DOE/MC/30086 -- 5027
(DE96000578)



# Naturally Fractured Tight Gas Reservoir Detection Optimization

## Quarterly Report
## January - March 1995

May 1995

Work Performed Under Contract No.: DE-AC21-93MC30086

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Advanced Resources International, Inc.
Lakewood, Colorado

## DISCLAIMER

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Distribution Category UC-132

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By
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165 South Union Boulevard, Suite 800
Lakewood, Colorado 80228

May 1995

**U.S. DEPARTMENT OF ENERGY**
**MORGANTOWN ENERGY TECHNOLOGY CENTER**
**QUARTERLY STATUS REPORT**
**FOR THE PERIOD**
**January 1, 1995- March 31, 1995**
**DATE OF SUBMISSION: 4/30/95**

**CONTRACT NO.:**
DE-AC21-93MC30086

**CONTRACTOR:**
Advanced Resources International, Inc.

**CONTRACT NAME:**
Naturally fractured tight gas reservoir detection optimization

**CONTRACT PERIOD:**
September 30, 1993-March 31, 1997

**CONTRACT OBJECTIVE:** No Change

**TECHNICAL APPROACH CHANGES:** No Change

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**TASK NO. 1:**

## A. GEOLOGIC ASSESSMENT OF THE PICEANCE BASIN

## Geologic Interpretation:

### Reservoir Characterization:

Because of the undocumented presence of fractured reservoir conditions in many gas fields in the Piceance Basin, we are also conducting several detailed field studies to document production trends in these fields and the relationship between production, structure and depositional trends. Preliminary emphasis has been placed on Grand Valley Field (located just west of Parachute and Rulison fields) to augment our previous study completed in Parachute and Rulison fields. Upon completion of this study, we will concentrate our efforts on Plateau-Shire Gulch fields in the southwest basin. It is anticipated that White River Dome (in the northern basin) and Divide and Wolf Creek structures in the eastern basin will be studied to contrast fractured production controls and trends in thrust-cored fault-propagation anticlines.

**Seismic Interpretation:**

The seismic database at Barrett Resources was inventoried and used for basement and shallower structural analysis. Work continues on the generation of time-structure maps that demonstrate the link between basement and shallower-level structures. These maps and related 2D interpretations will be integrated with the high-resolution aeromagnetic data and the regional tectonic interpretation to determine the basement controls on shallower-level structures that control fractured reservoir production.

The seismic data available at Barrett Resources has been interpreted and data entered into a digital format for importation into the mapping software used by Advanced Resources International. Horizons picked include a Fort Union marker (Tertiary-age), a Rollins Sandstone (to facilitate comparision with conventional subsurface structure maps), the Dakota sandstone (to recognize sub-Mancos shale detachment surfaces) and Basement. A basement fault interpretation is underway and will be compared with fault maps constructed for each of the overlying seismic horizons.

**Remote Sensing Interpretation:**

Analysis of linear features from various regions of the basin shows that the basin has experienced a complex structural history. From this preliminary analysis, it appears certain that we will need to delineate distinct domains based on some criteria (e.g. lithology, basement structural domain, timing of structural development, and/or geographic location) that permits ready distinction of the different sets. Work in progress is attempting to determine the most suitable parameter to use to break out the different structural domains.

Overall, there appears to be a close relationship between observed linears (interpreted from both SLAR and TM data) and surface-mapped fractures. TM, because it lacks the look-direction bias, is preferable to SLAR and shows a close correspondence to surface-mapped faults. Surface-mapped joints, however, do not show such a close correspondence. At present, it is thought that faults exert a greater control on the development of geomorphic features than do joints. The reason for this relationship is under investigation.

The final stages of imagery analysis are nearing completion. Work in progress involves attempting to determine the structural significance of interpreted linears. Initial attempts have been made to separate linears based on structural domain. Additional effort has focused on interpretation based on host rock lithology. Using digital basin geologic maps, the outcrop polygons are used to partition the linear features data sets by bedrock geology. This information will allow us to see the differences in linear features between surficial host rock lithology. Previous fracture work in the basin has suggested that there is a difference in fracture characteristics between the Mesaverde, Wasatch and the Green River (oil shale) formations. Upon completion of the structural interpretation, the remote sensing interpretation can be finalized. Completion of the remote sensing interpretation is scheduled for late February.

**Stratigraphic Interpretation:**

Tectonics and sedimentation are closely related in the Rocky Mountain basins. Facies changes and rapid thickening are typically indicative of basement movement. Stratigraphic anomalies are interpreted as locators of basement faulting and associated fracturing. A grid of 150 wells was constructed throughout the southern Piceance Basin to conduct an investigation of the subsurface stratigraphy. This analysis has examined the interval from the top of the Mancos "B" shale up through the lower Tertiary-age Wasatch Formation. This interval includes producing horizons of the Cozzette, Corcoran and Rollins sandstones, Cameo coals and sands and

Mesaverde or Williams Fork fluvial channels, in addition to the lowermost Wasatch sands. Correlation of stratigraphic picks throughout the grid has been completed. The data used for these picks has been added to the digital database system used for geologic interpretation.

Results to date indicate the dominance of NW-trending fluvial axes in the Mesaverde Group that control reservoir quality. We are presently attempting to use the data set as a predictive tool in order to target areas possessing enhanced reservoir thickness and quality.

An attached report outlines the results of the stratigraphic study to date. The report has been written as a stand alone document in preperation for publication in a professional journal.

**Professional Meetings:**

The dissemenation of project results to the industry is a top project priority. Professional technical conferences are a low cost and effective method for technology transfer. As such ARI has aggresively pursued opportunites to present project results at these meetings. In this section we briefly review recent presentations and future commitments. ARI staff presented a poster session entitled "Delineation of Piceance Basin Basement Structures Using Multiple-Source Data: Implications for Fractured Reservoir Exploration" at the AAPG Annual Meeting in Houston, Texas in March. Response of academic and industry groups to the technical approach and interpretation was extremely good and numerous individuals are closely following the results of the project.

David Decker, Vello Kuuskraa,Thomas Hoak, and Alan Klawitter will attend the Intergas '95 conference in Tuscaloosa in mid-May and will present three papers on the DOE-METC program results in the Piceance Basin. The papers are attached at the end of this report in addition, these ARI staff and others will present a one-day Short Course on "Risk Management Strategies for Tight Gas Fractured Reservoirs" at this meeting.

Alan Klawitter will present a poster session at the AAPG Rocky Mountain Meeting in Reno, Nevada in July on the integrated results (aeromag, remote sensing, subsurface geology, seismic, production mapping) of the project. Thomas Hoak will present an invited talk on the tectonic evolution of the Piceance Basin and its implications for fractured reservoir detection.

Thomas Hoak and David Decker have been selected to present a poster session (and related paper) at the SPE Annual Meeting in Dallas, October, 1995.

**Project Review Meetings:**

A annual project review meeting was held in Morgantown and involved the DOE-METC staff, Advanced Resources International, Inc. staff and Peter Ortoleva and John Comer of Indiana University and the Indiana Geological Survey, respectively. This meeting discussed progress to date on the various subtasks of the project, in particular the geologic assessment phase preliminary results. Overall, the project allowed ARI staff to become familiar with the DOE staff and also permitted an introduction to DOE for the Indiana University researchers. In later interaction, ARI and Indiana University were able to discuss and more fully define the mutual technical objectives of the project. This is particularly important because of the need to mutually address common research objectives and avoid duplication of effort.

## B. SUBCONTRACTS

## Indiana University-Laboratory for Computational Geochemistry:

### 1. *Two-dimensional basin simulator:*

The transport modifications have been completed and preliminary tests indicate that the algorithm and code are correct and working properly. A modification of the diffusion model has been implemented so as to reflect the dependence of waterfilm thickness on the identification of the minerals on each side of the contact. This captures effects such as the promotion of quartz pressure solution in contact with a phyllosilicate.

The second order correct finite difference method for the pressure and temperature solver is complete, and the pressure solver is fully tested. Work continues on verifying the temperature solver.

The finite element, visco-plastic module has been updated to include the influence of fluid pressure on effective stress, as well as to include the non-linear viscosity model with the texture dependent yield criteria. More improvements have been designed for the iterative solver, making it more efficient, and implementation has begun. Work has begun on interfacing this module with CIRFB.3.

The finite element, visco-plastic module is being modified to handle larger scale deformations, like major faults, igneous intrusions, or salt intrusions.

Fracture modules are in various stages of development and integration with three-dimensional chemistry and stress solvers. When fluid pressure overcomes confining pressure, fractures are initiated, and grow; this increases local porosity and permeability and lateral stress, all of which then modify further fracture extension and aperture expansion.

The program which interpolates vertical (time) well data for the CIRFB.3 sediment and tectonic history input format is completed. Also, the input module has been adjusted so that selected minerals from the entire data suite can be included or omitted for simulation; the relative modes are normalized, maintaining the initial porosity value. Work is beginning on using published sedimentological data to develop an algorithm for decompaction to the original unlithified state. Improvements continue to be made on the data input interface, in order to make running of the program easier.

The module for interpolating well data between wells that respects sharp lithologic boundaries is completed and is being tested. It is serving both as a way of inputting data and as a check on geological data. The two-viscosity (compactional and shear) irreversible mechanical strain contribution (with yield) has been implemented into the three-dimensional stress/deformation solver. Careful testing of the pressure module using certain symmetry propeties of simple cases revealed some small errors in the curvilinear coordinate discretization. These errors have been found and corrected, which removed some instabilities and errors in previous calculations.

Improvements on the sediment input module allow for a smoother, more realistic contact shape in areas with low data density. Additionally, the algorithm used for interpolating between wells has been updated in order to better estimate the contact position between two wells, by looking before and after the time of interest at each well, thereby making maximum use of the known sedimentological data at the wells. A method was devised for interpolating stratigraphic data between wells, in order to reconstruct the distribution of lithologies at the surface for a given time slice. This has been coded and is being tested with data from the southern Piceance Basin.

*2. Data analysis and data base:*

**(a) Geological data:** A preliminary method has been devised for simulating the composition of rock fragments (as reported in MWX data) based on their likely sources, and the estimated mineralogical content of these sources. Also, we are now better able to constrain estimated mineralogical composition of the Wasatch and Green River Formations using published descriptions and data. Work has commenced researching the structural and stress history of the basin, using published data on timing and direction of lateral motion and subsidence, as well as from ARI aeromagnetic and other data. Input file format for CIRF.B3 has been revised, and more single well files have been created. Stratigraphic data for several more wells in the southern Piceance Basin have been entered into input files for CIRFB.3. ARI has sent Indiana University a preliminary lateral stress history of the basin. This data is being used to constrain the model boundaries. Several potential industrial contacts have been made through which additional data may be forthcoming.

**(b) Physico-chemical data:** A program is being written to calculate required input parameters from experimental rock mechanics data. Techniques are being developed for fitting rheological parameters to experimental results, extrapolated to geologic time scales. Rock rheological parameters for carbonates, sandstones, and shales are being determined by fitting two-viscosity rheology to published experimental rock mechanics data. Equations for determining initial detrital porosity as a function of grain sorting or grain size are being developed and calibrated using published porosity data of unconsolidated sediments. Work continues on determining parameters for the visco-elastic module and on developing the database managing protocol to make entry of well and other data most efficient.

### *3. Organic reactions and multi-phase flow:*

Work continues on developing the Newton-Raphson method for solving multi-phase flow. The partial-differential-equation solver has been discretized using a second-order-correct, finite difference adaptive grid method. This code will be able to handle an arbitrary number of liquid phases and components within each phase. Exchange of components between phases, and reactions within a phase, are asssessed in the program. Transport is by the black oil model. The Newton-Raphson method multi-phase flow solver is coded and debugging is nearing completion. Thereafter, testing of the code will begin with single phase, two component flow, using a rectangular grid and then a curvilinear grid.

### *4. Grid optimization:*

The routine to allow partial splitting of grids has been completed, allowing better grid density distribution for better adaptation to more complex geology. A method has been devised which can create a function that more evenly focuses grids at formation boundaries.

### *5. Piceance Basin simulations:*

One dimensional simulations comprising six minerals have been completed, including quartz, microcline, albite, kaolinite, calcite, and dolomite. Results indicate that, for the Mesaverde units, these simulations show better agreement with porosity trends at the MWX site, than the earlier four mineral simulation. Another one-dimensional simulation comprising eight minerals (those listed above, plus muscovite and anorthite) and rock fragments is currently being run, but the computation is slow due to small time steps. Aspects of the input data and control parameters are being examined, as well as the code itself, for ways to improve the speed. A one-dimensional, eight mineral simulation using CIRFB.2 terminated because of textural problems. Ways are being sought to overcome these problems in order to complete the simulation. Input files for two two-dimensional simulations of cross sections across the basin are being constructed. A preliminary three-dimensional simulation using Piceance Basin data has been accomplished. Work continues on modifying input parameters for one-, two-, and three-dimensional simulations of the southern Piceance Basin. Extensive work has been done examining the output of the sedimentation interpolation routine to improve the degree to which it automatically yields interpolations which are consistent with accepted sedimentological concepts (the sedimentation interpolation routine takes sedimentological data at well sites and interpolates to all locations in between).

## World Geoscience:

All data and hard copy maps have been received from World Geoscience. Detailed interpretation of the data set has been completed. Preliminary assessment of the data set demonstrates the dominance of NE- and NW-trending basement structures on the east side of a NW-trending basement discontinuity. In contrast, the western region across this discontinuity is dominated by E/W- and WNW-trending anomalies. Because of the abundant high frequency data the regional gradients needed to calculate a basement depth are equivocal. An accurate depth-to-basement calculation throughout the survey area is in progress.

Following receipt of this report, we will integrate this data set with seismic and other subsurface control.

**SUMMARY STATUS AND FORECAST**

Efforts in the next quarter will be addressed toward integration of the various data sets into a coherent, unifying interpretation. We are expecting significant results from the Indiana University modeling group to compare with the results generated internally at ARI. Future project emphasis will be planning of the 3D-3C seismic survey. The Rulison Field has been tentatively selected as the primary site for the seismic program. A detailed report defining the rationale for site selection and alternatives to the primary site will be submitted in the next quarterly report. Close coordination between DOE/METC project management and the cooperative industry partner, Barrett Resources, is being facilitated by the principal investigator, David Decker.

A. David Decker, Project Manager

**OPEN ITEMS:** None

# REGIONAL STRATIGRAPHIC STUDIES, UPPER CRETACEOUS MESAVERDE GROUP, SOUTHERN PICEANCE BASIN, COLORADO

## Introduction and Objectives

This study was undertaken as part of the ongoing "Naturally Fractured Tight Gas Reservoirs Detection Optimization" program funded by the Department of Energy's Morgantown Energy Technology Center under contract number DE-AC21-93MC30086. The objective of this component of the study was to evaluate the relationship between tectonics and sedimentation in the southern Piceance basin. More specifically, the study identifies unique stratigraphic alignments with respect to basement features interpreted from remote sensing imagery, high resolution aeromagnetics, and seismic data. The results of this analysis will help to understand the timing of structural movement and its effect on depositional patterns. When the various components of the program have been fully integrated, an exploration model will be developed that can be of significant value to operators pursuing naturally fractured tight gas reservoirs in the Piceance Basin and other analogous basins.

The purpose of this report is to summarize the stratigraphic framework of the Upper Cretaceous Mesaverde Group in the southern Piceance basin. Sedimentary basin fill from the Mancos Shale through the Williams Fork Formation was evaluated and mapped in order to determine the effect that structural movement had on interval thicknesses and sediment dispersal patterns.

## Methods

Database

Geophysical logs, including electric, resistivity, sonic, neutron and density logs were acquired from approximately 150 wells and served as the principal data set for the regional stratigraphic framework studies. The gamma-ray, conductivity and induction curves proved to be most useful for correlation purposes, and the vertical scale was reduced to allow correlation of the entire stratigraphic section of interest. Spontaneous potential (SP) curves were typically recorded in older well log suites, but due to the low permeabilities of the sandtones, SP curves are suppressed and do not provide the resolution needed to establish subsurface correlations. Sonic, density, and neutron logs were used to identify and quantify coal seams and their thicknesses.

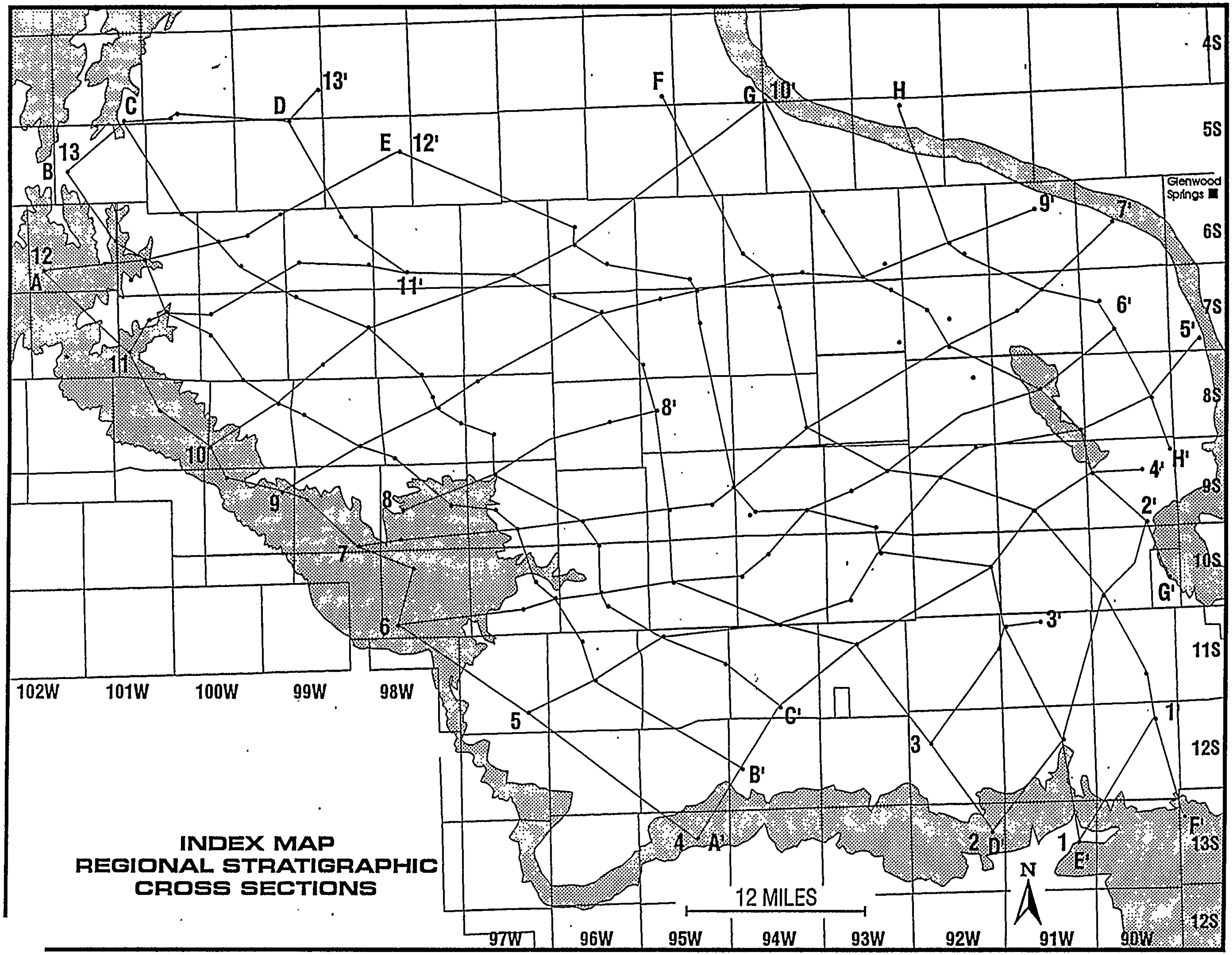
Twenty-one stratigraphic cross sections were constructed across the study area to facilitate correlations and illustrate the lateral and vertical variations in thickness and facies of Mesaverde Group deposits (Figure 1). The cross sections were prepared from hard copy logs at a vertical scale of 1 inch equals 200 ft and did not use a horizontal scale. The cross sections were referenced on the stratigraphic datum at the top of Cozzette stratigraphic interval, which is readily identified and correlated across the basin. One representative cross section was digitized and compressed so that it could be presented as a page-sized figure within this report.

Gross interval isopach maps and net coal thickness maps were generated by computer using GeoGraphix Exploration System (GES) 7.5. Interpretive maps such as net sandstone, percent sandstone and paleogeographic reconstructions were initially prepared by hand, then digitized and converted to report-quality figures.

The structure of this report is built on an initial discussion of the approach used herein and by previous authors to delineate the regional stratigraphic framework of the Mesaverde Group in the Piceance basin. The report explains observations made during the course of the analysis. The definition and general geologic characteristics of each major stratigraphic package within the Iles and Williams Fork Formations are briefly summarized. Finally, implications for exploration and exploitation of naturally fractured tight gas sands and coalbed methane resources will be discussed with respect to stratigraphic alignment with the basin hingeline.

## Stratigraphic Approach

During the last several years, various concepts, nomenclature and approaches to understanding stratigraphy have been compared as to their relative merit and practical application




INDEX MAP
REGIONAL STRATIGRAPHIC
CROSS SECTIONS

to the explorationist. Sequence stratigraphy is based on the study of genetically-related facies within a framework of chronostratigraphically significant surfaces. Vail and others (1984) emphasized the use of seismic data when developing the concepts of seimic sequence stratigraphy. Seismic reflections illustrate interfaces such as depositional or erosional surfaces. These surfaces (sequence boundaries) are unconformities that are formed during eustatically-controlled lowstands of sea level. The sequence is thus defined as a relatively conformable genetically-related succession of strata bounded by unconformities or their relative conformities (Van Wagoner and others, 1990).

Genetic stratigraphy is based on recognition of genetically-linked strata that were deposited during discrete episodes of general tectonic, climatic, or base level stability, and emphasis is placed on a common depositional system. These units are the time stratigraphic increments of the basin fill, and should be correlative and mappable (Galloway, 1989). The genetic stratigraphic sequence shares similarities with the depositional sequence of Van Wagoner and others (1987, 1990); it is most analogous to their parasequence set. However, the fundamental difference between the two approaches lies in the bounding surfaces. Marine flooding surfaces define and bound the genetic stratigraphic sequence, wheras the depositional sequences in sequence stratigraphy are centered on marine-flooding events.

In general, a genetic stratigraphic approach was applied to the analysis of the Mesaverde Group in the Piceance Basin. This is primarily because the application of a sequence stratigraphic approach requires identification of sequence boundaries to interpret the hierarchy of systems tracts and facies. These surfaces are most readily interpreted using a data set that includes seismic and whole cores, which this study did not use. Without identification of the bounding surfaces, sequence stratigraphic analysis is incomplete at best. Since the genetic stratigraphic approach uses marine flooding events as bounding surfaces and emphasizes the depostional system, identification and interpretation can generally be accomplished with a limited data set consisting of well logs. Additionally, the Williams Fork Formation was deposited in a predominantly nonmarine setting, in which the effective applications of sequence stratigraphic analysis are still controversial. In fact, stratigraphic framework studies in a nonmarine environment are typically complex and equivocal, because bounding surfaces that define the genetic stratigraphic sequence or parasequence in the marginal marine section are extremely difficult to correlate into the nonmarine section.

Kaiser and others (1994) and Tyler and others (1994) provide a genetic stratigraphic model for the Upper Cretaceous in the Sand Wash and Piceance basins that is believed to be practical and reasonable. Their approach was applied, particularly in the eastern part of the study area, to facilitate correlations and help to establish the stratigraphic framework.

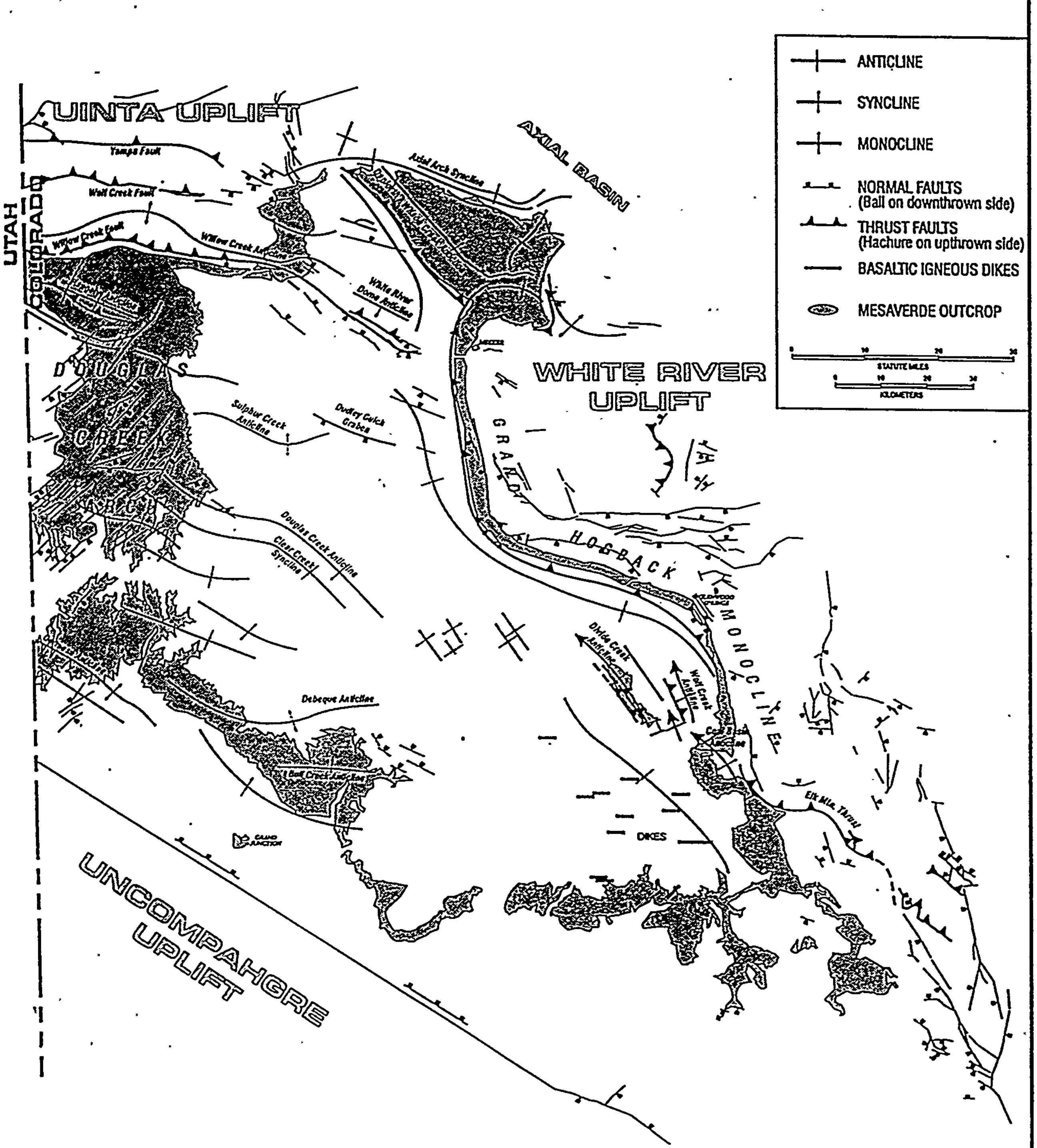
## General Geologic Setting

The Piceance basin is a complex intermontane basin formed by Laramide tectonism during latest Cretaceous through Paleocene time. The basin is bounded on the north by the Axial basin anticline, on the east by the White River Uplift, on the southeast by the Sawatch Uplift, on the south by the San Juan volcanics, and on the southwest by the Uncompahgre Uplift. It is separated from the Uinta basin to the west by the Douglas Creek Arch. The Piceance basin is highly asymmetrical with a gently dipping western flank and a steeply dipping eastern flank, known as the Grand Hogback Monocline (Figure 2).

Deposition of the Mesaverde Group mostly predates Laramide tectonism that formed the basin. The Mesaverde was deposited in what was then the Rocky Mountain foreland basin. The Sevier orogenic belt, located on the western margin of the basin, was an area of active uplift and eastward thrusting. The rapidly subsiding basin was the setting for a major marine incursion (the extensive Cretaceous epeiric seaway), during which deposition of the marine Mancos Shale occurred, which underlies the Mesaverde Group throughout the basin. Following deposition of the Mancos Shale, continued uplift from the Sevier orogeny provided the sediment source for a series of regressive pulses that prograded generally from west to east into the basin. The shoreline transgressed and regressed across the Piceance basin through much of late Cretaceous time. The regressive deposits of the Iles Formation (Corcoran and Cozzette sandstones) have been studied extensively by Johnson (1987, 1989); Brown and others (1986); Finley (1985); and other authors, and will be discussed briefly in this report. An analysis of the overlying and

FIGURE 2

# TECTONIC MAP
# PICEANCE BASIN, WESTERN COLORADO




From Hoak and others, 1995

predominantly nonmarine Williams Fork Formation will also be summarized herein. The Williams Fork Formation as defined by Tyler and McMurry (1995) includes the Rollins progradational episode and that definition will be adopted for the purposes of this report. The Williams Fork also includes (in the eastern part of the basin) the marine middle and upper sandstones of Collins (1970, 1976), along with the tight gas sands and coalbed methane reservoirs that are currently of interest to Piceance Basin operators.

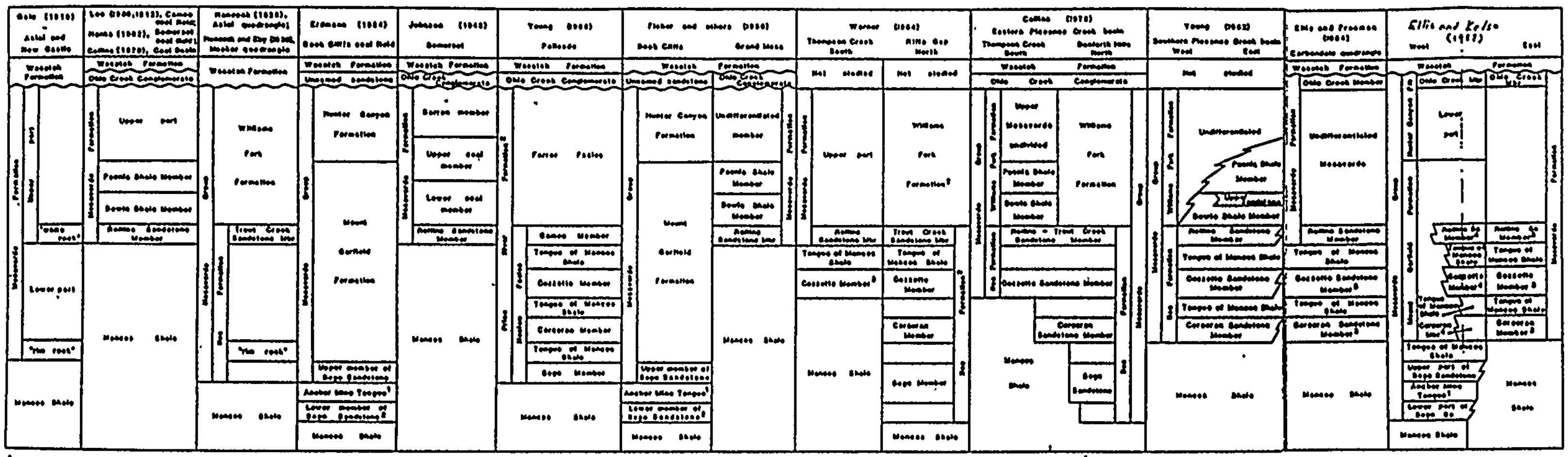
## Stratigraphy of the Mesaverde Group

The formation terminology of the Mesaverde Group is rather complicated, and the major stratigraphic units have different names depending on the author and their location within the basin. Figure 3 summarizes the varying terminology used across the basin. For purposes of this study, the Mesaverde Group in the southern Piceance basin has been designated to include the Iles Formation and the Williams Fork Formation (Figure 4).

### Iles Formation

The Iles Formation is defined by several thick sandstone members that cap regressive cycles (progradational parasequences/genetic units) throughout the basin. The Castlegate, Sego, Corcoran, and Cozzette sandstones comprise the operational Iles Formation in the study area. This differs from the traditional stratigraphic nomenclature in that the tongue of Mancos Shale above the Cozzette sandstone and the Rollins sandstone itself are traditionally assigned to the Iles Formation. Kaiser and others (1994) recognized a maximum flooding surface (MFS) above the Cozzette sandstone. From a genetic stratigraphic standpoint, this MFS signals the termination of the series of regressive episodes of the Corcoran and Cozzette intervals by an abrupt return to open marine conditions. The MFS also marks the initiation of the next major regressive sequence/cycle, which begins with deposition of the open marine shales and then shallows upward to include the marginal marine Rollins sandstone and its thick, extensive, associated nonmarine (and coal-bearing) section. Thus, this progradational cycle belongs genetically to the Williams Fork Formation. The earliest regressive cycles of the Iles Formation, the Castlegate

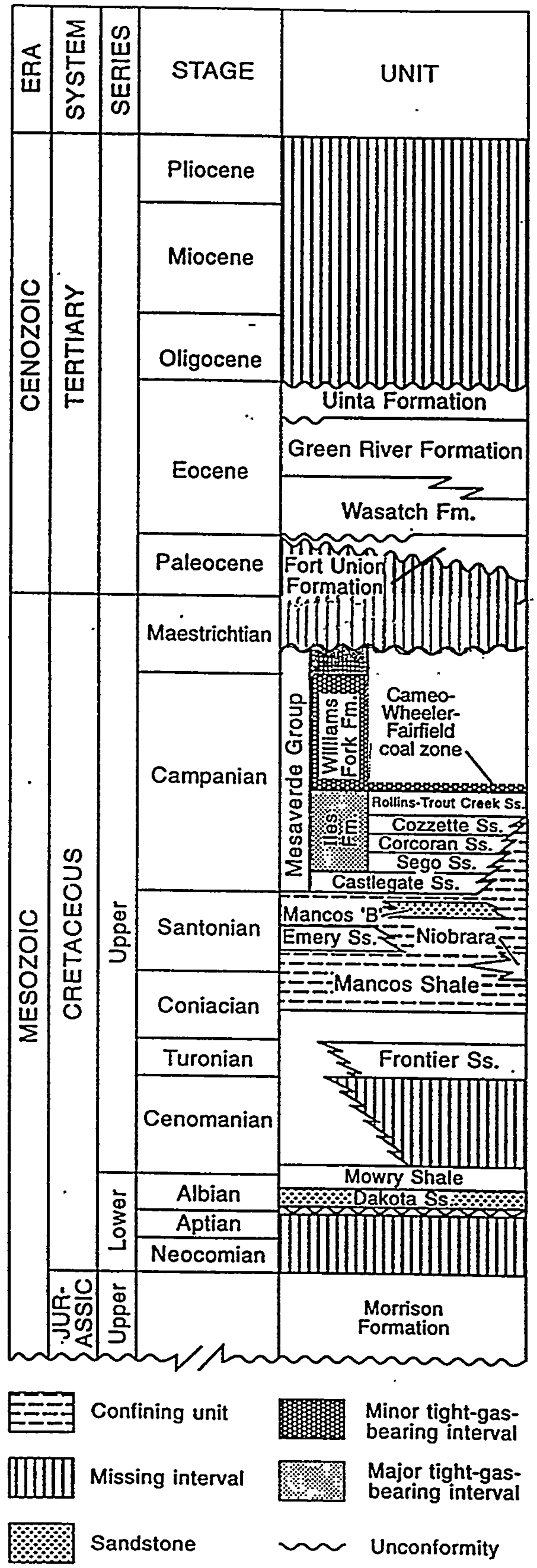
FIGURE 3



[1] of the Mancos Shale
[2] of the Mesaverde Group
[3] of the Mesaverde Formation
[4] of the Mount Garfield Formation

From Ellis and Kelso, 1987

FIGURE 4




Modified from Tyler and McMurry, 1995

and Sego intervals, are represented in the study area as generally distal shoreface and shelf siltstones and open marine mudstones and do not represent significant potential reservoirs. Consequently, they are not a topic of this report.

*Corcoran and Cozzette Stratigraphic Units*

An assessment of the Corcoran and Cozzette regressive units within the Iles Formation was undertaken to evaluate variations in interval thickness that might constrain the timing of recurrent basement block movement. Each of these regressive units was defined on the recognition of characteristic log curve signatures, particularly gamma ray, conductivity, and resistivity responses. The base of each cycle/genetic unit/parasequence is defined by a marine flooding surface or relative deepening event. The regressive cycle then "shallows upward", resulting in a coarsening-upward, or "funnel-shaped" log curve response, as the shoreline is built out into the basin. An abrupt transition back to open marine conditions (or a significant deepening event) defines the top of the genetic unit and serves as the base of the next successive cycle. This pattern is readily seen in the marginal marine intervals of the Corcoran and Cozzette regressive cycles (Figure 5). The recognition and identification of these major regressive cycles is fairly straightforward and adequately serves the purposes of this regional study, although it should be noted that both the Corcoran and Cozzette intervals contain additional genetic units (higher frequency parasequences) within them that were not delineated. Additionally, extending the definition of the regressive cycle into the nonmarine section is speculative, and confidence in the correlations is much lower. The nonmarine facies associated with the Corcoran and Cozzette intervals also contain coals of the Black Diamond Coal group (McFall and others, 1986), which were not investigated as part of this study.

The Corcoran stratigraphic unit is defined by a marine flooding surface at its base. This is an interpretation of the deepest marine conditions that preceded the regressive or progradational cycle and, as explained earlier, is based on the recognition of very low resistivity/high gamma ray shales. The facies succession of this regressive cycle coarsens upward from the open marine shales into shallower shelf siltstones, lower shoreface siltstones and sandstones, and upper shoreface, foreshore and beach sandstones. This sequence is repeated

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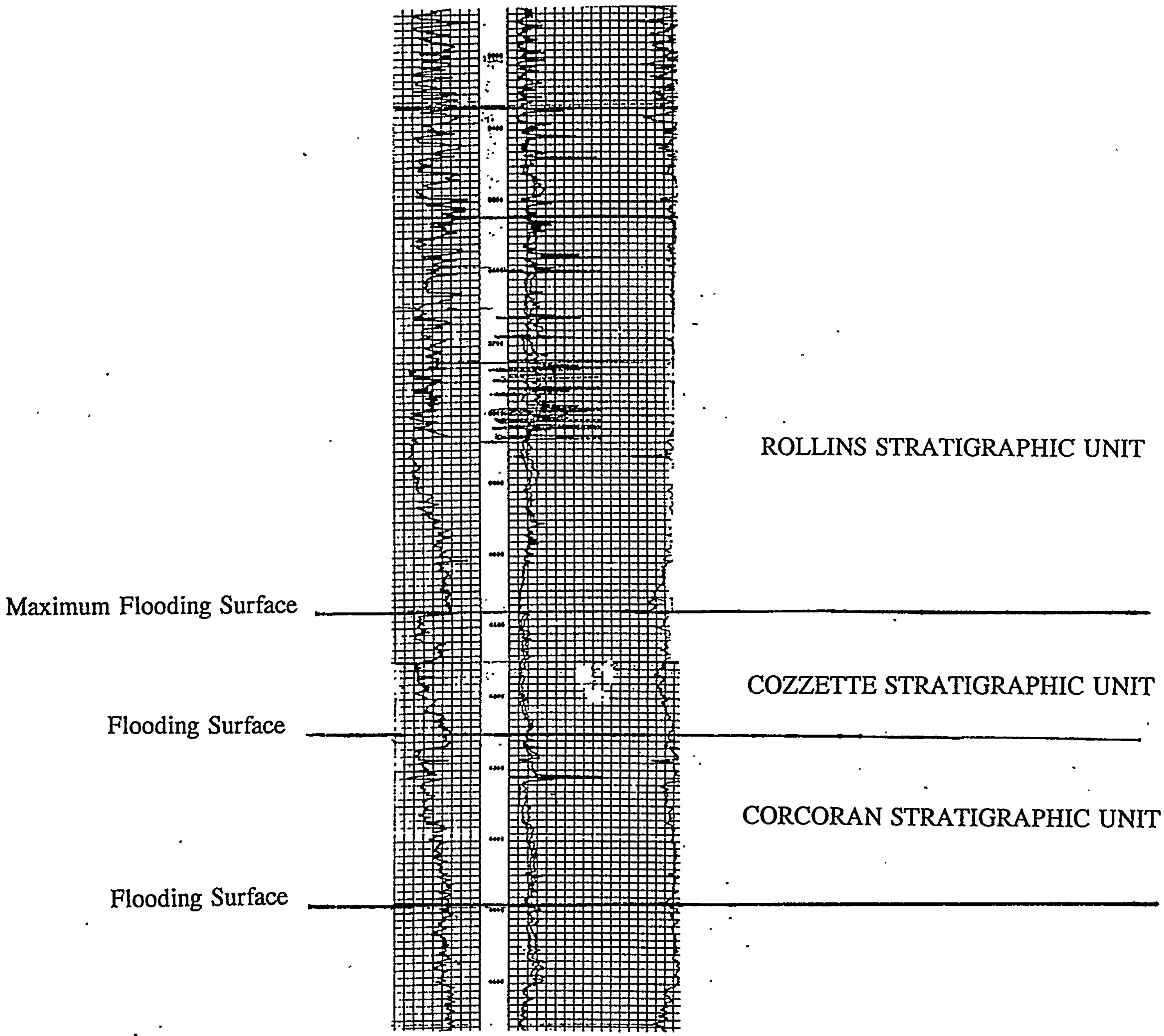


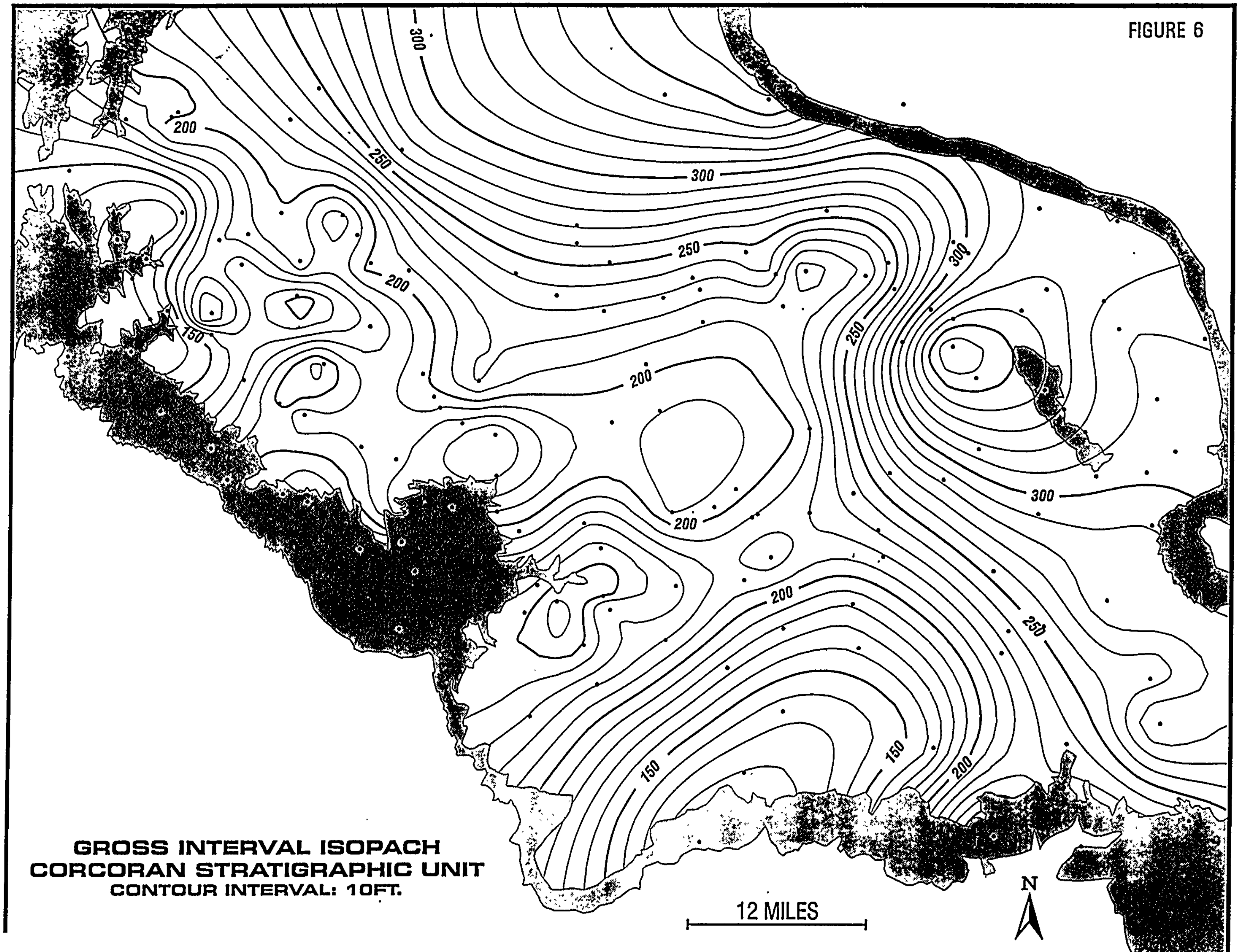
at least once again within the gross Corcoran interval (upper and lower subdivisions of Finley, 1985), indicating higher frequency cycles (parasequences) are present. Overlying the beach/nearshore facies of the final regressive cycle are facies indicating an abrupt return to deeper marine conditions. These facies mark the end (top) of the Corcoran unit and the beginning (base) of the Cozzette cycle (Figure 5).

