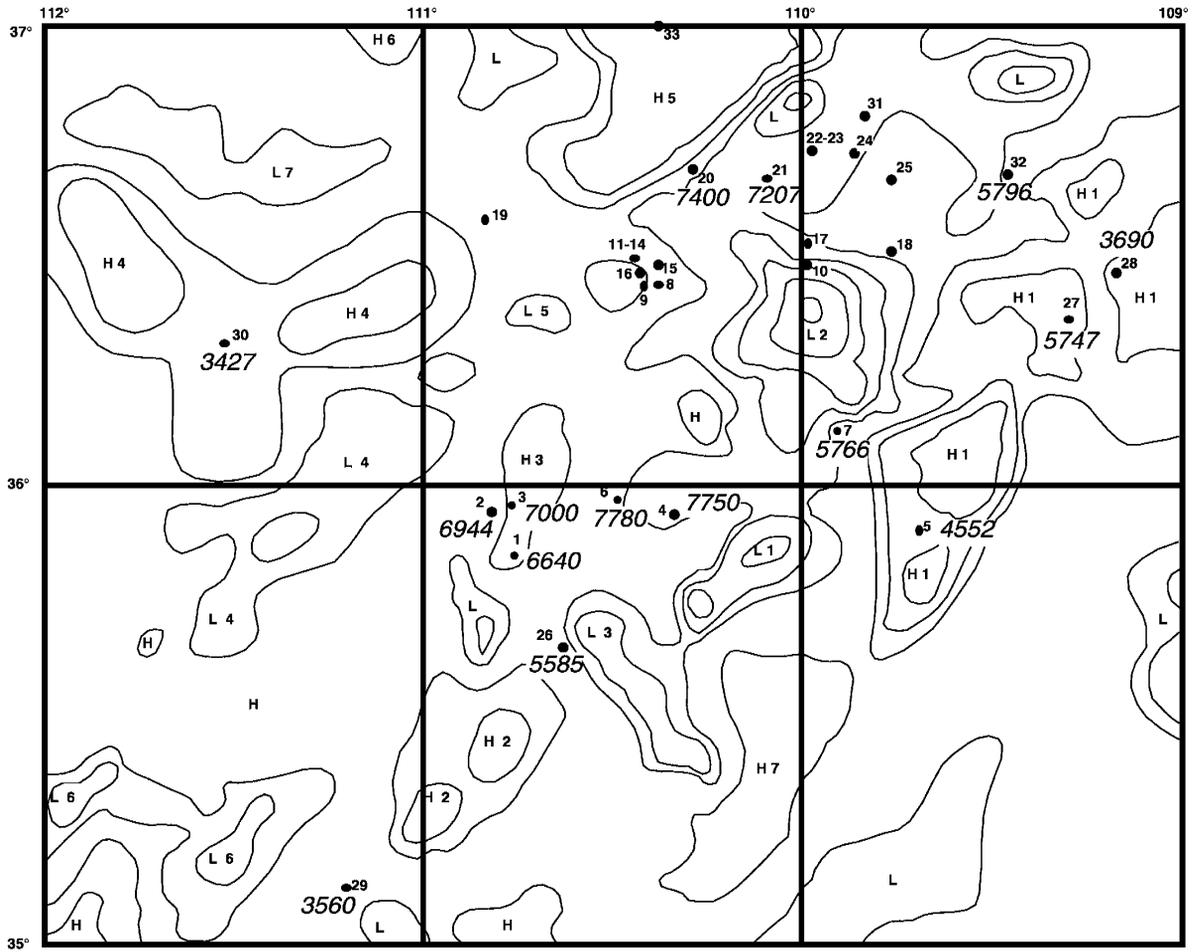


Figure 3-11 Basement Structure Map Obtained from Interpretations of Gravity Data Showing Locations of Highs (H) and Lows (L), Deep Wells Drilled (Numbers Refer to Table 3-1), and Depths in Wells that Penetrated the Basement

Table 3-1 Wells Drilled within the Black Mesa Basin and All the Deep Wells Drilled in the Surrounding Areas^{1,4,10}

Well No. (Fig. 3-11)	Operator	Well Name	Location	Total Depth (ft)
1	Atlantic Refining	Hopi-9 1	sec. 9-T28N-R15E	6640 *
2	Pennzoil	Hopi 1-111	sec.11-T29N-R14E	6944 *
3	Moore & Miller	Hopi 1	sec. 6-T29N-R15E	7000 *
4	Amerada Hess	Hopi - 5075 1	sec. 8-T29N-R19E	7750 *
5	Gulf	Navajo - CZ 1	sec. 21-T29N-R24E	4552 *
6	Skelly Oil	Hopi Tribe - A 1	sec. 35-T30N-R17E	7780 *
7	Amerada Hess	Navajo 1	sec. 3-T31N-R23E	5766 * H
8	Peabody Coal	Navajo 3	sec. 14-T35N-R18E	3599
9	Peabody Coal	Navajo 4	sec. 16-T35N-R18E	3534
10	Tenneco	Navajo - 8939 1	sec. 2-T35N-R22E	6754
11	R.Y. Walker	Navajo 1	sec. 20-T36N-R18E	1270 H
12	R.Y. Walker	Navajo 1-A	sec. 20-T36N-R18E	1258
13	Peabody Coal	Navajo 1	sec. 20-T36N-R18E	5745 H
14	Peabody Coal	Navajo 2	sec. 20-T36N-R18E	3649
15	Peabody Coal	Navajo 6	sec. 26-T36N-R18E	3571
16	Peabody Coal	Navajo 5	sec. 34-T36N-R18E	3749
17	Cactus Drilling	Navajo 1	sec. 14-T36N-R22E	6689
18	Cactus Drilling	Navajo 88-18 1	sec. 23-T36N-R24E	5720 H
19	Sinclair	Navajo 1	sec. 28-T37N-R14E	7211
20	Tenneco	Navajo - 8351 1	sec. 24-T38N-R19E	7400 * H
21	Superior	Navajo - W 21-29	sec. 29-T38N-R21E	7207 * H
22	McCulloch Oil	Navajo 1-1	sec. 1-T38N-R22E	5846
23	McCulloch Oil	Navajo 1-1X	sec. 1-T38N-R22E	765
24	Tesoro Petroleum	Navajo - Davis 1	sec. 13-T38N-R23E	5554
25	Exxcel Energy	Navajo Tribal 29-1	sec. 29-T38N-R24E	6020 H
26	Texaco	Texaco 1-A Hopi	sec. 15-T26N-R16E	5855 *
27	Amerada Hess	Amerada-Stanolind	sec. 3-T31N-R23E	5747 *
28	Kerr McGee	Kerr McGee 1 Navajo	sec. 32-T36N-R30E	3690 *
29	Roy Owen	Roy Owen 1 Diablo	sec. 12-T20N-R11E	3560 *
30	Collins	Collins 1 Navajo	sec. 22-T34N-R8E	3427 *
31	Amerada Hess	Amerada 1-91 Navajo	sec. 7-T39N-R24E	6442
32	Pan American	Pan American 1	sec. 20-T38N-R27E	5796 *
33	Texas et. al	1 Navajo A	sec. 34-T12N-R18E	4423

* Well drilled to basement

H Well had hydrocarbon show

The areas marked “L” in Figure 3–11 are expected to have the thickest sediment accumulations.

From Table 3–1, the thickest measured sedimentary section identified is around 7800 ft. This thickness is encountered in the Amerada Hess Hopi - 5075 1 (sec. 8, T29N, R19E), marked 4 in Figure 3–11, and in the Skelly Oil Hopi Tribe-A 1 (sec. 35, T30N-R17E), marked 6 in Figure 3–11. The gravity-magnetic modeling indicates several areas with considerably larger sediment accumulations than previously believed. Oil shows have been reported in the Upper Devonian McCracken Sandstones in the Amerada well. The modeling results suggest that the maximum sediment thickness could be as much as 10,000 ft in certain areas. Due to certain ambiguities inherently present in gravity modeling, the exact depth to the basement may be difficult to determine, but from relative changes in gravity anomalies, the change in basement depth from known locations may be determined quite precisely. For example, 12 miles southeast and northeast of the Amerada well (4 in Figure 3–11), the gravity anomaly is as much as 1 milligal lower than that in the Amerada well. These areas with low gravity anomalies may contain large thicknesses of lower Paleozoic sediments with good potential for source rock maturity.

The following structural features delineated in Figure 3–11 are of particular interest for hydrocarbon generation and entrapment in the study area:

- Within the lows L1, L2, and L3 are areas where sediment accumulations are expected to be close to 10,000 ft. Sediment accumulations in lows L4, L5, and L6 should be close to 8,000–9000 ft. According to Rauzi,¹¹ the maximum basement depth is close to 9,300 ft in an area about 30 miles north of the Amerada and Skelly wells. Rauzi, however, used only the available basement depths from drilled wells to obtain his basement depth contours.
- Several prominent highs (H1 through H6) have been delineated, and favorable trapping conditions may be present on the flanks of these highs.

