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Status Report

INTEGRATED RESULTS OF GEOLOGICAL, GEOPHYSICAL, AND REMOTE SENSING INTERPRETATION OF BASIN EVOLUTION, LITHOSTRATIGRAPHY, AND PRESENT STRUCTURE WITHIN THE GREATER BLACK MESA REGION, NORTHEASTERN ARIZONA

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Bartlesville Project Office, Department of Energy

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TABLE OF CONTENTS

TABLES

FIGURES

1.0 INTRODUCTION

The U.S. Department of Energy (DOE) has instituted a basin-analysis study to encourage drilling by independent oil companies within the continental United States. The work is being performed at the National Institute for Petroleum and Energy Research (NIPER) by BDM-Oklahoma, the manager of the facility for DOE. The Black Mesa region in northeastern Arizona (Figure 1–1) was selected by DOE for the initial NIPER-BDM Exploration and Drilling Group survey to develop prospects in unexplored/underexplored basins in the lower 48 states. The Black Mesa Basin is significantly underexplored, with only six wells having been drilled in the deep, central portion of the basin on the 1.5 million–ac Hopi Reservation, and an additional six wells on the flanks of the area. The Hopi wells were all drilled during 1965, and none had any follow-up testing or subsequent offsets. The study area includes the topographic Black Mesa (the site of the ancestral Hopi lands) and the geologically contiguous surrounding potential reservoirs beneath the southwestern parts of the Colorado Plateau. Much of this latter area underlies Navajo tribal lands.

The BDM-Oklahoma exploration and drilling team began a basin analysis study of the greater Black Mesa Basin of northeastern Arizona during the summer of 1994. Six highly-prospective regions within this basin (Figure 1–2) were quickly identified as being suitable for more detailed study (Reeves and Carroll 1994; Quarterly Technical Progress Report, September 1–December 31, 1994, NIPER/BDM-0110). The selection criteria were based on the preliminary identification of areas with a high potential for commercial hydrocarbon reservoirs and accumulations.

1.1 The Greater Black Mesa Region

The greater Black Mesa region in northeastern Arizona (named for its centrally located, dominating topographic/geomorphic feature, the Black Mesa) includes a large basin and surrounding shelves and slopes, ringed by a series of structural highs. The area is dominated by a single, unified hydrodynamic regime. The study area has been defined as the structurally deep southwestern corner of the Colorado Plateau that is west, southwest, or south of a series of structural divides that extends from the Defiance Uplift, through the Tyende Saddle, the Monument Upwarp, and the Shonto Plateau and Kaibito Saddle, to the Grand Canyon. The southern and western limits of the study area are formed by the steep slopes and outcrops of the Mogollon Rim and the gorge of the lower Grand Canyon. The structural Black Mesa Basin, as defined, covers nearly one quarter of the state of Arizona.

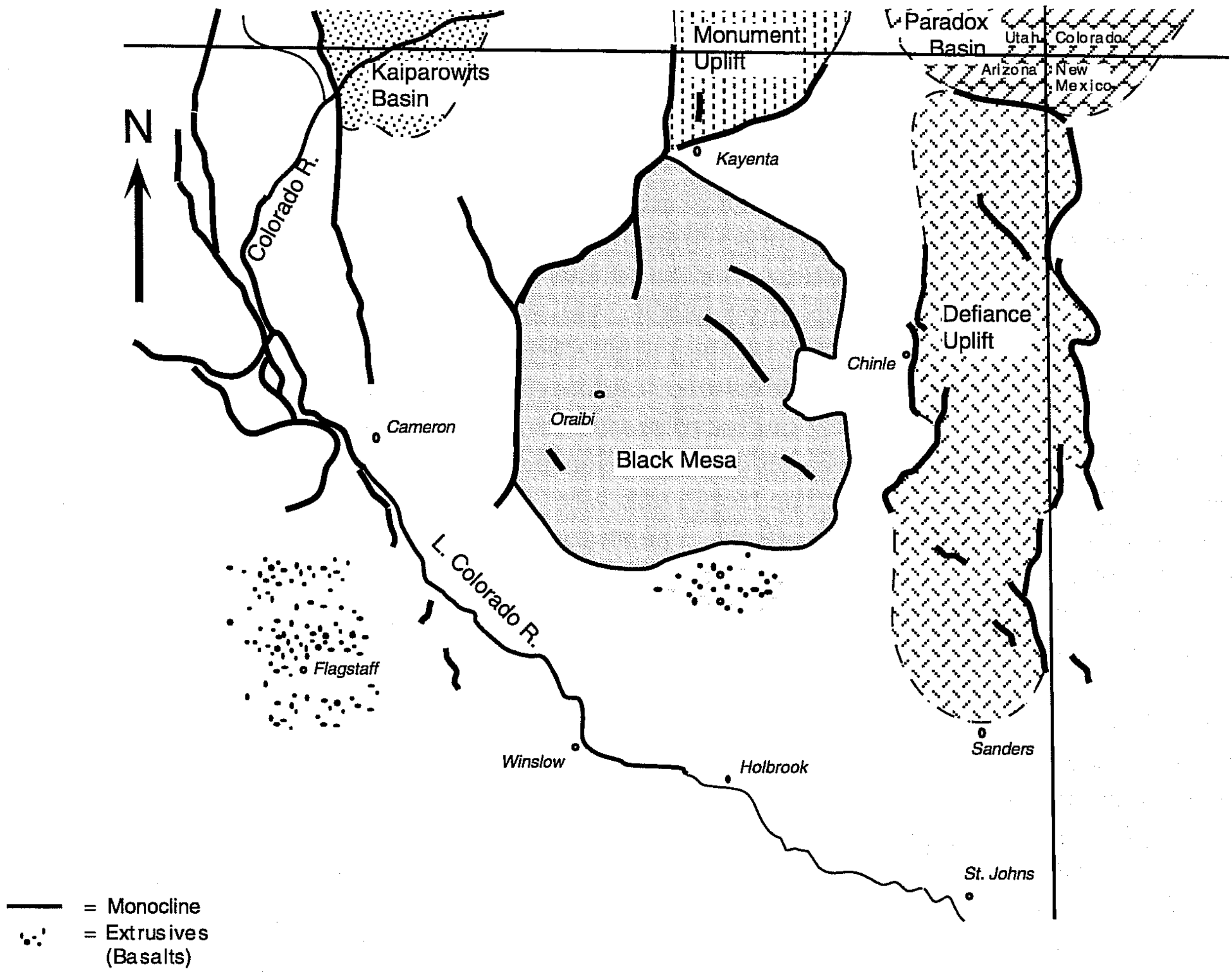

Figure 1–1 The Black Mesa Region in Northeastern Arizona

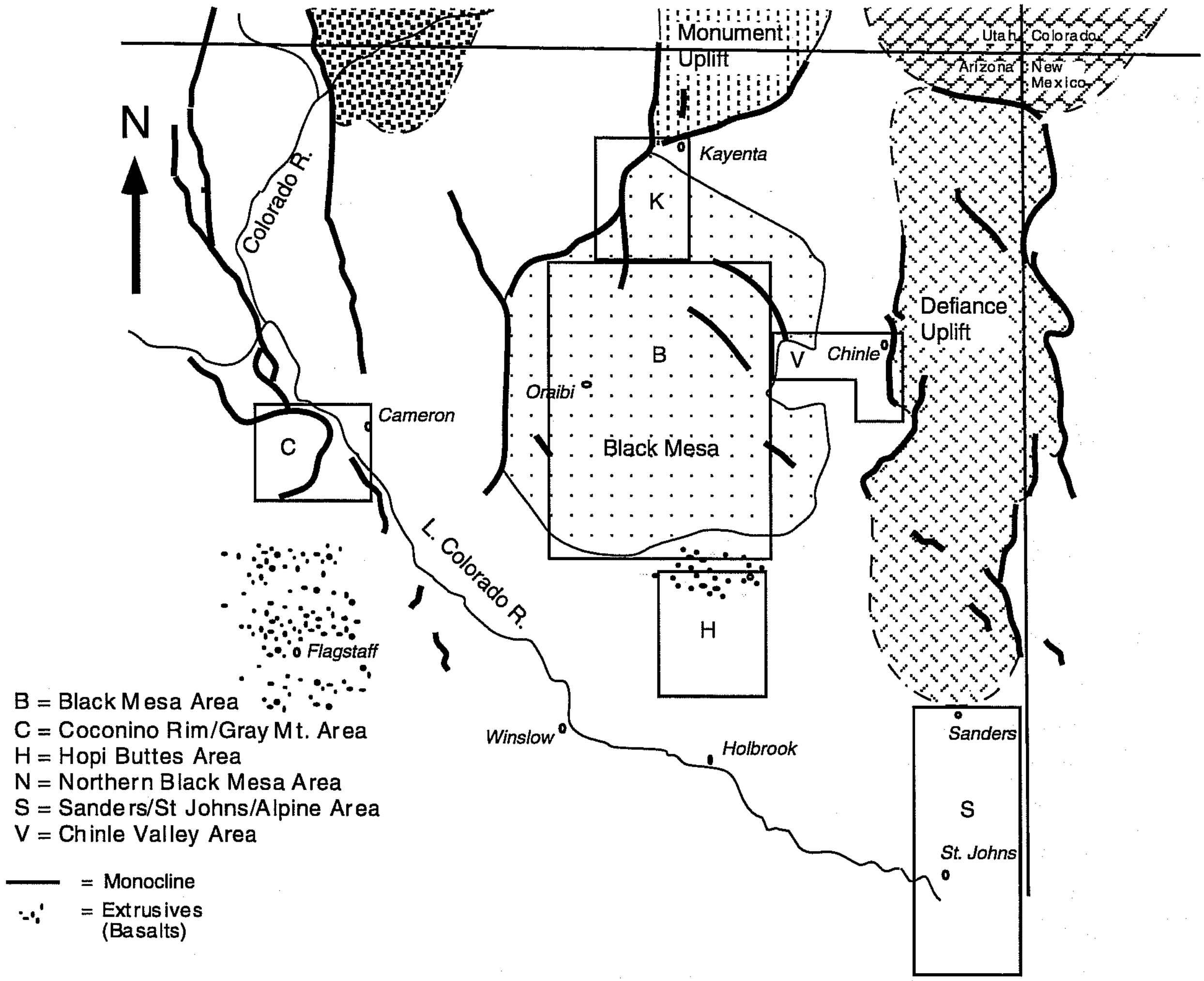

Figure 1–2 The Six Study Areas in the Black Mesa Region, Northeastern Arizona

1.2 The Six Study Areas

The study began with an orientation field trip and the comprehensive analysis of collected geological, geophysical, geochemical, and remote-sensing literature, data, maps, cross sections, and their interpretations. This early work led to the identification of six especially interesting areas that seem to hold high potential for hydrocarbon resources. The six target regions within the greater Black Mesa Basin are the following.

1. *The structurally deep, central portion of the Black Mesa Basin.* This area is generally coincident with the axis of the Oraibi Trough (a Devonian-age depression), the topographic Black Mesa, and the modern-day Hopi Indian Reservation
2. *The northern Black Mesa region.* This area is centered around the intersection of a complex of structures, including the Cow Springs, Comb Ridge, and Organ Rock Monoclines, plus several anticlines with significant closure. The prospect includes the northern boundary of the topographic Black Mesa Basin and Oraibi Trough, the southeast margin of the Shonto Plateau, and the southern tip of the Monument Uplift.
3. *The Chinle Valley region.* This prospect lies east of the Black Mesa. It forms the boundary between the Black Mesa and the Defiance Uplift, and is a region of rapidly changing dips and numerous stratigraphic pinch-outs. As at the northern Black Mesa, this is a margin of the basin and, possibly, of the Oraibi Trough.
4. *The Cameron–Coconino Rim–Gray Mountain area.* The Coconino Rim–Gray Mountain complex is another structurally complicated region, where several large monoclines intersect. The region forms a closed structural high on the Coconino Plateau, south of the Grand Canyon and west of the Black Mesa.
5. *The Hopi Buttes area.* This prospect is located south of the Black Mesa. The initial interest in this site was due to potential heating effects in an area of thin sedimentary cover above a basement high. The anticipated heating was due to a swarm of diatremes, intrusive volcanic rocks that might have helped to mature organic material in the thin sedimentary section and thus produce hydrocarbon reserves. The region ultimately proved to be of interest since it apparently lies along the southern margin of the Oraibi Trough.
6. *The Alpine-Sanders–St. Johns area.* A recent geothermal test, the Alpine Federal 1, on the Mogollon Slope, southeast of the Black Mesa and south of the Defiance Uplift, unexpectedly encountered several oil shows in a thin sedimentary cover over a shallow basement. This region is now receiving a large amount of attention in the press, from industry, and from other research institutes and agencies.

The reconnaissance field trip and a literature search produced additional information about the hydrocarbon potential in these prospect areas.

Most sedimentary units on the Colorado Plateau are relatively flat-lying, with few folds. The most significant shallow structural features in the Black Mesa region are a series of monoclines which overlie large faults in the basement. Reactivation of these deep-seated basement faults has strongly influenced the pattern of accumulation of several key potential source beds and reservoir sedimentary sections in the Black Mesa region. These faults have also controlled the location of most of the structures that have developed in the shallow sediments of the Black Mesa. For this reason, emphasis was placed on structural studies of the basement; on remote-sensing work, using aerial and satellite photography, to identify lineament and fracture trends; and on gravity and magnetic modeling of the area.

A remote-sensing study can be an especially useful tool in a region where basement movements have strongly influenced not just depositional and shallow structural patterns, but also where fractures may have offered migration pathways for hydrocarbons and where large quantities of hydrocarbons may be trapped in fractured reservoirs. The results of the fracture study have been reported in Guo and Carroll (1995).

The gravity and magnetic modeling of the basement beneath the Black Mesa region is of interest for an additional reason. The upper Precambrian section in northern Arizona and southern and central Utah includes an organic-rich, high-hydrocarbon potential, thermally mature, Upper Proterozoic sedimentary section that has attracted significant attention in recent years from research institutions and the petroleum industry. These prospective sediments are part of the Chuar group, a member of the Grand Canyon supergroup. The rocks are exposed and have been studied both in outcrop in side canyons west of the Colorado River opposite the entry point of the Little Colorado River into the Grand Canyon and from well samples. A section of dark mudstones and fine-grained clastics within the Chuar sediments have the requisite properties of good hydrocarbon source rocks. The Chuar beds are in the thermally mature oil window in Arizona, whereas to the north in Utah, the sediments are more deeply buried and presumably have reached the super-mature window for oil. The Utah section still has a high potential for natural gas generation in the areas of deeper burial.

2.0 HYDROCARBON POTENTIAL OF THE UPPER PROTEROZOIC CHUAR GROUP

An unusual organic-rich sequence, the Chuar, has been identified in the Precambrian section at the Grand Canyon and in southern Utah. The consideration of Precambrian rocks as potential source beds is unusual in the United States, although there are many locations in the former Eastern Block, China, and Australia where Precambrian oil has been documented, and oil is known in the Nonesuch shale at Lake Superior along the Mid-Continent Rift from beds that are contemporaneous with the upper Proterozoic deposits of Arizona. The interest in Precambrian sediments between the deep metamorphic and igneous basement and the Paleozoic cover led to the determination that gravity and magnetic studies and mapping would be of particular value in the Black Mesa area.

The Chuar was named by Walcott (1883), who recognized that the sediments contained fossils (1899), but the rocks of the group were little studied during the early part of this century due to their relative inaccessibility. The Museum of Northern Arizona sponsored a helicopter expedition to the upper reaches of some of the tributary canyons of the Grand Canyon in 1966 to perform the most extensive, systematic study of the Chuar to that date. Ford and Breed (1969, 1972a, b, 1973a, b, 1974a–c, 1975) and Ford (1990) subsequently published several landmark articles concerning the Chuar, renewing interest in the formation and making note of the fossil remains contained within these ancient beds.

Although Ford and Breed called attention to the fact that the Chuar sequence included stromatolitic reefs and other biologic remains, this was considered at the time to be of interest primarily to paleontologists. The Chuar was still ignored by the petroleum industry. Elston began work in the region of the Grand Canyon during the 1970s. By himself and in combination with several collaborators (Elston and Scott 1973, 1976; Elston and Gromme 1974a, b; Elston and Bressler 1977; Elston 1979, 1986, 1989a, b; Elston and McKee 1982;), he expanded on the earlier work and produced a significant series of studies and articles. Elston was tapped by the Geologic Society of America to write the Chuar section for the Decade of North American Geology (DNAG) (Elston 1993).

New studies and sampling, conducted in the late 1980s and early 1990s and led by Reynolds and/or Palacas, along with Elston and other associates (Chidsey et al. 1990; Palacas and Reynolds 1989; Palacas 1992, 1993; Pawlewicz and Palacas 1992; Reynolds and Elston 1986; Reynolds and Palacas 1988; Reynolds et al. 1988, 1989), demonstrated that the Chuar included potential hydrocarbon source beds in both Arizona and Utah. This finally attracted the attention of industry.

The quality and accuracy of the information on the Chuar has improved steadily since the Museum of Northern Arizona expedition in 1966. The Chuar group was remeasured during the 1966 field work and reported by Ford and Breed (1973a) as being 6,610 ft (2,013 m) thick in the eastern Grand Canyon. Elston (1979) and Elston and McKee (1982) removed the Sixtymile Formation from the Chuar and reassigned it to independent formation status (Figure 2–1). During the mid-1980s, Reynolds and/or Palacas and a series of collaborators took an interest in the Chuar, with members of the team going back to the field to collect samples for laboratory tests. While in the field, they continued to redescribe portions of the Chuar, remeasuring or recalculating new values for the formation thicknesses. Elston in the DNAG volume (1993) used a number of 5,500 ft (1,676 m), referencing Reynolds and Elston (1986) and personal communication with Reynolds (1988), as the definitive value for the Chuar thickness. Table 2–1 is adapted from the DNAG volume (Elston 1993).

Reynolds et al. (1988, 1989) noted that more than half of the Chuar sequence consists of organic-rich, gray to black mudstones and siltstones with common to abundant microfossils, interbedded with stromatolites and algal-rich carbonates. Palacas and Reynolds (1989) listed the Walcott Member as a good to excellent petroleum source rock, but they listed the Awatubi and Galeros as having a better potential (in general) as a source for natural gas than for oil, although they recognized selected beds within the Awatubi and Galeros that could have generated significant quantities of oil.

It has long been assumed that the Chuar shales were marine or coastal tidal flat in origin. The environment of deposition for these units was exceedingly quiet and persisted for a prolonged period (Elston 1993). It is clear that water depths were shallow, with well-oxygenated surface waters but reducing conditions at the sediment surface. The work by Reynolds, Palacas, and various coresearchers, and by Winston (1990) has suggested that these beds were, at least in part, deposited in intra-cratonic lacustrine or fluvial settings (Figure 2–2). Ford (1990) acknowledged some of the early work of Reynolds and Elston (1986) and described sedimentary features in the various members of the Chuar.

