Open-File Report 2008–1367
Version 1.0

Assessment of the Mowry Shale and Niobrara Formation as Continuous Hydrocarbon Systems, Powder River Basin, Montana and Wyoming

by Lawrence Anna [lanna@usgs.gov] and Troy Cook [tcook@usgs.gov] U.S. Geological Survey, Denver, CO 80225, AAPG Section Conference, July 09, 2008

Introduction

A recent U.S. Geological Survey (USGS) oil and gas assessment of the Powder River Basin (PRB), Wyoming and Montana, identified the Upper Cretaceous Mowry Shale and Niobrara Formation as the primary hydrocarbon sources for Cretaceous conventional and unconventional reservoirs. Cumulative Mowry-sourced petroleum production is about 1.2 BBO (billion barrels of oil) and 2.2 TCFG (trillion cubic feet of gas) and cumulative Niobrara-sourced oil production is about 520 MMBO (million barrels of oil) and 0.95 TCFG. Burial history modeling indicated that hydrocarbon generation for both formations started at about 0.60 percent R_o at depths of about 8,000 ft. At maximum depths, R_o for the Mowry is about 1.2 to 1.3 percent and about 0.80 percent for the Niobrara.

The Mowry and Niobrara continuous reservoirs were assessed using a cell-based methodology that utilized production data. The size of each cell was based on geologic controls and potential drainage areas in analog fields. Current and historical production data were used to determine the estimated ultimate recovery (EUR) distribution for untested cells (fig. 1). Only production data from unconventional fractured shale reservoirs with vertical wells were used. For the Mowry, the minimum, median, and maximum total recovery volumes per cell for untested cells are (1) 0.002, 0.25, and 0.35 MMBO, respectively; and for the Niobrara (2) 0.002, 0.028, and 0.5 MMBO. Sweet spots were identified by lineaments and faults, which are believed to be areas having the greatest petroleum potential; an upper limit of 8,000 ft depth was defined by overpressuring caused by hydrocarbon generation. Mean estimates of technically recoverable undiscovered continuous resource for the Mowry are 198 MMBO, 198 BCF (billion cubic feet of gas), and 11.9 MMBNGL (million barrels of natural gas liquid), and those for the Niobrara are 227 MMBO, 227 BCFG, and 13.6 MMBNGL (table 1).

Table 1. Estimated undiscovered technically recoverable resources for the Mowry and Niobrara, PRB.

Total Petroleum Systems (TPS) and Assessment Units (AU)	Field type	*Total undiscovered resources*											
		Oil (MMBO)				*Gas (BCFG)*				*NGL (MMBNGL)*			
		F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
Mowry TPS													
Mowry Continuous Oil AU	*Oil*	116.99	189.32	306.38	197.61	103.35	185.50	332.95	197.61	5.56	10.91	21.37	11.86
Niobrara TPS													
Niobrara Continuous Oil AU	*Oil*	135.53	217.49	349.03	226.67	119.54	213.10	379.87	226.67	6.43	12.53	24.40	13.60

