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Geologic Characterization of Tight Gas Reservoirs

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GEOLOGIC CHARACTERIZATION OF TIGHT GAS RESERVOIRS

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INTRODUCTION

The objectives of U.S. Geological Survey (USGS) work during FY 89 were to conduct geologic research characterizing tight gas-bearing sandstone reservoirs and their resources in the western United States. Additional critical objectives were to provide geologic consulting and research support for ongoing Multiwell Experiment (MWX) engineering, petrophysical, log-analysis, and well-testing research. The USGS research during the last few years has been in the Greater Green River, Piceance, and Uinta basins of Wyoming, Colorado, and Utah (fig. 1). However, beginning in FY-89 our efforts have mostly been restricted to the Uinta basin of Utah.

Previously, the Greater Green River basin had the highest priority because most of the Piceance basin studies were completed and the Greater Green River basin has the largest areal extent of the three basins as well as the greatest known thickness (>10,000 ft) of strata containing dominantly gas-bearing sandstone reservoirs. The Uinta basin may contain thicker tight gas-bearing strata, but there are presently no wells that have been drilled through the Cretaceous Mesaverde Group in the deeper parts of the basin. The top of the Mesaverde Group is estimated to be as deep as 19,000 ft in the structurally deeper part of the basin.

Our research has been regional in scope but, in some basins, our investigations have focused on single wells or small areas containing several wells where a large amount of data is available. The investigations include structure, stratigraphy, petrography, x-ray mineralogy, source-rock evaluation, formation pressure and temperature, borehole geophysics, thermal maturity mapping, fission-track age dating, fluid-inclusion thermometry, and isotopic geochemistry.

