Prediction of Fractured Reservoir Production Trends and Compartmentalization Using an Integrated Analysis of Basement Structures in the Piceance Basin, Western Colorado

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ABSTRACT

Subsurface structures control fractured production trends in most Cretaceous-age Mesaverde Group gas reservoirs in the Piceance Basin. Nearly all of these subsurface structures are directly related to deeper basement fault trends. Above these basement zones, fracture permeability is enhanced in the tip zone terminations where these basement-related thrusts terminate up-section. To identify these basement structural trends, a new integrated interpretation of basement structure and shallower production trends was conducted using gas production data, detailed aeromagnetic data, seismic surveys, well data, Landsat Thematic Mapper (TM), Side-Looking Airborne Radar (SLAR), aerial photography, and published outcrop maps. This new interpretation illustrates the critical control of basement structures on the development of shallow structures and related fracture-controlled production in the hydrocarbon-bearing intervals. We have demonstrated the ability of the methodology to accurately predict fractured reservoir production trends in Grand Valley-Parachute and Rulison fields in the Central Piceance Basin. We have used the Divide Creek Field in the southeast Piceance Basin to illustrate that reservoir compartmentalization can also be identified and predicted using the integrated methodology.

The most prolific gas fields in the Piceance Basin (Grand Valley, Parachute, Rulison, Plateau, Shire Gulch, White River Dome, and Divide Creek fields) produce gas from fractured tight gas sands and interstratified coal reservoirs within the Mesaverde Group. Given the low matrix permeability of this stratigraphic interval, tectonic fracturing related to basement structures is critical to the development of permeability and concomitant economic production. The close relationship between basement structures and fracture-controlled production trends underscores the importance of using an integrated methodology to characterize basement deformation and fractured reservoir production.

This integrated methodology uses data from widely-available, relatively inexpensive sources such as detailed aeromagnetics, remote sensing imagery, and regional geologic syntheses to develop and calibrate an internally consistent interpretative tool. The tool predicts subsurface fractured reservoirs controlled by basement features as target areas for exploration drilling, and related development programs. This internally consistent interpretation minimizes the subjectivity that has long plagued the results which arise from use of these methods by themselves.

INTRODUCTION

We applied an integrated fractured reservoir detection methodology to the Piceance Basin. The methodology involves the interpretation and integration of well data, aeromagnetic, seismic, and remote sensing imagery, within the context of a detailed regional tectonic synthesis (Hoak and Klawitter, 1995; 1996). Integration of these different independent data sets is critical to minimize the subjectivity and ambiguity that occurs when only a single data set and interpretation are used. Several Piceance Basin gas fields are used to demonstrate how this method allows us to understand and predict trends of fracture-controlled production. In the early development of the Piceance Basin, few gas fields were thought to contain fractured intervals. At that time, fields producing from fractured reservoirs included White River Dome, Divide Creek Anticline, and the Rulison Field (Brown et al., 1986). Since then, other fractured reservoirs have been confirmed by recognition of natural fractures in cores (Lorenz et al., 1988; Tyler et al., 1995), and wireline fracture logs from Grand Valley and Parachute fields (Reinecke et al., 1991), and from Plateau and Piceance Creek fields (T. Barrett, personal communication, 1994; 1995; 1996). The density of fractures in core from these areas has been summarized by Tyler et al. (1995). Given the extremely low permeabilities (5-30 microdarcies) observed in all Piceance Basin Cretaceous-age gas reservoirs (Reinecke et al., 1991; Lorenz et al., 1991; Lorenz and Finley, 1991), commercial production cannot occur except where natural fractures are present. Data collected by DOE researchers at the MWX site confirm that a production increase of over two orders of magnitude occurs when natural fractures are present (Lorenz et al., 1991; Lorenz and Finley, 1991). Figure 1 illustrates the location of the primary gas fields in the basin and those used in this study.

After a general overview of the Piceance Basin, and a discussion of the controls on gas production in this region, the following text is divided into two primary sections. The first section outlines the ability of the integrated exploration methodology to predict fractured reservoir production trends in the Central Piceance Basin. The second section demonstrates the ability of the methodology to identify structural-controlled reservoir compartmentalization in the Divide Creek Field located in the southeast Piceance Basin.

In both areas we demonstrate that an integrated analysis provides a cost-effective method to rapidly define regional structural trends, and to delineate potential zones of enhanced fracturing. Vigilance must be exercised, however, to insure that interpreted structures accurately reflect subsurface features, especially given the subsurface structural complexity in the Piceance Basin. The power of an integrated interpretation approach lies in its ability to cross-check hypotheses between data sets that do not, by themselves, provide unique geologic solutions. Additionally, the use of multiple, independently derived data sets constrains interpretation possibilities. Confirmation of the reservoir scale complexity of all fractured zones requires additional, detailed analysis to acccurately decipher the reservoir scale sedimentologic and fracture-related heterogeneity. Despite these restrictions and limitations on the application of integrated methodology procedures, we believe that this methodology represents the most cost-effective system to target potential exploration areas while maximizing the opportunity for successfully delineating fractured reservoir production trends.

OVERVIEW OF THE PICEANCE BASIN

The Piceance Basin is a Laramide-age, elongate, NNW-trending structure that was formed by basement-involved thrust tectonics (Figure 2). Thrust-cored structures of the Axial Arch and the Uinta Uplift define the northern basin boundary (Osmond, 1986; Richard, 1986). The sinuous eastern margin is formed by the basement-involved, thrust-cored, Grand Hogback Monocline lying along the western edge of the White River Uplift (Poole, 1955; Murray, 1966). The western boundary is formed by the N-trending Douglas Creek Arch which separates the Uinta and Piceance basins (Johnson and Finn, 1986). To the southwest, the Uncompahgre Uplift forms the basin boundary. To the southeast, the West Elk Mountains and the Gunnison Uplift forms the southeast boundary. All of the uplifts surrounding the basin have enjoyed multiple tectonic deformations extending from the Precambrian through the Pennsylvanian-Permian, culminating in the Laramide thrusting that formed the modern basin geometry (Tweto, 1980).

CONTROLS ON PICEANCE BASIN GAS PRODUCIBILITY

There are two primary controls on gas production in the Central Piceance Basin. Because most of this area has been clearly documented as being gas-saturated (e.g. Reinecke et al., 1991; Johnson and Nuccio, 1986; Johnson, 1989; Lorenz et al., 1991; Hoak and Decker, 1995), the two remaining controls on economic production in this area are reservoir thickness, and permeability or wellbore deliverability. The primary reservoir in this area is composed of lenticular fluvial channel sandstones of the Williams Fork Formation, part of the Mesaverde Group. The discontinuous and lenticular nature of these sands is clearly evident in Figure 3. This figure, for a U.S. Department of Energy production well (DOE 1-M-18, Sec 18, 6S 94W), shows the log traces and interpreted sand bodies for a junked wellbore, and a sidetrack recompletion that clearly demonstrates the difficulty in predicting sand thickness and reservoir quality. Initial drilling and logging operations found approximately 60 feet of net pay sandstone in the Mesaverde fluvial channel sands. During completion operations, the initial hole was lost after logging operations were completed. After the initial wellbore was lost, a sidetrack wellbore was completed and logged. The initial wellbore shows 60 feet of net pay sandstone. In contrast, the sidetrack well, with only 142 feet horizontal difference in bottomhole location, shows 120 feet of net pay sandstone. This large difference in net pay thickness underscores the problem of trying to predict reservoir sand thickness in advance of drilling for the fluvial sands of the Mesaverde Group reservoirs that dominate gas production throughout the basin. Nearly all sands in this area show a dramatic thinning between the two wellbores and several of the larger

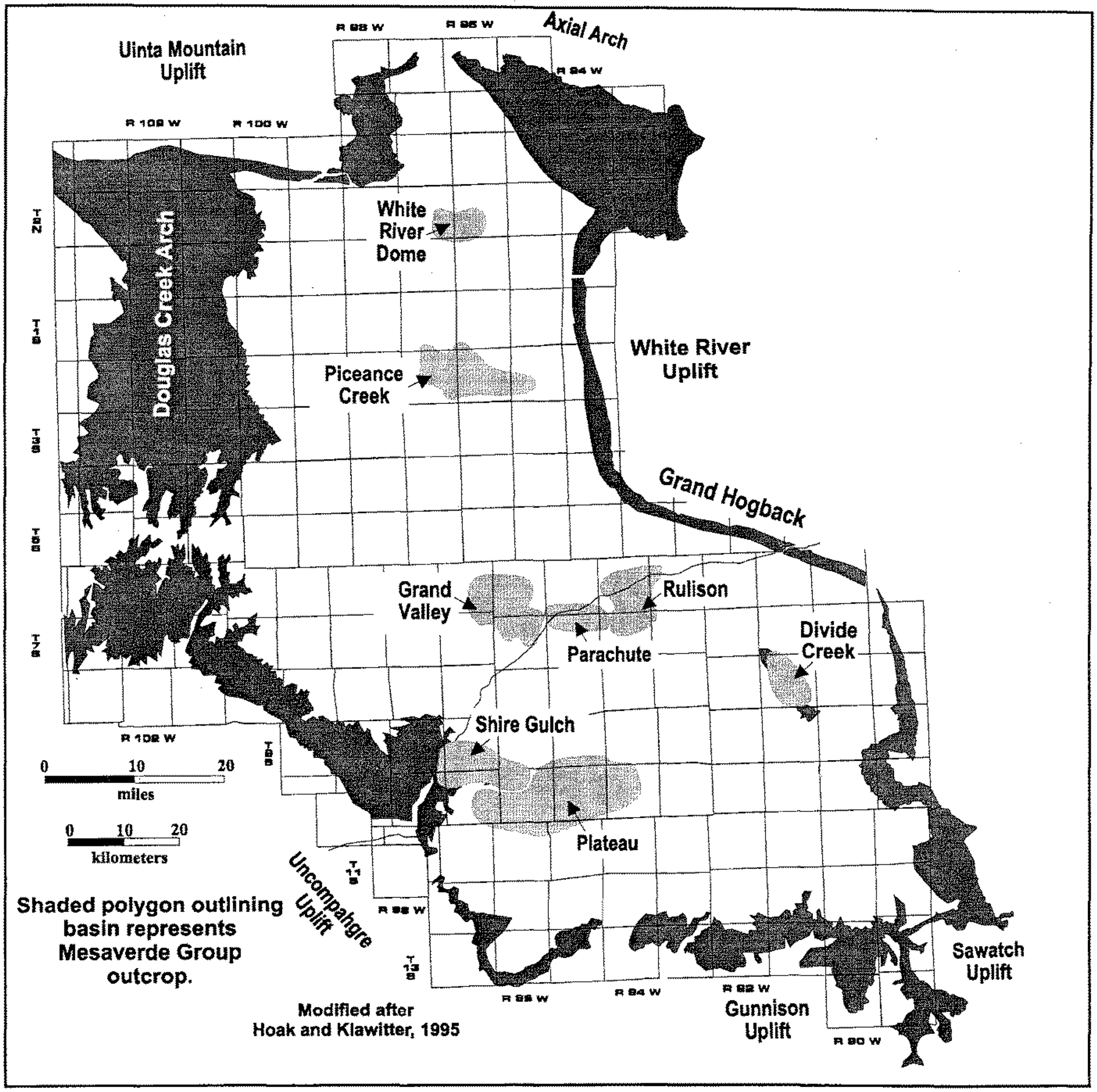


Figure 1. Location map of selected major gas fields in the Piceance Basin. See text for discussion.

sand packages cannot be correlated with certainty between wells. These relationships, combined with the current minimum requirements for well spacing (40 acres at present), effectively preclude accurate sand correlation between wells and efficient reservoir drainage.

To date, we have not encountered any methodology that will accurately predict, in advance of drilling, reservoir sand thickness in the central Piceance Basin. Recently, however, significant progress in understanding the complex depositional systems has resulted in a greatly improved predictive sedimentologic tool (Lorenz et al., 1991). However, this methodology has not been applied to the basin in an exploration methodology. In addition, delineating the orientation of sand bodies with this method requires detailed subsurface data not generally available to the exploration geologist, and data sets that are not typical of most tight gas reservoirs.

As a result of the limits on depositional systems predictability, we have chosen to focus our efforts on minimizing exploration and development risk by developing

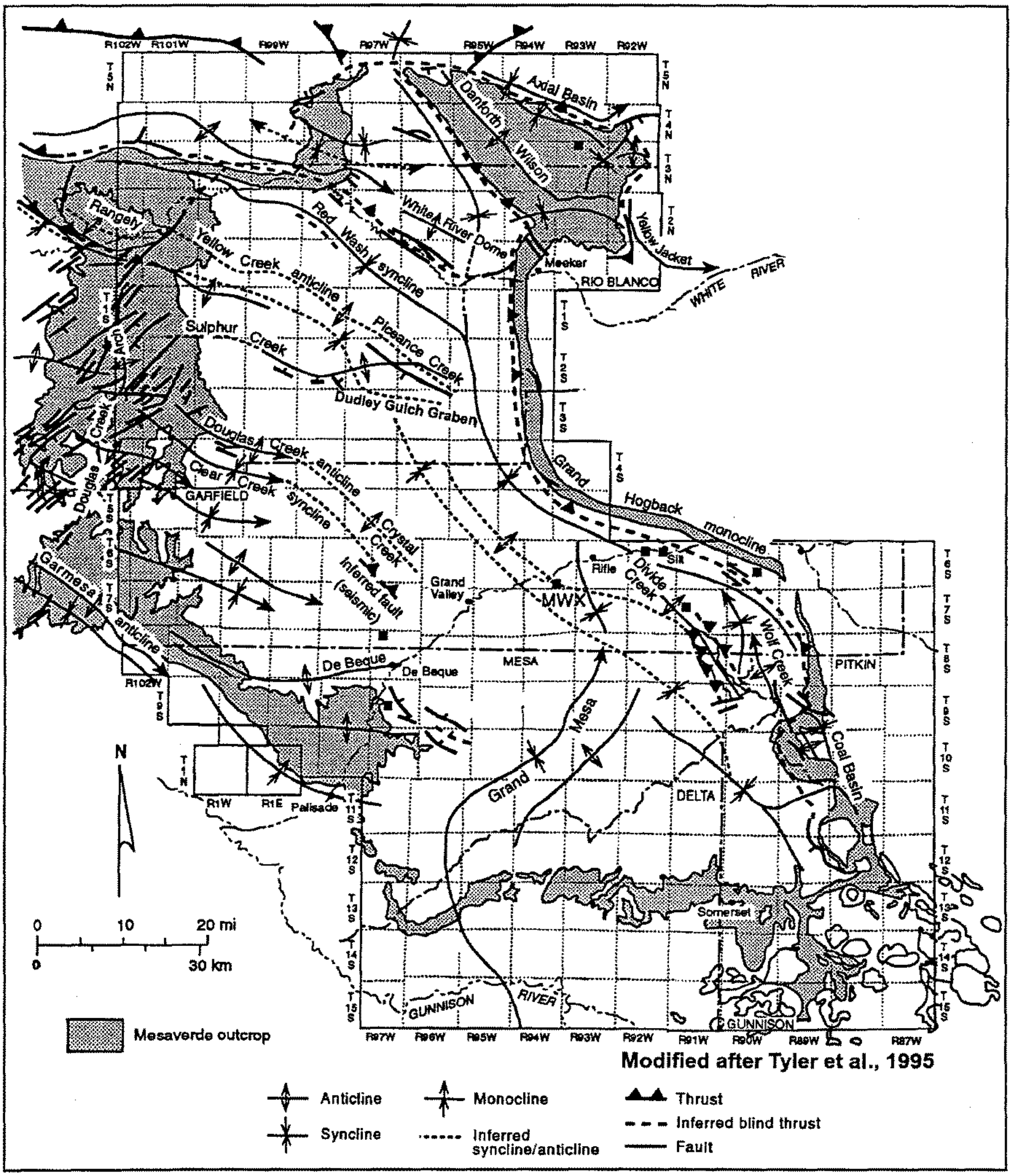


Figure 2. Major tectonic elements of the Piceance Basin. Note differences in dominant structural trends between the central and eastern basin (dominated by NW-trends), and the western basin, (dominated by WNW and E/W trends).

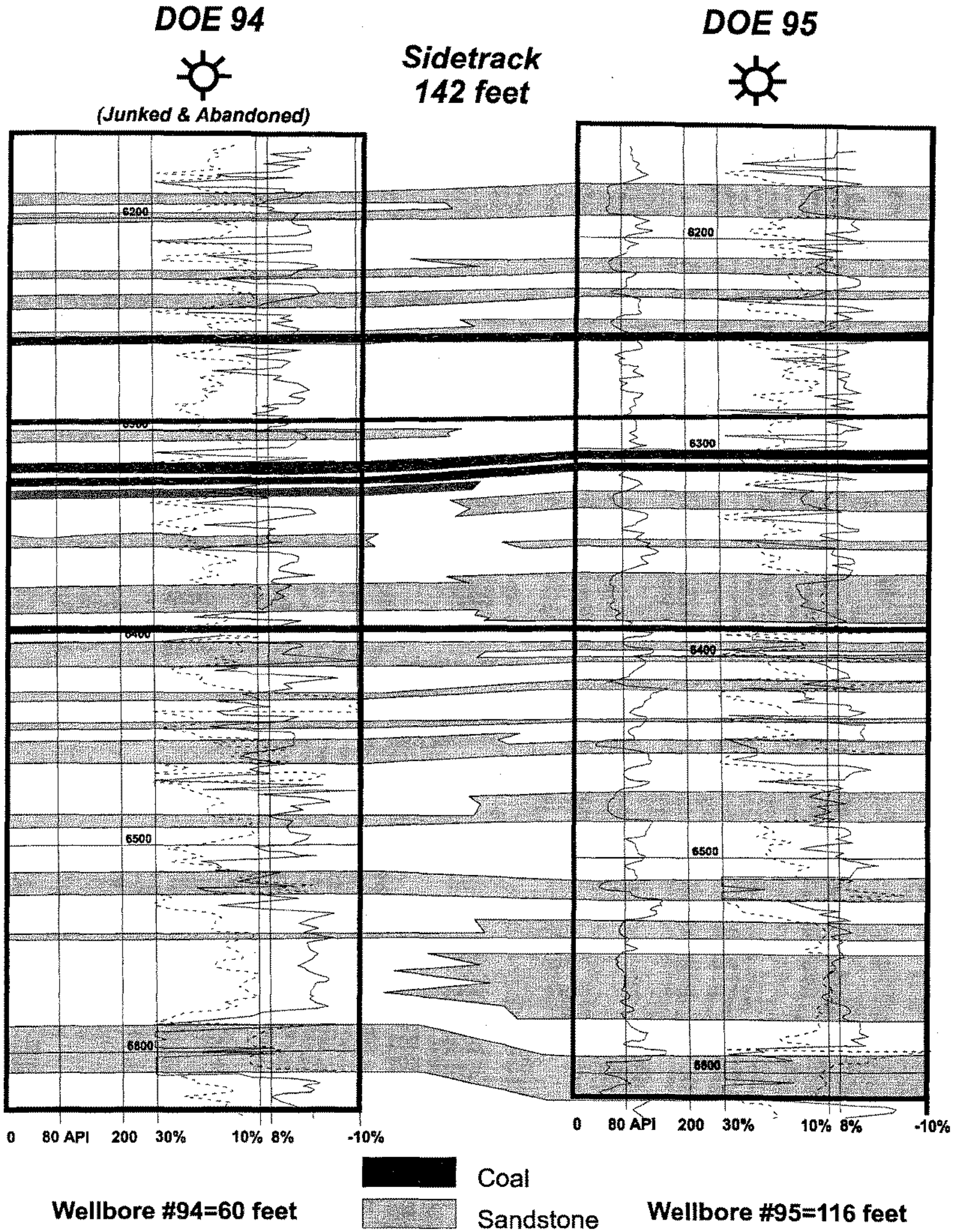


FIGURE 3. Comparison of net pay sandstone for the DOE 1-M-18 wellbore and sidetrack recompletion (sec 18, T8S, R94W). Total clean sand, defined by gamma ray <80 API units, shows a tremendous difference between the original logged wellbore and the sidetrack recompletion. There is only a 142 feet difference in bottomhole location between the two wells. This underscores the difficulty in predicting reservoir thickness in advance of drilling.

the ability to predict fractured reservoir production trends through the integrated analysis of diverse geological and geophysical data sets. By accurately predicting the presence of fractured reservoir conditions, a tremendous increase in wellbore deliverability and production (relative to less or unfractured zones) can be achieved with minimized operator risk. When potential fractured zones have been delineated, additional and more costly characterization technologies such as 3-D seismic, azimuthal AVO processing, and crosswell seismic, can be more effectively designed to characterize subsurface reservoir conditions.

Although simplification of basin geology to the two primary controls of fractures and reservoir thickness is most valid for the Central Piceance Basin, we believe that most of these considerations can be extended to other parts of the basin, and to analogous low permeability hydrocarbon-bearing systems. In these analog areas, of course, additional work must follow a conventional process of delineating source beds, thermal evolution, migration history, trap type, and seal integrity of the reservoir, before application of the integrated fractured reservoir detection methodology.

APPLICATION OF THE METHODOLOGY TO THE CENTRAL AND SOUTHWEST PICEANCE BASIN: GRAND VALLEY-PARACHUTE-RULISON AND PLATEAU-SHIRE GULCH FIELDS

The following discussion documents the stratigraphic and structural relationships to gas production for fields in the central and southwest Piceance Basin. From this starting point, we then outline subsurface structure, and the basement control on these subsurface structures. This interpretation is integrated and confirmed with seismic and detailed aeromagnetic data to extrapolate structural trends to areas where adequate conventional subsurface control is lacking. Finally, we use remote sensing data, Landsat Thematic Mapper (TM) and Side-Looking Airborne Radar (SLAR), to assess the relationship between surficial data and subsurface structures.

Gas Production Trend Controls: Structure and Stratigraphy

Controls on fractured reservoir production trends were assessed by overlaying maps of stratigraphy and structure data onto production trend data. This mapping was accomplished in Grand Valley, Parachute, Rulison, Shire Gulch, and Plateau fields (see Figure 1 for locations). Gas is produced from the Cretaceous-age Willians Fork Formation from all fields; additionally, gas is produced from the Tertiary-age Wasatch Formation in the Grand Valley, Parachute, and Rulison fields and the Cretaceous-age Iles Formation in the Plateau and Shire Gulch fields. In these reservoirs, gas is trapped in regional, structurally-enhanced basin-centered gas traps. In the Williams Fork, most gas is produced from fluvial channels, and from thick coal seams in the underlying Cameo Coal section. Production in the Cozzette-Corcoran marine sands (Iles Formation) is dominated by lithofacies present in the transition between marine and fluvial systems. Plateau and Shire Gulch fields straddle the transition zone and represent the location of a paleoshoreline trend. For discussions of reservoir sedimentology and regional stratigraphy, see Johnson and Nuccio (1986) for the Mesaverde Group, and Brown et al. (1986) for the Iles Formation sandstones. Lorenz et al. (1994) and Tyler et al. (1995) have also described the sedimentology of the Mesaverde Group in detail.