EUR Distribution

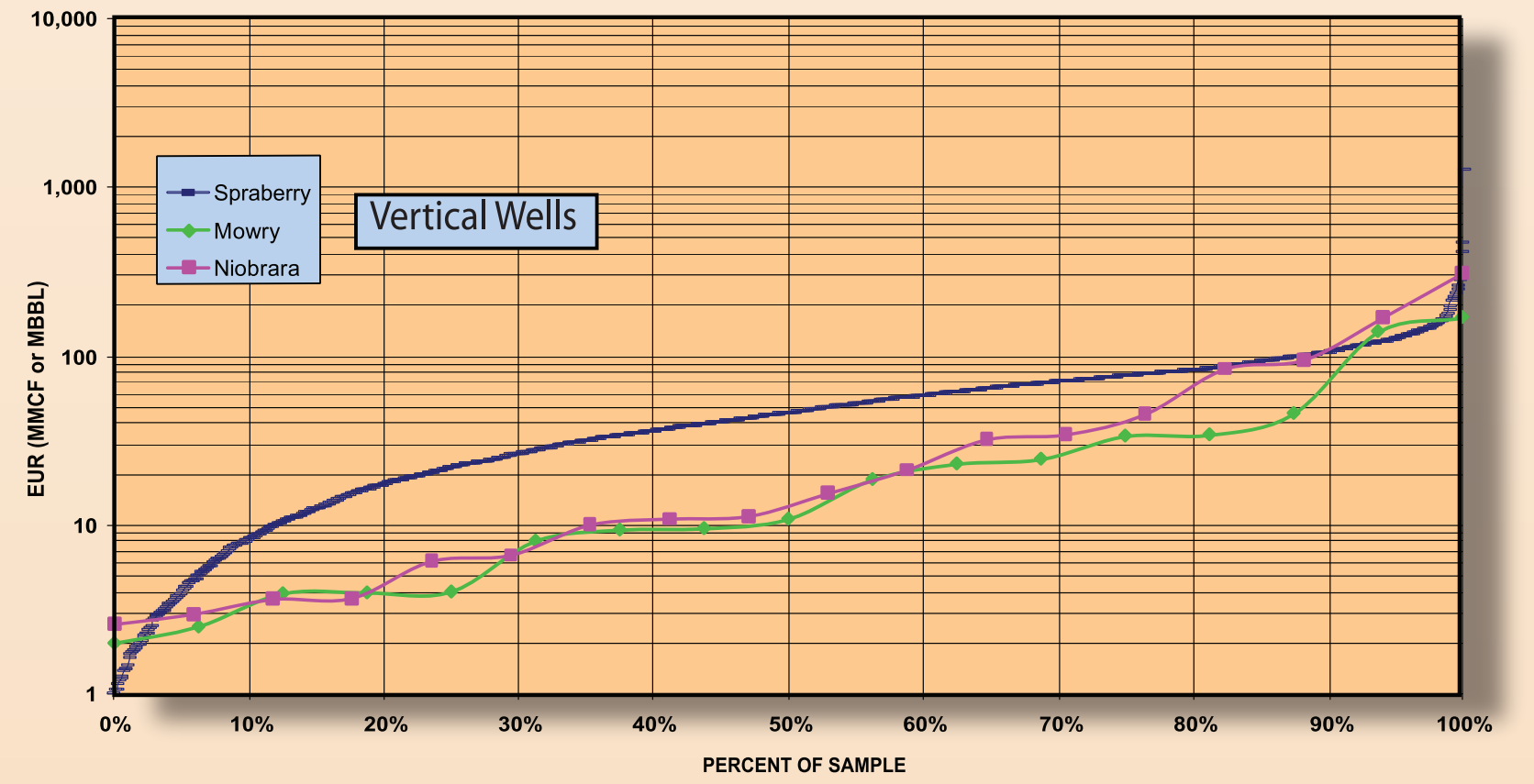

Figure 1. Estimated ultimate recovery distribution for Mowry and Niobrara Formations in the Powder River Basin and Spraberry Formation in the Permian Basin-(minimum removed).

Mowry and Niobrara EURs shown in figure 1 represent a minimum distribution, being based on vertical wells only. Horizontal drilling, state of the art completion practices, and comprehensive fracture and fault analyses may increase the Mowry and Niobrara EUR distribution similar to the Permian Spraberry Formation EUR in the Permian Basin, Texas.