The gross thickness of the Corcoran interval was mapped to provide evidence for reactivated basement structures during deposition of the gross genetic unit. The interval was evaluated to identify thickened or thinned section that may be related to deeply buried structures. Figure 6 illustrates the absence of any single prominent trend, although three possibly significant features emerge. An east-west trending thin in the central part of the study area roughly corresponds to a basement high interpreted from gravity and aeromagnetic data. The interval thickens both to the north and south of the area of the basement high, suggesting some degree of sediment bypass. Also, a north-northeast trend of increasing interval thickness is observed in the eastern third of the study area. This area is basinward of an interpreted structural hingeline and is also believed to be the synclinal axis of the basin.

The Cozzette stratigraphic unit is defined by a marine flooding surface at its base, which is the same surface that overlies and defines the top of the Corcoran (Figure 5). The facies succession of this regressive cycle coarsens upward from the open marine shales into shallower shelf siltstones, lower shoreface siltstones and sandstones, and upper shoreface, foreshore and beach sandstones. This sequence appears to be repeated twice again within the gross Cozzette interval, indicating higher frequency regressive cycles (parasequences). Overlying the beach/nearshore facies of the final regressive cycle is a return to deeper marine conditions, marking the end (top) of the Cozzette interval. This deepening event corresponds to the maximum flooding surface recognized by Tyler and McMurry (1995).

The gross thickness of the Cozzette interval was also mapped to provide evidence for reactivated basement structures during deposition of this genetic unit, and to identify thickened or thinned stratigraphic section that may be related to these structures. In addition, the orientation and greatest thickness of the gross interval identifies the areas of maximum

FIGURE 6




GROSS INTERVAL ISOPACH
CORCORAN STRATIGRAPHIC UNIT
CONTOUR INTERVAL: 10FT.

accommodation space. After a review of the gross isopach for the Cozzette interval (Figure 7), it is apparent that interval thickness was variable throughout the study area. As was the case with the Corcoran interval, no single dominant trend emerges, and the relationships are difficult to determine. There is a general east-west trending thin in the area of the basement high (central/south central part of the study area) with interval thickening to the north and northeast. In the eastern quarter of the study area, basinward of the interpreted hingeline, the gross interval also thickens. This thickening coincides with an area that was likely the basin axis. Finally, the southern part of the study area is dominated by a relative thin -- it is likely that this thinning represents the distal edge of the Cozzette stratigraphic prism.

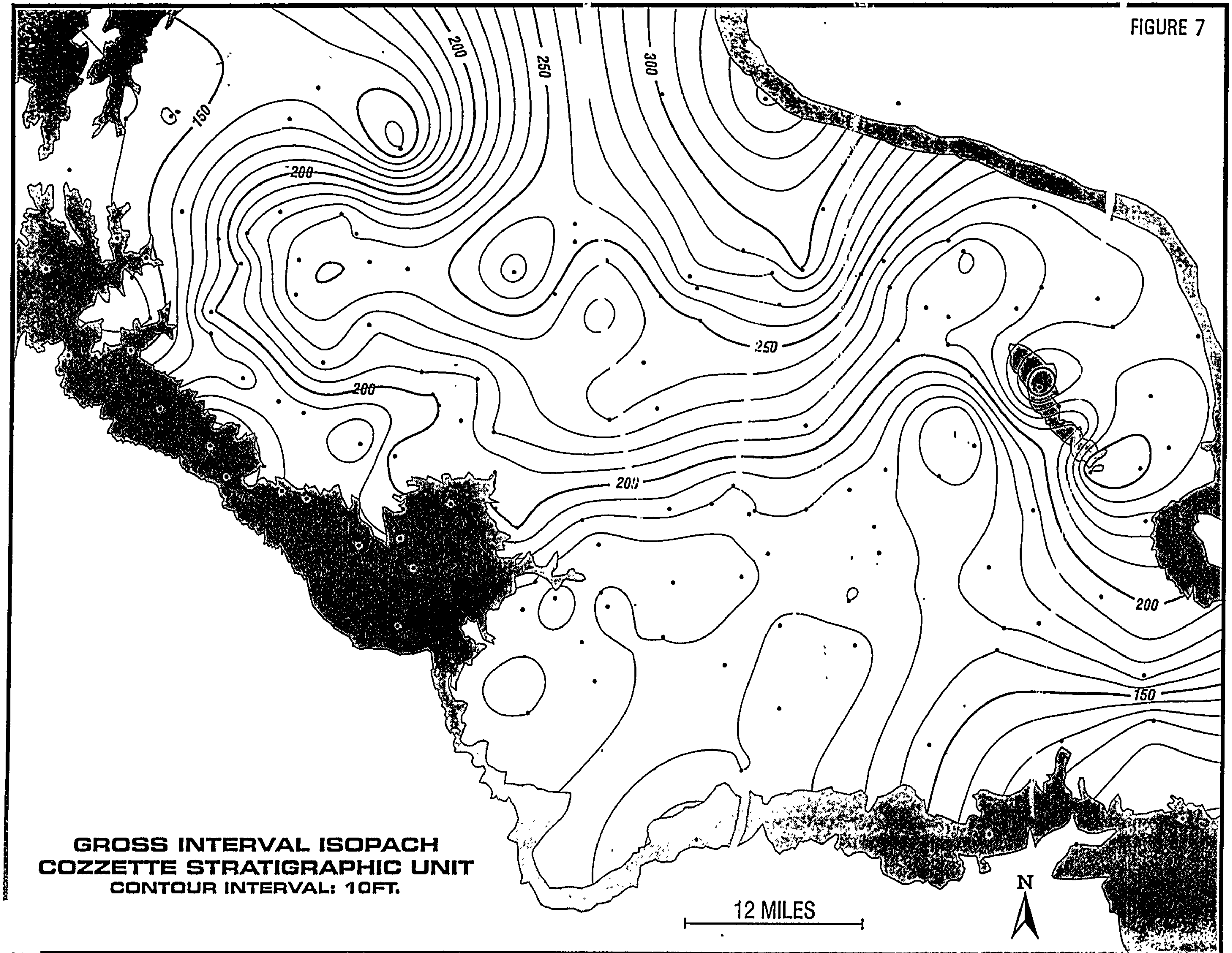
The Corcoran and Cozzette sandstones are generally considered to be of beach and bar origin deposited in a marginal marine environment (Dunn, 1974). They are considered Campanian in age, and were deposited primarily as southeastward-prograding sediments into the Cretaceous Interior Seaway. The sandstones overlie and intertongue with the marine Mancos Shale and underlie continental sandstones, shales, and coals (Brown and others, 1986). Lorenz (1983, 1989) characterized the geometry of these sands as blanket, describing their deposition in a wave-dominated shoreline setting.

Shoreline trends for the Corcoran and Cozzette intervals are oriented in a northeast-southwest direction (Figure 8). Brown and others (1986) believe this orientation is the result of eastward extension of the Frontier-age deltas in central Wyoming. Figure 8 approximates the position of the Corcoran and Cozzette shorelines on the basis of recognition of dominantly marine (shoreface, beach) facies versus dominantly nonmarine (fluvial and distributary channels, coals) facies interpreted from well log signatures. The position of the Cozzette shoreline landward of the Corcoran shoreline suggests an overall retrogradation or backstepping between these two regressive cycles.

<u>Williams Fork Formation</u>

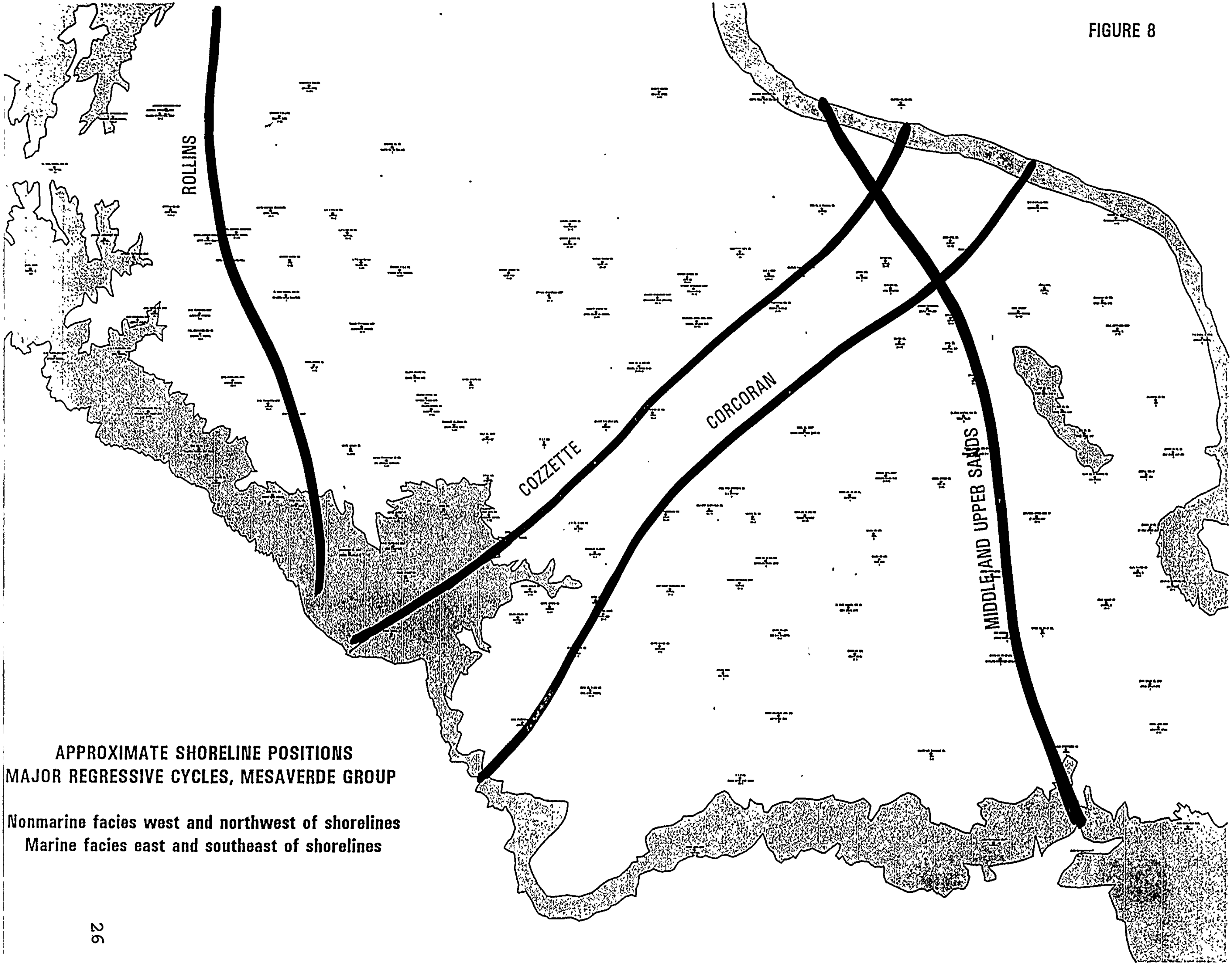
The overlying Williams Fork Formation is of particular interest to this study as it contains the fractured tight gas reservoirs and coalbed methane resource that are currently

FIGURE 7




**GROSS INTERVAL ISOPACH**
**COZZETTE STRATIGRAPHIC UNIT**
**CONTOUR INTERVAL: 10FT.**

FIGURE 8




APPROXIMATE SHORELINE POSITIONS
MAJOR REGRESSIVE CYCLES, MESAVERDE GROUP

Nonmarine facies west and northwest of shorelines
Marine facies east and southeast of shorelines

targeted by operators active in the basin. As mentioned earlier, the genetic stratigraphic approach to evaluating the Mesaverde Group used by Tyler and others (1994) and Kaiser and others (1994) was adopted in part for this study. The Williams Fork Formation nomenclature differs from the traditional stratigraphic usage in that the tongue of Mancos shale above the Cozzette sandstone and the Rollins sandstone itself are traditionally assigned to the Iles Formation. It was correctly observed that the interval defined by a maximum flooding surface above the Cozzette shallows upward to include the marginal marine Rollins sandstone and its associated paludal coal-bearing section and the thick, predominantly coastal plain and fluvial deposits that overlie it. Thus, this progradational cycle belongs genetically to the Williams Fork Formation.

This study subdivided the Williams Fork into two operational units, the lower and upper Williams Fork. The lower unit includes the Rollins regressive cycle and the Cameo Coal Group. The upper unit consists of the predominantly nonmarine facies between the Cameo coals and the Cretaceous-Tertiary unconformity (Figure 9).

*Lower Williams Fork Operational Unit*

The base of the lower Williams Fork operational unit is defined by the maximum flooding surface that overlies and terminates the Cozzette progradational interval. This flooding surface identifies the open marine conditions that immediately preceded the Rollins regressive sequence. The top of the lower operational unit is defined by the top of the Cameo Coal Group, which includes the Cameo-Wheeler-Fairfield and South Canyon coals (Decker, 1985). This marker is equivalent to flooding surface 2b of Tyler and others (1994) in the eastern part of the study area, but becomes a lithofacies pick throughout the western two-thirds of the basin. The thickness of the lower Williams Fork operational unit ranges from approximately 300 to 1,600 ft across the study area (Figure 10).

The Rollins stratigraphic sequence is the predominant interval within the lower Williams Fork operational unit, and consists of sandstones, siltstones, shales and coaly facies of several regressive cycles that have prograded eastwardly across the basin. The base of the interval is

FIGURE 9

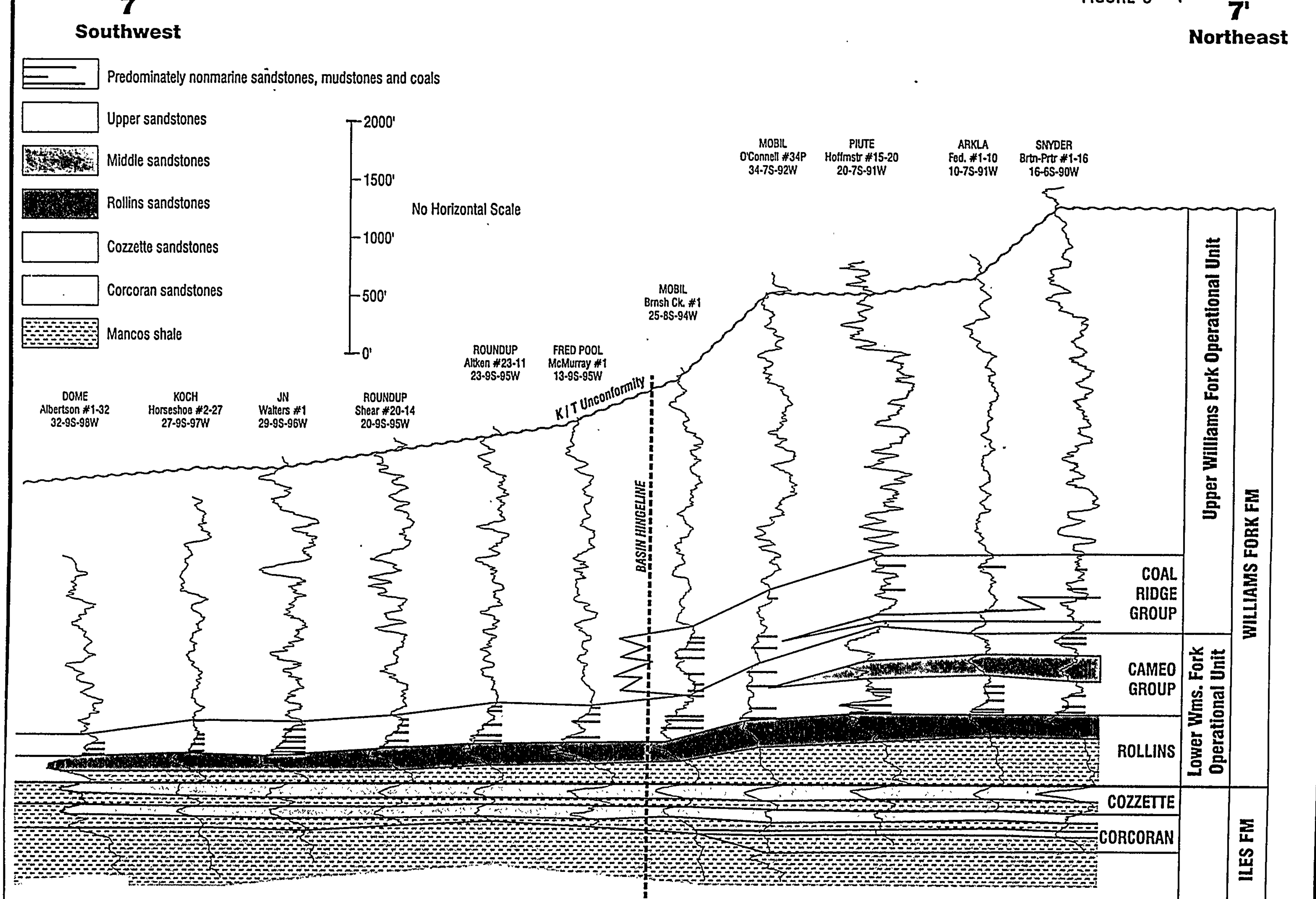
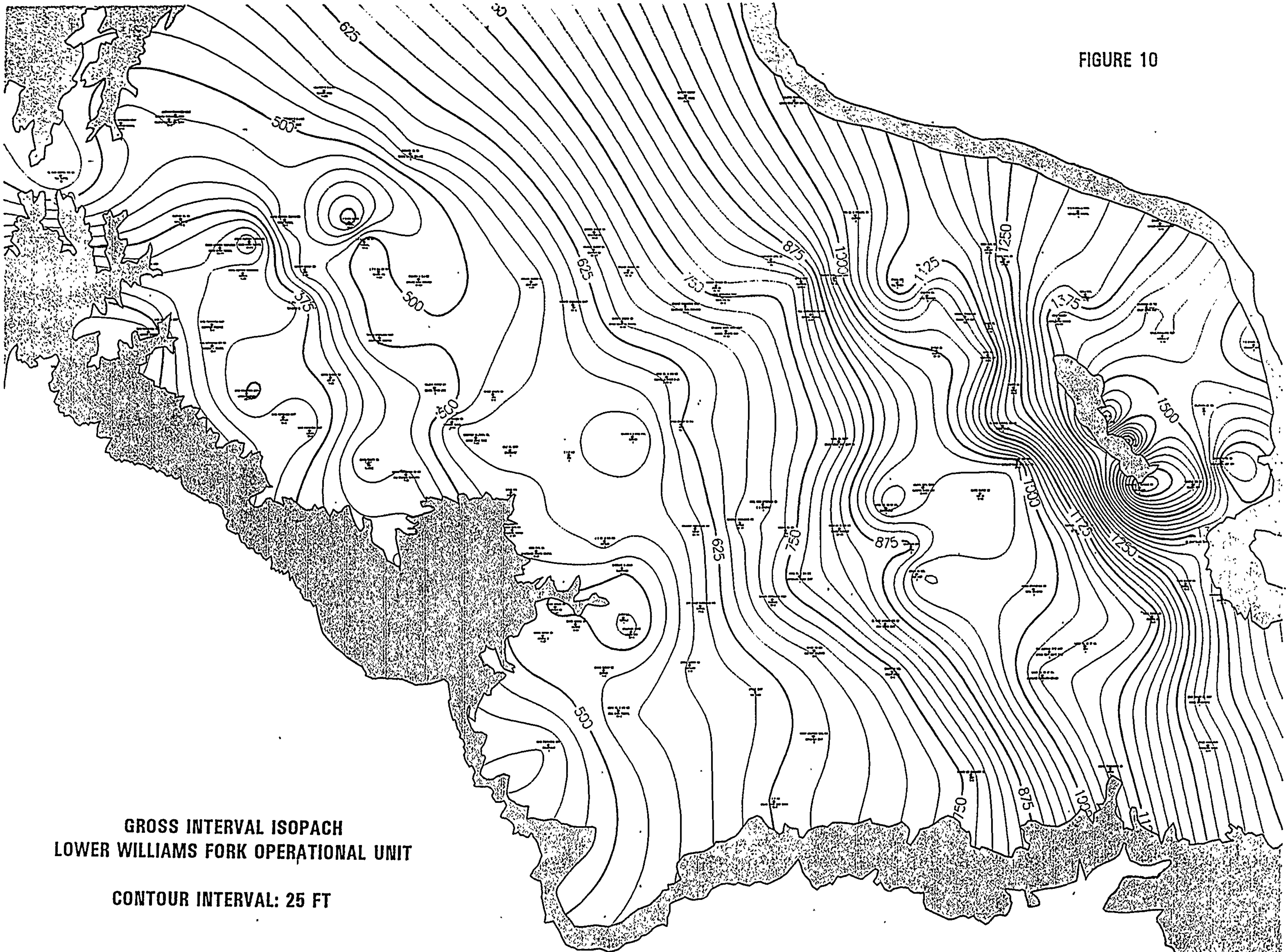

7
Southwest
7'
Northeast
Predominately nonmarine sandstones, mudstones and coals
Upper sandstones
Middle sandstones
Rollins sandstones
Cozzette sandstones
Corcoran sandstones
Mancos shale
2000'
1500'
1000'
500'
0'
No Horizontal Scale
DOME
Albertson #1-32
32-9S-98W
KOCH
Horseshoe #2-27
27-9S-97W
JN
Walters #1
29-9S-96W
ROUNDUP
Shear #20-14
20-9S-95W
ROUNDUP
Aitken #23-11
23-9S-95W
FRED POOL
McMurray #1
13-9S-95W
MOBIL
Brnsh Ck. #1
25-8S-94W
MOBIL
O'Connell #34P
34-7S-92W
PIUTE
Hoffmstr #15-20
20-7S-91W
ARKLA
Fed. #1-10
10-7S-91W
SNYDER
Brtn-Prtr #1-16
16-6S-90W
K / T Unconformity
BASIN HINGELINE
COAL
RIDGE
GROUP
CAMEO
GROUP
ROLLINS
COZZETTE
CORCORAN
Upper Williams Fork Operational Unit
Lower Wms. Fork
Operational Unit
WILLIAMS FORK FM
ILES FM

FIGURE 10




GROSS INTERVAL ISOPACH
LOWER WILLIAMS FORK OPERATIONAL UNIT

CONTOUR INTERVAL: 25 FT

defined by the maximum flooding surface above the Cozzette, and the unit shallows upward to include the marginal marine Rollins sandstones and their associated nonmarine (and coal-bearing) facies. The top of the Rollins genetic unit is marked by a flooding event overlying the thick Cameo coals. The nearshore sandstones of the Rollins interval have traditionally been treated as a continuous reservoir that is correlatable throughout the basin, although clearly they are time transgressive, and detailed investigation demonstrates that several progradational cycles/parasequences comprise the Rollins interval (Tyler and McMurry, 1995). The trend of the Rollins paleoshoreline, which is located in the northwest corner of the study area, is predominantly north-south (Figure 8). This orientation is in marked contrast to the northeast-southwest trending shorelines of the Cozzette and Corcoran intervals. These changes in sedimentation patterns are likely the result of tectonic activity that, at this point, is not fully understood.

The lower Williams Fork operational unit was mapped in order to determine the effects, if any, of recurrent basement block movement during deposition of this unit. Figure 10 illustrates a gradual eastward thickening of the interval. This trend is well established, and unlike the complex Corcoran and Cozzette intervals, indicates deposition on a fairly stable platform or shelf. An increase in the rate of thickening is seen basinward of the hingeline, in the eastern third of the basin, with the greatest thicknesses occurring in what was probably the basin axis. An alternate interpretation suggests that minor anomalous thickening within this interval in the area of the Divide Creek Anticline is the result of imbricate thrust fault-induced duplicate section within the Mancos Shale tongue that underlies the Rollins sandstones (Grout and Verbeek, 1989).

The Cameo Coal group (as defined for purposes of this study) consists of the basal coals and lower delta plain sandstones and shales reflecting a paludal environment landward of the prograding Rollins shoreline (Collins, 1976; Lorenz, 1983, 1989; Reinecke, 1991). Included in the interval are the Cameo coals, the regressive marginal marine middle sandstones and shales (Collins, 1976) that are found in the eastern part of the study area, and the South Canyon coals that appear to be associated with the middle sandstones.

Net coal thicknesses for the Cameo Group were mapped (Figure 11) to delineate a potential coalbed methane fairway; the added well control used for this study improves upon the fairway model delineated by McFall and others (1985).

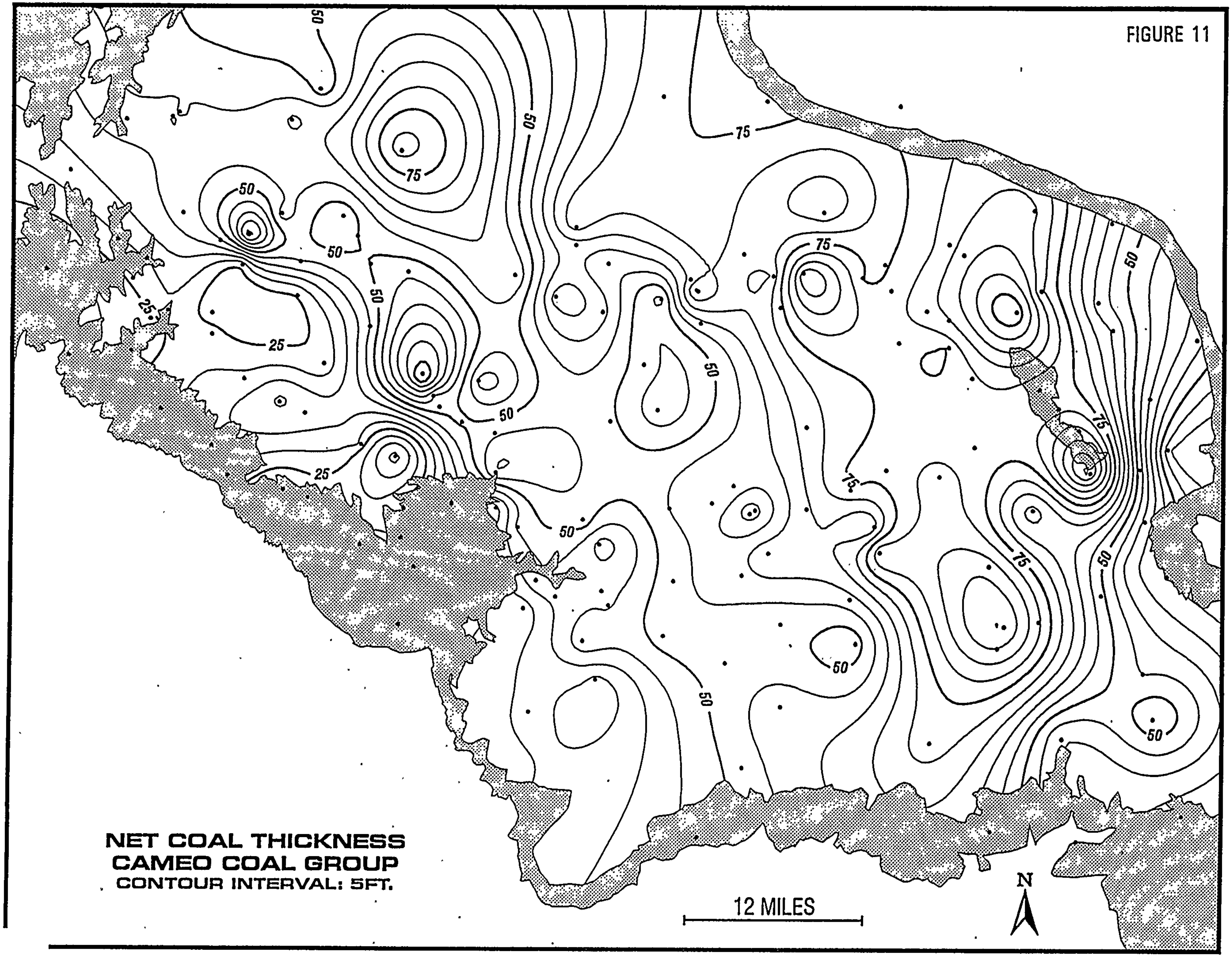
Significant differences in interval thickness, coal content, and depositional environment occur within the Cameo group interval between the eastern and western parts of the basin. Cross section 7-7' (Figure 9) illustrates the variations between these areas. This is primarily due to the thickened interval containing the regressive cycles (parasequences) of the middle sandstones, which are only present in the eastern part of the basin. The presence of regressive sandstones in this interval is evidence for a transgressive event, immediately following formation of the Cameo coals associated with the Rollins progradational episode. Figure 8 illustrates the approximate position of the shoreline for the middle sands, and shows a north-northwest trend. The South Canyon coals are interpreted as reflecting a paludal environment landward of the middle sands prograding shoreline, and this coal group does not appear to extend westward beyond the mid-point of the basin. The limited distribution of the South Canyon coals is reflected in the westward thinning of the net coal thicknesses of the Cameo Coal Group (Figure 11).

*Upper Williams Fork Operational Unit*

The base of the upper Williams Fork operational unit is defined by the top of the Cameo coal group and the top is marked by the Cretaceous-Tertiary unconformity (Figures 4 and 9). The section includes predominantly nonmarine sandstones, siltstones, shales, and coals, although the marginal marine upper sandstones of Collins (1976) that are restricted to the eastern portion of the study area are also included in this unit. The upper Williams Fork operational unit ranges in thickness from approximately 1,400 to 3,700 ft across the study area (Figure 12).

As was the case in the lower Williams Fork operational unit, significant differences occur in the upper Williams Fork between the eastern and western portions of the study area (Figure 9). The interval containing the areally-restricted marginal marine upper sandstones expands in the eastern part of the basin. Another transgressive event followed formation of the upper coals

FIGURE 11


NET COAL THICKNESS
CAMEO COAL GROUP
CONTOUR INTERVAL: 5FT.
12 MILES
N
25
50
75

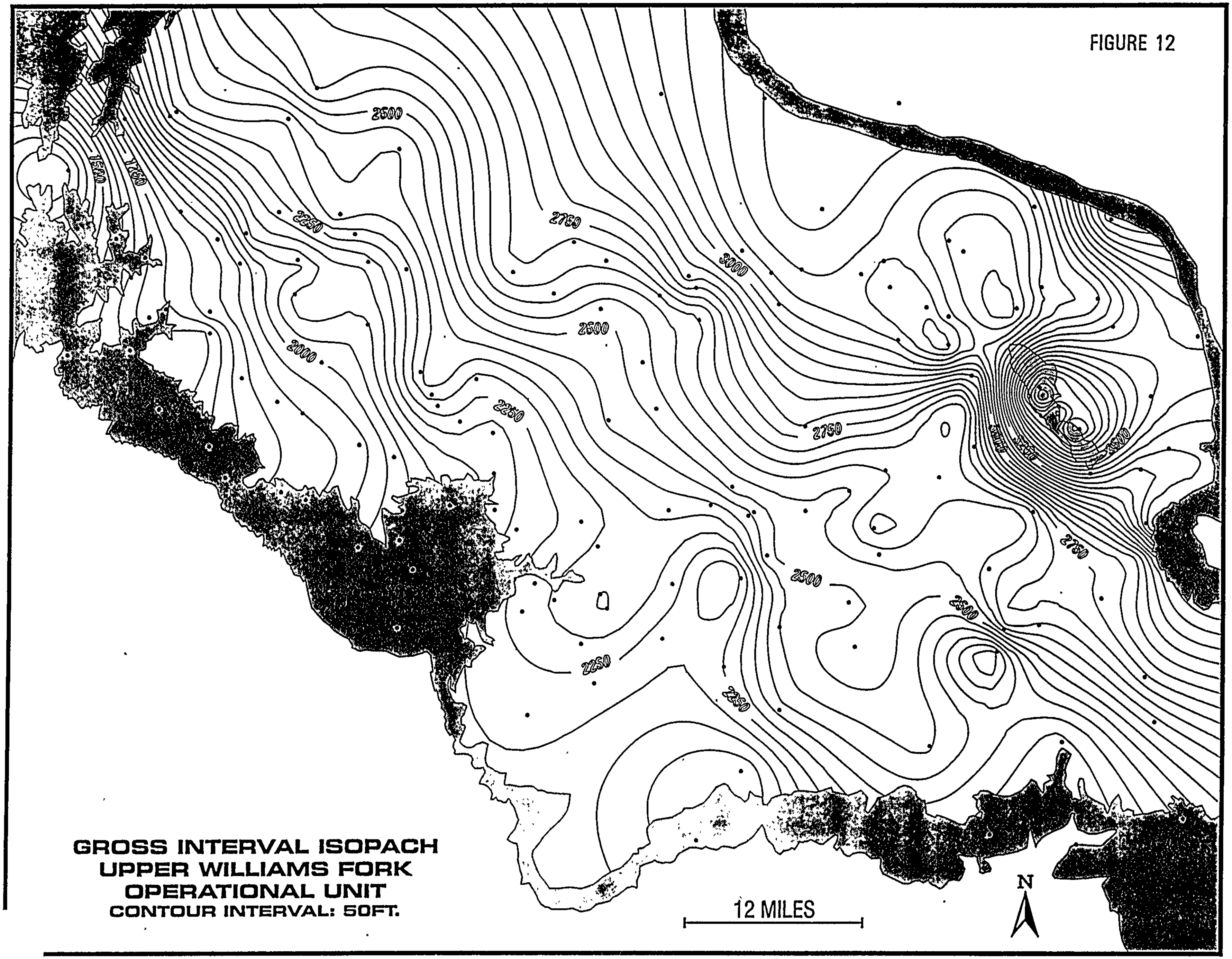



FIGURE 12

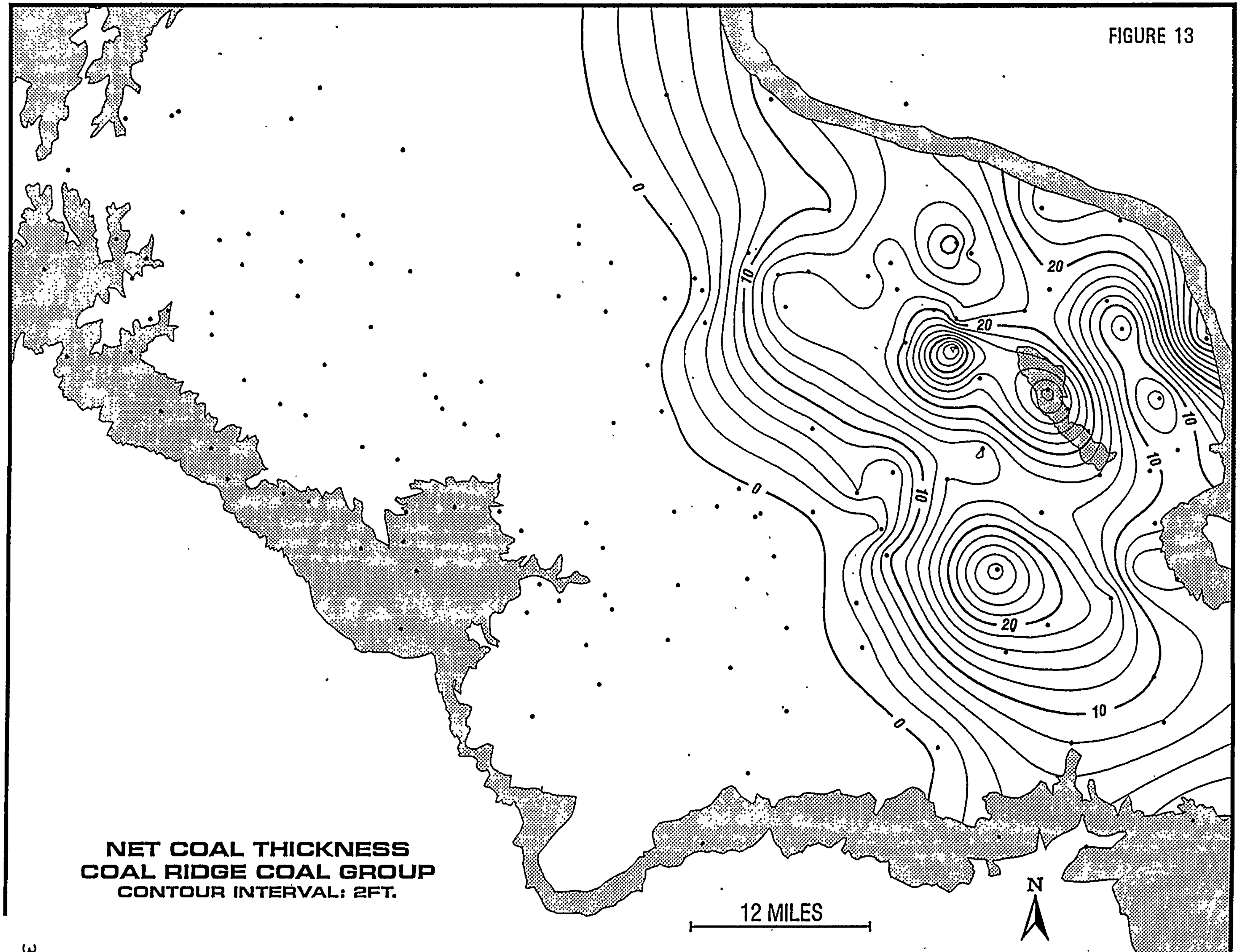
**GROSS INTERVAL ISOPACH**
**UPPER WILLIAMS FORK**
**OPERATIONAL UNIT**
**CONTOUR INTERVAL: 50FT.**

of the Cameo Group (South Canyon coals), but reached its landward limit in the eastern third of the basin. Deposition of the regressive cycles of the upper sandstones followed. Figure 8 maps the approximate location of the paleoshoreline of the upper sandstones. A northwest trend suggests that sedimentation patterns were generally similar to those of the Rollins interval. Overlying the upper sandstones, and continuing this progradational cycle, was a return to nonmarine conditions which initiated the formation of coals of the Coal Ridge Group. This coal group, which is characterized by thin, discontinuous seams and stringers, is found only in the eastern half of the basin. A net coal thickness map was prepared to illustrate the areal distribution and thickness of the Coal Ridge coals (Figure 13). Overlying the Coal Ridge coals in the eastern basin are upper delta plain/fluvial sandstones, siltstones, carbonaceous shales, and mudstones. Deposition of these sediments complete the overall Williams Fork progradational episode.

The upper Williams Fork operational unit in the western two-thirds of the basin is characterized by nonmarine sandstones, siltstones and shales. Figures 9 and 13 illustrate the variations in gross interval thickness for this unit across the study area. Lorenz (1989), as part of studies conducted at the DOE's Multiwell Experiment (MWX) site in the central Piceance basin, described four distinct depositional environments for rocks in the Mesaverde Group. Three of these environments are characteristic of rocks of the upper Williams Fork operational unit in the western part of the basin. Two of the three environments typical of this stratigraphic section are a generally progradational succession that includes upper delta plain (coastal plain), and fluvial environments. The third environment is a marine-influenced paralic environment interpreted for the Ohio Creek Member at the top of the Cretaceous, representing a shift from the previous regressive episode to a transgressive event.

The top of the Williams Fork Formation occurs at the Cretaceous-Tertiary unconformity, which is recognized as a major regional unconformity (Johnson and May, 1980). The Ohio Creek Member underlies and is truncated by the unconformity. Truncation of the Ohio Creek does not appear to be significant; the stratigraphic cross sections prepared for this report indicate localized downcutting of no more than a few hundred feet. It should be noted however that regional subsurface correlations of the Ohio Creek are poor, which contrasts with descriptions

FIGURE 13




NET COAL THICKNESS
COAL RIDGE COAL GROUP
CONTOUR INTERVAL: 2FT.

of its easily traceable, distinctive white color and conglomeratic nature observed in outcrop. The time gap represented by the unconformity, based on palynomorph studies, is from late Campanian or early Maestrichtian to late Paleocene time (Johnson and May, 1980).

Operators active in the southern Piceance basin frequently perform dual completions in both the coalbed methane resource of the Cameo coal group and the naturally fractured tight gas sandstone reservoirs of the upper Williams Fork Formation. Reinecke and others (1991) express particular interest in the fluvial sandstones found within this stratigraphic section. As part of this study, net and percent sandstone maps for the upper Williams Fork operational unit were prepared to delineate gross fluvial axes across the study area. Figures 14 and 15 illustrate three important trends. A predominant northwest-southeast orientation is seen for these amalgamated fluvial axes in the northern half of the study area. In the southern half of the study area, fluvial axes trends west to east, flanking both sides of the basement high, suggesting sediment bypass around this positive feature. The other area of significant net and percent sandstone concentration is in the eastern third of the study area, basinward of the hingeline, where more accommodation space resulted in increased interval thickness, the development of the thick, marginal marine upper sandstones, and better preservation of nonmarine sandstone facies. These types of maps, when combined with results of the structural components of the study, facilitate prediction of "sweet spots", or favorable exploration targets.