Central Piceance Basin Gas Fields

For the Grand Valley, Parachute and Rulison fields estimated ultimate recoverable (EUR) gas production data were obtained from Barrett Resources (T. Barrett, personal communication, 1997). These EUR data include actual and predicted production potential from the Williams Fork fluvial section, the Cameo Coal group, and unperforated producible intervals still behind-pipe at shallower levels. In all three fields, especially in Rulison Field, the zones of enhanced production and maximum EUR trend NW, parallel to the basement structure. To assess production controls, production data were contoured and correlated with sand thickness data and structural data contoured on the top of the Rollins Sandstone Member of the Iles Formation (Figures 4 and 5). Figure 4 illustrates the relationship between structure and production trends in the three fields Note that the production trends lie parallel to local structure trends in the three fields. In all three fields, the regional structure trends NW, parallel to the overall trend of the production contours. Zones of enhanced production are closely associated with areas where a local flexure is best developed. This relationship strongly suggests a structural control on fractured reservoir production.

In order to assess the effect of stratigraphic variation, a total sand isochore map was compared to production trends for Grand Valley, Parachute and Rulison fields (Figure 5). The depositional system consists of complexly anastamosing, interbedded fluvial channels. In general, it is extremely difficult to predict the location of thick Williams Fork Formation reservoir sands due to complex internal variability in the meander belt system. The overall depositional trend of the fluvial meander belt trends to the northeast (Peterson, 1984). More recent work in the coal-bearing interval of the Williams Fork Formation has confirmed that the depositional systems possess a NE trend in the Rulison Field, but possess a NW orientation in Parachute and Grand Valley fields (Tyler et al., 1995). We have been able to obtain considerable detailed

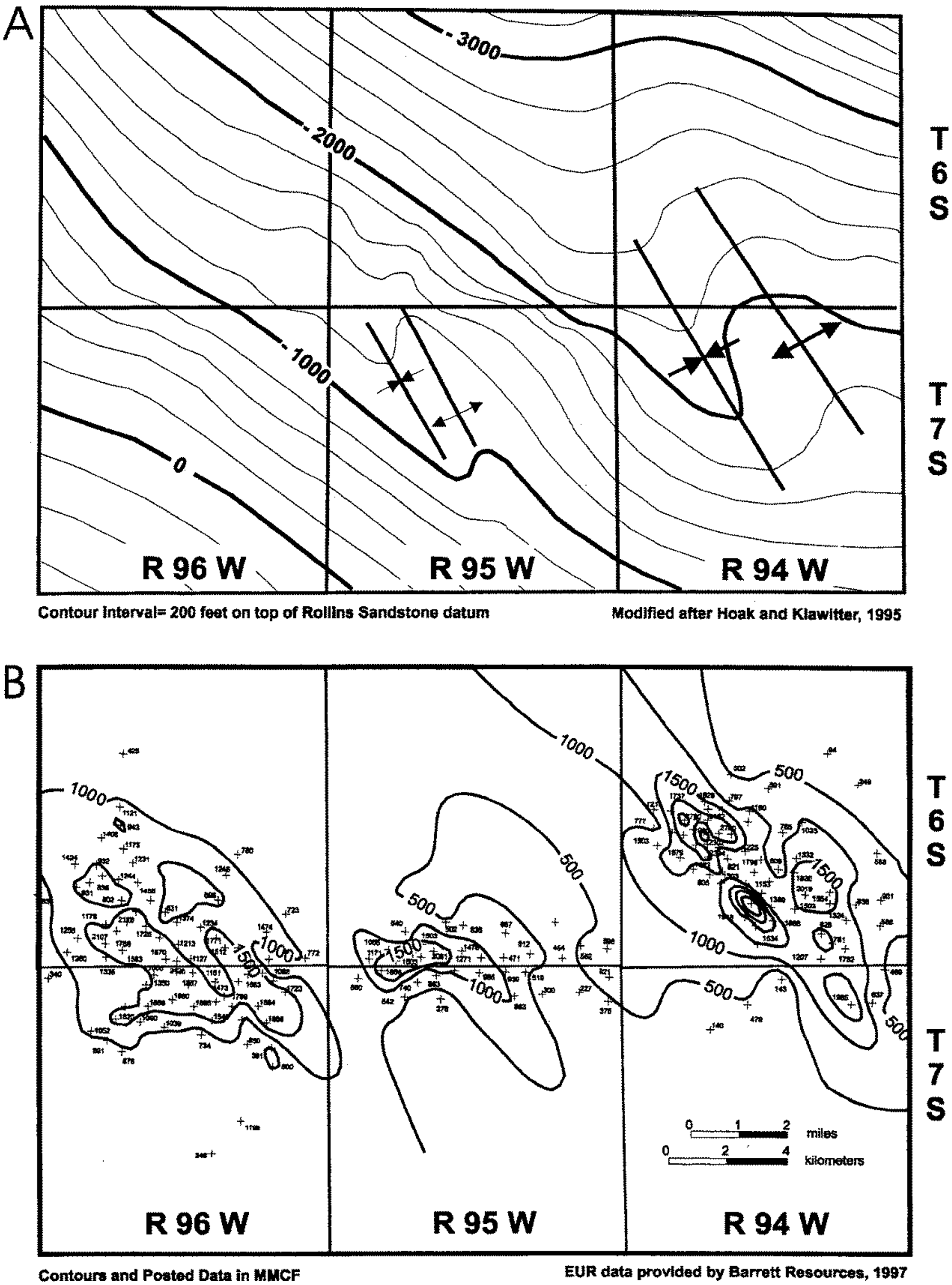


FIGURE 4. Comparison between (A) structure (Top Rollins Sandstone) and (B) estimated ultimate recoverable (EUR) data for the Grand Valley-Parachute-Rulison fields. Note how areas of enhanced production in Rulison and Parachute fields directly overlie the areas where local folding is most pronounced. Overall, there is a close correspondence between the NW-orientation of the structure and the NW-trending EUR contours. Neither of these trends parallels the subsurface fracture azimuth in the reservoirs (WNW or N 70 W). See text for discussion.

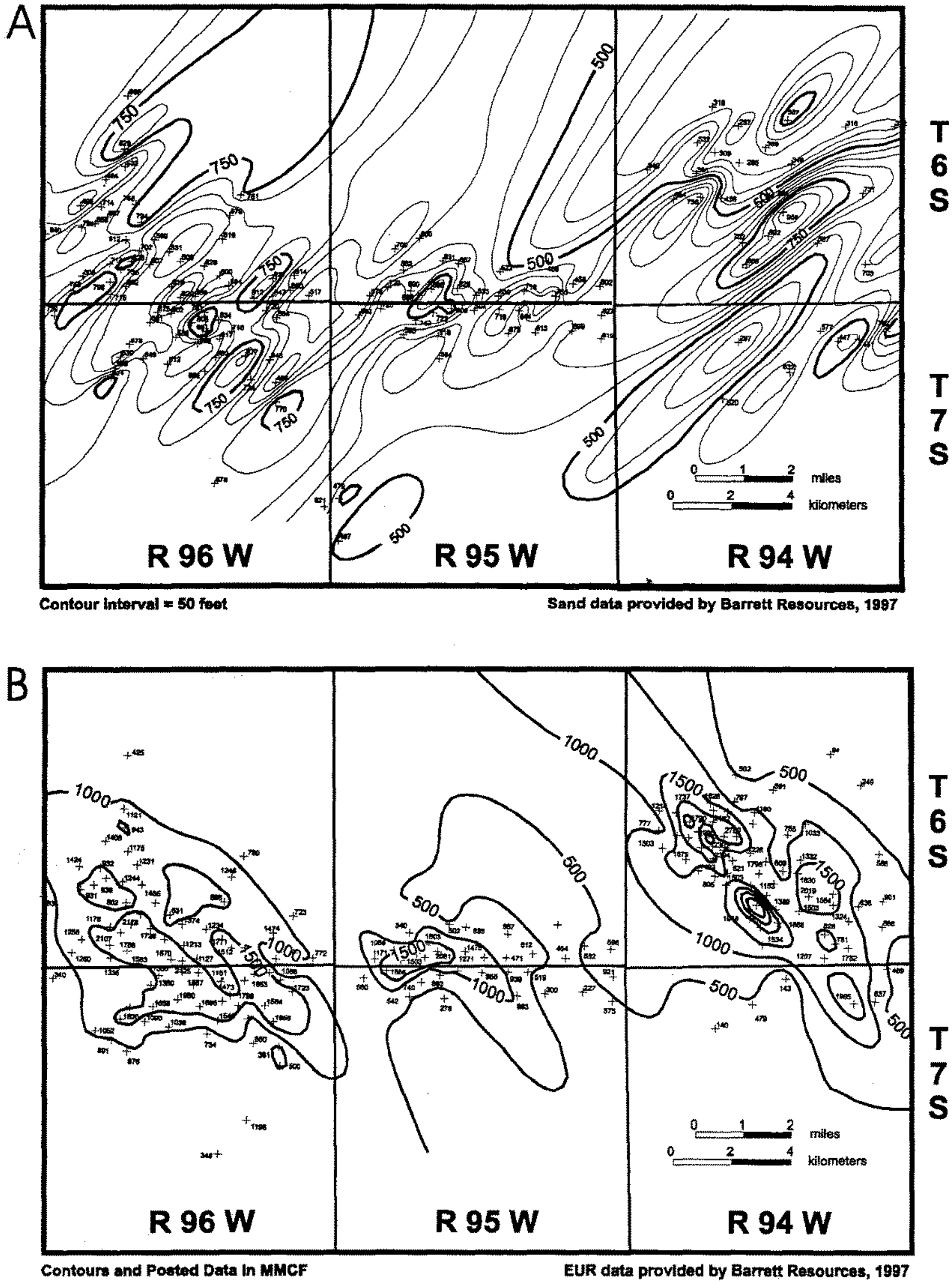


FIGURE 5. Comparison between (A) sand thickness (<80 API units gamma ray) and (B) estimated ultimate recoverable (EUR) data. Note that EUR trends lie perpendicular to maximum sand thicknesses. Most importantly, areas of enhanced production do not overlie areas of greater sand thickness. This strongly indicates that sand thickness is not the primary control on wellbore quality and deliverability. See text for discussion.

reservoir sand data from the field operator, Barrett Resources, to assist our interpretation (T. Barrett, personal communication, 1997). The NW-striking production trend lies perpendicular to the depositional systems trends (Figure 5), confirming the dominance of structural control on the zones of enhanced production in Rulison field where the greatest production is observed. This is a function of the overpressure in Rulison and the greater intensity of natural fractures. Natural fractures measured from fracture detection logs and oriented core in the three fields lie oblique (WNW-trend) to the production trends observed in the central basin (Lorenz and Finley, 1991). It is important to note that the NW-striking production trends and local structure lie oblique to the dominant WNW or E/W fracture trends measured during the extensive and thorough MWX coring program completed in both vertical and horizontal wells (Lorenz and Finley, 1991). There are several possible explanations for this relationship.

The obliquity between the well-documented WNW-oriented fracture systems seen at the MWX site and the NW-oriented production trends in Rulison and the adjacent fields appears problematic. Although several workers have mapped the EUR contours to parallel natural fracture trends, the data clearly show that this interpretation is invalid (see Figures 4&5; T. Barrett, personal communication, 1997). It is necessary to develop a more sophisticated argument to explain these observations.

The most plausible explanation is that local tectonic deformation caused by structures, such as the Rulison Anticline, generates enhanced dilatancy along pre-existing, "regional" fracture sets oriented oblique to the structure. The zone of dilatancy, however, parallels the structural axis, not the trend of the subsurface fractures. This model agrees with the detailed work of Lorenz and Finley (1991), and Lorenz and Hill (1994), who interpret the WNW or E/W fractures as part of a regional set that is found throughout the eastern and central Piceance Basin. Evidence of overprinting fracture sets and shear reactivation of the "regional" set is not present . Figure 6 illustrates the characteristics of this model. Note that although the "regional" WNW fracture set is present in most areas, and is critical to production, the WNW fracture set is most important where the local NW-trending Rulison anticlinal flexure enhances permeability. It is parallel to this flexure that we see a profound production enhancement. In the model (Figure 6), tectonic folding also enhances the propagation of older fractures to form linkages between individual fractures. These linkages greatly enhance reservoir connectivity and wellbore deliverability. Although similar zones of enhanced production are observed in the Parachute and Grand Valley fields, the intensity of the local flexure is not as significant as at Rulison so that the increase in permeability is less. Also, it should be mentioned that Rulison lies in a zone of reservoir overpressure and has been able to sustain higher production rates compared to the other two fields.

Alternative explanations, including those in which the WNW fracture set formed later, are not supported by the detailed field studies of fracturing that have been completed (Lorenz and Finley, 1991; Lorenz and Hill, 1994). A third possible explanation is that the MWX and SHCT coring program fortuitously cored only the E/W or WNW fracture trend and did not manage to intersect a more NW-trending dominant set that controls production. Lorenz and Hill (1994) calculated the probability of this circumstance and demonstrated that the SHCT coring program followed a trend which would have cored any fracture orientation given the observed frequency and orientation of fractures in the basin. As a result, these alternative explanations are dismissed in favor of our model.

Southwest Piceance Basin Gas Fields

Production data from Corcoran and Cozzette Sandstones (Iles Formation) in Plateau and Shire Gulch fields were also correlated to structural and stratigraphic data. (Figures 7 and 8). Structure contours on the Rollins Sandstone show that the regional structure in this area is composed of a WNW-trending series of broad, open anticlines and synclines that lie subparallel to the underlying basement fault systems (Donnell et al., 1984). Eastward, these folds die out into the regional NW-trending, east-dipping western synclinal limb of the basin. The WNW-trending folds appear to have formed late in the tectonic evolution of the basin, and are thought to be related to differential subsidence over basement fault zones because they appear to affect only post-Laramide sediments; however, the obliquity between folds and faults suggests a more complex relationship. Additional subsurface, especially seismic data, are necessary to confirm this interpretation. A Rollins structural datum was used in these two fields for consistency with regional maps and because of the large amount of Rollins data. The deeper Corcoran-producing horizon structure is nearly identical to that of the Rollins datum. This relationship is confirmed by isochores of the Rollins-Corcoran interval that show a uniform south-eastward-dipping surface. Plateau and Shire Gulch production trends strike northwest, parallel to the orientation of faults mapped on the outcrop (Donnell et al., 1984). Production trends lie parallel to the trend of mapped surface faults and basement fault zones. However, it should be emphasized that there is a slight obliquity between the structural trend of the field and production contours for these two fields (Figure 7).

Corcoran-Cozzette paleoshorelines trend northeast (Zapp and Cobban, 1960; Brown et al., 1986), perpendicular to the trend of the production axes (Figure 8). The paleoshoreline separates nearshore continental and offshore marine facies. The boundary between the two facies is based primarily on the presence or absence of coal in the subsurface. There appears to be little stratigraphic variation along the northeast paleoshoreline trend (Zapp and Cobban, 1960; Warner, 1964; Brown et al., 1986). Some complexity appears

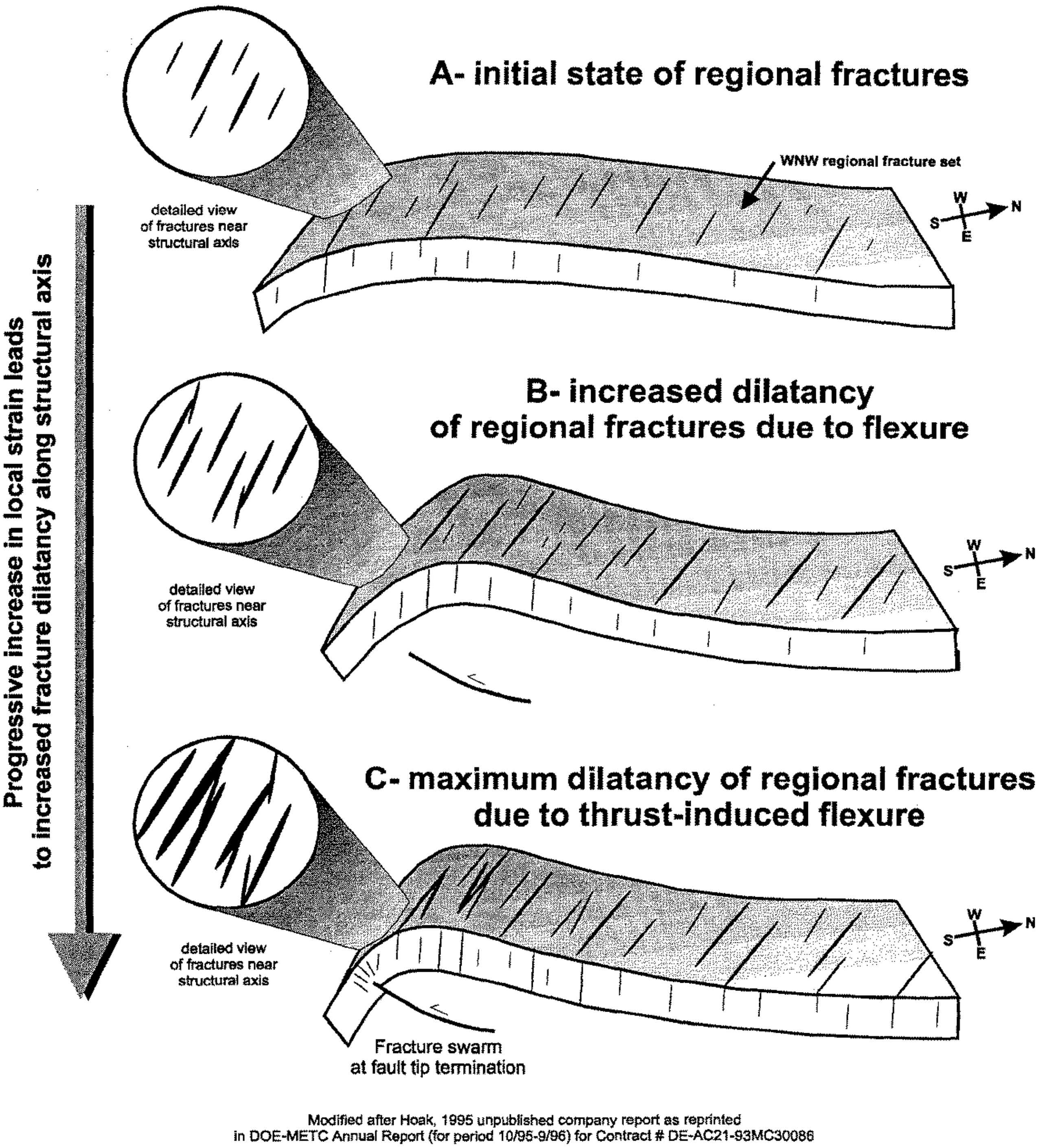


FIGURE 6. Tectonic fracturing model for Rulison Field. An initial rock slab containing a regional fracture set experiences increased dilatancy along these fractures, most noticably in the area of the flexure, as rock strain increases (A-C). Flexure is assumed to be related to subtle thrust structures as indicated in later figures and text. The flexure is not parallel to the trend of the regional fractures, as has been documented at Rulison. At thrust terminations, additional fracture swarms develop. At time of maximum dilation, fractures propagate and develop enhanced connectivity despite their lack of parallelism with the local structure. Fractures develop and propagate because of the pronounced pre-existing anisotropy along which additional failure is more easily accommodated, rather than failure of intact rock.

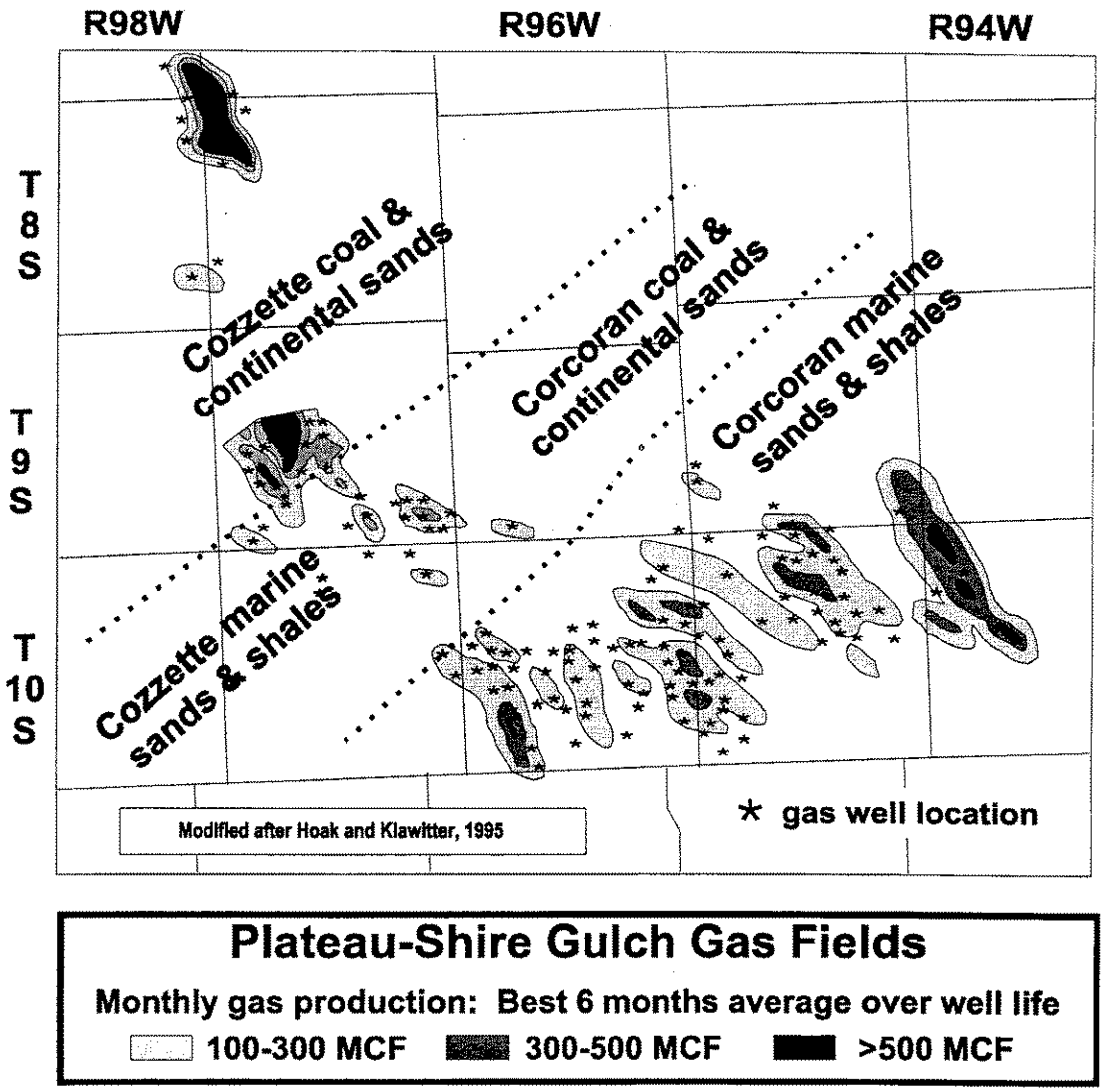


FIGURE 7. Comparison between stratigraphic trends and gas production rates (monthly rate, normalized for the best six months of production) for Plateau and Shire Gulch fields. Note that the overall depositional trends are oriented to the NE, perpendicular to the trends of the maximum production rates.

to occur in the continental facies regarding the relative influence of fluvio-deltaic vs. wave-dominated facies (Warner, 1964). There is some evidence that some of the wave-dominated sediments have been reworked (Warner, 1964). This reworking makes it more difficult to interpret and predict local reservoir sand continuity for accurate reserve calculations. The inability to predict reservoir sand quality and continuity in these fields makes the ability to predict fractured reservoir production trends even more important. By successfully implementing our integrated methodology, one can minimize exploration and development risk by outlining the boundaries of zones of enhanced production. In Plateau and Shire Gulch fields, it appears that identifying basement fault trends is the key to identifying and predicting production trends, given that depositional and flexure-related controls are less obvious or absent.