From a comparison with detailed interpretation of seismic line 5 (see discussion in section 3.1.3), it has been demonstrated that the model studies can also effectively delineate locations of major basement faults and igneous intrusive bodies having distinctly different densities or magnetic susceptibilities compared to the overlying sediments.

- Several basement faults have been shown in the models. From the sharpness of the aeromagnetic anomalies associated with the intrusive igneous bodies, it appears that, in many cases, these bodies have penetrated considerable distance into the sedimentary section after penetrating the basement surface.

Several areas with potentially good structural and stratigraphic trapping conditions have been mapped and appear to be good exploration targets. The above results are integrated with the discussions of stratigraphy, oil and gas shows, and hydrocarbon maturity throughout this report.

3.1.3 Interpretations of Seismic Line 5

A good overall confirmation of the gravity modeling results was obtained from interpretation of the 23-mile-long regional seismic line 5, which runs parallel to gravity model profile GH (see Fig. 3-5 for locations). The main objectives of interpreting seismic line 5 were to obtain information on structure of the lower Paleozoic section and also the topography of the basement surface which could control oil accumulations in the area. The three formation tops mapped in this study were the tops of the Mississippian, the McCracken Sandstone Member of the Elbert Formation, and the basement rock complex.

For converting seismic times into depths, a velocity function was generated by integrating the sonic logs from two wells (Cactus 1 and Champlain 1) in the study area. The core descriptions for the two wells were also available¹⁰ for correlating the integrated travel times to different formation tops.

The Sonvel computer program was developed to automatically integrate the digitized sonic log data from the seismic datum (4,900 ft above sea level) down to the tops of the different formations. From the integrated travel times, the average velocities from the datum to the various formation tops were computed. The average velocities were also computed at 500-ft depth intervals, and plots of average velocities as a function of depth developed (see Fig. 3-12). Due to the presence of a gradually increasing thickness of a high-velocity carbonate rock sequence¹² in the northerly direction, the updip well Champlain 1 has a significantly higher velocity than Cactus 1. The presence of this strong velocity gradient will affect precise structural mapping if this velocity gradient is not taken into account in time depth conversion at each shotpoint location.

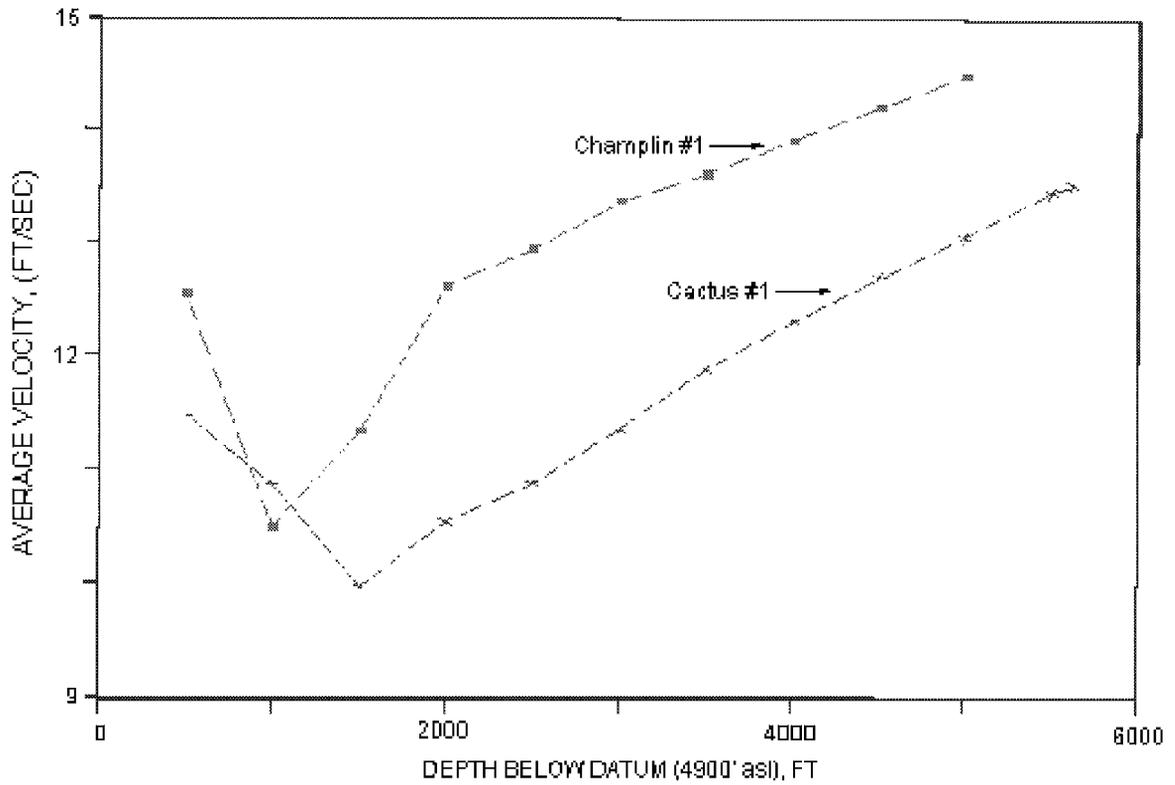


Figure 3-12 Plots of Average Velocities as a Function of Depth in Wells Cactus 1 and Champlain 1

Three reflectors identified on seismic line 5 from velocity functions derived for Cactus 1 were mapped (see Fig. 3-13), as were the faults that affected the three reflectors. In most cases, the structure of the lower Paleozoic formations faithfully follow the basement topography, indicating that there is a strong effect of basement tectonics on present lower Paleozoic structures.

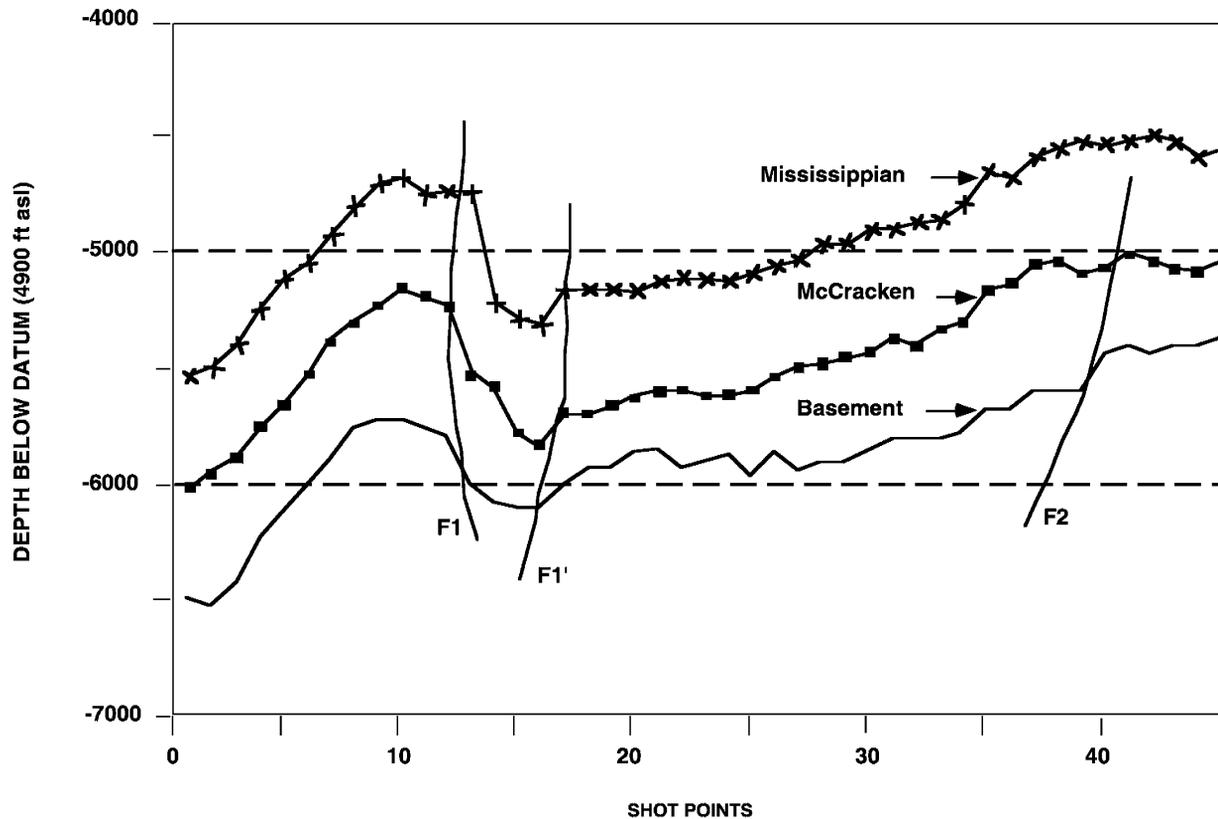


Figure 3-13 Mapping of Reflectors on the Top of the Basement, the McCracken Sandstones, and the Mississippian on Seismic Line 5

As discussed earlier, for precise structural mapping, the presence of a strong velocity gradient must be taken into account. If a linear velocity gradient correction between Cactus 1 and Champlain 1 is applied, the basement reflector will occur at progressively deeper levels (in the direction of higher shotpoint numbers) (see Fig 3-14) than that indicated from computations based on a single velocity function in the downdip well (Cactus 1).