## Stratigraphically Aligned Hingeline Deposits

A comparison of Mesaverde Group regressive deposits described above, to those found in the San Juan Basin to the south, reveals stratigraphic, depositional, and paleogeographic similarities. Perhaps most importantly, each of these important gas-bearing intervals has in common a relationship to a structural hingeline. The late Campanian Pictured Cliffs shoreline sandstones in the San Juan Basin are believed to be time equivalent to the Rollins/Trout Creek sandstones in the Piceance Basin through age relationships determined by ammonite zonations of the regressive wedges that bracket the sandstones (Newman, 1982). Newman (1982) also postulates that sediments from the Piceance Delta (Collins, 1970, 1976) were swept to the

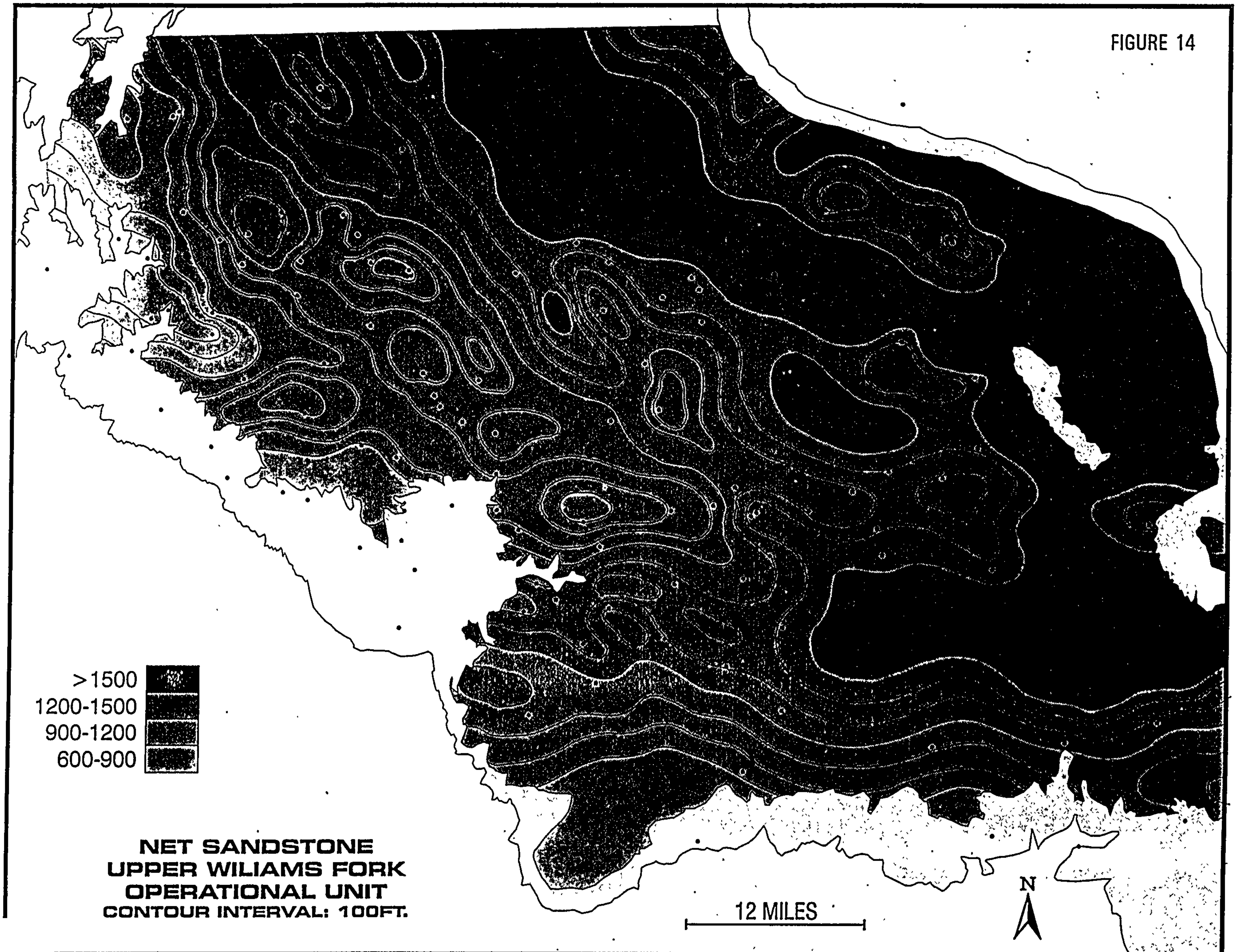
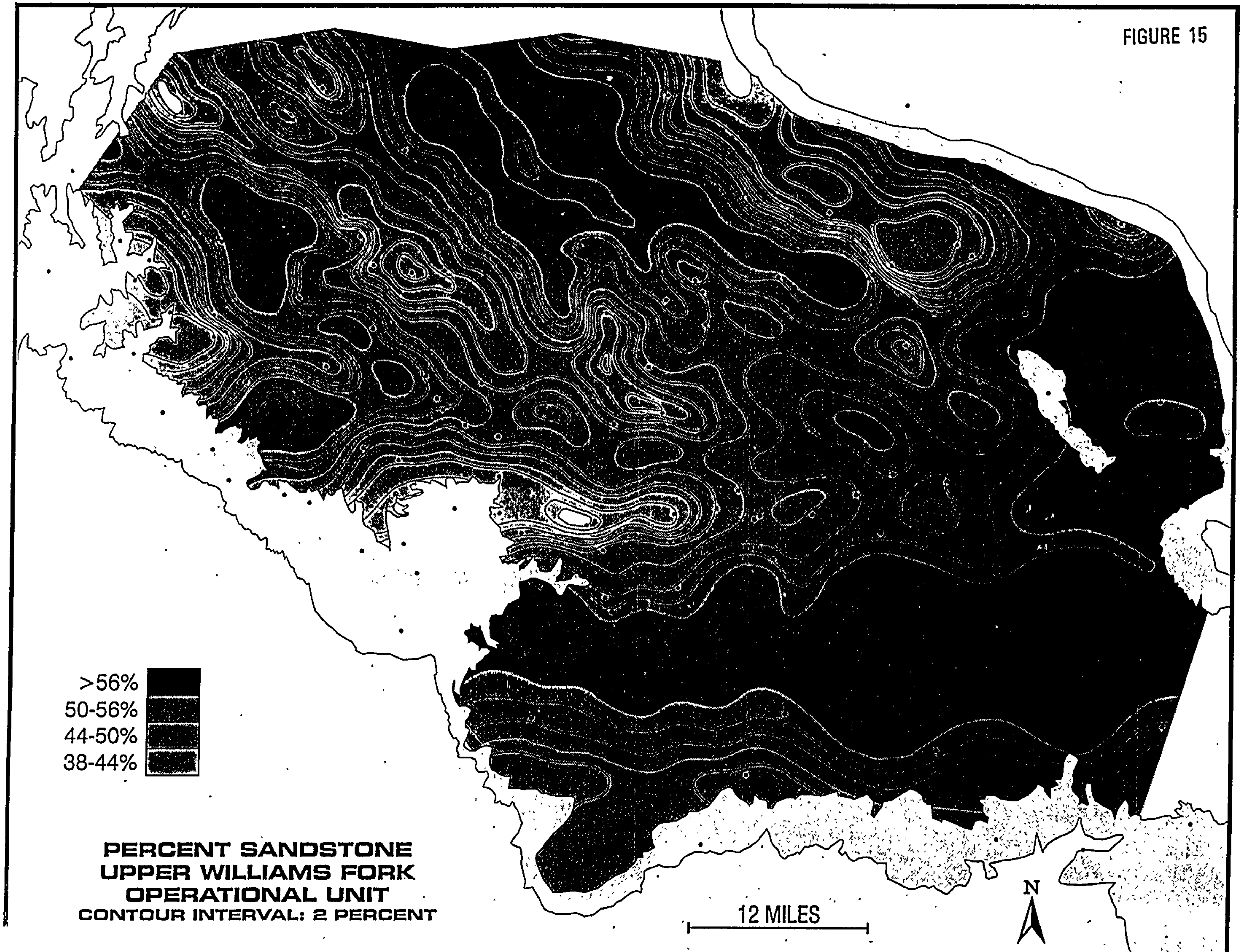

>1500
1200-1500
900-1200
600-900
NET SANDSTONE
UPPER WILIAMS FORK
OPERATIONAL UNIT
CONTOUR INTERVAL: 100FT.
12 MILES
N

FIGURE 14

FIGURE 15




PERCENT SANDSTONE
UPPER WILLIAMS FORK
OPERATIONAL UNIT
CONTOUR INTERVAL: 2 PERCENT

southeast by longshore currents and deposited as linear barrier sheet sands of the Pictured Cliffs. The progradational Pictured Cliffs-Fruitland coals succession in the San Juan basin is therefore equivalent to the Rollins/Trout Creek-Cameo coals succession in the Piceance Basin. Franczyk and others (1992) have also interpreted a continuous shoreline and related paleogeographic setting between the Piceance and northern San Juan Basins during late Campanian time.

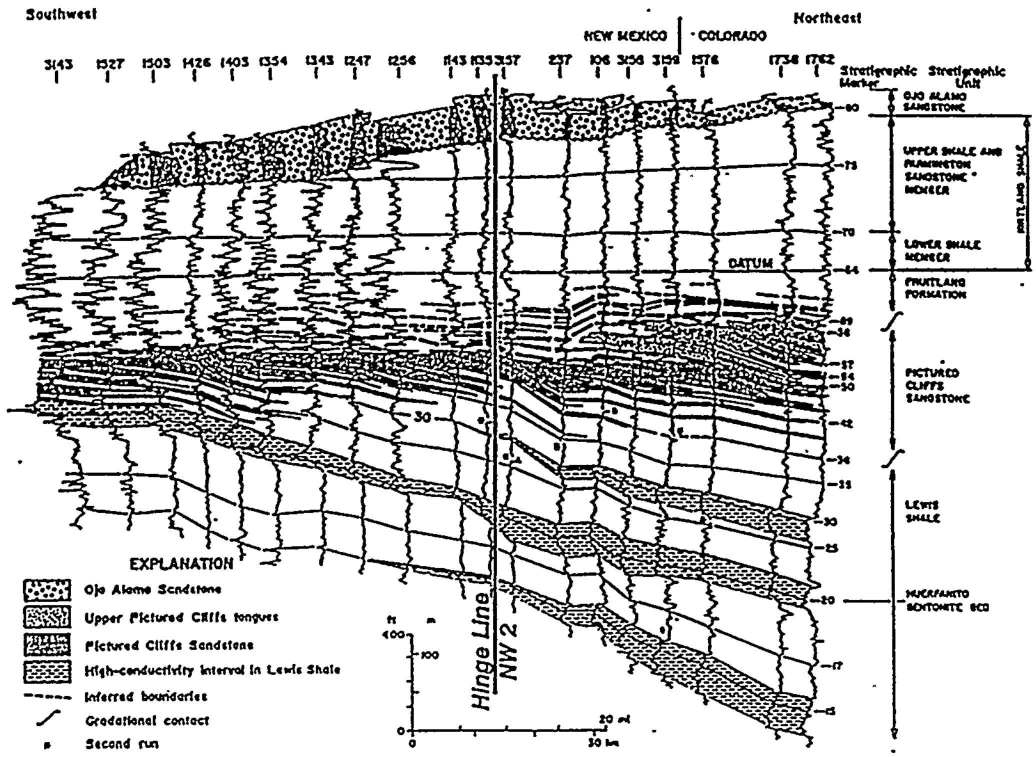
Stratigraphic studies of the Mesaverde Group in the southern Piceance Basin suggest the presence of a northwest-southeast trending hingeline. The identification and interpretation of the hingeline is supported by the following observations: 1) Gross interval isopach mapping indicates an increased rate of sediment thickening east of R93 -R94; 2) Net thickness of the Cameo coals and gross thickness of the Williams Fork interval increases significantly east of the hingeline; 3) At least three marine sequences are present in the lower part of the Williams Fork and reach their landward limits near the approximate hingeline position; and 4) Similar relationships are observed in the northern San Juan basin, located approximately 60 mi (96 km) to the south.

Gross interval thickening, maximum thickness of net coal, and the identification of transgressive events and their relationship to the NW2 hingeline are observed in the San Juan Basin. The upper Cretaceous interval thickens northeast of the hingeline, and the regressive marine Pictured Cliffs sandstones pinch out near the structural hingeline that separates the northeast-dipping monocline of the southern half of the basin from the low-relief basin floor (Figure 16). In addition, the greatest net-coal thickness of the Fruitland coals occurs in the north-central part of the basin, parallel to this southern hingeline (Ayers and others, 1990).

In the Piceance Basin, gross interval isopach maps were prepared for two discrete stratigraphic units as well as several major intervals in the Upper Cretaceous section. These maps include isopachs of the Corcoran and Cozzette stratigraphic units (Figures 6 and 7); the Cameo Coal-bearing lower Williams Fork operational unit (Figure 10); the upper Williams Fork operational unit (which includes the interval containing the Coal Ridge coals; Figure 12); and the gross interval isopach for the total Williams Fork Formation (Figure 17). As each of these preliminary maps illustrates, a gradual rate of interval thickening occurs from the position of the

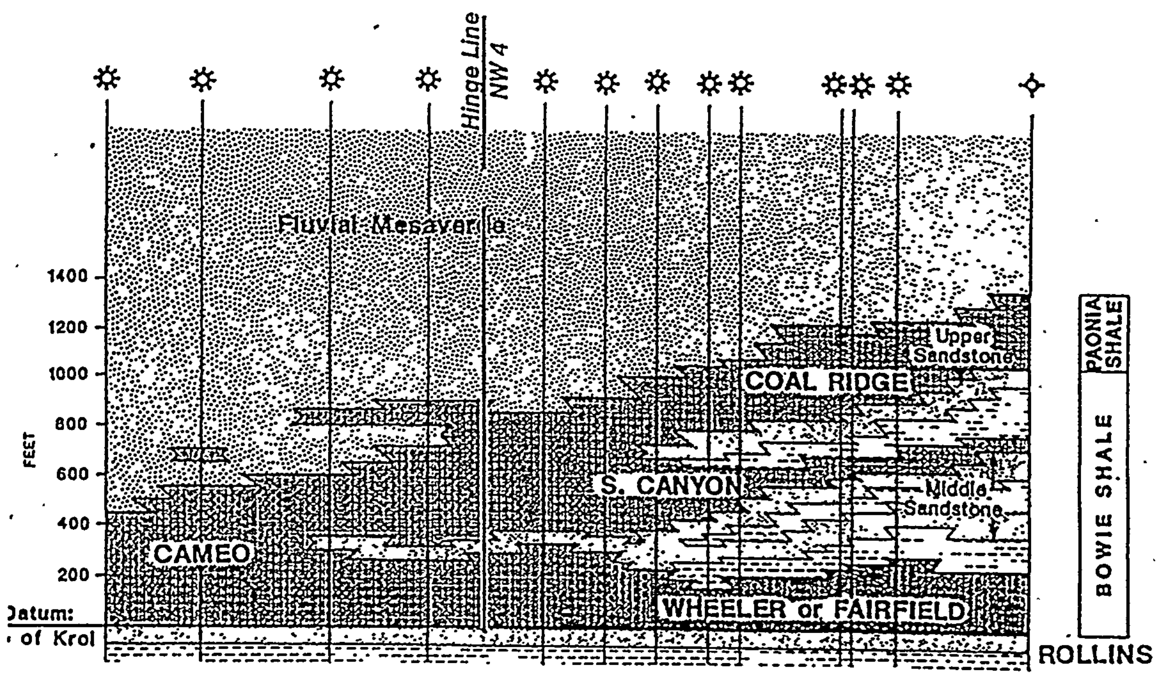
## SAN JUAN BASIN

FIGURE 16



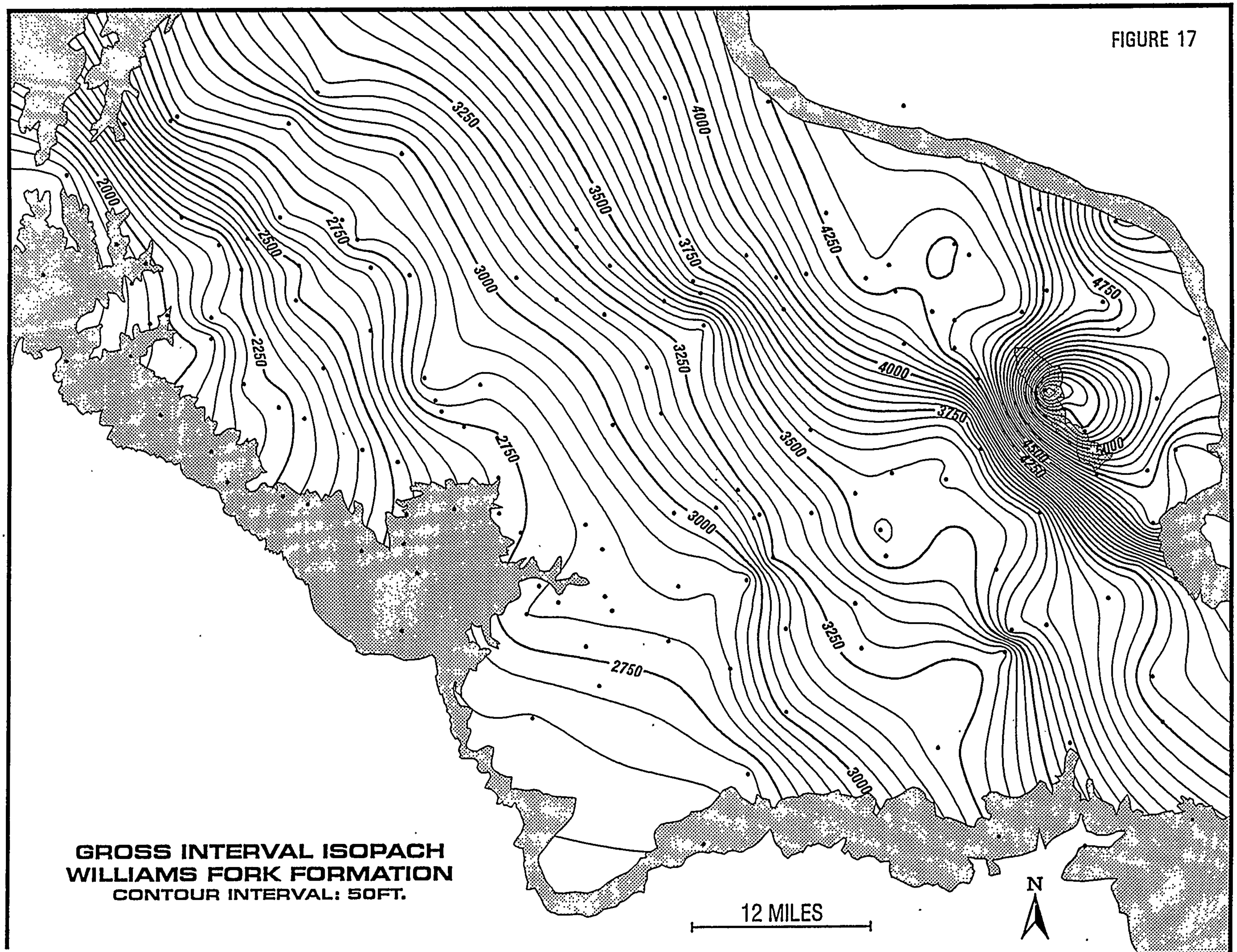

Modified from Ayers and Others, 1990

## PICEANCE BASIN




Modified from Reinecke and Others, 1991

FIGURE 17




GROSS INTERVAL ISOPACH
WILLIAMS FORK FORMATION
CONTOUR INTERVAL: 50FT.

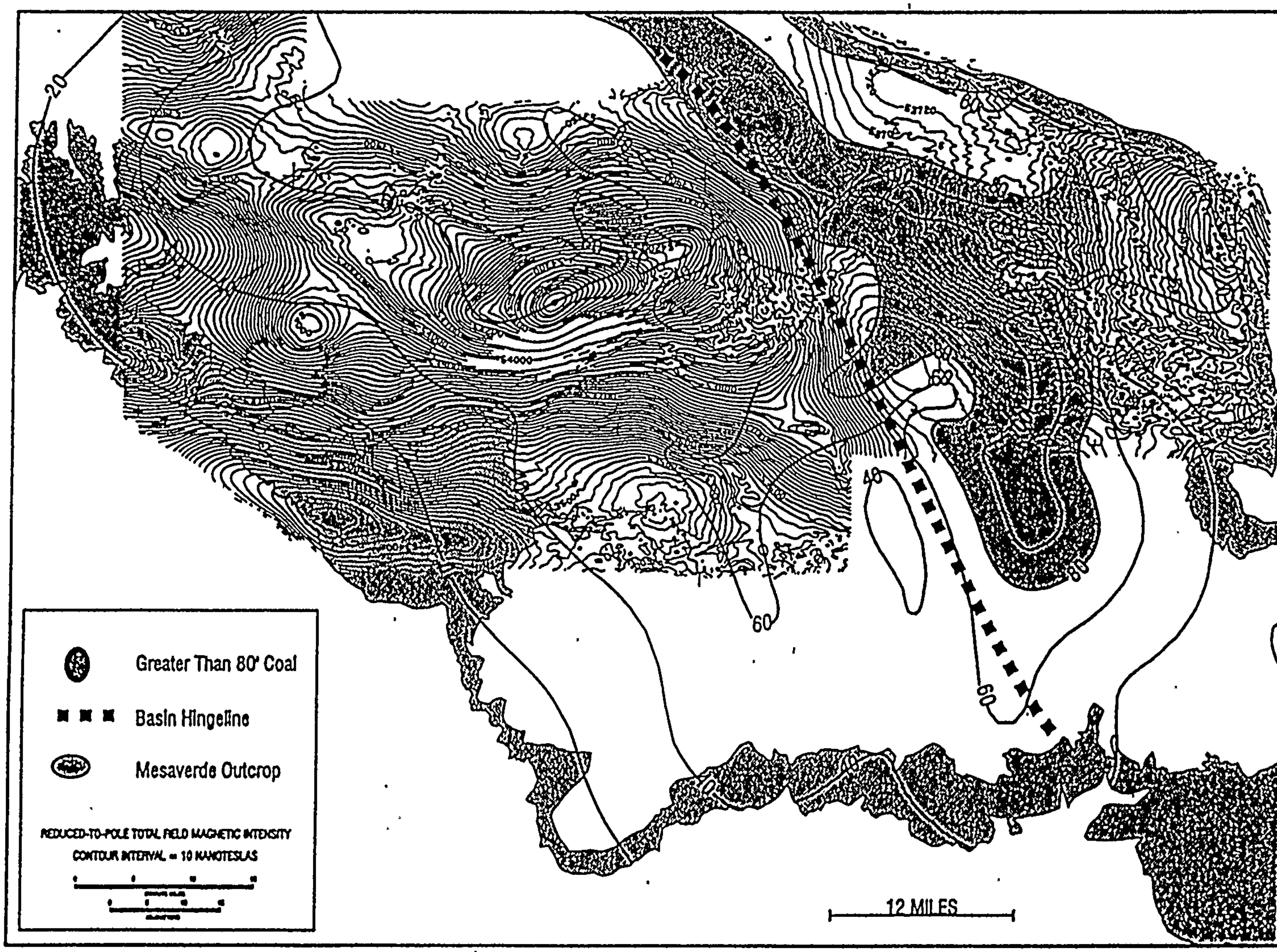
hingeline eastward to the limit of subsurface control.

Total thickness of Williams Fork coals (Coal Ridge, South Canyon and Cameo coals) reaches a maximum in an area parallel to and east of the hingeline (Figure 18). The fact that coal thickness is greatest in the eastern part of the basin also implies that a significant amount of accommodation space was made available for the deposition of sediments and the compaction of organics necessary to produce the thick coal seams and total net coal that is found in this part of the basin. In addition, a stratigraphically higher coal-bearing interval in the Williams Fork Formation (the Coal Ridge coal group) is present only in the area of the basin east of the hinge line. The Coal Ridge coals are associated with what was one of the final marine transgressions in the late Campanian.

At least three late Campanian marginal marine sequences have been identified along the eastern margin of the Piceance basin overlying the nonmarine coastal plain/lower delta plain facies of the early Williams Fork Formation. Marine sandstones within this section have been termed the middle and upper sandstones (Collins, 1970). As the early regressive sequences shoal upward into lower delta plain and coastal plain facies, coal beds of the South Canyon group (the upper coals of the Cameo Coal group) were formed. As the later regressive sequences shoaled upward into lower delta plain and coastal plain facies, coal beds of the Coal Ridge Group were formed. Interestingly, the general position of the transition from marine to nonmarine facies (and the pinching out of the Coal Ridge coals) in these sequences occurs near the hingeline (Figures 8 and 9). Again, this suggests increased subsidence/greater accommodation space in the eastern portion of the basin. This results in a relative rise of sea level with marine incursions reaching a landward limit at approximately the same position as the hingeline.

# TOTAL COAL ISOCHORE - WILLIAMS FORK FORMATION

FIGURE 18



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INTERGAS '95

May 15-19, 1995
The University of Alabama
Tuscaloosa, Alabama USA

9564

# Structurally Controlled and Aligned Tight Gas Reservoir Compartmentalization in the San Juan and Piceance Basins: Foundation for a New Approach to Exploration and Resource Assessments of Continuous Type Deposits

## ABSTRACT

Recurrent basement faulting is the primary controlling mechanism for aligning and compartmentalizing upper Cretaceous aged tight gas reservoirs of the San Juan and Piceance Basins. Northwest trending structural lineaments that formed in conjunction with the Uncompahgre Highlands have profoundly influenced sedimentation trends and created boundaries for gas migration; sealing and compartmentalizing sedimentary packages in both basins. Fractures which formed over the structural lineaments provide permeability pathways which allowing gas recovery from otherwise tight gas reservoirs. Structural alignments and associated reservoir compartments have been accurately targeted by integrating advanced remote sensing imagery, high resolution aeromagnetics, seismic interpretation, stratigraphic mapping and dynamic structural modelling. This unifying methodology is a powerful tool for exploration geologists and is also a systematic approach to tight gas resource assessment in frontier basins.

## INTRODUCTION

Tight gas reservoir performance is controlled by fracture permeability, reservoir pressure, gas saturation and reservoir distribution. Within the Rocky Mountain Basins these critical reservoir properties are formed and compartmentalized by recurrent basement faulting. This paper presents examples of structurally aligned sedimentary (reservoir) packages that have been identified in the San Juan and Piceance basins. Structural lineaments act as barriers to hydrocarbon and water migration thereby forming compartments of abnormally pressured gas accumulations. Fractures which form over the structural lineaments provide permeability pathways allowing gas recovery from otherwise tight reservoirs. Mapping these first and second order structural elements provided the explorer a powerful tool for partitioning a basin by reservoir properties. Moreover, accurate prediction of reservoir characteristics in advance of drilling enables the producer to select drilling sites and optimize completion strategies thus maximizing gas production and reducing the cost of producing gas.

Beyond the benefits of this methodology to operators, a similar approach can be used for larger scale resource studies to asses and economically grade the vast continuous type deposits (tight sands, gas shale and coalbed methane).

The San Juan and Piceance Basins have been extensively exploited for tight gas sand and coalbed methane production. Numerous wells producing from tight gas reservoirs provide excellent information on permeability anisotropy. Both basins are undergoing comprehensive integrated geologic evaluation relying on advanced methods of remote sensing imagery, high resolution aeromagnetics, stratigraphic mapping, seismic interpretation and dynamic structural modeling to establish the origin of the geologic systems controlling gas production. Three additional papers, presented at this symposium, one by Klawitter on the San Juan Basin and two by Hoak on the Piceance Basin, detail the results of the integrated exploration approach. This paper builds on the geologic work of Klawitter and Hoak to establish the application of integrated exploration for basin partitioning.

## Dynamic Tectonic Modeling of the San Juan and Piceance Basins

The western Crétaceous basins formed as part of a larger foreland basin. Similarities or differences in these basins can be best understood by establishing the tectonic framework that caused the basins to become stratigraphically and structurally distinct. The inseparable linkage between tectonics and sedimentation is the foundation for all interpretations.

The NW-trending Uncompahgre Precambrian Highlands is a prominent boundary separating the San Juan and Piceance Basins (figure 1). This NW anisotropy trend was multiply reactivated during Precambrian, Paleozoic and Tertiary orogenies. Although surface mapping has located the core structure and overall dimensions of this NW basement block, recent geologic evaluation has established corresponding NW structural domains that extend to the interior of the San Juan and Piceance Basins. Structural lineaments NW1, NW2, NW3, NW4, and NW5 that formed in conjunction with the Uncompahgre Highlands have profoundly influenced sedimentation trends and created boundaries for hydrocarbon migration by sealing and compartmentalizing these sedimentary packages. Horst and graben development during the Paleozoic orogeny caused regional NW-trending truncations of Paleozoic sections within up thrown blocks of the core structure and basin interiors. Reactivation and structural inversion during Cretaceous sedimentation formed a NW-trending embayment separating the San Juan and Piceance basins. Northwest trending strand plain deposits of the Pictured Cliffs sandstone and the Rollins sandstone formed simultaneously on both sides of the embayment. Deposition of the two strandline deposits and coals forming behind the strandlines marked the simultaneous development of structurally aligned reservoir compartments in two adjacent basins.

**Stratigraphically Aligned Hingeline Deposits**

A comparison of late Campanian regressive deposits in the Piceance Basin to those found in the San Juan Basin to the south reveals stratigraphic, depositional, and paleogeographic similarities. Most importantly, each of these important coal-bearing intervals have in common a relationship to a structural hingeline. The late Campanian Pictured Cliffs shoreline sandstones in the San Juan Basin are believed to be time equivalent to the Rollins/Trout Creek sandstones in the Piceance Basin through age relationships determined by ammoniate zonations of the regressive wedges that bracket the sandstones (Newman, 1982). Newman (1982) also postulates that sediments from the Piceance Delta (Collins, 1970, 1976) were swept to the southeast by longshore currents and deposited as linear barrier sheet sands of the Pictured Cliffs. The progradational Pictured Cliffs-Fruitland coals succession in the San Juan Basin is therefore equivalent to the Rollins/Trout Creek-Cameo coals succession in the Piceance Basin. Franczyk and others (1992) have also interpreted a continuous shoreline and related paleogeographic setting between the Piceance and northern San Juan Basins during late Campanian time.

Gross interval thickening, maximum thickness of net coal, and the identification of transgressive events and their relationship to the hingeline (NW2) in the San Juan Basin are also observed in the Piceance Basin. The upper Cretaceous interval in the San Juan Basin thickens markedly northeast of the hingeline, and the regressive marine Pictured Cliffs sandstones pinch out near the structural hingeline that separates the northeast-dipping monocline of the southern half of the basin from the low-relief basin floor (fig 2). In addition, the greatest net-coal thickness of the Fruitland coals occurs in the north-central part of the basin, parallel to this southern hingeline (Ayers and others, 1991).

Stratigraphic studies of the Upper Cretaceous Mesaverde Group in the southern Piceance Basin have suggested the presence of a northwest-southeast trending hingeline (NW4). The identification and interpretation of the hingeline is supported by the following observations: 1) gross interval isopach mapping indicates an increased rate of sediment thickening east of the NW4 hingeline; 2) net thickness of the Cameo coals and gross thickness of the Williams Fork interval increases significantly east of the hingeline; 3) at least three marine sequences are present in the lower part of the Williams Fork and reach their landward limits near the approximate hingeline position; and, 4) similar relationships are observed in the northern San Juan basin, located approximately 60 mi (96 km) to the south. Reservoir properties that evolved in the hingeline sedimentary packages will be discussed within the context of the individual basins.

**Hingeline Development and Reservoir Compartmentalization in the San Juan and Piceance Basins**

The San Juan Basin hingeline is a northwest trending structural lineament extending an estimated 70 miles long, transecting the northern basin roughly overlying and parallelling the basin structural axis. The hingeline was first inferred by Stevenson (1983) due to sudden thickening in Paleozoic section near the northwest basin margin along an interpreted basement alignment. The northwest stratigraphic alignment in the Pictured Cliffs barrier-strand plain system and pulsatory oscillation of the shoreline led Ayers (1991) to conclude that a structural hingeline existed at Cretaceous time to accommodate the stratigraphic thickening. More recently, Klawitter (this publication) identified the structural hingeline, NW2, and its associated fractures using the integration of remote imagery, gravity, seismic, stratigraphic and structural studies.

The hingeline has compartmentalized basin wide coal reservoir properties and is responsible for the favorable coal reservoir properties that have led to the prolific coalbed methane production "fairway" that overlies and parallels the hingeline (figure 3). The economically favorable implications of structurally aligned production "fairways" involving tight gas reservoirs give incentive for establishing an exploration rationale so that similar reservoir trends can be identified and exploited.

Pronounced geometry of the strong NW elongate production trend suggests structural involvement. As in most western basins, structural activity causes changes in depositional systems. The close correlation of the San Juan basin hingeline (figure 4) to total Fruitland coal thickness supports syndepositional subsidence. The NW elongate high pressure cell parallelling and immediately to the north of the hingeline (figure 5) is a remnant from gas generation in a gas centered basin. The hingeline traps southward gas migration thus creating conditions for overpressuring. South of the hingeline, Fruitland coals and Pictured Cliffs sandstones are fully gas saturated and underpressured. North of the overpressured cell, slight overpressuring has been interpreted (Kaiser, 1991) to be due to artesian conditions from an elevated outcrop. Immediately north of the hinge and directly overlapping the production fairway is a high density cluster of surfical linear features interpreted from satellite imagery (figure 6). The combination of high fracture permeability, overpressuring, thick coals and high gas saturation account for the origin of the prolific production fairway. In turn, the origins and presence of this fairway have been accurately identified by integrating remotely sensed data, stratigraphic mapping and dynamic tectonic modelling.

The integrated exploration approach used in the San Juan Basin provides a useful analog for identifying commercial reservoir compartments in other basins. The Piceance Basin will serve as the demonstration site for further verification and development of this integrated exploration approach.

**Multiple Source Data Interpretation for Structural Analysis of the Piceance Basin**

When compared to the San Juan Basin, the Piceance Basin has undergone a more complex tectonic history and is sparsely drilled. A rigorous approach to structural analysis has been undertaken to successfully determine basement features under these challenging conditions. To provide a foundation for structural interpretation, a high resolution aeromagnetic survey was acquired and processed over the southern basin. To minimize interpretation subjectivity and establish credibility of interpreted features, basement features were also interpreted utilizing 400 line miles of seismic surveys, and utilizing Landsat Thematic Mapper (TM) and Side Looking Airborne Radar (SLAR) imagery for the basin and surrounding areas.

Spatially detailed aeromagnetic maps were used to interpret zones of basement structure. Basement structures, some verified by seismic profiles, corresponded to steep magnetic gradients and linear trending contours. Utilizing this technique, first order and second order basement features have been located on the reduced-to-pole total field magnetic intensity contour map (figure 7). The most prominent features include an interpreted paleobasement high in the east central portion of the basin flanked on the east and west by northwest trending faults NW3 and NW4 and on the north and south by EW3 and EW2 respectively interpreted as east - west trending faults. Seismic coverage (figure 8) has confirmed the basement high which has caused truncation of the Paleozoic section. At basement level, structural lineament NW4 is formed by low angle thrust faults that typically terminate within the Mancos shale. Mild warping and draping of the sediments occurs along the fault termination boundaries.

Coincident features to the identified first and second order northwest lineaments have been mapped through linear feature analysis of TM imagery. These lineaments are a composite of individual linear features as interpreted from Landsat Thematic Mapper imagery. Northwest-trending linear features were contoured with respect to frequency of occurrence. Imagery lineaments are defined as zones of aligned and concentrated linear features, which are linear elements interpreted directly from imagery. Figure 9 presents lineaments interpreted from NW-trending linear features in the southern portion of the basin. Note on figure 9 the close correlation of lineaments as interpreted from imagery to basement faults as interpreted from aeromagnetics. This close correlation and further calibration from seismic lines establishes interpreted NW lineament features as significant structural lineaments. Surface analysis of the E-W trending features is in progress. Preliminary interpretation of E-W structural elements suggests lateral movement along fault zones. Stratigraphic interpretation indicates the NW4 structural element acted as a basin hingeline during Cretaceous deposition.

**Hingeline Development in the Piceance Basin**

Gross interval isopach maps were prepared for three discrete genetic sequences as well as several major intervals in the Upper Cretaceous section figure . These maps include isopachs of the late Campanian Corcoran, Cozzette, and Rollins genetic sequences; the coal-bearing interval between the top of the Cameo Coal group and the Rollins sandstone (figure 10); and other gross interval isopach maps such as the top of Cretaceous to base of the Rollins sequence, included as figure 11. As each of these preliminary maps illustrates, a gradual rate of interval thickening occurs from the position of the hingeline eastward to the limit of subsurface control.

Net thickness of Upper Cretaceous (Williams Fork Fm.) coals reaches a maximum in an area parallel to and east of the hingeline (figure 12). The fact that coal thickness is greatest in the eastern part of the basin also implies that a significant amount of accommodation space was available for the deposition of sediments and the compaction of organics necessary to produce the thick coal seams and total net coal that is found in this part of the basin. In addition, a stratigraphically higher coal-bearing interval in the Williams Fork Formation (the Coal Ridge coal group) is present only in the area of the basin east of the hinge line. The Coal Ridge coals are associated with what was perhaps one of the final marine transgressions in the late Campanian.

At least three late Campanian marine sequences have been identified along the eastern margin of the Piceance basin overlying the nonmarine coastal plain/lower delta plain facies of the early Williams Fork Formation. Marine sandstones within this section have been termed the middle and upper sandstones (Collins, 1970). As these regressive sequences shoal upward into lower delta plain and coastal plain facies, coal beds of the Coal Ridge group were formed. Correlation of the marine sequences westward into their nonmarine equivalents is difficult. Interestingly, the general position of the transition from marine to nonmarine facies (and the pinching out of the Coal Ridge coals) in these sequences occurs near the hingeline (figure 13). Again, this suggests differential subsidence and/or increasing accommodation space in the eastern portion of the basin. This results in a relative rise of sea level with marine incursions reaching a landward limit at approximately the same position as the hingeline.

**Structurally Aligned Reservoir Compartmentalization**

The best production from the Cameo coals and overlying tight gas sands of the Piceance Basin has been established in the Rulison, Parachute and Grand Valley Fields. Iso-production contouring of these three fields has been performed separately on the coal and tight gas sand as part of an effort to determine geologic controls on gas production. The strong NW trend of the production contouring from both intervals implies a common event causing permeability anisotropy. The close proximity and alignment of northwest trending basement faults (figure 14) to the production anisotropy is interpreted as being fracture controlled. Fractures have been generated by basement faults causing the northwest aligned production trend. A region of high stress occurring within close proximity to the structural lineament causes closure of the fracture system and results in a no-flow boundary. Gas migrating southward out of the gas-centered basin became trapped along the no flow boundary causing an overpressuring along the northwest flanks of the basin hingeline NW4 (figure 15). Southwest of the hingeline, the Cretaceous reservoirs are gas saturated and underpressured because the hingeline has isolated water recharge from the Northeastern basin elevated outcrop from the southwestern basin. High fracture permeability and overpressuring conditions are responsible for the better reservoir performance observed at Rulison field when compared to other fields producing from Cameo coals and overlying tight gas sands. Since the favorable reservoir properties at the Rulison Field are associated with the basin hingeline, similar reservoir compartments are likely to exist northwest and southeast of the Rulison field along the basin hingeline. A graphic summary of partitions in the two basins (figure 16 and 17) demonstrate the remarkable parallel reservoir properties development between the two.

**Use of Basin Partitioning Methods for Reconnaissance Exploration and National Resource Studies of Continuous Deposits**

Recent national level natural gas resource assessments, such as by the National Petroleum Council and the U.S. Geological Survey, show that "continuously deposited reservoirs", such as tight sands, gas shales, and coalbed methane, represent the largest undeveloped source of natural gas in the U.S. Recent presentations at the GRI sponsored Global Gas Resource Workshop indicates that this finding may be true not just for the U.S. but for the gas basins of the world.

While it has been possible to reasonably establish the volume of gas in place, no easy to use, reliable methods have been set forth for categorizing or grading these deposits into high, medium and low quality and thus establishing their economic viability. The coalbed methane portion of the recent USGS National Assessment took a step toward this goal by using detailed reservoir data supported by extensive reservoir simulation, using COMETPC 3-D. This simulation-based approach provided a strong foundation for defining the probable reserves in already partially drilled and defined basins. However, no comparably reliable methodology exists for frontier or lightly explored continuous type basins.

With modification appropriate to the scope and regional nature of the effort, the integrated exploration approach set forth in this paper would enable an exploration geologist or a resource assessor to partition a frontier-type, continuously deposited basin. The use of basin partitioning with reservoir simulation to establish distinct basin area of high gas flow and per well reserves would provide a solid foundation for determining the economics of frontier tight gas, gas shale and coalbed methane basins.

## CONCLUSIONS

Structurally aligned reservoir compartments represent some of the most prolific gas reservoirs in the San Juan and Piceance Basins. Accurate targeting of structural corridors and associated reservoir compartments is possible through the utilization and integration of advanced methods of remote sensing imagery, high resolution aeromagnetics, stratigraphic mapping; seismic interpretation and dynamic structural modeling. Utilization of this method is likely to yield additional gas discoveries in the San Juan and Piceance Basins. The analogs developed in these basins will serve as a valuable template for evaluation and exploration of other western basins and conducting improved resource studies of continuous type deposits.

## ACKNOWLEDGMENTS

The authors would like to acknowledge financial support for this paper from the U.S. Department of Energy, Morgantown Energy Technology Center, SBIR Phase II grant DE-FG03-93ER81502. We also thank Patricia Martinez-Valdez for manuscript preparation, Barry Perow and David Devitt for graphics, and Owen Fitzsimmons for geologic assistance and Lee Jirik for stratigraphic interpretations.