REGIONAL STRUCTURAL GEOLOGY

Structural mapping in Plateau, Shire Gulch, Grand Valley, Parachute and Rulison fields clearly demonstrates that local structure (faults or flexures, respectively) parallels production trends. To identify additional regional or basin-scale fractured reservoir exploration prospects, regional structure mapping was used to locate those areas where local structure will likely control fractured production trends (Figure 9). On this map, constructed on the top of the Rollins Sandstone, regional structural geometries have been delineated. Although the Rollins Sandstone Member is a

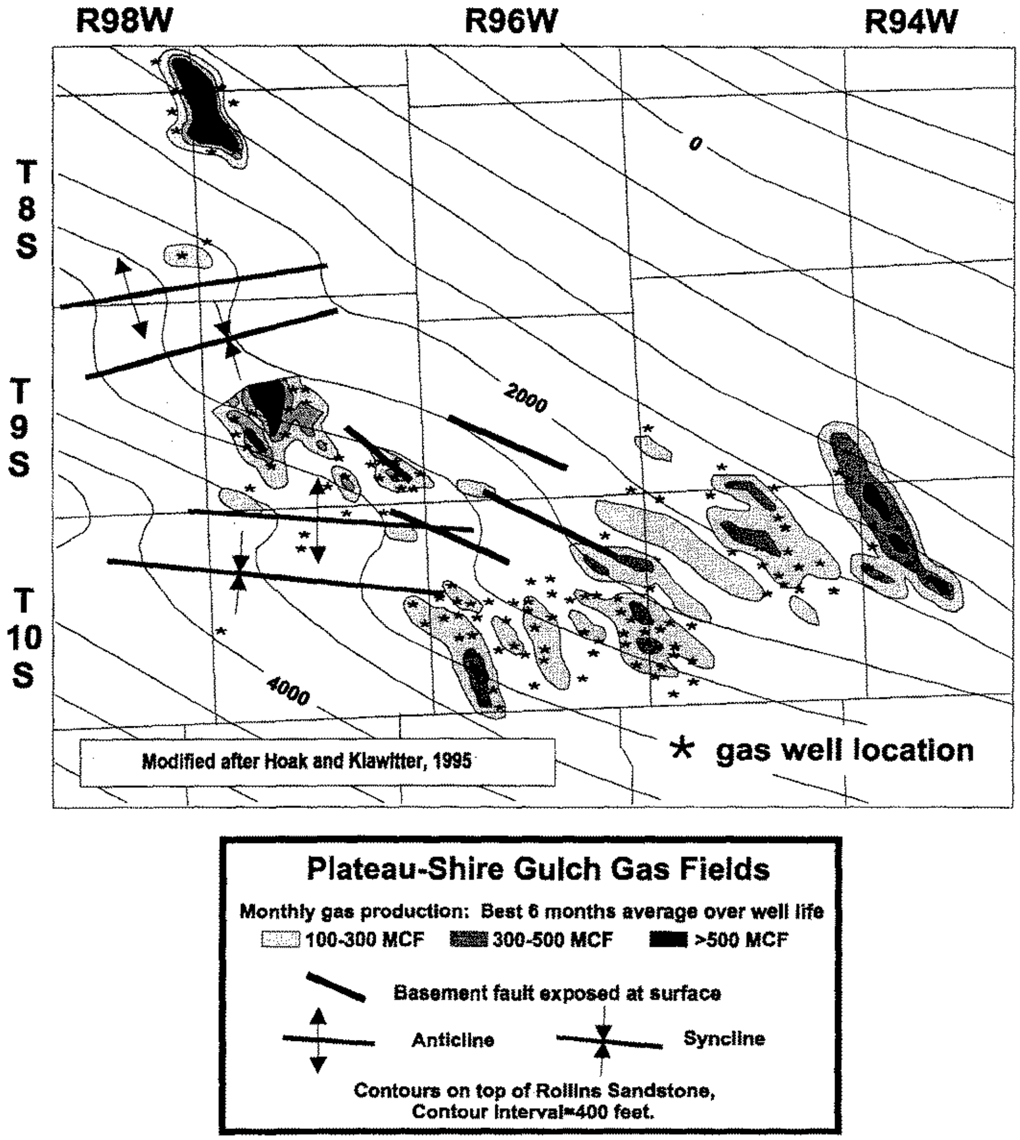


FIGURE 8. Comparison between structural trends and gas production rates (monthly rate, normalized for the best six months of production) for Plateau and Shire Gulch fields. Note that the overall structural trends are oriented oblique or subparallel to the trends of the maximum production rates. Instead, maximum production rates parallel basement fault trends, confirmed in seismic and aeromagnetic data, that also crop out on the surface. These surficial fault traces can be identified using remote sensing imagery analysis and confirmed by field mapping.

progradational system, shingled toward the southeast, the magnitude of shingling is small (<100ft.), such that regional structure maps are not greatly affected by this geometry. Detailed structural studies of gas fields throughout the basin are even less affected because the vertical variation caused by shingling is generally imperceptible within the boundaries of most Piceance Basin gas fields.

In the Piceance Basin, there are three dominant structural trends (Figure 9). In the eastern basin, NW-trending structures such as the Divide Creek, Wolf Creek and Coal Basin anticlines have been formed by WSW-directed thrusting (Grout et al., 1991; Gunneson et al., 1995). In the western basin, several broad, low amplitude E/W-trending anticlines are present, superimposed on the N/S trend of the Douglas Creek Arch and adjacent areas. These anticlines include the Debeque, Bull Creek Anticline (Figure 9, also see Hoak and Klawitter, 1995, located to the south of the Debeque Anticline in Plateau Field), and the Douglas Creek Anticline. The Douglas Creek fold possesses a WNW orientation. To the north, located on the Axial Arch, a WNW-trending fault-bend fold formed during south-directed Laramide thrusting (Stone, 1986). The last significant trend is the N/S trend exhibited by sections of the Hogback Monocline between Meeker and Rio Blanco, and from Carbondale to the West Elk Mountains.

By analogy with other fractured reservoir fields in the

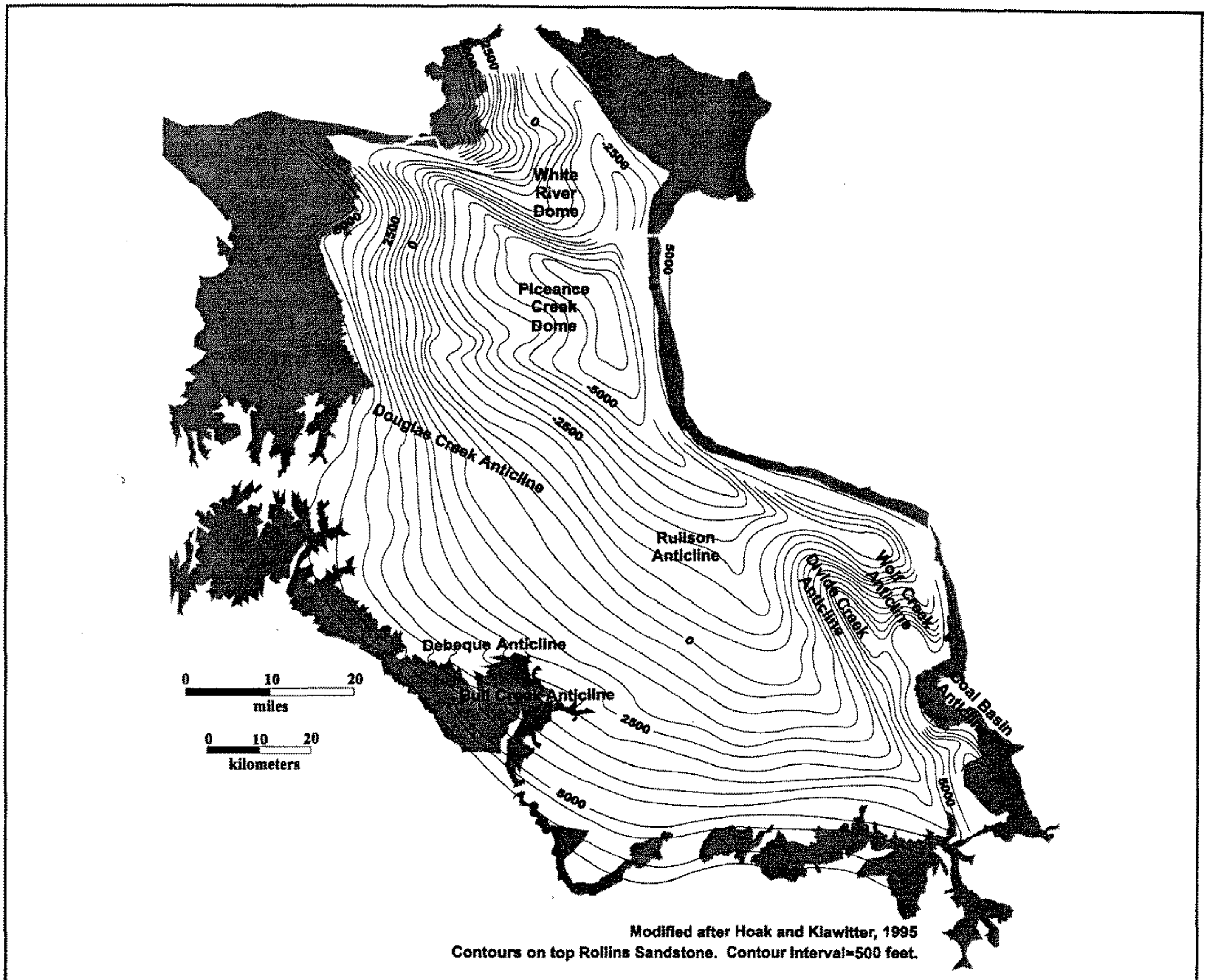


FIGURE 9. Structural features of the Piceance Basin revealed by a structure map on a Rollins Sandstone datum. Text labels parallel local structural trends. Note the differences in structural trends in different parts of the basin. Compare with Figure 2 for additional structural features.

basin, preliminary analysis of the regional structure map suggests that fractured reservoir conditions should be present in several of the anticlines along the southeastern flank of the Douglas Creek Arch. Proprietary core descriptions from these areas confirm that several of these reservoirs are indeed fractured. A limited summary of these wells is presented in Tyler et al. (1995). In the northern basin, the Powell Park and Sulphur Creek structures are likely to be fractured given their structural similarity to other fractured anticlines. Limited core control, combined with a lack of detailed aeromagnetic and seismic data in these areas, requires additional effort in order to fully delineate the fractured reservoir exploration potential of these structures.

Piceance Basin thrust-cored folds include the Grand Hogback (Gries, 1983), Wolf Creek Anticline (Grout, 1990) and Divide Creek Anticline (Grout, 1990; Gunneson et al., 1994; 1995), Rangely Anticline (Stone, 1986), Axial Arch and Maudlin Gulch (Richard, 1986), White River Dome, and Powell Park Anticline. Thrust involvement is also evident in the Rulison Anticline, an inverted Pennsylvanian-age paleohorst (Waechter and Johnson, 1986), and along the margins of older inverted structures such as the Pennsylvanian-age horst block beneath the Grand Hogback (Waechter and Johnson, 1986).

During Laramide tectonics, the thrust geometries that were initiated were locally complex. Extensive seismic data, over 400 line-miles, from throughout the basin center have been interpreted. These data show three primary detachment levels in the basin. The deepest level is an intrabasement detachment that allows thrust duplication within the Precambrian basement. In the eastern basin, where the Pennsylvanian-age Eagle Valley Evaporite is best developed, the evaporite forms a Paleozoic-level detachment surface. The uppermost detachment is found in the Cretaceous-age Mancos Shale. Locally, imbricate thrust systems splay off this detachment and cause local, dekameter-scale, thickening in the Iles Formation sandstones (Rollins Cozzette, Corcoran). Recent 3-D azimuthal AVO seismic in Rulison Field show small-scale (tens of meters or less) thrust displacements of the Rollins and overlying Cameo Coal and fluvial sands that appear to control the intensity of natural fractures (Gwilliams et al., 1997). These small thrusts appear to be splays that propagate up-section from a Mancos-level detachment surface. The complex thrust geometry in the eastern basin has been documented in detailed seismic data across the Divide Creek Anticline by Gunneson et al., (1995) and confirmed by aeromagnetic depth slicing integrated with this seismic interpretation (Hoak and Klawitter, 1996).

BASEMENT CONTROL ON CENTRAL PICEANCE BASIN SHALLOWER STRUCTURE

In the Piceance Basin, the critical relationship is that which exists between shallow and intermediate (<15,000 feet depth) fractured structures and basement. To assess this relationship, detailed aeromagnetic data were calibrated with published and proprietary seismic data to define the relationship between basement features and shallower fractured reservoir structures. From our understanding of these relationships, we believe that we have developed the ability to predict fractured reservoir production trends in shallow structures using the integrated exploration approach.

There are several areas where this relationship is pronounced and unequivocal. The Grand Valley, Parachute, and Rulison fields clearly demonstrate basement fault control on the shallower structures that control production trends. An older, non-proprietary seismic line through Parachute and Rulison fields demonstrates that the Rulison Anticline lies above a basement thrust block (Figure 10). From a seismic grid (see Figure 11 for line locations), we have interpreted the geometry of basement fault systems. The fault systems show a complex interplay of thrust faults (Figure 12). We have labeled several of those faults in the seismic section (Figure 10) that appear in the plan view map (Figure 12). It appears that while several of the faults may reflect Pennsylvanian-Permian-age extensional structures, the majority of these basement structures were inverted during younger Laramide thrust deformation. Several lines show areas where the older normal faults have been inverted during the Laramide. Most lines show the importance of the Mancos-level detachment, especially in the Central and Eastern Basin. The critical relationships we have observed are the parallelism between production contours, shallower subsurface structure and the basement fault orientations.

A recent 3-D azimuthal AVO seismic survey in the northeast part of Rulison Field outlines several of the key relationships between fractured reservoirs and underlying structures. In this area, small thrusts related to deeper basement structures terminate up-section in the coals and

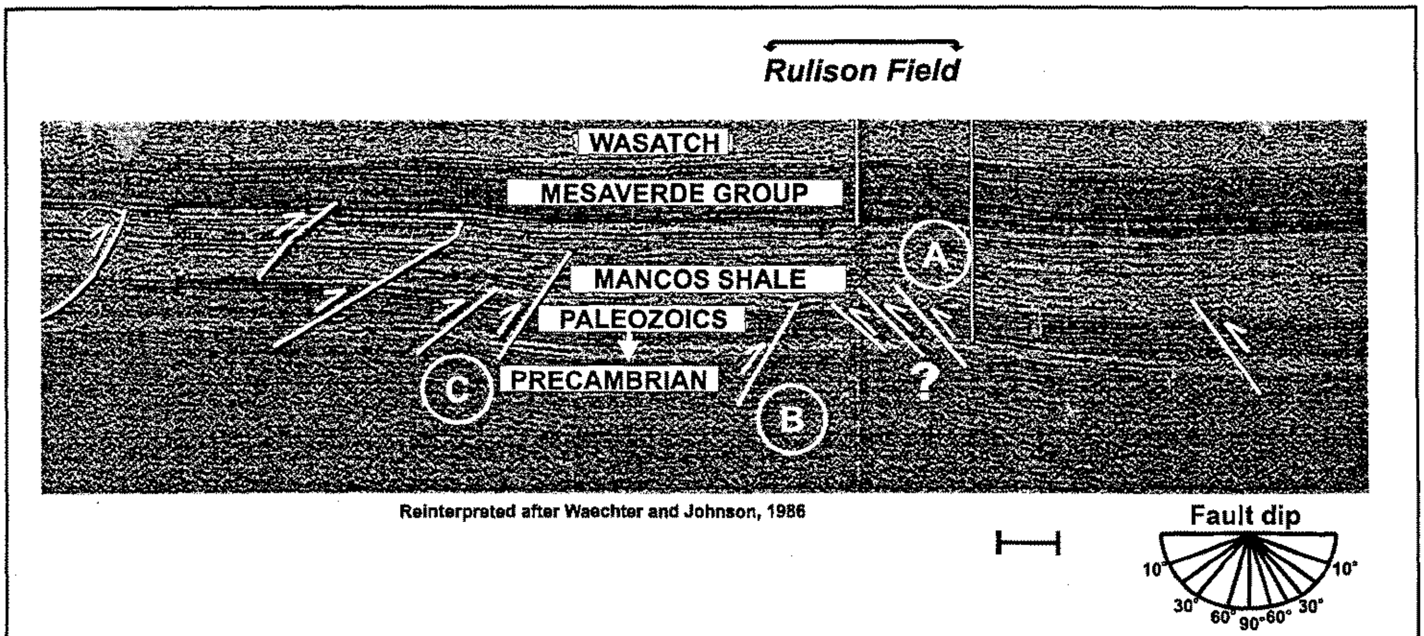


Figure 10. Typical older seismic line through Rulison Field. Note subtle flexures present in Mesaverde Group that appear related to deeper thrusts. This is more clearly expressed on more modern, proprietary data. Several of the interpreted faults (A,B,C) are indexed to Figure 12 which shows the basement interpretation compiled from seismic surveys integrated with aeromagnetic data. See Figure 11 for line location.

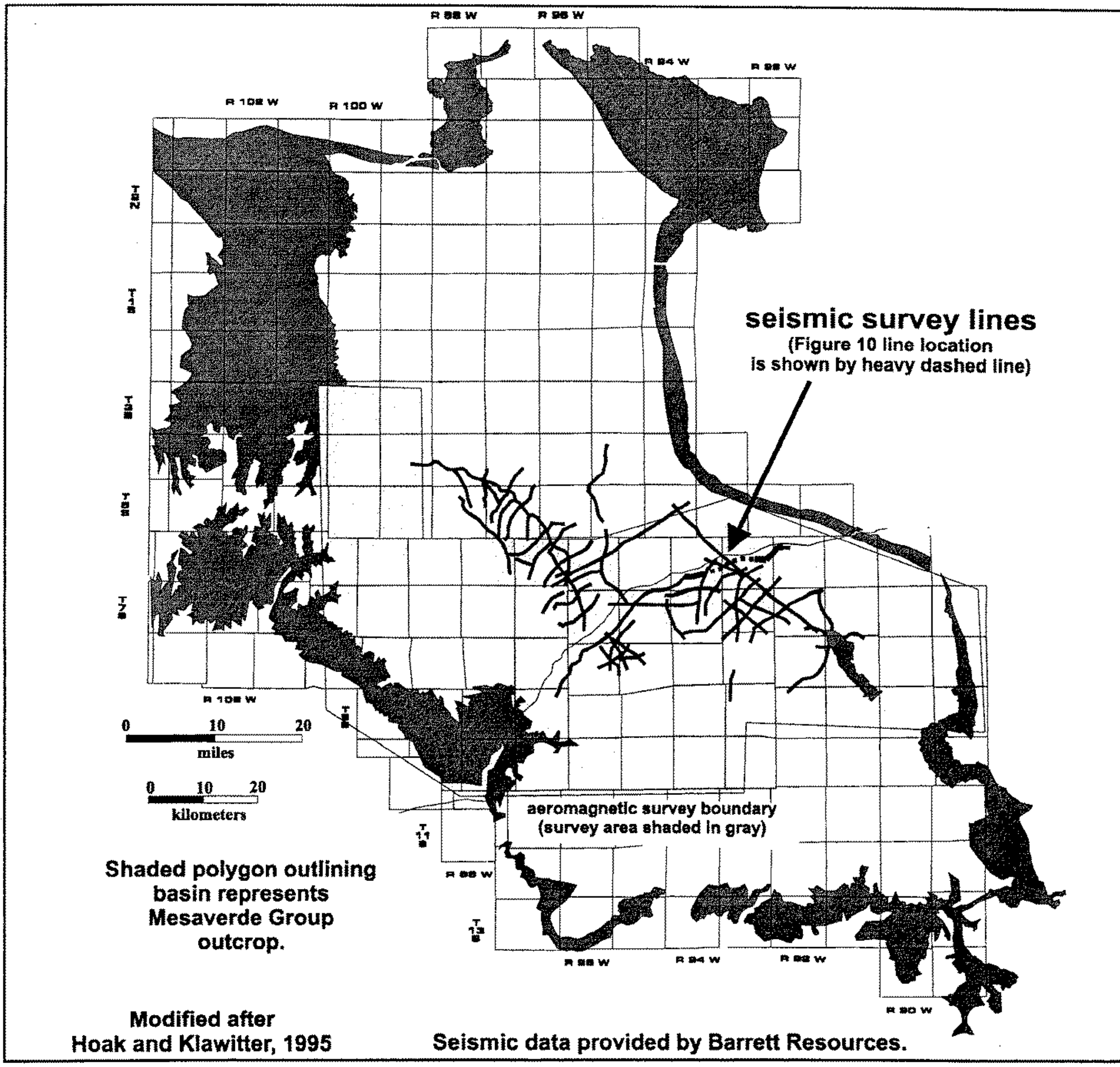
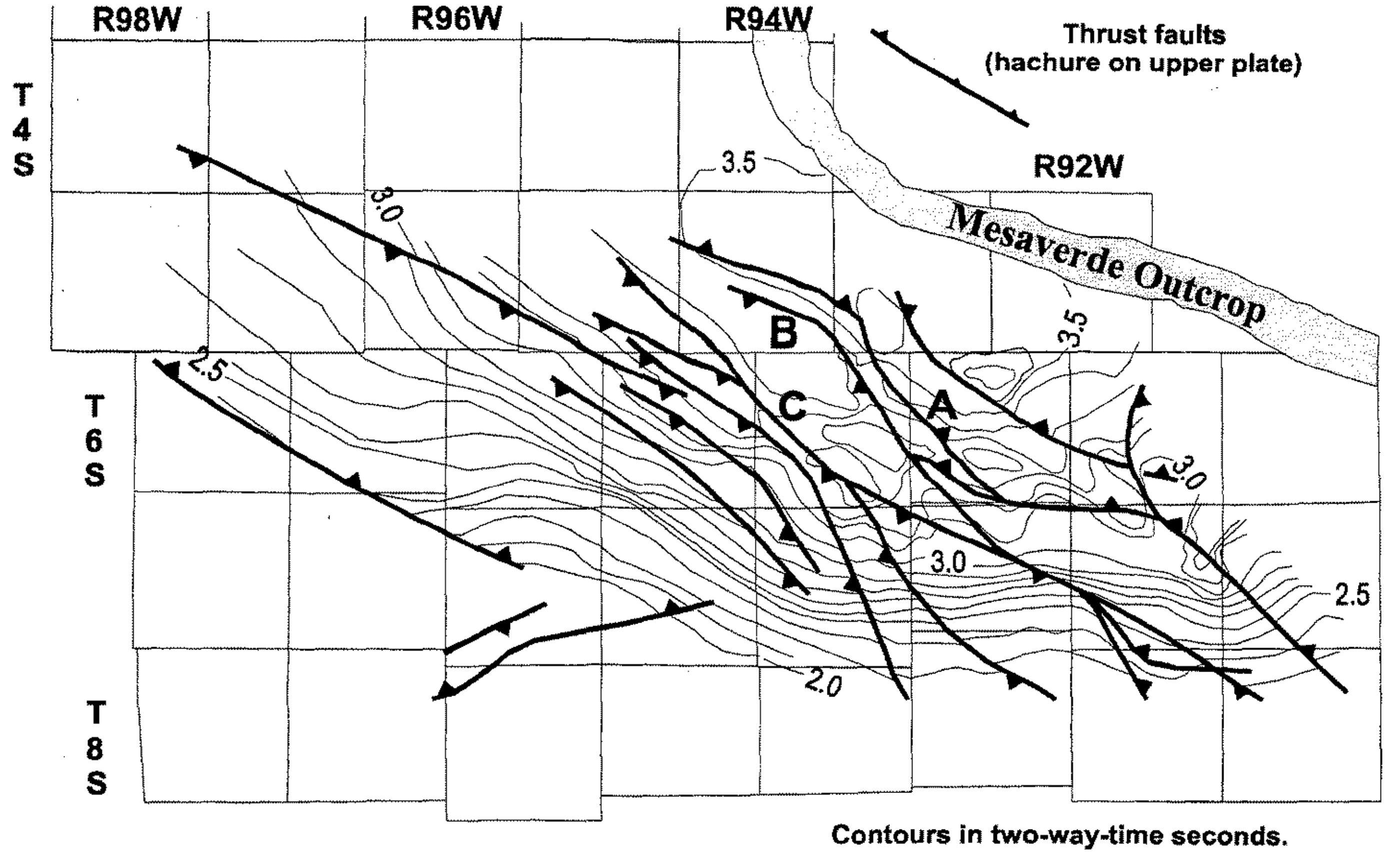


FIGURE 11. Location map for the four hundred line-miles of seismic used in the study, and the boundaries of the detailed aeromagnetic survey. The location of Figure 10 is also indicated. The aeromagnetic survey covers approximately 11,000 flight-line miles and was flown with quarter mile spacing N/S flight-lines with one mile spacing E/W tie-lines. See text for discussion.

fluvial sands of the Mesaverde Group. At the tip line terminations of these thrusts, fracture permeability is likely to be greatly enhanced. Figure 13 illustrates the structural geometry of these small thrusts along a NE-oriented section slice of the data, perpendicular to the regional structure trend. The Cameo Coal, Rollins and Corcoran sand datums are marked. The two halves of the figure represent different azimuthal processing enhancements of the same line along both a N30W and a N60E azimuth. These two orientations correspond to the minimum and maximum P-wave travel time azimuths, respectively. Additional details of this survey are available in the 1996 year-end DOE-METC Annual Report for Contract DE-AC21-93MC30086 available from DOE through the Freedom of Information Act.