Ford (1990) described the Tanner as having no identified primary sedimentary structures. He listed this unit as having accumulated in a starved basin with a rich organic content. This description could fit an intra-cratonic sag or rift setting, although Elston (1993) pointed out that there should be identifiable stream deposits along the margins of such a setting, and these deposits have not been found. The Jupiter, above the Tanner, includes stromatolitic limestones at the base, becoming shalier upward. Ripple marks, mudcracks, and raindrop impressions are occasionally found in coarser grained interbeds in the Jupiter. This unit has been interpreted as a shallow-water coastal or alluvial plain deposit. The Carbon Canyon consists of interbedded, thin carbonate, shale, and sandstone beds. Stromatolites occur in the carbonates, and mudcracks are seen in the sandstones. These rocks could be a coastal or swamp deposit. The Duppa Member is predominantly an accumulation of shale, with minor limestones. Ford (1990) described this as an alluvial plain deposit.

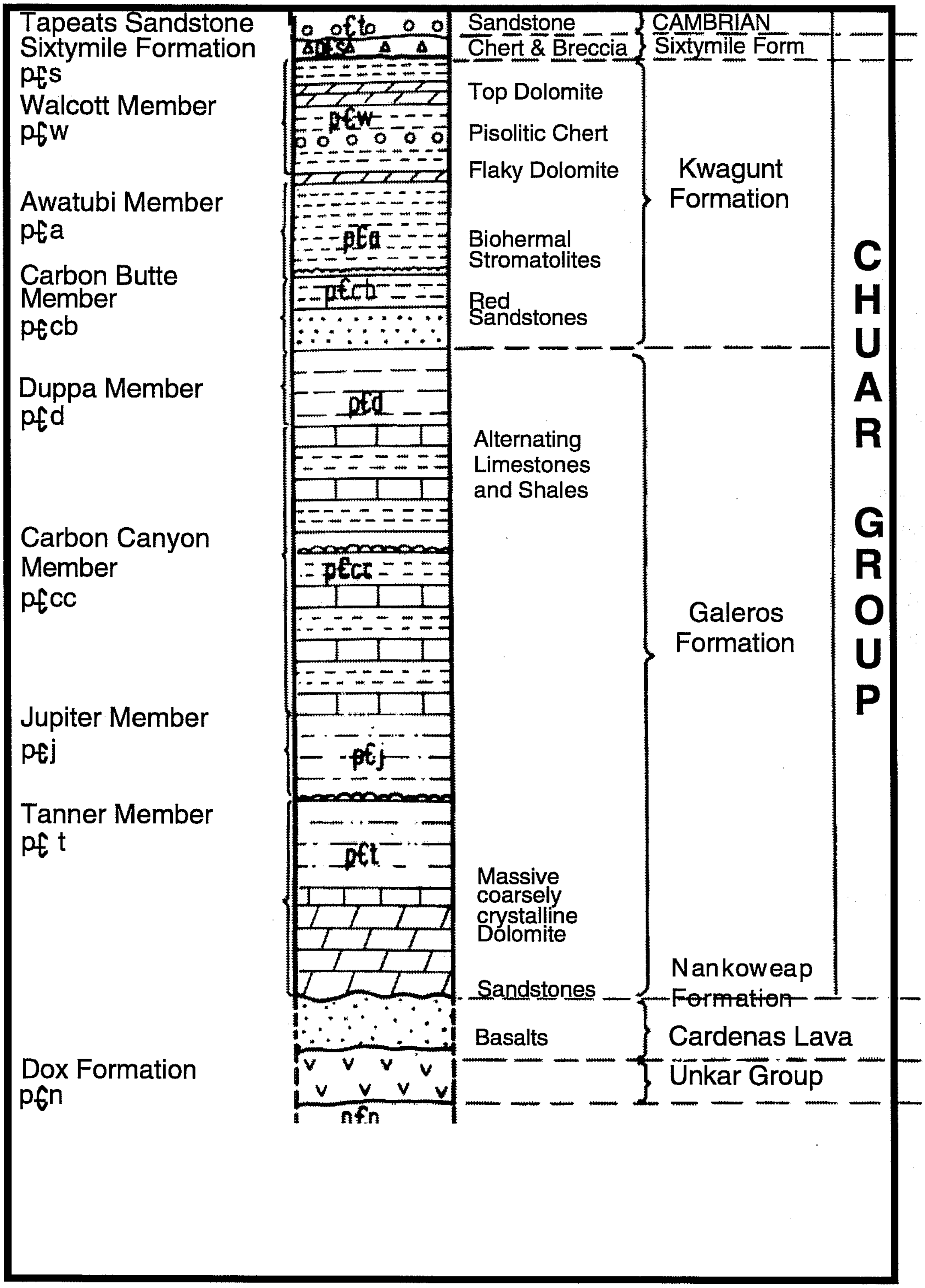

Figure 2–1 Chuar Stratigraphic Column

Table 2–1 Thickness and Setting of the Chuar Group

Stratigraphic Unit and Unconformities	Age or Thickness (m)	Environment of Deposition of Formation Members
	Phanerozoic	
	"Great Unconformity"	
	Late Proterozoic	
Grand Canyon Supergroup	3,623+	
Sixtymile Formation	59–64 +	
Upper and Middle Members	37+	Fluvial, Lacustrine?
	Unconformity	
Lower Member	22–27+	Marine/Subaerial
Chuar Group	1,676	
Kwagunt Formation	632	
Walcott Member	281	Marine or Lacustrine
Awatubi Member	301	Tidal Flat, Marine, or Lacustrine
Carbon Butte Member	50	Subaerial, Fluvial
Galeros Formation	1,044	
Duppa Member	104	Marine or Lacustrine
Carbon Canyon Member	350	Marine or Lacustrine
Jupiter Member	434	Tidal Flat/Lacustrine or Marine
Tanner Member	156	Marine/Marine or Lacustrine
	Unconformity	
	Middle Proterozoic	
Nankoweap Formation	113–250 +	
Unkar Group	1,775	
	"Greatest Unconformity"	
	Early Proterozoic	

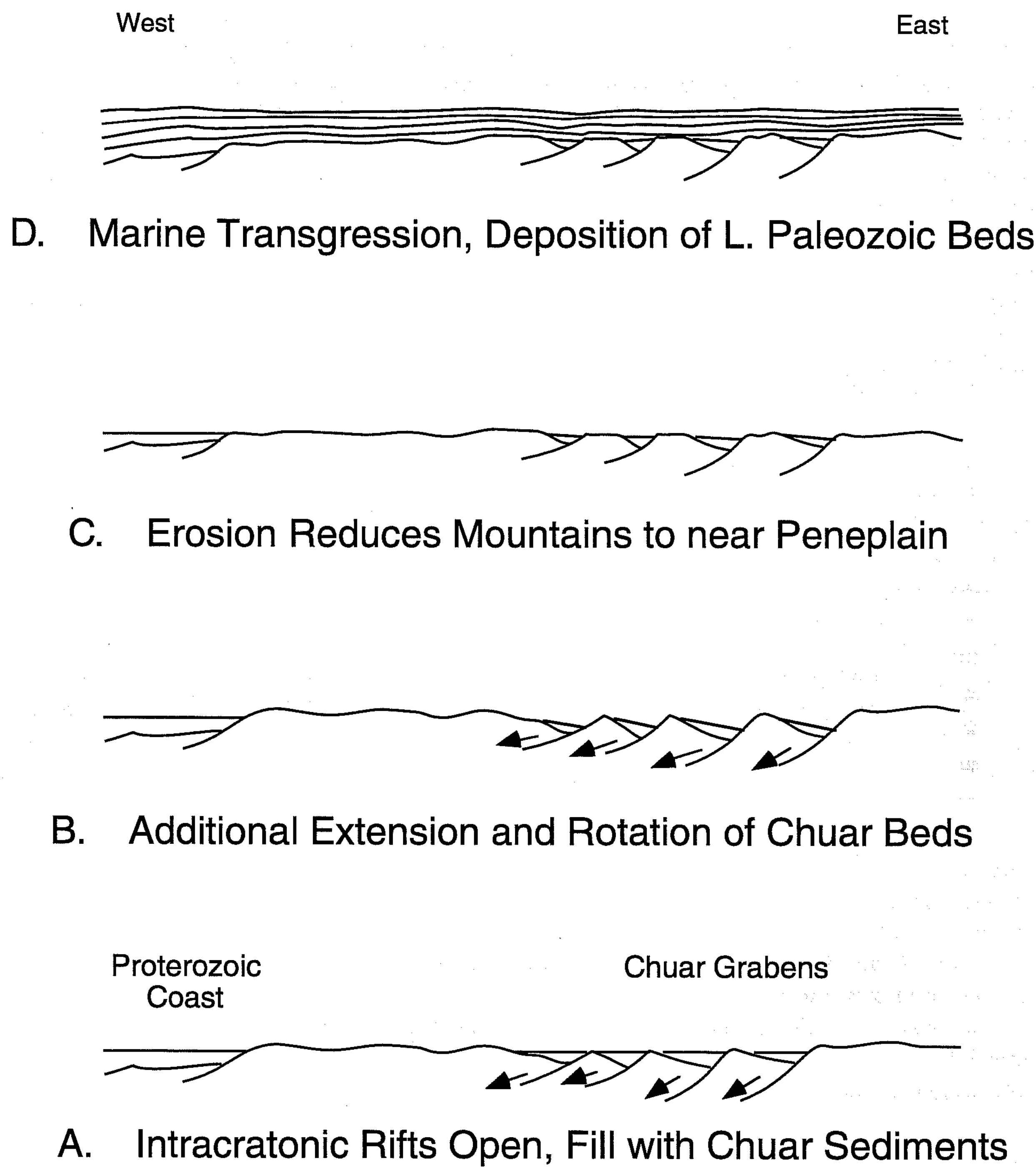

Figure 2–2 Tectonic Setting of the Chuar Group

Within the Kwagunt Formation, the Carbon Butte Member is distinguished by a thick sandstone at its base, the only thick sandstone in the entire Chuar Group. Cross-bedding and mudcracks developed within this sandstone. The upper portions of the Carbon Butte are largely mudstones. The overlying Awatubi Member is predominantly shales and mudstones. The Awatubi includes a 12-ft thick, massive stromatolitic layer, with numerous 8- to 10-ft biohermal domes. The uppermost unit of the Kwagunt is the Walcott Member. The Walcott includes dolomites, including algal remains and oolites, which could indicate a well-lit, energetic, oxygenated environment in the surface and near-surface waters in which primitive lifeforms could flourish. Black shales are also common in the member. The sediment color and structure indicate that bottom conditions included a reducing environment. This combination of conditions are frequently found in rift settings. Elston (1993) discussed the depositional setting of the Chuar briefly, and concluded that further study was required.

Just as additional work has refined the thickness information for the Chuar, the accuracy of the value for the organic content of the formation has been improving. Reynolds et al. (1988, 1989) reported a 5% total organic carbon (TOC), a hydrogen index (HI) of 190 mg HC/g TOC, and a genetic potential ($S_1 + S_2$) as high as 6 kg/ton (6,000 ppm). With additional testing, Palacas and Reynolds (1989) found samples with numbers as high as 7% TOC (averaging about 3% TOC), an HI as high as 204 mg HC/g TOC (averaging 135 mg HC/g TOC), and a genetic potential of nearly 16,000 ppm (averaging about 6,000 ppm) for the lower Walcott. Rauzi (1990), citing a 1989 personal communication with Palacas , upgraded the TOC for the Walcott to as high as 8%. Reynolds et al. (1988, 1989) determined a Rock-Eval T_{max} of 430–440° Celsius, indicating that the Chuar is thermally mature and within the principal oil-generation window.

Summons et al. (1988) confirmed that the organic material in the Chuar is in situ and has not migrated in from younger, outside sources. They also demonstrated that the organic content has not been significantly degraded from weathering, despite the great age of the rocks. The rocks fall into the mature region of the Van Krevelen diagram, and the original material includes both type I and type II kerogen. On a regional structural basis, the depths of burial and paleothermometry indicate that although the northern Arizona region falls within the oil window, portions of Utah, well to the north, may have reached the natural gas window. Rauzi (1989, 1990) did much to publicize the potential for hydrocarbons within or sourced from the basement, and concluded that the Chuar has a high potential for hydrocarbon prospecting.

Rauzi (1989, 1990) suggested that Chuar sediments may be preserved in a series of half grabens over a broad area of north-central Arizona and southern Utah north of the Mesa Butte Fault and west of the Organ Rock Monocline, with particularly thick sections being preserved beneath the Kaibab, Kaibito, and Shonto Plateaus. Rauzi stated, however, that there is little possibility of the Chuar having been deposited and surviving in the region beneath the topographic Black Mesa. This view is still open to investigation and reinterpretation. Various reports in the literature suggest that Precambrian sediments may be preserved in outcrops as far to the east as the Defiance Uplift. Much more work remains to be done on the extent of preservation of the Chuar beneath northeastern Arizona.

The Chuar Group is a prime potential candidate for hydrocarbon source rock and possible reservoirs under northern Arizona, especially in the western part of the study area. The beds may extend as far east as the structural Black Mesa basin, and beyond. Lineament and fracture studies provide clues to the possible locations of faults bounding the blocks where Chuar might be preserved. Gravity and magnetic studies provide clues to the lithologic nature of the basement fault blocks and to a large number of intra-basement and shallow intrusive igneous rocks.

Recognizing the importance of the Proterozoic sediments, it was determined that an effort should be made to identify areas east of the Grand Canyon where a Chuar or Chuar-like section might be preserved beneath the Paleozoic and Mesozoic cover. To this end, computer modeling of available geophysical data was initiated. The modeling process combined available stratigraphic, gravity, and magnetic data to formulate an interpretation of the deeper subsurface structures. The model suggests that several ancient, intrabasement grabens or half grabens may lie beneath the Phanerozoic sedimentary cover in the Black Mesa region. These half grabens may preserve sizable blocks of organic-rich Precambrian mudstones and clastic sediments which may be fertile targets for oil exploration.

3.0 DRILLING HISTORY IN THE REGION SURROUNDING THE BLACK MESA

Drilling density in the greater Black Mesa basin region is very low (Pierce and Scurlock 1972; Dwight's 1995; Gautier et al. 1995). Coverage in the basin as a whole is one well per 185 square miles. This value somewhat overstates the actual rate of testing in the central basin area, however, since it includes the wells in several productive oil fields, where the drilling density is relatively high. However, even in the productive area of northeasternmost Arizona where there are several oil fields, the wells are widely spaced, compared to most productive areas, with only one well per six to seven square miles (Gautier et al. 1995). When the concentration of wells in the oil fields is discounted, the well density in the remainder of the basin is approximately one well per 420 square miles. The basin has been overlooked by oil exploration companies primarily due to difficulties of access and leasing, not because of unsatisfactory geologic conditions or a lack of shows.

3.1 Description of the Region

Much of the Four Corners area remains "remote," in oil industry terms, even today, with northeastern Arizona and southeastern Utah being the most remote. The first white settlement in the region (in southwestern Colorado) was not founded until 1873 (Matheny 1964). The Four Corners area did not really open up commercially until the Denver and Rio Grande Railroad reached northwestern New Mexico in 1905. Even today, the population in northeasternmost Arizona is minimal. About 98% of northeastern Arizona, and virtually all of the Black Mesa basin, is held by the Hopi or Navajo Nations or by the Federal Government as public, park, or monument land. Northeastern Arizona has traditionally been considered to be too rugged and too remote to be of interest to local or outside interests for industry or for drilling. Land disputes and similar factors have inhibited leasing in the region during the last few decades.

Only one railroad crosses northeastern Arizona near the Black Mesa region, and it lies well to the south of the prime, most-prospective, deep portion of the Black Mesa basin. Railroad lands have played a key role in oil exploration in much of the western United States, where huge blocks of land are mountainous and difficult to reach. Railroads have generally been built on relatively flat, easy-to-reach land. The oil industry tends to favor these same lands due to the low relief and concomitant ability to move around, because of economic incentives from the government and/or from the railroad companies to develop the land, and due to the ability to export their product easily by rail.

The railroad in northeastern Arizona follows the low, flat lands of the Little Colorado River drainage, well south of the Navajo and Hopi reservations. A band of wells has been drilled over the years following the railroad route. Drilling has become quite dense around Holbrook, Arizona, the largest town in the area. The discovery of helium in sediments on the Pinta Dome, northeast of Holbrook, also led to a cluster of wells in that area. The topography of the Little Colorado River plain has made drilling relatively easy, but the results, in oil prospecting terms, have been poor, as would be expected, due to a generally unfavorable structural geologic setting for hydrocarbon generation. Much of this area is underlain by a Precambrian basement high, the ancient Defiance-Zuni positive feature, above which the Paleozoic sedimentary column thins dramatically. Few conventionally recognized potential source beds exist in this region.

This Defiance-Zuni high has formed a structurally positive feature throughout most of the Phanerozoic. The helium on the Pinta Dome apparently is sourced from deep within the basement (Turner 1968), or even the mantle, and its leakage into the shallow sediments probably is due to fundamental structural characteristics, including major fault zones that extend to great depths. Although the structural framework associated with the dome has favored the leakage and entrapment of helium, it apparently has not been favorable for the production of oil in this region. Many of the prime potential source beds in the lower Paleozoic section of northern Arizona were never deposited in this area. The upper Paleozoic sedimentary section has relatively little source rock potential, according to conventional interpretations, and relatively thin reservoir beds on a regional scale, although small shows and local production may be found from these units. Thus, the subsurface geology in this region apparently has long been unfavorable for the generation of large, commercial quantities of hydrocarbons or their entrapment on the high. It must be pointed out, however, that shows and production at several well locations on similar nearby shallow-basement structures (i.e., the Defiance Uplift and southern Mogollon Slope) indicate that industry geologists still have much to learn about the habitat of oil in Arizona.

3.2 Factors Affecting Hydrocarbon Exploration in Northeastern Arizona

Unfortunately, the large amount of drilling along the shallow-basement trend has provided a sizable quantity of data which can easily be misinterpreted. These data have sometimes been taken as being representative of all of northeastern Arizona, suggesting that the entire region is lacking in source bed material with a thin Paleozoic sedimentary section. The few deep wells in the central Black Mesa region (Pierce and Scurlock 1972; Dwight's 1995) have shown that a promising lower and middle Paleozoic section exists just to the north of the densely drilled rail corridor. The general lack or thinness of Cambrian and Devonian beds in most of the wells along the railroad means that petroleum explorationists have extremely limited information on many of the most important formations in the region. The standard well databases for northern Arizona (Pierce and Scurlock 1972; Dwight's 1995; Gautier et al. 1995) do not provide the amount of information oil companies want before they become comfortable with a prospect. Oil companies doing a quick survey, or even a detailed study of the region, have tended to be misled or impeded by the lack of crucial data.

The basement surface rapidly drops 4,000 ft from the highly drilled railroad lands and the area around Holbrook to the region of the Hopi towns to the north, in the central basin–Oraibi Trough region (Pierce and Scurlock 1972; Dwight's 1995). This major break in the basement relief is quite ancient. It apparently led to abrupt changes in water depth and environments of deposition between the Defiance-Zuni structural high and the deeper water area to the north. There are many facies changes in the lower Paleozoic section that have not been documented in well cuttings or on outcrop. Prime prospecting targets for the Black Mesa basin include stratigraphic pinch-outs and fracture zones in areas along the basin margin. The subtleties of structure and stratigraphy in the deep basin are almost total unknown. A primary factor that has inhibited development of the Black Mesa region has been a lack of information on key sediments in the deeper portion of the basin.