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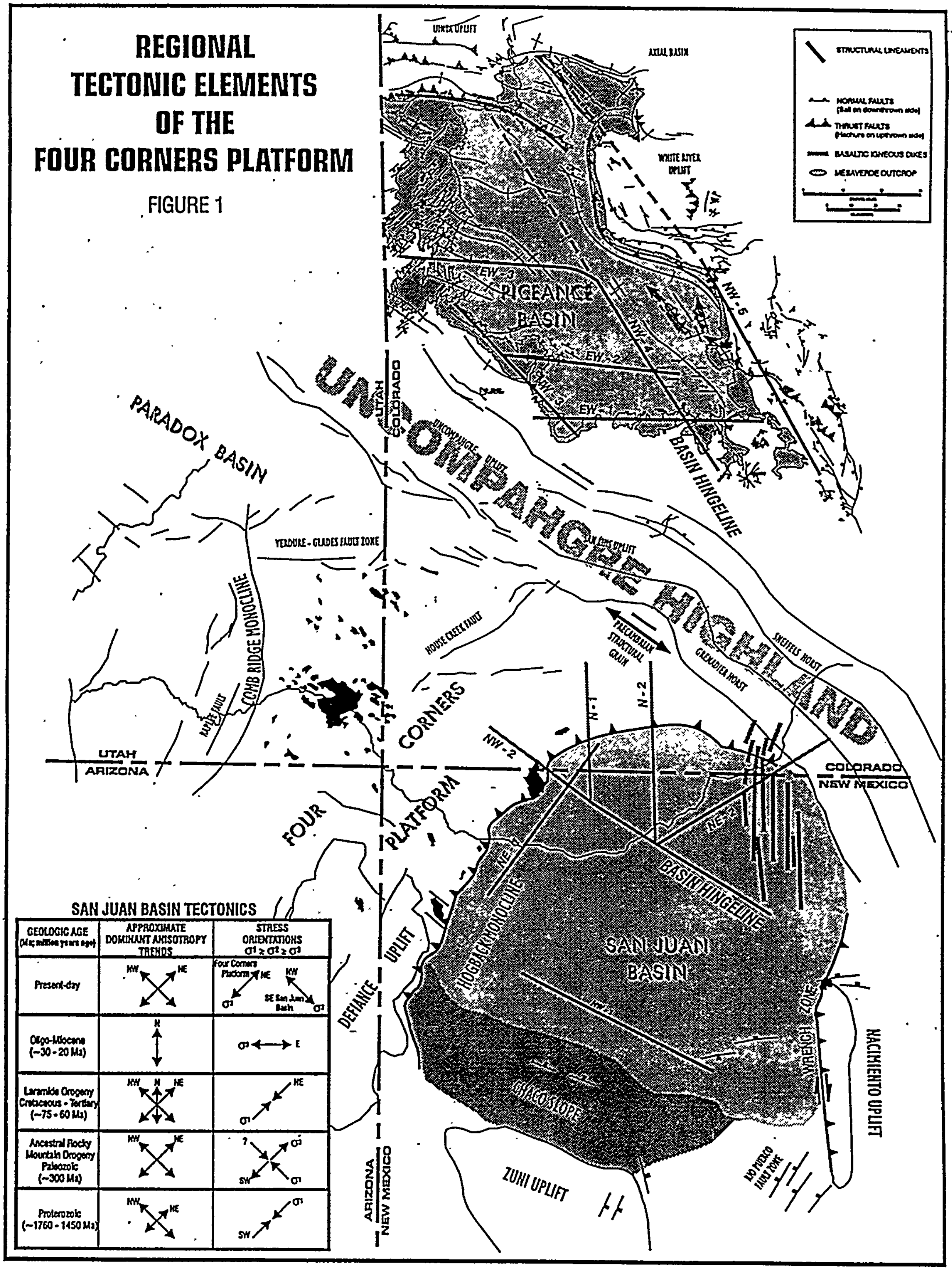
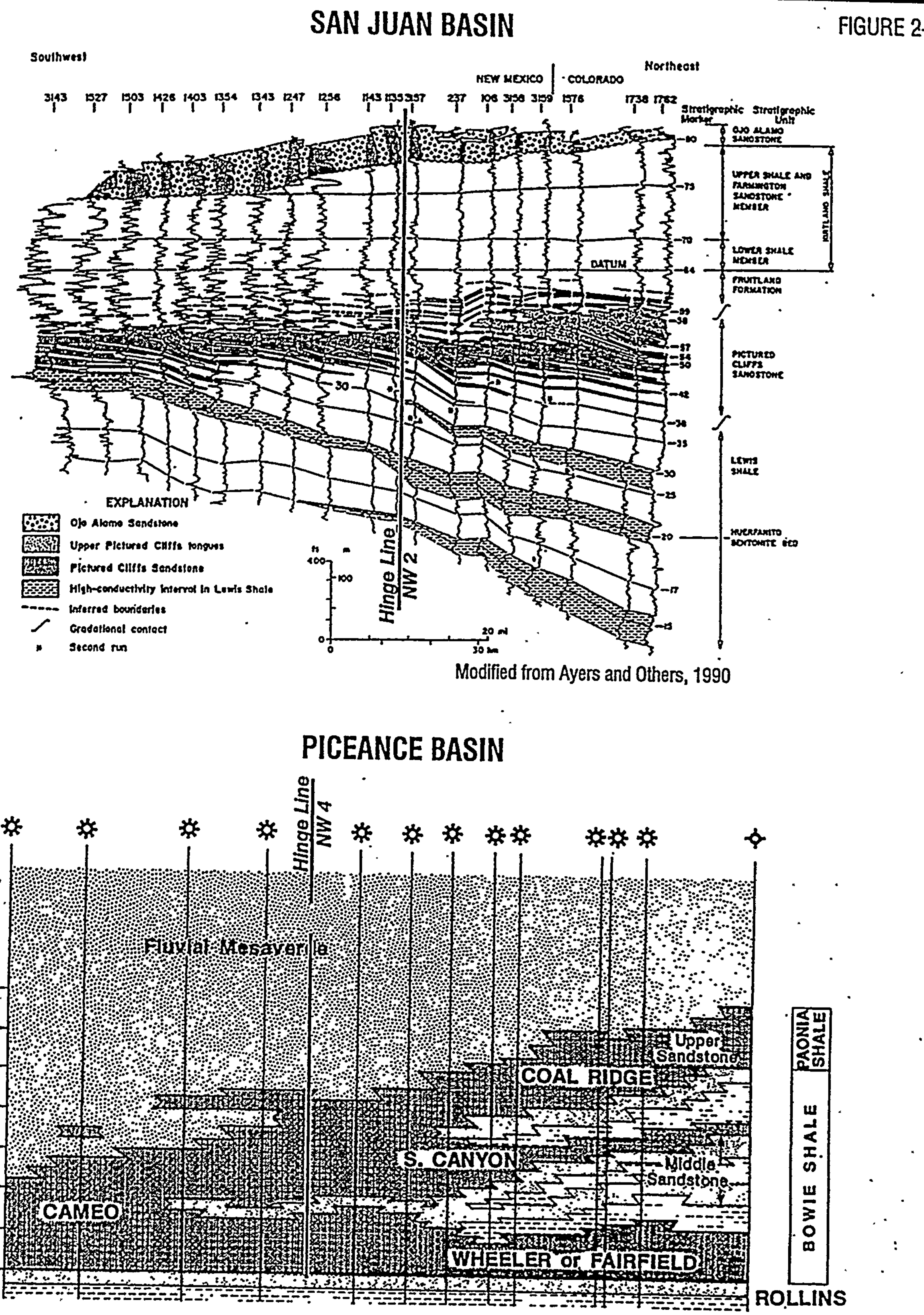

REGIONAL
TECTONIC ELEMENTS
OF THE
FOUR CORNERS PLATFORM
FIGURE 1
UINTA UPLIFT
AXIAL BASIN
STRUCTURAL LINEAMENTS
NORMAL FAULTS
THRUST FAULTS
BASALTIC IGNEOUS DIKES
MESAVERDE OUTCROP
WHITE RIVER UPLIFT
PICEANCE BASIN
EW-3
EW-2
EW-1
NW-3
NW-4
NW-5
UTAH
COLORADO
UNCOMPAHGRE HIGHLAND
UNCOMPAHGRE UPLIFT
BASIN HINGELINE
PARADOX BASIN
VERDURE - GLADES FAULT ZONE
COMB RIDGE MONOCLINE
HOUSE CREEK FAULT
PRECAMBRIAN STRUCTURAL GRAIN
GRENADIER HORST
SNEFFELS HORST
FOUR CORNERS PLATFORM
N-1
N-2
NW-2
NE-1
NE-2
UTAH
ARIZONA
COLORADO
NEW MEXICO
HOGBACK MONOCLINE
BASIN HINGELINE
SAN JUAN BASIN
DEFIANCE UPLIFT
CHACO SLOPE
ZUNI UPLIFT
NACIMIENTO UPLIFT
WRENCH ZONE
ARIZONA
NEW MEXICO
SAN JUAN BASIN TECTONICS
GEOLOGIC AGE
APPROXIMATE DOMINANT ANISOTROPY TRENDS
STRESS ORIENTATIONS
σ1 ≥ σ2 ≥ σ3
Present-day
Four Corners Platform
SE San Juan Basin
Oligo-Miocene (~30 - 20 Ma)
Laramide Orogeny Cretaceous - Tertiary (~75 - 60 Ma)
Ancestral Rocky Mountain Orogeny Paleozoic (~300 Ma)
Proterozoic (~1760 - 1450 Ma)
NW
NE
N
E
SW

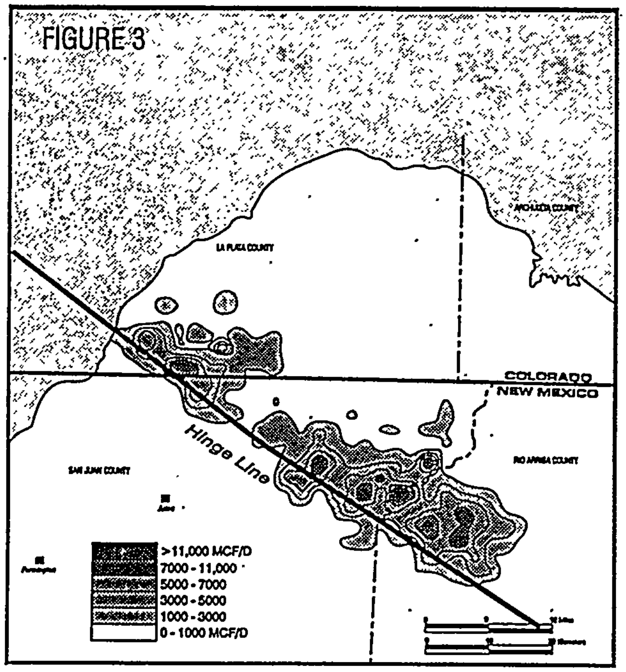
FIGURE 2



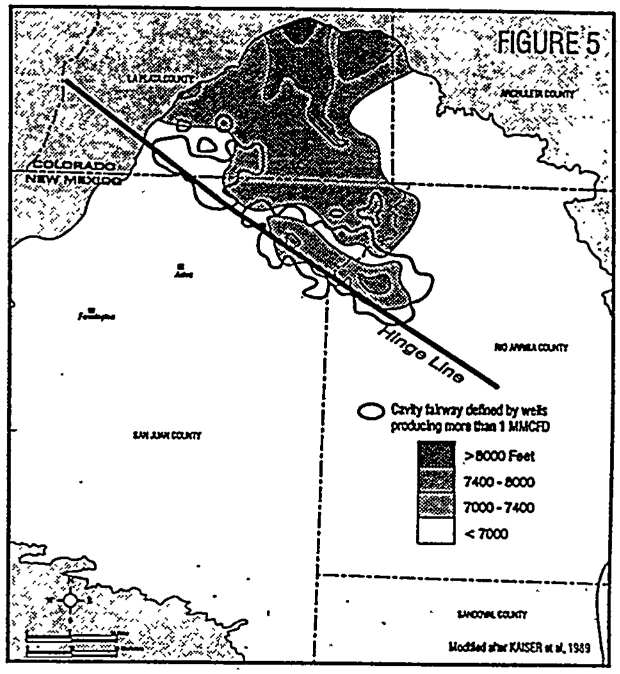

Modified from Ayers and Others, 1990

Modified from Reinecke and Others, 1991

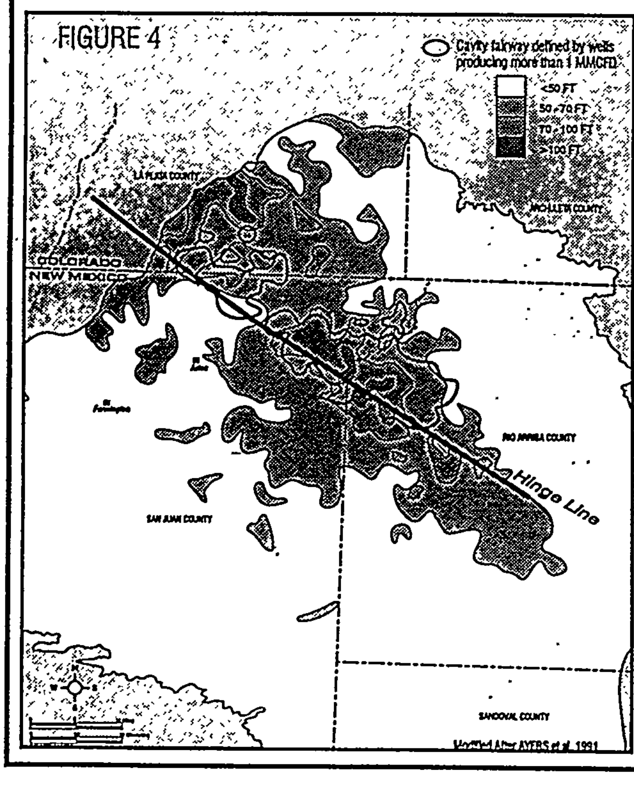
## AVERAGE DAILY GAS PRODUCTION FROM FRUITLAND COALS IN CAVITATION FAIRWAY



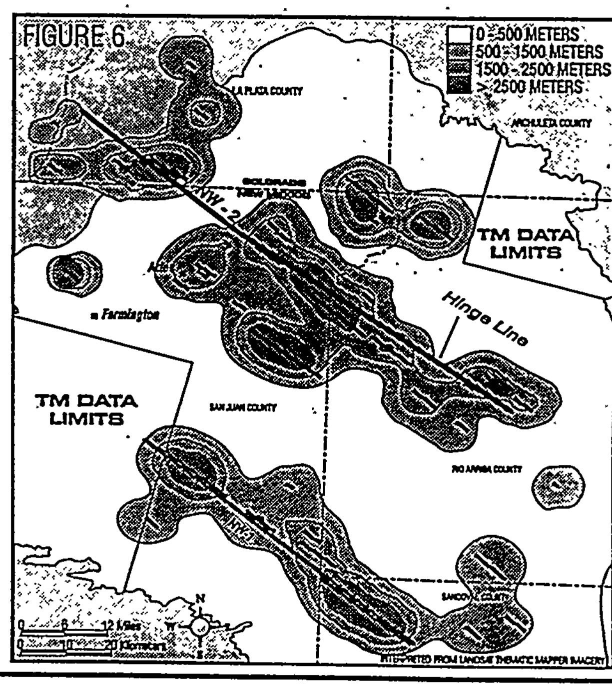

## POTENTIOMETRIC SURFACE OF THE FRUITLAND COALS

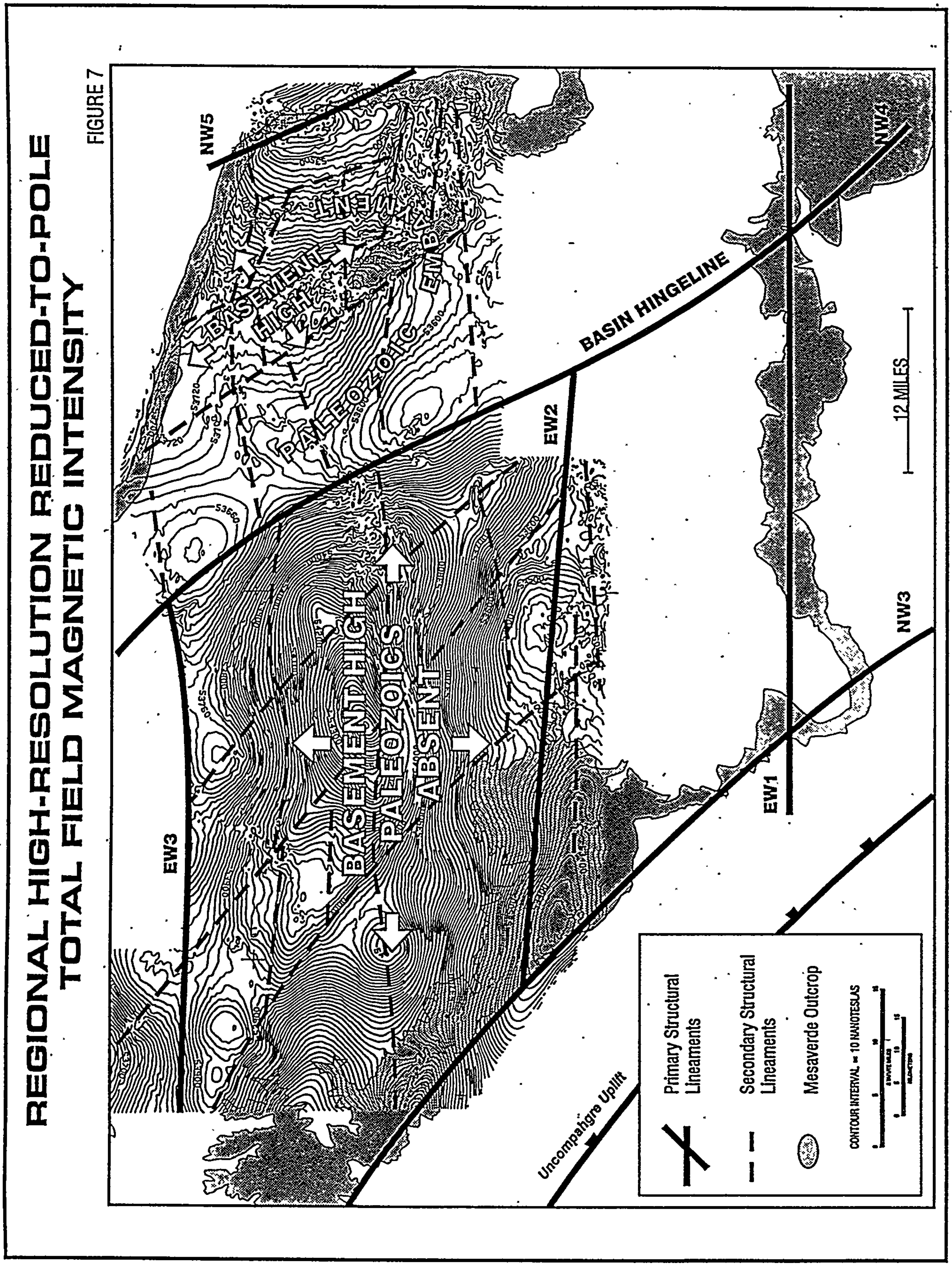


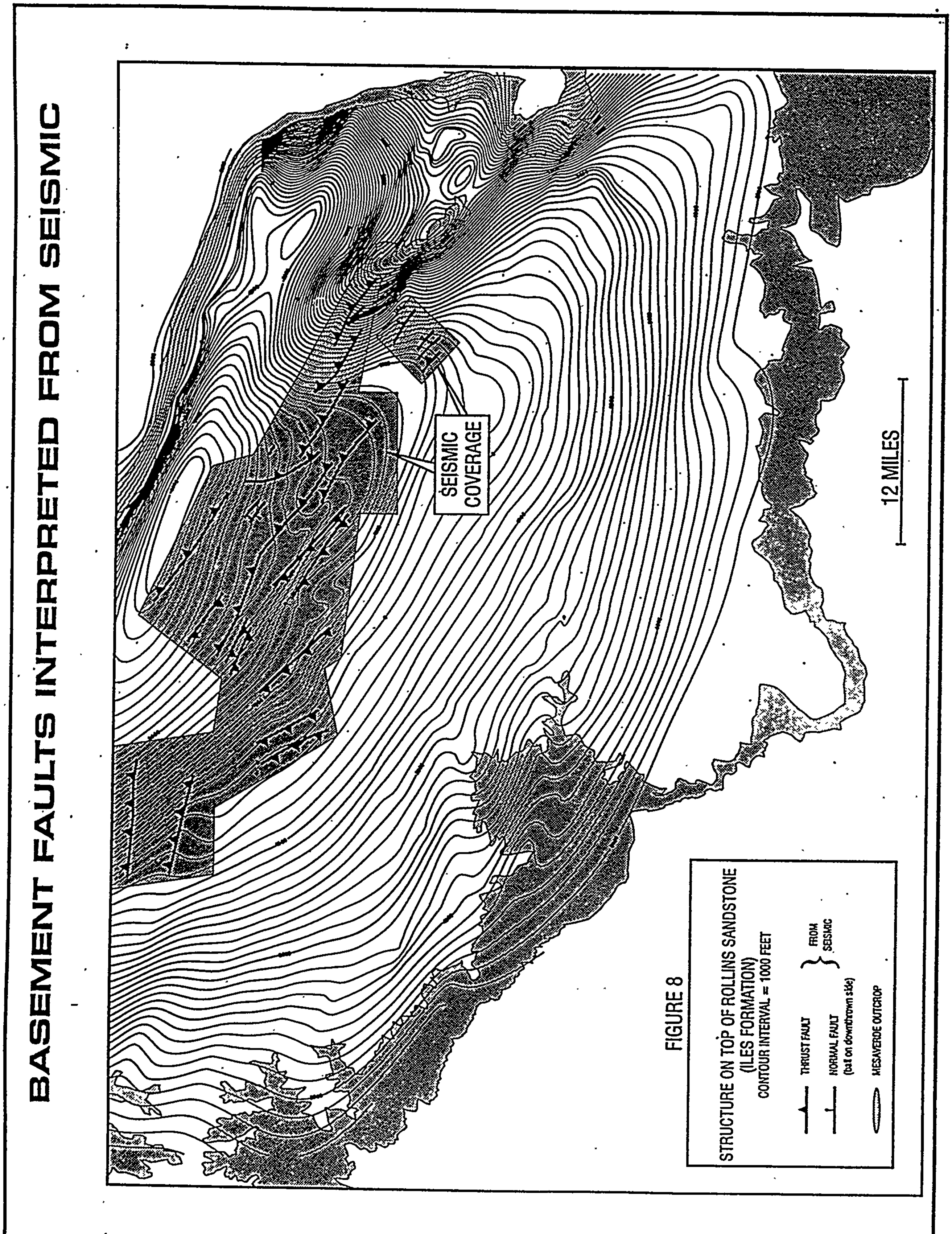

## NET COAL THICKNESS OF FRUITLAND FORMATION




## LINEAR FEATURE ANALYSIS NW-TRENDING LINEAR FEATURES COMBINED FREQUENCY GRIDS

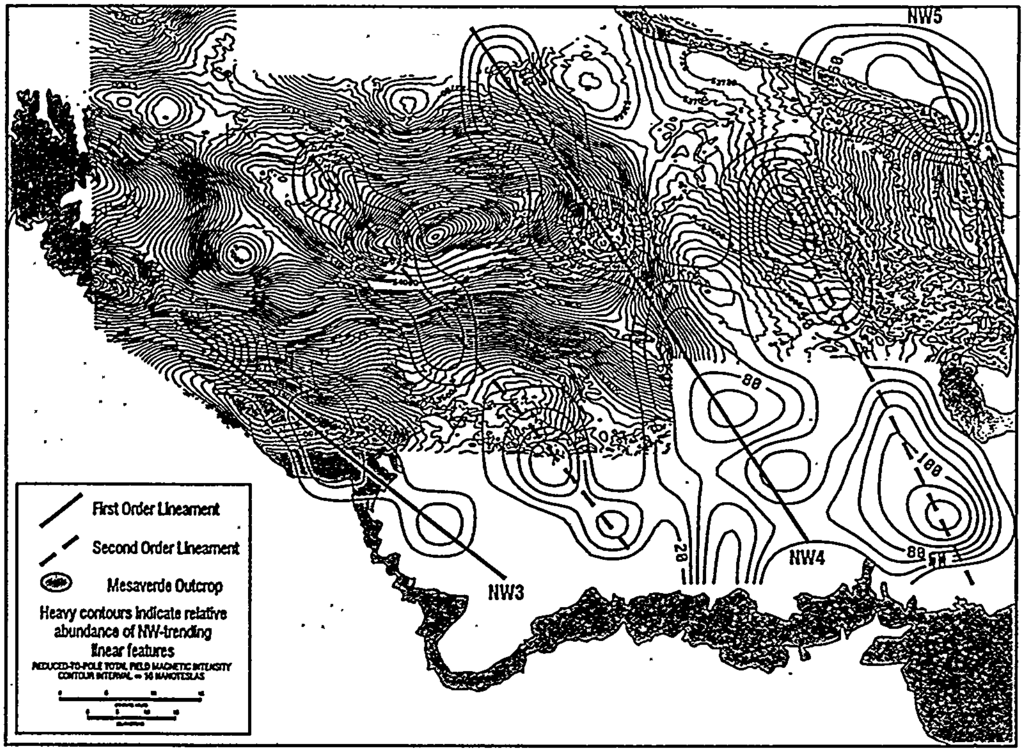



REGIONAL HIGH-RESOLUTION REDUCED-TO-POLE
TOTAL FIELD MAGNETIC INTENSITY
FIGURE 7
NW5
BASEMENT HIGH
PALEOZOIC EMBAYMENT
BASIN HINGELINE
EW3
EW2
BASEMENT HIGH
PALEOZOICS
ABSENT
EW1
NW3
NW4
12 MILES
Uncompahgre Uplift
Primary Structural Lineaments
Secondary Structural Lineaments
Mesaverde Outcrop
CONTOUR INTERVAL = 10 NANOTESLAS


BASEMENT FAULTS INTERPRETED FROM SEISMIC
SEISMIC COVERAGE
12 MILES
FIGURE 8
STRUCTURE ON TOP OF ROLLINS SANDSTONE
(ILES FORMATION)
CONTOUR INTERVAL = 1000 FEET
THRUST FAULT
NORMAL FAULT
(bal on downthrown side)
FROM SEISMIC
MESAVERDE OUTCROP

**LINEAR FEATURE ANALYSIS - NW TRENDING INTERVAL**
**CONTOURED LINEAR FEATURE FREQUENCY**

FIGURE 9



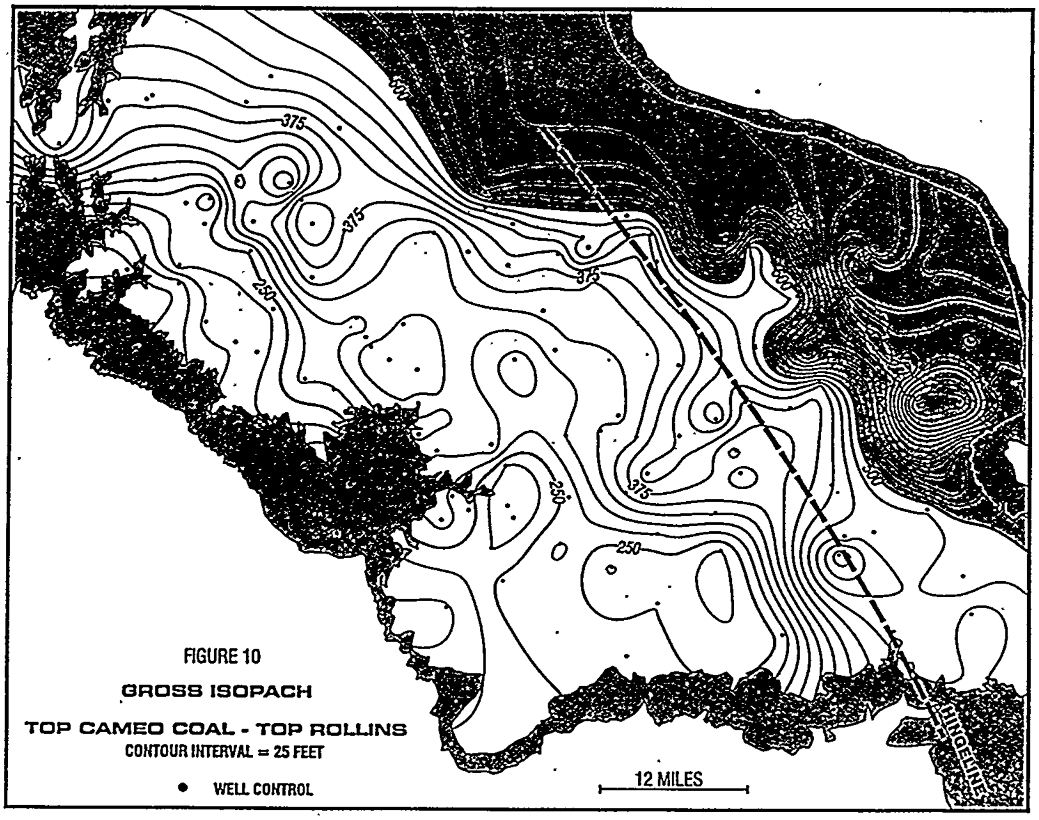




FIGURE 10

GROSS ISOPACH

TOP CAMEO COAL - TOP ROLLINS

CONTOUR INTERVAL = 25 FEET

• WELL CONTROL

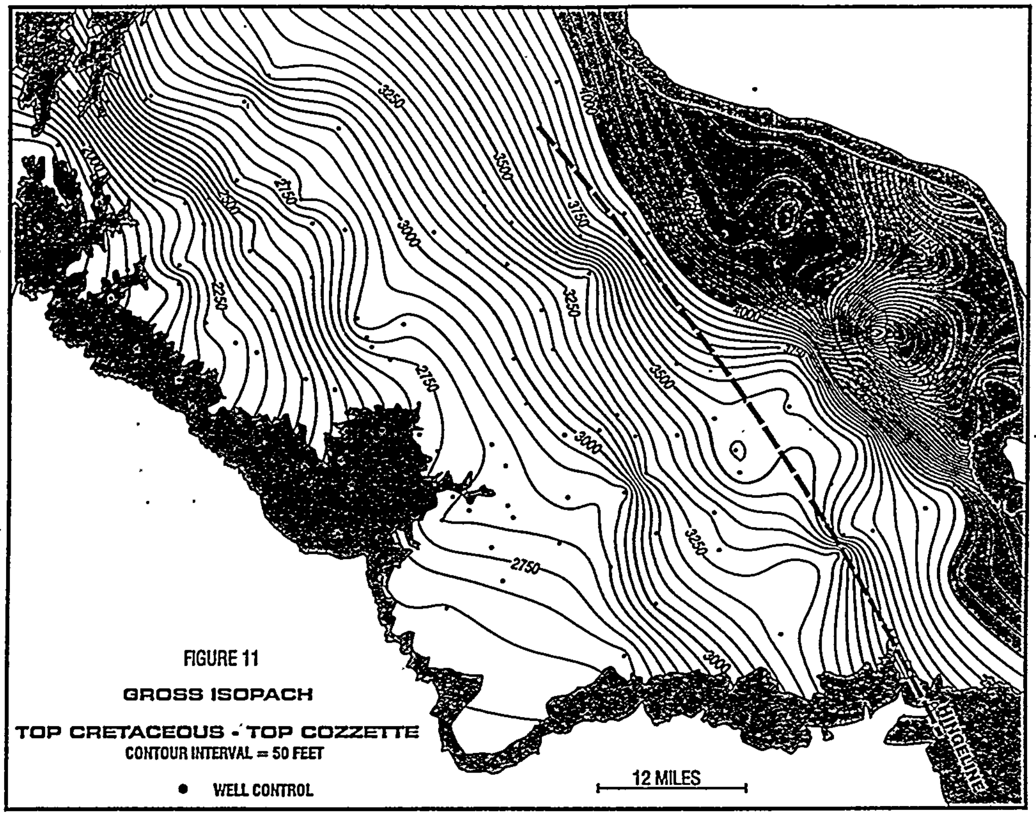
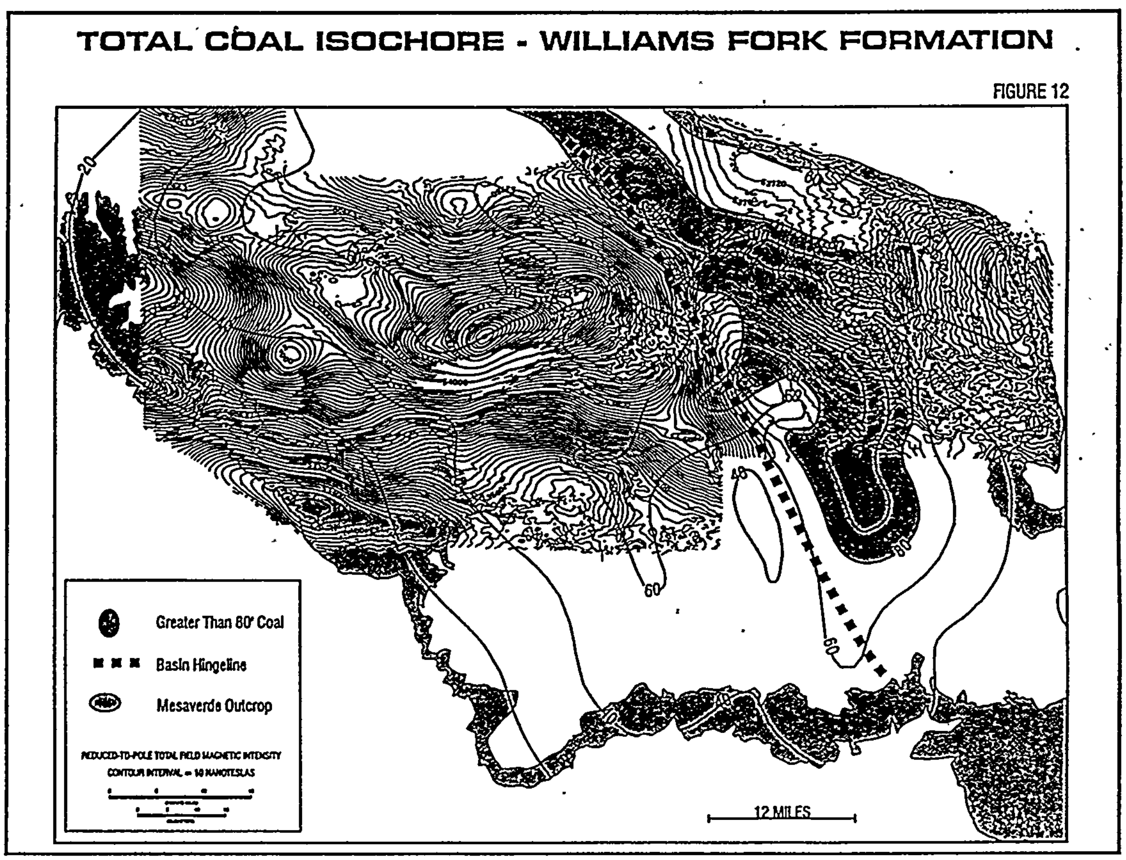
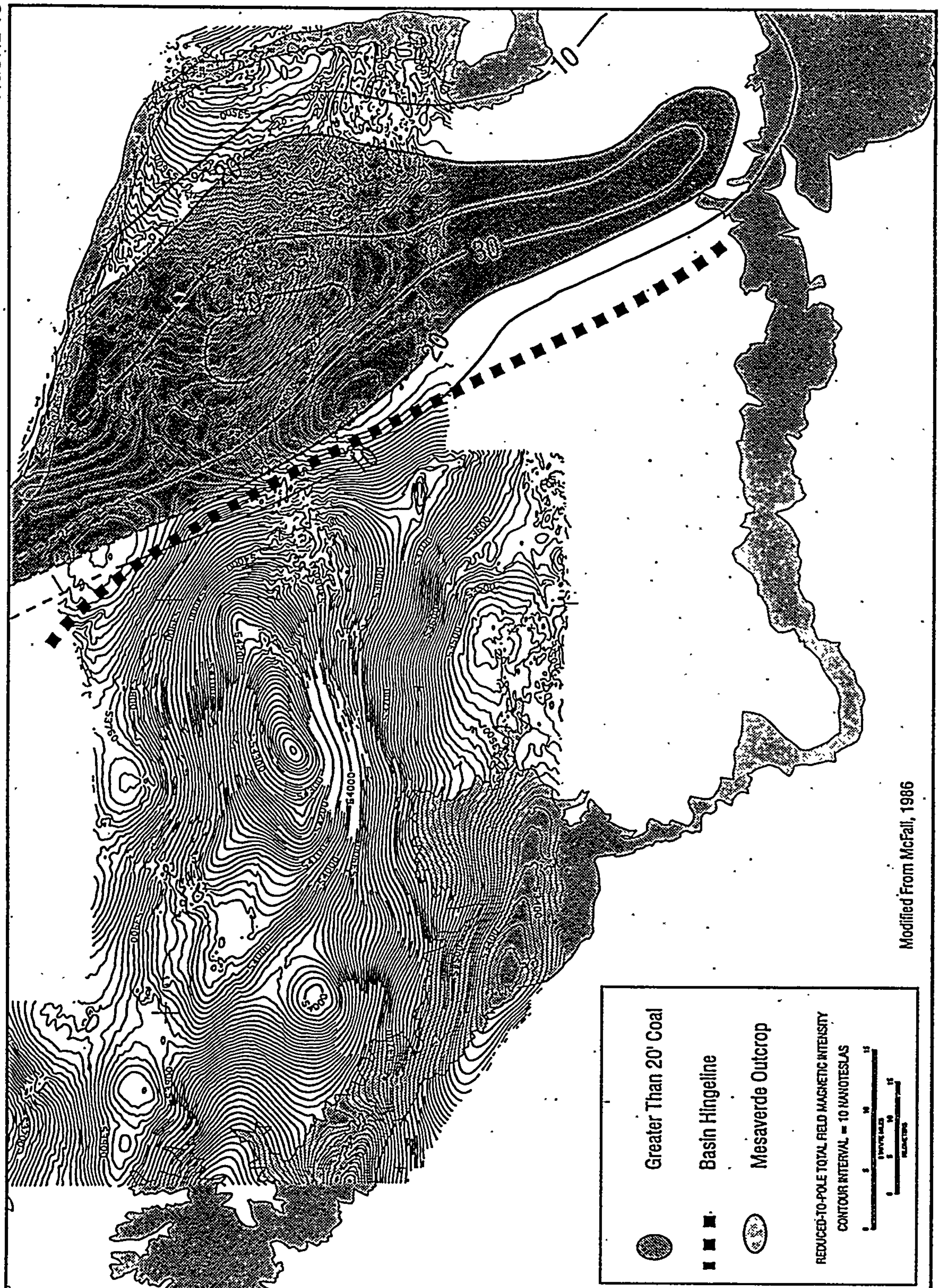


FIGURE 11
GROSS ISOPACH
TOP CRETACEOUS - TOP COZZETTE
CONTOUR INTERVAL = 50 FEET
WELL CONTROL
12 MILES
HINGELINE
3250
3500
3750
3000
2750
2250


TOTAL COAL ISOCHORE - WILLIAMS FORK FORMATION
FIGURE 12
Greater Than 80' Coal
Basin Hingeline
Mesaverde Outcrop
12 MILES
20
60

TOTAL COAL ISOCHORE - COAL RIDGE GROUP

FIGURE 13



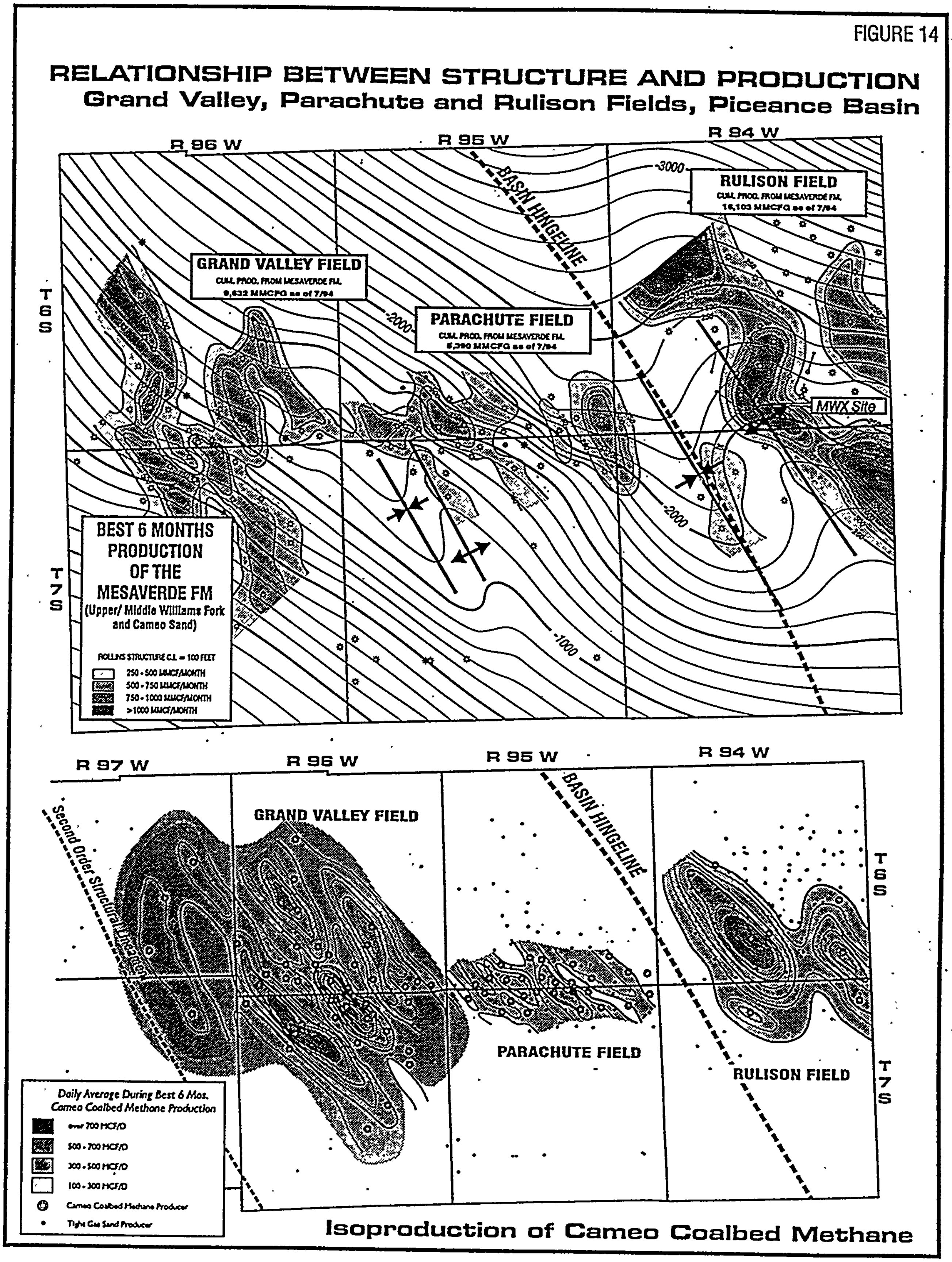
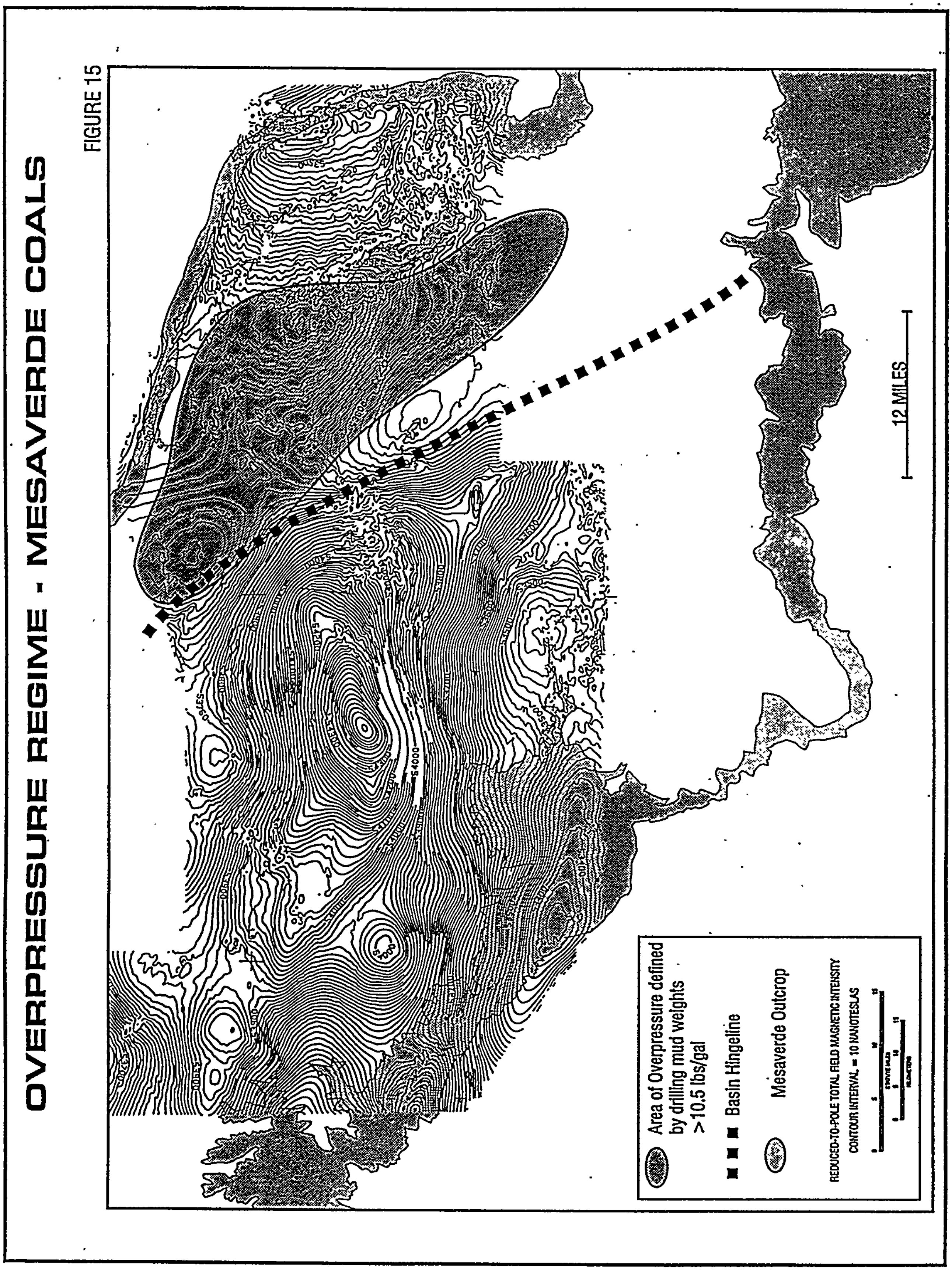
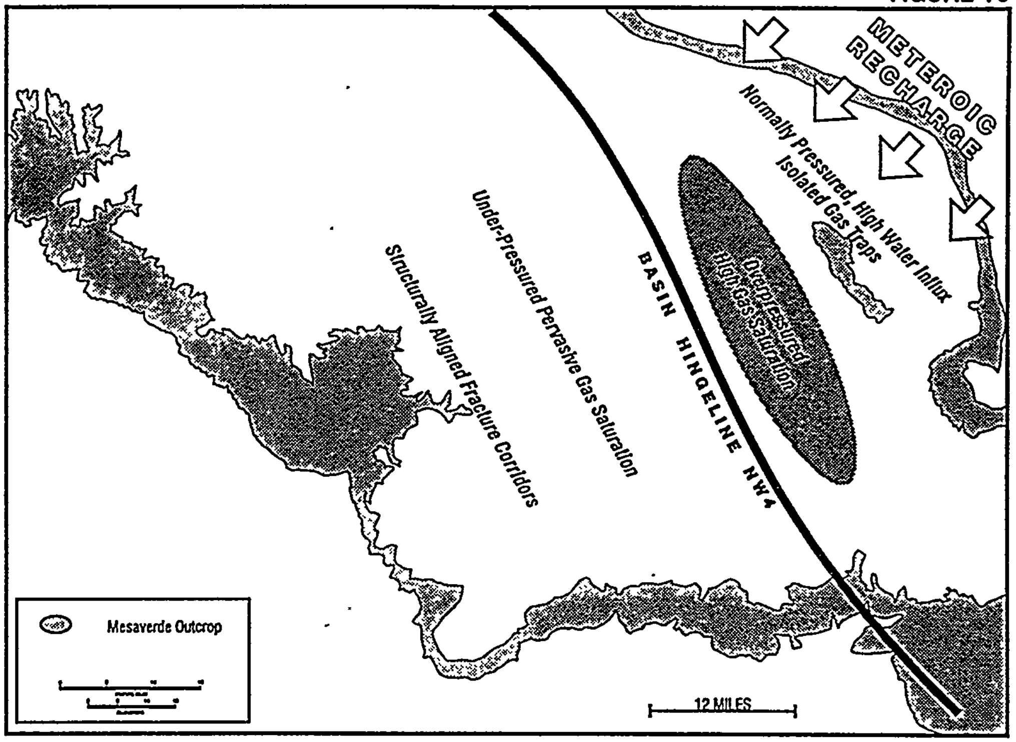


FIGURE 14
RELATIONSHIP BETWEEN STRUCTURE AND PRODUCTION
Grand Valley, Parachute and Rulison Fields, Piceance Basin
R 96 W
R 95 W
R 94 W
T 6 S
T 7 S
BASIN HINGELINE
RULISON FIELD
GRAND VALLEY FIELD
PARACHUTE FIELD
MWX Site
-3000
-2000
-1000
BEST 6 MONTHS PRODUCTION OF THE MESAVERDE FM
(Upper/ Middle Williams Fork and Cameo Sand)
R 97 W
Second Order Structural Line
Daily Average During Best 6 Mos. Cameo Coalbed Methane Production
Isoproduction of Cameo Coalbed Methane


OVERPRESSURE REGIME - MESAVERDE COALS
FIGURE 15
12 MILES
Area of Overpressure defined by drilling mud weights >10.5 lbs/gal
Basin Hingeline
Mesaverde Outcrop
REDUCED-TO-POLE TOTAL FIELD MAGNETIC INTENSITY
CONTOUR INTERVAL = 10 NANOTESLAS

# SOUTHERN PICEANCE BASIN PARTITIONS

FIGURE 16



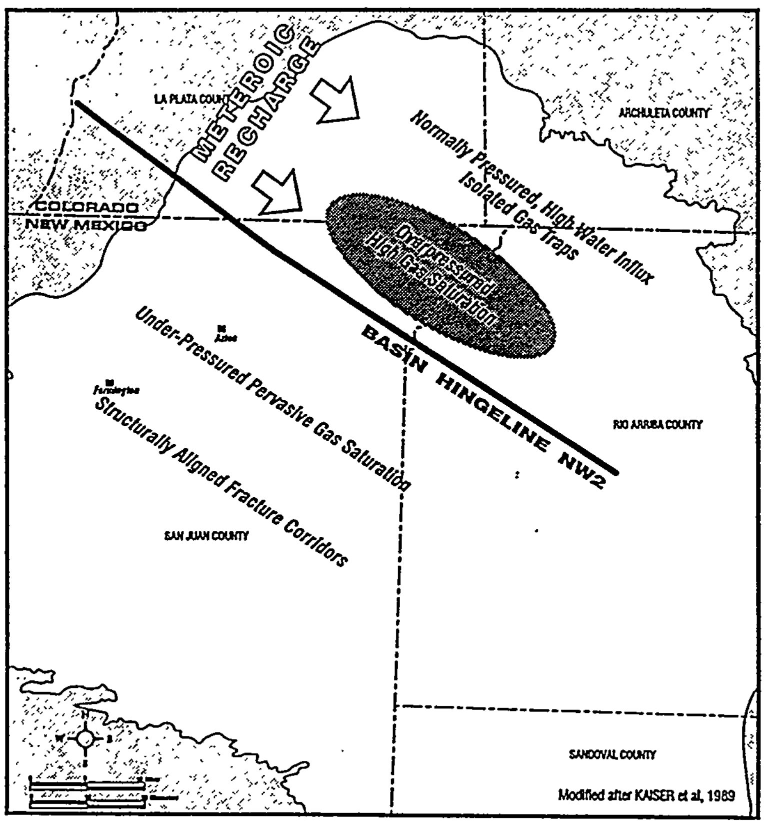




FIGURE 17

## SAN JUAN BASIN PARTITIONS

INTERGAS '95

May 15-19, 1995
The University of Alabama
Tuscaloosa, Alabama USA

9515

# Delineation of Piceance Basin Basement Structures Using Multiple Source Data: Implications for Fractured Reservoir Exploration

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## ABSTRACT

Fractured production trends in Piceance Basin Cretaceous-age Mesaverde Group gas reservoirs are controlled by subsurface structures. Because many of the subsurface structures are controlled by basement fault trends, a new interpretation of basement structure was performed using an integrated interpretation of Landsat Thematic Mapper (TM), side-looking airborne radar (SLAR), high-altitude, false color aerial photography, gas and water production data, high-resolution aeromagnetic data, subsurface geologic information, and surficial fracture maps. This new interpretation demonstrates the importance of basement structures on the nucleation and development of overlying structures and associated natural fractures in the hydrocarbon-bearing section. Grand Valley, Parachute, Rulison, Plateau, Shire Gulch, White River Dome, Divide Creek and Wolf Creek fields all 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 allowing economic production from the reservoirs. In this context, the significance of detecting natural fractures using the integrated fracture detection technique is critical to developing tight gas resources.