We have developed a schematic model of the relationship between the thrusts in the Mesaverde Group, the Mancos Shale and basement involved thrusting (Figure 14). In the eastern basin, the basement thrusting is more intense but it



Modified after Figure 4.5, Annual Report (report period 10/1/94-9/30/95) for U.S. DOE-METC Contract # DE-AC21-93MC30086

FIGURE 12. Interpreted basement faults and structure on a basement datum for the central Piceance Basin. Letters A,B,C refer to faults shown in seismic section in Figure 10. Note overall dominance of NW-oriented thrust faults. Zones of enhanced production appear to overlie and be closely associated with local transfer zones and complex linkages observed in the basement-level thrust systems.

appears that the Mesaverde reservoirs are more strongly influenced by the Mancos-level detachment. Small thrusts observed in the Mesaverde Group (eg. Figure 13), sole out to this detachment surface, especially in the eastern basin. To the west, many of the thrust systems can be traced back to a basement fault. However, many Mesaverde thrusts cannot be easily related to underlying basement structures because of complex ramp geometries through which the thrust stair-steps its way up-section. As a result, the use of aeromagnetic data alone, is often insufficient to fully resolve shallower thrust complexity, because the aeromagnetic data are largely recording basement structure. The Mesaverde Group structure may be significantly offset from this underlying basement feature as the fault propagates up-section through a stair-step trajectory. This geometry is shown in the center of Figure 14. Through the use of pseudo-depth slices of the aeromagnetic data, it may be possible to refine the structural model at shallower levels. In areas where seismic data are lacking, the depth-slicing method will identify where detailed seismic data should be collected to verify subsurface structures.

The correspondence of basement faults to structures mapped on the regional Rollins map, reveals the close relationship between the shallower subsurface structures and the deep fault systems (e.g. Figure 12). There is an excellent correspondence between basement and shallower structures in the Grand Valley, Parachute, and Rulison fields similar to relationships found to the southwest in the Plateau and Shire Gulch fields. Seismic-interpreted basement faults in the Divide Creek-Wolf Creek anticlines also show similar relationships (Gunneson et al., 1995), and Cozzette-Corcoran production data from this area show strong compartmentalization caused by the interaction between basement-involved thrust systems and later cross-structure normal faults (Hoak and Klawitter, 1996). The Divide Creek area will be discussed in more detail in later sections.

Central Piceance Basin Detailed Aeromagnetic Calibration and Interpretation

Due to severe topography and complex environmental concerns, seismic acquisition costs in much of the Piceance Basin are high. In effect, these acquisition considerations effectively preclude regional seismic surveying along

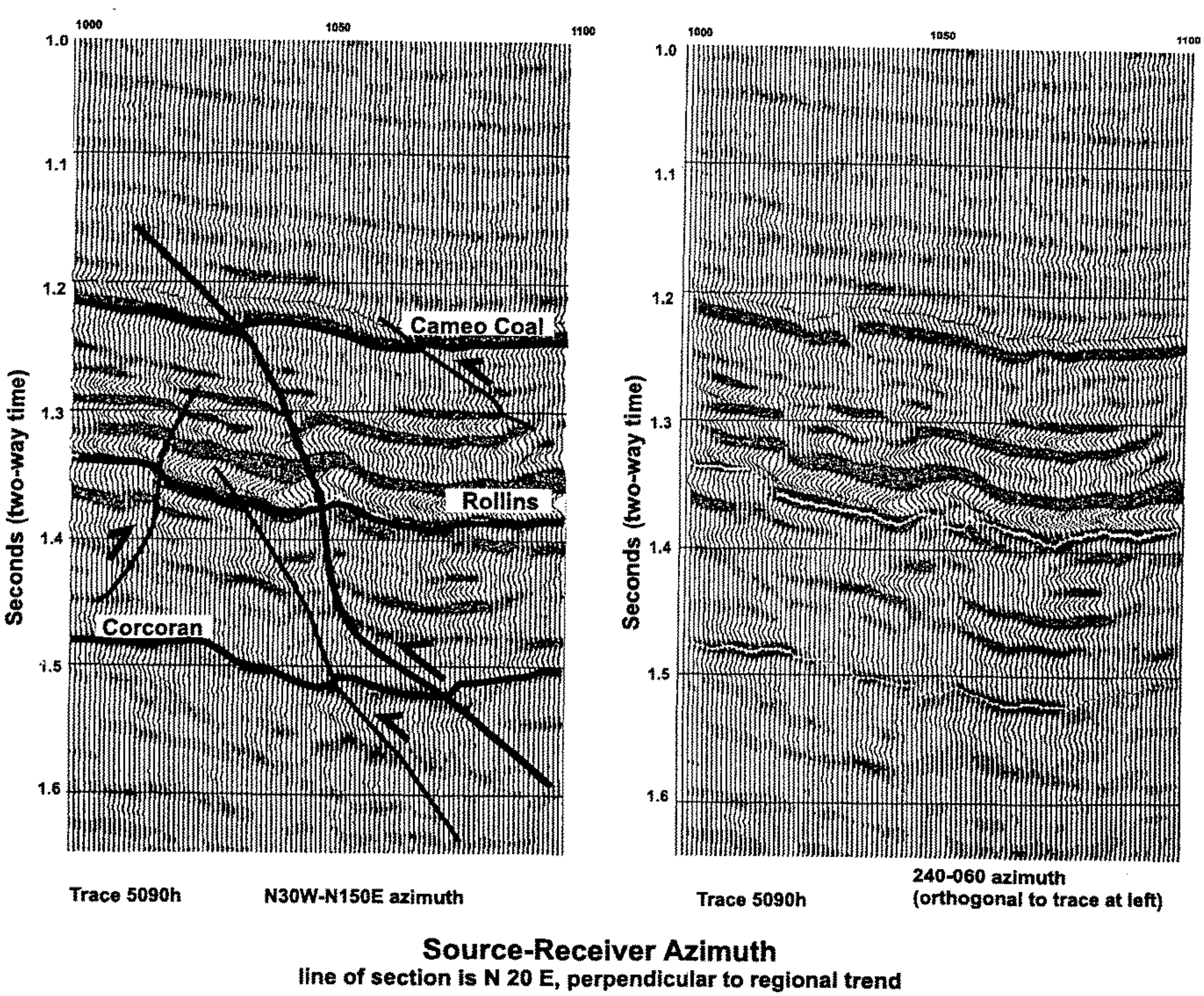


Figure 13. NE-oriented time-slice through 3D seismic survey in northeast Rulison Field. Note how subtle thrusts cause small-scale offsets of key marker beds such as the Cameo Coal, Rollins and Corcoran sands. The two images (left and right) represent the same section that has been enhanced by AVO analysis using two orthogonal azimuths. See text for discussion.

conventional grid systems. In this area, single seismic lines are inadequate to fully resolve the three-dimensional complexity of subsurface structures. Because of the strong magnetic susceptibility contrasts present in the Piceance Basin basement, combined with the pronounced basement influence in shallower fractured reservoirs, we calibrated a detailed aeromagnetic survey against the existing seismic grid to assist in the delineation of intersedimentary and basement structures. An aeromagnetic survey was chosen for several reasons: 1) Existing NURE (National Uranium Reconnaissance Evaluation) data showed that aeromagnetics contained important basement information; 2) the survey is relatively low-cost; and, 3) the data can be rapidly acquired at virtually any time of the year. In addition, review and digital reprocessing of regional, lower-resolution NURE aeromagnetic data (Grauch and Plesha, 1989), outlined major boundaries between basement domains (Figure 15). Using the major boundaries as guidelines, we collected data to maximize our ability to interpret the complex transitional areas between the different domains. Most importantly, we wanted to characterize and interpret the magnetic basement beneath the largest producing fields in the southern basin. The aeromagnetic survey was flown with N/S flight lines (1/4 mile spacing) with orthogonal E/W tie lines acquired every mile. This detail contrasts sharply with the regional NURE aeromagnetic data that was acquired at 3 mile E/W flight line spacing with 12 mile N/S tie line spacing.

Aeromagnetic contours from the spatially detailed survey clearly identify regions in the basin corresponding to differences in basement structure. In general, basement fault zones with significant throw correspond to steep magnetic gradients. Examination of the regional map reveals numerous areas where

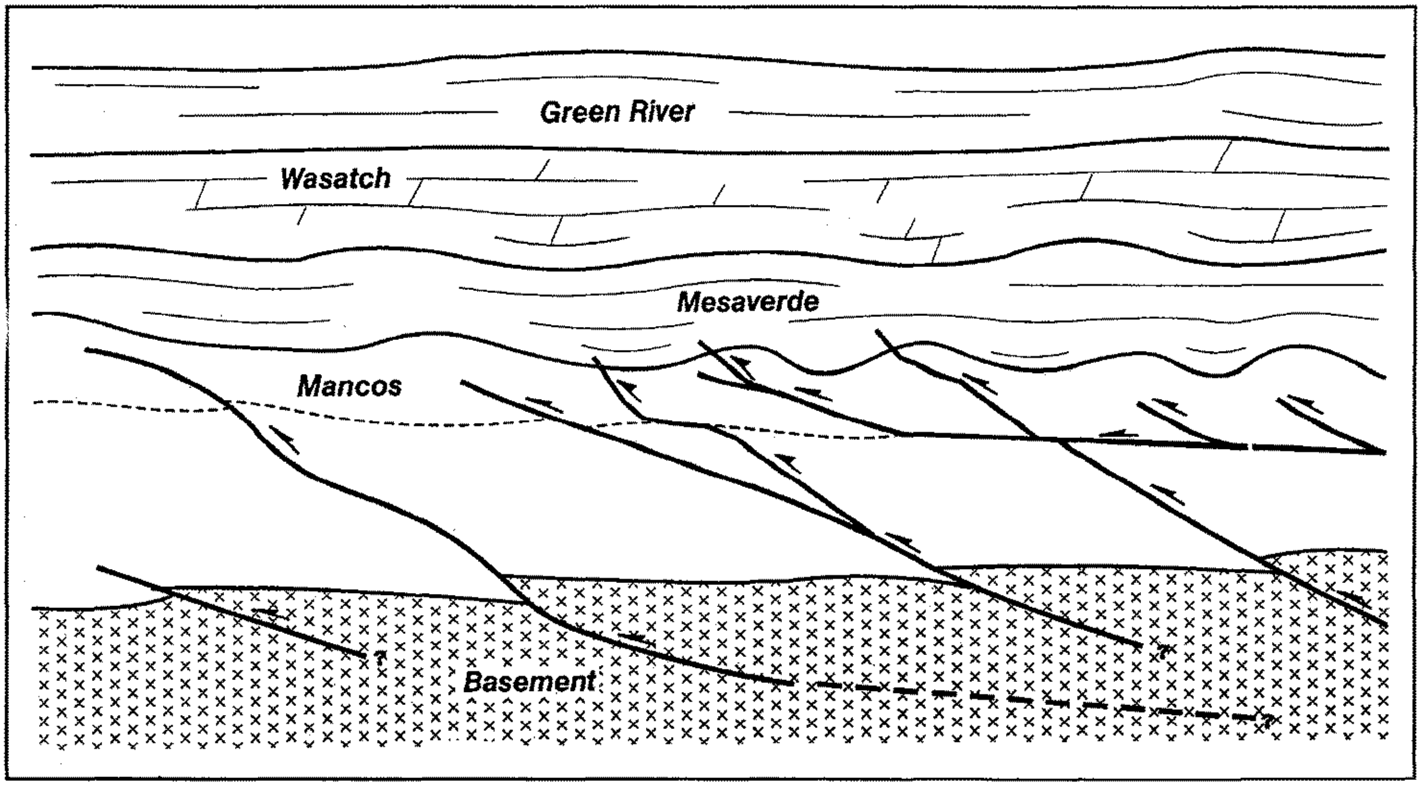


FIGURE 14. Schematic illustration of the multiple detachment surfaces interpreted from regional seismic typical of the eastern and central Piceance Basin. The two detachments, one in the basement, the other in the Mancos Shale, makes it very difficult to establish correlation between basement faults and shallower reservoirs using aeromagnetics and remote sensing imagery analysis. Note the considerable lateral offset that can be observed between the basement fault location and where the fault actually causes a flexure in the shallower fractured reservoir horizons.

basement faults are likely to be present (see Figure 16). It is important to note that Figure 16 is a total magnetic field intensity map. It is a mixture of long, intermediate, and short wavelength data which correspond to sources that are at decreasing distances to the magnetometer. In order to constrain the depths at which magnetic signatures were sourced, pseudo-depth slices were generated from reduced to pole total magnetic field intensity data. In doing so, we were able to demonstrate that the majority of E/W trending features represent very shallow anomalies that do not persist to deeper structural levels where fractured reservoirs are present. In contrast, the majority of NW trending anomalies correspond to basement-involved thrust systems. The ability to frequency filter magnetic data allowed us to demonstrate the compartmentalization of the Divide Creek Anticline sandstone reservoirs by showing the close correspondence between various seismic time-structure maps and the corresponding pseudo-depth-slice maps generated from aeromagnetic data (Hoak and Klawitter, 1996). We will focus our attention on the Grand Valley-Parachute-Rulison and Plateau-Shire Gulch areas where the majority of seismic and subsurface control was available to calibrate our basement interpretation.

Grand Valley, Parachute, and Rulison fields lie on the north trending flank of a large amplitude, long wavelength E/W trending magnetic structure. This magnetic feature corresponds to an area where the Paleozoic section is thought to be absent (confirmed by Barrett Resources-Arco Deep #1-27; Sec 27, 6S 97W). Along the northeast margin of this E/W-trending magnetic structure, there are abundant NW-trending thrust and normal faults confirmed by seismic interpretation (Figure 17). These NW-trending zones truncate the E/W-trending magnetic anomaly and represent the western margin of the Paleozoic-age Eagle Basin (see DeVoto et al., 1986). In the central Piceance Basin, NW-trending basement faults parallel the structural and production trends observed in the subsurface gas reservoirs. The magnitude of the displacements associated with the basement faults is difficult to establish from the aeromagnetic data; however, seismic data on the basement datum show that displacements vary from 50-2500 feet. In Figure 17, we have used pseudo-depth slices of the total field data, prepared using frequency filtering algorithms, to assign interpreted aeromagnetic anomalies to approximate structural depths. In general, most E/W oriented features are very shallow, near surface anomalies. The majority of NW-trending anomalies are basement-related. In the western basin, there is a mixture of shallow and deeper NW-trending anomalies. We believe that this accurately reflects the surficial outcrop of basement faults (shown earlier in Figure 7), and deeper basement faults that did not propagate to shallow levels. It is considered likely

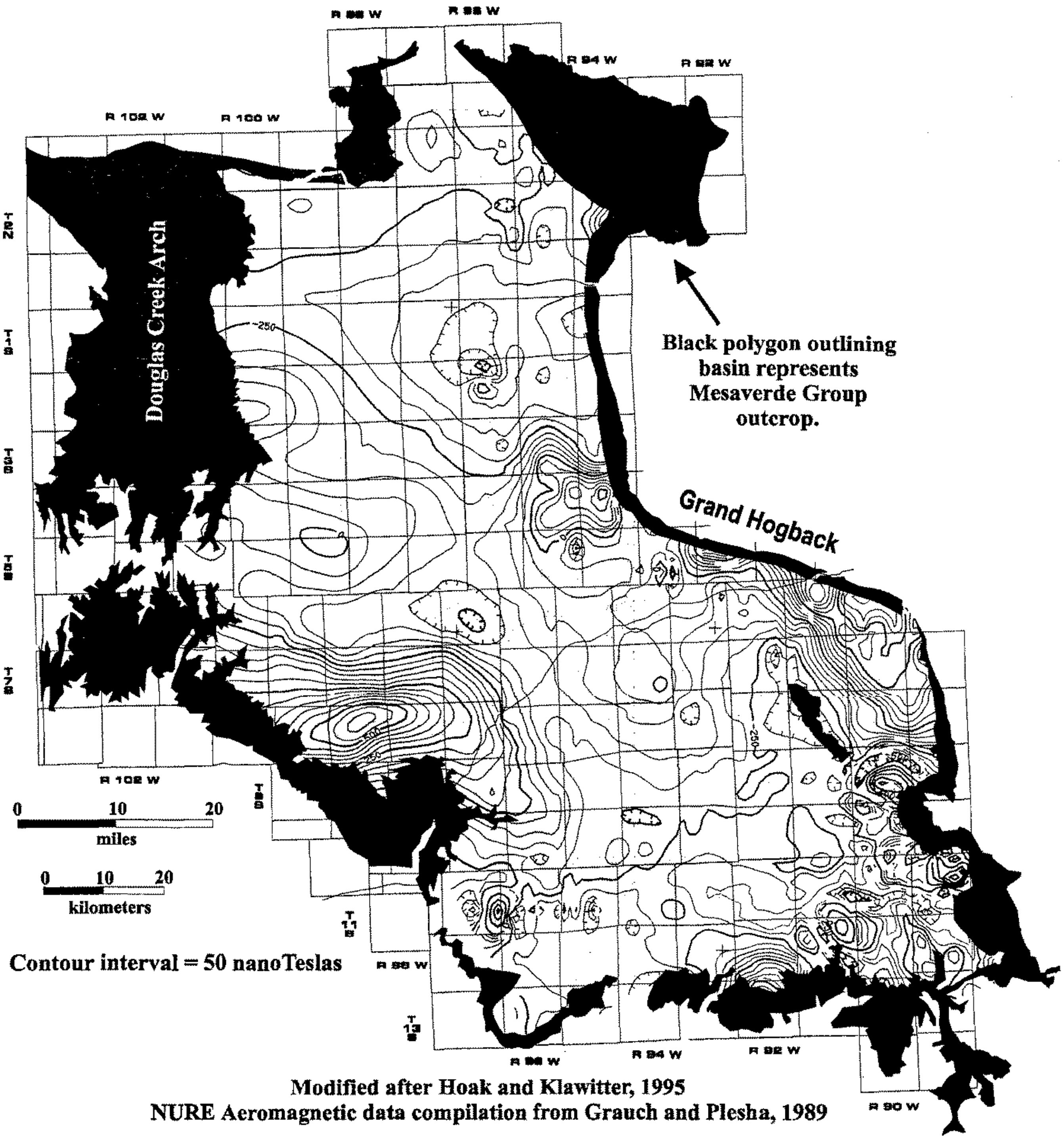
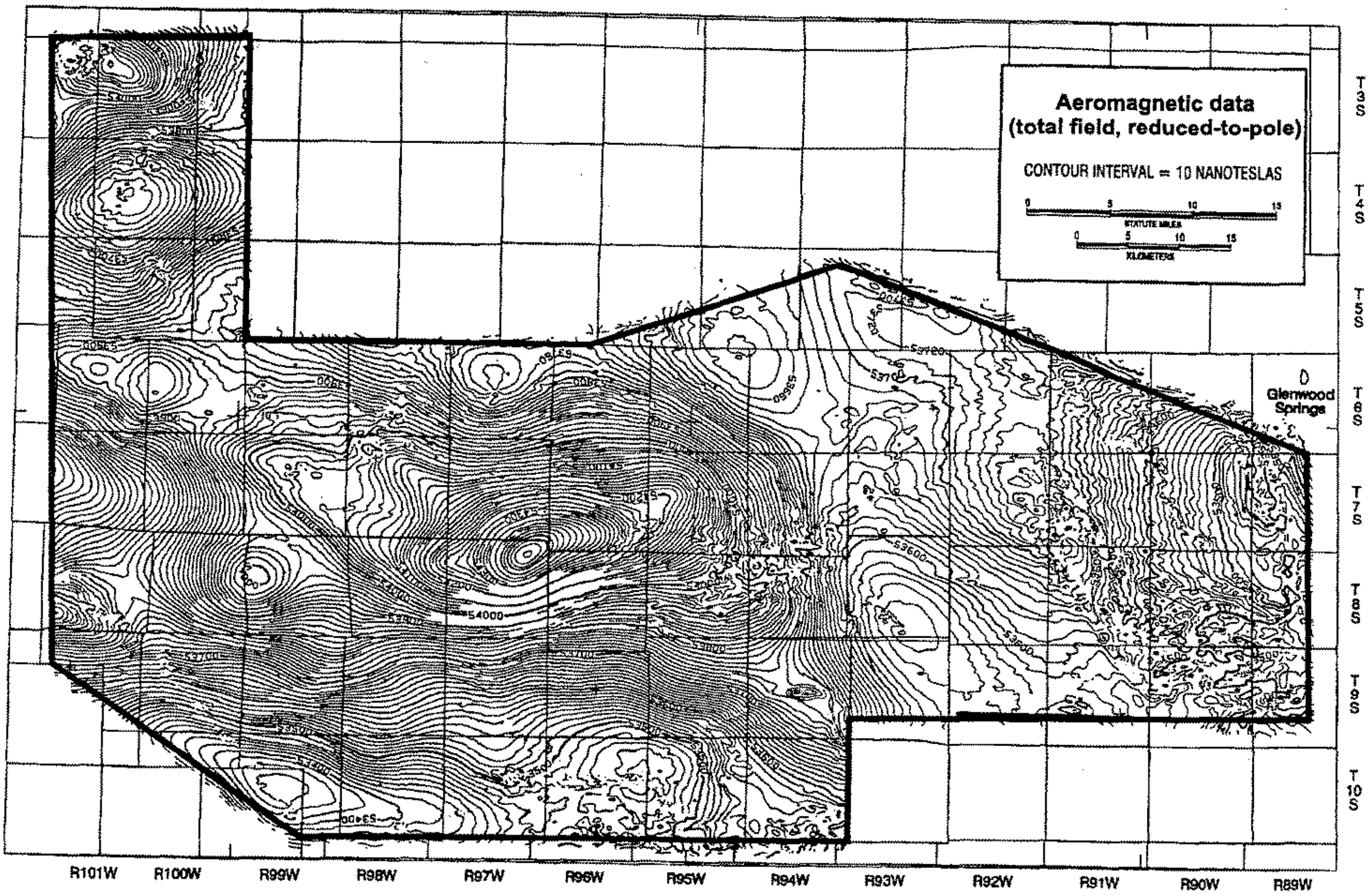


Figure 15. Regional aeromagnetic data (NURE) used to guide our selection of the optimum area for the detailed survey. Note overall dominance of WNW and E/W trends in the western basin. This contrasts sharply with the NW-trends in the eastern and central basin. Chaotic magnetic structures in the far southeast corner of the basin are Tertiary basic intrusives that post-date basin development.