A second problem has been ready access to the region. Throughout most of its history, drilling in the Four Corners region has been closely tied to lands that were open, in a commercial sense, with simple land titles and easy physical access. For decades, northeastern Arizona was lacking in highways. Route 66 was the only major highway that passed near the Native American lands of the Four Corners. The first two major paved roads that were built across the reservations were not constructed until the 1950s. The railroads have always been interested in adding value to their extensive land holdings by proving up potentially valuable mineral and hydrocarbon resources on their properties. Unfortunately, as discussed above, the railroad in northeastern Arizona passes through an area with little oil potential. In the last few years, with the opening and expansion of commercial coal operations at the northern Black Mesa, additional roads have been opened or improved, and access to the Black Mesa has become relatively easy.

A third significant factor affecting development in northeastern Arizona has been the leasing picture and land titles in the region. Oil drilling in the Four Corners region has traditionally progressed most rapidly on privately owned lands. There was little drilling in the early decades of this century on Native American lands. There were several reasons for this. Firstly, the lands that had been relegated to the Native Americans tended to be remote and hard to reach, under the best of conditions. In cases where industry was interested in drilling on specific Native American lands, there have been numerous impediments, ranging from protected lands in parks or monuments, to legal suits, to development moratoria. The paperwork associated with work on Native American lands has traditionally been much greater than that required for drilling on private tracts.

3.3 Drilling on Native American Lands

Conversations with representatives of the Hopi Nation, the Navajo Nation Minerals Department, and university and industry personnel in Flagstaff provided a number of insights into the history of oil development in northeastern Arizona and the surrounding area. The first major breakthroughs for oil drilling on Native American lands came in the 1950s. As Table 3-1 (based on data in Schicktanz 1963) demonstrates, there was an explosion of drilling on Navajo lands during that decade.

Table 3–1 Drilling on Navajo Lands, 1950–1960

Year	Number of Wells	Annual Production (bbl)	Annual Royalty
1950	51	133,000	$42,000
1956	54	354,000	not available
1960	860	34,273,000	$8,835,000

The great change was brought about through a major leasing program that began in 1957 (Schicktanz 1963). As drilling took place, and royalty checks grew from a few tens of thousands to millions of dollars, the Navajo Nation came to appreciate the value of oil to the tribe. A Navajo Nation oil company has now been organized to encourage additional development. Although there has been a substantial growth in drilling on Navajo lands since mid-century, even in the 1990s few wells have been drilled on the Navajo reservation in northeastern Arizona (Pierce and Scurlock 1972; Dwight's 1995; Gautier et al. 1995). Most of the existing Navajo wells are located in the states surrounding Arizona.

There has been much less activity on the Hopi reservation. Smith and Carpenter (1955) pointed out that the Hopi could realize considerable revenue from oil leasing, if they were willing, but what they called the "tribal religion" prohibited the tribe from offering acreage. Following the highly productive results of the Navajo leasing program of 1957, Washington, without any consideration for Hopi religious feeling, decided in 1961 to put Hopi lands up for bid. The arrangements for this were not be completed until 1964. Because of the successes on Navajo lands nearby, there was extensive interest in the industry. The minimum bids were set so high that they almost totally discouraged smaller, local companies from participation and significantly cooled local interest in the leases. A few major oil companies did submit winning bids, but they held the results of their exploration confidential for a prolonged period, further dampening potential participation in the region by independent companies.

In 1965, six wells were drilled on the Hopi reservation and an few additional wells on surrounding lands near the Black Mesa (Pierce and Scurlock 1972; Dwight's 1995; Gautier et al. 1995). These have been the only deep tests in this central structural-basin area to the present day. Several of the wells had promising shows, and drill-stem testing was done (Pierce and Scurlock 1972; Dwight's 1995), but none of the wells were ever completed. With the data from the Hopi wells having been kept tight for an extended period of time, other companies eventually lost interest in the wells.

In 1966, the year following the drilling of the Hopi wells, a large coal mine on the northern portion of the Black Mesa was opened by the Peabody Corporation. The inevitable disruptions of the land around the mine and of local water supplies were very upsetting to the Hopi residents of the mesa. At exactly the same period, long-standing land disputes over reservation boundaries between the Hopi and Navajo flared up again (Barwin 1971). Legal suits were filed between the Hopi and the Navajo, and even between Hopi factions and the Hopi Tribal Council over the right of the tribal council to grant leases and responsibilities for protecting the land. These legal problems, which moved in and out of court throughout the late 1960s and 1970s, inhibited oil companies from following up on the 1965 programs. Recently, many of these legal questions have been resolved, offering renewed opportunities for cooperation with the two Native American nations in the Black Mesa region.

3.4 Early Drilling in the Four Corners Area

Even on non–Native American, non-government lands in the Four Corners area, the oil industry has developed slowly. Persistence has been necessary to establish production footholds in the basins of Utah, southwestern Colorado, and New Mexico that surround the Black Mesa region. Early exploration and drilling results in all of these states were poor. The fact that production was eventually established in the San Juan, Paradox, and Kaiparowits basins, all around Black Mesa on the Colorado Plateau, demonstrates the importance of such perseverance in exploratory areas where available data is nonexistent or minimal.

Mexican Hat field was discovered on March 4, 1908 in the deep portion of the Paradox Basin in southeastern Utah just northeast of the Black Mesa basin. This field has been extensively reported on (Gregory 1909, 1917, 1938; Woodruff 1912; Wengerd,1951, 1955; Borden 1952; Wengerd and Strickland 1954; Kunkel 1961; Matheny 1964; Huber 1973). Development drilling continued at Mexican Hat at least into the 1970s but, elsewhere in the basin, no successful wells were completed for almost 50 years. Exploratory drilling looking for similar plays was pursued elsewhere in the Paradox region, and tens of dry holes were drilled in what had seemed to be prime locations in a futile search for oil (Gautier et al. 1995).

Eventually, a small oil pool was discovered in 1954 in the Paradox basin at Desert Creek (Spalding, 1955; Carter, 1958). This was followed by the discovery by Texaco in February 1956 of the much larger Aneth field in San Juan County, Utah (Matheny, 1964; Gautier et al. 1995). This discovery led to the development of a new model of the geology and production in the area. Once geologists understood this model of basin-margin reefs, drilling surged, and a string of fields was discovered and developed in southeastern Utah. Within 18 months, there were 28 seismic crews and 105 drilling rigs active in the region (Carter 1958). Within a two-year period, ten new fields had been discovered with more than 2,000 producing wells and 32,000 ac "proved" (Carter, 1958). The Paradox Basin now has widespread production.

Exploration in the nearby Kaiparowits basin, also in Utah and northwest of the Black Mesa, began in 1921 with a well drilled by the Ohio Company. An intermittent exploratory program continued over the next several decades (Gautier et al. 1995). Twenty-seven dry holes were drilled in the deep portion of the basin before the initial hydrocarbon discovery. The first producing well in the Kaiparowits basin was completed in 1964 (Campbell 1969; Kornfeld, 1964).

The San Juan Basin, east of the Black Mesa region, has similar stratigraphic units to the Black Mesa and has had a similar geologic history, but this basin has been much more open to development during this century (Gautier et al. 1995) because much of the land is privately held. In addition, the deep portion of the basin has been accessible by rail since 1905 (Matheny 1964). Drilling began early in this region, with numerous wells being drilled near many of the local towns (Gautier et al. 1995). The first oil discovery well in the San Juan Basin was drilled in 1911, just six years after the completion of the railroad. By 1925, there were 40 productive wells in the area (Gautier et al. 1995).

In contrast to the surrounding basins, the population in the San Juan basin was large enough to provide a local market for hydrocarbons. Natural gas distribution systems were installed soon after the first successful gas wells were drilled, supplying local towns (Matheny 1964). In addition, several small refineries were built in the early years of the industry to service local oil production. Even with this active local drilling industry, extensive production was not established until a larger market became available. Washington approved the construction of a large pipeline system through the basin in 1950. Following approval of this pipeline, the drilling rate in the San Juan Basin went from 47 wells in 1949 to 267 wells in 1951, even though the pipeline had not yet been constructed. It was the growth of the petroleum industry in this region and the identification of prime prospects on reservation lands that prompted early tests on the Navajo lands and the eventual growth of the Navajo Nation oil company.

3.5 Future Drilling Potential in the Four Corners Area

Development drilling followed the early discovery wells in each of the basins surrounding the Black Mesa. With better geologic understanding came an improvement in well-success ratios in the states surrounding Arizona. Improved success ratios and good payouts encouraged additional successful drilling in many difficult-to-reach areas in Utah, Colorado, and New Mexico (Gautier et al. 1995). Each of these basins today is known to be productive, but this production was only established after extensive testing and a very high percentage of dry holes. The type of concerted drilling necessary for prolonged success has never taken place in the prime deep-basin region of Arizona.

To date, only six deep exploratory oil wells have been drilled on the prime Hopi lands. These six wells were all drilled during 1965. Oil shows were recorded in most of these wells (Pierce and Scurlock 1972; Dwight's 1995). In the Amerada Hess 1 Hopi-5075, east of Oraibi, good oil shows were recorded at three different stratigraphic levels. There was no follow-on work conducted in the region (Gautier et al. 1995). A similar number of wells were drilled during the same period in the area immediately surrounding the Black Mesa in the deeper portions of the Oraibi Trough play. This is far fewer than the number of wells necessary to adequately evaluate, learn about, and test an area of this size.

The potential for oil production abounds in northeastern Arizona, especially in the deepest portion of the basin where there may be thick source beds in the lower Paleozoic section (Pierce and Scurlock 1972; Dwight's 1995). Quality reservoirs should exist in deeper basin sandstones, along closed structures in the northern and western portions of the basin, and in stratigraphic pinch-outs along the steeper slopes on the basin margins. Well-developed fracture trends, with associated porosity and permeability, may have been produced above reactivated basement-fault trends (Kelley 1955; Davis 1975) and along the knee areas of local monoclines. In the shallower section, there is the potential for a number of small reef plays. Very little seismic work has been done in the Black Mesa region. The combination of small reefs and stratigraphic pinch-outs should lend itself to identification with 3D seismic surveys.

4.0 STUDY APPROACHES

Well tops and log data for the Black Mesa were gathered, but proved to be of limited value. With large distances between wells and rapid lithologic changes along reactivated basement fault trends, many correlation problems exist in the region. Discussions with geologists who previously worked the Black Mesa region revealed widely varying opinions as to the accuracy of logs, sample studies, and descriptions in the region. Many of these experts noted frequent errors and miscorrelations on logs and in databases in the Black Mesa region. Even normally easy-to-identify tops like the Precambrian are questionable in some of the logs and sample descriptions that were reviewed. Abrupt changes in reported formation thicknesses (Pierce and Scurlock 1972; Dwight's 1995; Gautier et al. 1995), in the lower Paleozoic section between closely spaced wells can be accurate if they are due to high relief on the Precambrian erosional surface, but they also may reflect differences of opinion as to standards for formation identification in a significantly underdrilled, poorly understood sedimentary section. Additional drilling in the Black Mesa region will probably demonstrate a need for refinement of the standard correlation charts for the area and for revision of many of the old geologic interpretations.

Core samples allow the only available direct look at the rocks beneath the Black Mesa region. Plans had been made to conduct thermal-maturity studies of some of these samples. Of special interest were cores from potential source beds in the basin. Few cores had been collected during the drilling of the 1960s wells in the Black Mesa region, however, and the prime target for core collection had been potential reservoir units, not the source rocks. Based on contacts with industry, it was determined that all or most of the few cores that were collected have been dumped over the years and are not available today for geological examination and geochemical sampling. As a result, the exploration effort has had to be redirected to concentrate on indirect techniques and surface methods such as gravimetric, magnetic, seismic, remote sensing, and direct and indirect surface geochemical surveys of hydrocarbon leakage, and on outcrop sampling for geochemical analyses of organics and thermal maturity.

Early analysis of the region suggested that six areas were of special interest to the study. The locations of the six prospective areas are shown in Figure 1–2. The rationale for the designation of each of these areas and a brief discussion of their characteristics is given below.

4.1 Central Black Mesa

The surface and mineral rights for the much of the topographic Black Mesa belong to the Hopi Nation and are administered by the Hopi Tribal Council in Kykotsmovi (shown on many maps as New Oraibi), Arizona. The main Hopi towns are located on the crest of cliffs in the southern and central portions of the mesa and on the immediately surrounding plains. The largely unpopulated, even more rugged northeastern portion of the mesa was allocated by the federal government to the Navajo Nation during a series of land disputes between the tribes. This land is administered by the Navajo Tribal Council in Window Rock, Arizona.

4.1.1 Morphology

The thickness of the sedimentary section above the Precambrian basement varies greatly across the area. Closely-spaced wells drilled to the basement in some of the oil fields in the Four Corners vicinity (Pierce and Scurlock 1972; Dwight's 1995) plus exposures at the Grand Canyon and around the Mogollon Rim reveal that the erosion surface which had formed on the Precambrian landscape was quite rugged in places as the Cambrian Period began.

Typical depths to the basement on the Defiance Uplift, east of the Black Mesa, vary from zero to more than 3,000 ft. In the Four Corners–Tyende Saddle area, the basement is generally between 5,500 and 6,500 ft in depth (Pierce and Scurlock 1972; Dwight's 1995). The Coconino Plateau, west of the Black Mesa, is a very large area with few deep wells (Heylmun 1990), but the basement depth averages between 3,400 and 3,700 ft here. Additional data in this region can be expected to reveal more variation and significant local relief on the Precambrian. South of the Black Mesa, the basement depth is typically between 3,300 and 3,900 ft (Pierce and Scurlock 1972; Dwight's 1995) in an area of extensive drilling around the town of Holbrook (Gautier et al. 1995). This deepens to the southeast, toward St. Johns, to depths of more than 4,400 ft, then rises again toward the Mogollon Rim (Pierce and Scurlock 1972; Dwight's 1995). The thickest sedimentary section in northeastern Arizona has accumulated in the central Black Mesa region (Kornfeld 1963; Lessentine 1965) along the axis of the Paleozoic sag known as the Oraibi trough (Pierce and Scurlock 1972; Dwight's 1995). The basement depths here generally exceed 7,000 ft, reaching a maximum of 7,760 ft in one of the Hopi wells at the topographic Black Mesa (Figure 4–1).

This thick accumulation of sediments in the Oraibi Trough appears to offer excellent opportunities for the development of source beds (Kashfi, 1983), reservoirs, trapping structures, and seals. The Devonian section in this part of Arizona includes several hundred feet of shale and carbonates that could form high-quality source beds. Similar Devonian units are assumed to be the source for the hydrocarbons in at least two of the oil pools in the Four Corners area. The Devonian section in the trough, as well as organic-rich, fine-grained Cambrian clastics and Mississippian carbonates, have the potential to be the source of large conventional hydrocarbon reservoirs in the deeper, thermally-mature parts of the Black Mesa region (Kornfeld 1963; Lessentine 1965). The U. S. Geologic Survey (USGS) 1995 National Assessment of United States Oil and Gas Resources (Gautier et al. 1995) identified the Oraibi Trough as an official "play." It is designated play number 2402 in USGS Province 24.

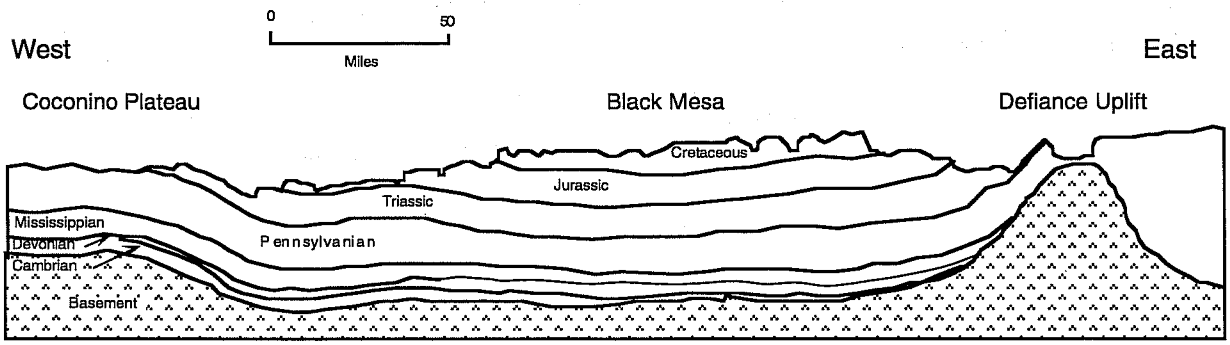

Figure 4–1 Structural Cross Section of the Black Mesa Region

As discussed above, there are many possibilities for stratigraphic pinch-outs along the traces of the basement faults beneath the Black Mesa Basin, where units rapidly thicken and thin. Monoclines flank the basin to the northwest and along the Defiance Uplift, and several anticlinal axes have been mapped crossing the Black Mesa. These anticlines generally have very low relief in the southern Black Mesa, but are better developed in the western and northern portion of the basin. Several minor monoclines are also developed over basement breaks within the Black Mesa. Structural prospects in the deep portion of the Black Mesa include closure on the western and northern anticlines as well as fracture zones along the trends of the monoclines. On the basis of this favorable combination of stratigraphy and structure, the central Black Mesa was designated as a prime study site in the larger region.

4.1.2 Thermal Modeling

Since the deep central portion of the Black Mesa was the area with the greatest depths of burial in the basin, computer modeling was performed on the thermal history of the stratigraphic sequence in two of the deepest wells in the region: the Hopi-1 and the Hopi-9. The study was performed to determine whether the deep sediments in these wells were immature, mature, or overmature, for oil generation. The modeling study strongly suggested that the pre-Permian Paleozoic and Precambrian stratigraphic sections in the deeper portion of the basin reached a thermally mature regime for oil generation approximately 200 million years ago, and then were stripped of cover before they advanced into the overmature stage or natural window.

As a part of the modeling process, it was necessary to make certain assumptions about paleogeothermal gradients and the amount of section removed at unconformities. The assumptions made were apparently realistic because the results are consistent with the results from an earlier conodont-based thermal-maturation study of the Paleozoic rocks in Arizona by Wardlaw and Harris (1984). This work showed that conodont color alteration index (CAI) values for northern Arizona fluctuate around a value of 2.0, indicating that entire northern portion of Arizona should be in the "mature" region for oil, in contrast to mostly overheated, super-mature central and southern parts of the state, where the measured conodont indices frequently are more than 3.0. The new data reinforces interest in the hydrocarbon potential of the selected prospective target areas.

Geomorphologically, the present-day Black Mesa is supported by resistant Cretaceous rocks that form the high cliffs that surround the mesa. These Cretaceous beds include several thin to thick coal seams. The coal seams are best developed in the northern portion of the basin, largely on Navajo lands, where Peabody Coal Company is actively mining. The presence of commercial-quality coal at the surface in the Cretaceous of the Black Mesa region provides additional evidence that the area has been buried sufficiently deeply for thermal maturation of the Paleozoic rocks of the central Black Mesa.

Not all the available data are in agreement with these maturity studies. ARCO drilled the Hopi-1 well, one of the deep wells in the basin, in 1965 and collected well-cutting samples from the Aneth portion of the prime Devonian source beds for laboratory analysis. ARCO derived S_1, S_2, HI and OI values on the samples through pyrolysis and an analysis of total organic carbon (TOC) and vitrinite reflectance. These reports were disappointing. TOC values for the cuttings were below 0.26%. R_o values were below 0.43%. These data are in sharp conflict with USGS values for the Aneth Formation in the Oraibi Trough play, as reported on the 1995 National Assessment of U. S. Oil and Gas Resources CD-ROM report (Gautier 1995). The USGS values are much more positive, generally two to four times the ARCO results: 0.50–1.03% TOC and 0.90–2.1% R_o. The discrepancy may be a result of sample size and condition. Based on a description of the procedures which were followed, the ARCO tests were apparently run on a very small selection of cuttings, which were in poor condition at the start of the test. The sample condition and handling may have led to significant degrading of the chips prior to the laboratory testing by ARCO.