Integration of data from widely-available, relatively inexpensive sources such as high-resolution aeromagnetics, remote sensing imagery analysis and regional geologic syntheses provide diagnostic data sets to incorporate 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 target areas for exploration drilling, and infill and step-out development programs.

## INTRODUCTION

The objective of this investigation is to provide a perspective into the dynamics of an integrated fracture detection methodology applied to the Piceance Basin tight gas sands and coals. The integrated methodology involves the parallel interpretation and ultimate integration of conventional subsurface data (wells), aeromagnetic, seismic, and remote sensing imagery interpretation, integrated within the context of a detailed regional tectonic synthesis (Decker et al., 1994). To illustrate the approach, several gas fields from the Piceance Basin are used as examples to demonstrate the power of the method as it applies to understanding production trends and the controls on gas production in fractured fields in the Piceance Basin. Previously, few Piceance Basin fields were thought to contain fractured reservoirs (Brown et al., 1986). Those fields known to contain fractures include White River Dome, Divide Creek and Wolf Creek anticlines and the Rulison Anticline (Brown et al., 1986). Additional fractured reservoirs have subsequently been documented by fractured cores from Grand Valley Field (Reinecke et al., 1991), Parachute Field (Reinecke et al., 1991), Plateau and Piceance Creek fields (T. Barrett, Personal communication, 1994). Given the extremely small permeabilities observed in central Piceance Basin tight gas sands (5-30 microdarcies, Reinecke et al., 1981) commercial production cannot be achieved unless natural fractures are present in these fields. Data collected at the MWX site has confirmed that a 100 fold increase in reservoir permeability is achieved when natural fractures are present (Lorenz et al., 1991; Lorenz and Finley, 1991).

This paper is organized into several sections. After a brief basin overview, we demonstrate the relationship between production, and structural geology and stratigraphy. Because production trends are structurally controlled, we describe areas of the basin where regional subsurface structural mapping suggests that other fractured regions may exist. Because of the basement control on subsurface structure, we have used high-resolution aeromagnetics to delineate basement structures, confirmed by seismic, that control the shallower structures and production trends. Finally, we demonstrate how remote sensing imagery analysis provides a cost-effective method to rapidly define regional structural trends and to delineate zones of enhanced fracturing. Confirmation of the reservoir scale complexity of these fractured zones requires additional, more detailed analysis to clearly understand the nature of the fracture anisotropy using seismic or other advanced geophysical methods. However, the integrated methodology represents the most cost-effective system to minimize potential exploration area while maximizing the opportunity for success.

## BASIN OVERVIEW

The Piceance Basin is an elongate, NNW-trending structurally-downwarped region that formed as a result of Laramide contractional tectonics. The northern boundary of the basin is defined by the thrust-cored structures of the Axial Arch and the Uinta Uplift. The sinuous eastern margin is formed by the "S"-shaped, thrust-cored, Grand Hogback Anticline lying along the flank of the White River Uplift. The western boundary, formed by the Douglas Creek Arch, separates the Uinta Basin from the Piceance basin. The southwestern boundary is formed by the Uncompahgre Uplift. The West Elk Mountains and the Gunnison Uplift form the southeastern boundary of the basin. All uplifts surrounding the basin have experienced multiple phases of tectonic deformation ranging from Precambrian tectonism through Pennsylvanian-Permian deformation, culminating in the Laramide thrusting that defines the present-day basin geometry. Additional details regarding the tectonic evolution of the basin will be discussed later in the paper.

## STRUCTURAL AND STRATIGRAPHIC CONTROLS ON GAS PRODUCTION

To assess the importance of fractured reservoirs on production trends, detailed structure and production mapping was performed in Grand Valley, Parachute, Rulison, Shire Gulch and Plateau fields (see Figure 1 for locations) to determine the relationship between production and structure. These fields produce gas from the Tertiary-age Wasatch Formation (primarily Grand Valley, Parachute, Rulison), the Cretaceous-age Williams Fork (all fields), and the underlying Cretaceous-age Iles Formation (primarily Shire Gulch and Plateau). In these zones, gas is trapped in regionally-extensive, structurally-enhanced gas-centered basin-type traps. A large percentage of Williams Fork gas is produced from vertically-stacked fluvial sand channels, and from thick coals in the Cameo Coal section located below the fluvial interval. Production from marine sands in the Cozzette-Corcoran sandstones (Iles Formation) is dominated by shoreface sands in the transition between the marine and continental facies. Plateau and Shire Gulch fields straddle the transition zone between the two facies. For discussions of reservoir sedimentology and regional stratigraphy, see Johnson and Nuccio (1986) for the Williams Fork, and Brown et al. (1986) for the Rollins, Cozzette and Corcoran sandstones.

The primary objective of this section is to characterize the relationship between production trends in these fields, regional stratigraphy and structure, most notably the influence of structural and stratigraphic trends on reservoir productivity.

### Production Trends in Grand Valley, Parachute and Rulison Fields

To understand production controls, gas production data for the best six months during the life of the well were contoured and normalized by the total days of production. By normalizing the best six months production, it is possible to minimize reporting inaccuracies and the effects of variable seasonal production. To assess the controls on production, production contours were overlaid with depositional systems information and structural geology (Figures 2a and 2b). Figure 2a illustrates the relationship between structure and production trends in the three fields. The structure contours are drawn on the top of the Rollins Sandstone Member (Iles Formation). The production trends lie parallel to local structure trends in the three fields. To examine the effect of stratigraphic variation, a total sand isochore map was compared to production trends for Parachute and Rulison fields (Figure 2b). The depositional system consists of vertically-stacked 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). The NW-striking production trend lies perpendicular to the depositional systems trends (Figure 2b), strongly confirming the structural control on production in these fields. 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).

Grand Valley, Parachute and Rulison fields illustrate the importance of structural controls on production trends. It is interesting 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 MWX coring program in vertical and horizontal wells (Lorenz and Finley, 1991). There are several possible explanations for this relationship. The most plausible is that local tectonic deformation caused by structures, such as the Rulison Anticline, generates enhanced dilatancy along "regional" fracture sets oriented oblique to the structure. In such a scenario, the fractures cored at MWX are not necessarily the trend controlled by the local structure. Instead, the local structure, possessing its own strike-parallel fracture set merely dilates the MWX set and increases its connectivity. If this is true, and the regional fractures formed first, the MWX fractures would likely show minor amounts of shear displacement during formation of the anticline. Alternatively, if they formed later, they would not necessarily show any surface ornamentation characteristic of shear displacement (e.g. slickensides). Given that there is no obvious surficial ornamentation on the mineralized fracture planes cored in the MWX wells, it suggests that these fractures may post-date formation of the anticline. A further complexity is introduced by the small NE-trending normal fault found in the MWX #2 well (Sattler et al., 1985; Branagan et al., 1985). This fault lies orthogonal to the NW-striking production trend and the dominant measured fracture orientation. It is possible 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 dominant set that controls production. It is also possible that E/W fractures are localized and are restricted to the E/W-trending section of the Colorado River while the other fields lie along NW-trending structures that control the NW-striking drainages. Available data are presently unable to resolve this complexity.

### Production Trends in Plateau and Shire Gulch Fields

Production data from Corcoran and Cozzette Sandstones (Iles Formation) were contoured and compared with structural contours to investigate the relationship between the two parameters (Figures 3a and 3b). Production trends in Plateau and Shire Gulch fields strike northwest, parallel to the trend of mapped surface faults. Interestingly, there is a slight obliquity between the trend of field structure (contoured on top of the Rollins Sandstone Member of the Iles Formation) and production contours in these two fields (Figure 3a). Instead, the production trends lie parallel to the trend of mapped surface faults (Donnell et al., 1984) and basement fault zones to be discussed below. Structure contours on the Rollins Sandstone Member of the Iles Formation show that the regional structure in this area is a WNW-trending series of broad, open and upright anticlines and synclines. 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. These folds are probably related to differential subsidence over basement fault zones. The Rollins structural datum is used in these two fields to maintain regional consistency and because of the greater number of Rollins penetrations. The Corcoran structure is nearly identical to that of the Rollins, only deeper. This relationship is confirmed by isopachs or isochores of the Rollins-Corcoran interval that shows a monoclinally southeastward-dipping surface.

Corcoran-Cozzette depositional strandlines trend northeast (Zapp and Cobban, 1960; Brown et al., 1986), perpendicular to the trend of the production axes (Figure 3b). The strandline differentiates between nearshore continental and offshore marine facies. The boundary between the two facies is primarily delineated by the presence of coal in the continental facies. There appears to be little stratigraphic variation in the depositional system along the northeast strandline trend (Zapp and Cobban, 1960; Warner, 1964; Brown et al., 1986). Some complexity appears 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 destroys the diagnostic internal geometry of the sediments and makes it difficult to characterize the log response of the facies.

## REGIONAL STRUCTURE MAPPING

Detailed structural mapping of the Plateau-Shire Gulch and Grand Valley-Parachute-Rulison fields clearly demonstrates the structural control on production trends (Figure 4). To focus regional or basin-scale exploration efforts, regional structure mapping was used to locate other areas where local structure controls fractured production trends. Such regional structural trends are readily observable on regional structure maps constructed on the Rollins Sandstone Member (top of the Iles Formation). Although the Rollins Sandstone Member is a progradational system, shingled toward the southeast, the magnitude of the shingling is small (< 100') 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 typical Piceance Basin gas fields.

Three dominant regional structural trends persist throughout the basin. In the eastern basin, the NW-trending Divide Creek, Wolf Creek and Coal Basin anticlines have been formed by WSW-directed thrusting. In the western basin, several broad, low amplitude anticlines have formed with dominant E/W trends. These anticlines include the Debeque, Unnamed (here designated Bull Creek Anticline, located to the south of the Debeque anticline in Plateau Field) and the Douglas Creek Anticline. The latter anticline has an WNW trend. The northern boundary of the basin, the Axial Arch, is a WNW-trending fault-bend fold formed during south-directed Laramide thrusting (Stone, 1986). The last significant trend is the N/S trend typified by the sections of the Hogback between Meeker and Rio Blanco, and from Carbondale to the Elk Mountains.

Preliminary overview of the basin suggests that fractured reservoir conditions should be present in several of the anticlines along the eastern flank of the Douglas Creek Arch. In addition, the northern basin contains the Powell Park and Sulphur Creek structures that are likely to be fractured. Limited well control, combined with a lack of high-resolution aeromagnetic data and seismic confirmation, makes additional effort into understanding the fracture potential of these structures a future priority for regional exploration efforts.

The thrust-cored structures in, and adjacent to, the Piceance Basin include the Grand Hogback (Gries, 1983), Wolf Creek Anticline (Grout, 1990) and Divide Creek Anticline (Grout, 1990; Gunneson et al., 1994), Rangely Anticline (Stone, 1986), Axial Arch and Maudlin Gulch (Richard, 1986), and the White River Dome, and Powell Park Anticlines. Thrust involvement or basin fault inversion is also evident in the Rulison Anticline, a Pennsylvanian-age paleohorst (Waechter and Johnson, 1986), and along the margins of older horst blocks including the Grand Hogback (Waechter and Johnson, 1986).

The tectonic evolution has been assessed using published sources integrated into a dynamic structural analysis. To perform this synthesis, a tectonic chart (see Figure 5) was prepared that tracks the evolution and development of major structures (see Figure 6) throughout the geologic evolution of the Piceance Basin and precursor basins and uplifts located in the region. At the initiation of the Late Cretaceous-Early Tertiary Orogeny, there were two dominant regional anisotropies that formed during extensional tectonics that were part of the Precambrian and the Pennsylvanian-age Ancestral Rockies Orogeny. The Precambrian anisotropy trends WNW in the Uinta Uplift and trends NW in the Uncompahgre Uplift. The Pennsylvanian-age structural grain trends more NW and forms the Rulison paleohorst (beneath Rulison Field) and a paleohorst beneath the Grand Hogback Monocline (Waechter and Johnson, 1986). It is important to note that recent seismic interpretation in the central Piceance Basin shows that many, if not most, of the basement faults show reverse sense of displacement. This relationship is valid for all basement faults, not just those reactivated during Laramide contraction. This is contrary to older interpretations of Precambrian tectonics that emphasized the dominance of extensional tectonics (Tweto, 1975). Given the complexity and timeframe involved in Precambrian deformation throughout Colorado, complete understanding of this problem requires extensive additional research.

These two anisotropy trends were reactivated during the Laramide Orogeny. Initially, the compression axis was oriented NNE. Structures formed during this phase include the Rangely, White River Dome, and Uinta Uplift features. Later, the overall compression axis shifted and was oriented NE/SW to form major NW-trending thrust-cored folds such as the Divide Creek Anticline, Wilson Creek Anticline, the Axial Arch and related structures. As this phase of tectonism abated, the compression axis shifted to a more easterly trend and a broad gentle regional uplift occurred resulting in the formation of the Douglas Creek Arch.

Following the end of Laramide contraction, the region has experienced slight WNW to E/W compression that persists to the modern day. During the transition period, the White River and Dudley Gulch grabens formed and basaltic dikes were emplaced in the southeast basin.

During Laramide tectonics, the thrust geometries that were initiated were locally complex. Exclusive seismic data from throughout the basin center have recently 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 fan off this detachment and cause local, dekameter-scale, thickening in the Iles Formation sandstones (Rollins Cozzette, Corcoran). The complex thrust geometry in the eastern basin has been documented in high-resolution seismic data across the Divide Creek Anticline by Gunneson et al., (1994) but these relationships have not been previously demonstrated to extend into the basin center. We are attempting to obtain permission to publish seismic data from the basin center that illustrates the multi-level detachments. Work in progress is assessing the influence of these multiple displacements on production.

## BASEMENT CONTROL OF SHALLOWER STRUCTURES

The critical relationship in the Piceance Basin is the relationship between shallow and intermediate (<10,000 feet depth) fractured structures and deeper basement structures. To assess this relationship, high-resolution aeromagnetic data, calibrated with published and proprietary seismic data was used to establish the relationship between basement structures and the shallower structures that delineate fractured production trends. By delineating the geometry of basement structures, we appear to have confirmed our ability to predict fractured reservoirs in shallow structures in other areas of the basin using the integrated approach.

There are several areas where this relationship is extremely clear and unequivocal. The Grand Valley-Parachute-Rulison area clearly demonstrates the basement control on shallower structures that control production trends. A detailed view of a seismic line under Parachute and Rulison fields demonstrates that the Rulison Anticline lies above a reactivated or inverted fault system lying along a basement horst block (Figure 7). The timing of the extensional tectonics that formed the horst are clearly Paleozoic (Pennsylvanian) in age because the Paleozoic section shows evidence of syntectonic deposition. Other proprietary seismic lines in the central Piceance Basin seismic grid more clearly illustrate this relationship. From this grid (see Figure 8 for line locations) we have interpreted the geometry of basement fault systems. The fault systems show a complex interplay of normal and thrust faults (Figure 9). It appears that many of the normal faults may represent older structures, whereas the thrusts are generally younger, thought to be formed during Laramide deformation. Work in progress is refining the temporal and spatial evolution of the faults in the context of a detailed tectonic evolution. The critical and confirming relationship is the similarity in trends of the production contours, shallower subsurface structure and the basement fault orientations.

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 (Figure 9). There is excellent correspondence between basement and shallower structures in Grand Valley-Parachute-Rulison 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., 1994) although Cozzette-Corcoran production data from this area in the public domain is extremely limited due to the mid-late 1950's age of the original production and drilling activity. Work in progress is attempting to collect production information from these fields to confirm basement control on fractured reservoir production trends.

### Calibration With High-Resolution Magnetics

High acquisition costs, especially in the Piceance Basin, associated with regional seismic surveying effectively prohibits its use for regional reconnaissance studies. In addition, single seismic lines generally do not satisfactorily explain complex structural geometries. To obviate this problem, we have calibrated a newly-acquired high-resolution aeromagnetic survey against the seismic grid. Aeromagnetic surveying was chosen for several reasons. Existing NURE data demonstrated that aeromagnetics provided important basement information; the survey is relatively low-cost; and the data can be rapidly acquired. In addition, analysis and digital reprocessing of regional, lower-resolution NURE aeromagnetic data (Grauch and Plesha, 1989) (Figure 10) appeared to define gross boundaries between basement domains. From this information, we attempted to maximize new data acquisition in the transitional areas between these domains. In addition, we wanted to clearly image the magnetic basement beneath the majority of producing fields in the southern Piceance Basin. The aeromagnetic survey was flown with N/S flight lines at four hundred meter spacing with perpendicular tie lines acquired at sixteen hundred meters. This is in sharp contrast to the NURE aeromagnetic data acquired at three mile E/W flight line spacing with twelve mile N/S tie line spacing.

Detailed aeromagnetic contours 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. Detailed examination of the regional map reveals numerous areas where basement faults are likely to be present (see Figure 11). We will focus our attention on the Grand Valley-Parachute-Rulison and Plateau-Shire Gulch areas.

The Grand Valley-Parachute-Rulison area in the basin center lies on the margin of a large E/W trending basement high recognized on the aeromagnetic survey. The magnetic high corresponds to a missing Paleozoic section confirmed by drilling (Barrett Resources-Arco Deep #1-27). Along the northeast margin of this structure, there are numerous NW-trending normal and thrust faults evident on the aeromagnetic maps that have been confirmed by seismic surveying (Figure 12). In this area of the basin, basement faults trend NW, parallel to the structural trends observed in the shallow subsurface and parallel to production trends observed in subsurface reservoirs. The magnitude of the displacements associated with the basement faults are difficult to establish from the aeromagnetic data. Seismic data suggest that the displacements vary from 500-2500 feet at the basement level.

In the Plateau-Shire Gulch area, it appears that some of the high-angle normal faults observed in the basement propagate to the surface as evidence by surface mapping discussed earlier. Seismic lines in this area show several normal faults that drop the hangingwall down to the northeast (Brown et al., 1986). In this field, the trend of basement faults in the aeromagnetic data is the same as the trend of faults mapped on the surface (Figure 13). We have already demonstrated how production trends in these fields lie parallel to the subsurface and surface fault trends. The aeromagnetic data suggest that these fault trends continue down to the basement level. In addition, using this information, we can extrapolate or predict fracture-controlled production trends using aeromagnetic data for areas lacking other subsurface controls.

## REMOTE SENSING IMAGERY ANALYSIS

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.

The Plateau-Shire Gulch area contains several NW-trending normal faults that lie parallel to the production trends. These trends are also recognized by remote sensing imagery analysis of this area. To determine the relationship between regional subsurface structure and surficial trends observed on remote sensing imagery, remote sensing imagery analysis was performed using Thematic Mapper (TM) data, Side-Looking Airborne Radar (SLAR) and high-altitude, high-resolution, false-color infrared aerial photos (NHAP). Figure 14 presents linear features interpreted from aerial photos and TM data registered onto a regional structure map constructed using the top of the Rollins Sandstone Member. To verify the nature of these linears, interpreted linears were compared to published maps of surface geology (USGS MF- and GQ- map series for the area of the fields). Remote sensing imagery analysis accurately locates the surface fault locations. In addition, numerous parallel linear features are noted that may also represent faults or fault-parallel fractures. These linear features were not recognized during field mapping. There appears to be little relationship between the fracture orientation or density and the location of the linears on the fold geometry. This relationship, combined with the apparent absence of oblique-slip slickenlines on these fractures, suggests that the fractures formed after the fold. Additional fieldwork is necessary to confirm the regional persistence of these limited field observations.

The relationship between production and linear features is shown in Figure 15. Production trends directly correlate to trends and locations of surficial linears. All linears are shown in Figure 15. Because of the trend of surface faults and the production trends, a rose diagram (Figure 16) was constructed that shows the dominant linear features trends in the field. There is a wide range of orientations. We know, however, that the WNW-NW range of linears corresponds to mapped surface faults. Because of this, we filtered the data set to only contain these trends (Figure 17). From this map, the excellent correspondence between linear features interpreted from remote sensing imagery analysis can be seen. Nearly all significant production trends are overlain by a surficial linear. The confirmation of subsurface production trends by remote sensing imagery analysis suggests that we should be able to use a combination of high-resolution aeromagnetic data to locate basement faults and remote sensing imagery analysis to identify the surficial manifestation of these same zones. From this information, we are able to predict the orientation and location of subsurface production trends.

## REGIONAL ASSESSMENT OF SURFICIAL FRACTURES

Because of the relationships established at Plateau and Shire Gulch fields, a regional assessment of the relationship between surficial linears and mapped surface faults 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 has also been compared against the remote sensing imagery analysis linear features interpretation (see Figure 18 for example areas). Overall, there is excellent agreement between the remote sensing-based interpreted linear features, and the surficial mapping. 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.

There are numerous examples of the ability of remote sensing image analysis to document trends verified by field mapping of joint systems. In the White River Dome area and the Douglas Creek Arch area in the northern Piceance Basin, remote sensing imagery analysis recognizes all of the surface-mapped linear trends (Figure 18). In the Douglas Creek area, surface faults possess a dominant NE-trend (Figure 18). There are considerably lesser number of NW-trending faults. Remote sensing imagery analysis accurately identifies the location and trend of the surface structures. Similarly in the White River Dome, surface mapping shows three dominant joint trends. These trends (NW, NNW and NNE) are also confirmed by the remote sensing imagery analysis (Figure 18).

The surface joints at Rifle Gap are also identified in the remote sensing data set (Figure 18). In the Colorado River and Debeque areas, the remote sensing analysis identifies additional linear trends that do not correspond to the dominant surface mapped joint trends. The significance of these additional linear trends requires ground confirmation to identify their significance. It is important to stress, however, that the remote sensing imagery analysis does correctly identify the abundant surface mapped joints.

In general, there is excellent agreement between the orientation of the significant trends determined from imagery analysis and ground-based studies. Given the similarity of 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. The rapidity of remote sensing analysis provides an extremely rapid process to recognize 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.

## CONCLUSIONS

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.

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

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 economic 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.

Remote sensing imagery analysis appears to provide a cost and time-effective method to locate 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.

Integration of data from widely-available, relatively inexpensive sources such as high-resolution aeromagnetics, remote sensing imagery analysis and regional geologic syntheses provide excellent data sets to incorporate 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 target areas for exploration drilling, and infill and step-out development programs

## ACKNOWLEDGEMENTS

The authors would like to acknowledge financial support for this paper and the associated Fractured Reservoir Detection Optimization project from the Department of Energy-Morgantown Energy Technology Center (DOE-METC contract DE-AC21-93MC30086). Royal Watts (DOE-METC) is thanked for project management and encouragement. Seismic data were obtained from Barrett Resources, our industry partner in the project. Special thanks to Terry Barrett for helpful discussions and generous cooperation. Seismic interpretation was by Stuart Squires (Advanced Resources International). The aeromagnetic survey was performed by World Geoscience, Houston, Texas. Linear features analysis of the Plateau and Shire Gulch fields was by Peter Blomquist (Advanced Resources International), production trend mapping in all fields was conducted by Grant Carnie (Advanced Resources International).

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FIGURE 1

# SELECTED CRETACEOUS GAS FIELDS AND BASIN LOCATION MAP

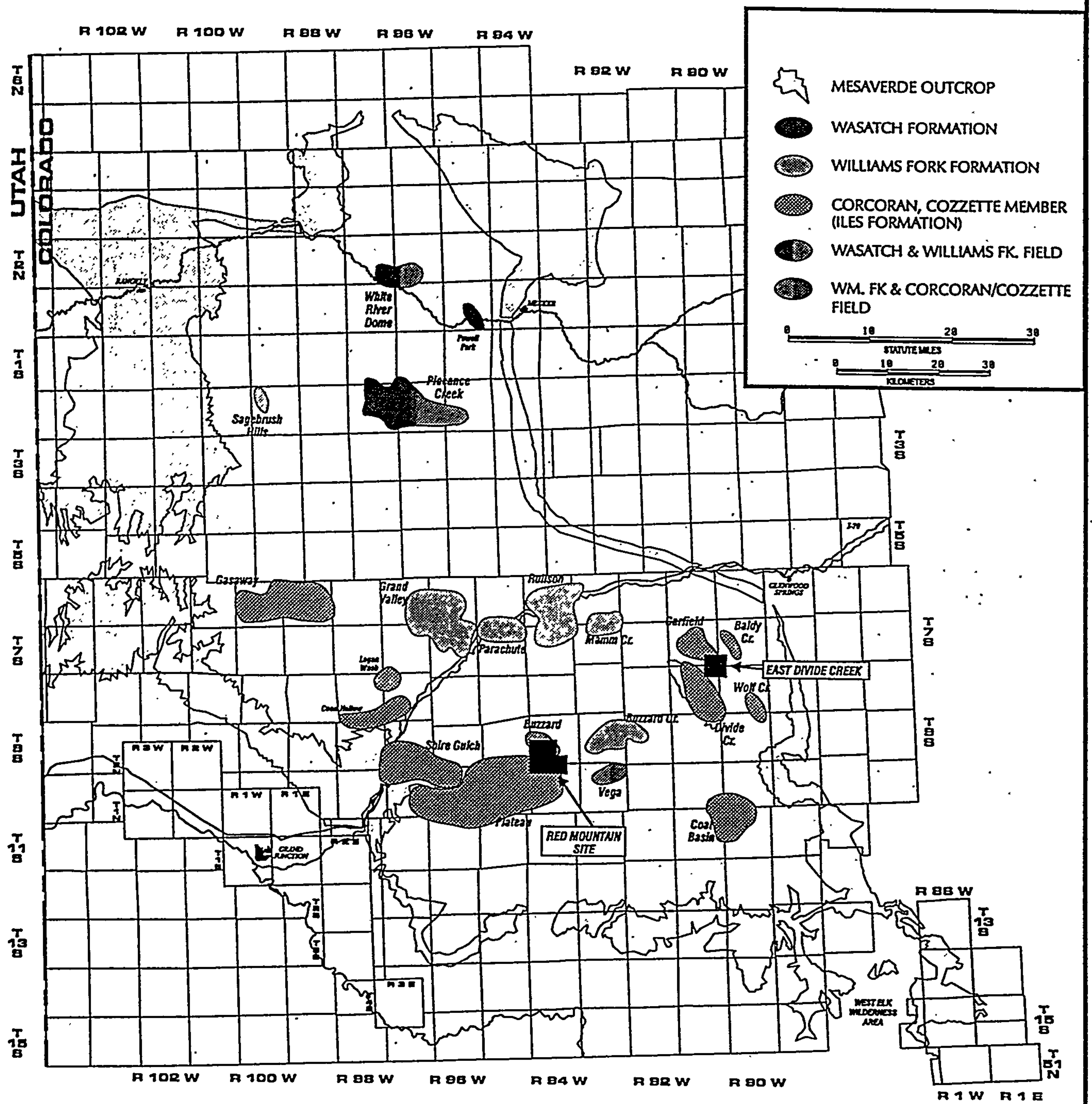
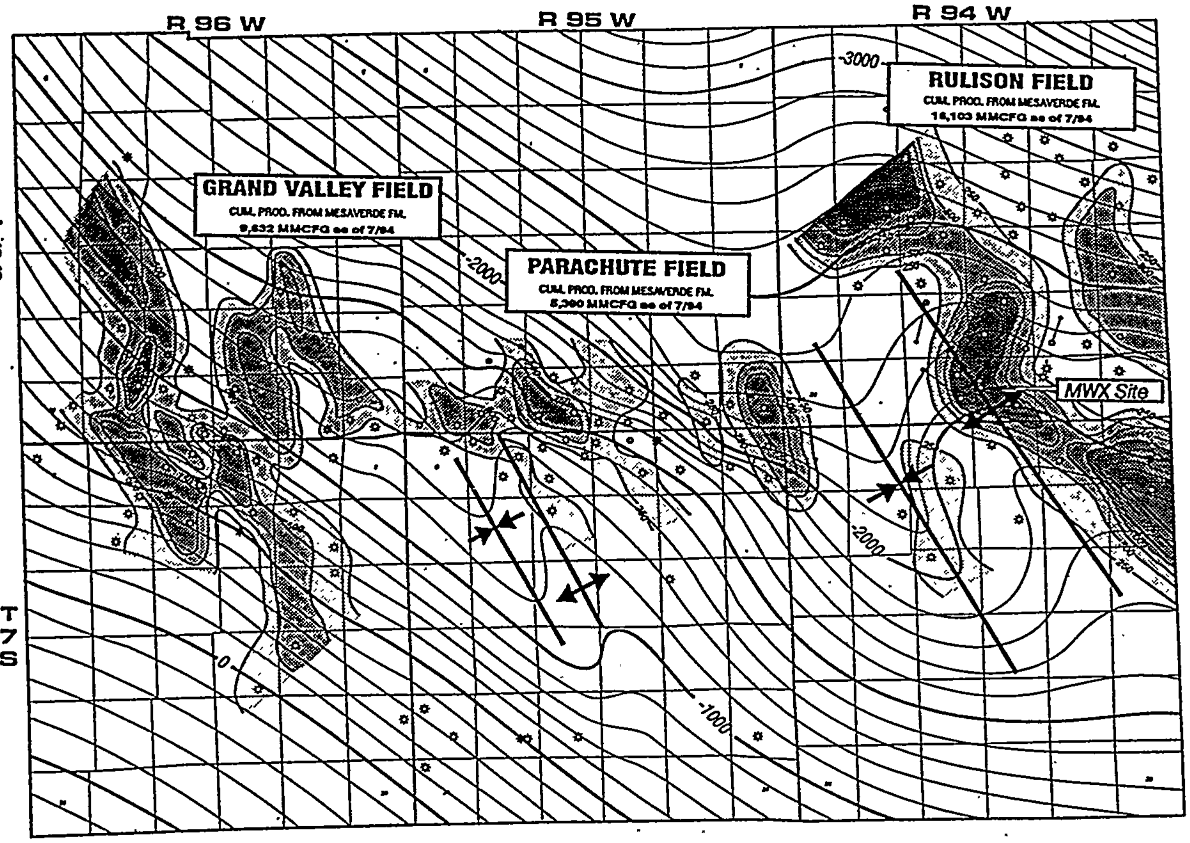
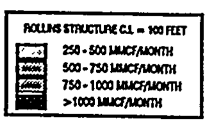


FIGURE 2A

## RELATIONSHIP BETWEEN STRUCTURE AND PRODUCTION
### Grand Valley, Parachute and Rulison Fields, Piceance Basin

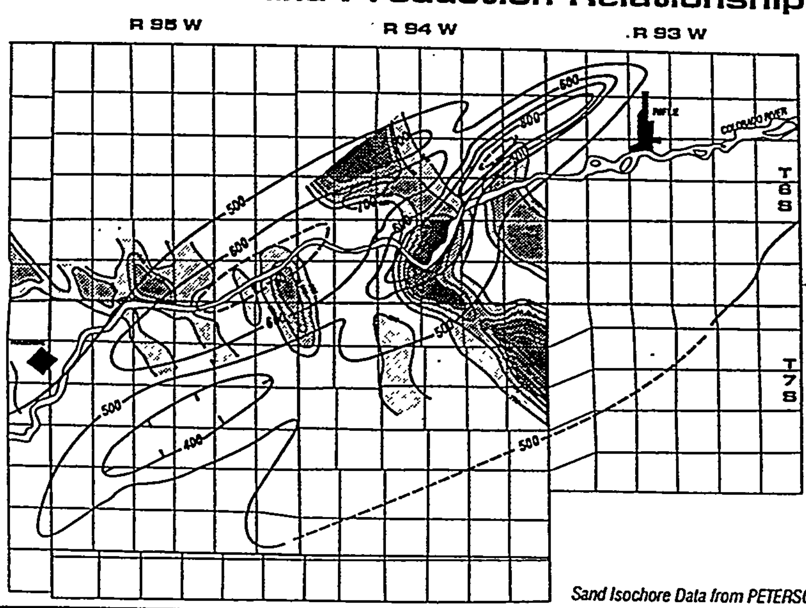



**BEST 6 MONTHS PRODUCTION OF THE MESAVERDE FM**
**(Upper/ Middle Williams Fork and Cameo Sand)**



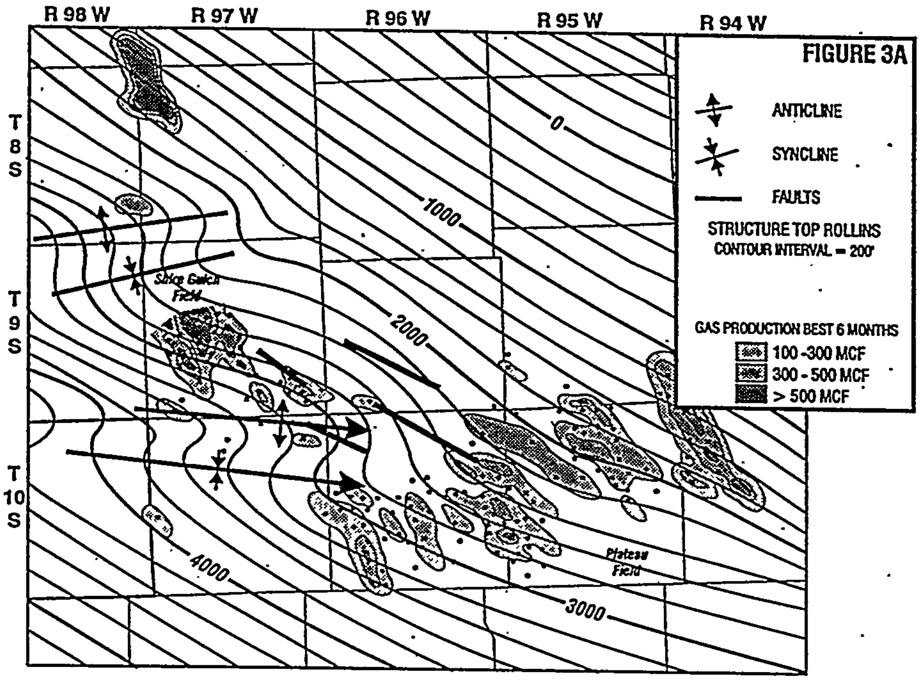

## PARACHUTE - RULISON FIELD
### Sand Isochore and Production Relationship

FIGURE 2B

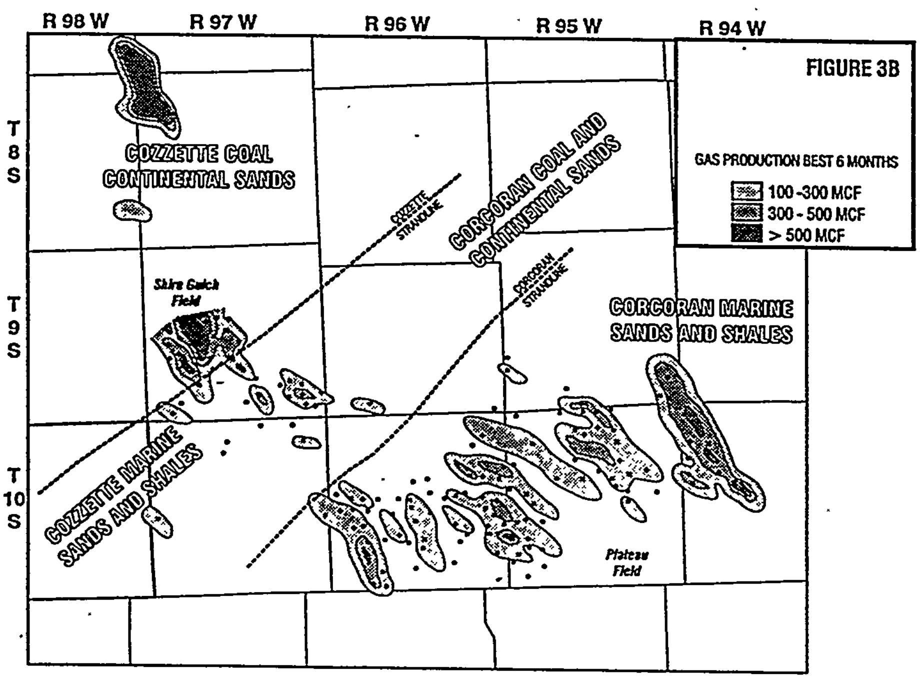



*Sand Isochore Data from PETERSON, 1984*

## PLATEAU - SHIRE GULCH RELATIONSHIP BETWEEN STRUCTURE AND PRODUCTION




## PLATEAU - SHIRE GULCH RELATIONSHIP BETWEEN STRATIGRAPHY AND PRODUCTION



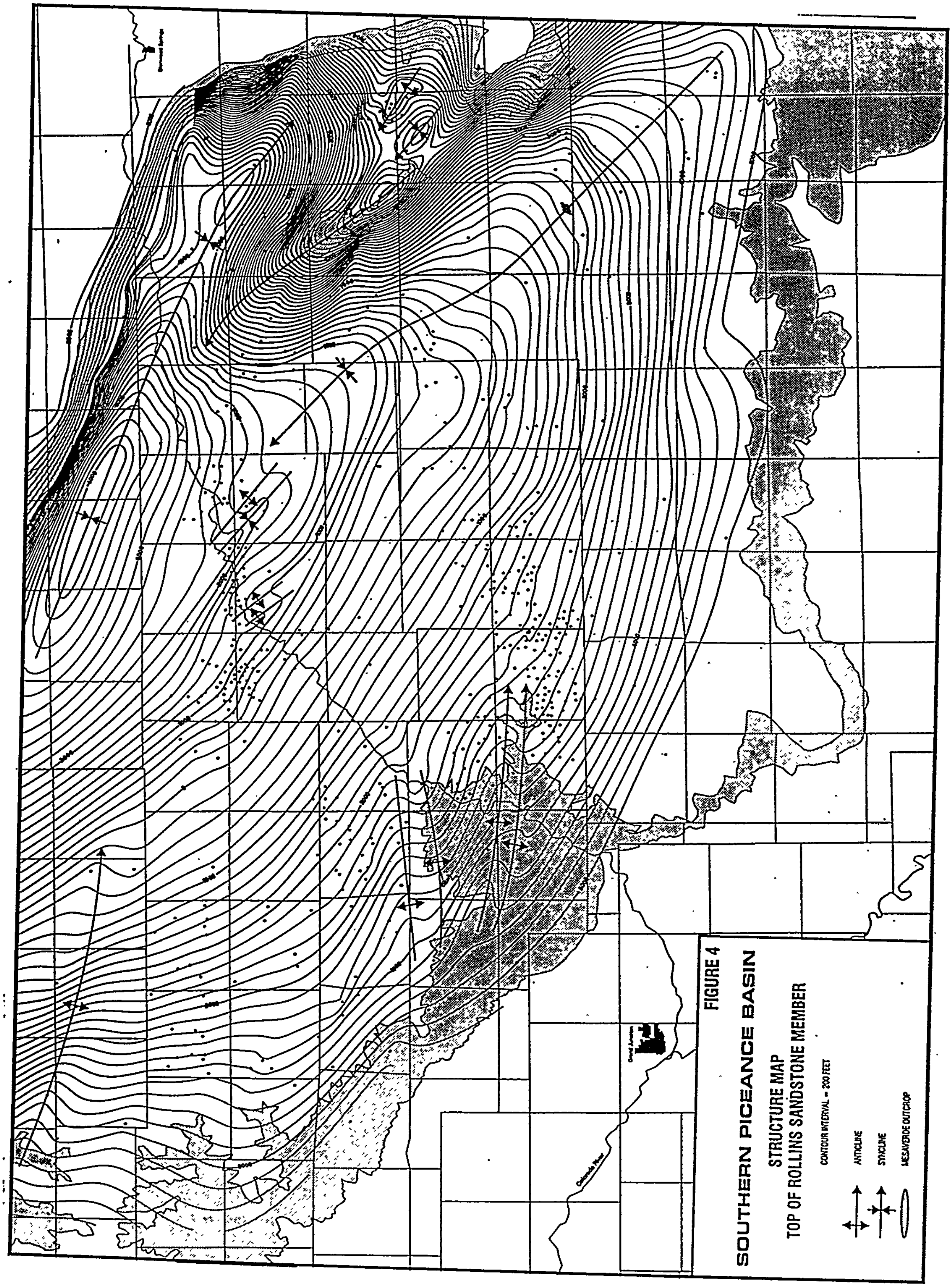
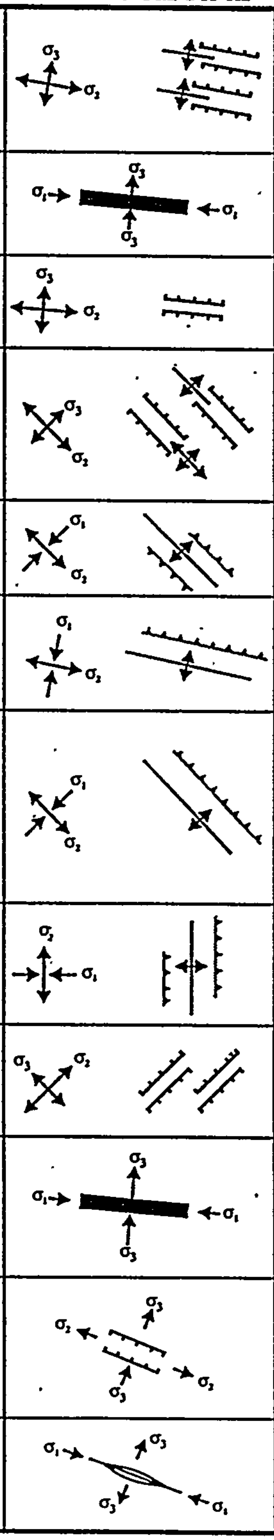