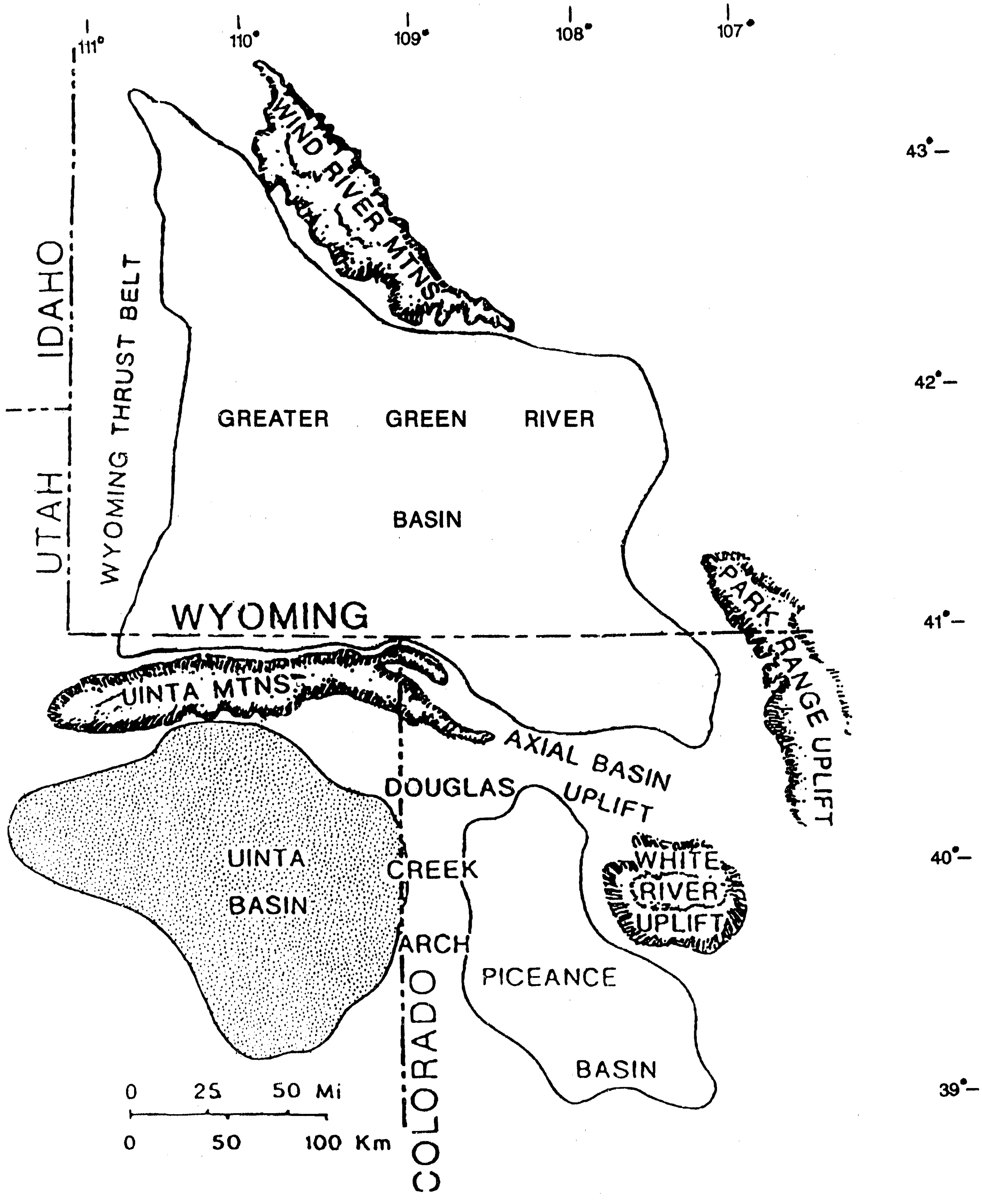

Figure 1.--Index map showing location of the Uinta basin (shaded area) and adjacent basins containing low-permeability gas-bearing reservoirs.

The objectives of these focused investigations are to provide geologic models that can be compared and utilized in tight gas-bearing sequences elsewhere.

Nearly all of our work during FY 89 was devoted to developing a computer-based data system for the Uinta basin and collecting, analyzing, and storage of data. The data base, when completed will contain various types of stratigraphic, organic chemistry, petrographic, production, engineering, and other information that relate to the petroleum geology of the Uinta basin, and in particular, to the tight gas-bearing strata. This data base will facilitate the resource estimate portion of our work and provide fundamentally important information for subsequent geologic investigations.

STRATIGRAPHIC DISTRIBUTION OF RESERVOIRS

Gas-bearing tight sandstone reservoirs in the Uinta basin are dominantly found within two major sedimentary systems (Fouch, 1985). In the first system, Upper Cretaceous tight reservoirs occur within the Tuscher, Farrer, Neslen, Blackhawk, Castlegate, and Price River Formations of the Mesaverde Group. Figure 2 shows a generalized west to east stratigraphic cross section of Cretaceous and Tertiary rocks in the Uinta basin. These Upper Cretaceous stratigraphic units were deposited by streams flowing east from central Utah, across the area of the present-day basin, to a marine shore that fluctuated between eastern Utah and western Colorado. As a result, Upper Cretaceous marginal marine sandstones tend to occur in "sheets" or "packages" that can be traced over