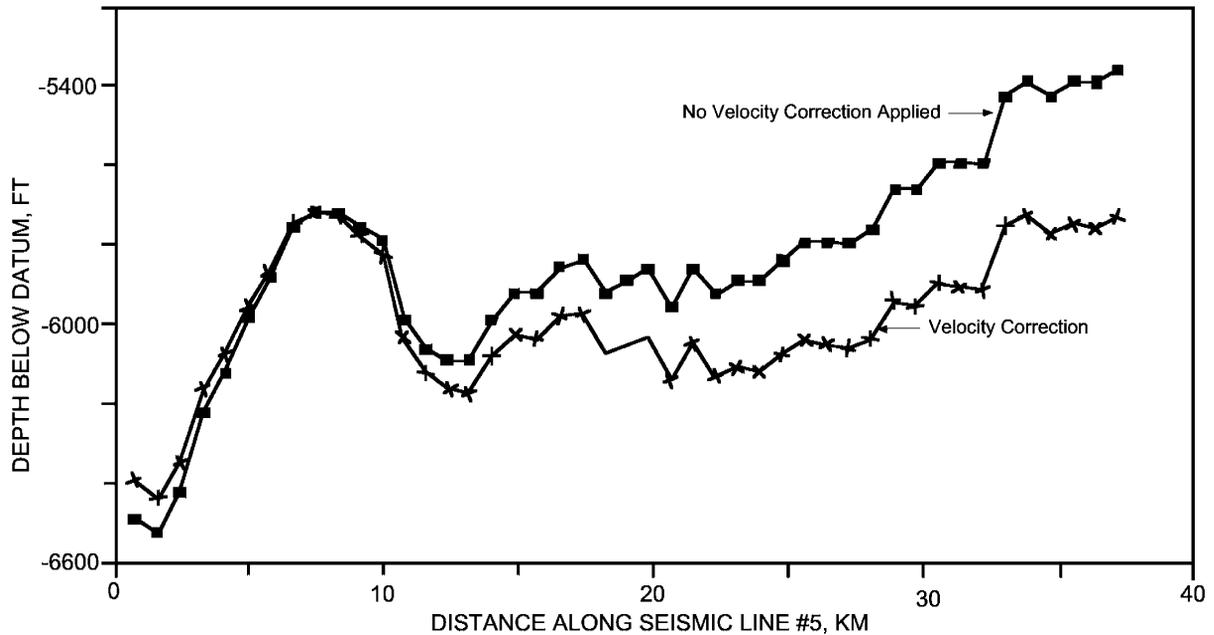


Figure 3-14 Application of a Linear Velocity Gradient Correction for Time-Depth Correction of Basement Reflector on Seismic Line 5

3.1.4 Comparison of Seismic Results with Gravity Model Studies

Since seismic data usually provide accurate information on structure and faulting, the accuracy of other investigations may be determined by comparison with the seismic data. For example, the general topography of the basement surface and the location and type of faulting (faults F1 and F2 in Figure 3-13) obtained from seismic interpretations agree well with the structure generated from gravity model studies along profile GH (see Fig. 3-9).

3.1.5 Comparison of Seismic Results with Satellite Imaging of Surficial Features

The basement structure identified along seismic line 5 (see Fig. 3-13) shows a close correspondence to surficial features identified on satellite image (see Fig. 3-15). The locations of shotpoints on seismic line 5 have been superimposed on Figure 3-15. A strong association can be seen between the locations of the Chilchinbito anticline and Church Rock syncline axes and basement faults. This type of deformation is typical of the Colorado Plateau. Fault F2 correspond to the erosional cut of the Chinle Wash. This suggests that the present drainage follows the line of faulting and fracturing, and that the other surficial features at Black Mesa are probably controlled by basement tectonics as well. This raises the possibility that at certain locations the Laramide tectonic activity could have provided escape routes for hydrocarbons generated in the lower Paleozoic section.

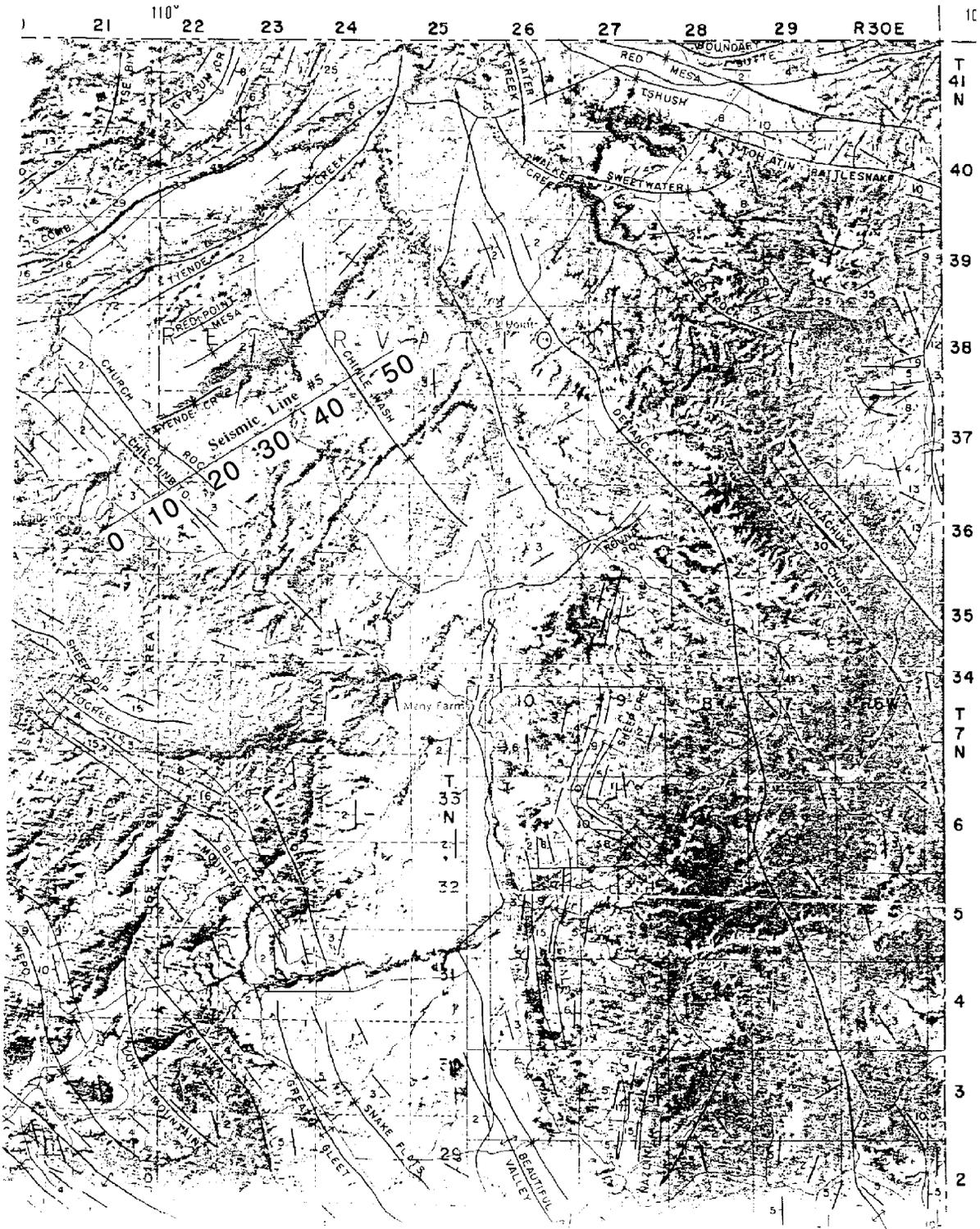


Figure 3-15 Close Correspondence between Basement Structure Identified on Seismic Line 5 and Surficial Features Identified on Satellite Image Data

3.1.6 Interpretation of Aeromagnetic Data

The computer program Maganom was used to compute the total intensity anomalies along the basement profile of seismic line 5 for comparison with the observed aeromagnetic anomaly along the seismic line. The susceptibility of the basement rock used was 0.002 cgs units (i.e. the average susceptibility of granitic rocks). From the aeromagnetic map of the area, the strike of the basement surface was taken as 70° to magnetic north. The magnetic inclination of the earth's field was assumed to be 60°, and the earth's total field was assumed to be 60,000 gammas.

When the computed total intensity magnetic anomaly is compared with the observed aeromagnetic anomaly, it was found that the computed anomaly is about ten times smaller than the observed. This implies that there must be other igneous sources contributing to the observed anomaly. Exactly the same conclusion had been drawn from gravity modeling. For a satisfactory match between the observed and the computed anomalies, the presence of higher density (possibly mafic) igneous rocks was postulated. It is apparent that only the combined effect of igneous basement rocks and high susceptibility intrusives can give a satisfactory match.