4.1.3 Basement Structure and Lithology

Studies have also been conducted of the hydrocarbon potential trapped within the Precambrian basement beneath the Black Mesa region (Reynolds et al., 1988, 1989; Palacas and Reynolds 1989; Rauzi 1990). There is a very high probability that organic-rich Precambrian clastic sediments, similar to the Chuar units of the Grand Canyon region, are preserved in a series of grabens or half grabens throughout much of northern Arizona and southern and central Utah. Examples of these half grabens are visible and can be studied in the deep gorge of the Colorado River (in the national park), revealing details of the structures. The Chuar section has potential and is of interest both as a source rock and as a reservoir.

A large system of faults cuts the basement beneath the southwestern portion of the Colorado Plateau (Karlstrom and Bowring 1993). Several of these faults pass beneath the Black Mesa region (Figure 4–2). Prominent examples of such faulting underlie the Cow Springs, Comb Ridge, and Organ Rock Monoclines. The uppermost Paleozoic and the Mesozoic sediments of the plateau have been virtually undisturbed since they were laid down. In most areas, the beds are still relatively flat-lying, with very low dips. The monoclines of the Colorado Plateau formed during the Laramide Orogeny at the close of the Mesozoic, when some of the ancient basement faults were reactivated, warping the overlying, nearly flat sediments into the typical plateau single-limbed structures (Kelley 1955; Davis 1975). The monoclinal trends are generally believed to lie almost directly above the major faults, providing a straightforward relationship between the deep and shallow structures that makes it easy to trace the course of the major basement breaks (Sears 1990).

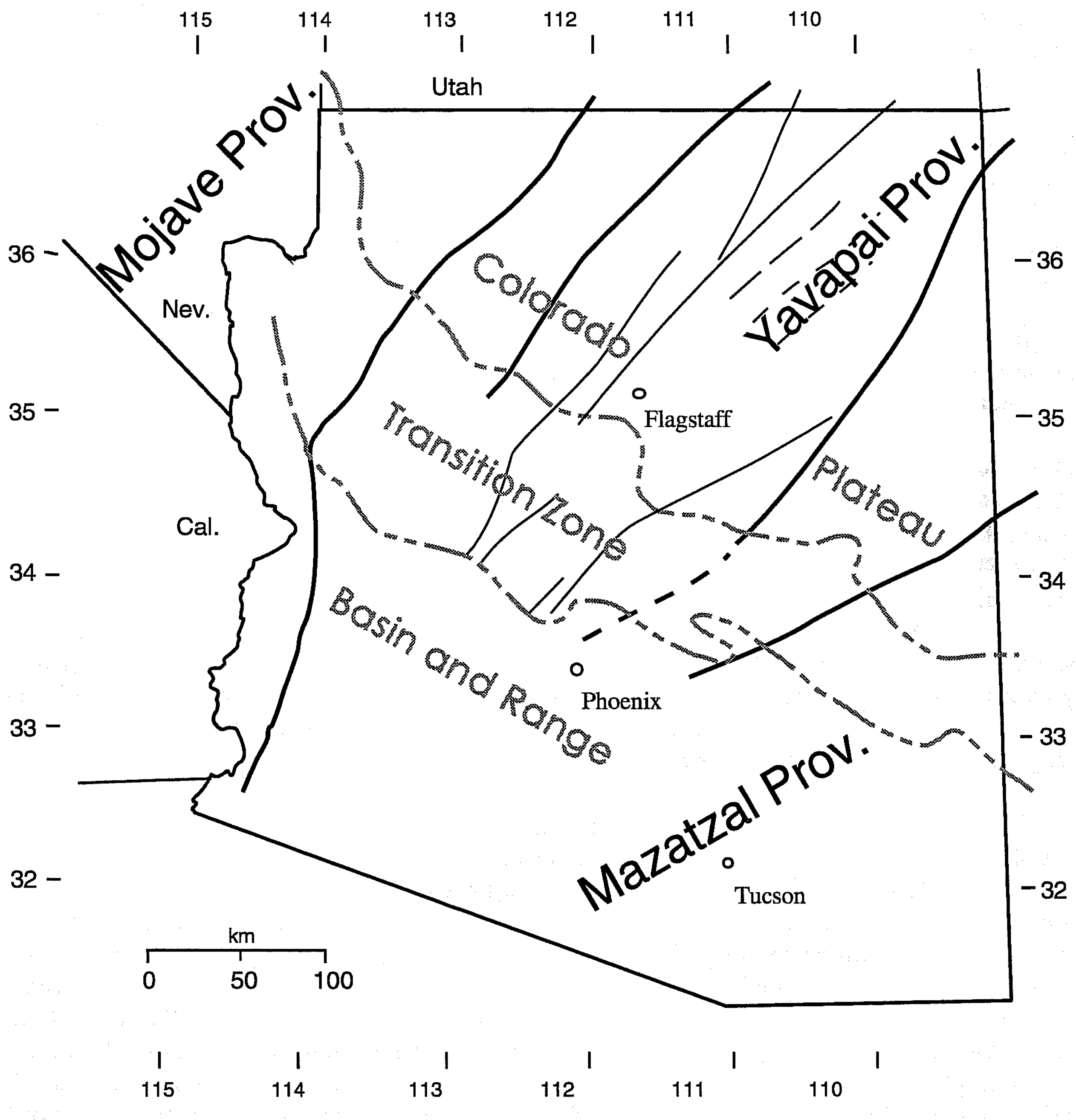

Figure 4–2 Tectonic Provinces and Suture Zones (Heavy Lines) within the Basement of Arizona

The faults that were reactivated during Laramide events are generally the same basement breaks that bound the ancient half grabens where the Chuar-like sediments could be preserved. Not all of the basement breaks moved sufficiently during the Laramide to form monoclines. To ensure more complete identification of the basement structures, and the grabens, a lineament study (Guo and Carroll, in press) was conducted for the Black Mesa region. This study was performed to identify any graben-boundary faults that might not have moved significantly during the Laramide events. This study revealed a rectilinear pattern that outlines many of the half grabens. Gravity and magnetic studies also helped in the identification of these ancient troughs.

The lithology of the Chuar sediments studied in exposures at the Grand Canyon demonstrates that a flourishing late Precambrian biota existed in a series of shallow, possibly lacustrine, water bodies in northern Arizona during the late Proterozoic. Rauzi (1990) discussed the evidence, most of it indirect, concerning the extent of this trough. He suggested that the axis of the Chuar deposits ran through the eastern Grand Canyon area and the area of the present-day Kaibab plateau. He dismissed any possibility of Chuar-like deposits beneath the Monument Uplift area, and stated that "Middle and Late Proterozoic strata are also absent in the Black Mesa basin and on the Defiance and Monument uplifts ...". This last statement is based on minimal well data, some of which may be of questionable accuracy.

Of the wells that reached the basement on or immediately adjacent to the Hopi reservation, the Texaco 1 Hopi-A penetrated 32 ft of "metasediments," then entered "granitic" rock (Pierce and Scurlock 1972; Dwight's 1995). All the other wells reported "granite" or "granitic" rock at total depth (TD), but some of these reports may be suspect. Other studies (e.g., Sumner 1985) indicated that the basement beneath the Black Mesa region should be primarily schist at depth, not granite. A Late Proterozoic sedimentary cover might mask this schist, but that lithology should not be confused with granite in well cuttings, if they are checked. The granite may be a younger, but still very ancient, intrusive or may have been emplaced when the Mesa Butte fault–suture zone formed, but this scenario should have left more of a mark on the gravity and magnetic data that Sumner interpreted.

It is also possible that drillers expecting basement, and knowing that "basement" = "granite," simply reported "granite" on hitting the first hard drilling break around the projected basement depth, with little attention being paid to samples. In one notorious case (outside of the Black Mesa region) during the 1960s, a deep exploratory test was drilled by a major oil company. The formation at TD was recorded as "granite" near the projected total depth. The well was not productive and was plugged. No one paid any attention to the "granite" until several years later when a graduate student working on a thesis looked at the records of the hole. Upon study, the "basement" samples proved to be intrusive rocks from a basic igneous sill that did not resemble granite in any manner. A seismic survey revealed that the true basement was still several thousand feet beneath the TD, and that the opportunity to test a major trough deposit had been missed by the company. The possibility exists that some of the Black Mesa so-called granites may actually include other lithologies, among them graben deposits.

Several much shallower tests that reached the basement on the structurally shallower Coconino Plateau and Defiance-Zuni positive feature reported poorly defined, potentially-prospective lithologies within the basement (Pierce and Scurlock 1972, Dwight's 1995). Several wells in northeastern Arizona in the region around the Black Mesa reportedly penetrated "metasediments," "quartzite," or some similar lithology that could be descriptive of Grand Canyon supergroup sediments from half graben structures.

The Superior 21-29 Navajo-W (in T38N R21E, northeast of the Black Mesa cliff face) drilled 65 ft of reported Precambrian quartzite before shutting down (Pierce and Scurlock 1972; Dwight's 1995). This could be sedimentary material from either the Chuar or Unkar groups and may represent evidence for a graben in this area. Quartzite was also reported in the Lydia Johnson 1 Aztec, south of the town of Holbrook (Pierce and Scurlock 1972; Dwight's 1995). Collins-Cobb drilled a basement test on the Coconino Plateau west of the Black Mesa in 1946. Records are so poor for this well that the location is not even certain. The rig was apparently skidded at least once after the initial hole was lost. There are no electric logs. An old sample description exists, which has been studied by the USGS (Pierce and Scurlock 1972). Many of the formation tops and some of the formation names are listed with question marks. The log of the deep section includes a "Cambrian Tapeats" listing, then "Precambrian basement." The listing of wells in Arizona Well Information (Peirce and Scurlock 1972) states that it cannot be determined from the log if the total depth is in "Cambrian Tapeats or Precambrian quartzite." This suggests that the Precambrian here demonstrates very little indication of metamorphism, and could be part of the Chuar sequence.

One very early Navajo County well (in T17N R20E, near the town of Holbrook), the 1 Great Basin, was drilled by Taylor-Fuller in 1927 and passed from the Pennsylvanian section into what has tentatively been described as an "undifferentiated Lower Paleozoic" sedimentary section at 3,645 ft. The driller then encountered what was described as "Precambrian" at 3,685 ft. The crew continued drilling for an additional 785 ft and entered "granite" at 4,670 ft. Five feet of granite was drilled before the rig shut down (Pierce and Scurlock 1972; Dwight's 1995). The formation tops have been reinterpreted from an old, uncredited sample log. This log ends at 3,630 ft, leaving in question what the 785 ft of rock was between the so-called top of the Precambrian and the top of the granite. Could this interval be sedimentary in origin and a possible source or reservoir rock?

Many Arizona well records leave the same frustrating questions. If the drilling crew of the 1 Great Basin encountered metamorphosed Precambrian rocks at 3,685 feet, why did they keep drilling? If the section at 3,685 feet was relatively fresh looking and unaltered by metamorphism, how was it identified as Precambrian instead of Lower Paleozoic, and how was the age determined? When this well was drilled in the late 1920s, there was little stratigraphic information or control for the region. Since interest in the area has been revived, what was the basis for reinterpretation of the old sample log? The old sample log supposedly ends at 3,630 ft, but the *reinterpreted* "Lower Paleozoic undifferentiated" top was picked at 3,645 ft, 15 ft deeper than the supposed end of the log (Pierce and Scurlock 1972; Dwight's 1995). These numbers do not fit together. They point out the inadequacies in much of the data for northeastern Arizona.

While no direct evidence for intra-basement grabens could be documented from the well control around the Black Mesa or further east, there are reports in the literature concerning Precambrian sediments identified as far to the east as Hunters Point on the Defiance Uplift and in wells in the San Juan Basin. These outcrops have not been studied during this project. The general description of the exposures in the literature is sufficiently vague that it could represent any rock type from schist, which originated as sediments prior to metamorphism, to barren Unkar-like rocks, to possible Chuar-like source beds and reservoirs. With so little direct evidence of basement lithologies, indirect means were used by the BDM NIPER team to infer basement types below the study region.

In addition to the remote-sensing lineament and fracture work, which identified a well-developed rectilinear pattern of northeast-southwest and northwest-southeast oriented faults in the basement beneath northern Arizona, a series of gravity and magnetic studies was performed in the Black Mesa region (Reeves and Sharma in press). To date, modeling has been completed along four transects in the Black Mesa area. These sections reveal the possible existence of several deep troughs that appear to penetrate well into the basement. The modeling of these features suggests that they are filled with rocks of low density. The analysis of the trough fill using both gravity and magnetic data supports the concept that relatively uncompacted, unmetamorphosed Precambrian sediments may fill these troughs. The Paleozoic section above these troughs is relatively flat-lying and undisturbed, supporting the concept that the trough fill must include Precambrian-age detritus. Grand Canyon Supergroup sediments are the logical candidates for this fill material.

4.1.4 Structural Evolution of the Region

The structural history of the Colorado Plateau shows that the Arizona part of the Four Corners region formed the southern section of the Late Proterozoic-Chuar trough or aulacogen described above. Massive block faults then rent the area at approximately 800 Ma, with extensional, normal movements on some faults exceeding 10,000–15,000 ft (Elston and McKee 1982; Elston 1989a, Sears 1990). Offsets were sufficient to juxtapose Chuar sediments against Vishnu Schist in half grabens, as can be seen at exposures in the Grand Canyon. The graben-bounding faults were major crustal breaks, which continued to control depositional patterns and structural features in the region from the Precambrian onward (Kelley 1955; Davis 1975). An understanding of source bed and reservoir depositional patterns in northeastern Arizona requires knowledge of the faulting through the area. These same faults were reactivated during the Devonian, Pennsylvanian, and Cretaceous, producing minitroughs (e.g., the Oraibi Trough), the Paradox Basin, and the complex post-Laramide pattern of basins, uplifts, and saddles throughout the Four Corners of Arizona and surrounding states.

Overall, the southwestern portion of the Colorado Plateau has remained exceedingly stable since the end of the Precambrian. The few exceptional periods of instability have played key roles in the formation of economic hydrocarbon resources. The region was tilted gently to the west at some time between the end of the Cambrian and the Middle Devonian, producing an unconformity at the top of the Cambrian (Beus, 1990). This unconformity could form pinch-out traps for Chuar- or Lower Cambrian-sourced hydrocarbons which may have leaked into Cambrian clastic units.

During the Middle Devonian and possibly the Mississippian, there are indications, based on limited sample control from the few wells in and to the immediate west of the Black Mesa, that the basement fault beneath the Cow Springs and Comb Ridge Monoclines was reactivated. The block southeast of this fault may have subsided a few hundred feet at this time. This type of relaxation would explain the thickening of sediments into the Oraibi Trough beneath the central portion of the Black Mesa (Pierce and Scurlock 1972). This trough may hold the best Phanerozoic source beds in the region (Kornfeld 1963; Lessentine 1965; Kashfi 1983), including dark, organic-rich, fine-grained clastics and carbonates. Other than the minor movements at the Oraibi Trough, the plateau was generally tectonically quiet during the early Paleozoic, with relatively uniform bed thicknesses across large areas of the plateau.

During the Pennsylvanian, a series of northwest-southeast basement faults in central Utah and southwestern Colorado relaxed, forming the Paradox Basin, a trough (or aulacogen) with its depositional axis running through the region just northeast of the Four Corners. The influx of sea water into this area apparently was highly restricted, and thick accumulations of salt built up in the basin, especially along the northeastern margin of the aulacogen. These salts have been mobilized, like those in the Gulf of Mexico, and have flowed into large structures. They now core the La Sal Mountains and other large fold structures in eastern and southeastern Utah.

The southwestern margin of the Paradox Basin appears to have received an influx of fresh sea water across a shallow barrier from the southwest in Arizona and southern Utah, the areas of the future Black Mesa and Kaiparowits Basins. Sea water crossing shallow shelves generally is rich in life, having been warmed by sunlight and tossed by waves and storms. The agitation of the waves mixes large quantities of oxygen into the water. This highly oxygenated, organic-rich sea water flowed across the shallow shelf, then merged with the hypersaline waters of the deeper area of the Paradox Basin. Strings of small reefs flourished on the edge of this shelf, where the shelf floor gave way to deeper water. These reefs form many of the better reservoir units that have been identified in the Paradox Basin in southeastern Utah. Extensive drilling through the area has tested the Pennsylvanian section, but drilling to the sub-Pennsylvanian has been limited because of the relatively high success rates in the reefs.

Several additional analogous shelf edges may exist in northern Arizona along the margins of deeper water areas and minibasins. The Holbrook Basin of Pennsylvanian and Permian age, south of the Black Mesa, is an example of one such feature. Many wells have been drilled along the Holbrook Anticline, a positive structure within this basin, but the basin-margin shelves have been much less extensively tested for reefing. Prospective areas for Pennsylvanian reefs include the lineaments and fractured zones surrounding the Holbrook Sag and surrounding the Oraibi Trough, especially along the northwestern margin of the trough, where the water may have deepened abruptly. With limited well control, the shapes and sediment history of Pennsylvanian-age sags in northern Arizona is largely speculative, although the lineament and fracture study suggests locations for basin edges.

The Pennsylvanian basins developed due to reactivation of the previously described Precambrian breaks identified in the lineament and fracture analysis study. There were relatively few of these Pennsylvanian troughs or sags. Pennsylvanian deformation and extension was relatively minor. The scale of Pennsylvanian movements on the faults was in the hundreds of feet in places like the Holbrook Basin, but included significantly larger offsets along multiple faults in the Paradox Basin. Overall basement movements were minimal at most locations across the southwestern Colorado Plateau during the Pennsylvanian and Permian. Numerous small reservoirs will likely be found in reefs around the rims of these basins in northern Arizona. 3D seismic surveys would be appropriate prospecting tools for these plays.

In post-Pennsylvanian time and continuing through most of the Mesozoic, the plateau was a tectonically quiet area. This accounts for the remarkably flat bedding across great stretches of the region. At the end of the Cretaceous, compression associated with the Laramide Orogeny reactivated the basement faults once again. Offsets along the faults warped the flat-lying sediments into the monoclines which typify the region today. This Laramide activity tilted the area, disturbing the regional hydrodynamic regime and fracturing the shallow formations, potentially creating extensive reservoir zones in fracture trends along the monoclinal-fold axes.

When the program started, the topographic Black Mesa region had been assumed to be the prime target for hydrocarbon prospecting. The ensuing review and study has confirmed this assumption, showing that the Lower Paleozoic section is quite thick along the axis of the Oraibi Trough directly beneath the mesa. The flanking areas contain both structural and stratigraphic possibilities for hydrocarbon traps. The shallower Pennsylvanian section has potential for smaller, but still economic, localized reservoirs, similar to the economically productive fields found in the Paradox Basin. There is also a high potential for fracture reservoirs along the monoclines around the mesa. Thus, the central Black Mesa region remains the best prospect area for hydrocarbon production in northeastern Arizona.