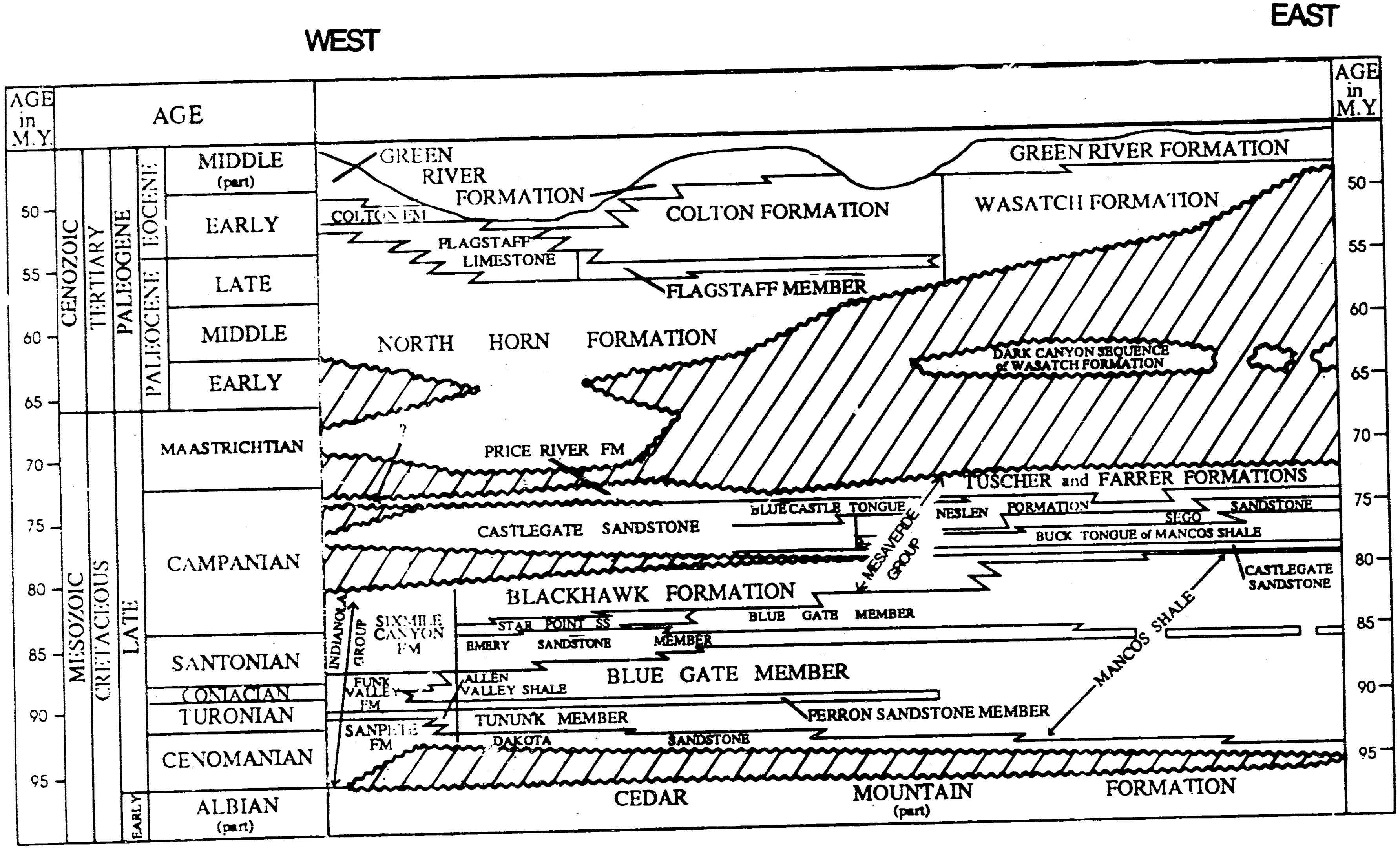

Figure 2.--Generalized west to east stratigraphic cross section of major Albian to middle Eocene rock units in the Uinta basin. Diagonally ruled areas represent hiatus. Modified from Franczyk and others (1989).

wide regions of the basin, and they can be projected to deeply buried undrilled depths in the western part of the Uinta basin.

A second system consists of Tertiary reservoirs that exhibit a large degree of variability over short distances. They occur primarily in the Paleocene and Eocene Colton and Wasatch Formations and the Maastrichtian to early Eocene North Horn Formation. Locally, fluvial sandstones of the Green River Formation are tight gas-bearing reservoirs but many operators frequently group the fluvial Green River reservoirs with the Wasatch.

Fouch, (pers. com., 1989) indicates that in the Paleogene part of the oil- and gas-bearing strata of the second system in the Uinta basin, most reservoirs formed in an internally-drained intermontane depositional system. The Paleogene strata of the second system can be related to two major phases of lake development that gave rise to deposition of sediments that became petroleum source and reservoir rocks, tar sandstone, thick sequences of evaporite units, oil shale, and local uraniferous beds. Principal oil- and gas-bearing sandstone reservoir rocks are diagenetically altered fluvial channel, deltaic, and open lacustrine sandstones including turbidites (in Altamont), that formed near the lake margin, and nearshore lacustrine bars and beaches that apparently developed parallel with the northeastern margin of a large lake.

Lake sediments of the first phase of development are typical of deposition in shallow water. Although permanent lakes existed, many were intermittent, and large areas were subject to long periods of subaerial exposure and soil-forming processes and fluvial deposition was extensive.

During the second phase of intermontane lake development in early Eocene to early Oligocene time, a single large lake complex developed and reached its greatest areal and volumetric extent. The thickest fluvial and lacustrine sequence formed near the Altamont field in front of the rising Uinta Mountains along the central segment of the axis of the subsiding Unita basin. In this area, more than 3,000 m of Paleocene and Eocene lacustrine rocks are preserved. The largest complex of fluvial sandstones that became gas reservoirs (Colton and Wasatch Formations) formed on an alluvial deltaic plain that bounded a large lake (Lake Uinta) in the area of the present-day southeast quadrant of the basin. The latter reservoirs have been tested in Natural Buttes and other fields that historically have been sites of DOE-funded research.

Rocks of the first phase of sedimentation produce oil and gas from deeply buried, overpressured, fractured reservoirs in the Greater Altamont-Bluebell field (Fouch, 1975, 1981, 1985; Fouch and Cashion, 1979). Though overpressured strata exist locally, second phase rocks yield oil and/or gas primarily from normally pressured rocks at Altamont, Bluebell, Red Wash, Natural Buttes, Pariette Bench, and other fields (Pitman and others, 1982,1986) (fig. 3).