3.1.7 Surface Fracture Analysis

A surface fracture analysis¹ of the study area was conducted that involved mapping surface lineaments using Landsat data, interpretation of surface fracture zones from monoclinical data, and mapping of surface fracture traces from infrared photographs. This study showed that the basic structural grains of northeastern Arizona consist of three components trending northwest, north, and northeast. It was concluded that the Precambrian basement rocks were divided into regular blocks bounded by northeast- and northwest-trending fault systems. Many of the basement faults have been reactivated and have propagated to the surface. Consequently, they could exert some control on hydrocarbon accumulations.

The northwest-southeast fracture trend, which roughly parallels the Uncompahgre Uplift, is believed to be of Paleozoic age, and the secondary trends (northeast-southwest and north-south) are post-Paleozoic (Laramide) in age. The older northwest-trending structures are considered the most favorable for commercial production. Oil and gas producing areas in the Paradox (including the Four Corners area in Arizona) and San Juan basins generally have a northwest trend with local variations. Baars¹³ demonstrated that major facies changes in the Pennsylvanian and Permian systems are closely associated with the paleotectonic faulted structures and, therefore, could have an important bearing on the entrapment of hydrocarbons.

3.2 Stratigraphy and Lithology of Reservoir and Source Rocks

Northeastern Arizona is underlain by sedimentary rocks that range in age from the Cambrian to the Tertiary.^{4,5} Ordovician, Silurian, and Lower and Middle Devonian rocks are not present in most of the region; either they were not deposited or they were later eroded. Cambrian and Upper Devonian rocks are particularly prospective for hydrocarbon accumulations^{4,5,12,14}

although there is some oil and gas production from Pennsylvanian and Mississippian rocks in the extreme northeasterly part (the Four Corners Area) of Arizona. Along the southern edge of the Black Mesa basin in the Holbrook anticline area, the Pennsylvanian is considerably thick. In this area, these rocks may have better hydrocarbon prospects. The Permian rocks in the study area are principally of nonmarine or transitional marine origin; consequently, they are not attractive targets for this investigation. The discussion here on stratigraphy of potential reservoir rocks will be confined primarily to the Cambrian and the Upper Devonian rocks which are considered most prospective in the study area.¹⁻⁶

3.2.1 Lower Paleozoic Exploration Targets

The epeiric sea setting of the Black Mesa basin area during the Paleozoic provided the conditions for numerous shifts of the sea and, therefore, abrupt facies changes and complex intertonguing of the sedimentary rocks.^{5,6,12,14} Because such a depositional environments is conducive to the development of different types of stratigraphic traps, for a long time the lower Paleozoic rock formations have been recognized as an important commercial oil and gas production target. Besides some amount of oil production from the Four Corners area, oil shows have been reported from several sandstone and carbonate zones of the Upper Devonian unit. Of particular interest is the regressive facies of the medium- and coarse-grained McCracken Sandstone Member because similar facies have been good producers of oil in different basins around the world (e.g., in the U.S. Gulf Coast, Nigeria, Trinidad, and Sumatra). The Aneth Shale and dolomites underlying the McCracken Sandstone are good potential source rocks.^{5,6,12,14} In the Cambrian, the Tapeats Sandstone and the Bright Angel Shale of the Tonto Group are promising reservoir and source rocks, respectively, and are therefore important targets in Cambrian exploration.

3.2.2 Stratigraphic Cross Sections

Available wireline logs were used to construct six regional stratigraphic and structural cross sections in the study area (see Fig. 3-16 for location of sections OO', XX', YY', BB', PP', and QQ') to study variations in structure and stratigraphy of the Upper Devonian and Cambrian formations. The locations of four stratigraphic sections discussed here are also shown in Figure 3-10, where the isopach contours of the Upper Devonian section obtained from drilling information from the Arizona Bureau of Mines⁴ are also superimposed. This superposition has helped in the visualization of trends in the development of Upper Devonian and Cambrian rocks. For correlation of different rock formations, the log signatures were studied on the available gamma-ray, sonic, density, neutron, and electrical logs. From examination of core samples, the depths to tops of different formations in each well were also available.¹⁰

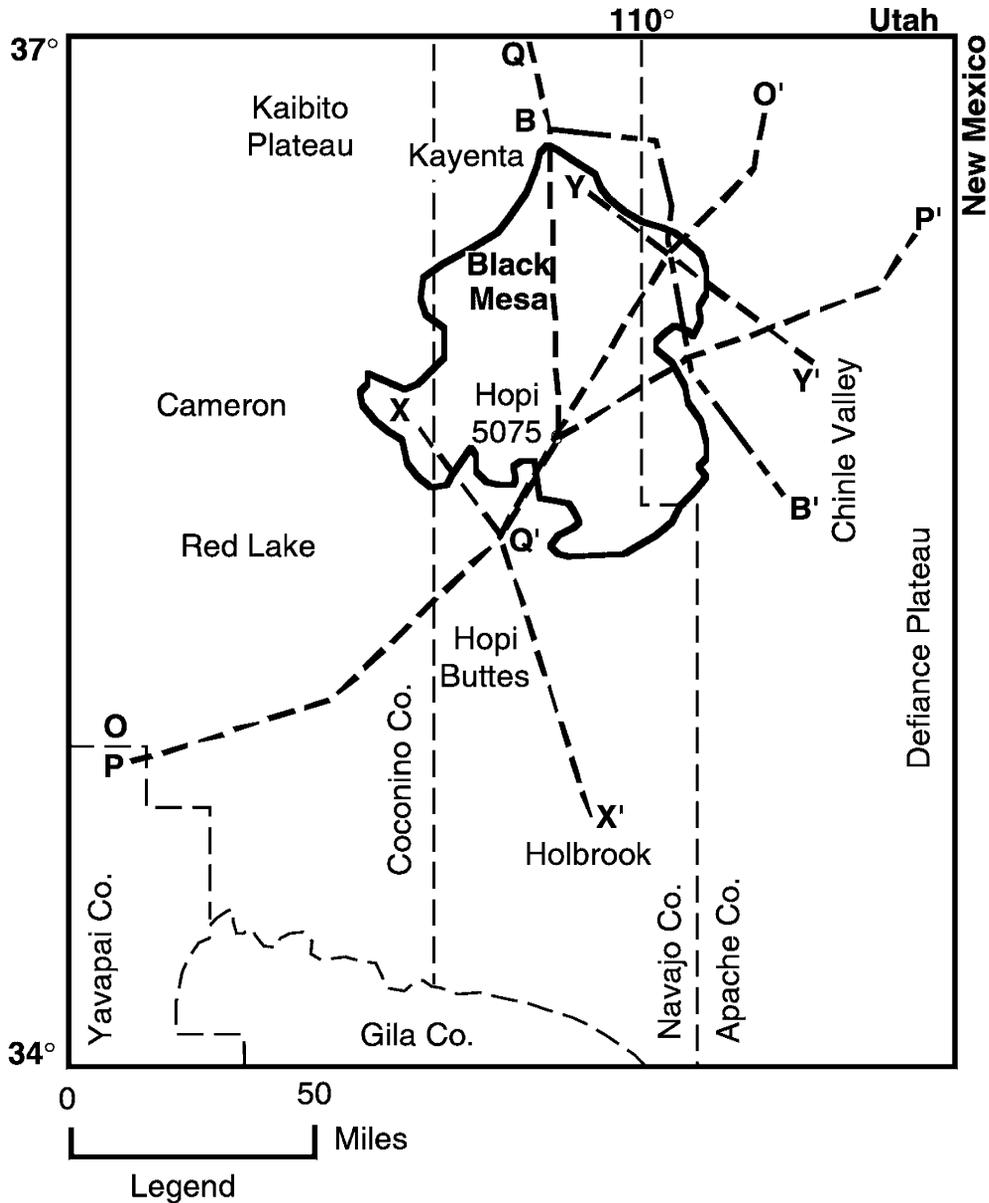


Figure 3-16 Locations of Stratigraphic Sections OO', XX', YY', BB', PP', and QQ', along which Variations of Structure and Stratigraphy were Studied.

Stratigraphic cross sections OO', XX', YY', and BB' (shown in Figs. 3-17, 3-18, 3-19, and 3-20, respectively) indicate the following.

The Cambrian and the Upper Devonian sections show a sharp thickening trend in the westerly and northwesterly directions. The thickest parts of the combined Cambrian and the Upper Devonian sections may be located farther west of the western extremity of sections XX' and YY'. On the structural map of Figure 3-11, the axis of the combined Cambrian and Upper Devonian section lie along the northeasterly prolongation of the lows L4 and L5. The location of

this axis could be slightly to the west of the axis of the Oraibi trough shown in Figure 3-10. It should be noted that the structure on the top of the basement surface (see Fig. 3-11) may not accurately reflect structural conditions during the Cambrian and the Devonian because of structural adjustments that were invariably associated with the Laramide orogeny.