Modified after Hoak and Klawitter, 1995

FIGURE 16. Total field (reduced-to-pole) aeromagnetic data set used in this study. Comparison between this survey and previous figure shows that our survey attempts to cover most of the transition zones between different magnetic domains in the basin. In addition, we have achieved greatly enhanced resolution of several key producing areas such as Rulison and Divide Creek fields.

that many of the intermediate-depth features in the eastern basin probably represent lateral ramps or transfer zones for well-documented thrust systems in the Divide Creek and Wolf Creek anticlines.

Analysis of Remote Sensing Imagery in the Central Piceance Basin

A key component of any basin fracture analysis is the relationship between surficial features and subsurface and basement structures. Basement control of shallow subsurface structures has been previously demonstrated. To extrapolate or calibrate this information against surficial geology requires the recognition of subsurface and basement fractures on the surface. To investigate the relationship between surficial data sets and subsurface structures, remote sensing imagery analysis was integrated with surficial mapping to evaluate the relationship between these two data sets, and the relationship between the surface and subsurface data sets.

Satellite and airborne imagery analysis of the Grand Valley-Parachute-Rulison and Divide Creek field areas was conducted to determine if surficial features interpreted from imagery correlated to subsurface structures in these hydrocarbon productive areas. The locations of surficial and subsurface structures were determined from independently derived geological and geophysical data. Subsequent analysis revealed that imagery interpretations integrated with the aforementioned data types provide results that give a more complete geologic picture than could be derived from any single data source.

Seven spectral channel Landsat TM and USGS SLAR digital data were acquired for imagery analysis. X-band, 1 inch wavelength, SLAR data were acquired for the Grand Junction 1:250,000 quadrangle in September 1986. Radar was flown along north-south lines with a SE-look direction and a ground resolution of 12 meters. Radar polarization was HH and the depression angle was 13-16 degrees. Due to the SE-look direction with a shallow depression angle, the Rulison-Parachute-Grand Valley area was not adequately imaged with radar, as shown in Figure 18. Vertical relief along the Roan Cliffs in the vicinity of the Parachute Field is 1,100 meters,

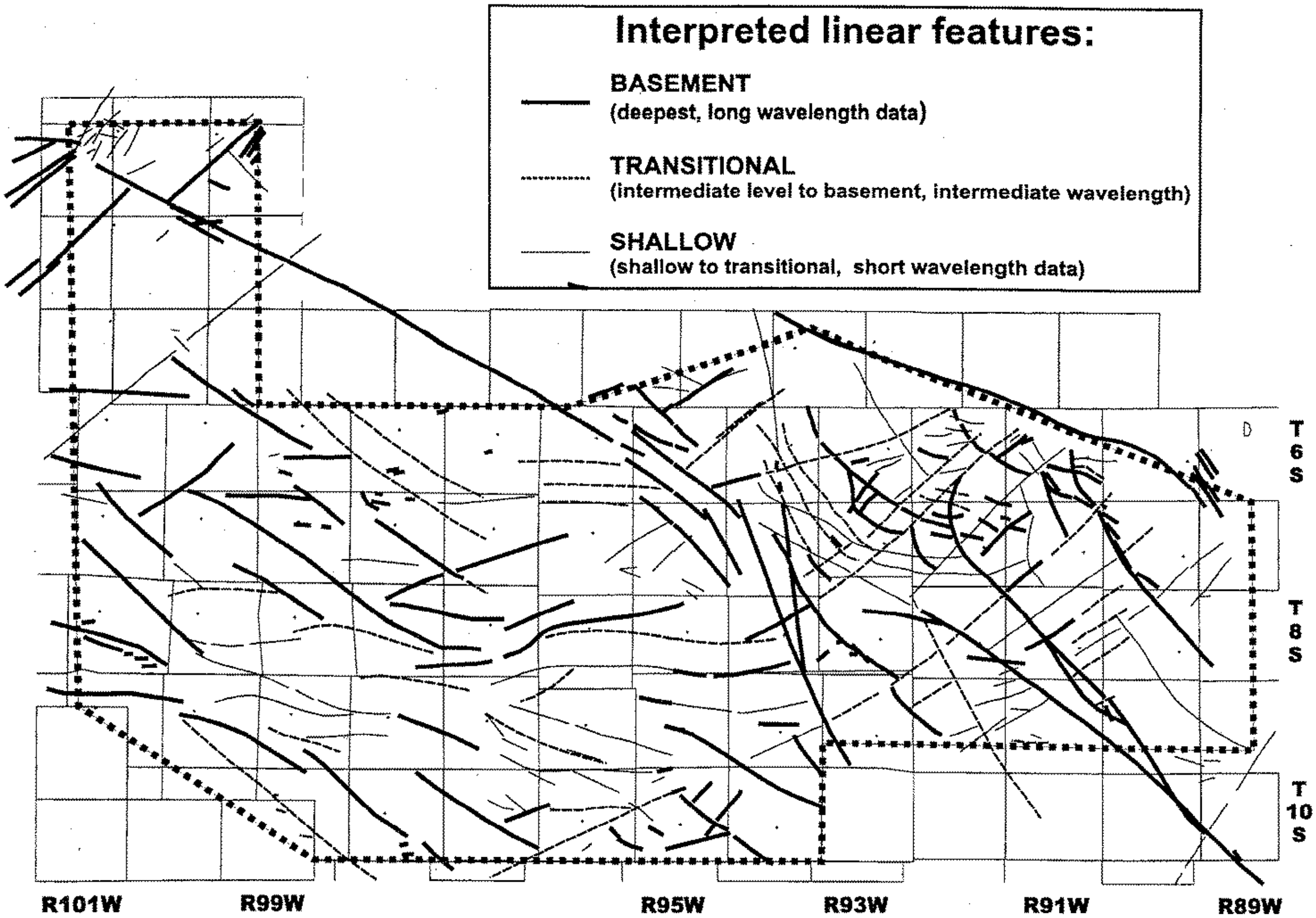


FIGURE 17. Linear anomalies interpreted from detailed aeromagnetic data. Depth determination was based on frequency analysis and pseudo-depth-slicing interpretation verified with seismic data. Note that most NE and E/W-trending anomalies, especially in the eastern and central basin are very shallow and probably are not found at the reservoir levels of interest.

causing the phenomena known as radar shadow to occur over the area of interest. Landsat TM is a vertical viewing instrument and therefore does not exhibit these characteristics. The TM image, 30 meter ground resolution, was acquired in June 1986.

A Landsat TM band 5, reflected infrared, image encompassing the Grand Valley-Parachute-Rulison fields is presented as Figure 19. The image has been contrast stretched and edge-enhanced. The Colorado River bisects the image from the northeast to the southeast corner of the image. The Uinta Sandstone forms the caprock of the Roan Cliffs and is characterized by distinctive, incised drainage patterns. Talus, gravel, and flood plain deposits occupy the lower ground along the river and Parachute Creek (left-center). Because these fields lie partially within continually changing unconsolidated material, extreme care must be exercised when drawing conclusions from imagery interpretations of this area.

Linear features, non-cultural linear elements interpreted directly from imagery, mapped on band 4, 3, 1, and 5, 7, 1, color composite images, are presented as Figure 20. A rose diagram, which contains only linear elements from within Figure 20, is presented as Figure 21D. Rose diagrams depicting the orientation of linear features mapped from Landsat imagery often reveals the structural fabric of a region, if large areas are mapped (Sawatsky and Raines, 1981; Knepper, 1982; and Perry, 1985). We have compared the local orientations of the mapped imagery features to the orientations of measured surficial fractures from ground surveys, and vertical and horizontal well cores.

Figure 21A depicts the orientation of 54 natural fractures cored in the Mesaverde by the horizontal CER SHCT-1 well located in Section 34, T6S-R94W. The horizontal wellbore azimuth was oriented north in the reservoir horizons. This figure clearly demonstrates that the fracture network at the reservoir level trends WNW, and that no NE-trending fractures were present. Sixty-two fractures were cored in the Mesaverde by the CER MWX-1 vertical well also in Section 34, T6S-R94W. Orientations of intersected fractures, (Figure 21B) were also WNW. Surficial fractures measured in the

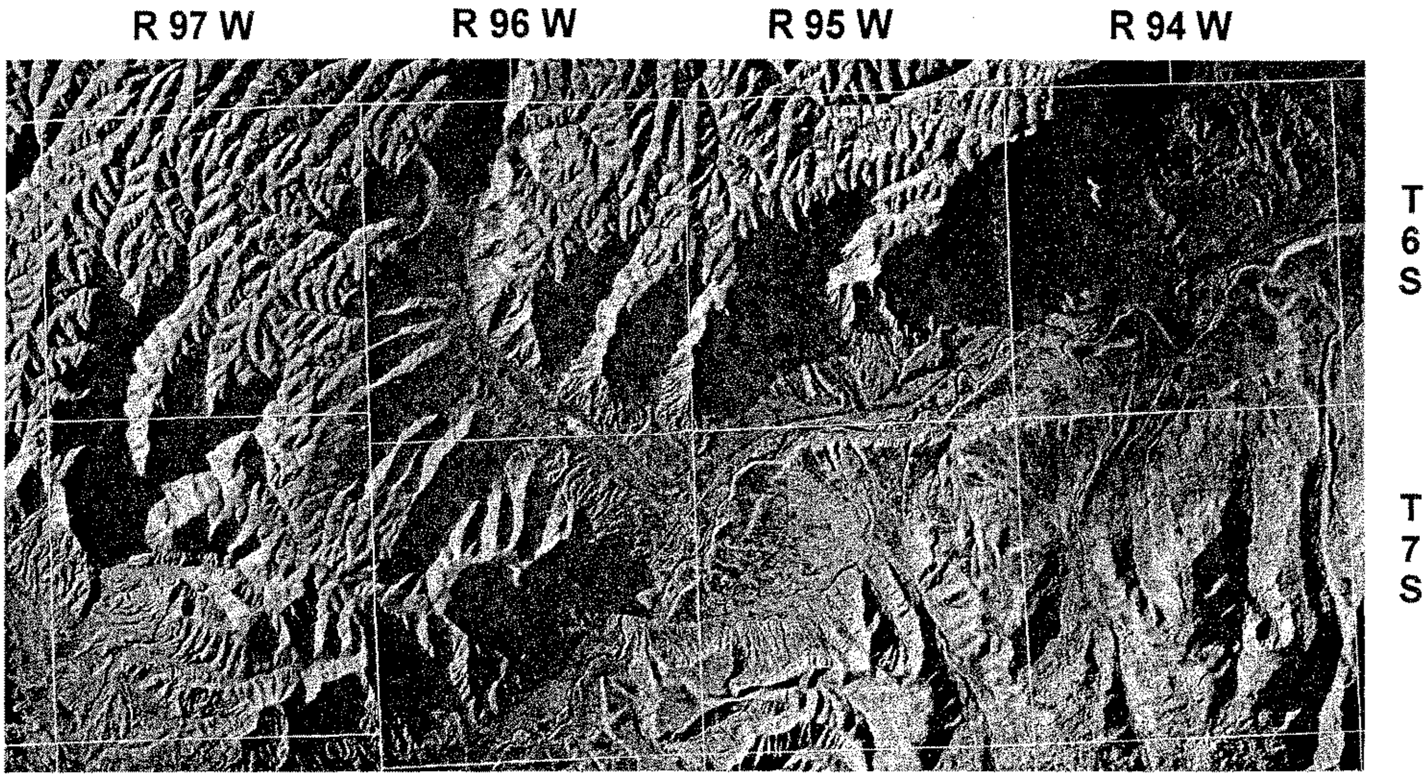


Figure 18. Side-looking-airborne radar (SLAR) image of Grand Valley-Parachute-Rulison fields in Central Piceance Basin. See text for additional discussion.

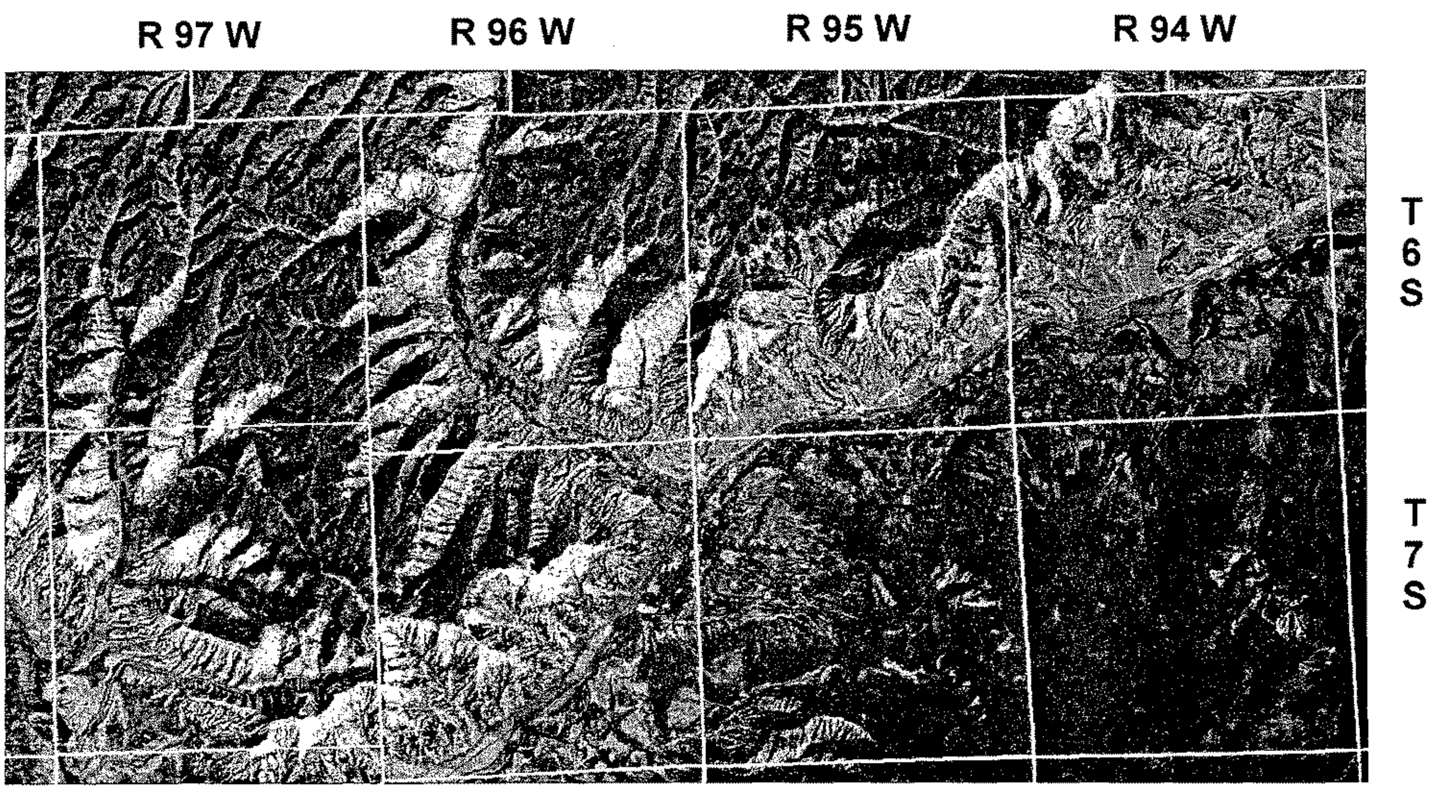


Figure 19. LANDSAT Thematic Mapper (TM) image of Grand Valley-Parachute-Rulison fields in Central Piceance Basin for the same area shown in Figure 18. See text for additional discussion.

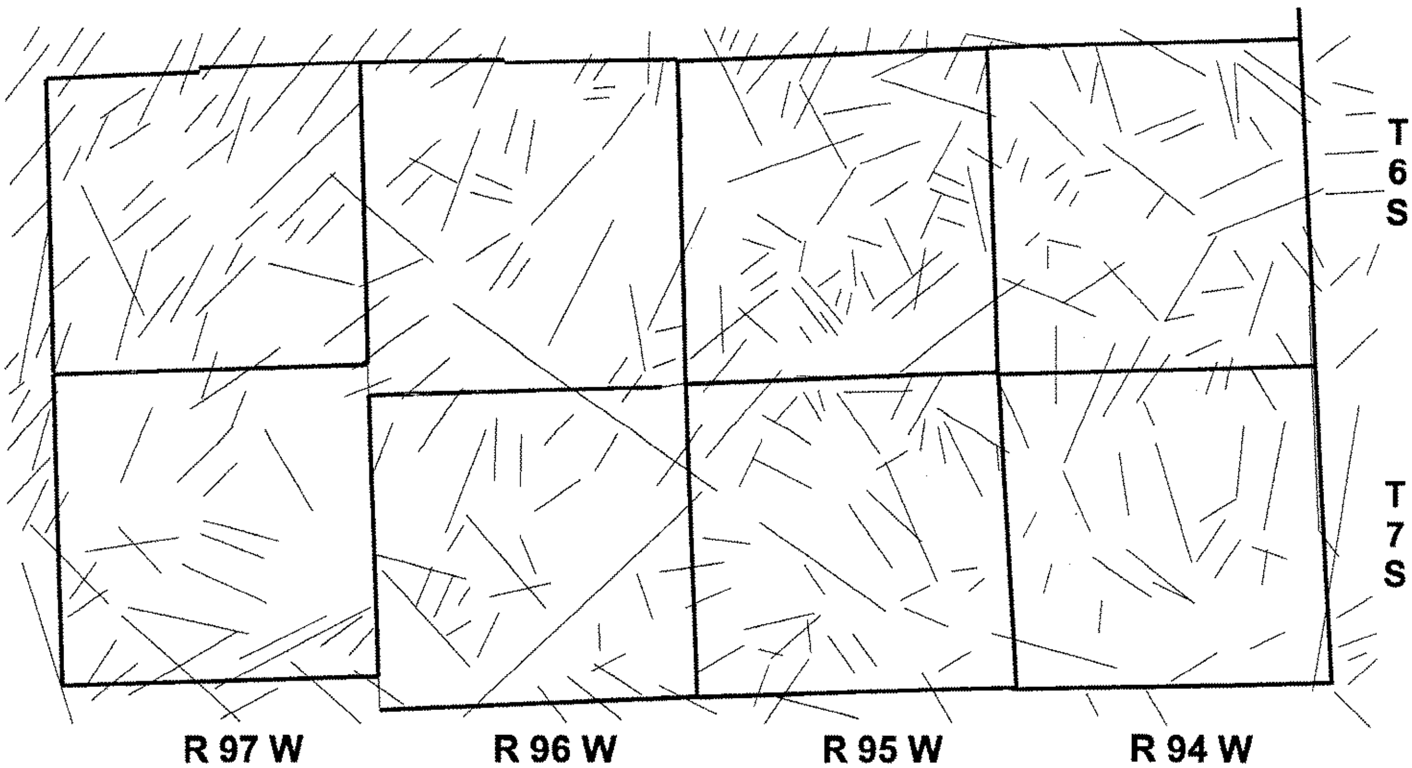


Figure 20. Interpreted linear features derived from LANDSAT Thematic Mapper (TM) imagery for Grand Valley-Parachute-Rulison fields.

immediate vicinity of the MWX well are presented in Figure 21C. In addition to WNW-trending joints, dominant sets are oriented NE and ENE. Although NE and ENE-trending fractures are prevalent on the surface, they do not persist to the reservoir level. Surficial trends interpreted from satellite imagery are predominantly oriented NE (Figure 21D), with only a minor WNW population. This large NE-trending population correlates to the orientation of the F4 joint set, Figure 21C, interpreted by Verbeek and Grout, 1984. The F4 set was the most recent set formed in the Rulison area. Commonly, when surficial fracture trends interpreted from imagery do not correlate to fracture trends within basement, there are intermediate depth structural detachment horizons present in the section. In such areas (e.g. the Central Piceance Basin), use of surficial-based linears to infer subsurface production trends is fraught with uncertainty. The use of ancillary data may permit the prediction of subsurface trends, provided that the ancillary data interpretation is highly objective and circular reasoning is avoided.

The location and orientation of linear features interpreted from Landsat TM imagery (Figure 20) were compared to structure (e.g. Figure 4), reservoir sand trend (e.g. Figure 5), and EUR gas production (e.g. Figures 4 and 5) maps to establish any relationships between these data sets. Imagery derived linear features show no consistent relationships to structure at the Rollins level, or to basement structures (e.g. Figure 12). Interpreted linears intersect contours at varying angles, do not correlate to local changes in slope or dip, and do not delineate the folds. Some NE-trending linear features do correlate to the location and trend of thick reservoir sand packages in the Mesaverde, however, the majority of NE-trending linear features do not.