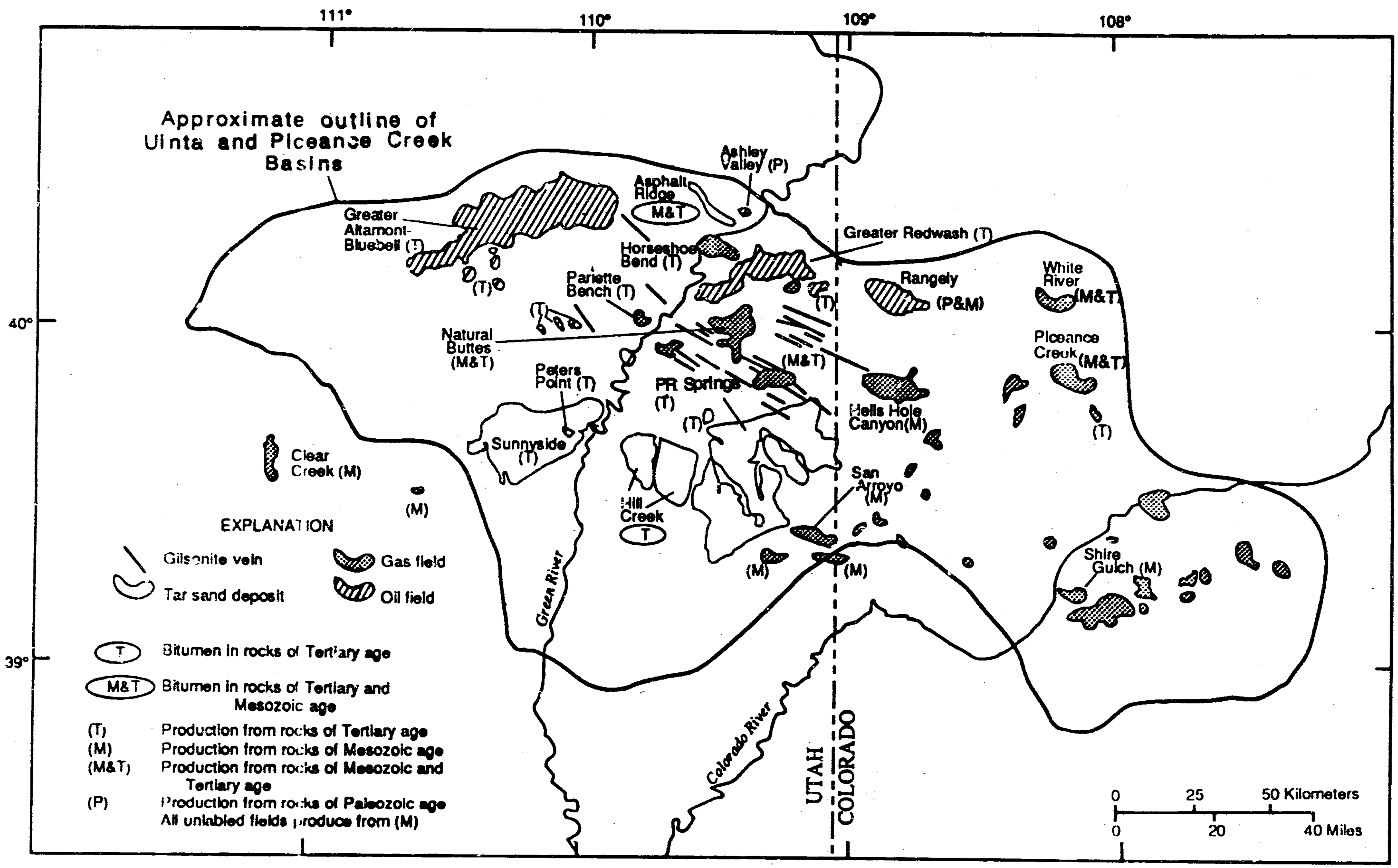

Figure 3.--Distribution and type of principal hydrocarbon resources (excluding coal) in the Uinta and Piceance basins. From Franczyk and others (1989).

RESERVOIR ATTRIBUTES

Preliminary analyses of surface exposures and cored strata indicate that, in most cases, Uinta basin tight reservoirs were formed in bedload and mixed load stream channels. In general, bedload and mixed-load stream systems form sand bodies that vary greatly in size and shape, and as a result, form reservoir bodies that vary greatly in size, character, and thus, reservoir quality. Uinta basin tight reservoirs reflect this fundamental variability. As a result, in our assessment of the basin's tight reservoirs we are attempting to determine those factors that quantify the size of individual reservoirs and their heterogenities, and the sum effect of these factors on the resources present.