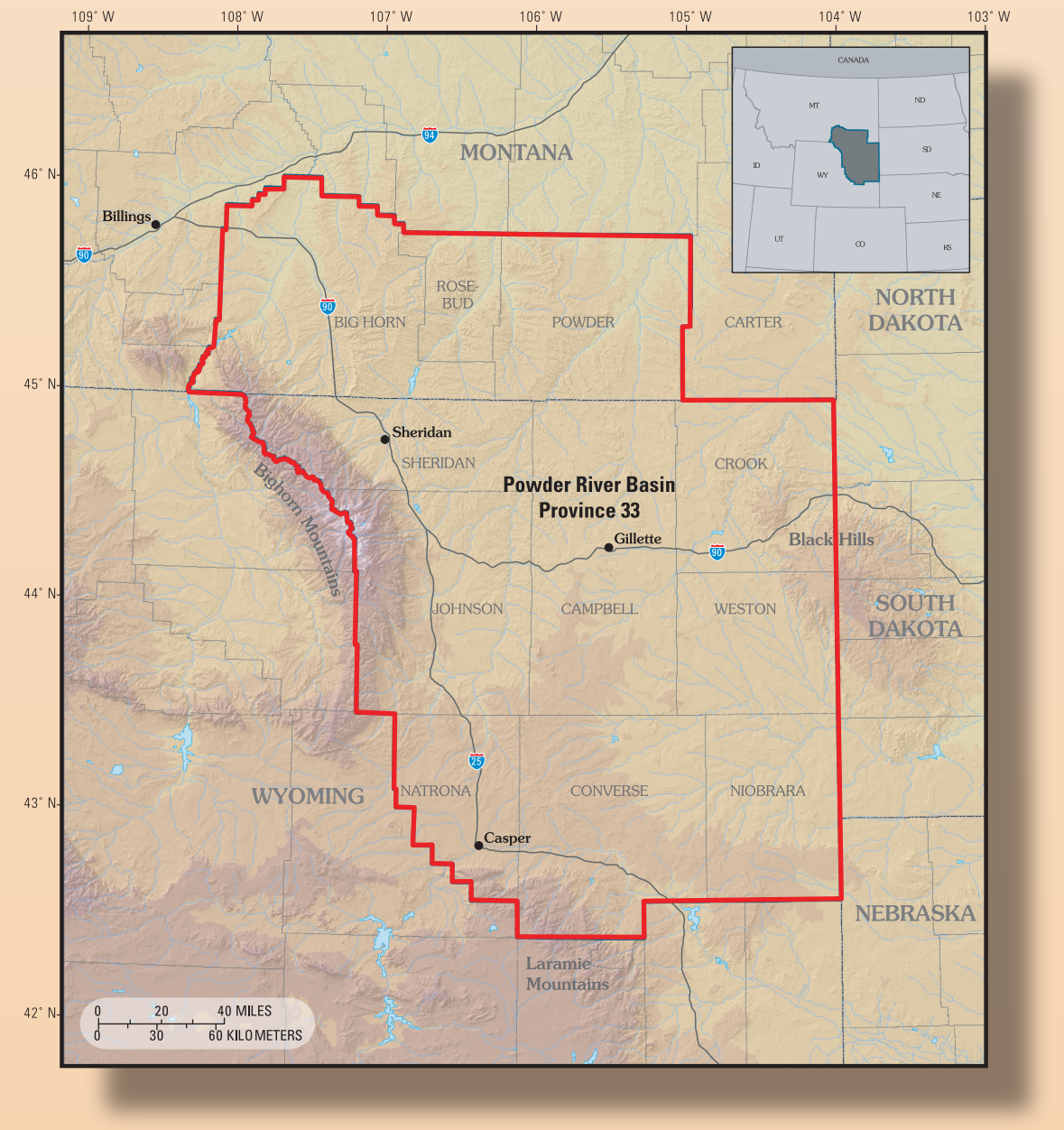

Figure 2. Map showing boundary of Powder River Basin Province (red line).

U.S. Department of the Interior
U.S. Geological Survey

Niobrara Burial History

Thermal maturity of the Niobrara Formation was evaluated using standard methods, including R_o and depth plots, Rock-Eval pyrolysis data, correlation of resistivity and R_o, and constructing burial history models for the east and west sides of the PRB.

The software PetroMod 1 D (Integrated Exploration Systems) was used to model burial history curves. Two 1-D burial history plots were used to determine (1) depth at which oil generation started; (2) depth at which maximum oil generation occurred; and (3) age range of petroleum generation. The models were calibrated to various sources of R_o data, including Higley and others (1997), Hunt (1979), and Surdam and others (1994). Results show that on the east side of the basin, the Niobrara did not reach thermal maturity, but on the west side hydrocarbon generation started at the base of the Niobrara, at a R_o of 0.6 percent, about 30 Ma at a depth of about 8,000 ft (fig. 3). Model results also indicate that Niobrara reached a maximum R_o of about 0.68 percent at about 10 Ma at a depth of about 9,700 ft and is currently at about 0.68 percent. The modeled R_o values indicate that the Niobrara probably never reached a level of thermal maturation to generate nonassociated gas, but could have reached gas-generation temperatures in the deepest parts of the basin.