The relationship between gas production and imagery interpreted features was accomplished through overlaying Figure 20 and Figure 4. The NW-trending Grand Valley Field in T6 and 7S-R96W lies along the flood plain of Parachute Creek. Topographic relief between the incised creek and surrounding cliffs is approximately 1000 meters and drilling activity has been on the flood plain in order to minimize drilling costs. The production trend in this field is northwest. Two long, NW-trending linear features were interpreted along the creek because the creek is a linear element of non-cultural origin. Therefore, a spatial correlation exists between the location of the creek and gas production. The location of the creek may be structurally controlled, however further analysis is necessary to determine the nature, if any, of this relationship.

The geometry of the EUR production trend at Parachute Field does not correlate to linear features or linear feature patterns interpreted from TM imagery. In the Rulison Field, one, short, NW trending linear feature corresponds to an area of enhanced gas production around Section 21, 6S 94W, however all others do not. On a local basis, there is little or no correlation

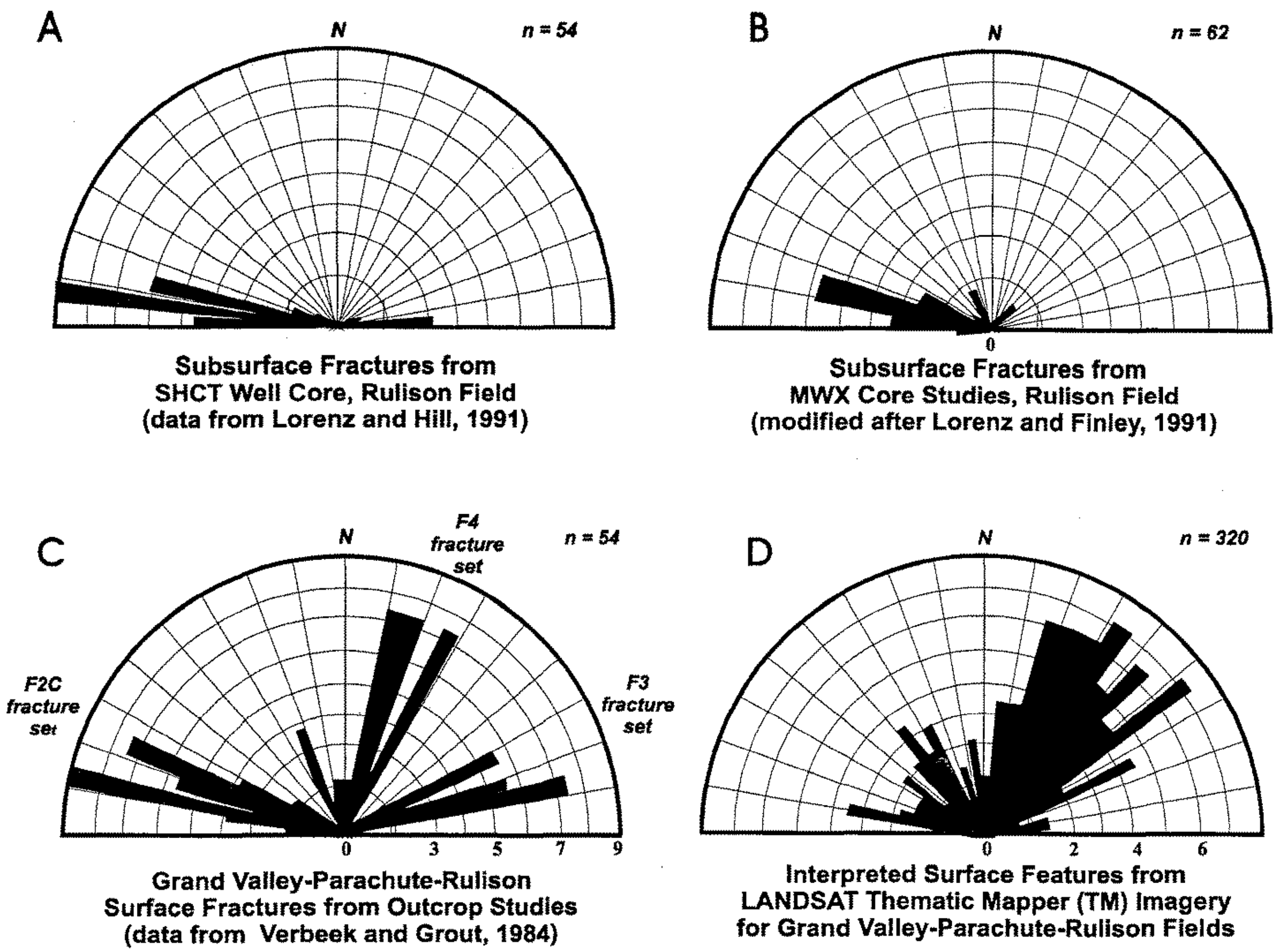


FIGURE 21. Comparison of Central Piceance Basin fracture orientations. Rose diagrams compare orientations of fractures, joints and linear features interpreted from core (A&B), outcrop (C) and remote sensing imagery (D), respectively. Note that outcrop studies are able to identify the dominant subsurface fracture trend. In contrast, both the remote sensing and outcrop studies find two additional sets of features that do not appear to correlate with observed production. In particular, the remote sensing analysis is strongly affected by the most recent NE-trends developed parallel to the Colorado River during downcutting. See text for further discussion.

between production or sand trends and imagery interpreted features. A detailed regional analysis is necessary to determine if gas production in the Central Piceance Basin may be related to zones or structures only discernible at a smaller scale. Based on initial reconnaissance studies we have performed on a regional scale throughout the basin, there appears to be little correlation between surficial linear features trends and production trends for most of the Central Piceance Basin.

An assessment of the relationship between surficial linears and mapped surface fractures was conducted. It was hoped that this effort would clearly establish the dominant surficial fracture patterns in a time and cost-effective manner. To accomplish this objective, data regarding timing relationships between fracture sets and trends were compiled from the extensive work on regional fractures and joints collected by Grout and Verbeek (1985; 1989). This data set was also compared against the remote sensing imagery analysis linear features interpretation (see Figure 21). Overall, there was excellent agreement between the remote sensing-based interpreted linear features, and the results obtained from outcrop mapping. Some of the differences apparent in the rose diagrams are due to the facts that not all imagery interpreted features represent fractures and that imagery analysis encompassed a much larger region than measured outcrop in an area where fracture patterns can vary greatly (Hoak and Klawitter, 1995). However, it is important to note that remote sensing analysis is generally unable to fully determine the structural sequence in which fracture sets formed. For this reason, it is essential that remotely-sensed interpreted linear features be ground-checked to verify the characteristics of the linears.

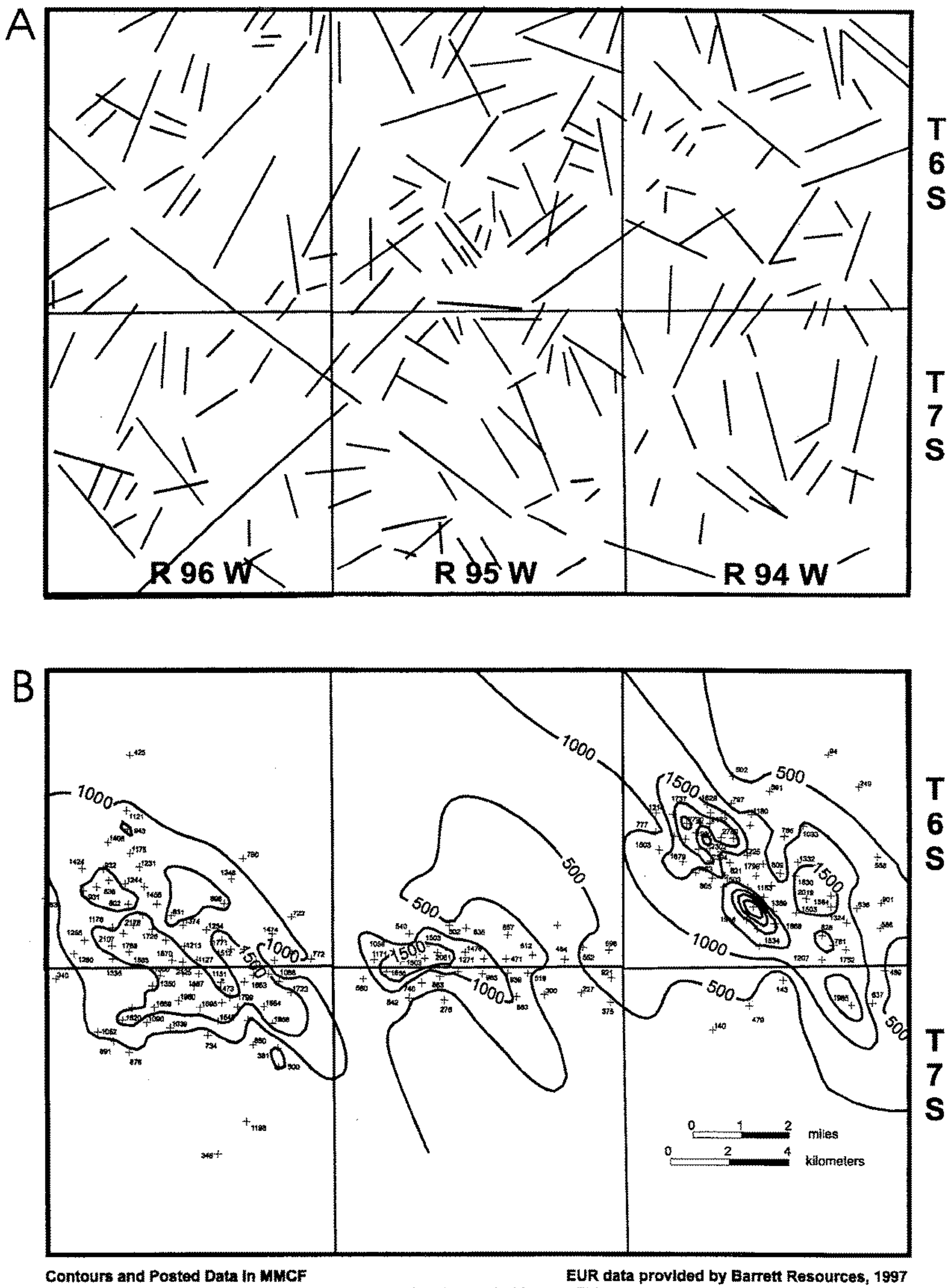


FIGURE 22. Comparison between linear features interpreted from LANDSAT Thematic Mapper (TM) imagery (A) and estimated ultimate recoverable (EUR) production maps (B). Note that although correlations between enhanced production and linear features can be locally established, most areas show no correlation. In this area, we believe that it is not possible to objectively define EUR and production trends using remote sensing imagery interpretation. See text for additional discussion.

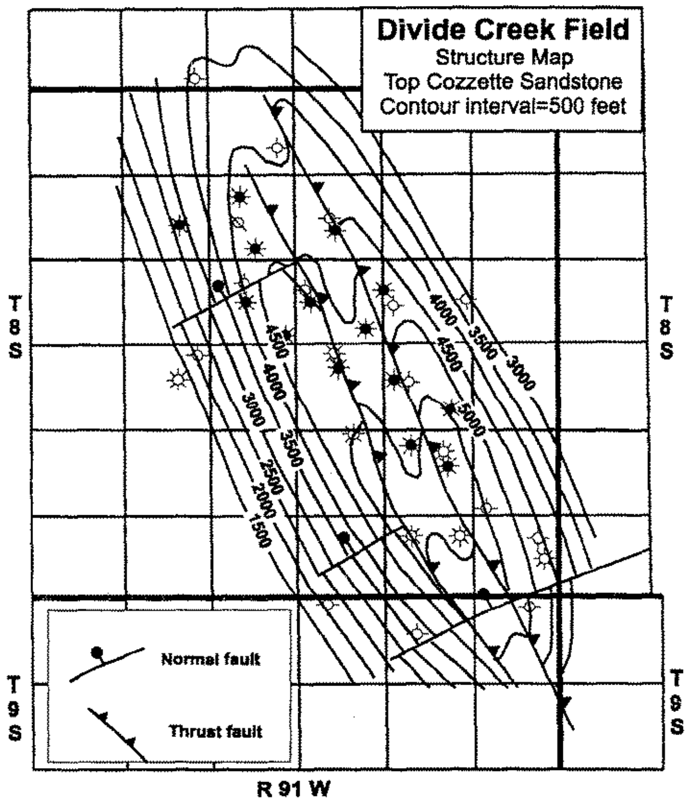


FIGURE 23. Structure map on a top Cozzette Sandstone structural datum for Divide Creek Field. Structure is defined by two parallel thrust faults crosscut by younger normal faults. Map modified after unpublished Sun Oil Company map (former field operator).

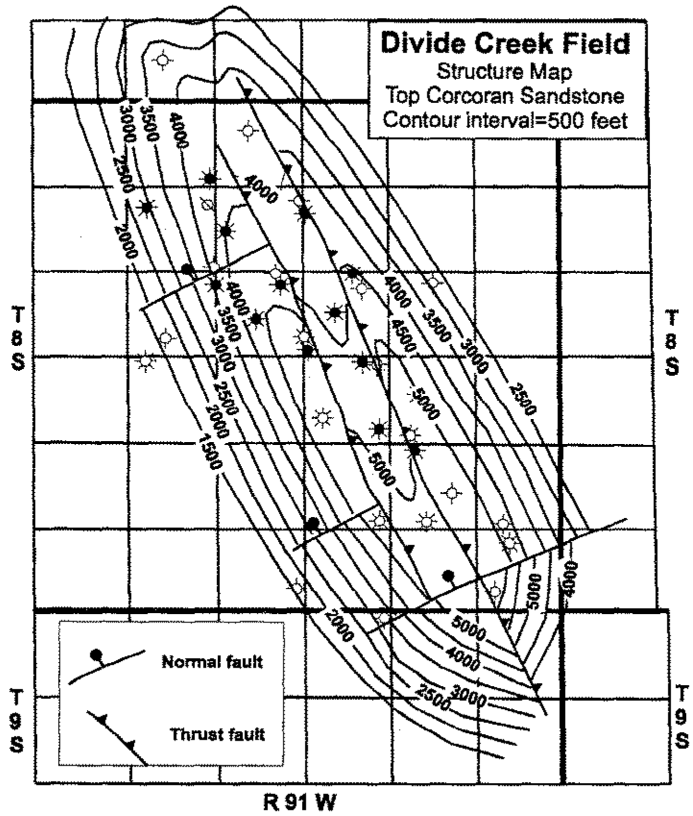


FIGURE 24. Structure map on a top Corcoran Sandstone structural datum for Divide Creek Field. Structure is defined by two parallel thrust faults crosscut by younger normal faults. Map modified after unpublished Sun Oil Company map (former field operator).

IDENTIFICATION OF COMPARTMENTALIZED STRUCTURES: THE EXAMPLE OF THE DIVIDE CREEK FIELD

Divide Creek Field (see Figure 1 for location) is a NW-trending, asymmetric anticline that was originally identified in 1922, based on surface mapping by geologists working for the State of Colorado (Berry, 1959). The structure is approximately 15 miles long and 3 miles wide. Interbedded sandstones and shales of the upper Mesaverde Group crop out along the crest of the structure. These outcrops today lie at surface elevations up to 10,750 feet. The overlying Wasatch Formation crops out along the flanks of the structure, and presumably was present above the anticlinal crest in the past. To date, approximately 53 BCF of gas have been produced from the Cozzette and Corcoran sandstones, fluvial sands and coal beds of the Mesaverde Group (Colorado Oil and Gas Commission records). Active hydrocarbon exploration on the structure commenced with the drilling of the Superior Miller #1 (1945), and the California Company's Hurd Government #1 (1955). These wells tested the Dakota and Entrada sandstones and found duplicated stratigraphic section (due to thrusting), steeply-dipping beds and extensive tectonic thickening in the Mancos Shale and overlying Mesaverde Group. However, in these wells, the underlying Dakota and Entrada sands were nearly horizontal in orientation. During the late 1950's through the mid 1960's, the Cozzette and Corcoran intervals of the Mesaverde Group were tested and produced from approximately a dozen wells. Commencing in the late 1980's several coalbed methane wells were drilled and completed in the Cameo Coal Formation of the Mesaverde Group. It was not until the early 1990's after extensive seismic analysis, that the structural complexity of the structure was fully appreciated (Gunneson et al., 1994; 1995).

Following the work of Gunneson et al. (1994; 1995), Hoak and Klawitter (1996) identified structural compartmentalization within the field, using an integrated analysis of newly-acquired detailed aeromagnetic data, existing subsurface and seismic mapping, an interpretation of SLAR data, and the integration of pressure, gascomposition and EUR data (donated by Snyder Oil, 1997, the current field operator) into the model.

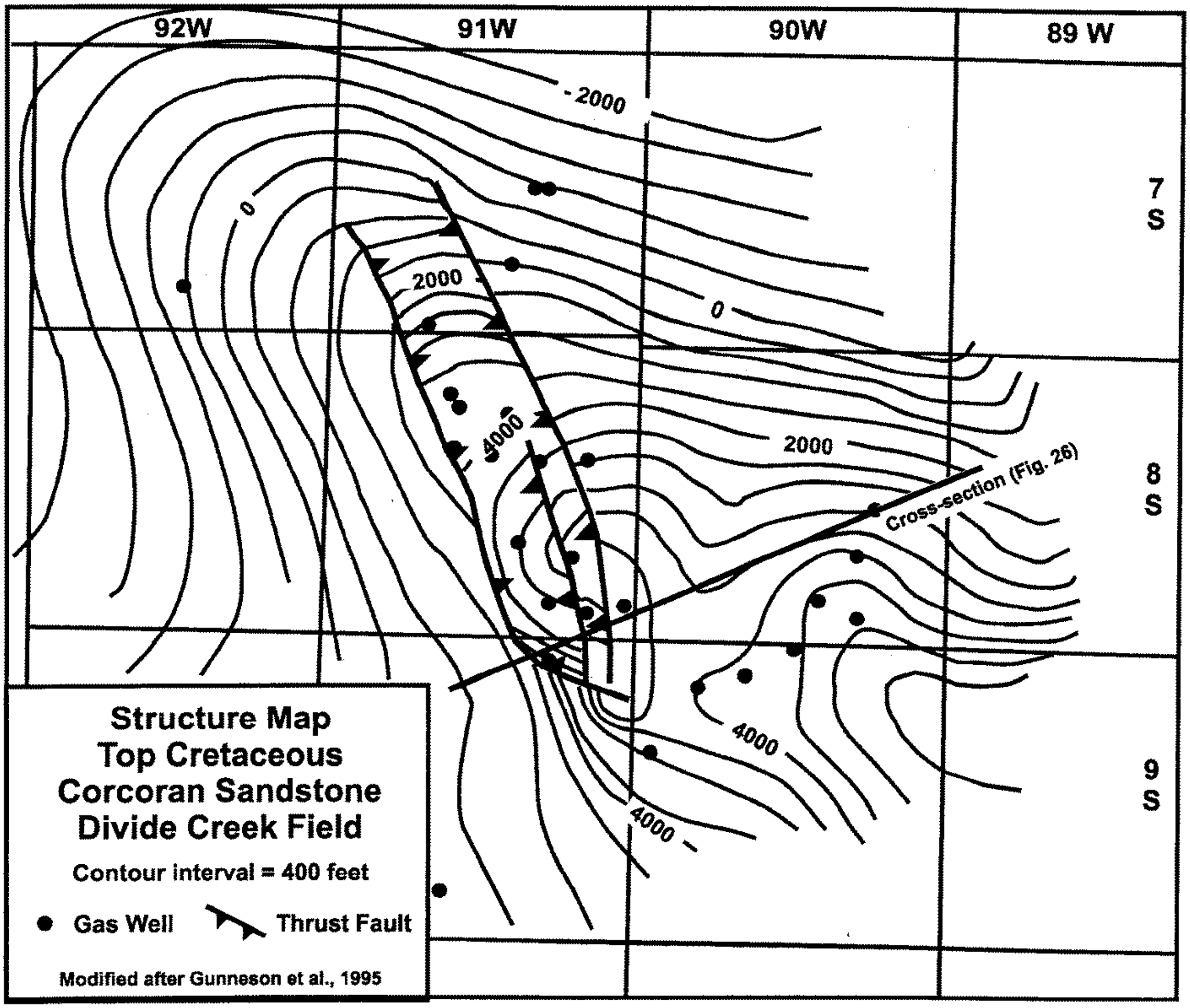


FIGURE 25. Re-interpretation of Divide Creek structure on a Corcoran Sandstone datum based on seismic data integrated with subsurface information. Comparison with older, non-seismic interpretation (Figure 24) shows that the eastern thrust is actually a backthrust and that a second, smaller backthrust is present in the south end of the structure. As a result, the Divide Creek Anticline has been reinterpreted as a pop-up block instead of an imbricate fan. See text for discussion.

Divide Creek Subsurface Structural Mapping

Original subsurface mapping in the Divide Creek area recognized the presence of several thrust slices based on mapping of the Cozzette and Corcoran structural datums. Figures 23 and 24 illustrate two of the original map interpretations through the structure. At both the Cozzette and Corcoran structural levels, the structural axis is an imbricate slice bounded to the east and west by NW-trending thrusts. Due to the fault-bend geometry of the asymmetrical structure, the eastern flank is structurally higher than those fault blocks to the west.

More recently, Gunneson et al. (1995), have reinterpreted the structure at the Corcoran level using an integration of well and seismic data. This interpretation (Figure 25) shows a similar interpretation of two thrust slices in the structural axis. Note, however, that the structural vergence of the easternmost thrust has been reinterpreted as a backthrust with eastward vergence. Also, a second, smaller, east-verging, imbricate thrust is interpreted in the southeast area of the map. At the southern end of the structure, an oblique transfer zone is interpreted, in contrast to the normal fault interpretation presented in earlier work. None of the NE-trending normal faults were added to the map, presumably due to the small displacement. One of the seismic lines used in the latter interpretation has been published (Gunneson et al., 1995).

Divide Creek Seismic Data and Interpretation

The complexity of the Divide Creek structure was not fully recognized until the work of Grout et al., (1991), followed by Gunneson et al. (1995). Grout et al. (1991) realized the tectonic significance of the Mancos Shale detachment horizon, and were able to document tectonic thickening and imbrication of the overlying Mesaverde Group gas reservoir sands. However, Grout et al. (1991) did not recognize the decapitated pop-up anticline geometry of the structure, largely a reflection of the difficulty in processing and interpreting seismic data in this area.

Gunneson et al. (1995) were able to resolve many of the processing difficulties in this area, and developed a remarkable image of the subsurface complexity of the Divide Creek structure. Figure 26 is a line-drawing interpretation of the structure based on seismic interpretion. Note that the shallower, Mesaverde Group reservoirs, and the related pop-up structure, are decapitated, and thrust westward an additional 1.5-2 miles. As a result, the Mesaverde Group pop-up anticline in the hangingwall is underlain by a footwall flat. The footwall anticline beneath the Mancos-level structural detachment lies further to the east. The lateral continuation of the Mancos detachment out into the basin is unknown, although it has been suggested (J. Minelli, personal communication, 1995), that small-scale thrusting affects the lower Mesaverde Group strata in the Rulison area, approximately 6 miles further west in the basin. This has been confirmed by Gwilliams et al., 1997 (also see Figure 13, this paper).