Our study indicates that the marginal-lacustrine channel-form bodies of the basin's south flank can be separated into two distinct types with respect to geometry and width/depth (W/D) ratios. Type one is characterized by a tabular geometry controlled by a planar lower bounding surface, an average channel depth of 7.6 m, and an average W/D ratio of 8.9. The planar channel bottom results from underlying resistant carbonate units whose early lithification restricted downcutting and caused more extensive lateral channel migration compared to that of streams forming type two sandstone bodies. Type two bodies are characterized by a lenticular geometry, by an average channel depth of 5.7 m, an average W/D ratio of 3.6, and a concave-upward lower bounding surface. The absence of resistant carbonate rocks underlying streams that deposited type two sand bodies resulted in stream channels that, although similar in size, did not migrate laterally as much as those sand bodies of type one. This researcn indicates that the size of individual marginal-lacustrine channel sandstone bodies (reservoir units) is largely dependent upon induration of substrate across which streams flow.

Our recent analyses of core, production, and drill-stem test data indicate that deeply buried overpressured, tight gas strata are characterized by reservoirs whose matrix permeability values are at, or commonly less than 0.1 md and whose porosity values. most of which is secondary porosity, range from 5 to 10%. However, these same strata contain open fractures and transmissivity (T) values that are commonly high through producing intervals . Combined primary and secondary porosity values of 10-16% are common in normally pressured oil and gas reservoirs and matrix permeability values may be as high as l d. T values for such sequences can be relatively high because of their high matrix permeability. Gas-bearing sandstone reservoirs in the basin that commonly contain porosity values that range from 8-16%, but whose matrix permeability values are 0.1 md or less, are frequently termed "tight gas" sandstones. Transmissivity values for productive "tight gas" intervals are apparently very low because of few natural open fractures (also see Knutson and Hodges, 1981); relatively few natural open fractures have been observed in core of the "tight" intervals. However, production is best in these latter units where some natural mineralized open fractures have been found in cored "tight" gas strata.

Previous petrographic and petrophysical work in the basin (Keighin and Fouch, 1981; Keighin and Sampath, 1982; Pitman, and others, 1982) has shown that the sandstone reservoirs are predominantly fine-grained litharenites and sublitharenites. Rock fragments, primarily of chert and fine-grained sedimentary rocks are abundant. Although deformation of weak grains has occurred, chemical diagenesis has had a much larger effect on reservoir quality. Porosity is mainly secondary and silica and several generations of authigenic calcite, dolomite and ankerite form cements. Where carbonate cement has been incompletely dissolved, abundant authigenic illite, partially ordered mixed-layered illite-smectite, and small amounts of chlorite partly to completely fill secondary pores.

During the past year core samples were collected from four wells in the deeper part of the basin. Nearly all samples have been prepared for analyses. In addition, core plugs have been collected from the Upper Cretaceous Mancos B and submitted for special core analyses.

THERMAL MATURATION

During the year thermal maturity studies were conducted in the Uinta basin to more accurately define areas of high gas potential, to aid investigations of reservoir diagenesis, and to acquire an improved understanding of the burial and thermal history of the tight gas-bearing sandstones in the basin. During our earlier involvement with DOE-supported research in the Uinta basin (Johnson and Nuccio, 1984; Nuccio and Johnson, 1986; Nuccio and Johnson, 1988), the level of thermal maturity for the upper Cretaceous Mesaverde Group was determined for all but the more deeply buried parts of the basin, where the Mesaverde has not been penetrated by drill holes.

In these earlier studies, coal rank data were obtained from published reports of samples taken from coal mines in the Mesaverde Group and from vitrinite reflectance analyses of samples from outcrops and drill holes. A structure contour map drawn on the top of the Upper Cretaceous Castlegate Sandstone (Johnson, 1986) was utilized to determine the relationship between structural configuration and the development of thermal maturation. In terms of coal rank, thermal maturity of the Mesaverde ranges from sub-bituminous C along the northwestern margin of the basin to low-volatile bituminous in the south-central part of the basin. Along the southern and eastern margins of the basin, coal rank ranges from sub-bituminous B to C. Isorank lines (lines of equal coal rank) are subparallel to the structural attitudes of the Castlegate Sandstone. Isorank lines dip gently towards the structurally deeper part of the basin, intersecting the structural attitudes of the Castlegate at a low angle. Some workers might interpret this relationship of thermal maturity to structure as the result of thermal maturity occurring contemporaneously with structural deformation. However, this interpretation may be incorrect, because in most cases the isoreflectance lines were determined by linear extrapolation from only a few measured values. Recent work by Law, and others (1989) shows that linear projections from only a few vitrinite reflectance values through a thin sampling interval may be in error due to local or even basin-wide perturbations of the thermal gradient caused by convective heat transfer related to the origin of abnormally high fluid pressures.