FIGURE 4
SOUTHERN PICEANCE BASIN
STRUCTURE MAP
TOP OF ROLLINS SANDSTONE MEMBER
CONTOUR INTERVAL = 200 FEET
ANTICLINE
SYNCLINE
MESAVERDE OUTCROP
Colorado River

FIGURE 5

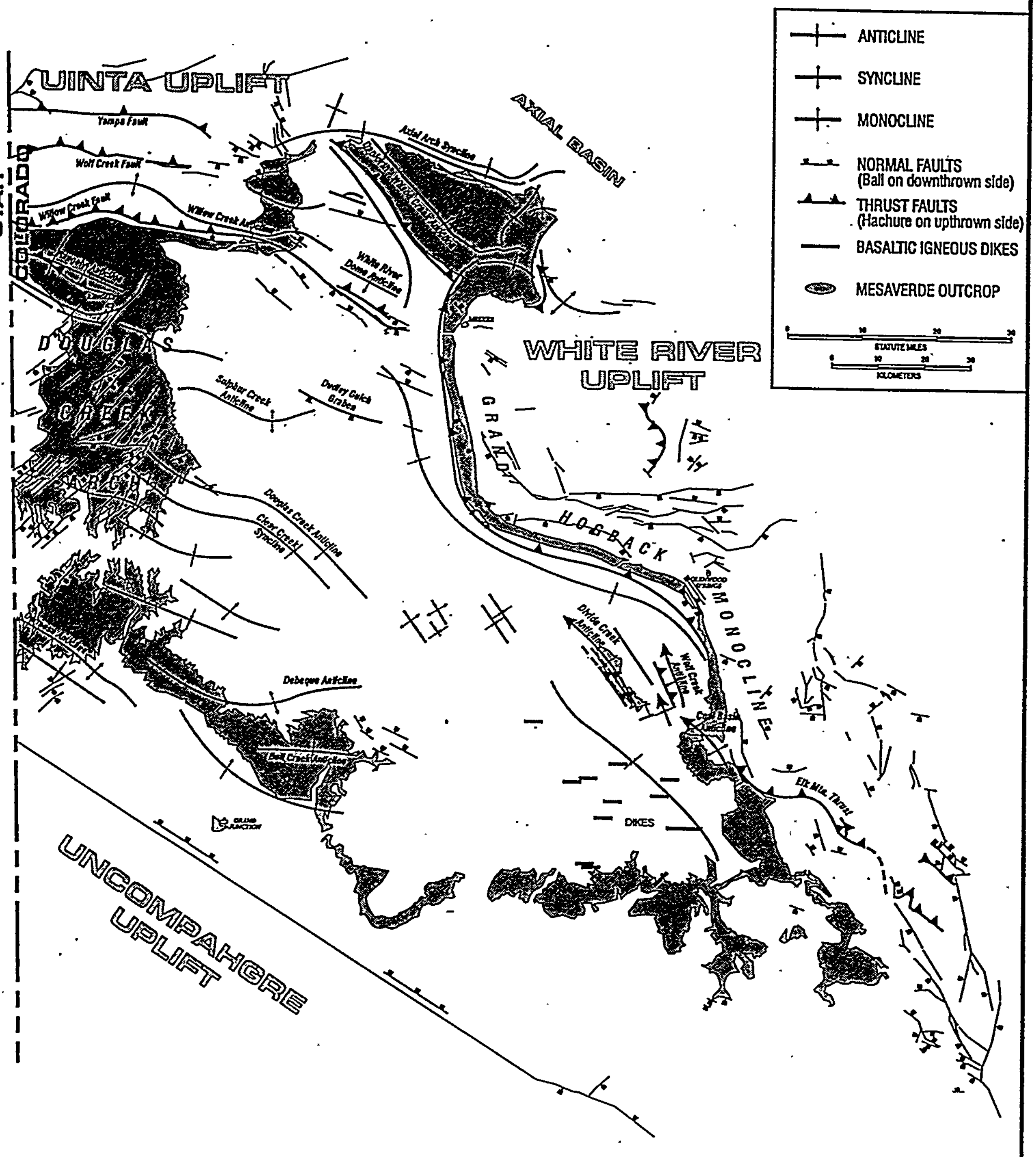
# PICEANCE BASIN TECTONIC EVOLUTION



| M.Y.A. | AGE | STRESS REGIME | STRUCTURES | REFERENCES |
|---|---|---|---|---|
| | PRECAMBRIAN | | Uncompahgre Uplift elements<br>Horsts, grabens, forced folds | Tewksburry, 1989<br>Tweto, 1980<br>Heyman et al., 1986 |
| | CAMBRIAN | | Basaltic dikes along N. Uncompahgre | Tweto et al., (map) 1976 |
| | MISS. | | Block faulting | Landis and Tschauder, 1990 |
| | PENNSYLVANIAN | | Horsts, grabens, forced folds<br>Hogback Paleohorst<br>(Des Moines and Morrowan-age) | De Voto et al., 1986<br>Waechter & Johnson, 1986 |
| | LATE PERMIAN | | Thrust inversion along older horsts<br>(SW Uncompahgre and Eagle Basin) | De Voto et al., 1986<br>Waechter & Johnson, 1986 |
| 65 – 57.8 | LATE CRETACEOUS -PALEOCENE | | Uinta Uplift<br>Rangely Anticline<br>Uncompahgre Uplift<br>White River Dome | Osmond, 1986; Hansen, 1986<br>Richard, 1986<br>Tweto, 1975<br>Quigley, 1965 |
| | EARLY - MID EOCENE | | White River Uplift, Grand Hogback<br>Divide Creek Anticline<br>Elk Mountain Thrust,<br>Wilson Creek Anticline, Axial Arch<br>Mesaverde maximum burial<br>Lake Uinta formed-oil shale deposited | Johnson & Nuccio, 1986<br>Richard, 1986<br>Bryant, 1966<br>Stone, 1986<br>Johnson, 1987 |
| 36.6 | LATE EOCENE EARLY OLIGOCENE | | Douglas Creek Arch<br>Piceance Creek Dome | Osmond, 1986<br>Johnson & Nuccio, 1986<br>Tweto, 1975; Johnson, 1987 |
| 23.7 | MID-LATE OLIGOCENE | | NE-trending faults on Douglas Creek Arch<br>SE basin volcanics commence | Johnson & Finn, 1986 |
| 5.3 | MIOCENE-PLIOCENE | | Basaltic dikes in SE basin<br>10 Ma - Colorado River downcutting and Basin-wide unconformity<br>9.7 Ma - Grand Mesa Basalt | Tweto, Muench & Reed, 1978<br>Osmond, 1986<br>Johnson, 1987 |
| 0.01 | PLIOCENE-PLEISTOCENE | | Dudley Gulch Graben<br>White River Graben<br>Debeque Anticline<br>Bull Creek Anticline | Eckert, 1982<br>Johnson & Nuccio, 1986 |
| | HOLOCENE | | Volcanics in SE basin (4,150 years ago)<br>N 70° W hydraulic fracture stimulations<br>N 50°-70° W breakouts in central basin | Giegengack, 1962<br>Bredehoeft et al., 1976<br>Industry sources |

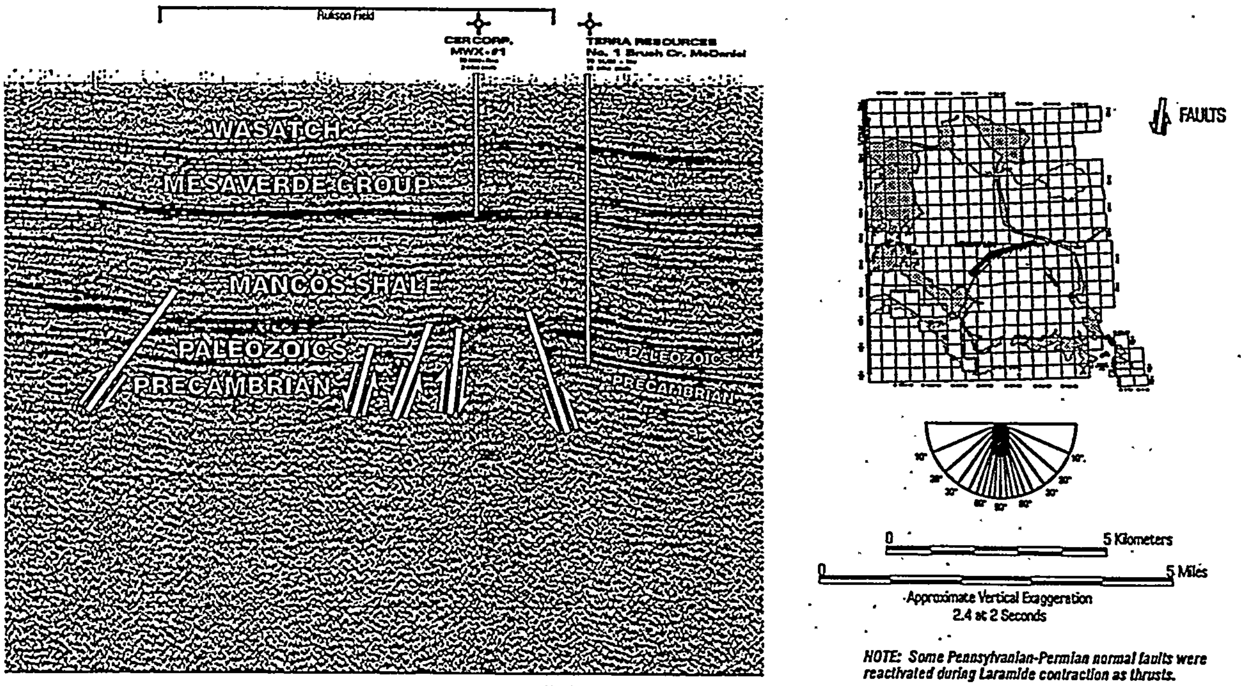
FIGURE 6

# TECTONIC MAP
# PICEANCE BASIN, WESTERN COLORADO



## BASEMENT STRUCTURE BELOW RULISON FIELD

FIGURE 7

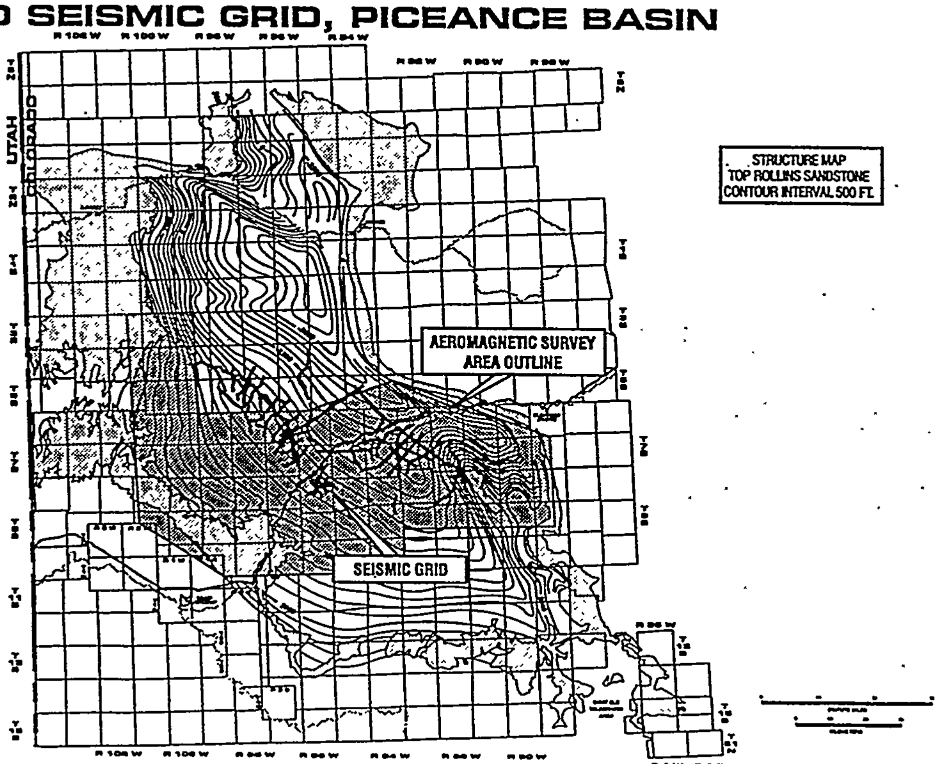



*NOTE: Some Pennsylvanian-Permian normal faults were reactivated during Laramide contraction as thrusts.*

Modified after WAECHTER and JOHNSON, 1985

## AEROMAGNETIC SURVEY AREA AND SEISMIC GRID, PICEANCE BASIN

FIGURE 8



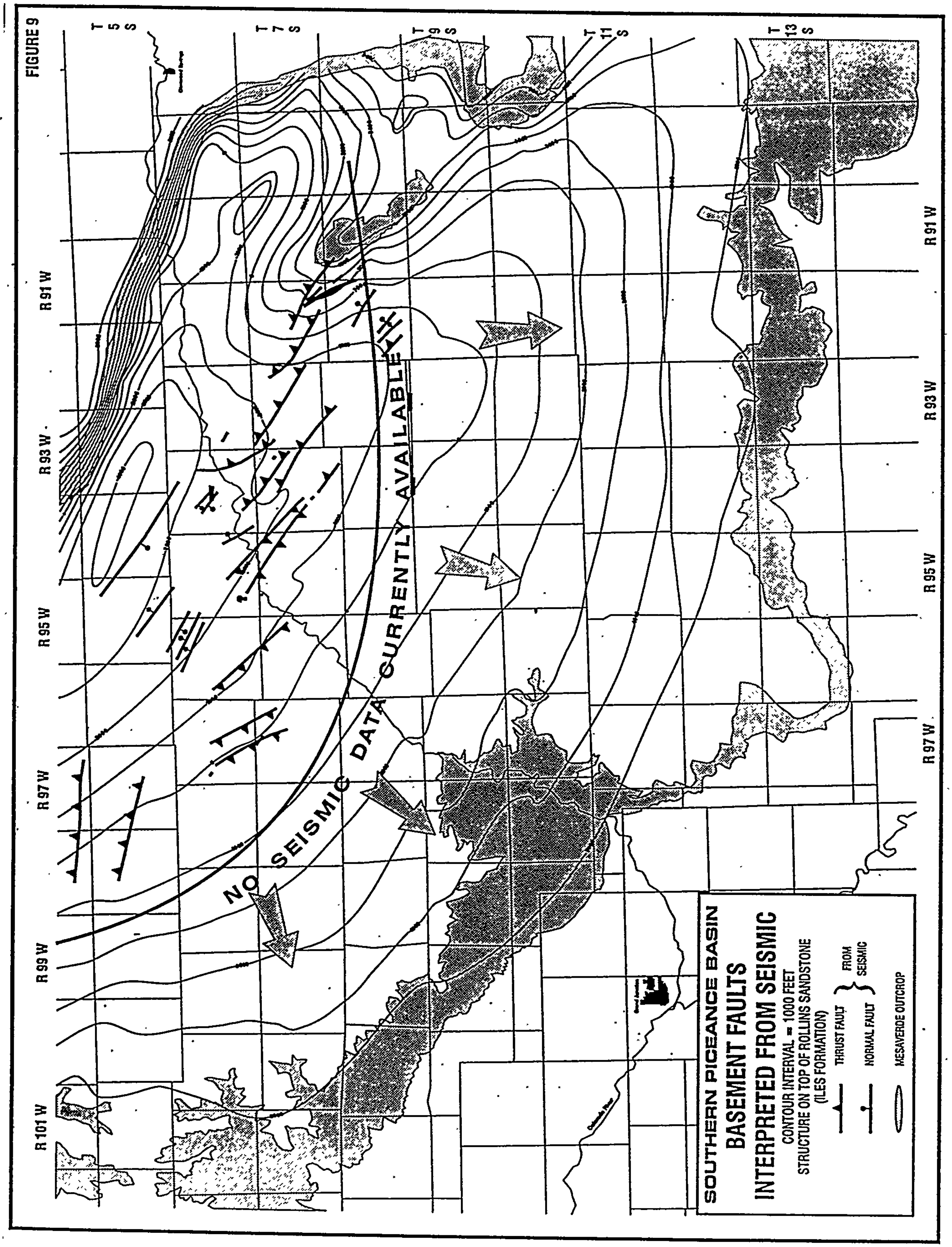

NO SEISMIC DATA CURRENTLY AVAILABLE
R 91 W
R 93 W
R 95 W
R 97 W
R 99 W
R 101 W
T 5 S
T 7 S
T 9 S
T 11 S
T 13 S
SOUTHERN PICEANCE BASIN
BASEMENT FAULTS
INTERPRETED FROM SEISMIC
CONTOUR INTERVAL = 1000 FEET
STRUCTURE ON TOP OF ROLLINS SANDSTONE
(ILES FORMATION)
THRUST FAULT
NORMAL FAULT
FROM SEISMIC
MESAVERDE OUTCROP

FIGURE 9

FIGURE 10

# NURE REGIONAL RESIDUAL MAGNETIC INTENSITY

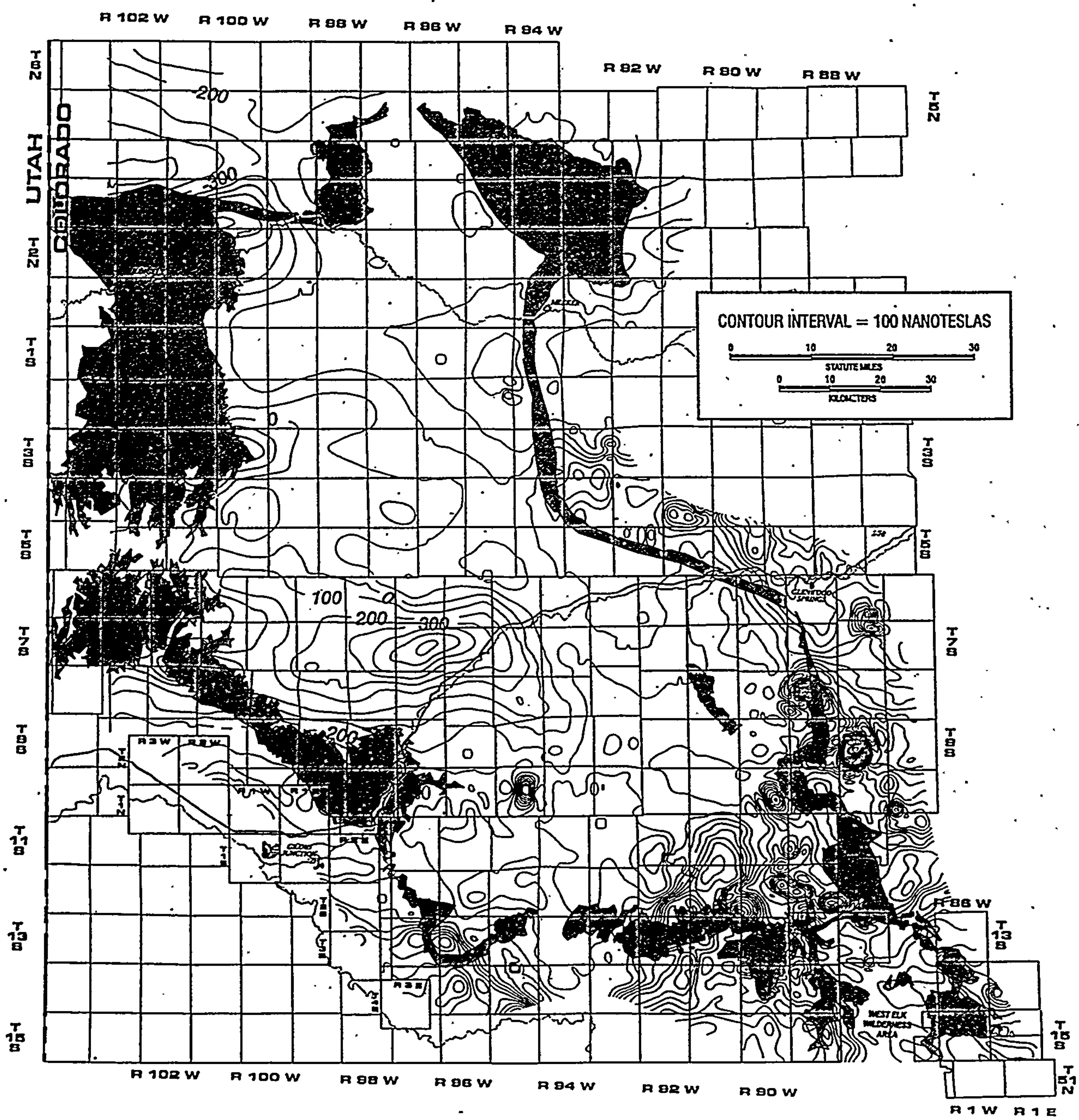
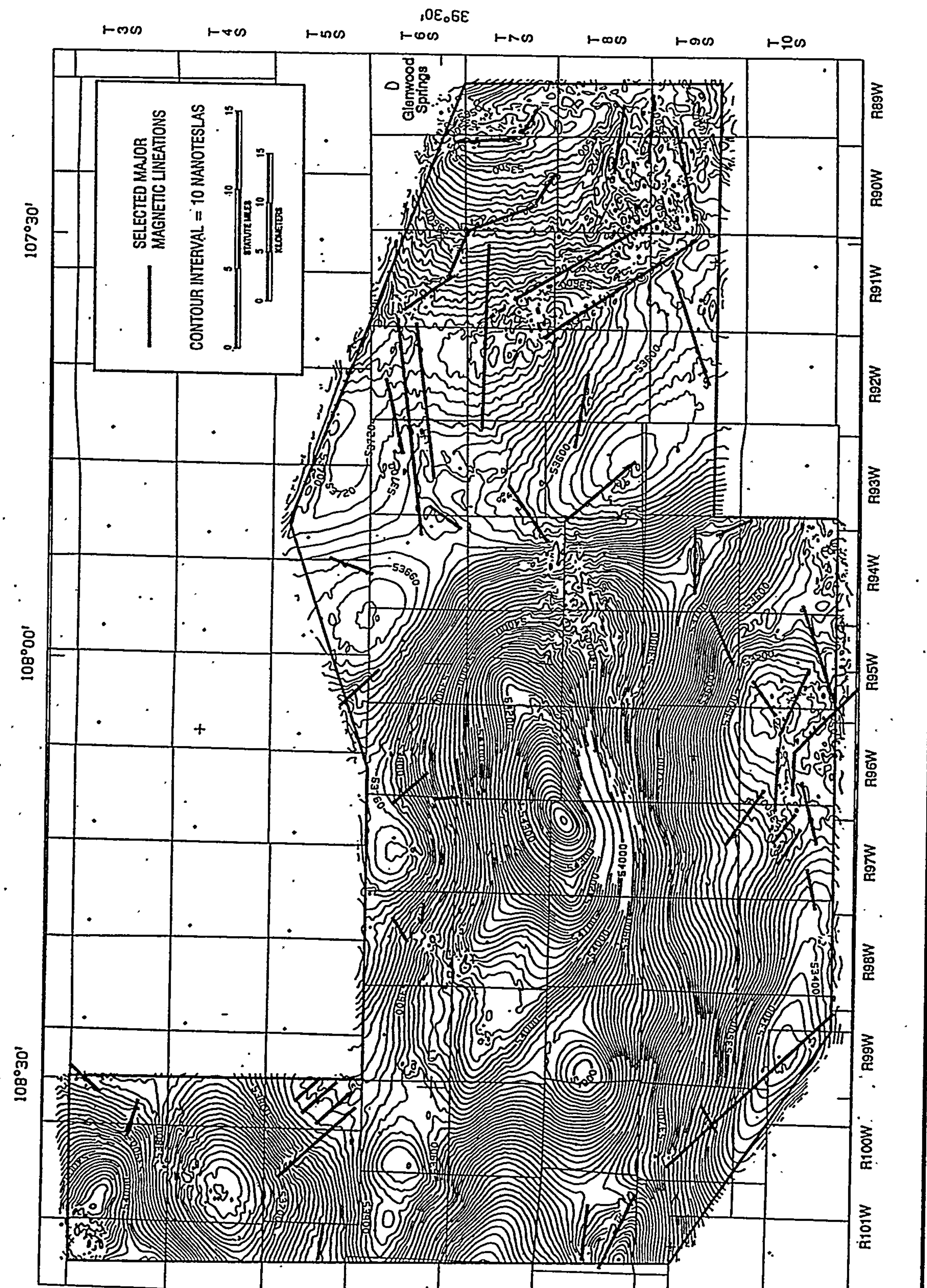


FIGURE 11

REGIONAL HIGH-RESOLUTION TOTAL FIELD MAGNETIC INTENSITY WITH INTERPRETED FEATURES



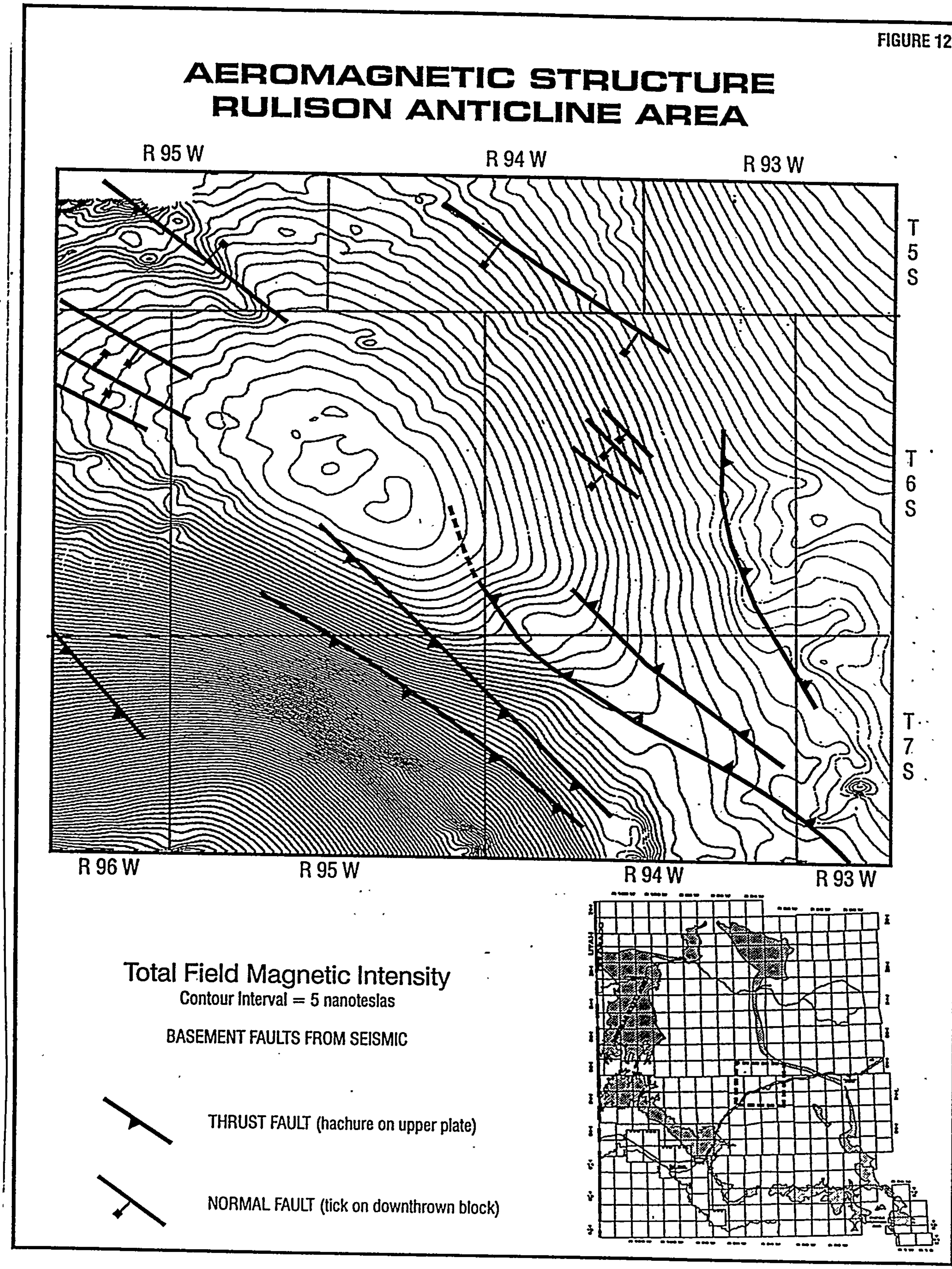
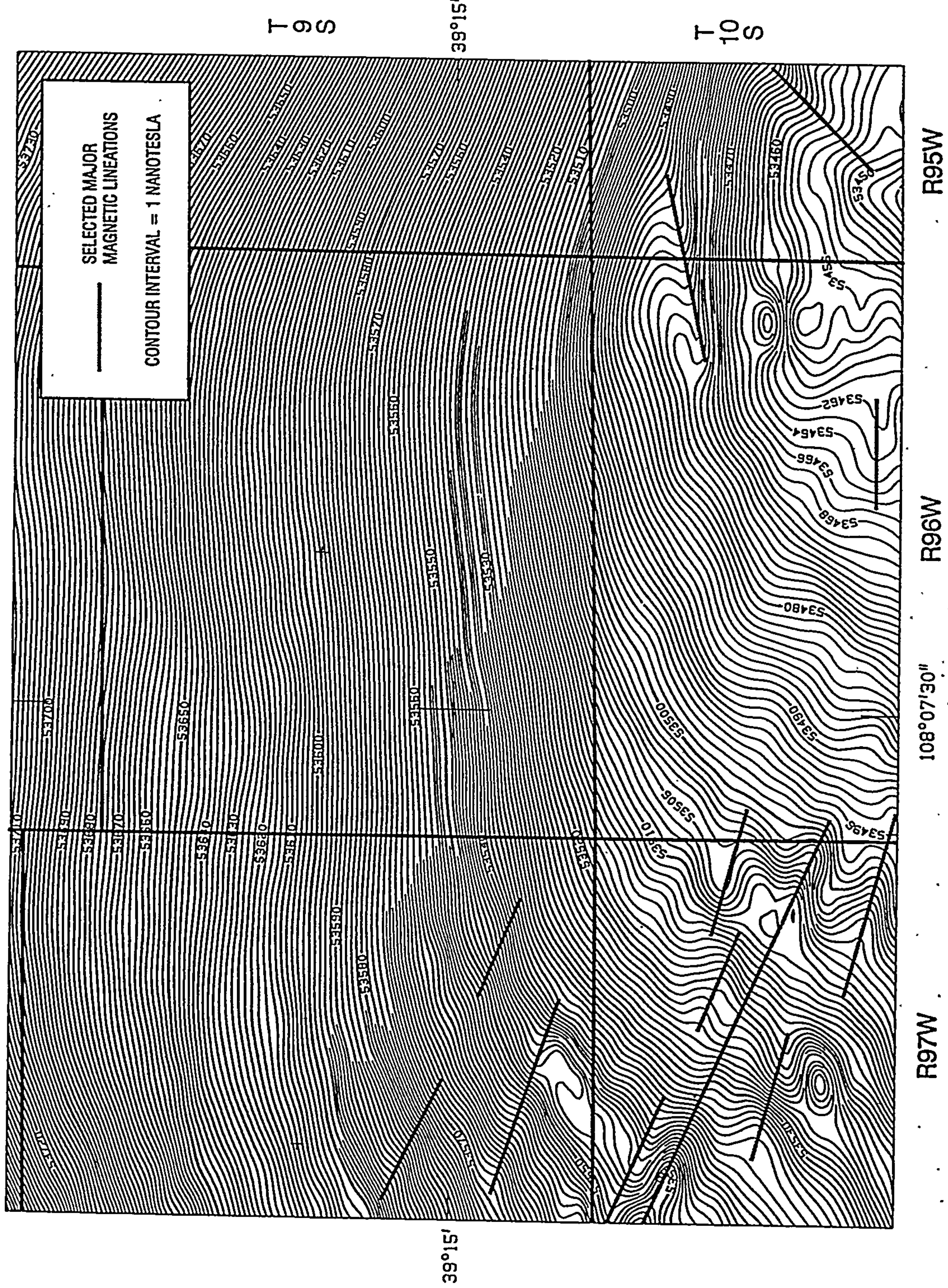


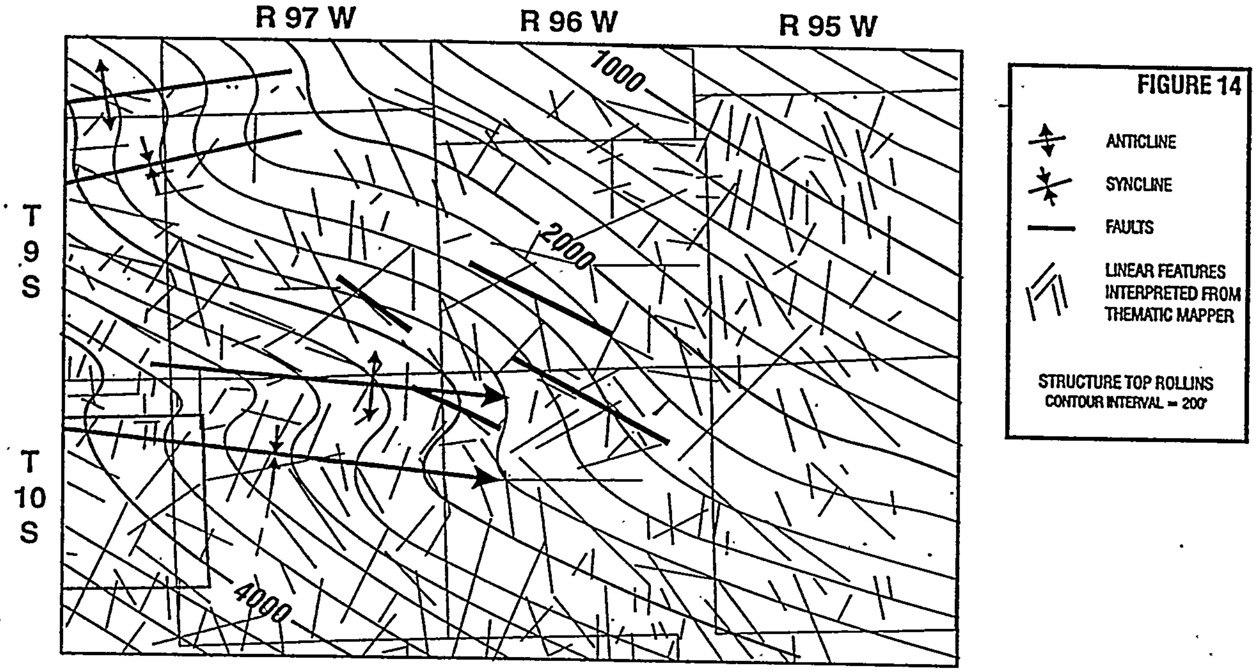
FIGURE 12
AEROMAGNETIC STRUCTURE
RULISON ANTICLINE AREA
R 95 W
R 94 W
R 93 W
T 5 S
T 6 S
T 7 S
R 96 W
R 95 W
R 94 W
R 93 W
Total Field Magnetic Intensity
Contour Interval = 5 nanoteslas
BASEMENT FAULTS FROM SEISMIC
THRUST FAULT (hachure on upper plate)
NORMAL FAULT (tick on downthrown block)

FIGURE 13

HIGH-RESOLUTION REDUCED-TO-POLE MAGNETIC INTENSITY WITH INTERPRETED FEATURES OF PLATEAU-SHIRE GULCH AREA



# PLATEAU - SHIRE GULCH RELATIONSHIP BETWEEN INTERPRETED THEMATIC MAPPER LINEARS AND STRUCTURE




# PLATEAU - SHIRE GULCH RELATIONSHIP BETWEEN INTERPRETED THEMATIC MAPPER LINEARS AND PRODUCTION

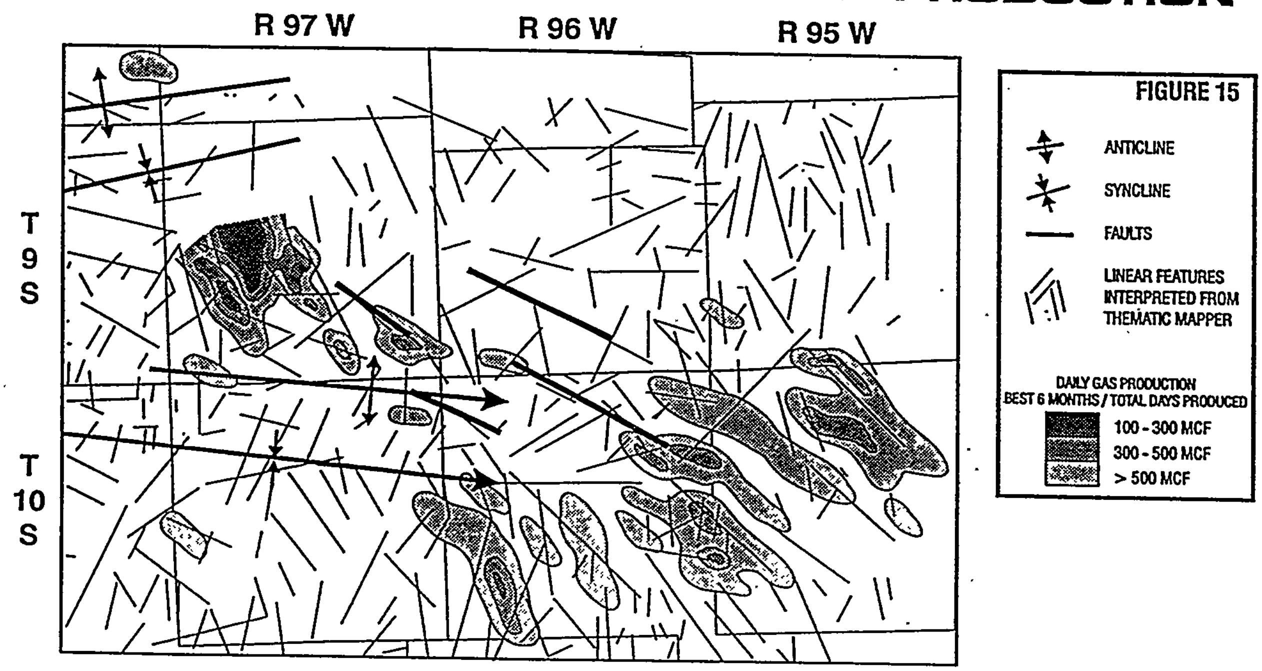
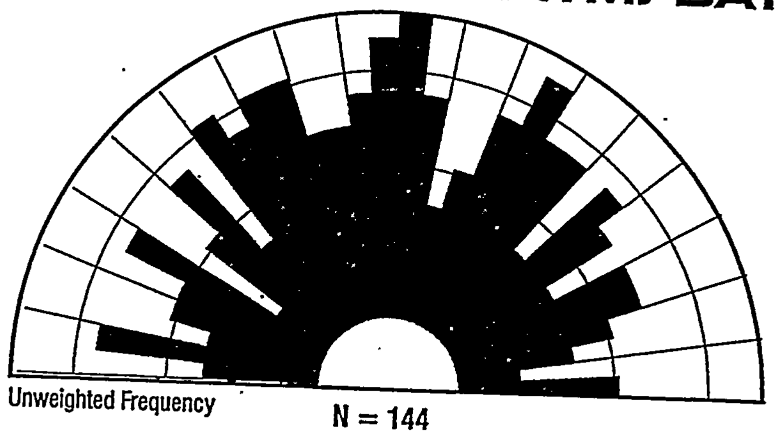
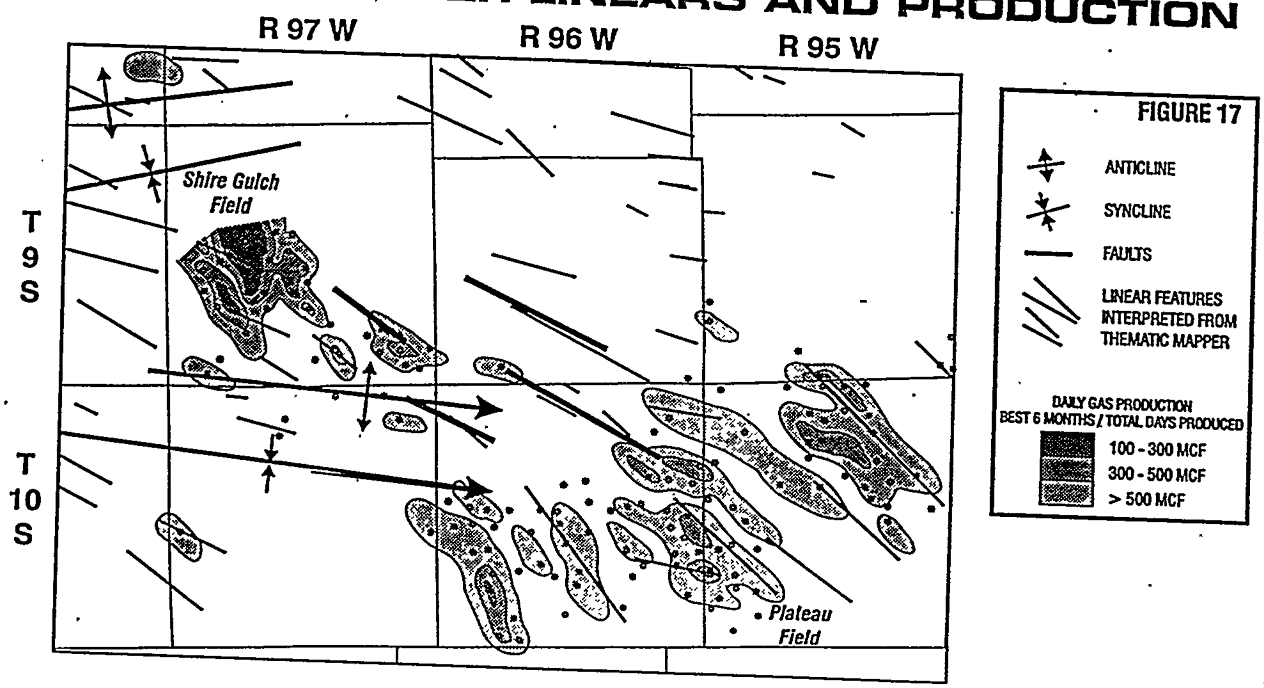


FIGURE 16

# PLATEAU - SHIRE GULCH INTERPRETED LINEAR FEATURES FROM THEMATIC MAPPER (TM) DATA




# PLATEAU - SHIRE GULCH N 90 W - N 45 W INTERPRETED THEMATIC MAPPER LINEARS AND PRODUCTION



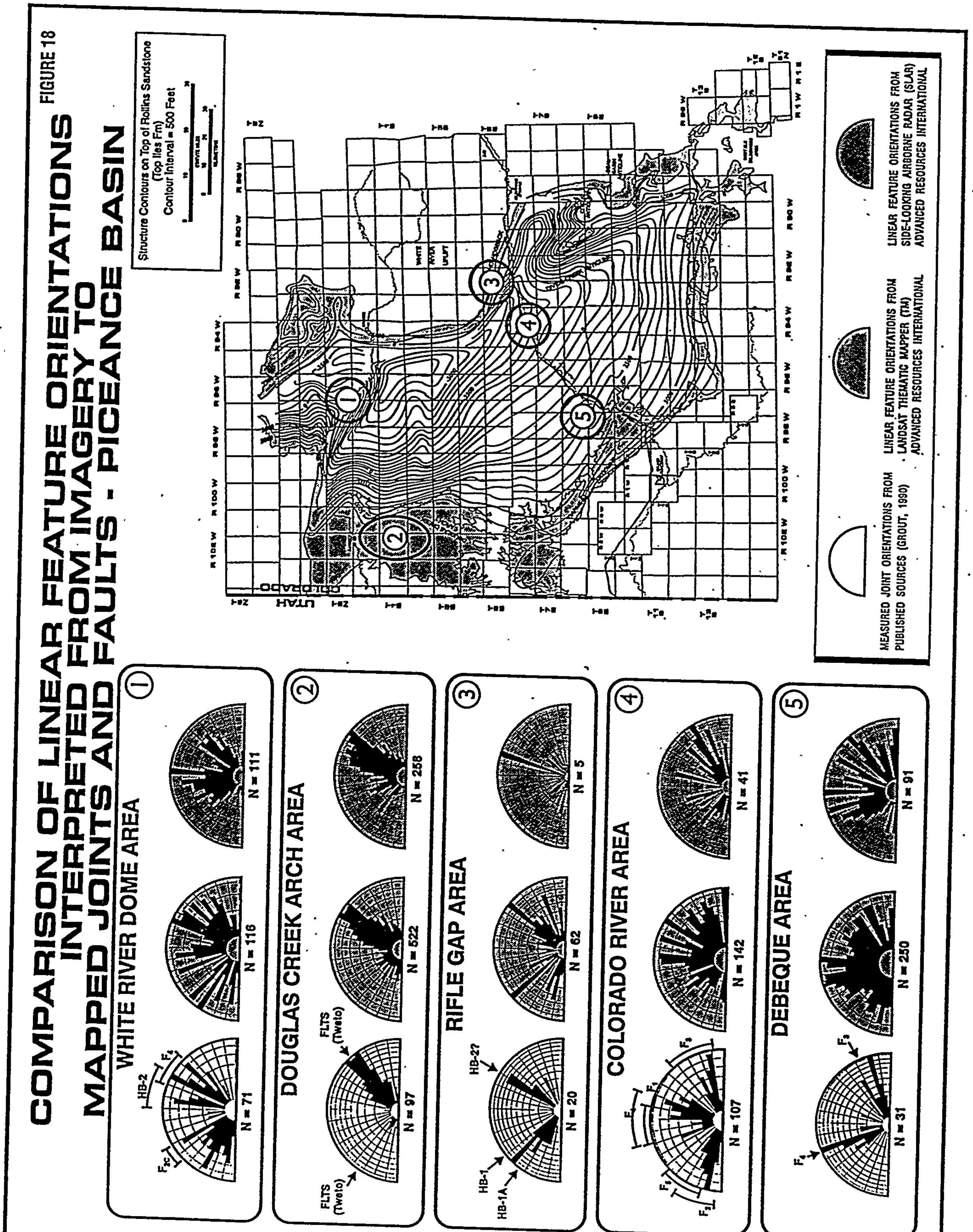


FIGURE 18
COMPARISON OF LINEAR FEATURE ORIENTATIONS
INTERPRETED FROM IMAGERY TO
MAPPED JOINTS AND FAULTS - PICEANCE BASIN
Structure Contours on Top of Rollins Sandstone
(Top Iles Fm)
Contour Interval = 500 Feet
UTAH
COLORADO
1 WHITE RIVER DOME AREA
HB-2
N = 71
N = 116
N = 111
2 DOUGLAS CREEK ARCH AREA
FLTS (Tweto)
N = 97
N = 522
N = 258
3 RIFLE GAP AREA
HB-22
HB-1
HB-1A
N = 20
N = 62
N = 5
4 COLORADO RIVER AREA
N = 107
N = 142
N = 41
5 DEBEQUE AREA
N = 31
N = 250
N = 91
MEASURED JOINT ORIENTATIONS FROM
PUBLISHED SOURCES (GROUT, 1990)
LINEAR FEATURE ORIENTATIONS FROM
LANDSAT THEMATIC MAPPER (TM)
ADVANCED RESOURCES INTERNATIONAL
LINEAR FEATURE ORIENTATIONS FROM
SIDE-LOOKING AIRBORNE RADAR (SLAR)
ADVANCED RESOURCES INTERNATIONAL

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# Gas and Water-Saturated Conditions in the Piceance Basin, Western Colorado: Implications for Fractured Reservoir Detection in a Gas-Centered Coal Basin

*Thomas E. Hoak and A. David Decker,*
*Advanced Resources International, Inc.*

## ABSTRACT

Mesaverde Group reservoirs in the Piceance Basin, Western Colorado contain a large reservoir base. Attempts to exploit this resource base are stymied by low permeability reservoir conditions. The presence of abundant natural fracture systems throughout this basin, however, does permit economic production. Substantial production is associated with fractured reservoirs in Divide Creek, Piceance Creek, Wolf Creek, White River Dome, Plateau, Shire Gulch, Grand Valley, Parachute and Rulison fields. Successful Piceance Basin gas production requires detailed information about fracture networks and subsurface gas and water distribution in an overall gas-centered basin geometry. Assessment of these three parameters requires an integrated basin analysis incorporating conventional subsurface geology, seismic data, remote sensing imagery analysis, and an analysis of regional tectonics.