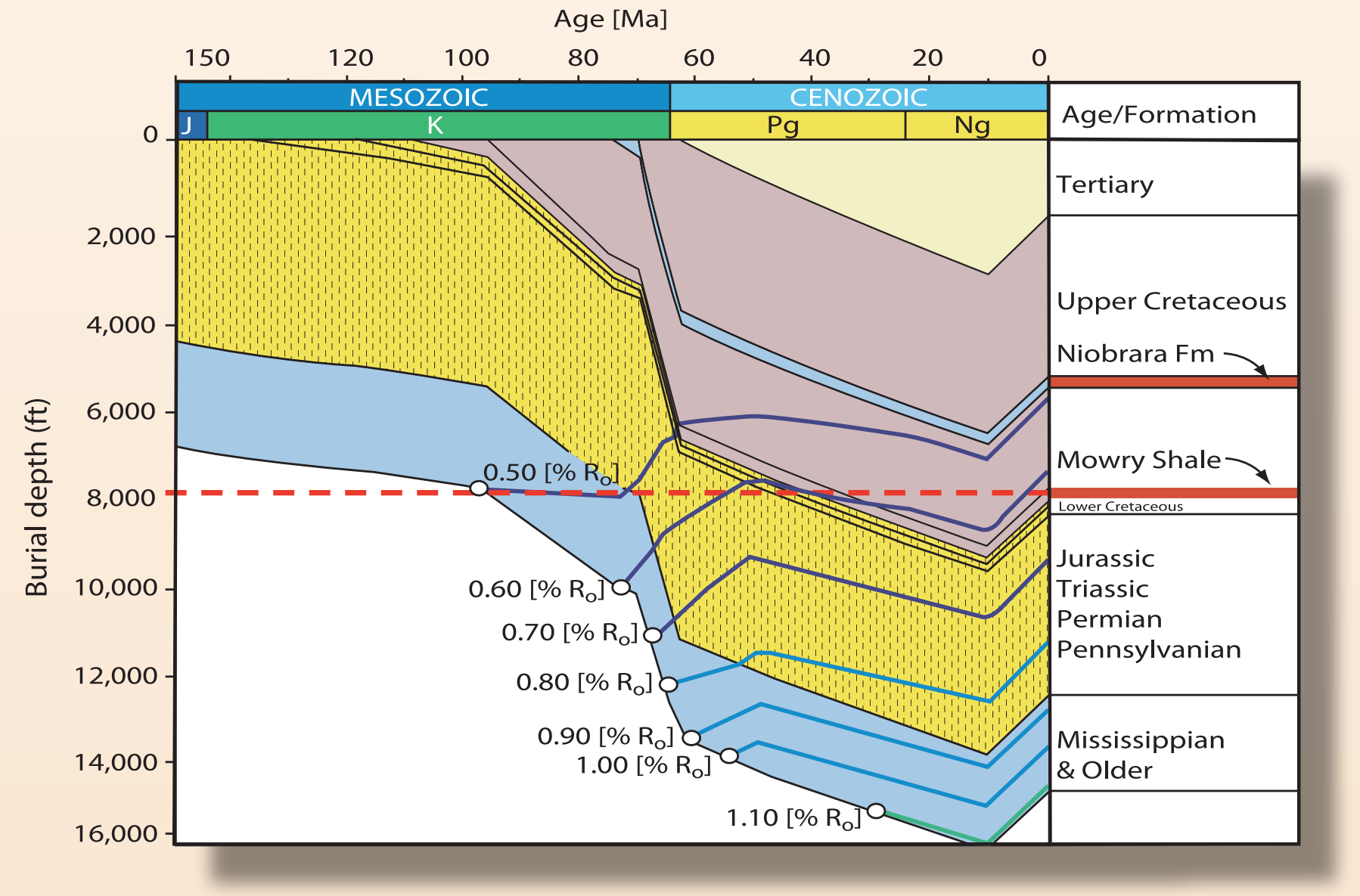

Figure 3. Burial history curve for Niobrara formation on east side of the Powder River Basin.

Mowry Burial History

Because of hydrocarbon mixtures, types, and temperatures, the Mowry Shale probably started generating hydrocarbons at a depth of more than 7,000 ft (Nixon, 1973). Basin and R_o modeling, for example, show that significant hydrocarbon generation could have started at about 8,000 ft (fig. 4). On the east side of the basin, results show that at the base of the Mowry, hydrocarbon generation started at a depth of about 8,000 ft, and a R_o of 0.6 percent at about 50 Ma, which started formation overpressuring within the Mowry. Model results also indicate that on the east side, R_o values didn't reach more than 0.63 percent and is currently about 0.63 percent. On the west side of the basin, results show that hydrocarbon generation started at about 65 Ma at a depth of about 8,000 ft and a R_o of 0.6 percent, which also started formation overpressuring. Model results further indicate that the Mowry reached peak R_o of about 0.9 percent at about 10 Ma at a depth of about 13,000 ft, and is currently at about 0.92 percent. The model and R_o values show that the Mowry would be in the gas generation window at depths more than 13,000 ft.

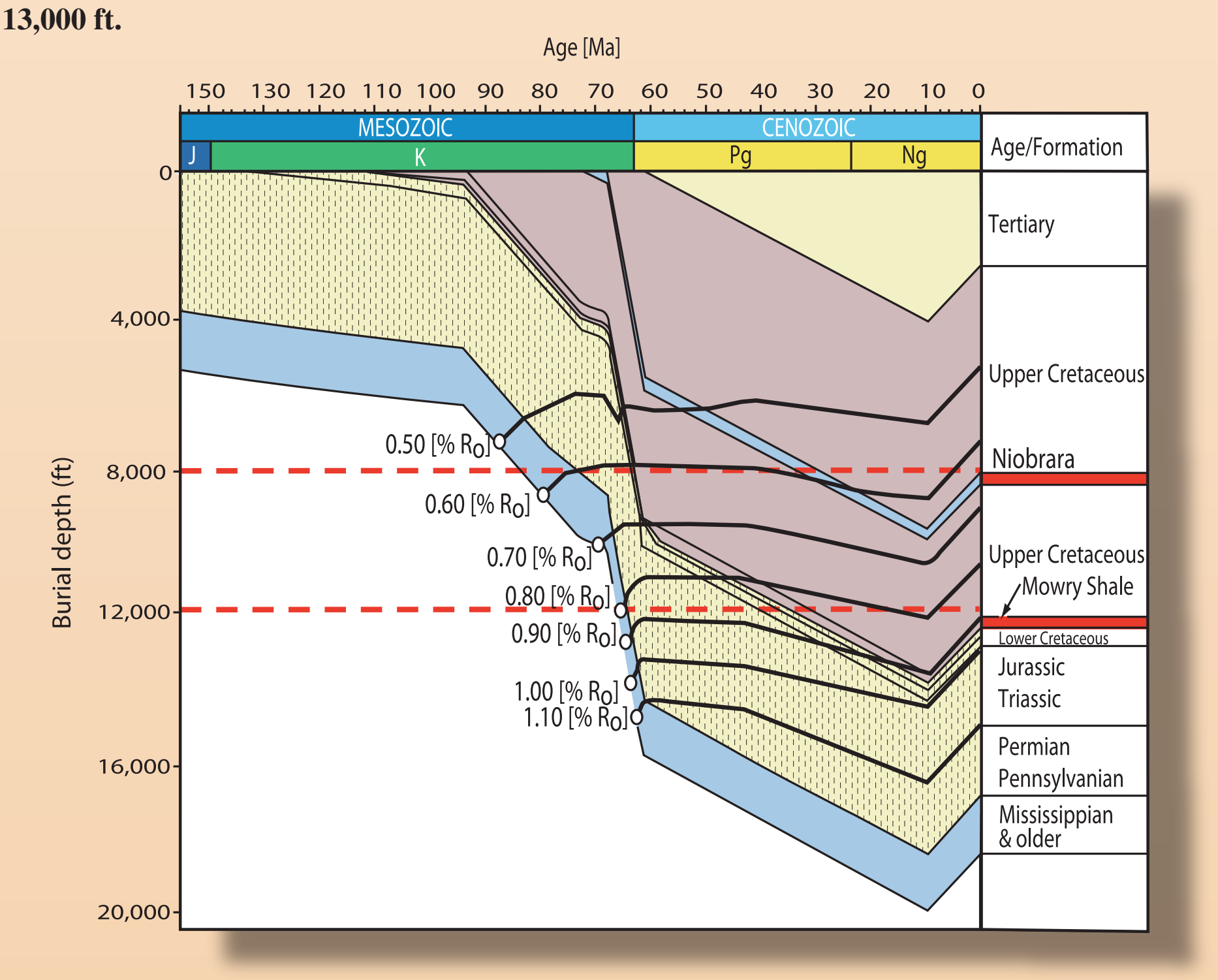

Figure 4. Burial history curve for the Mowry Shale on west side of the Powder River Basin.