In order to evaluate, more accurately, the temporal relationship between structure and thermal maturity and to determine what the nature of the paleo-thermal gradient may have been, additional core and cuttings samples were collected from four wells and analyzed for vitrinite reflectance. Additional outcrop samples of coal and carbonaceous shale from the Tertiary Green River and Uinta Formations were collected and analyzed for vitrinite reflectance. These data indicate that vitrinite reflectance values generally increase with increasing age of the rock. Rocks of the same age show a general decrease in maturity from south to north, which may be related to the observation by Chapman and others (1984) of decreasing present-day thermal gradients from south to north. Within the Green River and Uinta Formations, vitrinite reflectance ranges from about 0.40% (immature with respect to oil and gas generation) to 0.70% (thermally mature with respect to oil and gas generation) around the margins of the basin. From these surface data, estimates can be made of the maximum amount of burial in the basin and the depths at which hydrocarbons were generated.

FRACTURE STUDIES

The presence of fractures, whether natural or induced, have been shown to be of great importance to economic production of gas from tight reservoirs at the MWX Site in the Piceance basin. An investigation of surface fractures in the Uinta basin was initiated during the year by Marilyn Grout and Earl Verbeek. Their initial investigations were focused on the well-known gilsonite dikes in the eastern part of the Uinta basin (fig. 3). Gilsonite, a type of asphaltic oil, occurs as fracture-filled dikes in the Eocene Green River, Uinta, and Duchesne Formations. Older rocks are not exposed in the vicinity of the dikes, although the trace of one of the dikes can be inferred to continue into the Paleocene and Eocene Wasatch Formation. Most of the dikes strike N 40° W to N 70° W and are nearly vertical. The traces of many of the dikes can be physically followed for distances of several miles. The dikes range in thickness from less than 2 cm to 4.5 m.

On geologic maps the dikes are shown as continuous features. However, more detailed investigations by Grout and Verbeek show that the dikes are much more complex. They consist of multiple, subparallel, discontinuous segments that are connected by cross-fractures which are also filled with gilsonite. These cross-fractures occur at right angles to the northwest-trending dikes and are thin, ranging from 2 to 12 cm. The presence of these cross-fractures demonstrates that extension, parallel and perpendicular to the major dike trend, occurred during the forceful intrusion of the dikes. Most of the dike walls are moderately-to-heavily stained with limonite and some are coated with a druse of a lustrous transparent mineral, indicating that a fluid has migrated through the fractures now occupied by gilsonite. Grout and Verbeek tentatively think that the dikes represent pressure-induced fractures resulting from abnormally high fluid pressures in the Green River Formation. They believe that the precursor to gilsonite, a liquid hydrocarbon derived from the Green River Formation, was forcibly driven into the pressure-induced fractures where it then lost many of the more volatile components and formed gilsonite.

The ratio of maximum to minimum horizontal stress, as suggested by the dike geometry, must have been small at the time of their formation. The apparently small ratio probably increased with time, culminating in a regional set of joints that strike subparallel to the major dike set. Dike and joint walls have much different lengths and geometries, despite being subparallel. None of the joints are filled or coated with gilsonite, even where the joints are within 1 m of a dike. Grout and Verbeek conclude that (1) the dikes and joints formed at approximately the same time, although, the joints slightly post-date the dikes, and (2) the dikes are pressure-induced hydraulic features, whereas the joints that are subparallel to them are not.

The age of the joint system in the Uinta basin is presently unknown, however, Grout and Verbeek have noted from their previous work in the Piceance basin that the overall joint system in the area of the gilsonite dikes is similar to joints associated with igneous dikes in the Piceance basin. They suggest that if further work supports this similarity, an opportunity exists in the Piceance basin to radiometrically date those igneous dikes, and thus, date the time of the gilsonite intrusions in the Uinta basin.

UINTA BASIN DATA BASE

A geologic and engineering data base for the Uinta basin was initiated during the year. The purpose of the data base is to accumulate geologic and engineering data that can be utilized in the geologic characterization, resource estimates, and other studies of low-permeability sandstone reservoirs in the Uinta basin. Categories of information that may be included in the data base are enumerated below:

Data Type:

1. Drill hole or measured section name
2. API number
3. Surface elevation
4. Spot location (township-range and longitude-latitude)
5. Kelly Bushing elevation
6. Spud date
7. Completion date and total drilling depth
8. Producing intervals and initial potentials
9. Perforated intervals
10. Drill-stem test intervals
    - Top of packer
    - Bottom of packer
    - Initial shut-in pressure
    - Final shut-in pressure
    - Fluid recoveries
        - Fluid composition
        - Fluid volumes
    - Temperatures
    - Calculated permeability
    - Calculated fluid-pressure gradient
11. Cored intervals
    - Core description
    - Core location (depository)
        - Core plug analyses
        - Porosity
        - Permeability