4.2 Northern Black Mesa

The northern Black Mesa region encompasses the northern portion of the Black Mesa, the southern Shonto Plateau (including Skeleton Mesa and Tsegi Canyon), and the steep limb of the Cow Springs Monocline along Klethla Valley, which separates the mesa from the plateau. This region was chosen for detailed investigation primarily because of the structural complexity and the proximity of the deep portion of the Oraibi Trough. This area includes some of the thickest sediments and deepest Precambrian basement in northeastern Arizona (Pierce and Scurlock 1972). The basement sags to more than 2,600 ft below sea level near the Comb Monocline, northeast of the Black Mesa. The thick Phanerozoic cover, including a promising Upper Devonian sedimentary section, makes the northern Black Mesa an attractive target area from both a sedimentary and source rock point of view. Geological and geophysical data suggest that there may be several grabens filled with Chuar-like Precambrian sediments in the basement beneath the Shonto Plateau (Rauzi 1989, 1990).

The area is also of interest structurally. Whereas structural relief in the central Black Mesa is relatively subdued with minimal closure and very low amplitude folds, the degree of tectonism increases toward the north and west. Several of the folds along the margin of the basin have as much as several hundred feet of relief, potentially forming sizable structural traps. The large northeast-trending Cow Springs Monocline, which forms the northwestern margin of the basin and isolates the basin from the adjacent Shonto Plateau, is also of interest for potential reservoirs.

The tight flexures along the monoclines (Kelley 1955; Davis 1975) include intensely fractured rocks along the knee portion of the monoclines. Such fracture systems can produce high-quality secondary-porosity reservoirs. The proximity of these fracture zones, just updip from the deeper beds of the basin, offers an excellent dynamic system with structures and fracture reservoirs juxtaposed against nearby source rocks in the Devonian section of the Oraibi trough, plus nearby Cambrian, Mississippian, Pennsylvanian, and possible Precambrian sedimentary source rocks. Hydrocarbon migration into the reservoirs would be directly updip.

In addition to structural traps along the Cow Springs Monocline, stratigraphic plays may also exist in this area. The basement fault beneath the monocline may have been the feature that controlled the northern margin of the Oraibi Trough. As the thicker sediments within the trough abruptly thin along the margins of the feature, numerous stratigraphic traps should have formed in pinch-outs and beneath unconformities or disconformities at the edge of the deep sag.

Oil production is known from the Tyende saddle (Pierce and Scurlock 1972; Dwight's 1995), near the northern Black Mesa region, but the northern Black Mesa study area itself remains largely untested. The minimal drilling done in the immediate area has been promising. Oil shows have been recorded in at least 5 wells located in the region, including two wells near the Peabody Coal Company mine and in three wells near Kayenta. With so few wells in the region, little specific data on formation tops and lithologies could be collected, nevertheless, the region remains quite high in the ranking of prospects.

4.3 Chinle Valley

The Chinle valley prospective area lies between the morphologic Black Mesa and the Defiance Uplift. The prime prospective area here is the river valley west of the uplift, stretching from the region west of Canyon de Chelly National Monument, near the town of Chinle, south to an area known as Beautiful Valley, where the Beautiful Valley anticline offers trapping opportunities.

The north-south oriented Chinle valley is another basin-edge region with many similarities to the northern Black Mesa. The Defiance-Zuni positive area was structurally high during much of the Paleozoic, and virtually all of the lower Paleozoic section from the Cambrian through the Mississippian pinches out somewhere in the Chinle valley region along the eastern margin of the Black Mesa Basin. The nature of the eastern margin of the Oraibi Trough and its location are poorly defined, but a feather edge of the Devonian must be located somewhere in this area. As at the Cow Springs Monocline, source beds are physically close to potential reservoir structures and stratigraphic traps along the margin of the basin.

Structurally, beds dip relatively steeply along the margin of the Defiance Uplift, and several north-south trending monoclines are developed on the east side of the Chinle valley. These monoclines almost certainly overlie basement faults there as they do elsewhere on the Colorado Plateau (Kelley 1955; Davis 1975). The drainage in the Chinle valley also flows south to north, in contrast to the southwest- and northwest-oriented streams and washes of the Little Colorado drainage in the Black Mesa region. The long, straight Chinle drainage is presumably following a zone of fracturing. This suggests that the structural trend through the Chinle valley region has been controlled by a different set of stresses than those seen throughout most of the Black Mesa region.

The Beautiful Valley area, in the southern Chinle valley region, has been identified (by Gutman and Heckmann 1977) as potentially prospective for hydrocarbons due to well-developed fracture trends. Beautiful Valley is also the site of a closely spaced syncline-anticline couplet, which could have produced an interesting opportunity for structural trapping. The proximity of source rocks is more questionable in this southern region, which has been influenced by both the Defiance-Zuni positive feature, and the Laramide-age Defiance Uplift. There is little well control to outline the various lower Paleozoic sedimentary basins in this region (Pierce and Scurlock 1972; Dwight's 1995).

The Defiance Uplift has been punctured by several Tertiary and Quaternary volcanoes and intrusive bodies. The most productive oil field in Arizona, Dineh-Bi-Keyah, was found within a Tertiary igneous sill on the Defiance Uplift, pointing out that igneous activity has not precluded the accumulation of oil or natural gas in this region and that the Black Mesa region is not overmature, even proximal to rocks involved in volcanism. The Tertiary sill may have been sourced from adjacent Pennsylvanian sediments. The fact that these Pennsylvanian sediments, high on the crest of the Defiance Uplift, are thermally mature suggests that even the high areas of northern Arizona have been deeply buried in the past, and that immaturity of sediments should not be a problem in the deeper basin regions.

Two strongly developed bands of northeast-southwest trending anomalies show up on both the gravity and magnetic maps of Arizona (Sumner, 1985). The area between these bands includes the Black Mesa and immediate surrounding plains. These anomaly trends continue on into Colorado, where they correlate with the Colorado mineral belt (Sumner 1985). The area between the bands has consistently high gravity values. The northwestern band is believed to mark the trace of the Mesa Butte fault system from Arizona into Utah. The southeastern band runs near the town of Holbrook, and is referred to as the Holbrook Line. Sumner (1985) and Titley (1982) attributed the gravity highs throughout the Black Mesa region to a basement beneath the mesa composed primarily of Yavapai province rock, predominantly schists and volcanic rocks which originated in an island arc complex.

The Mesa Butte fault and Holbrook line may represent the edges of suture zones where a band of suspect terrane collided with the ancient North American continent (Karlstrom and Bowring

1993). It appears that at approximately 1.7–.8 Ga, the southern margin of the continent ran roughly between the northwesternmost corner of Arizona and the present trend of the Mesa Butte fault. An island arc system collided with this coastline, adding a new strip of land (referred to as the Yavapai province) to the edge of the continent. This process shifted the coastline many miles to the southeast, approximately to the area of the Holbrook line.

Between 1.7 and 1.6 Ga, a second collision occurred, plastering still another zone, the Mazatzal province, onto southeastern Arizona (Karlstrom and Bowring 1993). Due to sharp lithologic contrasts across the two boundaries, the suture zones can be identified by gravity and magnetic signatures. If this interpretation is correct, the Black Mesa region is underlain at depth by Yavapai series rocks, which crop out in central Arizona, near Prescott, where they are composed predominantly of schists. Sumner (1985) studied the gravity and magnetic signature of the Black Mesa region, and concluded that the basin is largely underlain by these schists. Sumner does not explain why the gravity signature of the schists is so much stronger beneath the Black Mesa than it is south and west of Flagstaff. Nor does he explain a prominent magnetic low beneath the northern Black Mesa region. The deep basement lithology of the Yavapai province is complex, including lithologies that are not exposed along the Mogollon Rim.

The Yavapai schists are much older than the Grand Canyon Supergroup, and would be buried beneath any remnants of Chuar or Chuar-like sediments that are preserved in grabens in this region. This interpretation of extensive schists beneath large areas between the Grand Canyon and the Defiance Uplift (Sumner 1985) does not correspond to the "granites" reported at TD in many wells throughout the region. The Yavapai schists can be seen at Prescott in central Arizona, but their gravity and magnetic signatures are quite different in that region from the appearance of the basement beneath the Black Mesa. The lithology within the schists may change substantially to the southwest, or the term "schist" may be inaccurate at the Black Mesa area. As stated above, drillers through the years have been reporting "granite" for the basement in northeastern Arizona. Whatever the lithology of the basement there, the rocks do seem to belong to the Yavapai province, in contrast to an older Mojave province in extreme northwestern Arizona.

The suture zones have apparently remained as sites of weakness in the crust and have been favored by intrusive igneous activity. The Mesa Butte and Holbrook trends are made up of a number of discrete features, including many small gravity or magnetic anomalies. One of the most prominent of these anomalies occurs at the spot where the Holbrook line intersects the edge of the Defiance Uplift. A combined gravity high–positive residual gravity anomaly is located at this site. This anomaly is the result of an intrusive basaltic plug (Sumner 1985). Many other intrusive basalt bodies can be identified in the same area, in a string along the Holbrook line, and on the Defiance Uplift. The complexities of intrusive bodies need to be factored in when doing gravity or magnetic modeling in a region like northern Arizona. A gravity-magnetic transect extending into the Chinle valley has suggested that there may be late Precambrian sediments preserved in grabens in this region (see section 5). Exposures of Precambrian rocks in three pits or quarries at Hunters Point, plus some well cuttings from the Defiance Uplift, have shown that there are bits of Precambrian sedimentary rock preserved on and around the uplift, but the literature does not make clear if these rocks could include Chuar-type sediments.

Drilling in the Chinle valley, east of the Black Mesa, has been minimal (Pierce and Scurlock,1972; Dwight's 1995). Oil shows were reported within the Paleozoic section in two wells drilled during the 1960s near the mesa, high on the plains to the west of the Chinle valley.

The close proximity of a thick sedimentary section in the Oraibi Trough to the pinch-out zone against the Defiance-Zuni structure has once again provided an ideal combination of reservoir rocks and stratigraphic traps. As at the northern Black Mesa region, pinch-outs and subtle stratigraphic traps will probably be the primary prospecting targets in the Chinle valley. Updip migration into these stratigraphic traps and fracture zones should be common on the steep eastern side of the Black Mesa basin. 3D seismic work will probably be the most appropriate and effective prospecting tool for work in an area like this. The topography in the valley should make this an ideal approach for exploration. The Chinle valley has a high potential for hydrocarbon traps.

4.4 Cameron-Coconino Rim–Gray Mountain Area

Rauzi (1990) suggested that the area of the plateau east of the Grand Canyon has a high potential for the preservation of an exceptionally thick Chuar section. This trend projects through the Coconino Rim–Gray Mountain area near the town of Cameron, where there is a combination of favorable shallow structural features that could act as traps for hydrocarbons. Gravity and magnetic data suggest the possible presence of Precambrian clastics in the basement in the region. These units could provide a good local source for hydrocarbons in the immediate area of a number of structural traps, at a location where Laramide disturbances could have mobilized the hydrocarbons. Many of the Laramide movements on the Colorado Plateau reversed the sense of late Precambrian (Grand Canyon Orogeny) movements on these faults. This suggests that the Coconino Rim–Gray Mountain uplift directly overlies the edge of a Grand Canyon Supergroup graben, an ideal situation for maximized hydrocarbon potential.

The Coconino Rim and Gray Mountain structures, form a local high, a moderate-relief "blister" on the normally near-flat rocks of the gently dipping Coconino Plateau. This blister has been created by the intersection of several basement faults, creating a small trapdoor structure in the basement. The faulting led to the formation of multiple large- to moderate-size monoclines which pass through this region. Five monoclines intersect around Gray Mountain, north of Flagstaff and west of Cameron. The feature is quite unusual for the normally low-relief plateau. Maximum relief on the Coconino Rim occurs at Coconino Point on the northeastern corner of the feature, where it is more than 2,000 ft, and some beds have actually been overturned along the steepest portions of the monoclines.

Well control in the plateau area north of Flagstaff is insufficient (Heylmun 1990) to ensure accurate formation identification and correlation in the case of some of the sedimentary units of the Coconino region and to unravel the complexities of depositional histories or detailed migration pathways, but it appears that the Gray Mountain region may have been unstable and a high as early as the Permian (Pierce and Scurlock, 1972). There have been several hydrocarbon shows and other signs of oil in the subsurface of the central Coconino Plateau. Heylmun (1990) was quite enthusiastic about the potential for hydrocarbon at the Coconino Plateau. Simple updip migration would have caused petroleum to drain into the Gray Mountain region in a relatively large portion of this region.

The assumption that hydrocarbons could have migrated into and survived in the shallow sedimentary column in this part of Arizona is supported by the pattern of a large number of uranium-rich deposits in the area. Processes and conditions on the Colorado Plateau that allowed concentrations of radioactive ores to precipitate are similar to those that would have allowed hydrocarbons to mobilize and accumulate. A strong association can be seen around the Four Corners area between oil fields and areas of uranium-rich deposits. Co-occurrences of petroleum and radioactive deposits are common throughout the corners of New Mexico, Colorado, Utah, and northeasternmost Arizona. This is because similar conditions of porosity, permeability and oxidizing/reducing states favor the concentration and precipitation of both economically important products.

Uranium and hydrocarbons both accumulate in reducing environments. In the presence of oxygen, hydrocarbons tend to degrade rapidly, and uranium assumes a more mobile state. In stratigraphic zones where uranium can precipitate, conditions will generally be favorable for oil reservoirs. Whereas most of the known radioactive ores are concentrated in the shallow, near-surface sediments and the anticipated hydrocarbons around Gray Mountain are believed to have accumulated in the deeper sediments, the evidence for the existence of migration pathways, seals, and locally reducing conditions is a positive factor for the region. Uranium and hydrocarbons tend to follow similar types of pathways and fracture systems during migration and accumulation. In the presence of free oxygen, hydrocarbons will quickly be destroyed and uranium will tend to continue to migrate.

Prior to accumulation in the commercial deposits, the uranium was in an oxidized, mobile state. Uranium-bearing fluids moved through fractures and permeable zones until they reached a reducing setting, at which point they precipitated. This type of migration and trapping also occurs with oil. Oil can only accumulate in a reservoir and survive over geologic time if the conditions in the reservoir are reducing. The numerous uranium concentrations in the sedimentary section around the Cameron area and Gray Mountain suggest that migration pathways exist and that oxidizing/reducing conditions in this region have been favorable to hydrocarbon accumulation over an extended span of geologic time.

The two primary targets for hydrocarbon prospecting around the Coconino Rim and Gray Mountain region should be closed structural highs and zones of intense fracturing along the knee areas of the monoclines. Mapping of the region has been sufficiently extensive to identify most of the closed highs, but additional work will be needed on the monoclinal knee regions. 3D seismic work can be used in some of these areas, but rough terrain will preclude seismic work on some of the steeper limbs. Geochemical surveys may also be an effective tool in this dry country.

4.5 Hopi Buttes

The Hopi buttes area was originally selected because of the presence of unusual intrusive bodies (known as diatremes) and deep-seated, intense fracturing across the area. These diatremes generally follow the trend of the ancient Defiance-Zuni positive feature. It was recognized that the Defiance-Zuni feature was structurally relatively high throughout much of the lower Paleozoic, and that there would be little opportunity for the accumulation of significant quantities of lower Paleozoic beds in the region. The interest was to determine if the heat associated with the diatremes might have produced satisfactory conditions to mature organic material which might have been preserved in shallower units, thus forming shallow-sourced hydrocarbons. The possibility was also considered that the intense, deep-seated faulting might have allowed ultra-deep-sourced hydrocarbons to have leaked from grabens or even deeper locations within the basement.

Helium has been discovered on the Defiance-Zuni positive area in exceptionally rich concentrations on the Pinta Dome, northeast of Holbrook and near the Hopi buttes. The structural setting at the Pinta Dome resembles that at the Hopi Buttes in many ways. However, the Hopi Buttes are farther from the railroad and have not been drilled. The Pinta region, in contrast, has been thoroughly drilled for oil, helium, natural gas, and potash.

Helium is generally believed to have been trapped deep within the interior of the Earth by primordial processes. It is assumed that some of this helium is occasionally released to the surface under unusual conditions from ultra-deep sources. Some experts, especially in Europe and the former Soviet Union, have suggested that hydrocarbons could have been produced at similar depths and may slowly seep to the surface at selected sites in a similar manner. These experts argue that where there is deep-sourced helium, there can also be deep-sourced hydrocarbons. Thus, the Hopi Buttes was considered to have a hydrocarbon potential from deep sources (Pierce et al. 1970), from basement grabens, and from locally heated shallow beds.

The study of the area did not prove to be especially promising. The ultra-deep sourcing is highly speculative and can only be documented by drilling, discovering producable hydrocarbons, and studying samples from the wells to determine provenance. The concept of heating of shallow units during volcanism proved to be invalid at this location. The intrusive bodies at the buttes turned out to be diatremes. Diatremes are noted for their unusual means of emplacement, which has been referred to as "cold volcanism" due to the peculiar means and speed of intrusion.

Diatremes are thought to originate when unusually "wet" sea floor material is subducted and carried to exceptional temperature-pressure regimes. Under specific, poorly understood conditions, the subducted plate can retain its moisture, carrying the water to great depths where it "flashes" to vapor in the form of superheated steam. This steam then literally explodes upward through the crust in an extremely rapid process. Diatremes penetrate the surficial material so rapidly that the upper crust and overlying sediments are minimally impacted. Very little heat is transmitted from the intrusions to the country rock due to the speed of the process. The magma has a very large gas (steam) component which cuts like a knife to the surface. There, it is nearly instantaneously released, dissipating most of the heat in the system directly into the

4.6 Alpine-Sanders–St. Johns Area

The Alpine-Sanders–St. Johns area was chosen as a prospect area for this study because of hydrocarbon shows encountered in a recently drilled geothermal test. This area is also lacking in what are conventionally regarded as source beds, and is another unlikely habitat for oil, where facts seem to be contradicting the standard concepts of petroleum geology. This southern prospect is well up on the Mogollon slope, south of the Black Mesa proper. Depth of burial is generally considered to have been inadequate to mature the sediments in this region. Conventional wisdom says that this area should be barren of hydrocarbons.

The Phanerozoic cover on this slope is relatively thin and should include relatively little source material. There is no indication that this southern plateau margin was buried to depths great enough to generate sufficient heat and pressure to produce oil, even if source beds are present. In addition, numerous red beds and light-colored sediments in exposures throughout this region have suggested that the setting should be too oxidized for the preservation of significant hydrocarbon resources. In addition, the proximity of the White Mountain volcanic sequence could be considered to be a negative factor for the area. On the other hand, many of the characteristic factors in this region match those on the heights of the Defiance Uplift, where Dineh-Bi-Keyah (Kornfeld and Travis 1967; McKenny and Masters 1968; Williams and Roth 1969; Barwin 1971) has become the best oil field in Arizona.

Since the NIPER exploration study started, it has become apparent that the Alpine area is receiving considerable attention from Arizona state and other agencies, as well as from industry. The mission of the Exploration and Drilling Group is to look at unexplored or underexplored regions. Since interest by other groups in this site is so high, little time was spent by the NIPER team in evaluating it. Additional attention would have been redundant and overlapped with other government efforts. The Alpine-Sanders–St. Johns area of the Mogollon Slope will be studied in detail by other institutions, with no additional efforts being necessary from NIPER or BDM-Oklahoma.