Basement Control on Divide Creek Structures

From the seismic data, it is clear that the basement exerts a strong influence on the localization of shallower hydrocarbon-bearing structures. Although the decapitated nature of the Divide Creek area makes it difficult to establish direct linkage between basement and cover, the basement-involved thrust appears to have nucleated the location of the shallower structure before it was decapitated along the shallower thrust horizon. In addition, continuation of the seismic line (proprietary and unpublished) to the east, shows that the basement block underneath the Grand Hogback Monocline is being actively thrust into the basin at the level of the Mancos detachment. As a result, the impetus for the observed decapitation is basement-involved shortening further to the east. Because of our success in linking basement and shallower producing structures in the central Piceance Basin, we compared the aeromagnetic data (proprietary at the time of this report, to be released later this year) to structural interpretations at the level of the Corcoran Sandstone Member fractured reservoir.

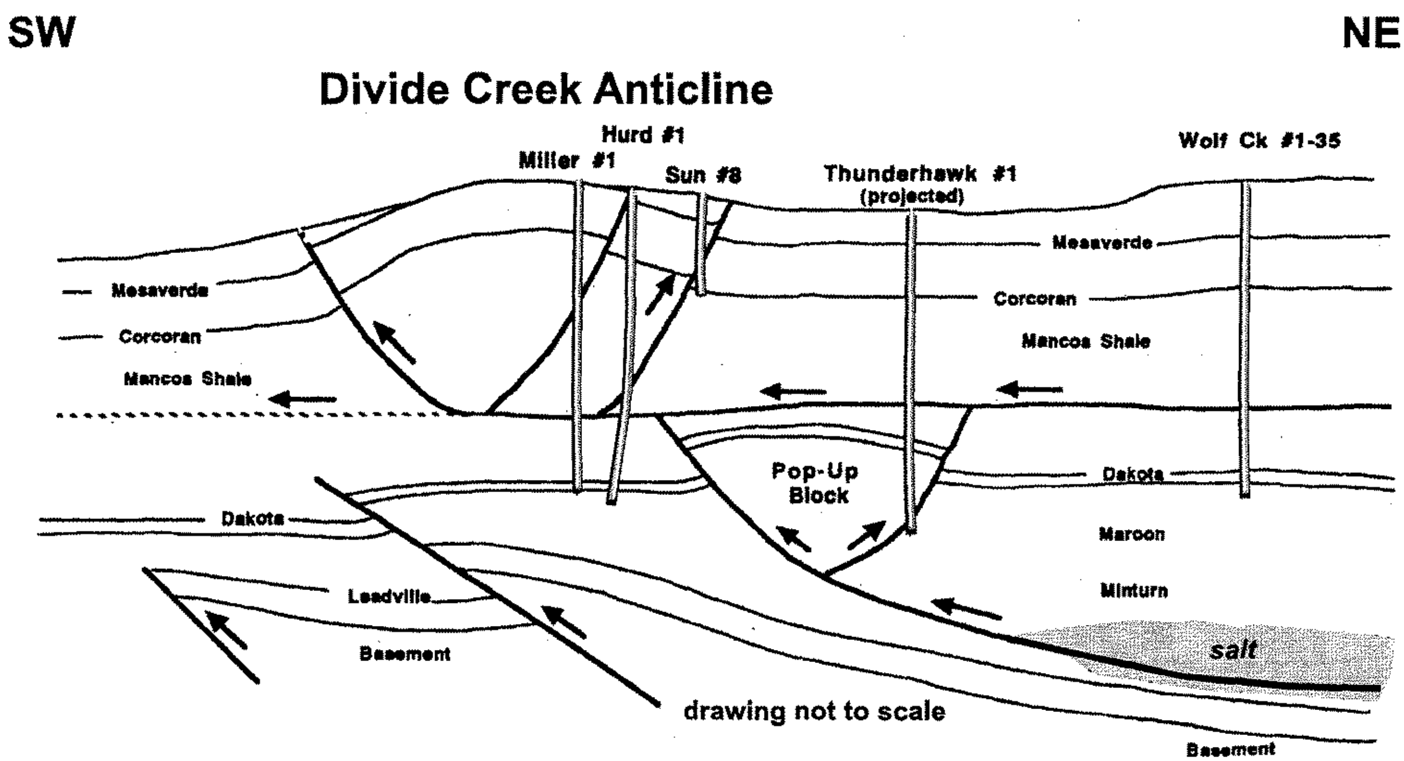


FIGURE 26. Schematic line-drawing interpretation of Divide Creek Anticline and related producing fields. Note that shallower reservoirs (Corcoran, Cozzette, Cameo Coal) all lie above the shallowest Mancos-level detachment. A deeper, basement-involved structure is also present to the east. In the interpreted sequence of structural development, the shallower pop-up anticline and associated reservoirs were decapitated and thrust westward due to later thrusting from the east along the Mancos detachment. This leaves a deeper pop-up block to the east of the present, shallower reservoir horizons.

Divide Creek Aeromagnetic Data and Interpretation

The detailed aeromagnetic survey described earlier in the text also acquired data over the Divide Creek Field. Because of the documented structural complexity of this area, Hoak and Klawitter (1996) compared published structural maps (based on seismic and well data) of the various structural datums, to the aeromagnetic data. Frequency filters were used to construct magnetic pseudo-depth slices and these were matched to available subsurface datums. The use of frequency filters in this area is critical for the correct interpretation because of the abundant high-frequency data present in the Divide Creek area. The source of this anomalous high-frequency data is unknown, although the presence of mafic igneous bodies further to the south and at Haystack Mountain at the south end of the anticline, suggest that there may be significant volumes of mafic intrusives in the shallow subsurface, and as eroded blocks in alluvium.

There is a close correspondence between the location of thrust faults mapped on various structural datums from seismic data, and the linear aeromagnetic anomalies. The aeromagnetic data allows the extrapolation of structural trends into areas where seismic and subsurface well data are not present. Hoak and Klawitter (1996) were able to create pseudo-depth slices of three structural horizons that illustrated the close correspondence between the frequency-filtered aeromagnetic data and the seismic-structure maps on the top of the Paleozoic-age Leadville Limestone, the Cretaceous-age Dakota Sandstone and the Corcoran Sandstone. Unfortunately, these maps are currently proprietary.

Identification of Pressure and Production Compartments

Gas and water cumulative production and rates, carbon dioxide content of the gas, and bottomhole pressure data all indicate that the Divide Creek structure is compartmentalized by several NE-trending normal faults that trend orthogonal to older NW-trending thrust faults and the anticline axis. Although the structural displacement along these NE-trending faults is small (up to 125 feet; Grout et al., 1991), the thin reservoir sands of the Cozzette and Corcoran members, along with the lenticular fluvial sandstones and coals of the Mesaverde Group, are easily isolated by such small displacements and sealing faults. Note that the Divide Creek Anticline has been broken up into a series of fault blocks by both the NW-trending thrusts, and also by the NE-trending normal faults. The variable completion histories, combined with complex structure, make interpretation of pressure compartmentalization difficult. The highest measured bottomhole pressures are found along the structural axis and differences along this trend appear to correspond to areas where the NE-trending faults have offset the reservoir continuity. Figure 27 illustrates the interpreted compartmentalization based largely on subsurface information and limited pressure tests compiled in 1973 by the former operator (Sun Oil) for the Corcoran and Cozzette sandstones. On this map, we have overlaid cumulative and daily gas and water production rate data for the coalbed methane wells. These data show a wide range of values. The greatest water production rates appear to be related to proximity to faults, especially the NE-trending normal fault in the northern part of the field. High water rates also appear associated with the structural culmination and the two thrust faults that flank this area. Those wells showing elevated water rates, also show enhanced gas production, further emphasizing the importance of permeability in these tight gas sand and coal reservoirs. In general, however, the coal gas and water production data are insufficient to resolve the complexity related to compartmentalization.

We have used the percentage of carbon dioxide in gas produced from the Corcoran and Cozzette sandstones to interpret reservoir compartmentalization. Figure 28 illustrates the wide range of carbon dioxide percentage that exists between the reservoir compartments shown earlier in Figure 27. At the south end of the structure, there is a tremendous range of carbon dioxide content, ranging from 1%-28%, These data, in conjuction with the structural mapping, support the compartmentalization of the structure. The south end of the structure shows a significant difference in gas composition across the NE-trending normal fault. Unfortunately the limited areal distribution of the data in the rest of the structure precludes a definitive interpretation. As a result, we have augmented this data with additional information.

The recent coalbed methane development program in Divide Creek Field involved the determination of static bottomhole pressure conditions. We have plotted these values on our base map to assess the differences in bottomhole pressure and its relationship to proposed compartmentalization. Figure 29 shows the range of bottomhole pressure values. In general, the northern part of the field shows the highest reservoir pressures. There are differences along-strike of the structure culmination suggesting compartmentalization in this area. The interpreted NE-trending normal fault that compartmentalizes the north part of the field is well-supported by the pressure data.

Because each of the data sets suggests a slightly different interpretation of the individual data set, we have used remote sensing imagery to assess the potential for additional, smaller compartments that were previously unrecognized. The NE-trending normal faults documented in the previous data sets are readily recognized on remote sensing imagery because they crop out at the surface. From this relationship, we have interpreted additional linear features from the imagery in order to identify other compartments in the structure that may represent untapped reserves. In doing so, we attempted to define those compartment boundaries that were considered to be of greater importance to production trend delineation and future field development programs.

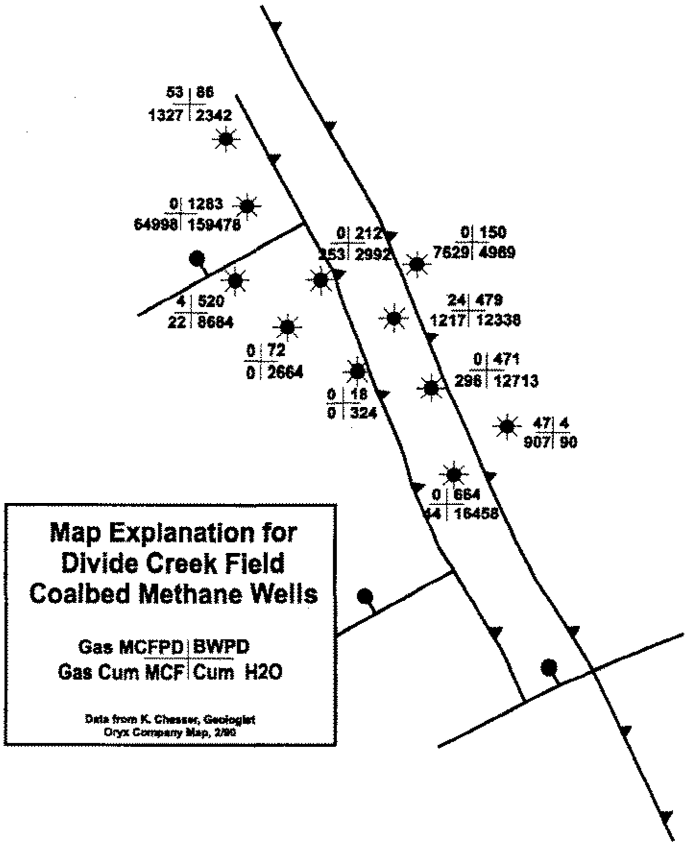


Figure 27. Relationships between interpreted fault blocks and variations in coalbed methane gas and water production rates. Interpreted fault blocks (originally delineated from pressure tests conducted on Corcoran-Cozzette tight gas sand wells) are overlaid with coalbed methane gas and water production rates. Note that several of the interpreted fault boundaries separate zones that possess tremendous differences in gas and water rates.

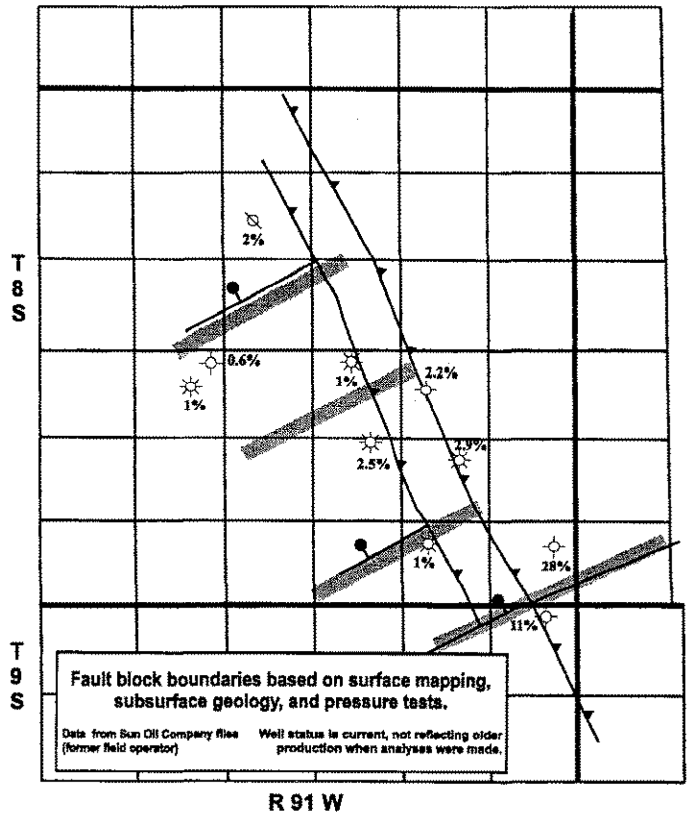


Figure 28. Differences in carbon dioxide content of the produced gas from Corcoran-Cozzette sandstone gas wells permit the identification of several reservoir compartments in the Divide Creek Field. Boundaries shown as thick gray lines indicate interpreted compartment boundaries. The gas composition data was collected early in the life of the field. Well symbols shown on map reflect current producing status.

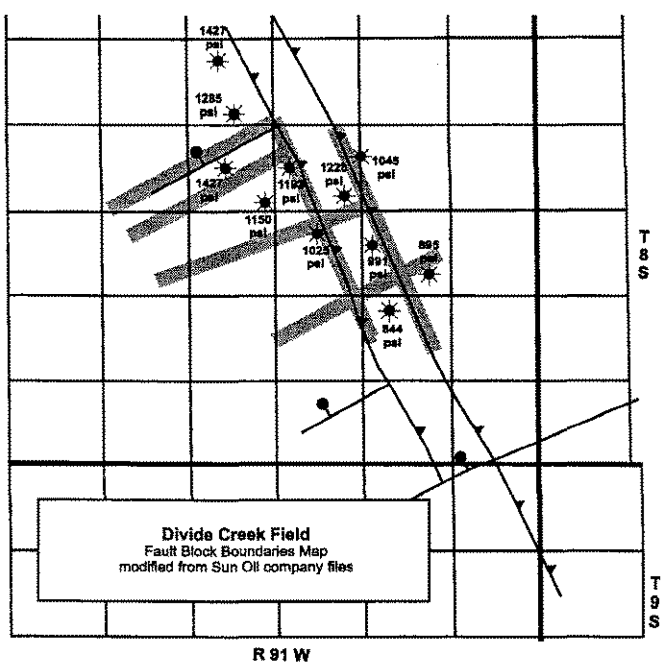


Figure 29. Pressure compartments defined by differences in static bottomhole pressure measurements for coalbed methane wells permit the identification of additional reservoir compartments in the Divide Creek Field. Boundaries shown as thick gray lines indicate interpreted compartment boundaries.

Remote Sensing Interpretation in the Divide Creek Area

In contrast to the producing structures in the Central Piceance Basin, the Divide Creek Anticline is exposed and covered with dense stands of pine and aspen. Figure 30 is a contrast stretched, edge enhanced Landsat TM band 4 image of the structure. Band 4, reflected infrared, is particularly sensitive to the density, type, and health of vegetation. Light tones in the image indicate very dense vegetation which mask geomorphic detail. Landsat sensors are nadir viewing instruments which minimize geometric distortions due to topographic effects relative to off-nadir viewing instruments. For structural interpretations of high relief, semi-arid regions, nadir views are usually preferable, (see Figure 18). In the Divide Creek area, however, the opposite is true and the use of off-nadir imagery is more desirable.

Figure 31 is the SLAR image of the same area covered in Figure 30. This image was contrast stretched and geometrically corrected to a UTM projection. The look direction of the radar becomes obvious because shadows lie on the southeastern flanks of the ridges. SLAR images contain an inherent directional filter. Radar backscatter is partially determined by the angle at which the microwaves strike the target. Generally, targets that are oriented perpendicular to the radar beam return more energy to the antenna than targets that are oriented parallel to the radar beam. Therefore, in this image, structures that trend NE/SW will be preferentially enhanced compared to features that trend NW/SE.

Comparison of Figures 30 and 31 illustrate that the radar image contains more geomorphic detail on the anticline than the Landsat TM image. Therefore, the SLAR image was used to assess the relationships between surficial features interpretable from imagery to compartmentalization within the reservoir horizons. Figure 32 reflects this interpretation.

Fracture orientations were acquired at three locations adjacent to the Divide Creek Anticline by Grout, (1991). A

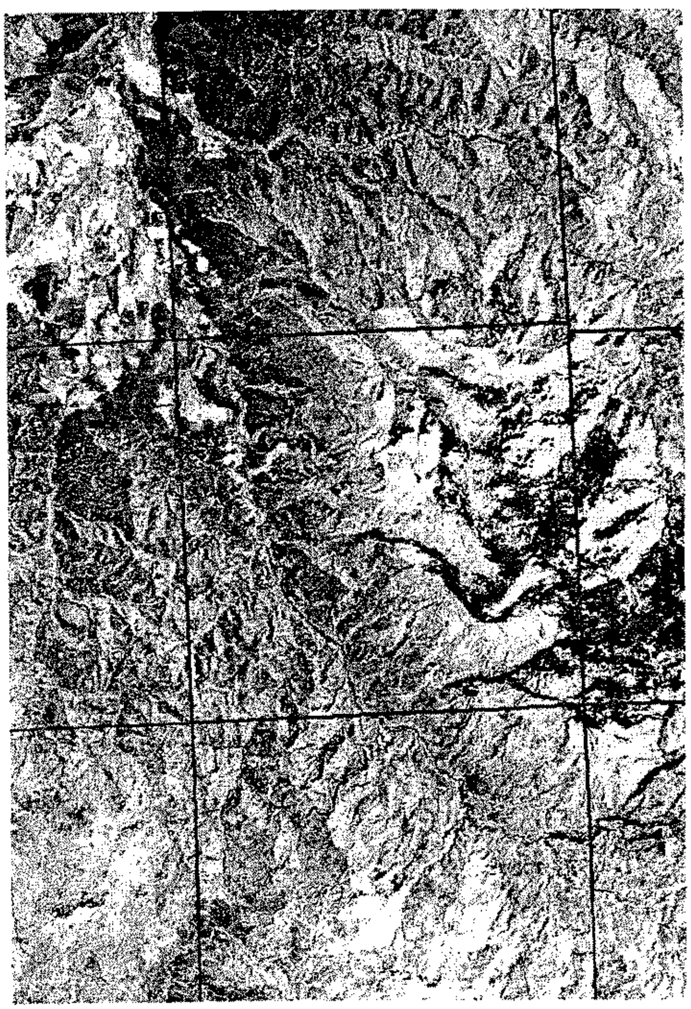


FIGURE 30. LANDSAT Thematic Mapper (TM) image of Divide Creek area. See text for additional discussion.

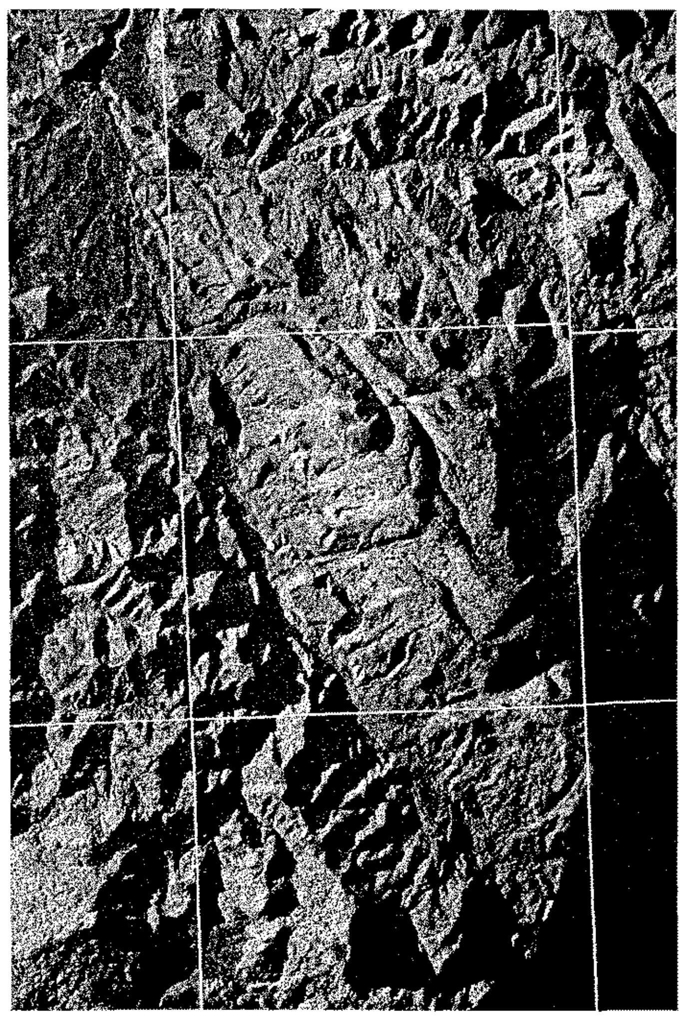


FIGURE 31. Side-looking airborne radar (SLAR) image of Divide Creek area. See text for additional discussion

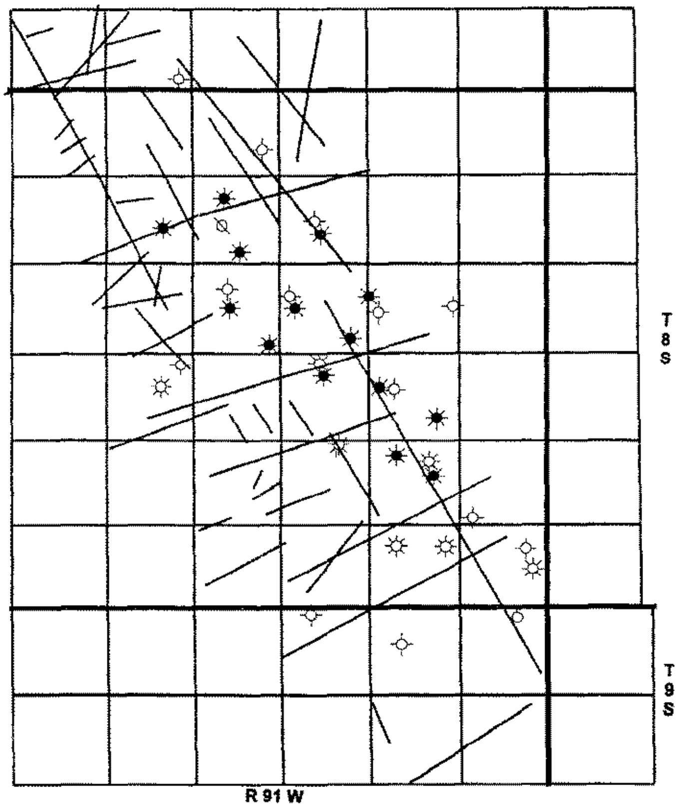


Figure 32. Linear features interpreted from side-looking-airborne radar (SLAR) imagery for the Divide Creek Field. Data acquired by USGS with SE-look direction. See text for additional discussion.