Analyzed interval

Location of core analysis report

12. Geophysical drill hole logs

Sonic combination

Interval

Scale

Digitized

Formation density combination

13. Electrical drill hole logs

Laterolog combination

Microlog

Spontaneous potential combination

Induction log combination

14. Other drill hole logs

Gamma ray combination

Lithologic log

Caliper survey

Temperature survey

Neutron

Sidewall neutron porosity

Mudlog

15. Liner and casing record

16. Formation tops

By driller

By operator

By scientist

By PI or other source

17. Formation bases

18. Bottom hole temperature

19. Production dates

20. Time marker tops

21. Hydrocarbon source rock

Vitrinite reflectance (Rm)

Rm value

Sample type (cuttings/core)

Lithology

Depth

Formation

Rock-Eval pyrolysis

Total organic carbon

Temperature of pyrolysis

S1,2,3 values

Production index

Hydrogen index

Oxygen index

Interpreted kerogen type

Chromatography

Total extracted hydrocarbons

22. Mud Weights

Calculated fluid pressure gradients

23. Petrographic/diagenetic data

Lithology

Depth

Framework grains

Relative abundance (%)

Principal clay type

Fracture-filling minerals

Isotopic composition

24. Drilling fluids

25. Completion medium and methods

26. Hydrocarbon type

Gas

Gas/oil ratio

Chemical composition

Isotopic composition

Oil

27. Net pay interval

As of the end of FY 89, data available through the system includes the following:

1. Permeability and porosity data (more than 1000 values)
2. Oil and water saturation values (more than 650 entries)
3. Lithologic descriptions (more than 400 entries)
4. Formation tops (more than 4000 entries)
5. Well location and production information (nearly all wells in basin)
6. Vitrinite reflectance values (more than 100 entries)
7. Grain density (more than 300 entries)

Additional data currently being added to the system include geochemical, petrographic, and drill-stem test data such as bottom-hole temperatures, shut-in pressures, production rates, and calculated permeabilities.

FY 89 PUBLICATIONS

During FY 89 ten reports of investigations were published.

Grout, M. A., and Verbeek, E. R., 1989, Prediction of fracture networks at depth in low-permeability reservoir rocks, Piceance and Washakie basins, western United States (abs.): American Association of Petroleum Geologists Bulletin, v. 73, p. 1158.

Johnson, R. C., and Nuccio, V. F., 1989, Use of vitrinite reflectance profiles to determine timing of structural development in Piceance basin, western Colorado (abs.): American Association of Petroleum Geologists Bulletin, v. 73, p. 369.

Keighin, C. Wm., Law, B. E., and Pollastro, R. M., 1989, Petrology and reservoir characteristics of the Almond Formation, Greater Green River basin, Wyoming, in Coalson, E. B., Kaplan, S. S., Keighin, C. Wm., Oglesby, C. A., and Robinson, J. W., eds., Petrogenesis and petrophysics of selected sandstone reservoirs of the Rocky Mountain region: Rocky Mountain Association of Geologists, p. 281-298.

Krupa, M. P., and Spencer, C. W., 1989, U. S. Geological Survey publications on western tight gas reservoirs: U. S. Department of Energy, DOE/MC/20422-2677, 133p.

Law, B. E., 1989, FY 1988 USGS annual report: U. S. Department of Energy, DOE/MC/20422- 2729, 40 p.

Law, B. E., Nuccio, V. F., and Barker, C. E., 1989, Kinky vitrinite reflectance well profiles: Evidence of paleopore pressure in low-permeability gas-bearing sequences in Rocky Mountain foreland basins: American Association of Petroleum Geologists Bulletin, v. 73, p. 999-1010.

Law, B. E., Spencer, C. W., Charpentier, R. R., Crovelli, R. A., Mast, R. F., Dolton, G. L., and Wandrey, C. J., 1989, Estimates of gas resources in overpressured low-permeability Cretaceous and Tertiary sandstone reservoirs, Greater Green River basin, Wyoming, Colorado, and Utah, in Eisert, J. L., ed., Gas resources of Wyoming: Wyoming Geological Association Fortieth Field Conference Guidebook, p. 39-61.

Rice, D. D., and Johnson, R. C., 1989, Occurrence and geochemistry of natural gases, Piceance basin, northwestern Colorado (abs.): American Association of Petroleum Geologists Bulletin, v. 73, p. 405.

Spencer, C. W., 1989, Review of characteristics of low-permeability gas reservoirs in western United States: American Association of Petroleum Geologists Bulletin, v. 73, p. 613-629.

Spencer, C. W., Law, B. E., Johnson, R. C.,and Crovelli, R.A., 1989, Western tight gas reservoirs - Resources for future (abs.): American Association of Petroleum Geologists Bulletin, v. 73, p. 414.