5.0 GRAVITY AND MAGNETIC MODELING

To provide more detailed information on the key areas of interest, a series of gravity, magnetic, and remote sensing studies were conducted at the Black Mesa in an attempt to identify possible areas where Chuar sediments may have been preserved in grabens within the basement. This work has been integrated with the geologic analysis of the sratigraphy and structure in the region.

5.1 Gravity Modeling in the Black Mesa Region

An analysis of gravity and magnetic data can provide valuable information on the structure and tectonics of the basement rocks in a region with complex intra-basement deformation. Sharp contrasts exist between the densities and magnetic characteristics of metamorphic rocks compared to sedimentary rock. These contrasts can be identified and mapped. Since targets for exploration in the Black Mesa region include upper Proterozoic sediments within the basement, gravity and magnetic studies are being used for identification of the structure and faulting in the basement.

5.1.1 Program for Modeling Gravity Data

A gravity modeling program was written in FORTRAN. The program is based on the formula for the gravitational effect of two-dimensional bodies developed by Hubbert (1948) in the form of a line integral. To make Hubbert's formula more useful in practical application and actual calculations, Talwani et al. (1959) transformed the line integral to the form of an integral around the periphery of an n-sided polygon. Using this transformation, the exact attraction of a two-dimensional body, described by the sides of an n-sided polygon, may be obtained by numerical integration along the periphery of the polygon. The number of sides (n) of the polygon can be increased in order to describe the causative body as precisely as desired. The program can simultaneously calculate the gravitational effects of a large number of sedimentary units (plus other geological bodies, such as intrusives or high-density blocks within the basement) and derive a model of all the geologic units at the point of calculation.

The most time-consuming aspect of gravity modeling is the data input necessary to describe the geological formations. A system was developed to use a digitizer for input, reducing the time and labor required.

5.1.2 Modeling of Black Mesa Gravity Data

The computer program Gravanom was used to generate regional geological structural sections from residual Bouguer gravity data of northern Arizona. Four lines (shown in Figure 5–1) have been completed:

- A 175-km, northeast-southwest-trending profile, running from Red Lake in the southwest to the Chinle valley in the northeast
- A 187.5-km, north-south-trending profile, running from Kayenta in the north to Holbrook in the south
- A 187.5-km, northwest-southeast-trending profile, running from the Kaibito Plateau in the northwest to Ganado in the southeast
- A 287.5-km, northeast-southwest-trending profile, running from the Cameron area on the Coconino Plateau to the Four Corners area in the northeast

Before beginning the model studies, logs were studied from wells which had been drilled close to the study area. Density distribution data in the various formations were obtained from the literature (Pierce et al. 1970, Aiken et al. 1972, Jenkins and Keller 1989) and from logs. Some of the density data were from laboratory measurements of core samples. The sedimentary section from the Cambrian to the Mesozoic was divided into a five-layer model, roughly representing the intervals in Table 5–1.

Table 5–1 Five-Layer Model of Cambrian to Mesozoic Sedimentary Section

Age of Formation	Average Bulk Density (g/cm^3)
Late Mesozoic	2.35
Early Mesozoic	2.40
Permian and Pennsylvanian (Late)	2.55
Permian and Pennsylvanian (Early)	2.60
Early Paleozoic	2.65
Basement	2.70

The densities of the sedimentary rocks were determined primarily by lithology, mineralogy, and degree of compaction. The overall trend for the density values is a gradual increase with depth. The basement rocks reported in nearby wells were mainly granites but, locally, quartzites and undifferentiated metamorphics were also encountered (Sumner 1985). The basement density could range between 2.65 and 2. 80 g/cm^3, but the value of 2.70 g/cm^3 should reflect the average density of the most common basement rocks in the study area.

By adjusting bed thicknesses and configuration, an attempt was made to match the observed gravity data with the computed values. Formation tops from nearby wells were used in constructing the geological model. The model is based on a datum level of 6,000 ft above sea level, the approximate average surface elevation in the study area.

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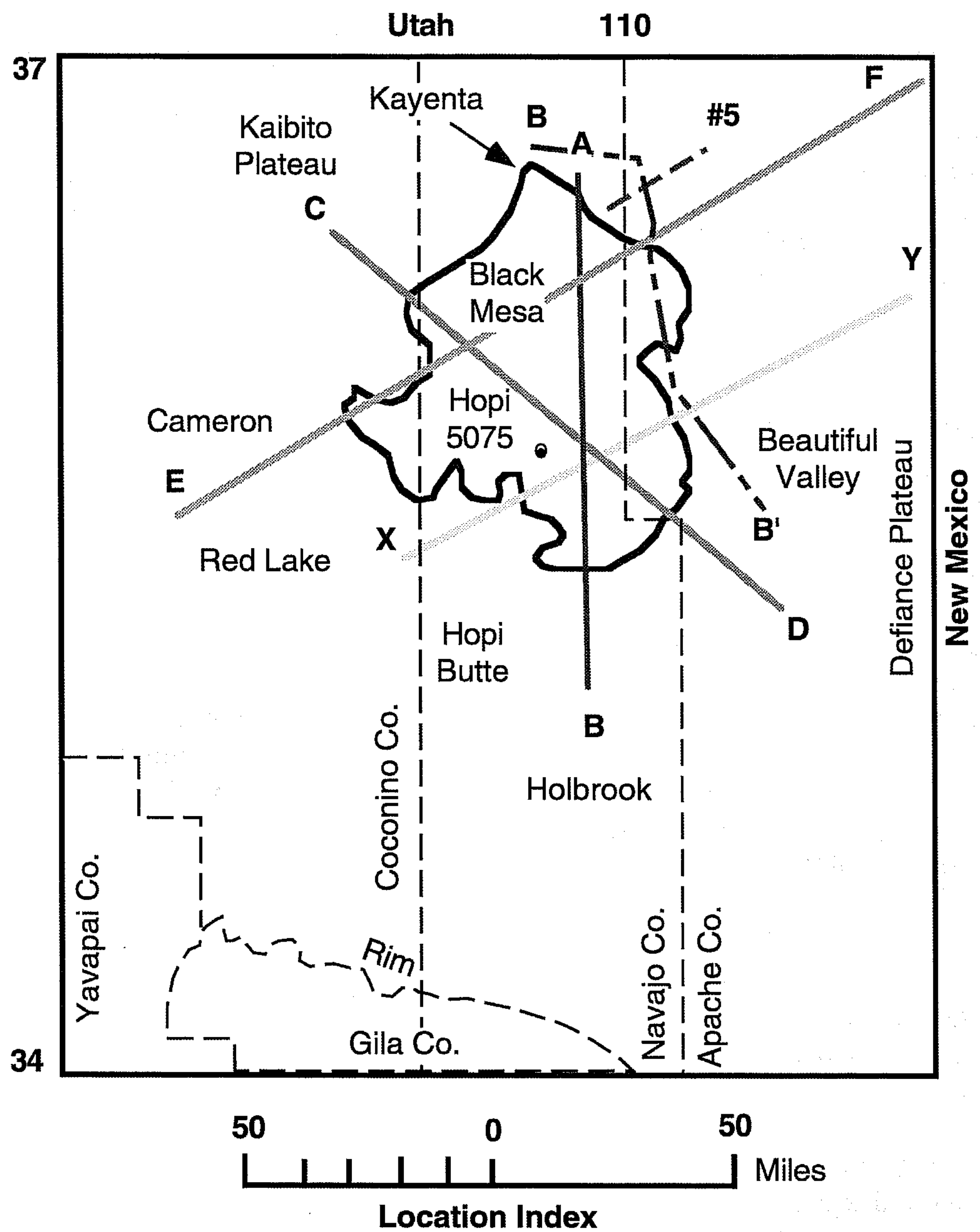

Figure 5–1 Location map of gravity-magnetic profiles XY, AB, CD, and EF; Log Stratigraphic Section BB′, and Seismic Line 5

Approximately 25 modeling runs were made before a good match was obtained between the observed and the computed profiles. The results are shown in Figures 5–2 to 5–5. In order to match the sharp gravity anomalies in certain parts of the profile, high density (around 3.0 g/cm^3) mafic intrusives were required. The presence of intrusive bodies of varying rock densities in the study area has been discussed in the literature (Shoemaker et al. 1978, Ander and Huestis 1982, Sumner 1985). A 30-milligal gravity high at the Chinle valley end of the line could only be matched by a large mafic intrusive in that region. This corresponds to the known geology of the region.

5.1.3 Discussion of Gravity Modeling Results

Several interesting observations were made during the modeling.

The model suggests that the deepest portion of the basin has not yet been tested by the bit. The thickest measured sedimentary section identified thus far in a well is around 7,800 ft in the Amerada 1 Hopi well (Sec. 8, T29N, R19E), where oil shows have been reported in the Upper Devonian McCracken sandstones. The modeling suggests that the sediment thickness increases to a maximum of 9,000 ft in the center of the basin. This area is approximately 12 mi southeast of the Amerada well. The area of maximum sediment accumulation is undrilled, but is typified by a much lower gravity value than that around the Amerada 1 Hopi. This area may contain a large thickness of Lower Paleozoic sediments, including rich source rocks, but from gravity modeling alone it will be impossible to resolve this.

Several intrusives were observed on the gravity profiles. The model studies suggest that the intrusives penetrate to varying depths in the sedimentary section, and that several types of intrusives may exist in the region. If the intrusives are composed of dense mafic rocks, then a relatively small penetration is sufficient for a match between the observed and the computed profiles. The intrusives may also be associated with faulting in the lower Paleozoic formations.

The gravity high near Chinle can be modeled with a large mafic intrusive body that has penetrated a granitic basement. The model suggests that there is a very thin cover of sediments above the postulated intrusive. The prospects for hydrocarbon accumulations in this area cannot be rated as high. On the other hand, the model indicates that favorable stratigraphic trapping conditions may be present in pinch-outs just west of the structure.

A large number of possible basement faults were seen in the models. Some of these features may not be faults. Intrusive bodies can produce similar effects.

Uncertainties about the lithologies of the various intrusive bodies has caused some ambiguity in the interpretation of the gravity data. The mean density of granite is 2.667 g/cm^3. Syenite runs 2.757 g/cm^3, diabase, 2.965 g/cm^3, and basalt is more than 3.000 g/cm^3. Some of the problems present in the interpretation of the gravity data was resolved by simultaneous modeling of magnetic data and integration of the modeling with seismic interpretation.

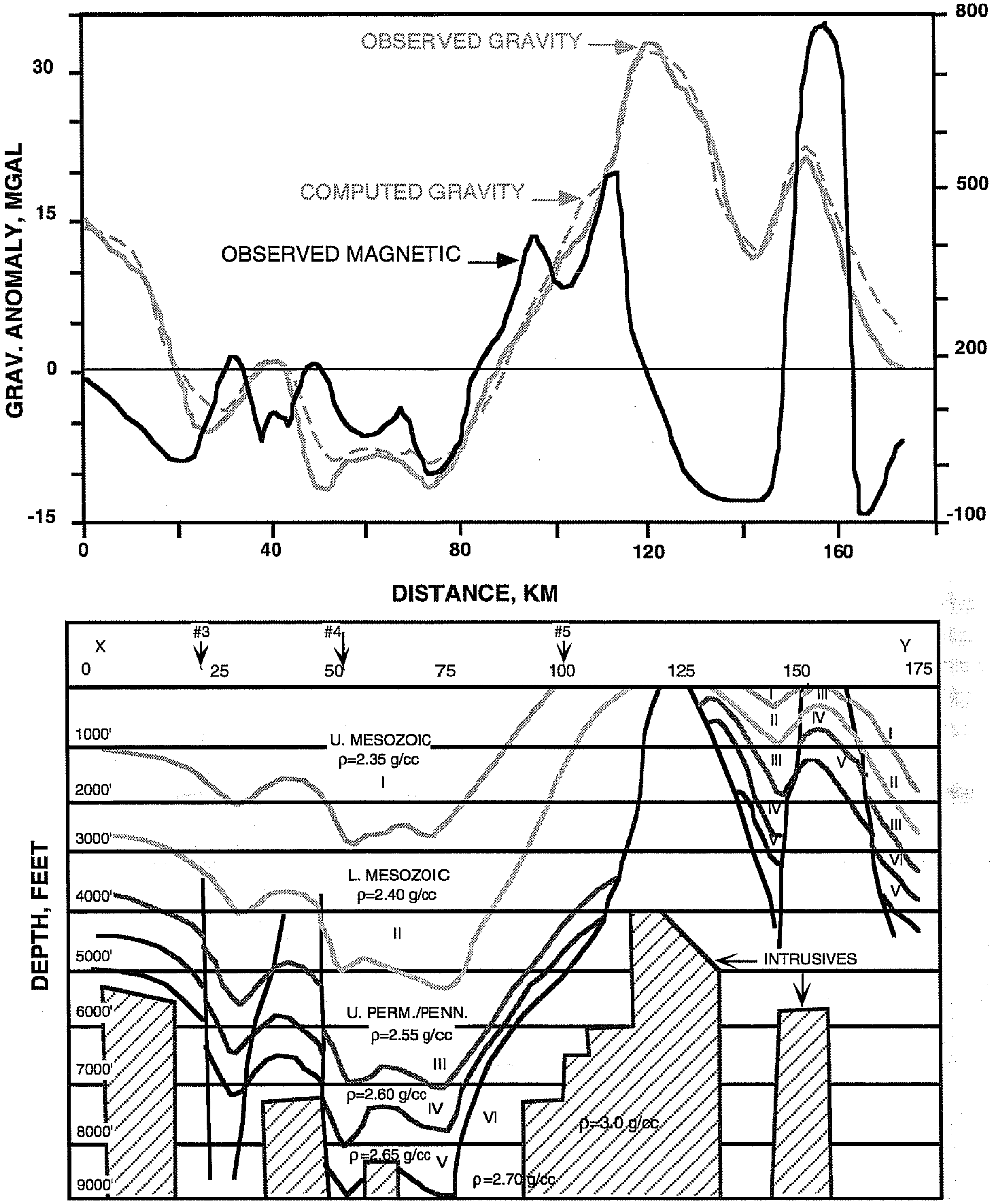

Figure 5–2 Gravity and Magnetic Modeling Profile XY (for Location, See Figure 5–1)

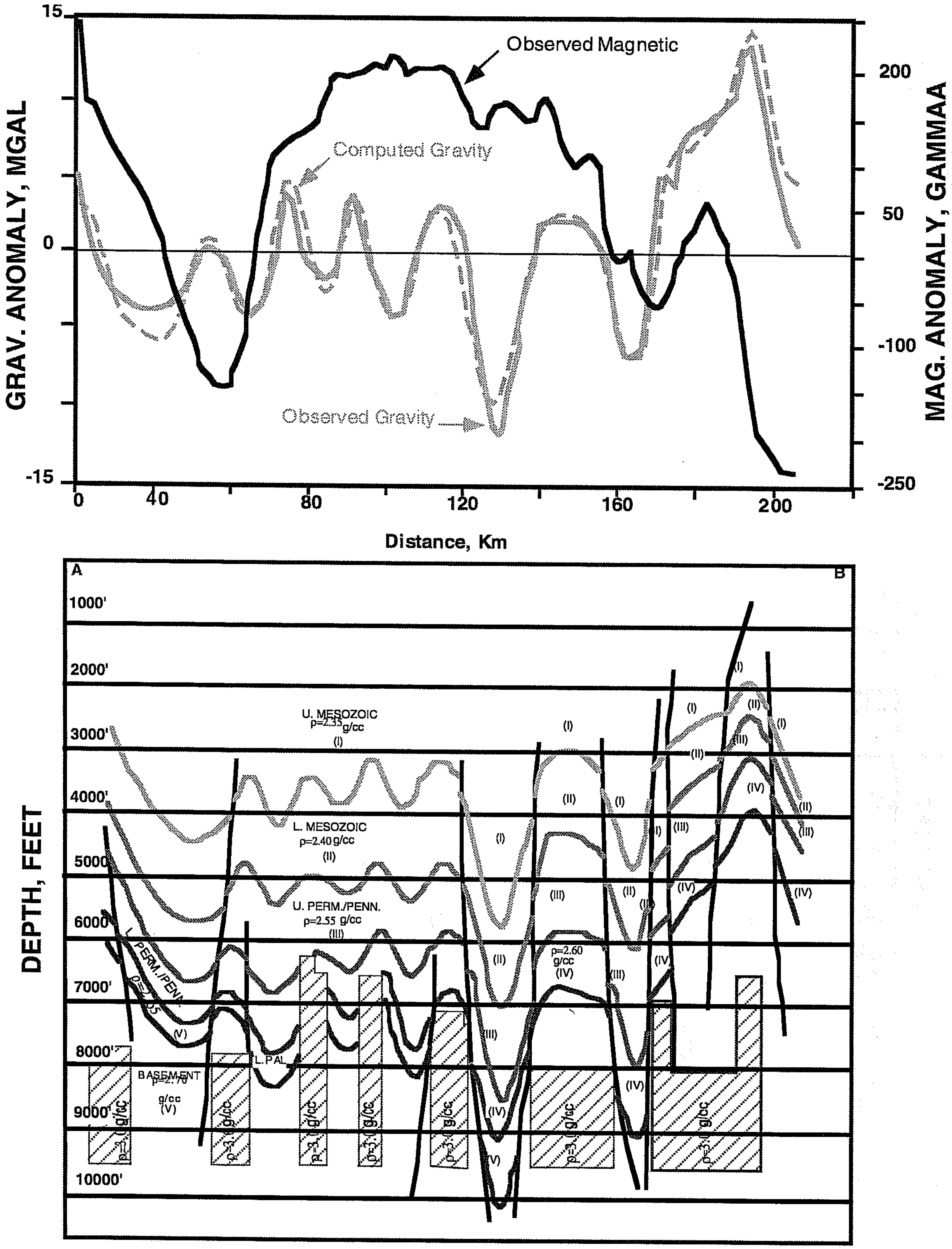

Figure 5–3 Gravity and Magnetic Modeling Profile AB (for Location, See Figure 5–1)