Mowry as a Continuous Reservoir

The Mowry Shale is a self-contained petroleum system; it is a hydrocarbon source rock for Lower Cretaceous reservoirs but is also a reservoir in itself, which is typical of a continuous petroleum system. Production from the Mowry is enhanced by fracture permeability and storage, but there is a possibility that it contains thin, fine-grained siltstones, which have been mapped in the Bighorn Basin to the west of the PRB (Davis and Byers, 1989). The siltstones could increase porosity and storage of the reservoir that supplies oil to fracture networks. Mowry Shale thicknesses average about 250 ft and range from about 100 ft to more than 400 ft. Three regionally persistent and lithologically distinctive units can be mapped within the Mowry, all bounded by bentonite markers that divide the formation into time intervals.

Geophysical log resistivities are typically used to define lithologies in the Mowry. For example, high resistivity indicates clay-rich shale and bentonite. However, the presence of hydrocarbons may alter the resistivity signature; therefore, lithologic interpretation should be made with caution. Plots of API gravity and gas/oil ratios (GOR) of several fields producing from Lower Cretaceous reservoirs (figs. 5 and6) show decreasing GORs from west to east. This may indicate that (1) generated oil was being degraded along its migration path from west to east, or (2) API is a function of generation temperature and early-generated oil migrated farthest east. Therefore, most of the oil may be from the Mowry Shale that was generated from depths greater than 8,000 ft and migrated eastward. Only along parts of the basin margin is there some change in oil characteristics because of degradation (Wenger and Reid, 1961).

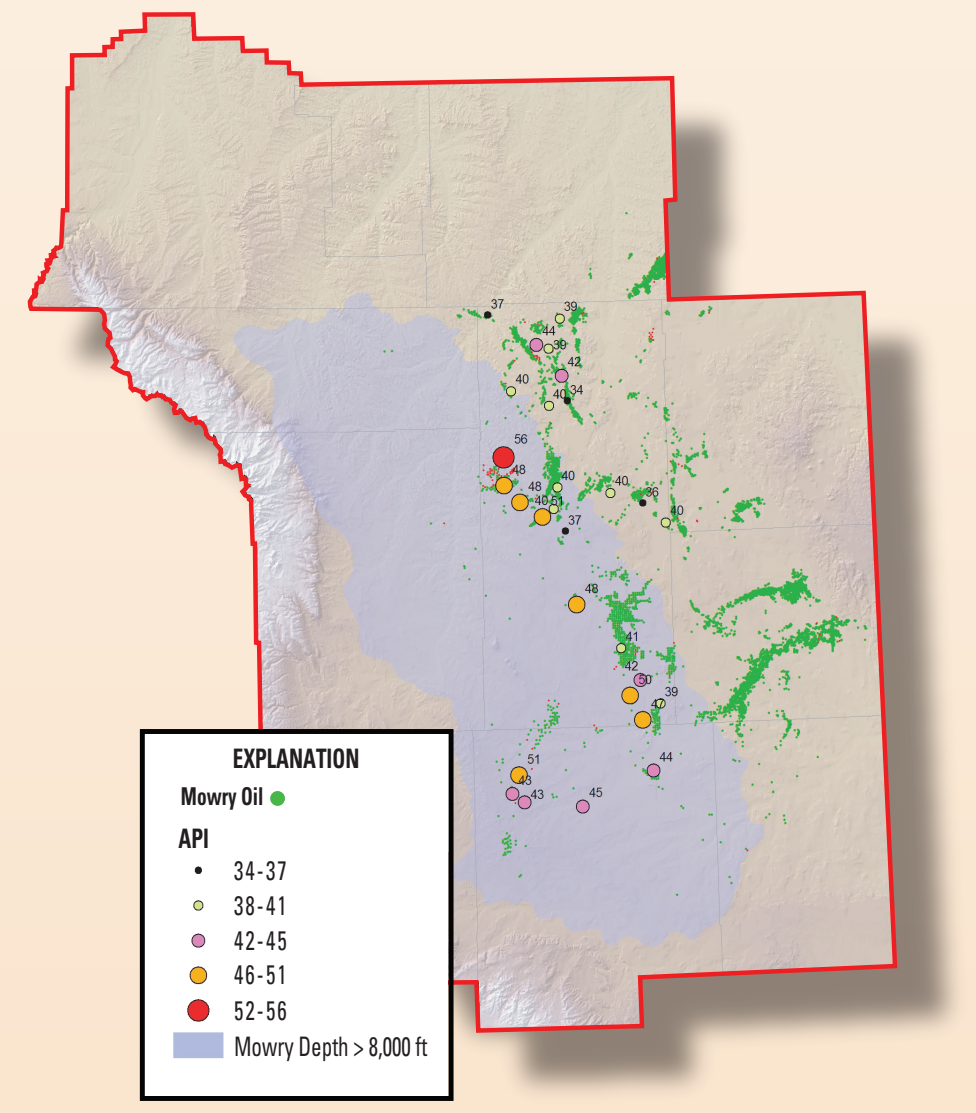

Figure 5. Map showing Mowry API gravity, Mowry generation area (depth > 8,000 ft), and Lower Cretaceous production (green).