REFERENCES CITED

Chapman, D. S., Keho, T. H., Bauer, M. S., and Picard, M. D., 1984, Heat flow in the Uinta basin determined from bottom hole temperature (BHT) data: Geophysics, v. 49, p. 453-466.

Fouch, T. D., 1975, Lithofacies and related hydrocarbon accumulations in Tertiary strata of the western and central Uinta basin, Utah, in Bolyard, D. W., ed., Symposium on deep drilling frontiers of the central Rocky Mountains: Rocky Mountain Association of Petroleum Geologists, p.163-174.

Fouch, T. D., 1981, Distribution of rock types, lithologic groups, and interpreted depositional environments for some lower Tertiary and Upper Cretaceous rocks from outcrops at Willow Creek-Indian Canyon through the subsurface of Duchesne and Altamont oil fields: U.S. Geological Survey Oil and Gas Investigations Map, Chart OC-81.

Fouch, T. D., 1985, Oil and gas-bearing Upper Cretaceous and Paleogene fluvial rocks in central and northeast Utah, recognition of fluvial depositional systems and their resource potential: Society of Economic Paleontologists and Mineralogists Short Course No. 19, p. 241-272.

Fouch, T. D., and Cashion, W. B., 1979, Distribution of rock types, lithologic groups, and depositional environments for some lower Tertiary and Upper Cretaceous, and Upper and Middle Jurassic rocks in the subsurface between Altamont oil field and San Arroyo gas field, northcentral Uinta basin: U.S. Geological Survey Open-File Report 79-365.

Franczyk, K. J., Pitman, J. K., Cashion, W. R., Chan, M. A., Donnell, J. R., Dyni, J. R., Fouch, T. D., Johnson, R. C., Lawton, T. F., and Remy, R. R., 1989, Evolution of resource-rich foreland and intermontane basins in eastern Utah and western Colorado: American Geophysical Union, Washington, D. C., 28th International Geological Congress Field Trip Guidebook T-324, 53 p.

Johnson, R. C., 1986, Structure contour map of the Castlegate Sandstone, eastern part of the Uinta basin and the western part of the Piceance Creek basin, Utah and Colorado: U. S. Geological Survey Miscellaneous Field Investigations Map MF-1826.

Johnson, R. C., and Nuccio, V. F., 1984, Thermal maturity of organic matter in Green River Formation, Piceance Creek basin, Colorado [abs.]: American Association of Petroleum Geologists Bulletin, v. 68, p. 492-493.

Keighin, C. W., and Fouch, T. D., 1981, Depositional environments and diagenesis of some nonmarine Upper Cretaceous rocks, Uinta basin, Utah, in Ethridge, F. G., and Flores, R. M., eds., Recent and ancient nonmarine depositional environments as models for exploration: Society of Economic Paleontologists and Mineralogists Special Publication no. 31, p. 109-125.

Keighin, C. W., and Sampath, K.,1982, Evaluation of pore geometry of some low-permeability sandstones, Uinta basin, Utah: Journal of Petroleum Technology, v. 34, p. 65-70.

Knutson, C. F., and Hodges, L. T., 1981, Development of techniques for optimizing selection and completion of western tight gas sands, comparison of core, geophysical log, and outcrop information, phase III report: U.S. Department of Energy Report, DOE/BC10005-3, 54 p.

Law, B. E., Nuccio, V. F., and Barker, C. E., 1989, Kinky vitrinite reflectance well profiles: Evidence of paleopore pressure in low-permeability gas-bearing sequences in Rocky Mountain foreland basins: American Association of Petroleum Geologists Bulletin, v. 73, p. 999-1010.

Nuccio, V. F., and Johnson, R. C., 1986, Thermal maturity of the lower part of the Upper Cretaceous Mesaverde Group, Uinta basin, Utah: U. S. Geological Survey Miscellaneous Field Study Map MF-1842.

Nuccio, V. F., and Johnson, R.C., 1988, Surface vitrinite reflectance map of the Uinta, Piceance, and Eagle basins area, Utah and Colorado: U. S. Geological Survey Miscellaneous Field Study Map MF-2008-B.

Pitman, J. K., Anders, D. E., Fouch, T. D., and Nichols, D. J., 1986, Hydrocarbon potential of nonmarine Upper Cretaceous and lower Tertiary rocks, eastern Uinta basin, Utah, in Spencer, C. W., and Mast, R. F., eds., Geology of tight gas reservoirs: American Association of Petroleum Geologists Studies in Geology No 24, p.235-252.

Pitman, J. K., Fouch, T. D., and Goldhaber, M. B., 1982, Depositional setting and diagenetic evolution of some Tertiary unconventional reservoir rocks, Uinta basin, Utah: American Association of Petroleum Geologists Bulletin, v. 66, p. 1581-1596.

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