From stratigraphic section OO' (see Fig. 3-17), the thickest part of the combined Cambrian and Devonian section lies in the vicinity of the lows marked L4 and L5 in Figure 3-11. The prospective McCracken Sandstone is very thick in this area; the greatest thickness along this profile is encountered in the Tenneco Navajo 8939 1 (marked 10 on Figure 3-11). From the isopachs of McCracken Sandstone reported earlier,⁵ there is a series of north-south isopach highs passing through the lows L1 and L2 area in Figure 3-11. This series of highs seem to abut against the "Defiance" high to the east.

The rapidly changing thicknesses of both the Cambrian and the Devonian units as observed in the stratigraphic cross sections may have produced favorable conditions for development of stratigraphic trapping conditions, such as pinch-outs of the McCracken Sandstone to the east. There could be other potential reservoir rocks in the Cambrian or in the Upper Devonian Aneth Formation, where similar trapping conditions may have developed.

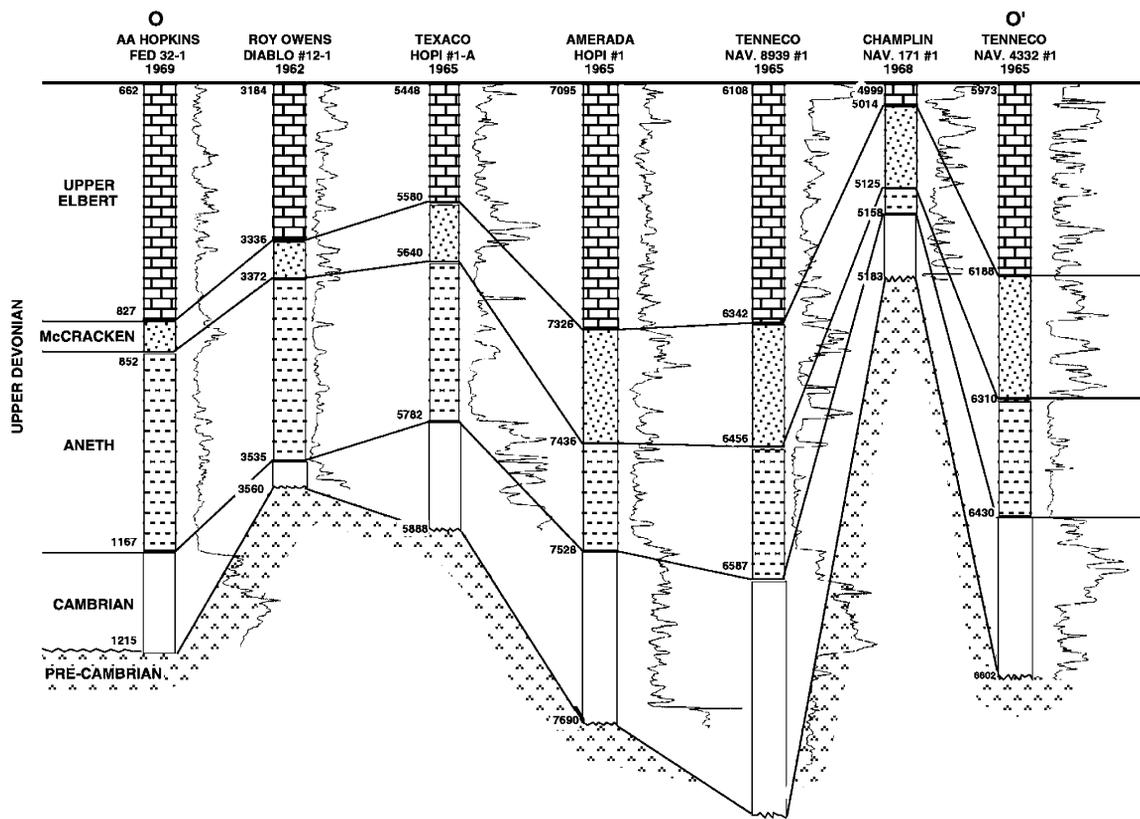


Figure 3-17 Stratigraphic Cross Section along Profile OO'

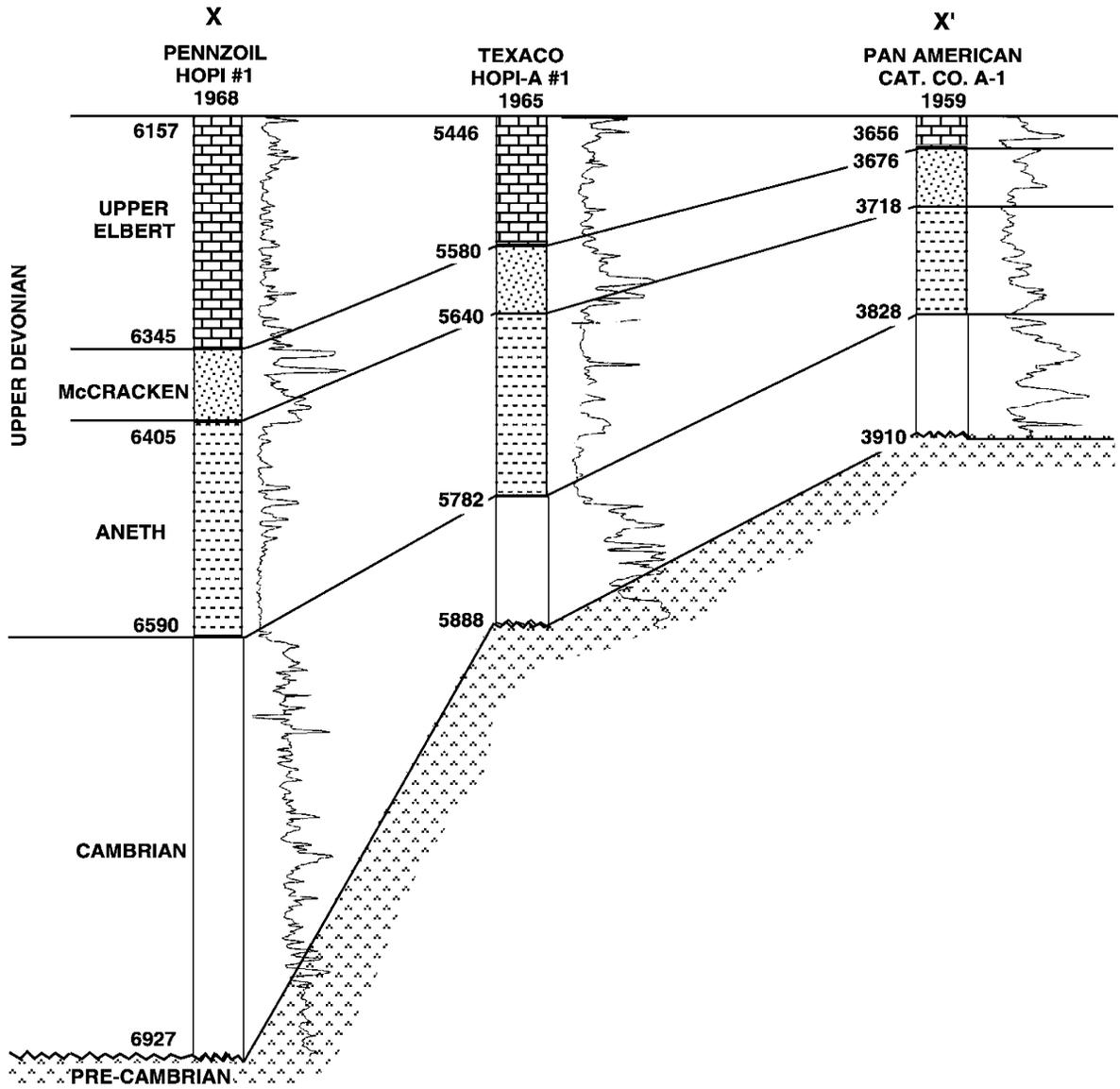


Figure 3-18 Stratigraphic Cross Section along Profile XX'