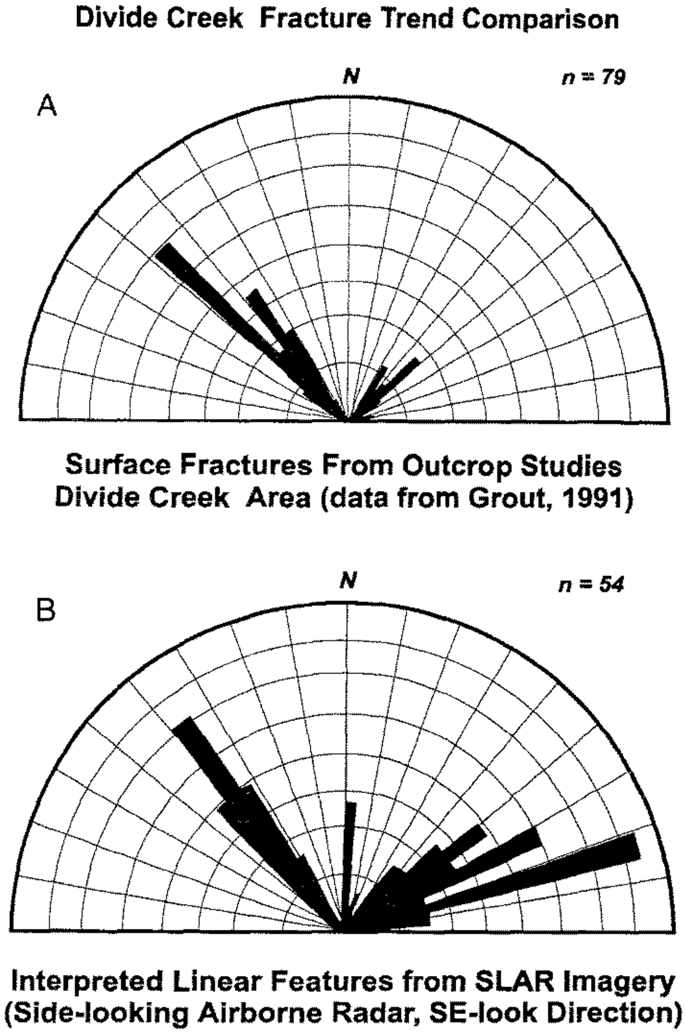


Figure 33. Comparison between fracture trends observed at surface outcrops (A) and linear features interpreted from SLAR imagery (B) for the Divide Creek area. Note close correspondence between the two data sets. Explanations for the observed slight misorientation between the two data sets are discussed in the text. This comparison clearly indicates the cost-effectiveness of using remote sensing to target localities and features to verify for outcrop studies.

rose diagram constructed from these data is presented in Figure 33A. This diagram shows that most surficial fractures trend NW with a minor component trending NE. Figure 33B illustrates similar trends and was constructed from data presented in Figure 32. The slight angular discordance between the NW trends in figures 33A and 33B are likely due to geometrical rectification errors, differences between reference frame north, initial measurement errors, or a combination of the above. The inherent enhancement of NE-trending features in the SLAR image due to the SE-look direction of the acquisition is apparent in Figure 33B. The similarity in orientations between the diagrams suggests a genetic relationship between orientations of imagery interpreted features and surficial fractures.

The spatial correspondence between locations and orientations of imagery derived features, and compartments of the gas reservoirs in the Divide Creek Anticline is shown in Figure 34. There exists a direct correlation in both orientation and location of interpreted features, known faults, and compartments within the Mesaverde reservoirs in all but one instance (the southernmost NE-trending fault). This is a remarkable correlation and in our experience quite exceptional. Based on our interpreted compartmentalization achieved by integration and independent interpretation of a diverse range of data sets, there is likely to be abundant opportunities for infill development of the structure, depending on unitization rules. Additional data not available to the authors (e.g. sandstone reservoir pressures, coalbed gas composition, more recent production data, water chemistry,

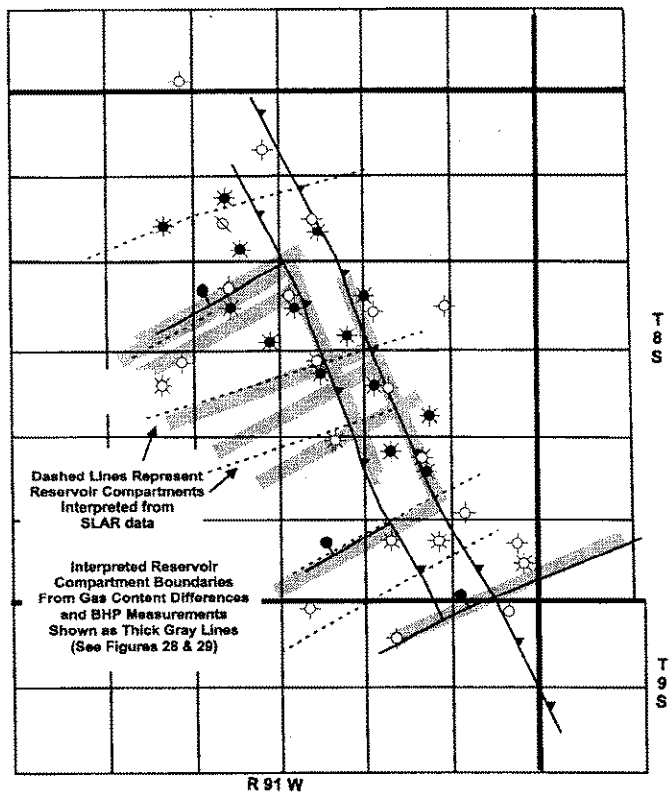


Figure 34. Interpretation of Divide Creek reservoir compartments integrating carbon dioxide content maps, static bottomhole pressure maps and remote sensing interpretation. Note close correspondence between the compartment boundaries interpreted from the different, independent data sources.

isotopic information, etc.) may refine the numbers, size and position of the interpreted compartments and should be used to refine the model for future development programs.

CONCLUSIONS

Parachute, Rulison, Divide Creek and Wolf Creek fields produce gas from fractured tight gas sand and coal reservoirs within the Mesaverde Group. Tectonic fracturing involving basement structures is responsible for development of permeability within the reservoirs. In this context, the significance of detecting natural fractures using the integrated fracture detection technique is critical to developing tight gas resources.

In Grand Valley-Parachute-Rulison fields, complex depositional systems preclude the development of predictive models for reservoir thickness and quality.

Basement faults can be effectively identified and interpreted using an integrated interpretation of remote sensing imagery data (Landsat TM), airborne radar (SLAR), detailed aerial photography, gas and water production data, detailed aeromagnetic data, subsurface geologic information, and surficial fracture maps. This new interpretation method demonstrates the importance of basement structures on the nucleation and development of overlying structures and associated natural fractures in the hydrocarbon-bearing section.

Fractured production trends in Piceance Basin Cretaceous-age Mesaverde Group gas reservoirs are controlled by subsurface structures. Many, if not most, of the subsurface structures are controlled by basement fault trends. Because of multiple detachment horizons in the basin, especially in the eastern and central basin, it is critical to have seismic data to confirm the relationship between basement and shallower reservoir horizons. We believe that through the use of integrated interpretation of the basement and shallower structures we can predict fractured reservoir production trends.

In the central Piceance Basin, production trends are NW-oriented and lie orthogonal to NE-trending depositional systems defined by sand isochore mapping.

We have developed an improved model for tectonic fracturing in Rulison Field to explain the lack of parallelism between NW-oriented production trends and WNW-trending natural fracture sets. This model involves dilatancy of pre-existing WNW-trending regional fracture sets flexure in the Rulison Anticline and similar smaller structures in adjacent areas.

Several zones of enhanced production rates and concomitant permeability in Rulison Field may represent small-scale thrusts that sole to a Mancos Shale-level detachment surface. 3-D seismic surveys in this field show subtle thrusts and thrust tip zones in which permeability may be greatly enhanced.

Remote sensing imagery analysis appears to provide a cost and time-effective method for locating regional structures, and surficial manifestation of basement-controlled fracture systems. Confirmation and delineation of the internal reservoir-scale characteristics of the fracture systems can then be performed by the application of more expensive exploration methods in a greatly-reduced area of interest.

In general, there is good agreement between the orientation of significant trends interpreted from imagery analysis and those determined from ground-based studies. Given the similar base for the two data sets, this outcome is not surprising. It is important to emphasize, however, the cost-efficacy of remote sensing analysis compared to field mapping. Remote sensing analysis provides an extremely rapid process for recognizing the dominant structural trends in the basin. Timing relationships, of course, still require surficial field work to confirm crosscutting relationships. Remote sensing analysis, however, readily identifies those areas where these relationships are best-expressed and must be ground truthed to verify their characteristics.

In regions such as the Piceance Basin, where abundant talus, gravel, and flood plain deposits occupy the lower elevations along the river and Parachute Creek, extreme care must be exercised when drawing conclusions from imagery interpretations of this area.

Imagery derived linear features show no consistent relationships to structure in the Grand Valley, Parachute, and Rulison fields at the Mesaverde reservoir level, or to basement structures. Interpreted features intersect structural contours at varying angles, do not correlate to local changes in slope or dip, and do not delineate the folds. Several NE-trending linear features do correlate to the location and trend of thick reservoir sand packages in the Mesaverde, however, the majority of NE-trending linear features do not. In addition, EUR production trends at Parachute field do not correlate to linear features or linear feature patterns interpreted from TM imagery. In the Rulison field, one, short, NW trending linear feature corresponds to an area of enhanced gas production around section 21, 6S 94W, however all others do not.

The use of remote sensing imagery analysis in the Divide Creek Field, integrated with ancillary data such as gas composition data, bottomhole pressure, seismic and subsurface mapping, permit the identification of significant reservoir compartmentalization. These interpreted compartments have tremendous potential for infill drilling and future development programs, especially given the maturity of the field.

Integration of data from widely-available, relatively inexpensive sources such as detailed aeromagnetics, remote sensing imagery analysis and regional geologic syntheses provide excellent data sets for incorporating into an overall methodology for targeting fractured reservoirs. The ultimate application of this methodology is the development and calibration of a potent exploration tool to predict subsurface fractured reservoirs and for targeting exploration drilling areas, as well as infill and step-out development programs.

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REFERENCES

Berry, G.W., 1959, Divide Creek Field, Garfield and Mesa Counties, Colorado, In: Haun, J.D. and Weimer, R.J. eds., Symposium on Cretaceous Rocks of Colorado and Adjacent Areas, Rocky Mountain Association of Geologists Guidebook, 89-91.

Brown, C.A., Smagala, T.M., and Haefele, G.R., 1986, Southern Piceance Basin Model-Cozzette, Corcoran and Rollins Sandstones, In: Spencer, C.W. and Mast, R.F. eds., Geology of Tight Gas Reservoirs, AAPG Studies in Geology #24, 207-219.

De Voto, R. H., Bartleson, B.L., Schenk, C.J., and Waechter, N.B., 1986, Late Paleozoic Stratigraphy and Syndepositional Tectonism, Northwestern Colorado, In: D.S. Stone, ed., New Interpretations of Northwest Colorado Geology, Rocky Mountain Association of Geologists Publication, 37-49.

Department of Energy Contractor's Report for Contract No. DEAC21-30086 for period, September 30, 1993-September 30, 1994, approx 200 p., available through DOE-Freedom of Information Act (FOIA) office, Morgantown, WV.

Department of Energy Contractor's Report for Contract No. DEAC21-30086 for period, October 1, 1994-September 30, 1995, 131 p., available through DOE-FOIA office, Morgantown, WV.

Department of Energy Contractor's Report for Contract No. DEAC21-30086 for period, October 1995-September 1996, approx 250 p., available through DOE-FOIA office, Morgantown, WV.

Donnell, J R., Yeend, W.E., and Smith, M.C., 1984, Preliminary Geologic Map of the Mesa Quadrangle, Mesa County, Colorado, USGS MF-1698 map.

Eckert, A. D., 1982, The Geology and Seismology of the Dudley Gulch Graben and Related Faults, Piceance Creek Basin, Northwestern Colorado, Unpub. M.S. Thesis, Univ. of Colorado-Boulder 139 p.

Grauch and Plesha, 1989, Aeromagnetic Maps of the Uinta and Piceance Basins and Vicinity, Utah and Colorado, U.S.G.S. Miscellaneous Field Studies Map MF-2008-C.

Gries, R. R., 1983, Oil and Gas Prospecting Beneath Precambrian of Foreland Thrust Plates in Rocky Mountains, American Association of Petroleum Geologists Bulletin, 67 1-28.

Grout, M.A., 1990, Fracture History of the Southern Piceance Basin and Tectonic Development of Intrabasin Folds, Northeastern Colorado Plateau, Colorado, Unpub. Ph.D. Dissertation, Univ. of Colorado-Boulder 232 p.

Grout, M.A., Abrams, G.A., Tang, R.L., Hainsworth, T.J., Verbeek, E.R., 1991, Late Laramide Thrust-related and Evaporite-domed Anticlines in the Southern Piceance Basin, Northeastern Colorado Plateau, American Association of Petroleum Geologists Bulletin, 75 (2) 205-218.

Grout, M.A., and Verbeek, E.R., 1985, Fracture History of the Plateau Creek and Adjacent Colorado River Valleys, Southern Piceance Basin-Implications for Predicting Joint Patterns at Depth, U.S. Geological Survey Open File Report 85-744, 17 p.

Grout, M.A., and Verbeek, E.R., 1989, Prediction of Fracture Networks at Depth in Low-Permeability Reservoir Rocks, Piceance and Washakie Basins, Western U.S., American Association of Petroleum Geologists Bulletin, 73 (9) p. 1158

Gunneson, B., Wilson, M., and Labo, J., 1994, A structural history of the Divide Creek Anticline, Piceance Basin, Northwest Colorado, Poster Session, AAPG Annual Meeting, Spring 1994, p. 160.

Gunneson, B., Wilson, M., and Labo, J., 1995, Divide Creek Anticline: A Decapitated Pop-up Structure with Two Detachment Zones, In: R. Ray, ed., High-Definition Seismic: 2-D, 2-D Swath and 3-D Case Histories, Rocky Mountain Association of Geologists Publication, 31-45.

Gwilliams, W.J., Kuuskraa, V.A., Decker, A.D., 1997, Integrating high-resolution aeromagnetic and 3-D Multiazimuth P-wave Surveys for Natural Fracture Data, Poster Session, AAPG Annual Meeting, Spring 1997, p. A45.

Harper, M.L., 1964, Mechanics of Basement Deformation in Glenwood Canyon, Colorado, Unpub. Ph.D. Dissertation, Univ. of Colorado-Boulder 102 p

Hoak. T.E. and Decker, A.D., 1995, Gas and Water Saturated Conditions in the Piceance Basin, Western Colorado: Implications for Fractured Reservoir Detection in a Gas-Centered Coal Basin, In: Proceedings of the International Unconventional Gas Symposium (Intergas '95), Tuscalossa, AL, 77-95.

Hoak. T.E. and Klawitter, A.L.,1995, Delineation of Piceance Basin Basement Structures Using Multiple Source Data: Implications for Fractured Reservoir Exploration, In: Proceedings of the International Unconventional Gas Symposium (Intergas '95), Tuscalossa, AL, 53-73.

Hoak. T.E. and Klawitter, A.L., 1996, Structural Compartmentalization in a Decapitated Anticline: The Example of the Divide Creek Anticline, Poster Session, AAPG Annual Meeting, Spring, 1996, p. A66.

Johnson, R.C., and Nuccio, V.C., 1986, Structural and Thermal History of the Piceance Creek Basin, Western Colorado, in Relation to Hydrocarbon Occurrence in the Mesaverde Group, In: Spencer, C.W. and Mast, R.F. eds., Geology of Tight Gas Reservoirs, AAPG Studies in Geology #24, 165-205.

Johnson, R.C., and Finn, T.M., 1986, Cretaceous Through Holocene History of the Douglas Creek Arch, Colorado and Utah, In: D.S. Stone, ed., New Interpretations of Northwest Colorado Geology, Rocky Mountain Association of Geologists Publication, 77-98.

Johnson, R., 1989, Geologic history and hydorcarbon potential of Late Cretaceous-age, low-permeability reservoirs, Piceance Basin, western Colorado, U.S. Geological Survey Bulletin 1787-E, 51 p.

Knepper, D.H., 1982, Lineaments Derived from Analysis of Linear Features Mapped from LANDSAT Images of the Four Corners Region of the Southwestern United States, U.S. Geological Survey Open-File Report 82-849, 79 p.

Lorenz, J., 1985, Predictions of Size and Orientation of Lenticular Reservoirs in the Mesaverde Group, Northwestern Colorado, Society of Petroleum Engineers SPE/DOE 13851, In: Proceedings of the 1985 SPE/DOE Joint Symposium on Low Permeability Reservoirs, 23-28.

Lorenz, J., Warpinski, N.R., Teufel, L., Branagan, P. T., Sattler, A.R., and Northrop, D.A., 1988, Results of the Multiwell Experiment, EOS (Transactions of the American Geophysical Union) v. 69 (35), 817, 825-826

Lorenz, J. C., Teufel, L. E., and Warpinski, N. R., 1991, Regional Fractures II: Fracturing of Mesaverde reservoirs in the Piceance Basin, American Association of Petroleum Geologists Bulletin, 75, 1738-1757.

Lorenz, J., Finley, S., 1991, Regional Fractures I: A mechanism for the formation of regional fractures at depth in flat-lying reservoirs, American Association of Petroleum Geologists Bulletin, 75, 1714-1737.

Lorenz, J., Warpinski, N., and Branagan, P., 1991, Subsurface Characterization of Mesaverde Reservoirs in Colorado: Geophysical and Reservoir Engineering Checks on Predictive Sedimentology, in: Miall, A. and Tyler, N., eds., The Three-Dimensional Facies Architecture of Terrigeneous Clastic Sediments, and its implications for Hydrocarbon Discovery and Recovery, Society Economic Paleontology and Mineralogy (SEPM), Concepts in Sedimentology and Paleontology, V. 3, 57-79.

Lorenz, J., and Hill, R., 1994, Subsurface Fracture Spacing: Comparison of Inferences from Slant/Horizontal and Vertical Cores, Society of Petroleum Engineers (SPE) Formation Evaluation, March, 1994, 66-72.

Murray, F.N., 1966, Stratigraphy and Structural Geology of the Grand Hogback Monocline, Colorado, Unpub. Ph.D. Dissertation, Univ. of Colorado-Boulder, 218 p.

Osmond, J.C., 1986, Petroleum Geology of the Uinta Mountains-White River Uplift, Colorado and Utah, In: D.S. Stone, ed., New Interpretations of Northwest Colorado Geology,, Rocky Mountain Association of Geologists Publication, 213-222.

Perry, S.L., 1985, Lineaments of the Northern Denver Basin and their Paleotectonic and Hydrocarbon Significance, unpublished M.S. theses, Colorado School of Mines, 111 p.

Peterson, R.E., 1984, Geological and Production Characteristics of the Nonmarine Part of the Mesaverde Group, Rulison Field Area, Piceance Basin, CO, SPE/DOE/GRI Joint Symposium on Unconventional Gas Recovery, SPE 12835, 47-56.

Poole, F.G., 1955, Geology of the Grand Hogback Area, Garfield and Pitkin Counties, Colorado, Unpublished M.S. Thesis, Univ. of Colorado-Boulder 128 p.

Reinecke, K. M., Rice, D. D. and Johnson, R. C., 1991, Characteristics and Development of Fluvial Sandstone and Coalbed Reservoirs of Upper Cretaceous Mesaverde Group, Grand Valley, Colorado, In: Coalbed Methane, Rocky Mountain Association of Geologists Publication, 209-225.

Richard, J.J., 1986, Interpretation of a Seismic Section Across the Danforth Hills Anticline (Maudlin Gulch) and Axial Arch in Northwest Colorado, In: D.S. Stone, ed., New Interpretations of Northwest Colorado Geology, Rocky Mountain Association of Geologists Publication, 183-190.

Sawatzky, D.L., and Raines, 1981, Geologic Uses of Linear Feature Maps Derived from Small-Scale Images, In: O'Leary, D.W., and J.L. Earle, Eds., International Conference on Basement Tectonics, Third, Durango, CO.

Stone, D., 1986, Seismic and borehole evidence for important pre-Laramide faulting along the Axial Arch in Northwest Colorado, In: D.S. Stone, ed., New Interpretations of Northwest Colorado Geology, Rocky Mountain Association of Geologists Publication, 23-30.

Tweto, O., 1975, Laramide (Late Cretaceous-Early Tertiary) Orogeny in the Southern Rocky Mountains, In: B.F. Curtis, ed., Cenozoic History of the Southern Rocky Mountains, Geological Society of America Memoir, 144, 1-44.

Tweto, O., 1980, Tectonic History of Colorado, In: H.C. Kent and K.W. Porter, eds., Colorado Geology, Rocky Mountain Association of Geologists, 5-9.

Tyler, R., Kaiser, W., McMurry, R., Nance, S., Scott, A., Zhou, N., and Tremain, C., 1995, Geologic Characterization and Coalbed Methane Occurrence: Williams Fork Formation, Piceance Basin, Northwest Colorado, Gas Research Institute Topical Report GRI-94/0456, Gas Research Institute Contract No. 5091-214-2261, 218 p.

Verbeek, E., and Grout, M., 1984, Fracture Studies in Cretaceous and Paleocene strata in and around the Piceance Basin, Colorado: Preliminary results and their bearing on a fracture-controlled natural gas reservoir at the MWX site, U.S. Geological Survey Open-file Report 84-156, 23 p.

Waechter, N.B., Johnson, W.E., 1986, Pennsylvanian-Permian Paleostructure and Stratigraphy as Interpreted From Seismic Data in the Piceance Basin, Northwest Colorado, In: D.S. Stone, ed. New Interpretations of Northwest Colorado Geology, Rocky Mountain Association of Geologists Publication, 51-64

Warner, D.L., 1964, Mancos-Mesaverde (Upper Cretaceous) Intertonguing Relations, Southeast Piceance Basin, Colorado, American Association of Petroleum Geologists Bulletin, 48 (7) 1091-1107.

Zapp, A.D., and Cobban, W.A., 1960, Some Late Cretaceous Strand Lines in Northwestern Colorado and Northeastern Utah, USGS Geological Survey Research-Short Papers in the Geological Sciences, B246-B249.