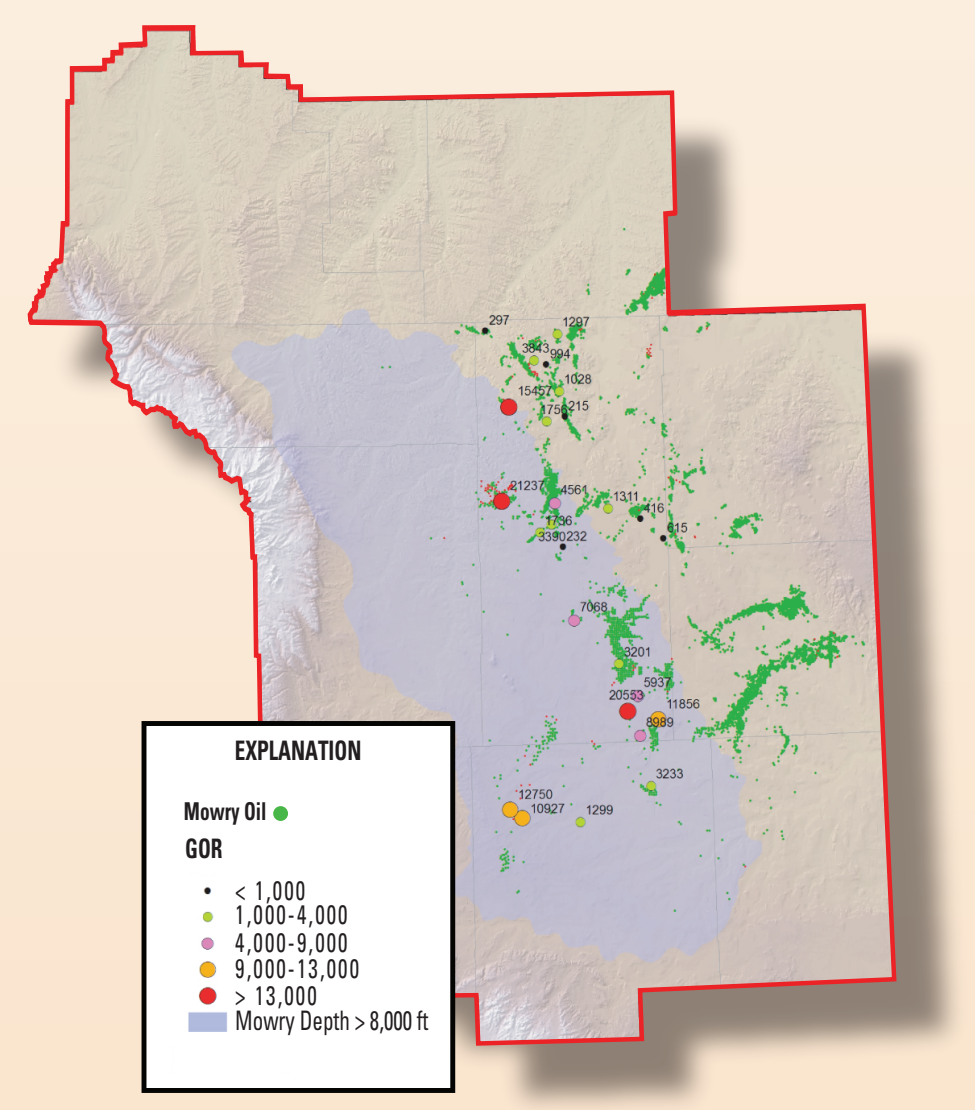

Figure 6. Map showing Mowry gas/oil ratios (GOR), generation area (depth > 8,000 ft), and Lower Cretaceous production (green).

Niobrara as a Continuous Reservoir

The Niobrara is also a self-contained petroleum system, containing both source and reservoir rocks. Production is enhanced by fracture permeability and various amounts of matrix porosity as reservoir storage. In the PRB, Niobrara thicknesses range from 50 ft near the Black Hills to more than 600 ft along the west flank of the basin, with an average about 400 ft. It is about 450 ft thick in the deepest parts of the basin.

Production data (IHS Energy Group, 2006) indicate that the Niobrara has cumulative production of almost 600 MBO and 1.9 BCFG from 34 wells over a 30-year reporting period. However, few individual wells have EURs exceeding 100,000 BO, with most having less than 50,000 BO. Individual well production plots indicate that most wells produce little if any water from either oil-or gas-designated wells. Most operators target middle to upper Niobrara intervals, although lower zones are also a target. Water saturations (Sw) in chalk reservoirs producing commercial quantities of oil are generally less than 50 percent (mean for deep Denver Basin Niobrara is 0.39 percent). Intervals with saturation above 50 percent are commonly marginal or noneconomic. However, highly chalky intervals with high pore surface area may produce economic quantities of oil at saturations greater than 50 percent.