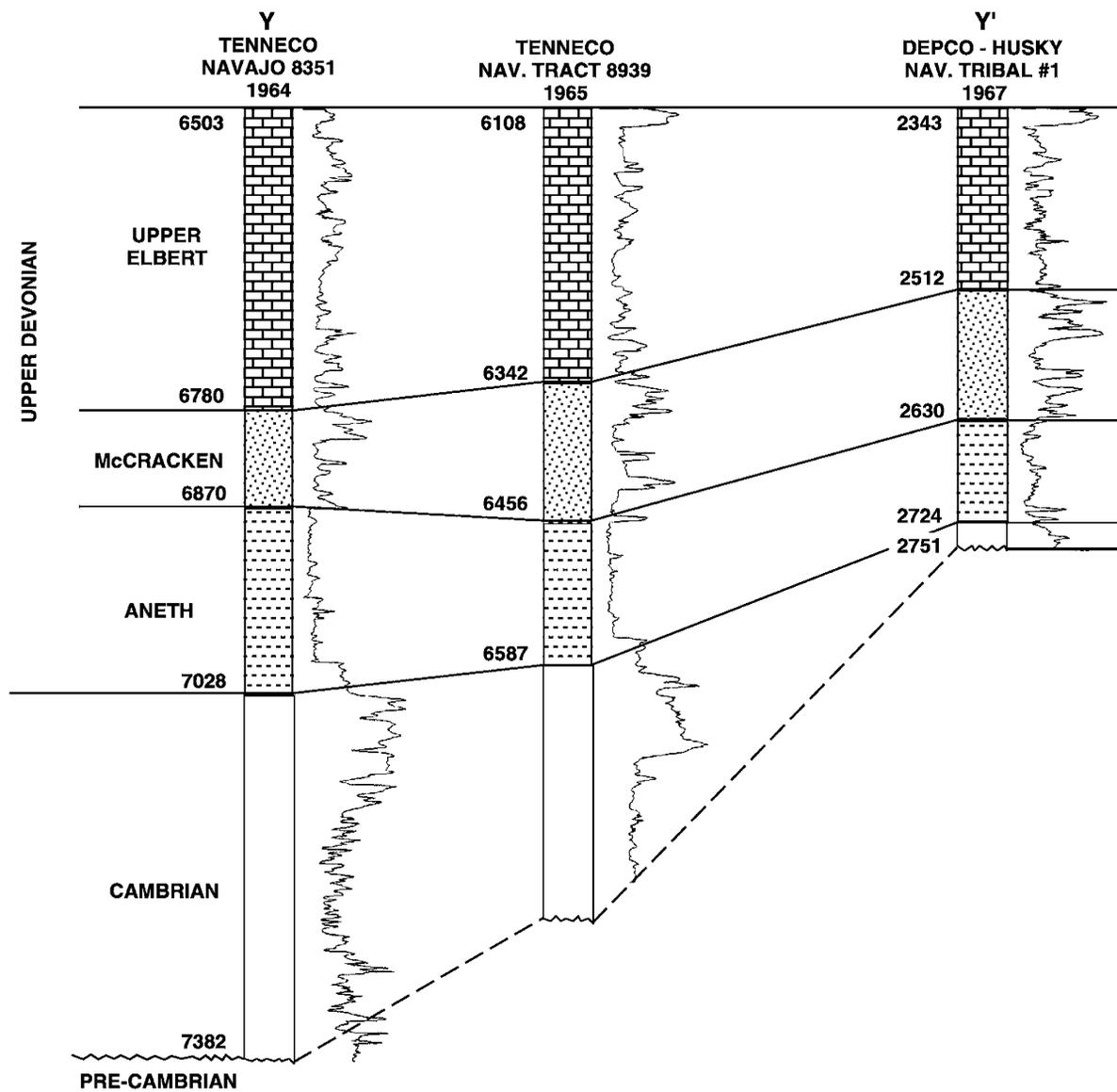


Figure 3-19 Stratigraphic Cross Section along Profile YY'

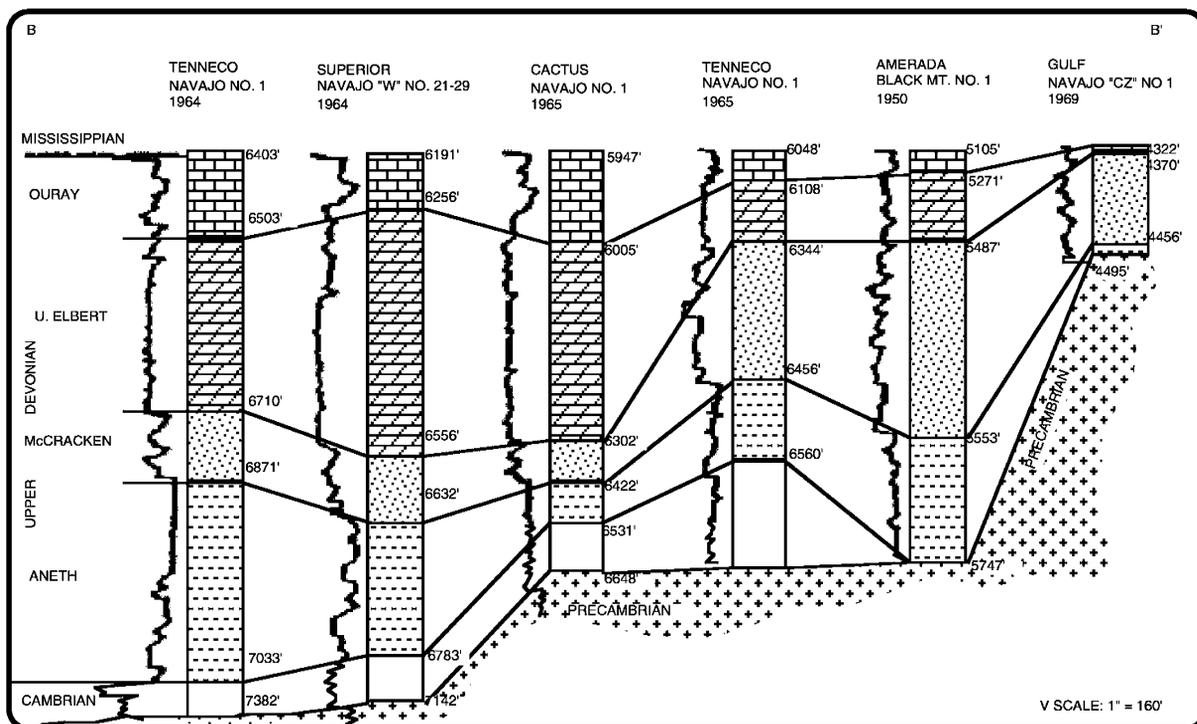


Figure 3–20 Stratigraphic Cross Section along Profile BB' on the East Flank of the Black Mesa Basin

3.3 Lithology and Petrophysical Properties of Reservoir and Source Rocks

Figure 3–10 shows the locations of wells for which the wireline logs were analyzed and the locations of profiles OO', XX', YY', and BB' along which computations were performed for distribution of lithology and petrophysical properties of reservoir and source rocks. The average values of clay content, porosity, and carbonate content for the combined Devonian and Cambrian sections were obtained at each well location from interpretations of gamma-ray, sonic, density, and neutron logs. Computer programs were developed for automatic computations of the petrophysical properties. The gamma-ray logs are a good indicator of clay content. The sonic transit times give a good indication of the trend in the variation of the carbonate content in the potential reservoir rocks because hard carbonate rocks have very short transit times whereas softer clastic rocks have longer transit times. Such information is critical to the understanding of the depositional environment of the Cambrian and Devonian sediments.

The Devonian of northeastern Arizona is predominantly of marine origin and consists of dolomites with subordinate amounts of sandstones, limestones, and shales. The Devonian rocks include the Aneth and the overlying Elbert Formation. The units are primarily dolomites, but the basal Elbert Formation includes the important McCracken Sandstone Member.

The Cambrian rocks are essentially similar throughout the study area: basal clastic rocks are overlain by limestone and dolomite; all units becoming younger and more sandy towards the east and the south.

Sonic transit times drop along profile OO' (see Fig. 3-21), indicating an increase in carbonate content in this dominantly dolomite section, whereas the average shale content along this profile has a fluctuating trend. Figure 3-22 indicates that small porosity variations are controlled by the shale content. The transverse sections XX' and YY' (see Figs. 3-23 and 3-24) indicate a trend of increase in clastic rocks towards the east and carbonate rocks toward the west. Sonic transit times for profiles XX' and YY' are not shown.