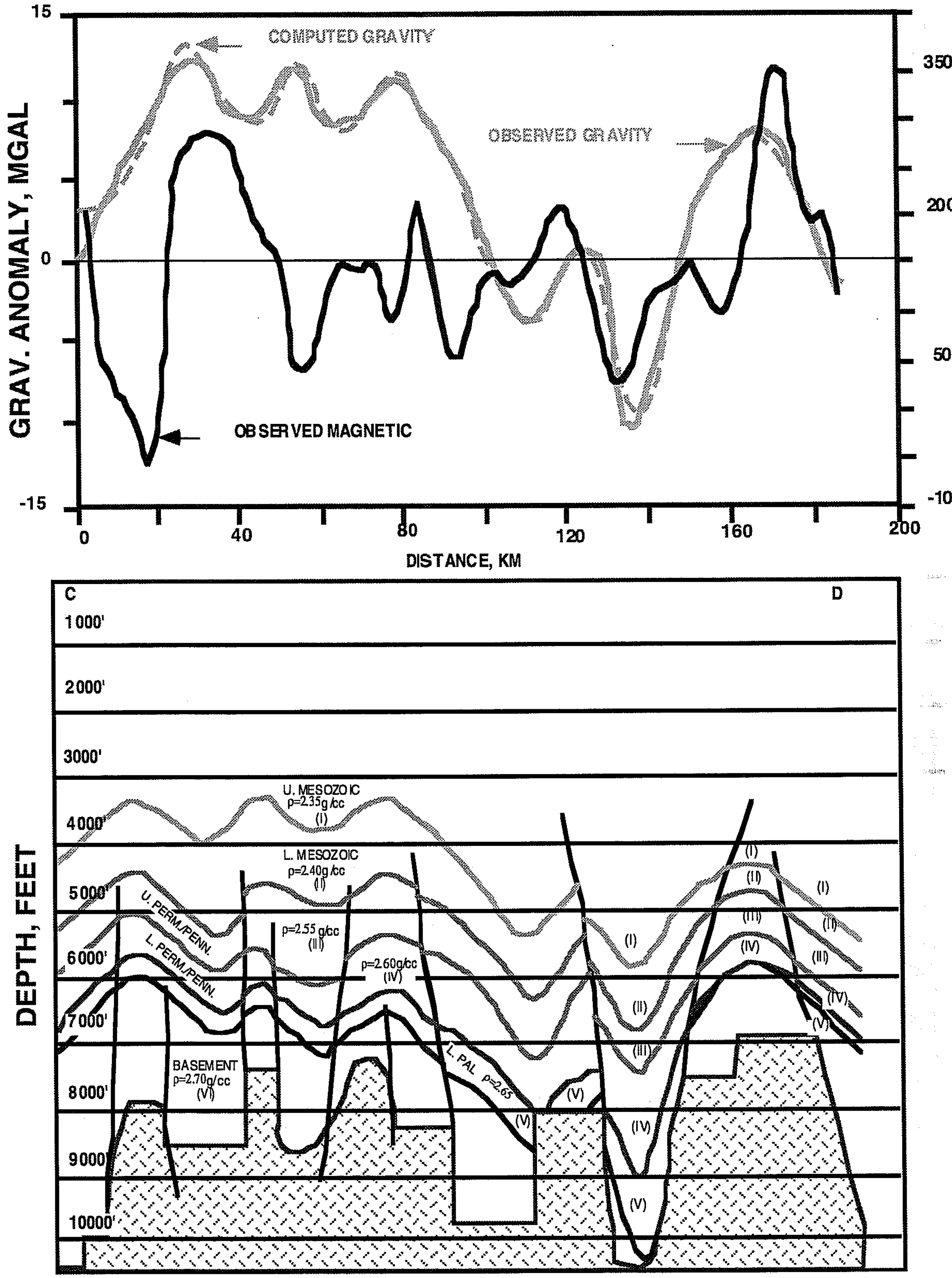

Figure 5–4 Gravity and Magnetic Modeling Profile CD (for Location, See Figure 5–1)

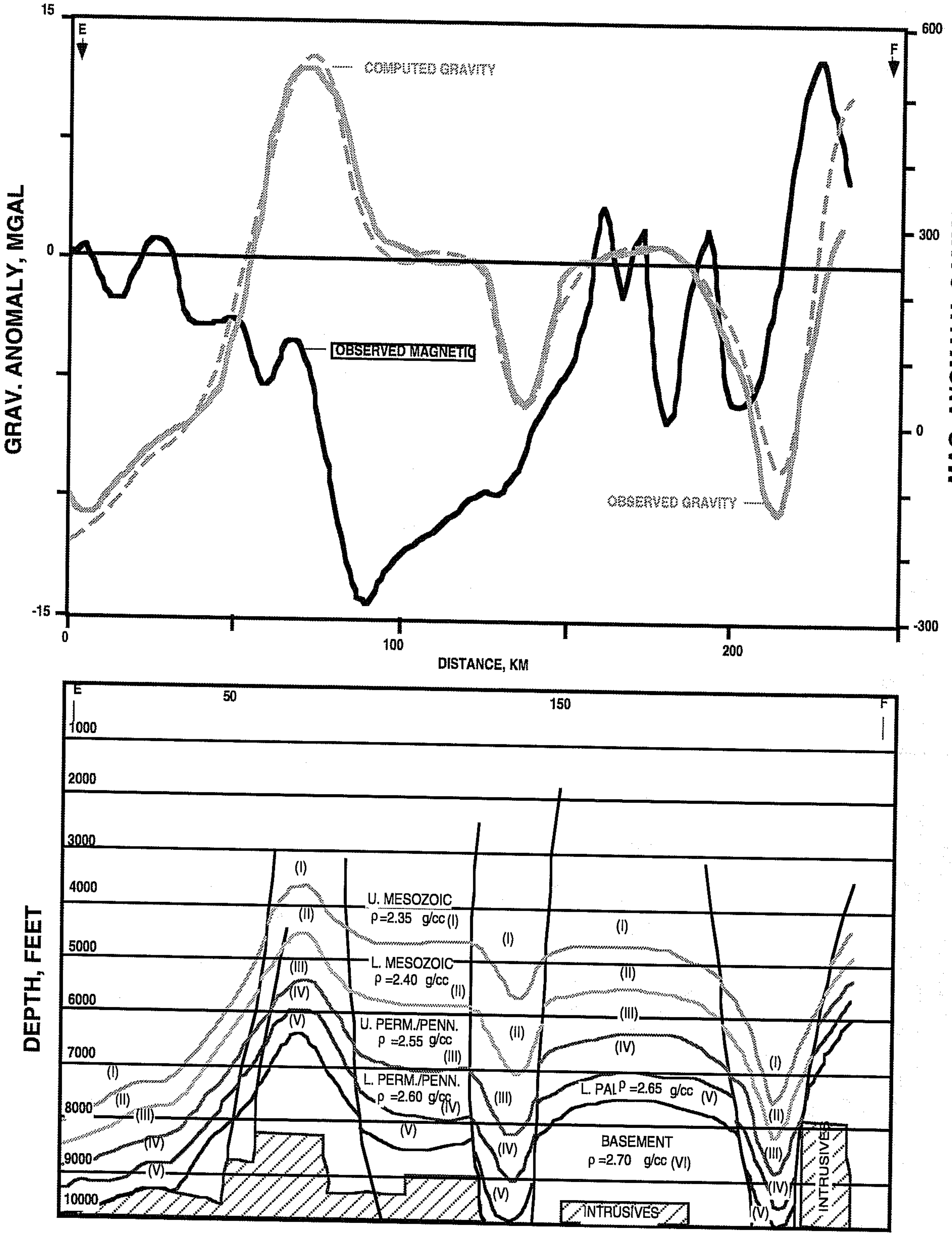

Figure 5–5 Gravity and Magnetic Modeling Profile EF (for Location, See Figure 5–1)

5.2 Development of a Computer Program for Calculating the Magnetic Anomalies of Two-Dimensional Bodies of Arbitrary Shapes

A computer program, Maganom, was written during for the modeling of magnetic data for two-dimensional structures, such as a basement fault or a buried basement ridge. The program can be used to model the total-intensity aeromagnetic data or to model vertical magnetic intensity data, such as that obtained from a ground survey using a hand-held magnetometer. The effect of remnant magnetization is not considered in this program because remnant magnetization is not important for most of the study area. Within Maganom, the magnetization readings are all attributed to the magnetizing field of the earth. For the interpretation of aeromagnetic data at the Black Mesa, the total field intensity (the vector sum of the Earth's field and any field associated with a buried source) is modeled. Magnetic computations are much more complicated than gravity modeling because of the presence of positive and negative poles and because the orientation of the buried body also affects the total intensity vector.

It should be noted that for most sedimentary rocks, the magnetic susceptibility value is very close to zero. Thus, it can be assumed that when an anomaly is found, it is almost entirely due to a feature within the basement or to an intrusive body in the shallow section. For magnetic modeling, therefore, it is not necessary to model effects of the sedimentary cover, as must be done in the case of gravity modeling.

The Maganom program was tested and verified against anomalies of simple geological structures for which known, standardized analytical expressions of magnetic values are available.

5.3 Interpretation Of Aeromagnetic Data from Black Mesa Basin

Maganom was used to compute the total intensity anomaly along the basement profile of seismic line 5 (Figure 5–6). The susceptibility of the basement rocks used was 0.002 cgs units, the average susceptibility of granitic rocks. From the aeromagnetic map of the area, the strike of the basement surface was taken as 70° from magnetic north. The magnetic inclination in the study area is around 60° and the Earth's total field is 60,000 gammas.

When the computed total intensity basement anomaly is compared with the observed aeromagnetic anomaly (Figure 5–6), it was obvious that the computed anomaly is much too small compared to the observed, implying that there must be other igneous sources contributing to the observed anomaly. This is exactly the same conclusion drawn from gravity modeling and, for a satisfactory match, the presence of higher density (possibly mafic) igneous rocks was postulated. It is apparent that the combined effect of high susceptibility igneous rocks and the basement anomaly can only provide a satisfactory match between the computed and the observed data.

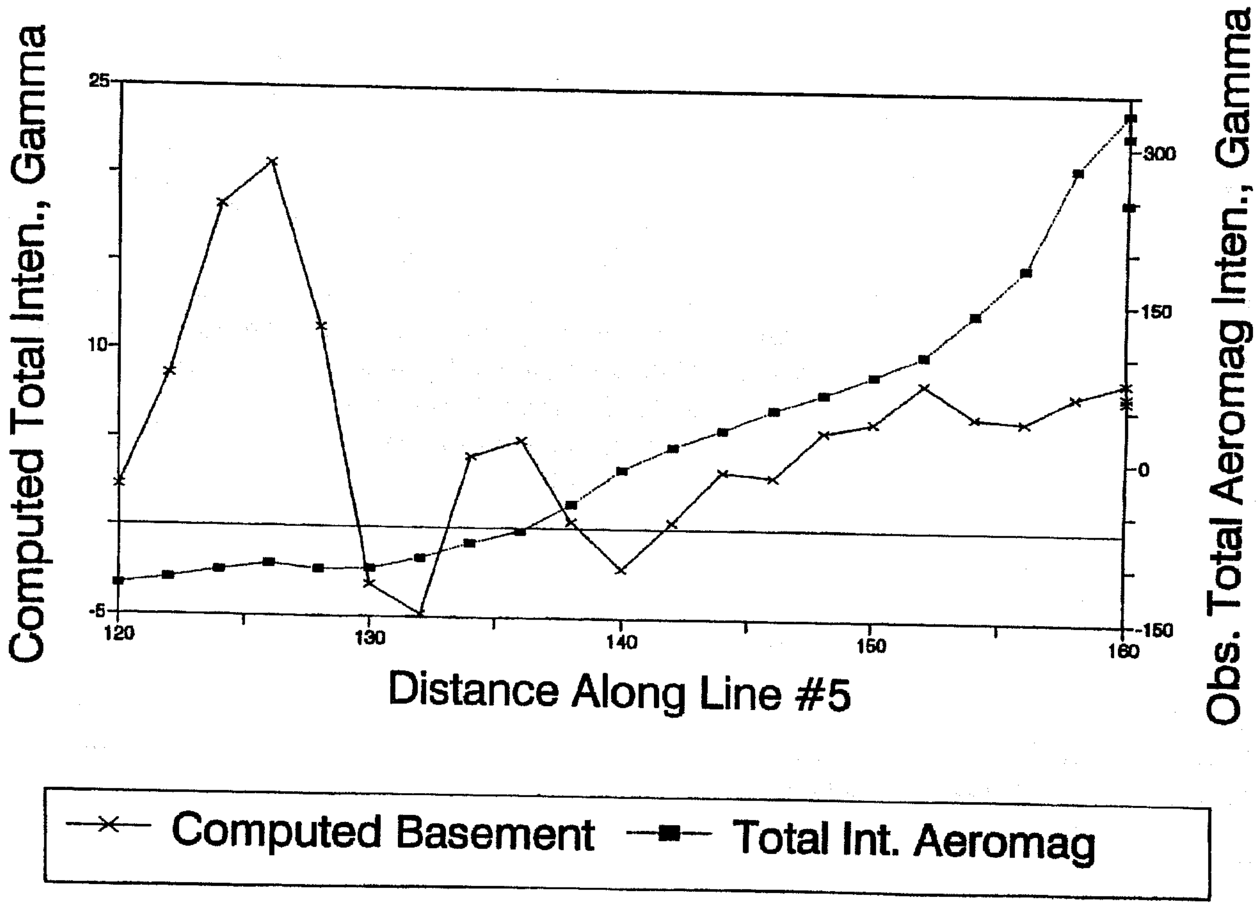

Figure 5–6 **Observed Aeromagnetic and Computed Basement Anomaly Along Seismic Line 5**

5.3.1 Magnetic Modeling

The integration of aeromagnetic data with the gravity-model studies provides information from two independent sources: one based on the lateral variations in rock densities and the other on variations in the magnetic properties of the rock. An agreement in the modeled structural interpretations produced by a combination of these different rock properties considerably enhances the reliability of the models.

The Bouguer gravity anomaly data for northeastern Arizona were used by Gutman and Heckmann (1977) to create a residual gravity anomaly map of the study area that was used in the model studies. The matching of the observed and computed gravity curves was achieved by adjusting the values of the bed parameters (thickness, configuration, etc.) until a satisfactory match was obtained between the two curves.

Total magnetic intensity values along the three profiles were obtained from Gutman and Heckmann's (1977) aeromagnetic survey work. Although there is considerable overlap in the magnetic susceptibilities of many rock types, the average magnetic susceptibility of most common sedimentary rocks are usually very low compared to acidic igneous rocks like granite or to basic igneous rocks like diorite or diabase. In general, therefore, it may be assumed that intense magnetic anomalies are the result of a magnetic basement or an intrusive or extrusive magnetic rock.

The magnetic work led to the identification of a large number of magnetic bodies that appear to be associated with faulting in the basement. These faults also affect the overlying sediments. The basement appears to be divided into fault-bounded blocks that generally trend northeast-southwest. The fault planes appear to be favored routes for intrusive bodies.

A prominent magnetic low in the western end of the studied area coincides with the postulated location of an Upper Proterozoic Chuar deposit identified by Rauzi (1990). The low magnetic intensities of the Chuar sediments would be expected in nonmagnetic mudstones and shales with thin to medium-thick beds of intercalated dolomite , sandstone, and stromatolitic carbonate (Reynolds et al. 1988).

A second area of interest was seen around the Hopi buttes. In general, the basement is considered to be structurally high in this area. Two gravity lows at the buttes, however, could indicate the existence of an intra-basement graben with a thick sedimentary accumulation.

The northern Kaibito Plateau area may also have a thick remnant section of organic-rich Chuar group sediments.

5.4 Stratigraphic Cross Sections from Wireline Log Correlations

Forty-five wireline logs were obtained for the primary target area within the Black Mesa. Two stratigraphic cross sections were constructed using wireline logs. The first trends northeast-southwest, and the other trends north-south across the morphological Black Mesa and Hopi Butte areas. Gamma ray, density, neutron, induction, SP, sonic, and resistivity logs were used for detailed investigation of the lower Paleozoic section. The main objective of the stratigraphic cross sections is the study of the distribution and lateral variations in the quality of the source, reservoir, and cap rocks in the study area.

Figure 5–7 shows a roughly north-south trending stratigraphic section (profile BB′ on Figure 5–1) for the lower Paleozoic interval. This section is hung on a datum at the top of Mississippian section and is constructed with gamma ray logs. The pinch-out of the Cambrian against the Defiance-Zuni positive structure can be seen, along with thickness variations in the Aneth and McCracken Devonian units.

Figure 5–8 displays the gamma ray and sonic transit-time plots for well Hopi 5075 (for location, see Figure 51). This well had hydrocarbon shows in the McCracken sandstones and also in the Chinle formation. The large scatter in log values in the McCracken sandstone interval indicates rapid lithological variations within that unit. The sandstone in this well is apparently interbedded with large amounts of shale, causing the high gamma-ray readings. The average sonic transit time is moderately high, indicating modest porosity development, although thin streaks in the sandstone may have fairly high porosities.

5.5 Acquisition of Seismic Data from the Black Mesa

Phillips Petroleum Company was able to locate in their files 19 seismic lines shot in 1963 in the Four Corners region, just northeast of the Black Mesa. The company agreed to provide these data, including sections and tapes and totaling approximately 240 line-mi, to the Exploration and Drilling Group for reprocessing and more detailed interpretation.

Examination and reprocessing of the data has begun. The overall data quality cannot be rated as better than "fair" due to the vintage of the data. Some prominent reflectors (e.g., the top of the basement surface), however, are easily mappable. With reprocessing, it is expected that the signal-to-noise ratio in the data will improve significantly. It is hoped that some of the lower Paleozoic reflectors may also be mappable.

The first line, line 5 (for location, see Figure 5–1), has been significantly improved through reprocessing, and work will continue on the other lines. The preliminary interpretation of line 5 shows a number of interesting structures in the basement and shallow sections.

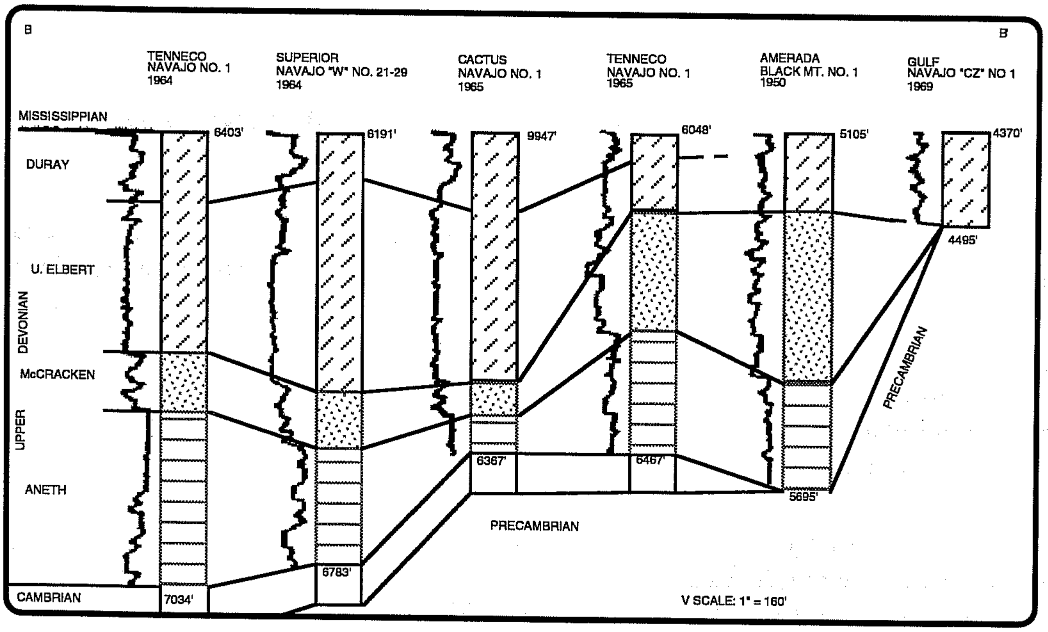

Figure 5–7 Wireline Log–Based Stratigraphic Correlation of Source Rocks and Fluid Carriers on the East Flank of the Black Mesa Region

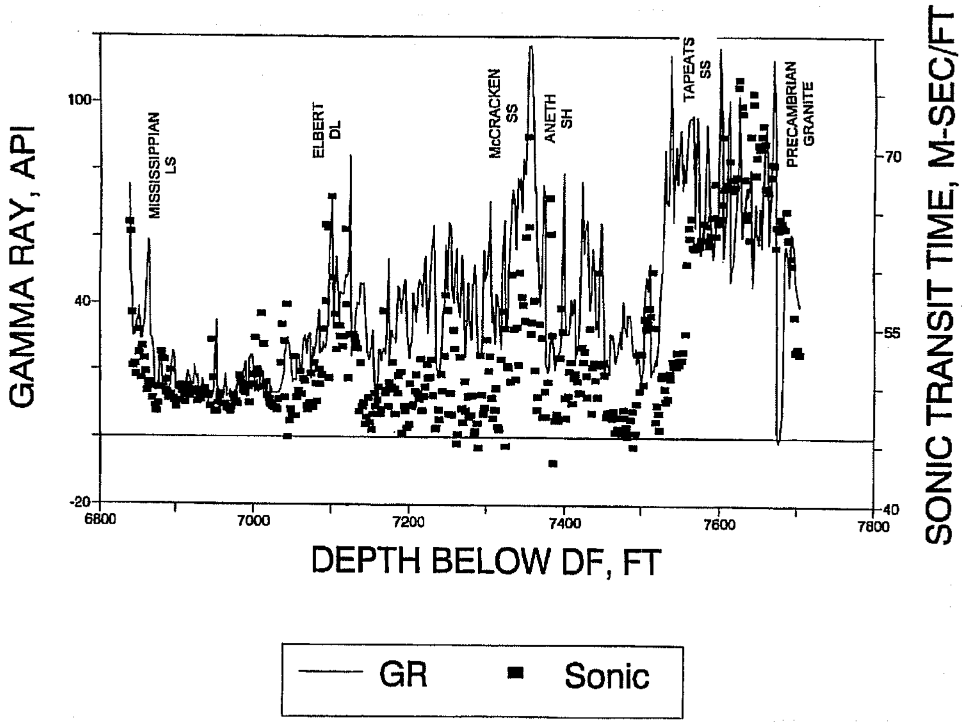

Figure 5–8 **Distribution of Source and Reservoir Rocks in the Lower Paleozoic Interval in Well Hopi 5075**

5.1.2 Comparison of Gravity and Magnetic Modeling Results with Seismic Line 5

An approximate configuration of the crystalline basement surface was obtained from an interpretation of line 5. Although the quality of the seismic line is only moderately good, the top of the basement surface is mappable. Two apparent faults show up on the line. A graben can be seen between the two faults. This structural interpretation is consistent with structural patterns identified in the gravity and magnetic modeling. Figure 5–5 shows the interpretation of profile EF; Figure 5–9 shows an interpretation of the basement structure along line 5.