Plots of API gravity and GOR of Upper Cretaceous oils (figs. 7 and 8) show a northwest-southeast trend. GOR values decrease sharply northwest and southeast from the Belle Fourche arch, and API values decrease only northwest of the arch. Additionally, oil from fields east of the Niobrara generation areas (Finn-Shurley field) have similar API values, as does the southern half of the Niobrara generation area, but GOR values are similar to those northwest and southeast of the arch. The arch has high API and GOR values, and both high and low values northwest of the arch. Southeast of the arch and east of the generation area there is high API but low GOR values. Because there is little hydraulic potential to move oil from the Niobrara generation area eastward, it is possible that those fields were locally sourced. Although the API and GOR data are not conclusive, they indicate that Upper Cretaceous fields are producing oil that appears similar to Niobrara-generated oil. The data also indicate that pathways forming the generation area to the eastern fields were relatively unobtrusive, not the tortuous routes commonly present in fractured shale (Neuzil, 1986). (Continued above, next column).

There appears to be no correlation, however, when comparing sweet spot zones (mapped as lineaments) and current Niobrara production in the PRB. This discrepancy may be due to several factors including (1) Niobrara production rates are not dependent on fractures and faults, (2) sweet spot areas are incorrectly mapped, (3) there is not sufficient control to make a valid comparison, (4) there is a bias in targeting other reservoirs rather than the Niobrara, therefore its potential has not been established; (5) the Niobrara is used as a bailout zone, independent of fracture potential; and (6) increase in shale content in the western part of the basin may increase fracture length but decrease spacing compared to the chalky and brittle intervals.

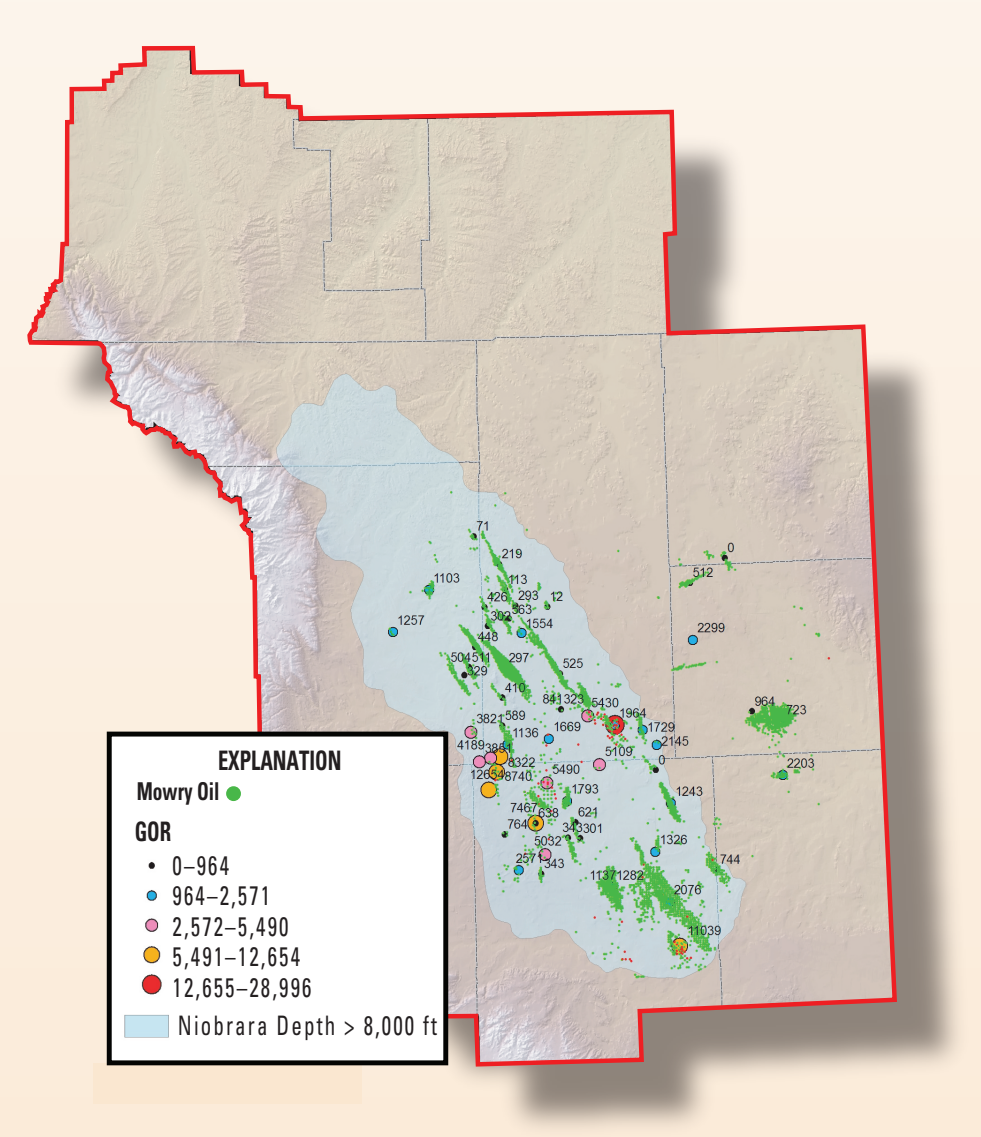

Figure 7. Map showing Niobrara gas/oil GOR and generation area (depth > 8,000 ft), and Upper Cretaceous production (green).