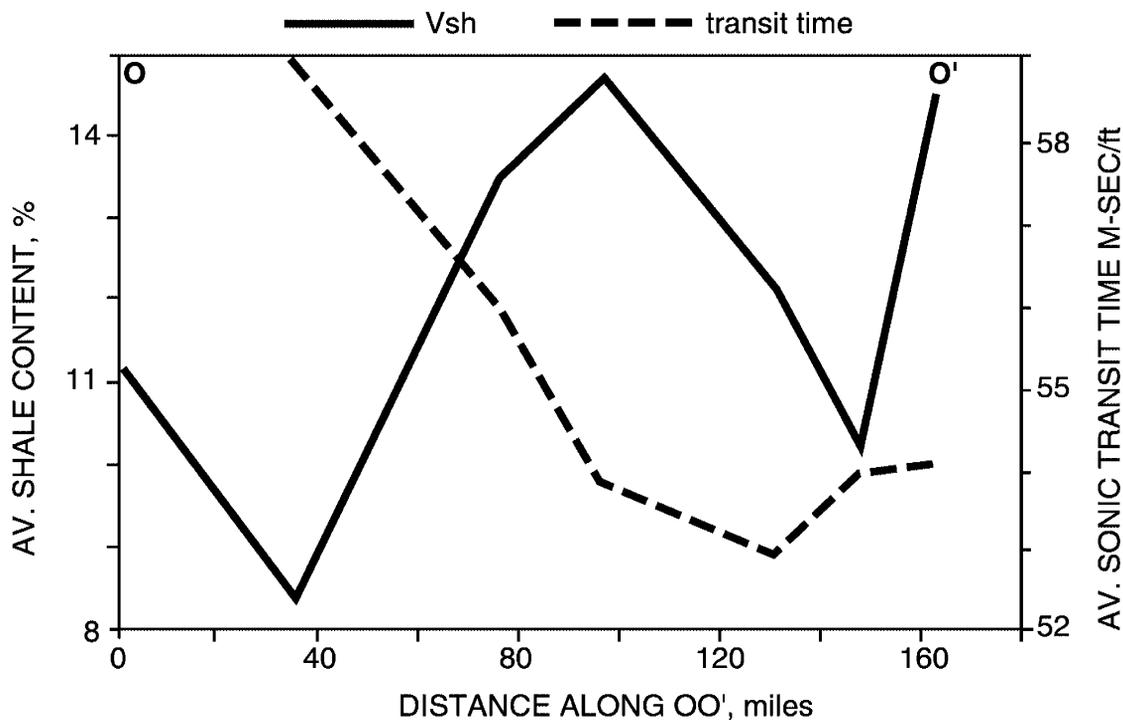


Figure 3-21 Distribution of Shale Content and Average Sonic Transit Times along Profile OO'

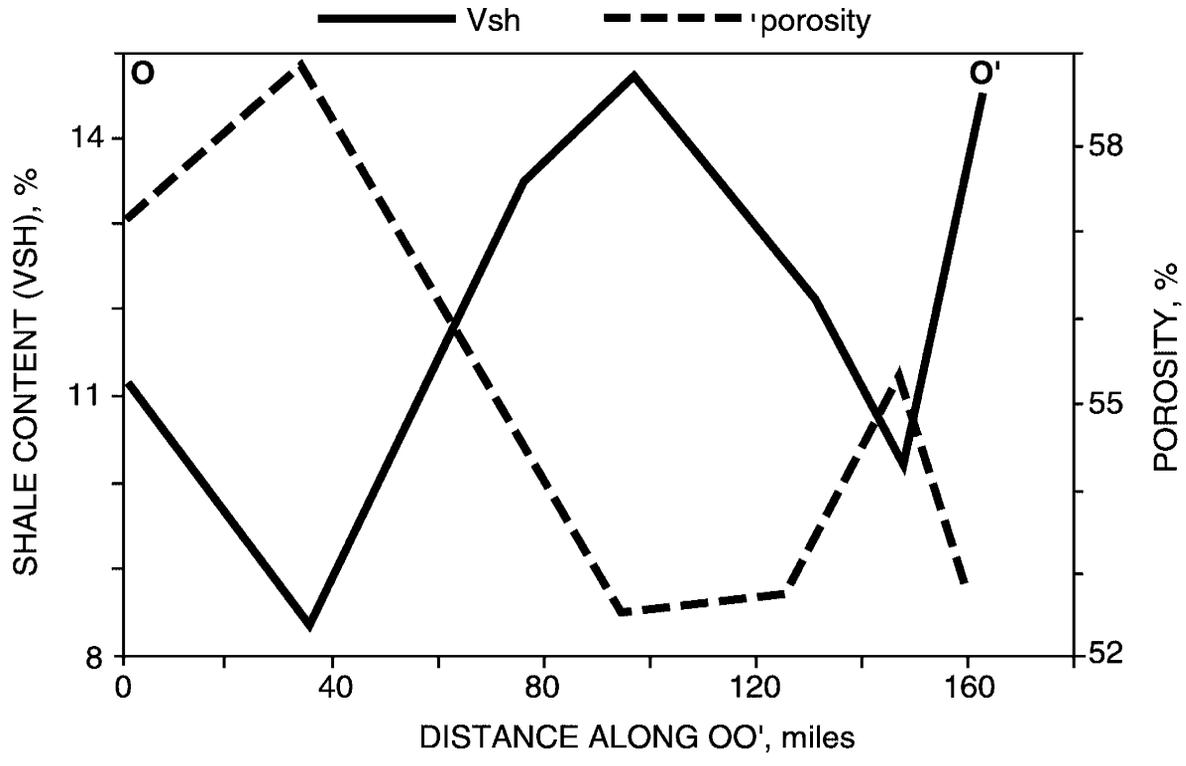


Figure 3-22 Distribution of Shale Content and Porosity along Profile OO'

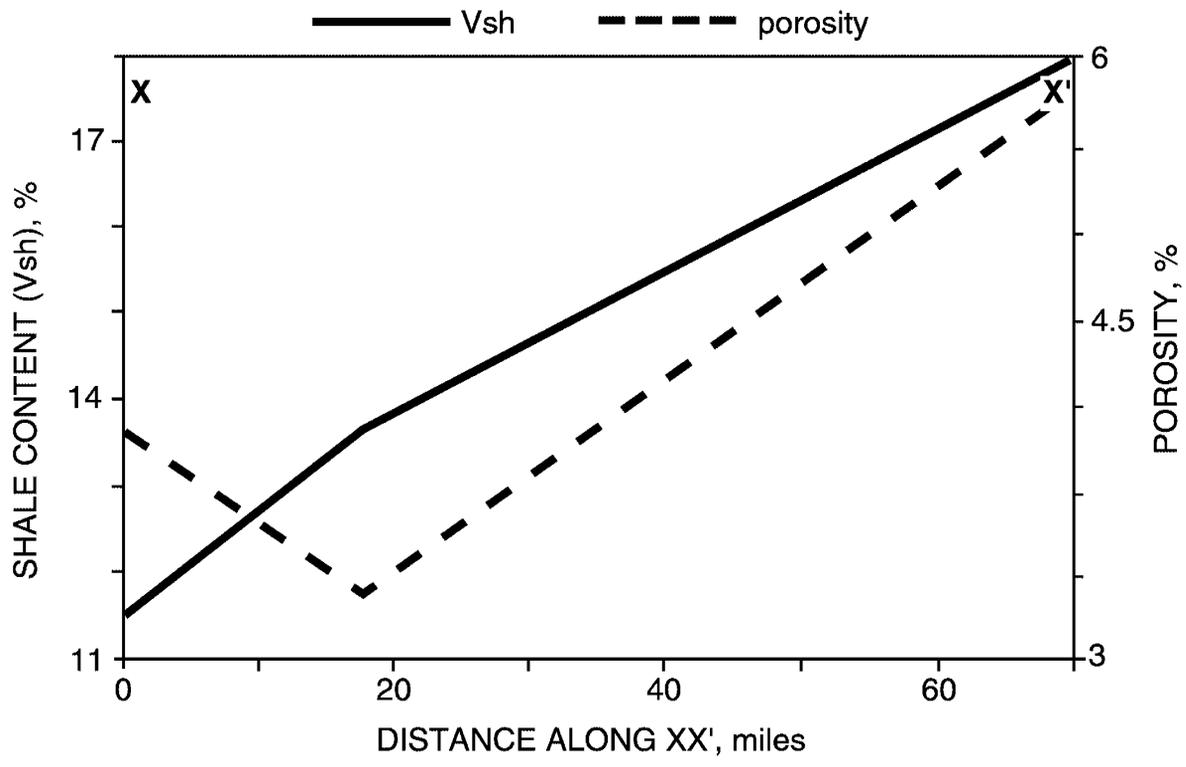


Figure 3-23 Distribution of Shale Content and Porosity along Profile XX'