To delineate the gas-centered basin geometry in the Piceance Basin, a regional cross-section spanning the basin was constructed using hydrocarbon and gamma radiation logs. The resultant hybrid logs were used for stratigraphic correlations in addition to outlining the trans-basin gas-saturated conditions. Mud weight, DST and bottomhole pressure data show that the present-day overpressured zone in the basin is concentrated within Williams Fork fluvial sandstones overlying the Cameo Coal section. The basin overpressured zone corresponds to the area where the maximum vitrinite reflectance is greater than 0.9. In this same area, the marine Iles Formation sandstones (Rollins, Cozzette and Corcoran) also exhibit overpressured conditions although the magnitude of the overpressure is less than in the overlying fluvial and paludal sections. The magnitude of both pressure gradients (paludal and marine intervals) is greater than can be generated by a hydrodynamic model.

To extend cross-sectional observations laterally into the third dimension, gas and water production data were used to evaluate gas and water-saturated areas throughout the basin. Several structurally positive areas (Divide Creek Anticline, Bull Creek Anticline) are breached to meteoric influx and are water-saturated. The Corcoran and Cozzette are largely gas-saturated, however, breached conditions are locally present for the Corcoran in the western basin. The Cozzette Member shows complex water-gas saturated conditions in the transitional area between the water-saturated eastern basin and gas producing horizons in the western region.

To investigate the relationships between structure and production, detailed mapping of the basin (top of the Iles Formation) was used to define subtle subsurface structures that control fractured reservoir development. The most productive fields in the basin possess fractured reservoirs. Detailed studies in the Grand Valley-Parachute-Rulison and Shire Gulch-Plateau fields indicate that zones of maximum structural flexure on kilometer-scale structural features are directly related to areas of enhanced production. These smaller structures, common throughout the basin, represent excellent targets for additional field development because most larger structures in the basin have been extensively drilled.

## INTRODUCTION

The following paper describes part of a multi-year fracture detection program calibrated using the Piceance Basin (see Figure 1 for location map) sponsored by the Department of Energy. Initial efforts have identified gas and water-saturated intervals in the Piceance Basin and the relationship between basement structure and production from fractured tight gas reservoirs. The fracture detection program is an integrated study involving detailed geologic characterization of the basin. To geologically characterize the basin, remote sensing imagery analysis, 2D seismic interpretation and newly-acquired, high-resolution, aeromagnetic data have been synthesized with a detailed tectonic/structural analysis to identify zones of enhanced fracturing. Production analyses of the larger gas fields in the basin have been performed to document the presence of fractured reservoir conditions. A parallel effort to numerically model the fracture genesis of the basin is being conducted at Indiana University by Dr. Peter Ortoleva using a self-consistent, reaction-transport forward model. In this model, an initial protolith is progressively varied using mathematically-consistent reaction equations to generate the final geologic characteristics observed in the basin. The results from these two efforts will be used to identify areas predicted to be contain fractured zones. In these areas, a 3D multi-component survey will be acquired, processed, and interpreted to more fully characerize subsurface fracture geometries in advanced of drilling. Barrett Resources will drill or recomplete several wells to verify the results of the 3D survey, the geologic predictions and the predictions of the numerical model.

This paper delineates the location of gas and water-saturated areas in order to establish the geometry of the gas saturated zone and the controls on production throughout the basin. The geometry of the gas and water-saturated areas is critical because it permits operators to avoid water-prone fractured areas and also provides insight into the basin hydrodynamics and the relationship between hydrodynamics and production. Knowledge of gas-saturated areas permits operators to develop exploration strategies to maximize production from these areas and restrict their prospect generation efforts to areas most likely to contain gas. A more complete integration of production, remote sensing, aeromagnetic, seismic and regional tectonic syntheses is provided in a companion paper (Hoak and Klawitter, this volume).

## BASIN OVERVIEW

The Piceance Basin is an elongate, NNW-trending structurally-downwarped region that formed as a result of Laramide contractional tectonics (See Figure 2 for basin structure map). The northern boundary of the basin is defined by the thrust-cored structures of the Axial Arch and the Uinta Uplift. The sinuous eastern margin is formed by the "S"-shaped thrust-cored, Grand Hogback Anticline lying along the flank of the White River Uplift. The western boundary, formed by the Douglas Creek Arch, separates the Uinta Basin from the Piceance basin. The southwestern boundary is formed by the Uncompahgre Uplift. The southern boundary is formed by the Gunnison Uplift and the West Elk Mountains in the southeast basin. All of these uplifts have experienced multiple phases of tectonic deformation ranging from Precambrian tectonism through Pennsylvanian-Permian deformation, culminating in the Laramide thrusting that defines the present-day basin geometry.

Three dominant regional structural trends persist throughout the basin. In the eastern basin, the NW-trending Divide Creek, Wolf Creek and Coal Basin anticlines have been formed by WSW-directed thrusting. In the western basin, several broad, low amplitude anticlines have formed with dominant E/W trends. These anticlines include the Debeque, Unnamed (here designated Bull Creek Anticline, located to the south of the Debeque anticline in Plateau Field) and the Douglas Creek Anticline. The latter anticline has a WNW trend. The northern boundary of the basin, the Axial Arch, is a WNW-trending fault-bend fold formed during south-directed Laramide thrusting (Stone, 1986). The last significant trend is the N/S trend typified by the sections of the Hogback between Meeker and Rio Blanco, and from Carbondale to the Elk Mountains.

The Cretaceous-age Mesaverde Group stratigraphy is pervasively gas-saturated and is overlain by the tremendous oil shale reserves of the Green River Formation. The focus of this report is the gas found within the Cretaceous-age Mesaverde Group (Williams Fork Formation) coals and interbedded sandstones. Additional significant gas resources are found within underlying marine sandstones of the Cretaceous-age Iles Formation, and within overlying fluvial sandstones in both the upper Williams Fork Formation, and the Tertiary-age Wasatch Formation (see Figure 1 for gas fields and producing horizons). The largest hydrocarbon resource (>13 trillion barrels, Taylor, 1987) is found within the lacustrine, Tertiary-age Green River Formation oil shale that overlies the northern half of the basin. Oil shale production from the Green River shales has gone through several periods of evaluation to develop extraction methods that can economically produce oil in an environmentally acceptable manner. The oil shale deposits, coupled with the gas resources hosted by Cretaceous-age sediments, represent one of the world's largest hydrocarbon accumulations.

## GAS- AND WATER-SATURATED CONDITIONS IN THE PICEANCE BASIN

A critical first step during basin exploration is to locate gas-bearing zones in the subsurface. Further partitioning of the exploration area can then be performed using integrated studies of remote sensing, high-resolution aeromagnetics, seismic, and structural geology to locate fractured reservoirs. To analyze the location of gas-bearing zones, water and gas data were assembled from initial production, and monthly and cumulative production data collected throughout the Piceance Basin. Production data were then used to delineate the areal distribution of the gas and water-saturated zones. A cross-section was constructed using gas volumes from mud logs to illustrate cross-sectional basin hydrodynamics. Recognition of subsurface fracture-related permeability caused by tectonic structures is a more complex problem. To determine zones or orientations of enhanced subsurface permeability, remote sensing imagery analysis was used to constrain regional macrostructures and related fracture trends. The results of this analysis are reported in a companion paper (see Hoak and Klawitter, this volume).

The following discussion of gas-and-water saturation is organized into two sections. The first section outlines the characteristics of typical gas-centered basins and then assesses water and gas-saturated conditions throughout the Piceance Basin. The second section outlines the relationship between subsurface structure and production.

### Basin-Centered Gas Model

Numerous models relating basin subsidence and hydrocarbon generation and retention have been proposed by such authors as Barry (1959) and Meissner (1978). Recently, Law and Dickinson (1985) have further extended this model and described the process by which thermal influences result in abnormal pressure in low-permeability systems. The central idea of this model is the dynamic relationship between thermal maturity, permeability changes and burial depth. In this model, there are four primary phases (Figure 3). The generation and existence of overpressured conditions is a key piece of data to be used in regional fracture studies. By knowing the timing of overpressure generation and the mechanical state of the host rock mass, the geometry of natural fractures that formed during this phase can be much more accurately predicted. Available data from the Piceance and other basins suggest that overpressuring may initiate and/or facilitate regional natural fracture development in many tight gas sand reservoirs (Lorenz et al., 1991).

In the gas-centered basin model of Law and Dickinson (1985), the first phase involves sediment deposition and basin dewatering. During this phase, sediments show high porosity (up to 40%) and elevated permeability. Throughout this initial phase, porosity is reduced by compaction and precipitation of early pore-filling cement, and the sediment mass experiences an increase in Young's modulus (a measure of rock stiffness).

The second phase is characterized by thermally-induced carbon dioxide generation commencing at a temperature of approximately $120^0$ F. Carbon dioxide produced during this phase reacts with existing water to form carbonic acid. The net effect is a lowering of the pH of the formation fluids that dissolves some of the early cement phases and causes the precipitation of other cements. The increase in carbon dioxide also serves to increase the overall fluid or gas pressure in the system.

The third phase commences when organic materials within the host sediments commence gas generation. During this phase, cementation causes a reduction in permeability and porosity because water mobility and mixing are reduced. Mechanical compaction is considered minimal at this stage. Water is forced up dip and/or up section when gas pressure exceeds the local hydrostatic value and more gas is generated than can be stored in the available pore space. The fluid migration direction is dependent on local pressure gradients.

In theory, provided sufficient quantities of organic materials, gas generation should continue as long as thermal cracking can occur. However, because of uplift and declining thermal gradients, combined with fracturing and concomitant leakoff, the overpressured zone generally cannot be sustained. As the overpressured zone experiences decay (a gradual decline in gas pressure due to cessation of gas generation combined with regional uplift), meteoric recharge is able to breach the reservoir and flush hydrocarbons from the system. This phase represents the present-day conditions in most gas basins that had a gas-centered origin. Thick, thermally mature coals interbedded within lenticular sand bodies are a common feature in many gas-centered basins. This geometry is also found in the Piceance Basin where the isolated hydrodynamics of lenticular sandstone reservoirs maintain unbreached and overpressured conditions.

### Piceance Basin Gas Genesis

In order to assess the present state of gas generation in the basin and the location of areas possessing sufficient thermal maturity for gas generation, thermal modeling using vitrinite reflectance data from Piceance Basin coals was used to construct the chronology of thermal maturation in the basin (Decker and Horner, 1987). The model used in this analysis was a fourteen layer model using appropriate layer thermal conductivity values to better reflect the thermal stratification and evolution of the system. A representative example of vitrinite reflectance profiles (thermal history plot) from the Red Mountain and East Divide Creek sites (see Figure 1 for location) are shown in Figure 4. These curves show that active gas generation (defined as the point at which the coals passed through a vitrinite reflectance value of 0.75) at all three sites commenced nearly simultaneously approximately 52 million years ago, suggesting a rapid and uniform subsidence of the central and eastern basin. These curves also indicate that the central and eastern Piceance Basin reached maximum thermal maturity and gas generation ceased approximately 22 million years ago when regional uplift occurred and thermal maturation ceased.

Vitrinite reflectance and basin thermal modeling also provide a mechanism to calibrate significant events during basin evolution such as fracture genesis and uplift chronology. Previous efforts to determine a fracture chronology have largely relied on relative age determination based on crosscutting relationships. Through the use of vitrinite reflectance and thermal modeling, we have a framework for assigning an absolute age to basin events. A typical burial history from the MWX location is shown in Figure 5. A basinwide distribution of thermal maturity values (Figure 6) shows that the majority of the basin center experienced a thermal maturity of 0.8 $R_o$ or larger and entered the gas generation window at approximately 0.75 $R_o$.

The geometry of the overpressured zone was delineated using calibrated mud weight information. Maximum mud weights during drilling in excess of 11.0 lbs./gallon were used to delineate the boundaries of the overpressured zone. This information is shown on Figure 6 as a shaded area. Several localities show mud weights in excess of 11.0 lbs/gallon, however, careful review of drilling records showed that heavier mud weights were used for hole stability problems, not to control overpressured conditions. Inside the overpressured area, several wells have been drilled under balance. Mud weights from these wells were disregarded in construction of the overpressured boundary. Extrapolation of the boundary along the basin axis to the northwest is precluded by the lack of drilling activity on the high mesas in that area. Complete definition of the overpressured zone requires data collection in this area.

### Cross-Sectional Gas and Water-Saturation, and Overpressured Conditions

A critical element in the gas-centered basin model is the thermal generation of gas and maintenance of overpressure due to low permeability reservoir conditions. In the Piceance Basin, the overpressured zone (as determined by drilling mud weights and calibrated against known bottomhole pressure data) has been identified in the lower section of the Williams Fork Formation within the Rulison Field. In this field, the top of the overpressured zone lies just above the Cameo Coal, and appears to have a gradational lower boundary along the top of the laterally continuous marine Rollins sandstone of the Iles Formation. Decayed or remnant overpressure is also present in the Cozzette and Corcoran sandstones, separated from the overlying Rollins sandstone by a tongue of the Mancos "A" shale in Rulison Field. It is difficult to determine from available data if the Rollins sandstone is also overpressured. The limited tests that have been performed on the Rollins suggest that it is gas-bearing but that it tends to also be water-saturated. The regional persistence of this relationship is known only anecdotally. Figure 7 illustrates the gas-centered basin geometry across the Piceance Basin. The geometry of this zone roughly parallels the vitrinite reflectance isotherm of 0.8 along the western boundary and the basin outcrop to the east.

This cross-section or basin profile was created from the digitized total gas curve from hydrocarbon logs, and wireline log gamma log traces from the same well. The combined gas and gamma log traces for these wells were hung on a structural datum (Top Mesaverde or Cretaceous/Tertiary boundary) to illustrate the basin geometry. Relevant information such as the location of the overpressured zone, stratigraphic correlations, and vitrinite reflectance values (isotherms) were added to the section. From this cross-section, lateral and vertical water/gas transitions are located in the basin. The east/west cross-section defines the overpressured zone as being restricted to Rulison field and approximately one-half township to the east. Parachute field is normally pressured except along the transitional eastern field margin where it grades into Rulison field. From hydrocarbon log traces, the lower Williams Fork Formation appears gas-saturated across the basin interior. The discontinuous, lensoidal geometry of the Williams Fork, combined with its low matrix permeability, requires natural fractures for economic gas recovery. The importance of fracture detection is to identify areas capable of economic production from this reservoir horizon. In sharp contrast to the Williams Fork lensoidal stratal geometries, the marine Iles Formation sandstones (lying underneath the Williams Fork Formation) are laterally continuous. However, the low-permeability conditions in these sands also require fracture permeability for economic gas yields.

In cross-section, the Cozzette and Corcoran Member sandstones in the Iles Formation appear to be gas-saturated across the basin and were probably once overpressured in the basin center. The Cozzette member sandstones are water-saturated along the eastern basin margin. The Rollins member sandstone is water-saturated across the basin except for scattered localities along the western basin margin where isolated tests have shown it to be dry and gas-bearing. In the gas-centered basin model, the discontinuous nature of the fluvial sandstones in the Williams Fork has enhanced the preservation of overpressured conditions. In the underlying Rollins sandstone, lateral continuity across the basin may allow this member to serve as a regional aquifer. The Cozzette member has probably behaved in a similar fashion although it appears to have greater internal complexity and may contain flow boundaries that impede ready migration of water through these sands. The Corcoran member has a relatively thin outcrop exposure on the eastern margin so that the area of potential meteoric influx is small compared to the other two Iles Formation sandstones.

A primary control on fluid flow through the basin subsurface has been thought to be the approximately two thousand feet of hydraulic head difference between the eastern and western margins of the basin. In this flow regime, artesian flow will occur from east to west (Figure 8). However, there are several problems with this model. The first, is the presence of overpressured conditions in the basin center that inhibits flow of fluids across the overpressured interface. Lithologic flow barriers are also created by the lensoidal geometry of the Williams Fork fluvial channels and the low-permeability of these sands and the underlying marine sandstones. The Rollins, Cozzette and Corcoran sands possess microdarcy permeability and regional flow regimes through these low-permeable systems seem untenable.

From the basin cross-section, an excellent perspective is gained into the origin and evolution of basin subsurface hydrodynamics. Determination of the areal extent of the water- and gas-saturated zones is the next step.

### Lateral Variability in Piceance Basin Water and Gas-Saturated Zones

Lateral variation in the geometry of the gas and water-saturated zones is most useful to explorationists and those creating basin syntheses. This perspective permits the cross-sectional information described above, to be expanded into the third dimension and then projected into plan view. To assess gas and water-saturated conditions, gas-saturated conditions were initially screened by the presence of gas fields producing from a particular reservoir horizon. This was confirmed by verifying the presence and magnitude of gas shows in mud logs from that area. Mud logs are often considered preferable to neutron density logs in the Piceance Basin because the "gas effect" or neutron crossover is commonly suppressed in tight gas sands despite the presence of high gas saturation. Numerous examples are available where significant gas shows are observed on the hydrocarbon log but the neutron density logs do not show any crossover effect.. Because of this observation, the cross-over effect is not always a reliable tool for identifying gas-bearing sands.

Initially, all publically-available hydrocarbon (mud) logs from throughout the basin were collected and the location of the gas-saturated zone was determined on these logs. From a subset of these logs, the cross-section described previously (Figure 7 & schematically in Figure 8) was constructed.

Water-saturation was determined by using initial production data (generally calculated by operators after approximately three months of flow to remove hydraulic fracture stimulation fluid returns from production information) and flagging all wells in the basin flowing greater than 5 barrels of water per day (BWPD). Production data for these wells were then examined to determine if the wells flowed more than 10 BWPD over time. By identifying wells as either "wet" or "dry", the boundaries of the gas and water-saturated zones were delineated. Because many areas show complex water production, those areas with increasing or variable water production over time were labeled as transitional.

In the Piceance Basin, the vast majority of Williams Fork Formation fields are gas-saturated (Figure 9). Significant local breaching of the system is evidenced by water-saturated conditions such as within the Divide Creek Anticline in the southeast area of the basin. Differential amounts of meteoric recharge occur along the basin margins where the Williams Fork Formation or its equivalent crops out. To date, the most productive Williams Fork fields appear to lie in an overpressured zone along the basin axis. If gas is sourced from the Cameo Coal group within the low-permeability Williams Fork, this is the logically the most likely zone for gas entrapment in a basin-centered gas model. Also, the majority of gas would have been generated at the most thermally mature, deepest part of the basin. Water produced in the Williams Fork is variable. In Divide Creek and the basin center, water appears to be sourced from the coal interval (Sattler et al., 1985).

Very limited production and test data are available for the Rollins Member sandstone. There are less than a half dozen wells in the south half of the basin that have reported tests in the Rollins. Most operators consider the Rollins to be water-saturated throughout the basin. Only along the western quarter of the basin (where significant facies changes occur in the Rollins and equivalent sands) does the Rollins appear to be gas-saturated, though the test data suggest uneconomic volumes. The source of water produced from the Rollins is unknown. Because of limited available information, a regional map of gas-saturation in the Rollins has not been constructed.

The Cozzette Member of the Iles Formation is a shingled, southeastward-prograding, laterally continuous, marine sandstone (Figure 10). The sandstone was deposited along approximately NE/SW trending strandlines with depositional limits present along the northern and southern boundaries (Brown et al., 1986). Meteoric influx occurs along both eastern and western basin margins. However, influx along the western margin is limited due to the semi-arid conditions that prevail in that region. The source of the Cozzette water is unknown.

Gas and water production from the Corcoran Member of the Iles Formation show that most of the Corcoran sandstone is gas-bearing (Figure 11). Only along the basin margins where subsurface depths are relatively shallow does the Corcoran produce water. There are several Corcoran producers that have apparent associated water, however, it is unclear from the reporting of the commingled production data whether the water is sourced from overlying reservoir horizons or from the Corcoran. Possibly, some of this water may be fracture flow water sourced from adjacent reservoir horizons. Similar to the Cozzette sandstone, the Corcoran is also breached along the Bull Creek Anticline structure just to the south of Debeque Canyon. The geology of the Corcoran and the Cozzette sandstones are both quite similar and represent regressive shoreline sequences. Like the Cozzette, the Corcoran also prograded to the southeast. The source of the Corcoran water is unknown.

Complex water-saturated relationships are particularly evident in the Cozzette Member of the Iles Formation. In this reservoir horizon, wells producing no water are often surrounded by wet wells. One possible explanation is that water is sourced from fractures that connect wet zones while gas is trapped in less-connected fractures. The presence of a small normal fault in MWX #2 providing communication between the Cozzette and Rollins sandstones suggests that the Cozzette water may be sourced from the overlying Rollins sandstone and transported along the fault. If this small-scale faulting is prevalent in the gray transitional area (see Figure 10), it may provide an explanation for the complex boundary between the gas and water-saturated zones in the basin center.

A major problem for most gas producers in the southern Piceance Basin is that high permeability zones are commonly water-saturated. Work in progress is attempting to determine if water production is controlled by fracturing and whether these zones are natural extension fractures or shear fractures/fault zones. In addition, ongoing efforts are underway to characterize the source of water and geochemical evolution of the basin.

## FRACTURED RESERVOIR ANALYSIS

To assess the importance of fractured reservoirs on production trends, detailed structure and production mapping was performed in Grand Valley, Parachute and Rulison fields to determine the relationship between production and structure. This section represents an abbreviated geologic and production synthesis of Grand Valley, Parachute and Rulison fields (see Figure 9 for field locations). These fields produce gas from the Tertiary-age Wasatch Formation, the Cretaceous-age Williams Fork, and the underlying Cretaceous-age Iles Formation. In these zones, gas is trapped in structurally-enhanced stratigraphic traps. A large percentage of Williams Fork gas is produced from fluvial sand channels, and from thick coals in the Cameo Coal section located below the fluvial interval. Limited production (approximately three wells) is contributed from marine sands in the Cozzette-Corcoran sandstones (Iles Formation).

The primary objective of this study is to understand the relationship between production trends in the three fields and regional structure, most notably the influence of structural trends on subsurface permeability and reservoir productivity.

### Reservoir Stratigraphy

Producing zones in the Rulison and Parachute fields can be dissected into three primary reservoir horizons. Most successful Williams Fork wells produce from fluvial sand channels. Extensive research at the MWX site in Rulison field demonstrated that the widths of these sand channels (approximately 300-500' wide, 20-50' thick; Lorenz, 1985) are significantly less than regulated well spacing. Recently, with new field rules (80 acre spacing, 2/94), additional production should be achieved from these lenticular, isolated channel sand reservoirs.

In the Piceance Basin, reservoir thickness is directly related to depositional environment. In the Iles Formation, shallow marine, shoreline deposits are composed of homogeneous, widespread blanket-type sandstones possessing sub-microdarcy permeability. Similar clean sands are found within fluvial channels and in the paludal (coal-bearing) interval of the Williams Fork Formation. These fluvial and paludal Williams Fork sands, especially where fractured, represent the best exploration targets. However, these zones are generally more complex targets because of the anastamosing, discontinuous nature of the reservoir. The complexity is further magnified by the complex internal structure of the reservoir sediments.

Limited production is also sourced from the marine sediments composing the Cozzette-Corcoran lying immediately underneath the Williams Fork Formation. In general, these sediments prograde to the southeast and have an internal shingled geometry typical of a transgressive systems tract.

### Production Trends in Grand Valley, Parachute and Rulison Fields

To develop an understanding of the controls on production, production data for the best six months during the life of the well were contoured. Figure 12 illustrates the relationship between production trends in the three fields. Production trends correlate to local structure trends in the three fields. To examine the effect of stratigraphic variation, a total sand isochore map was compared to the production trends for Parachute and Rulison fields (Figure 13). The production trend lies perpendicular to the depositional systems trends, strongly confirming the structural control on production in these fields. Work in other fields confirms these relationships (see Hoak and Klawitter, this volume).

These three fields illustrate the importance of structural controls on production trends. It is interesting to note that the NW-trending production trends and local structure lie oblique to the dominant WNW or E/W fracture trends documented by the MWX coring program (Lorenz and Finley, 1991). There are several possible explanations for this relationship. The most plausible is that local tectonic deformation caused by structures, such as the Rulison Anticline, generates enhanced dilatancy along fracture sets oriented oblique to the structure.

## REGIONAL STRUCTURE AND TECTONICS

Regional structural mapping, integrated with ancillary data, delineates the location of fracture prone areas. Linear features analysis using remote sensing imagery is used as a reconnaissance tool to locate regional structures and the surficial manifestation of deeper subsurface features. In those locations where local structures are breached to meteoric incursion, remote sensing imagery linear features analysis is used to recognize these zones to avoid local water-saturated areas. Prominent linear features proximal to seismic anomalies are also indicative of possible basement faulting.

Analysis of surficial structures from remote sensing imagery can also recognize subtle, subsurface structures such as the Rulison Anticline that are controlled by basement structures. These basement features can be clearly imaged on aeromagnetic data and confirmed by seismic data through these areas. Figure 14 demonstrates the geometry of the subsurface structure defined by aeromagnetic data in the Rulison Field. Note the presence of a NW-trending basement structure parallel to the trend of the shallower subsurface structure and the production trends that lie within this structure. This structure is confirmed by seismic. Seismic data, integrated with ancillary wellbore data in the southern Piceance Basin, clearly image the geometry of subsurface structure and the complex deformation history of the basin. A published E/W seismic line through Grand Valley, Parachute and Rulison fields has been interpreted by Waechter and Johnson (1986). Figure 15 is a reinterpreted portion of the seismic line interpreted by Waechter and Johnson. It is important to note that the primary focus of these authors was documentation of Paleozoic structural features. Because of this focus, an interpretation of Laramide contractional features has been added to this section. It is essential not to neglect the strong Laramide overprint superimposed on the older extensional horst and graben system because it is the tectonic event that dominates and was responsible for most of the major structures in the basin.

As shown by Waechter and Johnson (1986), a NW-trending, Pennsylvanian-age horst block is present underneath Rulison field. This block lies parallel to the Pennsylvanian-age tectonic grain, well documented in uplifted blocks flanking the margins of the Piceance Basin.

Southeast of the Rulison area is the Divide Creek Anticline, a fault-propagation-fold structure that plunges to the northwest. The explanation for the northwestward plunge and dissipation of the Divide Creek fold is probably related to the termination and/or decreased displacement of a thrust fault in the fold core whose displacement dies out along-strike to the northwest. The termination of the thrust and related fold probably is an analogous geometry to the termination of smaller-scale thrusts into folds common in both the Appalachian and Alberta fold-and-thrust belt. These thrust terminations and related folds represent the source of the fractures common in the Rulison field. The thrust tip termination requires regional strain to be accommodated by internal deformation of the rock (i.e. fractures) because strain cannot be accommodated by additional thrust displacement, or by folding or other ductile processes.

## CONCLUSIONS

Most of the Williams Fork Formation, and the Cozzette and Corcoran sandstones of the Iles Formation are gas-saturated throughout the Piceance Basin. Water-saturated conditions are present along the basin margins and where structural uplift and erosion have breached the reservoirs. The majority of Piceance Basin reservoirs require significant natural fractures to permit economic production from low permeability sandstones.

The model of thermal gas generation and preservation of overpressure for the Piceance Basin can be readily applied to other western coal-bearing basins that contain thick, thermally-mature coals and interbedded, low-permeability, vertically-stacked, lenticular sands.

Mud weight, DST and bottomhole pressure data show that the present-day overpressured zone in the basin is concentrated within Williams Fork fluvial sandstones lying above the Cameo Coal section. The basin overpressured zone corresponds to the area where the maximum vitrinite reflectance is greater than 0.9. In this same area, the marine Iles Formation sandstones (Rollins, Cozzette and Corcoran) also show overpressured conditions although the magnitude of the overpressure is less than in the overlying fluvial and paludal sections. Low permeability conditions in these sands allow the preferential preservation of overpressured conditions. In this context, the low permeability sands of the Williams Fork and Iles formations are best modeled as regional aquitards rather than major hydrodynamic flow units of a regional artesian system.

Williams Fork gas-saturated conditions extend from approximately eight miles basinward of the Mesaverde Group outcrop belt surrounding the basin. Several structurally positive areas are breached by meteoric influx and are water-saturated. The Corcoran and Cozzette members show similar relationships although breached conditions are only locally present for the Corcoran in the western basin. The Cozzette Member exhibits complex water-gas-saturated conditions in the transitional area between the water-saturated eastern basin and the gas-producing horizons in the western region. Some of this complexity may be the result of fault systems connecting the water-prone areas of the Rollins Sandstone to underlying, lower-pressured zones in the Cozzette.

The most productive fields in the basin represent fractured reservoirs. Detailed studies in the Grand Valley-Parachute-Rulison and Shire Gulch-Plateau fields indicate that zones of maximum flexure on kilometer-scale structural features are directly related to areas of enhanced production. These smaller structures, common throughout the basin, represent the best focus for additional field development because most larger structures in the basin have been extensively drilled.

To determine the complex tectonics of the Piceance Basin, significant information about burial and uplift history can be determined through the use of thermal modeling using vitrinite reflectance data from the abundant coals seams throughout the basin. By placing fracture genesis in the context of thermal gas generation and basin maturity, an appropriate window of fracturing can be determined and tectonic events related to this fracturing can, in turn, be calibrated against an absolute time frame. This approach represents a tremendous improvement to previously-utilized relative timing methods based on crosscutting relationships.

Detailed analysis of regional structure and gas and water production can be used to determine fractured reservoir conditions, the relationship between fractures, structure and producibility, basin hydrodynamics, overpressured zones and the geometry of a structurally-influenced, gas-centered basin. Integrated with remote sensing analysis of the basin, seismic data and numerical modeling of the basin evolution, these analytical tools represent a powerful means of understanding and predicting fracture-controlled hydrocarbon production.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge financial support for this paper and the associated research project from the Department of Energy-Morgantown Energy Technology

Center (DOE-METC contract DE-AC21-93MC30086). Special thanks to Royal Watts (DOE-METC) for project management and encouragement.

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FIGURE 1

# SELECTED CRETACEOUS GAS FIELDS AND BASIN LOCATION MAP

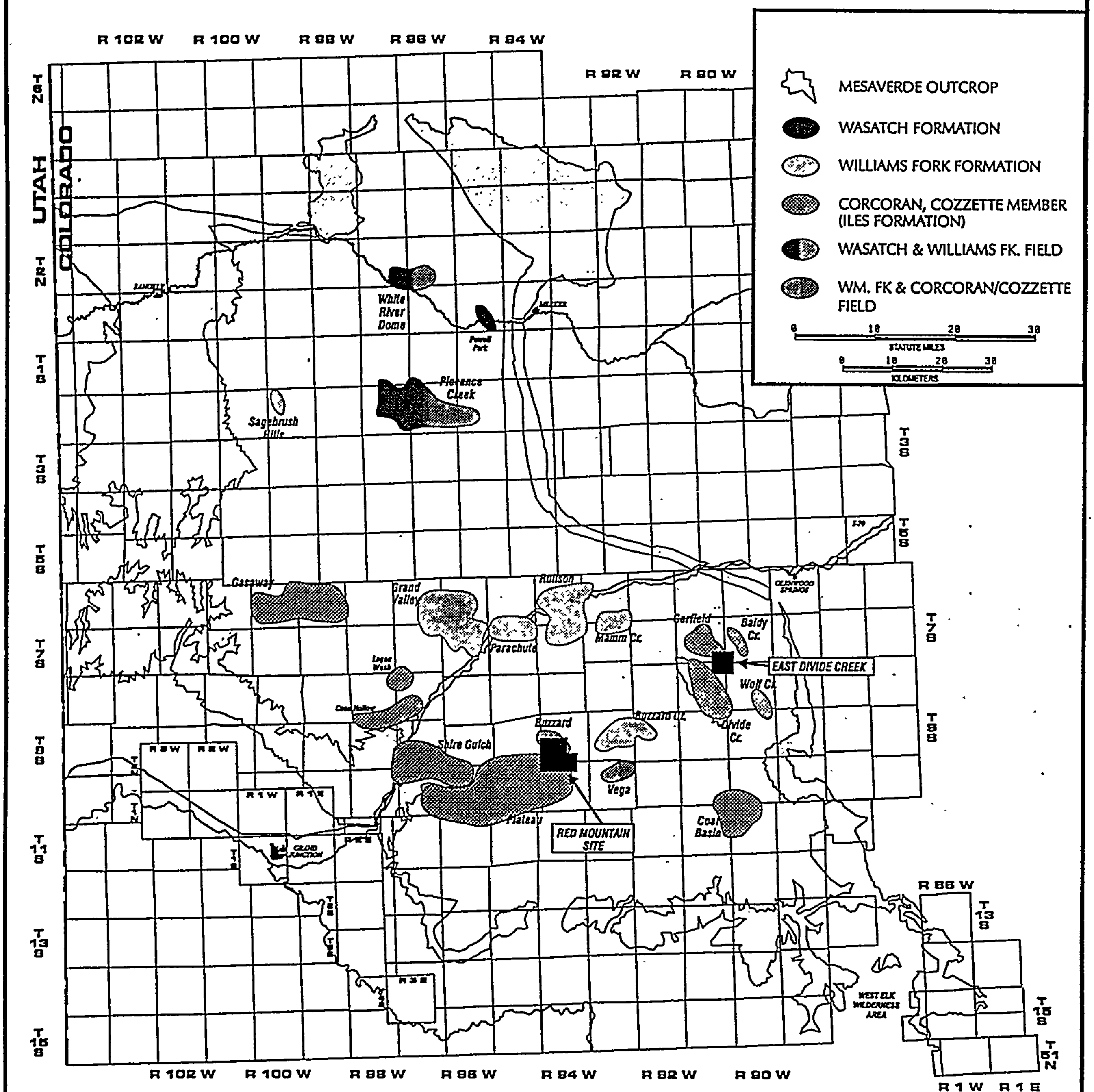
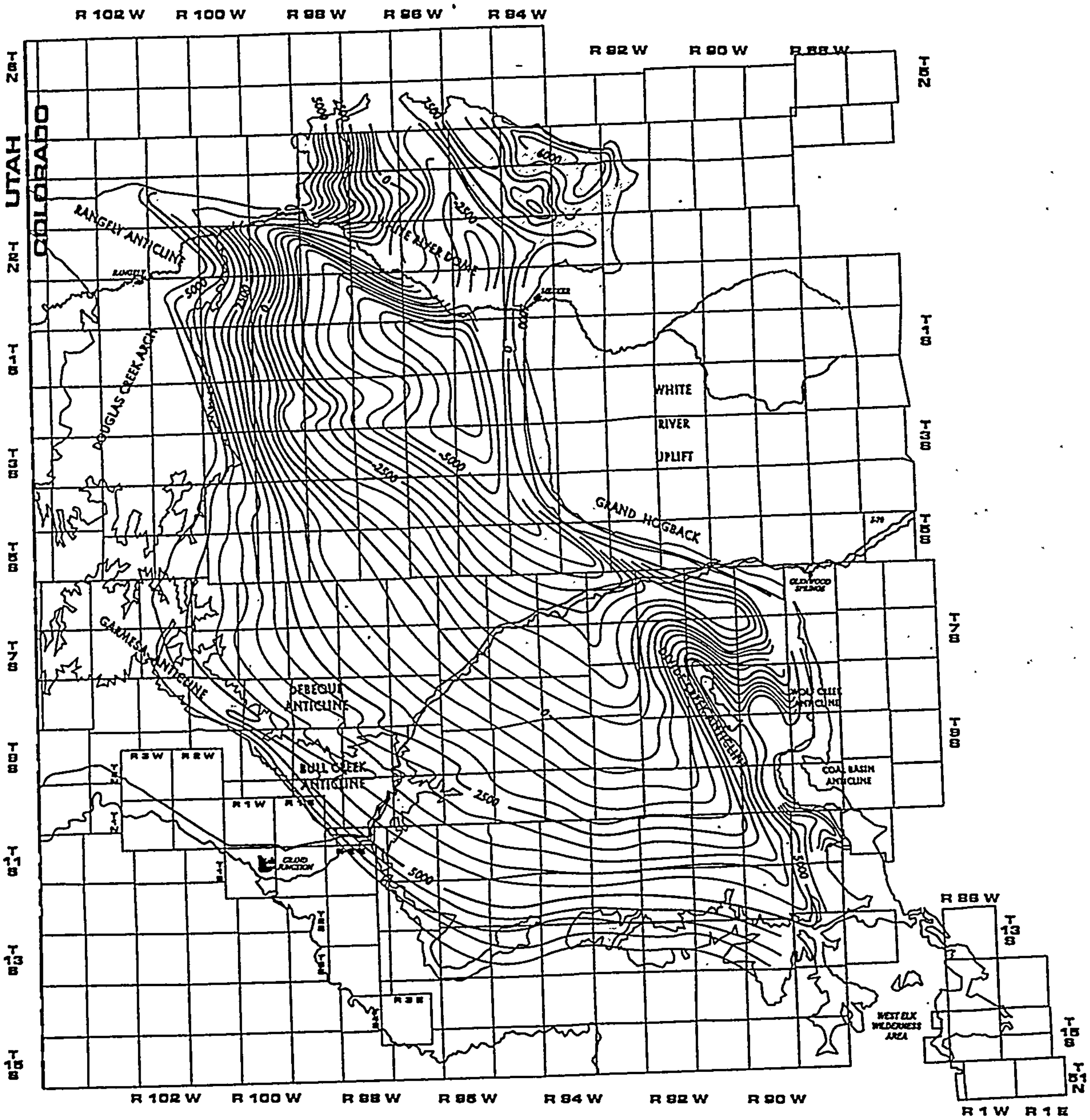


FIGURE 2

# PICEANCE BASIN REGIONAL STRUCTURE MAP

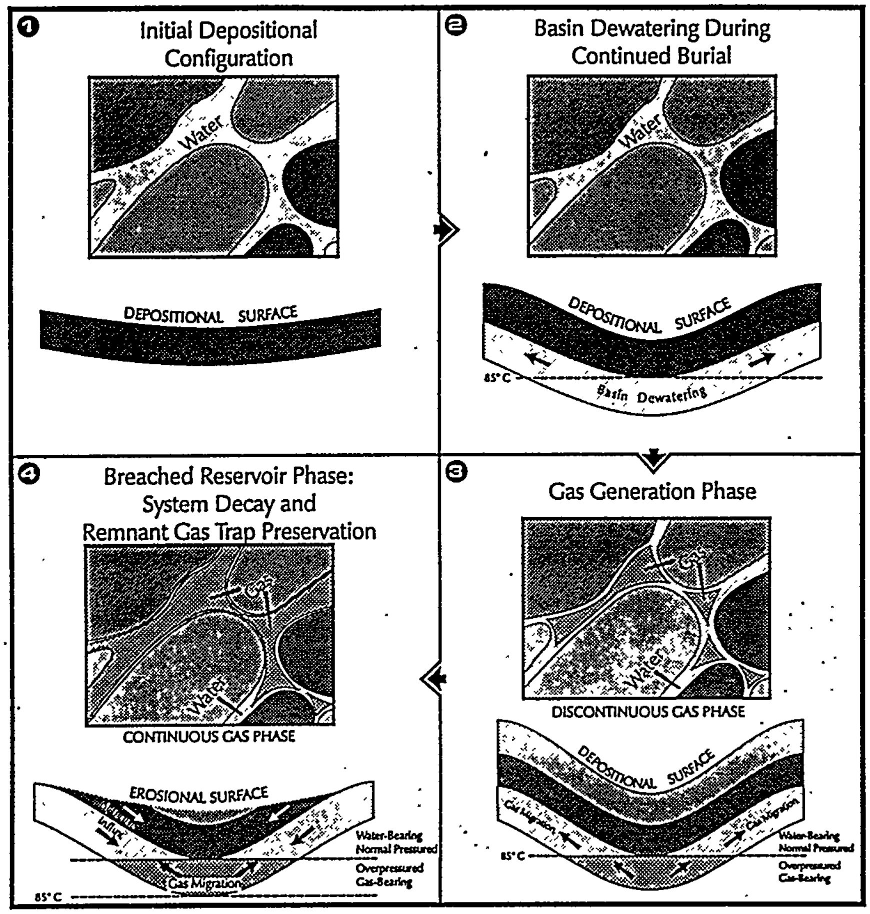



0 10 20 30
STATUTE MILES
0 10 20 30
KILOMETERS

Structure Contours on Top of Rollins Sandstone
(TOP ILES FM)