5.1.3 Comparison Of Basement Structure with Satellite Imaging of Surficial Features

The basement structure identified on seismic line 5 (Figure 5–9) shows a close correspondence to surficial features identified on satellite image (Figure 5–10). The locations of the line 5 shot points have been superimposed on Figure 5–10. A strong association can be seen between the locations of the Chilchinbito Anticline–Church Rock Syncline axes and basement faults. This type of deformation is typical of the Colorado Plateau. Fault F2 on Figure 5–10 corresponds to the erosional cut of the Chinle Wash. This suggests that the drainage follows the line of faulting and fracturing, and that many of the surficial features in Black Mesa are probably controlled by basement tectonics.

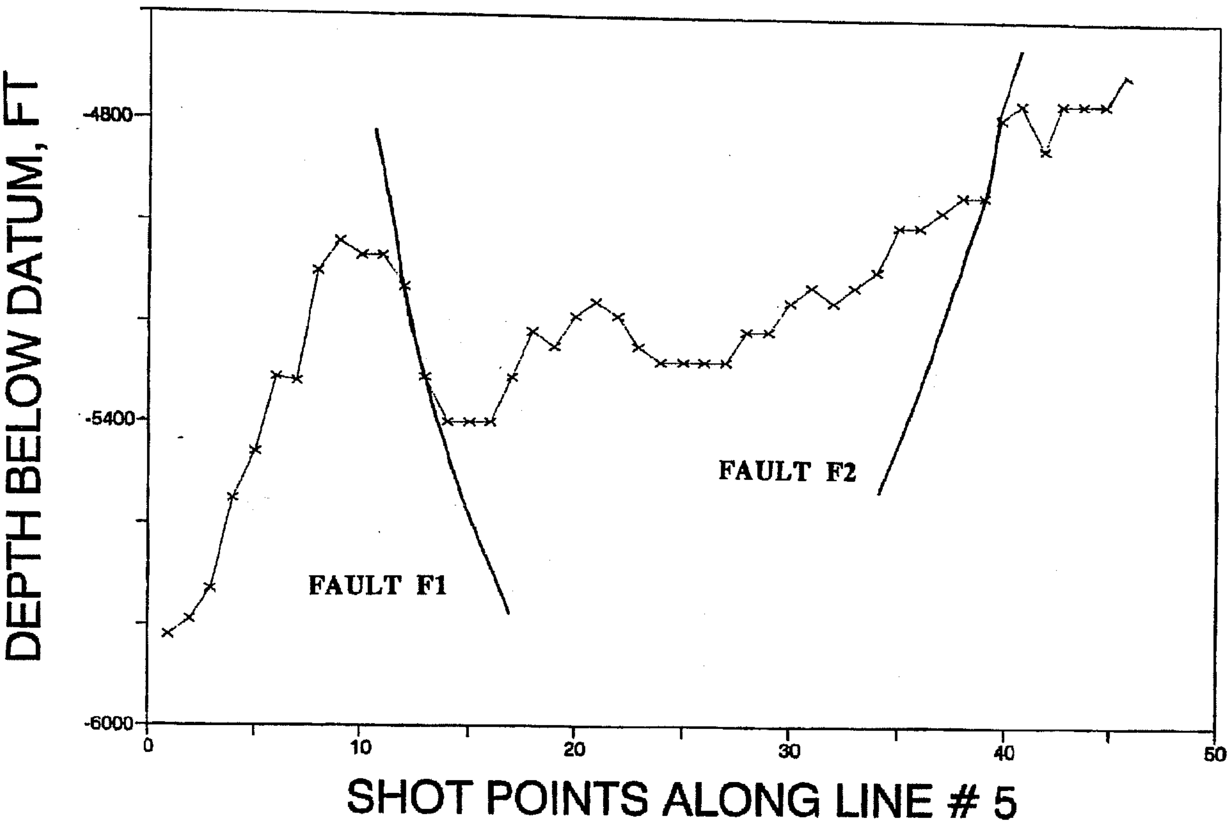

Figure 5–9 Depth to Basement Along Seismic Line 5 (for Location, See Figure 5–1)

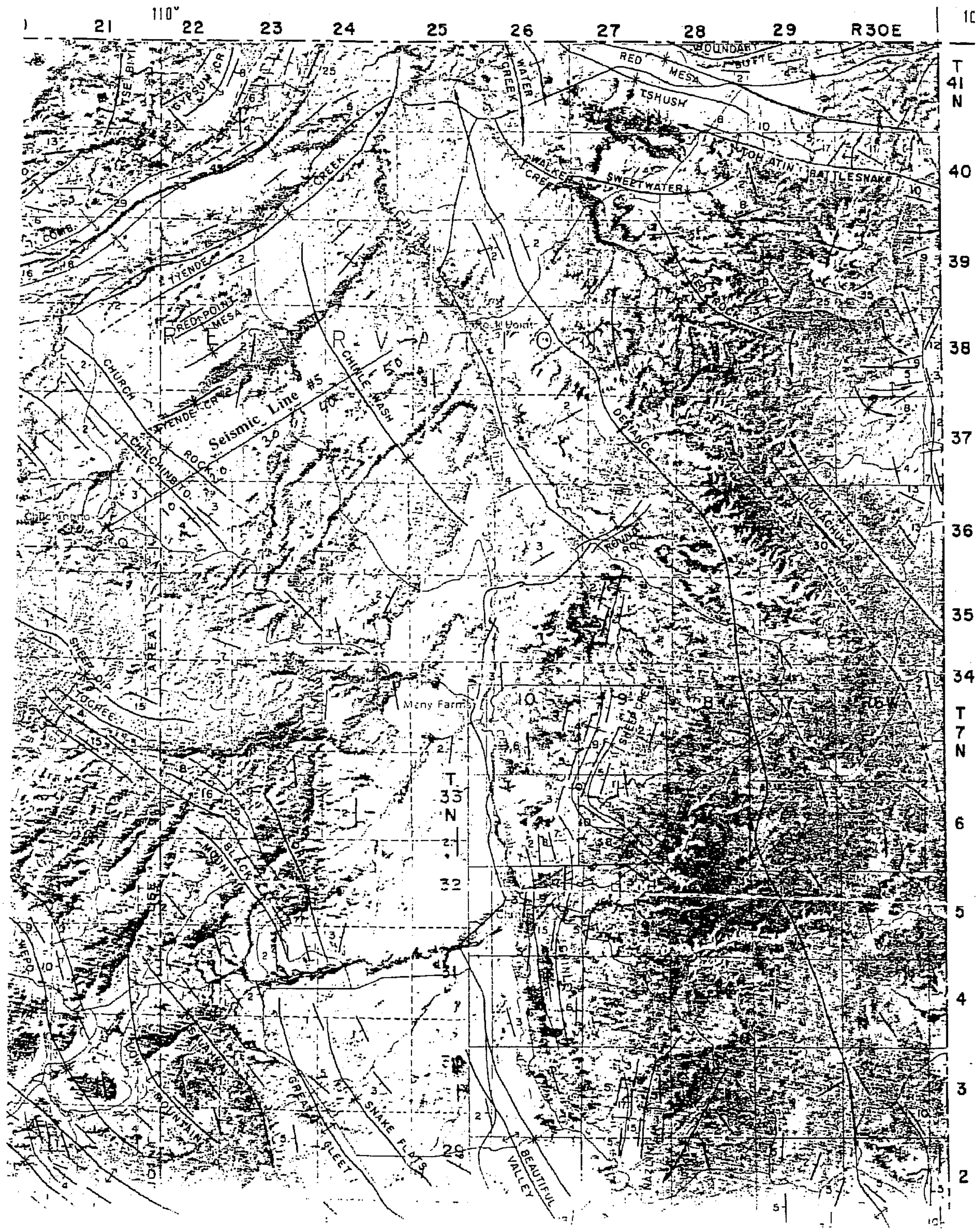

Figure 5–10 Comparison of Basement Topography with Satellite Imaging of Surficial Features

6.0 INTERPRETATION OF AERIAL PHOTOGRAPHS FOR FRACTURE ANALYSIS

Aerial and satellite photographs of northeastern Arizona were purchased and studied to identify lineaments, regional fracture trends, surface drainage systems, surface fracture traces, and circular and arcuate anomalies, as well as their relationship to production in the region. The study photographs were grouped into two areas. The smaller of these two areas is a 775-mi^2 block on the Coconino Plateau, west of the town of Cameron. The larger includes the central and northern Black Mesa regions, including the adjacent Shonto Plateau, Skeleton Mesa, and Tyende Mesa to the north, and the Chinle Valley area to the east. The larger area covers 4,950 square mi^2.

The study area required the purchase of almost 300 photographs. Nine Landsat images, covering the entire northeastern quarter of Arizona, were also acquired. They are being used to identify and map major surface lineaments and for interpreting other geological features. Extensive fractures were identified in the northern part of the Black Mesa Basin. Maps were prepared, the trends were digitized and analyzed, and rose diagrams were prepared. It was found that there are fewer fractures observed in the southern part of the region due to sand dune coverage.

The fracture zones in northeastern Arizona are consistent with the pattern for the majority of the Colorado Plateau, following northwest, , north-northwest, and northeast orientations. Surface lineaments interpreted from Landsat images follow the same general orientation although they differ in density. The pattern of the surface-fracture zones was apparently similar to that of the basement fault systems interpreted from surface lineament analyses. The same results have been observed in the San Juan and Paradox basins of the Colorado Plateau. It was concluded that surface fracture zones and basement fault traces can be used as a general guide to identify priority locations for exploratory drilling.

More than 36,000 surface fracture traces were interpreted from aerial photographs in the Cameron area. These were digitized, and rose diagrams were generated. The majority of the fracture traces in the Cameron area follow two major orientations: north-northwest and northeast. The north-northwest–trending fracture traces are dominant in the area.

The Precambrian basement structures of northeastern Arizona were investigated through outcrop observations, surface lineament analyses, and gravity and aeromagnetic surveys. The Precambrian basement rocks appear to be divided into regular, fault-bounded blocks, which trend predominantly northeast-southwest. The average width of these blocks is approximately 25 mi, and they tend to be truncated/or terminated by north-south and northwest-southeast trending faults. In addition, there are three basement arching systems corresponding to three volcanic areas: the San Francisco Mountains, Hopi Buttes, and the White Mountains.

Basement control of monoclines in northeastern Arizona has been described by many investigators (Kelly 1955; Davis 1975). It has been observed in the Grand Canyon region that many basement faults have been reactivated many times and have propagated upward to the surface. Many of the major monoclines (e.g., the Comb, Echo Cliffs, and Cow Spring Monoclines) are indeed associated with faulting in the Precambrian basement. The monoclines in the region are believed to be developed as a response to differential movements of basement blocks along high-angle faults. In the eastern Grand Canyon region, all of the monoclines exposed to the crystalline basement are underlain by Precambrian normal faults. The propagation of basement fault systems to the surface indicates the applicability of lineament and fracture analysis for hydrocarbon exploration in northeastern Arizona.

7.0 SUMMARY

With the exception of Dineh-Bi-Keyah, the productive oil and natural gas fields of northeastern Arizona are comprised of small reservoirs. Even Dineh-Bi-Keyah would be considered a modest field in many other regions. Resources in northeastern Arizona are trapped in subtle and difficult- and expensive-to-identify stratigraphic traps. Many of the traps are the small, self-sourced Pennsylvanian-reef type, which characterize the nearby Paradox Basin to the north. There may be many more of the small Pennsylvanian reefs in the Black Mesa area. If so, 3D seismic prospecting offers a potential prospecting technique, but mileage nets will be expensive and payouts relatively limited. Better targets appear to exist in the region.

In addition to the Pennsylvanian reservoirs, minor production and several shows were seen in or adjacent to Devonian clastics (Pierce and Scurlock, 1972). The Devonian production came from occurrences where the section pinched out against structure. Offset wells to Devonian production generally encountered Pennsylvanian sediment in direct contact with Precambrian hills. Production from the Devonian has not been encountered in a sufficiently large reservoir to develop offset locations. The central Oraibi Trough holds significant possibilities for Devonian development (Pierce and Scurlock 1972; Gautier et al. 1995).

Mississippian carbonates may also hold potential as source beds and reservoir units. Because so few wells penetrated beyond the Pennsylvanian section, data on the Mississippian section is inadequate for this region, but a number of shows and some production have been recorded in the Mississippian of the Four Corners (Pierce and Scurlock 1972; Dwight's 1995).

If there are larger, more conventional structurally trapped oil deposits to be found in the region, they probably are in the deeper portions of the trough. The Devonian Aneth carbonate/shale–McCracken sandstone combination may offer large reservoirs, relatively easy target identification, and prospecting, with low finding costs. The areas surrounding the trough are likely to have moderate to smaller fields due to thinner source areas and/or smaller trapping structures or pinch-out areas. The Cambrian section is a virtual unknown in the region of the Black Mesa Basin and may have potential in sandstones above the Bright Angle shale or Precambrian Chuar sediments. Little work has been done to identify traps around the margins of the Oraibi Trough, so little is known about potential reservoir size.

Table 7-1 is a preliminary summary of the potential of the six study areas selected in northeastern Arizona. The conclusions are subject to change as additional information becomes available.

Table 7–1 Petroleum Potential of Selected Study Areas in Northeastern Arizona

Area	Possible Source Beds	Trap Types	Ranking
Central Black Mesa (Hopi Reservation)	Local, thick	Structural, stratigraphic	Good
Northern Black Mesa	Local or adjacent, moderate to thick	Structural, stratigraphic	Moderate
Chinle valley	Local or adjacent, moderate to thick	Structural, stratigraphic	Moderate
Coconino Rim–Gray Mountain	Local or adjacent, moderate to thick	Structural, fractures	Moderate
Hopi Buttes	Limited to north side, moderate to thick	Structural, stratigraphic	Moderate?
Alpine-Sanders–St. Johns	Thin?	Stratigraphic	Confirmed

To appreciate the difficulty of prospecting for hydrocarbons in northeastern Arizona, it is important to understand that several of the larger and better fields in the Paradox Basin of Utah and Arizona and on the Defiance Uplift in Arizona were found in highly unlikely settings and in unconventional structural locations.

The first productive field in Utah was located in the deepest portion of a synclinal axis, from beds within one of the narrow goosenecks of the San Juan River, possibly at a depth above river level, just yards back from the local cliff face. In a more conventional producing region, the entire area should have been drained via exposures along the San Juan River. In the case of pools that were not drained, they should have been degraded by exposure to air and bacteria in this setting. In theory, the entire region should be severely underpressured, given the erosional history of the area. Despite these facts–and conventional wisdom–the initial 1907 discovery well gushed oil 50 ft into the air, and the field was developed over a period of decades, adding many additional producing wells through the years (Gregory 1909, 1917, 1938; Woodruff 1912; Wengerd 1951, 1955; Borden 1952; Wengerd and Strickland 1954; Kunkel 1961; Matheny 1964; Huber 1973).

The second Paradox Basin field was not discovered until the 1950s. Within a two-year period, the local petroleum industry exploded from some cleanup activities at one near-depleted field to eleven new fields with more than 2,000 wells and thousands of productive acres, all because of a better model developed following the discovery of Aneth field (Spalding 1955; Carter 1958). Production now extends along a large trend across the southern edge of the Paradox Basin into Colorado and New Mexico.

It took 43 years and 27 exploratory wells in what seemed to be the "best possible" locations before the first producing well was drilled in the Kaiparowits basin (Campbell 1969; Kornfeld 1964).

In Arizona, the largest field in the state, Dineh-Bi-Keyah (Kornfeld and Travis 1967; McKenny and Masters 1968; Williams and Roth 1969), is located on the crest of the Defiance Uplift. This is a region where the lower Paleozoic section is essentially absent, except for tiny remnants; where theory would doubt the possibility of any significant-size source units. Small source beds theoretically could exist in the Pennsylvanian section, but conventional wisdom states that these reservoirs should be too limited in size to have produced a field as large as Dineh-Bi-Keyah. In addition, the Pennsylvanian reefs were generally very tight, precluding migration of significant resource into an adjacent unit, as at Dineh-Bi-Keyah. If a sizable source existed, conventional ideas of burial depths on the uplift make it doubtful that there was ever sufficient cover to bring the sediments to maturity. Granting that the oil obviously did mature, the nature of the reservoir is peculiar. Dineh-Bi-Keyah produces from an unlikely formation: an igneous sill. This reservoir was originally overlooked when the initial well was drilled. Kerr-McGee had plugged the discovery well before taking a second look at the reservoir.

The shows around Alpine (Rauzi 1994) associated with the recent geothermal well on the Mogollon Slope indicate that there are other potentially productive locations in areas that should theoretically hold little potential for hydrocarbon production. Whereas many of these plays may be small, the Oraibi Trough region beneath the central Black Mesa holds great potential for larger reservoirs and resources. Large closed anticlines in the western portion of the basin are a logical target for early testing.

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