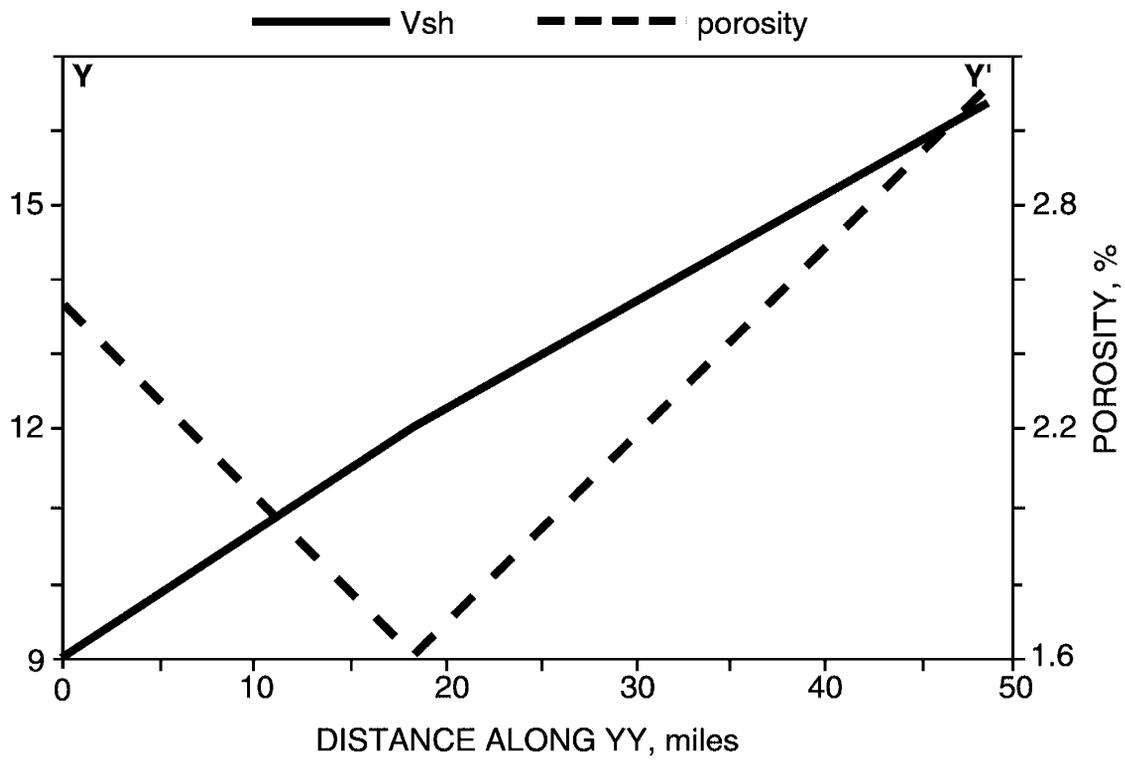


Figure 3-24 Distribution of Shale Content and Porosity along Profile YY'

4.0 OIL AND GAS SHOWS

Several oil and gas shows have been reported from the study area. The important shows from the upper and the lower Paleozoic formations are shown in Figures 3–1 and 3–2. The upper Paleozoic oil shows have a predominantly northwest-southeast trend which also coincides with one of the three fracture trends mapped in the study area. The northwest fracture, trend which roughly parallels the Uncompahgre Uplift, is believed to be of Paleozoic age, whereas the other two trends (southwest-northeast and north-south) are post Paleozoic (Laramide) in age. The older northwest-trending structures are considered the most favorable for oil and gas production because oil- and gas-producing areas in the Paradox (including the Four Corners area in Arizona) and San Juan basins generally have a northwest trend with local variations. Baars¹³ also demonstrated that major facies changes in the Pennsylvanian and Permian systems are closely associated with the paleotectonic faulted structures and, therefore, could have an important bearing on the entrapment of hydrocarbons.

The distribution of lower Paleozoic shows (see Figs. 3–1 and 3–2) do not have a clear cut trend but seem to be located along the zone of thick sediment accumulations in the Oraibi trough. Whether the lower Paleozoic hydrocarbon shows were the result of oil migrating from the northeast or the oil was generated in situ has not yet been resolved. In trying to decipher a production trend in a sparsely drilled basin like the Black Mesa, it should be noted that drilling locations were not always based on optimum geological considerations but sometimes were decided by factors like easy accessibility or ease of getting drilling permits.

4.1 Conditions Relevant to Generation and Entrapment of Hydrocarbons in the Study Area

From an analysis of the depositional environment, structure, and stratigraphy of the highly prospective lower Paleozoic rock formations in the study area, the following conditions are relevant to the generation and entrapment of hydrocarbons:

- Hydrocarbons trapped in the study area either were generated elsewhere and migrated to the basin along permeable beds, or they were generated in situ, provided favorable source rock conditions were present.
- Several areas with thick sediment accumulations are present in the basin where Paleozoic source rocks should have reached thermal maturity, even with the present geothermal gradient. During times of intense tectonic activity, geothermal gradients could have been higher, resulting in earlier maturity of source rocks.
- Surface fracture analysis indicates several lines of folding in the Black Mesa basin. The major one has a northwesterly trend, roughly paralleling the Uncompahgre Uplift, and is believed to be of Paleozoic age. Oil and gas producing areas in the Paradox

(including the Four Corners area in Arizona) and San Juan basins have a northwesterly trend with local variations.

- Stratigraphic trapping conditions could be present where lower Paleozoic rocks pinch out against the surrounding highs.
- Tectonic activity during the Tertiary period generated a number of faults, some of which have propagated right up to the surface. These faults could have provided escape routes for hydrocarbons generated at depth.
- Major facies changes in the Pennsylvanian and Permian systems are associated with paleotectonic faulted structures. Northwesterly trending paleostructures may be associated with facies changes and structures that are favorable to entrapment of hydrocarbons.
- Favorable conditions for development of biohermal reefing conditions were present in Pennsylvanian and Devonian shelf margin areas.

5.0 IDENTIFICATION OF AREAS FOR DETAILED EXPLORATION

In this discussion of hydrocarbon prospects in the Black Mesa basin, it should be noted that the tectonic activity during the Tertiary period generated a number of faults, some of which have propagated right up to the surface. It is possible that some or most of the hydrocarbons generated during the Paleozoic might have escaped through these faults. The late Tertiary tectonic activity must have affected pre-Tertiary sedimentary structures at Black Mesa, so the present structure may not be exactly the same as that during the early Paleozoic.

5.1 Thermal Maturity of Source Rocks

Hydrocarbons trapped in the study area either were generated elsewhere and migrated to the basin along permeable beds, or they were generated in situ, provided favorable source rock conditions with adequate organic content and favorable oil-generating conditions were present. Important oil-generating conditions are the depth and time of burial, which creates in the source rocks the necessary thermal maturity for generating oil. For thermal maturity of rocks for hydrocarbon production, an optimum geothermal gradient is necessary. It has been speculated that due to the tectonic activities (which are accompanied by excessive heat generation) during different geological times, the geothermal gradients during times of tectonic activities may be larger than the normal gradients found in tectonically quiet areas. Areas with such abnormally high gradients, as a result, may require less depth and time of burial for oil generation.

5.2 Areas for Detailed Exploration

From the discussions on structure, stratigraphy, lithological and petrophysical property variations of reservoir and source rocks in this report, the following areas in Figure 3-11 have been identified as possibly having very good hydrocarbon prospects:

- *Area Surrounding L1 and L3.* This area has large sediment accumulations, so there should be good thermal maturity of Paleozoic source rocks for hydrocarbon generation. The highly prospective McCracken Sandstone is very thick in this area. As indicated by gravity model studies, there are updip pinch-outs of the reservoir rocks in this area against the Defiance Uplift to the east, providing ideal conditions for the development of stratigraphic traps.
- *Area in the Vicinity of L2.* This area also has thick lower Paleozoic sediments. Oil and gas shows to the north of this area makes the entire area surrounding this low a particularly attractive target.

- *Northeast-Southeast-Trending Lows L4 and L5.* The string of northeast-southwest-trending lows in this area should have thick Paleozoic development. The area has not yet been probed by a deep test. Both structural and stratigraphic traps are potential targets for drilling.
- *Area in the Vicinity of H4 and H5.* The area southwest of H5 and northeast of H4 could be favorable for stratigraphic trap development.
- *Biohermal Reef Development.* Conditions were favorable for biohermal reef development in the Pennsylvanian and Devonian shelf margin areas in the study area, but high-resolution seismic data will be the only way to explore for these types of subtle structural features .
- *Precambrian Source Exploration.* Precambrian sources for hydrocarbons have been referred to in the past. Areas L4, L6, and L7 have both low residual gravity and aeromagnetic anomalies; gravity modeling suggests possible presence of graben-type structures in these areas. High-resolution seismic data will be invaluable in resolving the actual nature of structural anomalies in these areas. Also, combined gravity and aeromagnetic data modeling with more precise information on the magnetic susceptibility of the Chuar Formation and other Precambrian sediments will help to resolve the structural complexities and define the source rock potential of Precambrian sediments.

6.0 CONCLUSIONS

Areas have been identified from combined interpretations of gravity and magnetic maps, model studies, and other geophysical and geological data where large (around 10,000-ft) sediment accumulations are expected. The prospective lower Paleozoic source rocks are well within the oil generation window in these areas. Deep probing of these areas for lower Paleozoic and Precambrian prospects is highly recommended.

Carefully prepared gravity and magnetic maps supplemented by model studies with good density and magnetic susceptibility data can provide reliable information on basement structure. If the basement depths are not too great (i.e., less than 12,000–14,000 ft), the information provided by gravity, magnetic, and other satellite data should normally be quite reliable.

High-resolution satellite data (gravity, magnetic, gamma ray, infrared, etc.) should be an integral part of the explorationist's toolbox, because integration of information from these data could be invaluable in prioritizing areas for deep exploration, particularly because these techniques are much less expensive than seismic.

Excellent stratigraphic trap possibilities exist on the flanks of some of the highs, but precise locations of these stratigraphic traps is only possible through high-resolution seismic data.

High-resolution two-dimensional seismic surveys may be conducted across some of the delineated good prospect areas, followed by high-resolution three-dimensional surveys if required.

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