FIGURE 3

**EVOLUTION OF A GAS-CENTERED BASIN**




Modified after LAW & DICKINSON, 1985

FIGURE 4

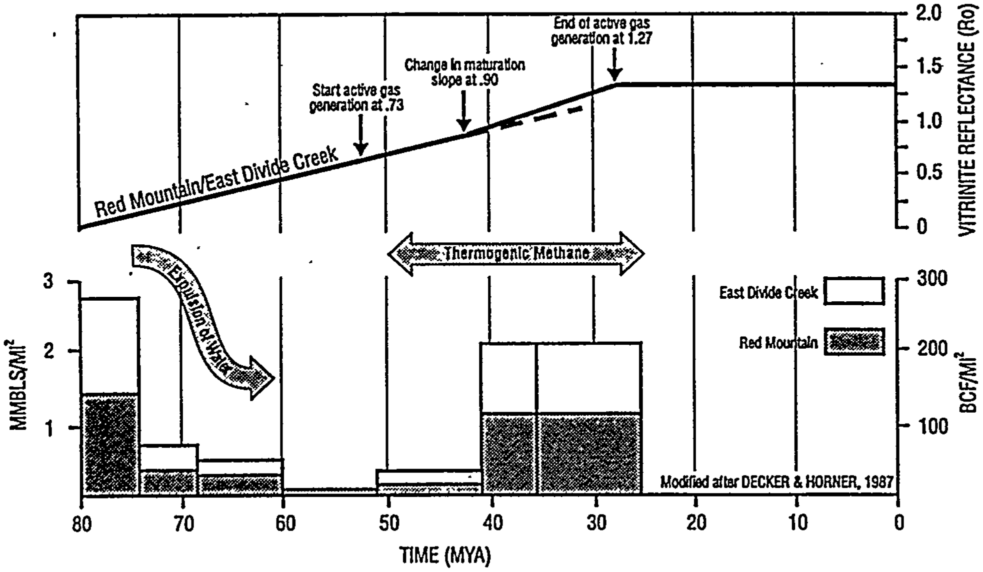


FIGURE 5

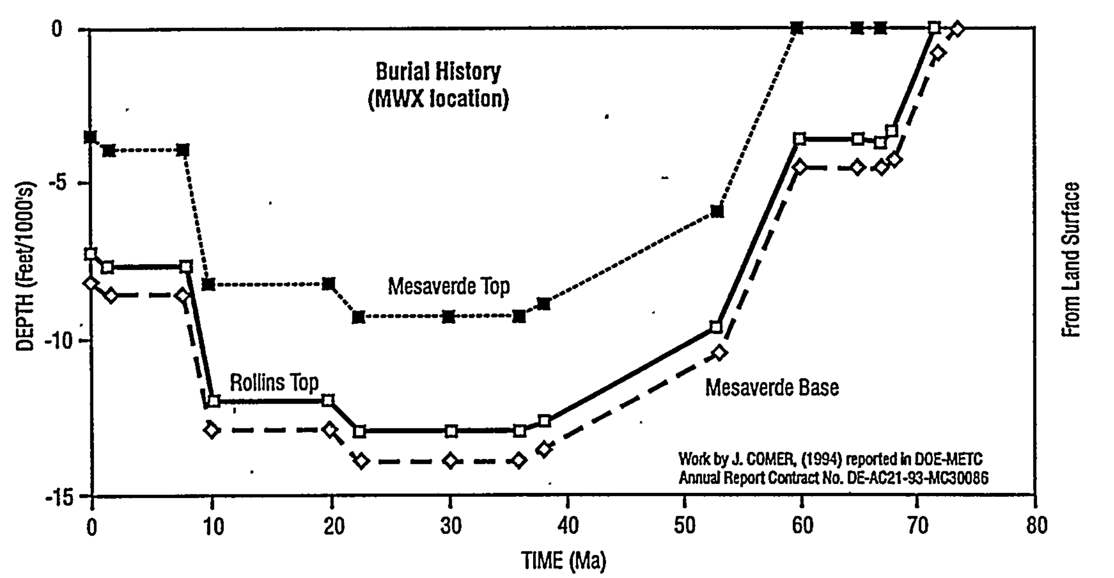
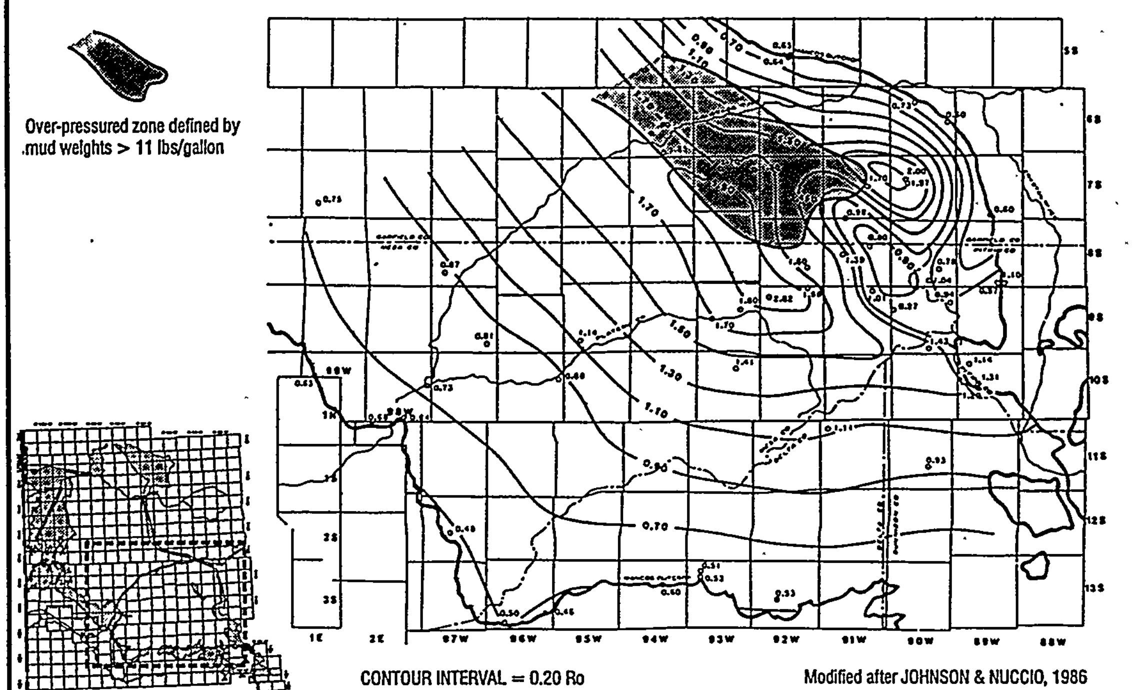



FIGURE 6

## SOUTHERN PICEANCE BASIN VITRINITE REFLECTANCE



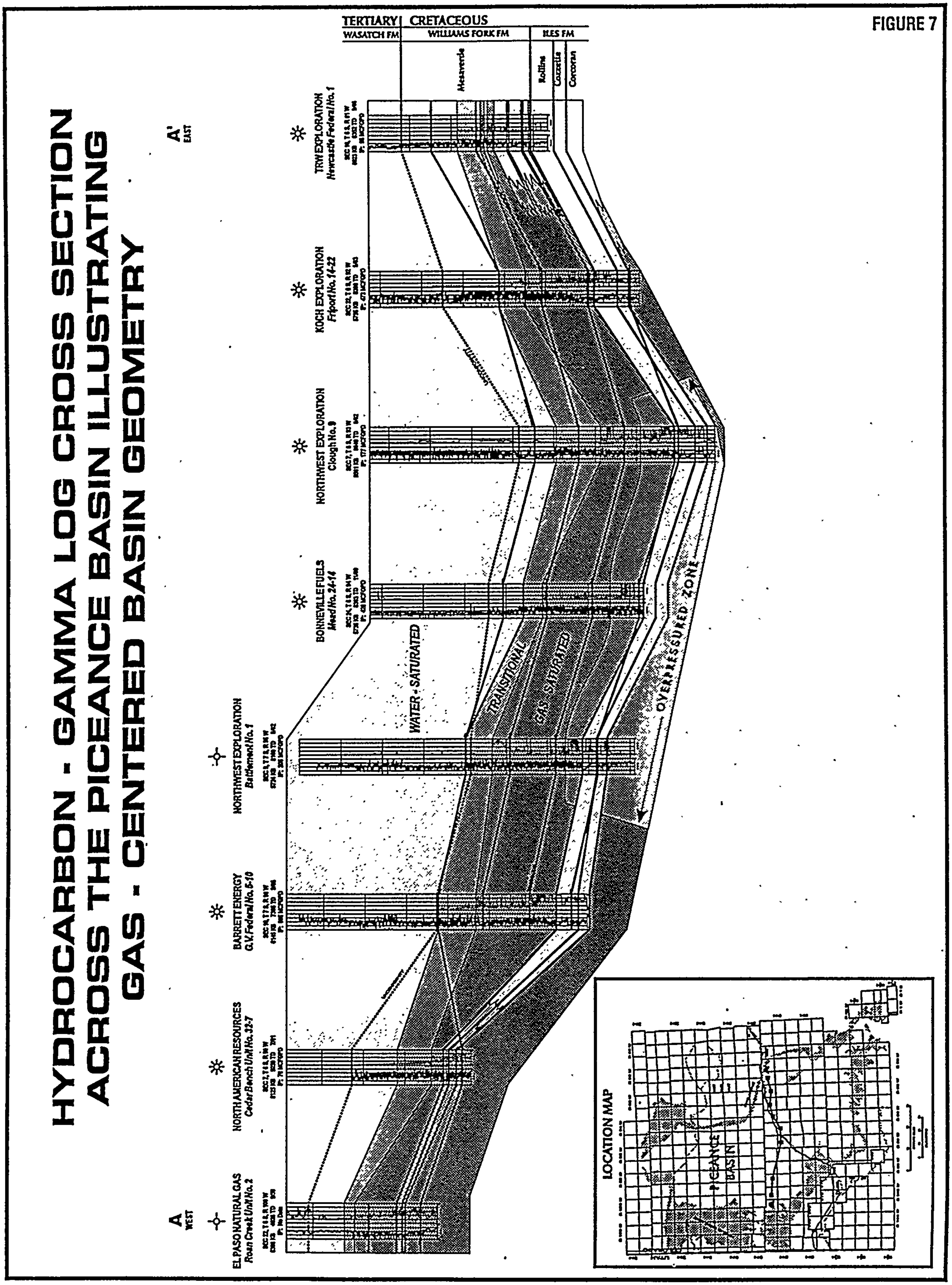

HYDROCARBON - GAMMA LOG CROSS SECTION
ACROSS THE PICEANCE BASIN ILLUSTRATING
GAS - CENTERED BASIN GEOMETRY
A
WEST
A'
EAST
TERTIARY
CRETACEOUS
WASATCH FM
WILLIAMS FORK FM
ILES FM
Mesaverde
Rollins
Cozzette
Corcoran
EL PASO NATURAL GAS
Roan Creek Unit No. 2
NORTH AMERICAN RESOURCES
Cedar Bench Unit No. 33-7
BARRETT ENERGY
G.V. Federal No. 6-10
NORTHWEST EXPLORATION
Battlement No. 1
BONNEVILLE FUELS
Mead No. 24-14
NORTHWEST EXPLORATION
Clough No. 9
KOCH EXPLORATION
Fitport No. 14-22
TRW EXPLORATION
Newcastle Federal No. 1
WATER - SATURATED
TRANSITIONAL
GAS SATURATED
OVERPRESSURED ZONE
LOCATION MAP
PICEANCE BASIN

FIGURE 7

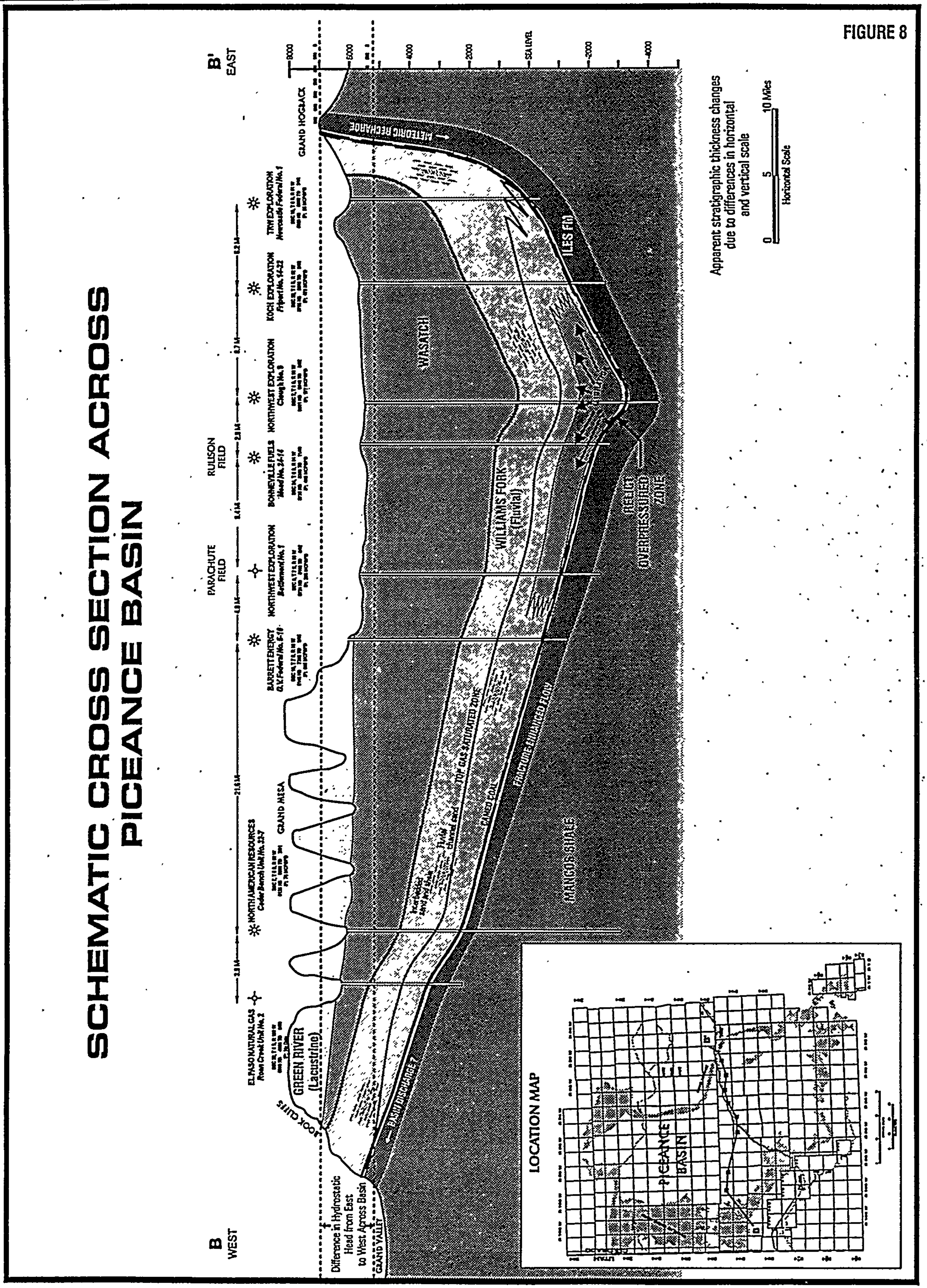


FIGURE 8
SCHEMATIC CROSS SECTION ACROSS PICEANCE BASIN
B WEST
B' EAST
GRAND VALLEY
ROOK CLIFFS
GREEN RIVER (Lacustrine)
GRAND MESA
PARACHUTE FIELD
RULISON FIELD
GRAND HOGBACK
WASATCH
WILLIAMS FORK (Fluvial)
ILES Fm
MANCOS SHALE
METEORIC RECHARGE
BASIN DISCHARGE
FRACTURE ENHANCED FLOW
OVERPRESSURED ZONE
EL PASO NATURAL GAS
NORTH AMERICAN RESOURCES
BARRETT ENERGY
NORTHWEST EXPLORATION
BONNEVILLE FUELS
KOCH EXPLORATION
TXW EXPLORATION
Difference in Hydrostatic Head from East to West Across Basin
Apparent stratigraphic thickness changes due to differences in horizontal and vertical scale
Horizontal Scale
0
5
10 Miles
LOCATION MAP
PICEANCE BASIN

FIGURE 9

# WILLIAMS FORK FORMATION GAS-SATURATED ZONE, PICEANCE BASIN

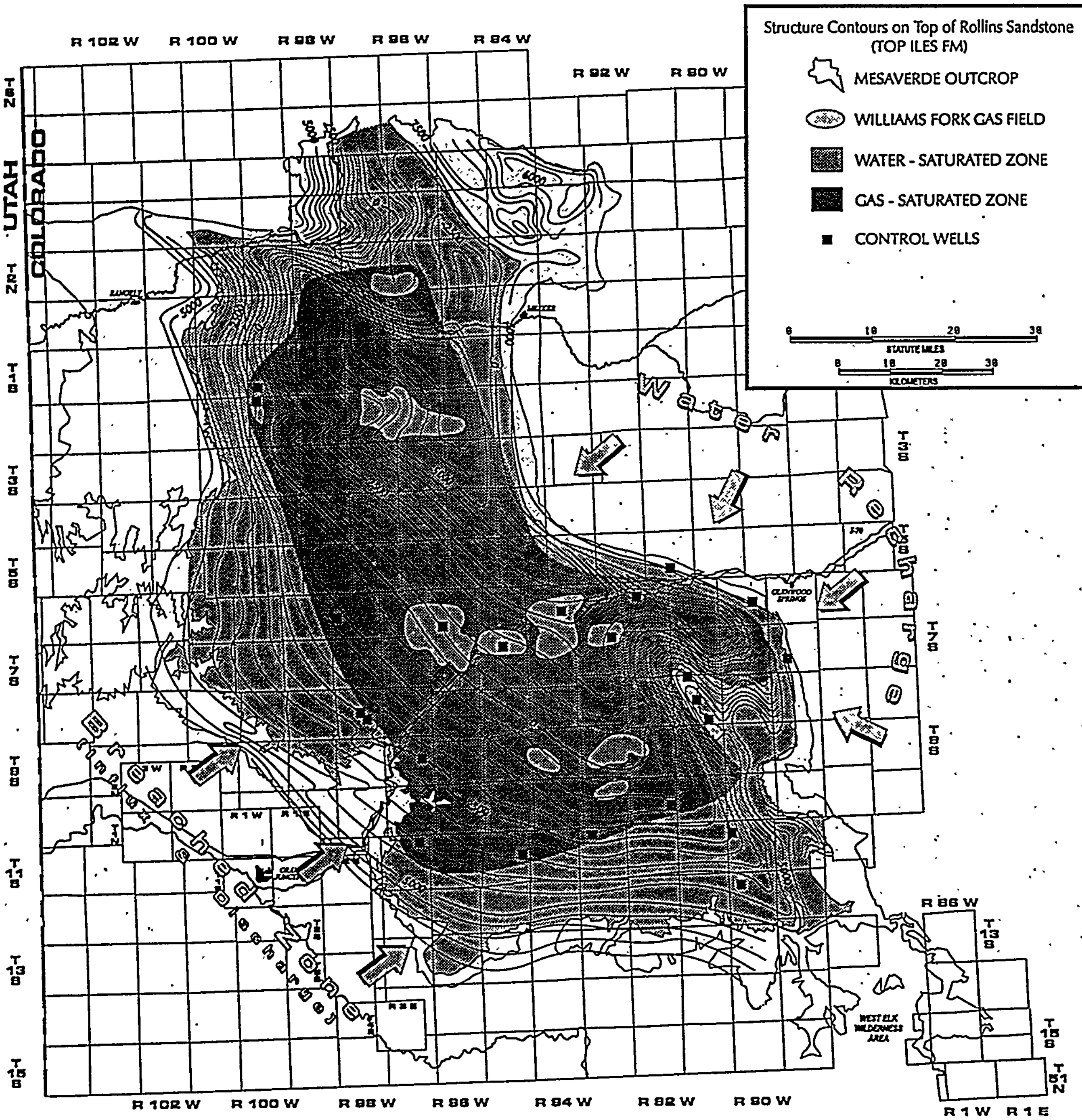


FIGURE 10

# COZZETTE SANDSTONE - ILES FORMATION GAS-SATURATED ZONE, PICEANCE BASIN

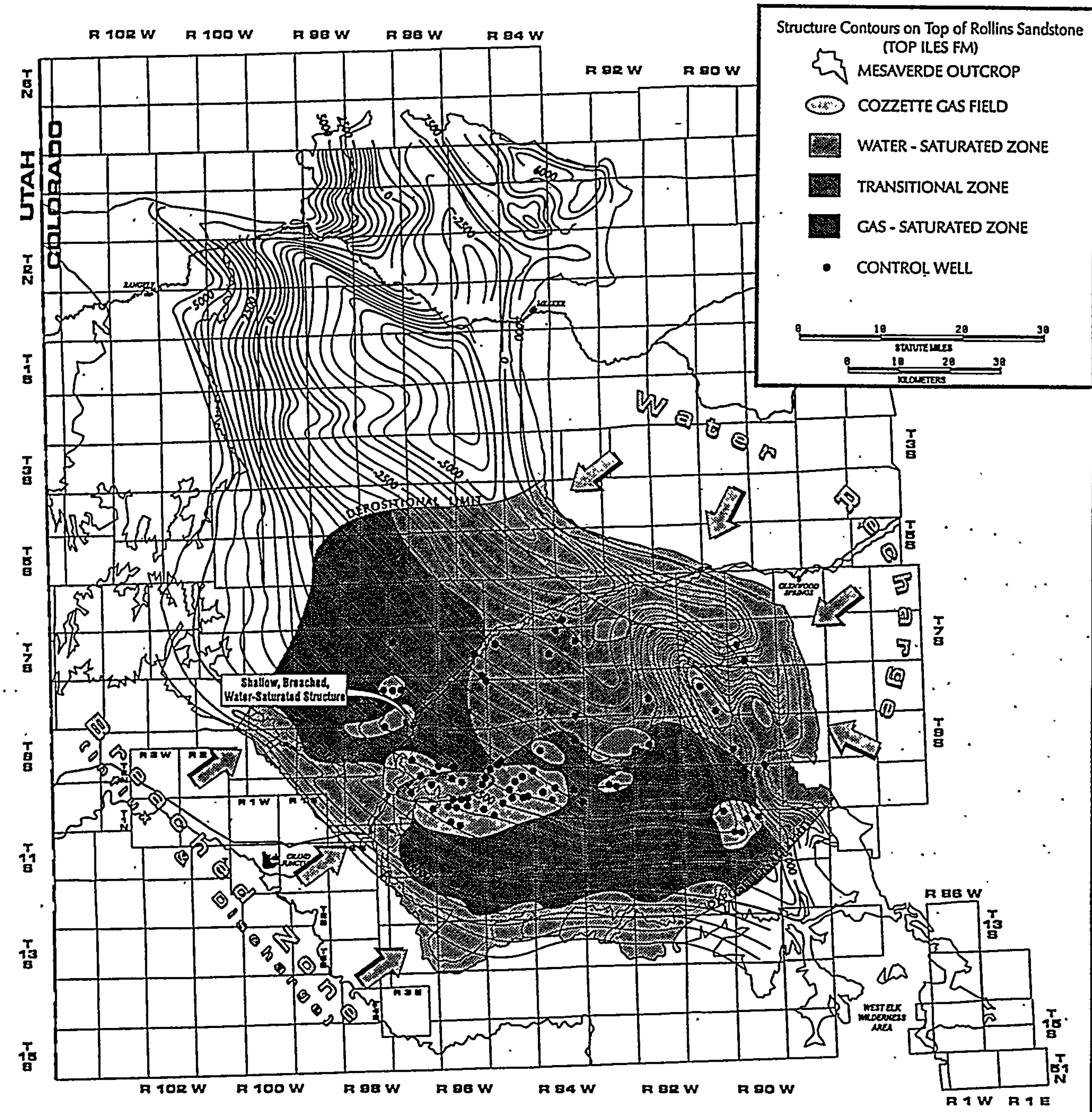


FIGURE 11

# CORCORAN SANDSTONE - ILES FORMATION GAS-SATURATED ZONE, PICEANCE BASIN

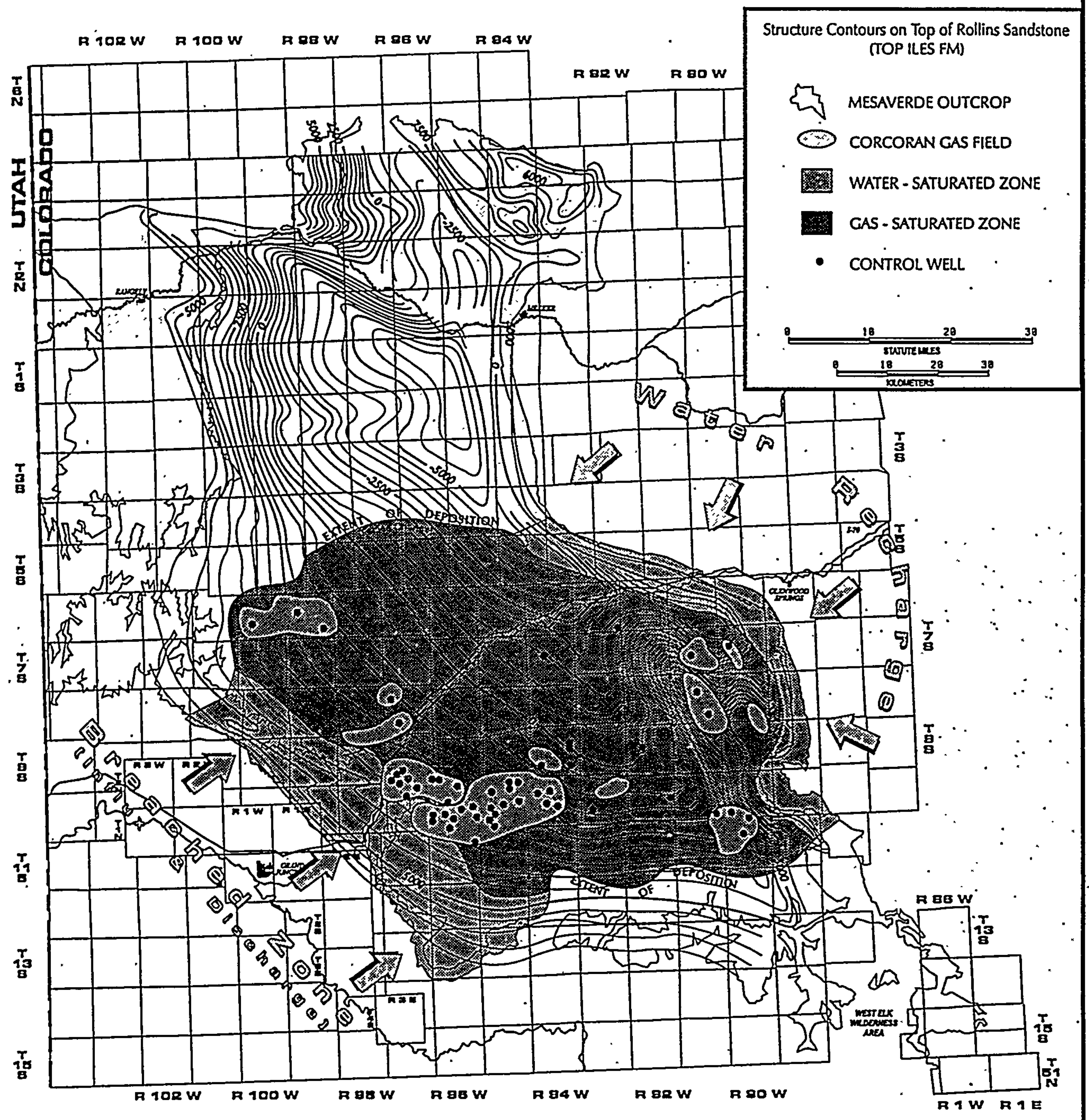


FIGURE 12

## RELATIONSHIP BETWEEN STRUCTURE AND PRODUCTION
### Grand Valley, Parachute and Rulison Fields, Piceance Basin

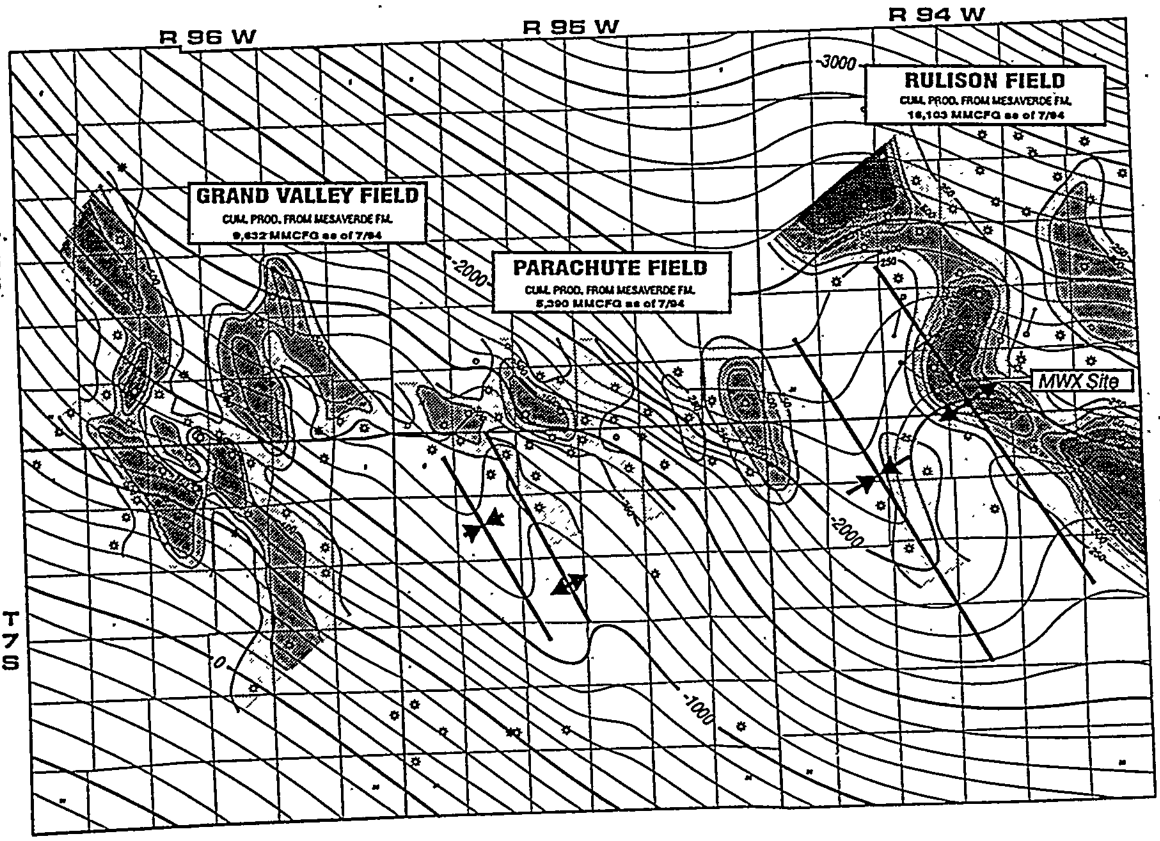
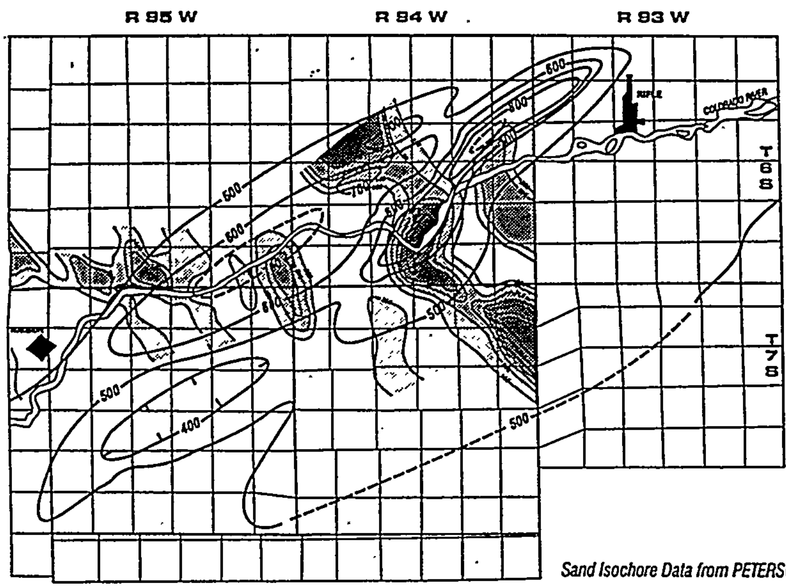



FIGURE 13

## PARACHUTE - RULISON FIELD
### Sand Isochore and Production Relationship




**BEST 6 MONTHS PRODUCTION OF THE MESAVERDE FM**
(Upper/ Middle Williams Fork and Cameo Sand)

ROLLINS STRUCTURE C.I. = 100 FEET
250 - 500 MMCF/MONTH
500 - 750 MMCF/MONTH
750 - 1000 MMCF/MONTH
>1000 MMCF/MONTH

*Sand Isochore Data from PETERSON, 1984*

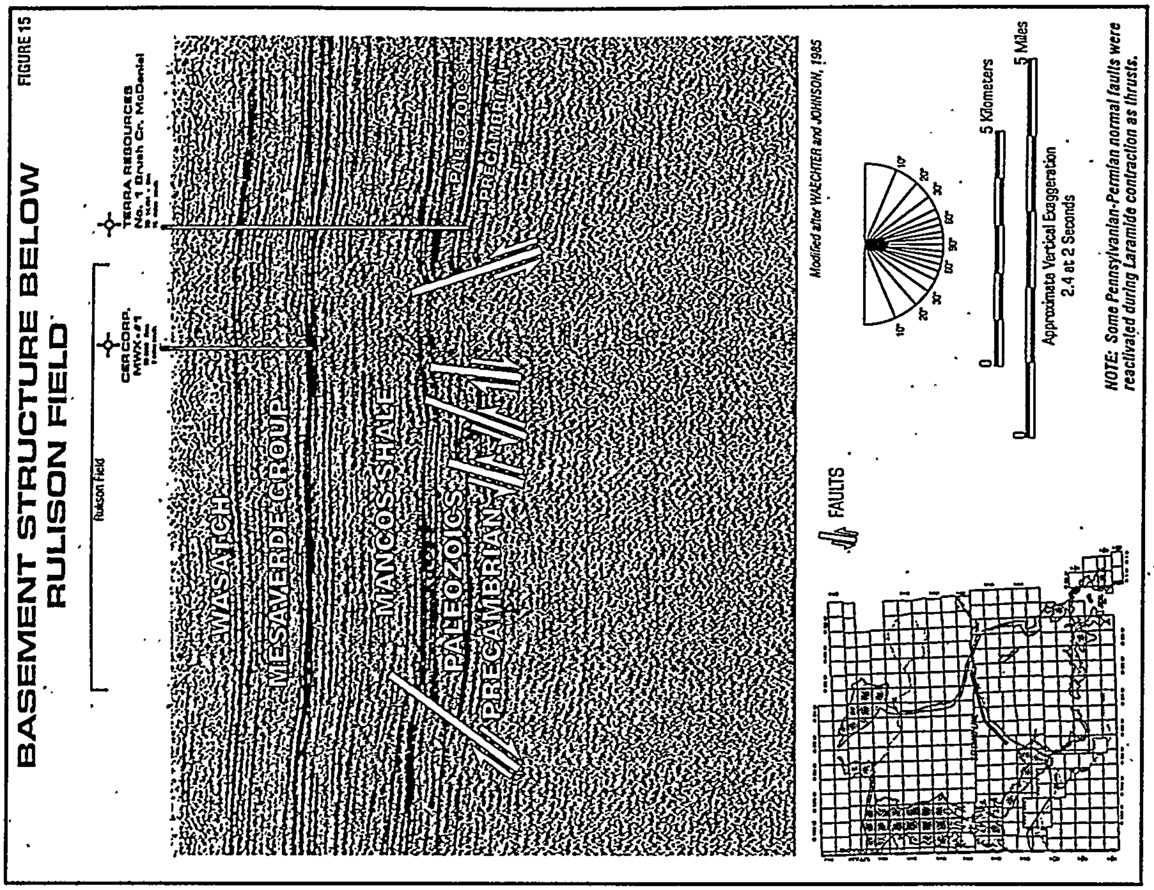


FIGURE 15
BASEMENT STRUCTURE BELOW
RULISON FIELD
Rulison Field
CERCORP. MWX-#1
TERRA RESOURCES No. 1 Brush Cr. McDaniel
WASATCH
MESAVERDE GROUP
MANCOS SHALE
PALEOZOICS
PRECAMBRIAN
FAULTS
Modified after WAECHTER and JOHNSON, 1985
0
5 Kilometers
5 Miles
Approximate Vertical Exaggeration
2.4 at 2 Seconds
NOTE: Some Pennsylvanian-Permian normal faults were reactivated during Laramide contraction as thrusts.

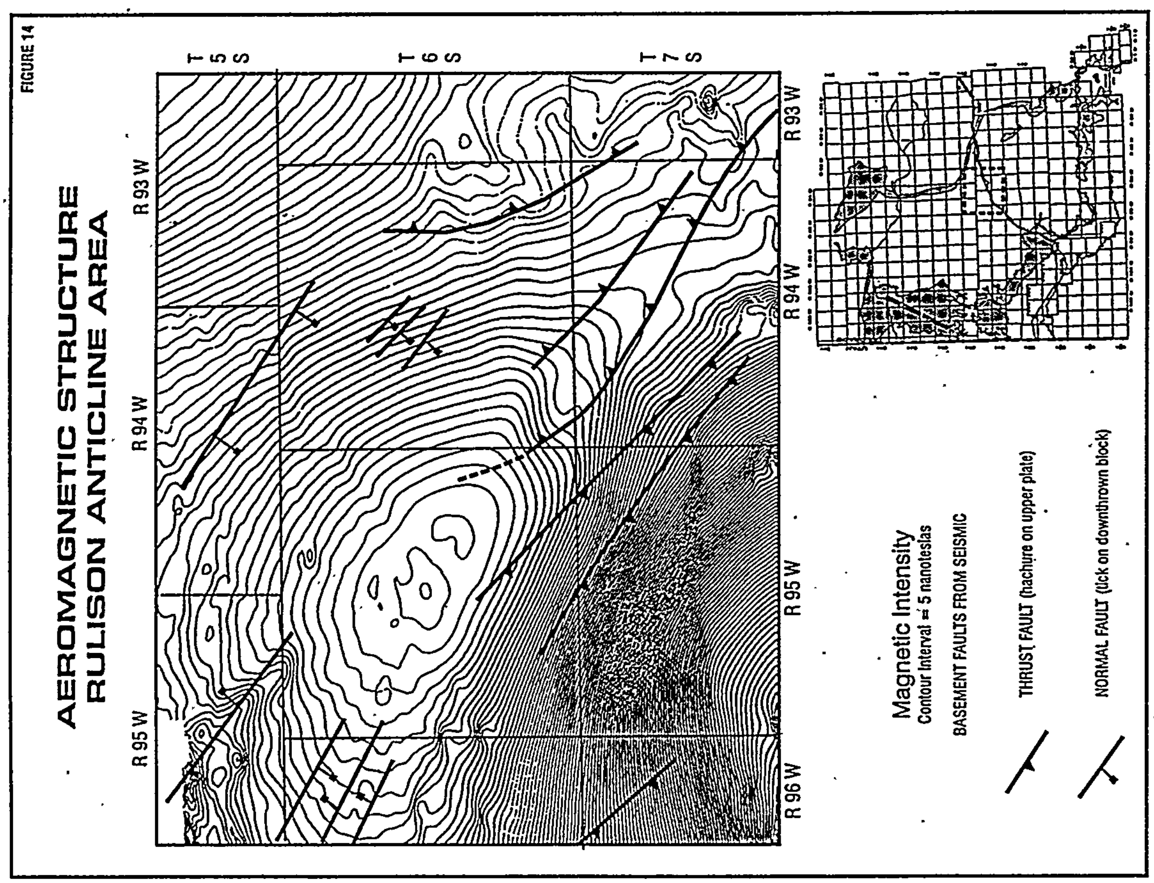


FIGURE 14
AEROMAGNETIC STRUCTURE
RULISON ANTICLINE AREA
R 95 W
R 94 W
R 93 W
R 96 W
T 5 S
T 6 S
T 7 S
Magnetic Intensity
Contour Interval = 5 nanoteslas
BASEMENT FAULTS FROM SEISMIC
THRUST FAULT (hachure on upper plate)
NORMAL FAULT (tick on downthrown block)

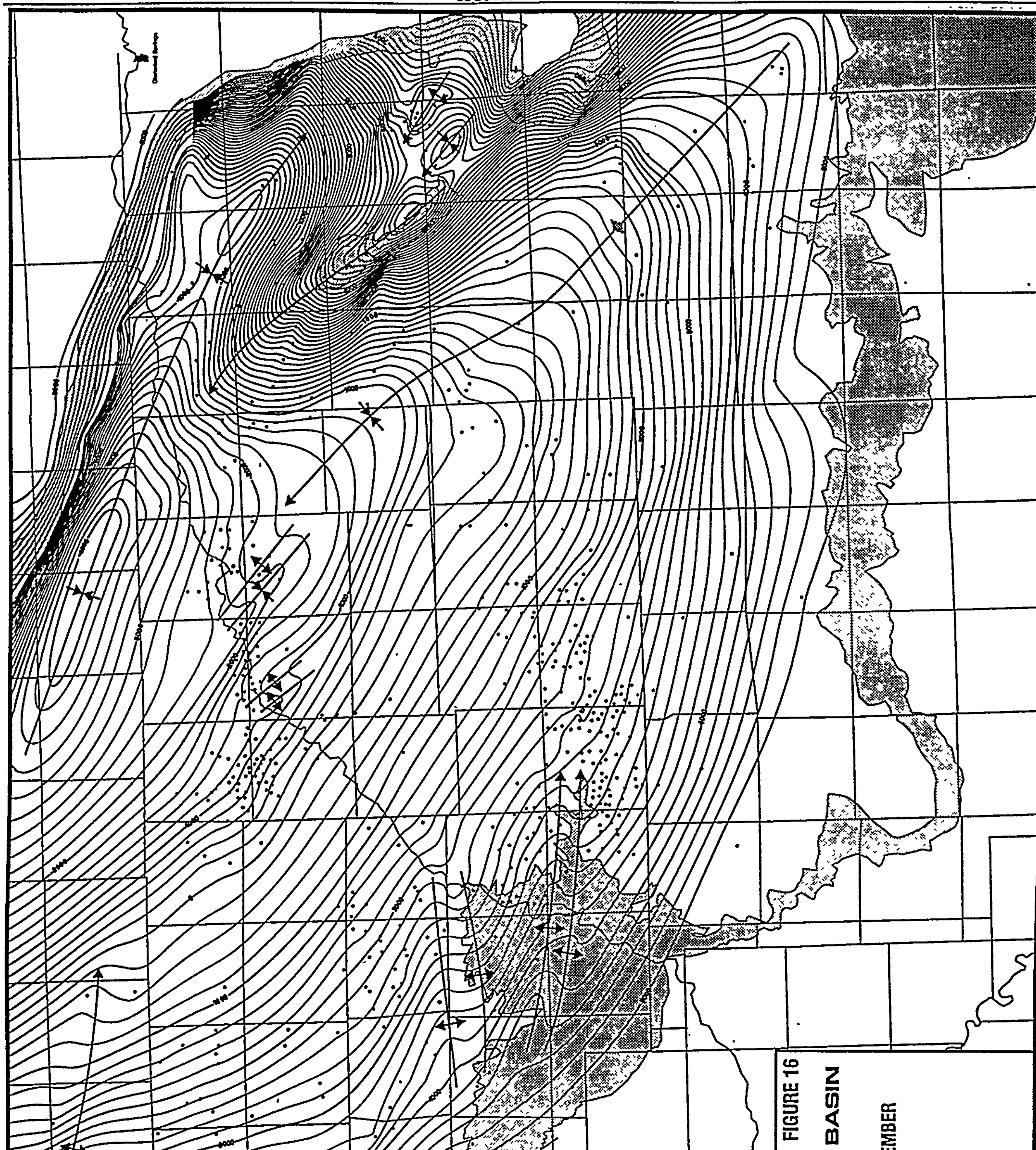


FIGURE 16
SOUTHERN PICEANCE BASIN
STRUCTURE MAP
TOP OF ROLLINS SANDSTONE MEMBER
CONTOUR INTERVAL = 200 FEET
ANTICLINE
SYNCLINE
MESAVERDE OUTCROP
Grand Junction
Colorado River