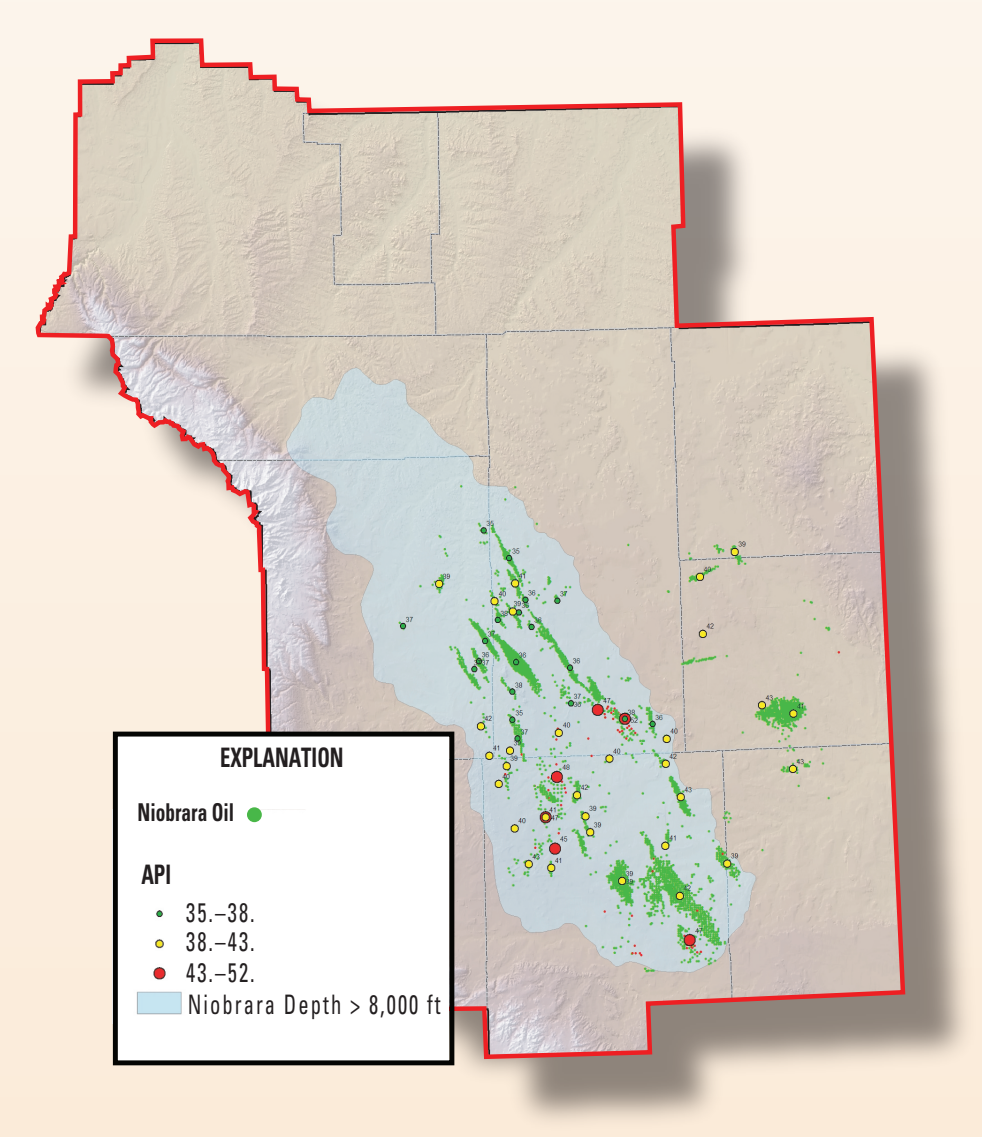

Figure 8. Map showing Niobrara API gravity, Niobrara generation area (depth > 8,000 ft), and Upper Cretaceous production (green).

Lineament Analysis

Most continuous reservoirs have sweet spots where production may be enhanced by an increase in secondary porosity or permeability. Several sweet spots were identified within the Mowry Shale associated with major lineaments and lineament zones (Slack, 1981; Anna, 1986a, 1986b; Maughan and Perry, 1986.) The lineaments are assumed to be associated with zones of structural deformation and may be areas of enhanced secondary porosity and permeability in the Mowry (figs. 9 and 10). For example, lineaments that coincide with the Belle Fourche arch may represent areas of increased fracture intensity along the arch because of flexing or enhanced stress, or they may coincide with folds where fractures develop as a mechanical response to folding. Most current production from the Mowry in the PRB is within sweet spot areas, but some consider the correlation circumstantial because the lack of control may not be statistically representative or current lineament locations do not represent all structural zones.

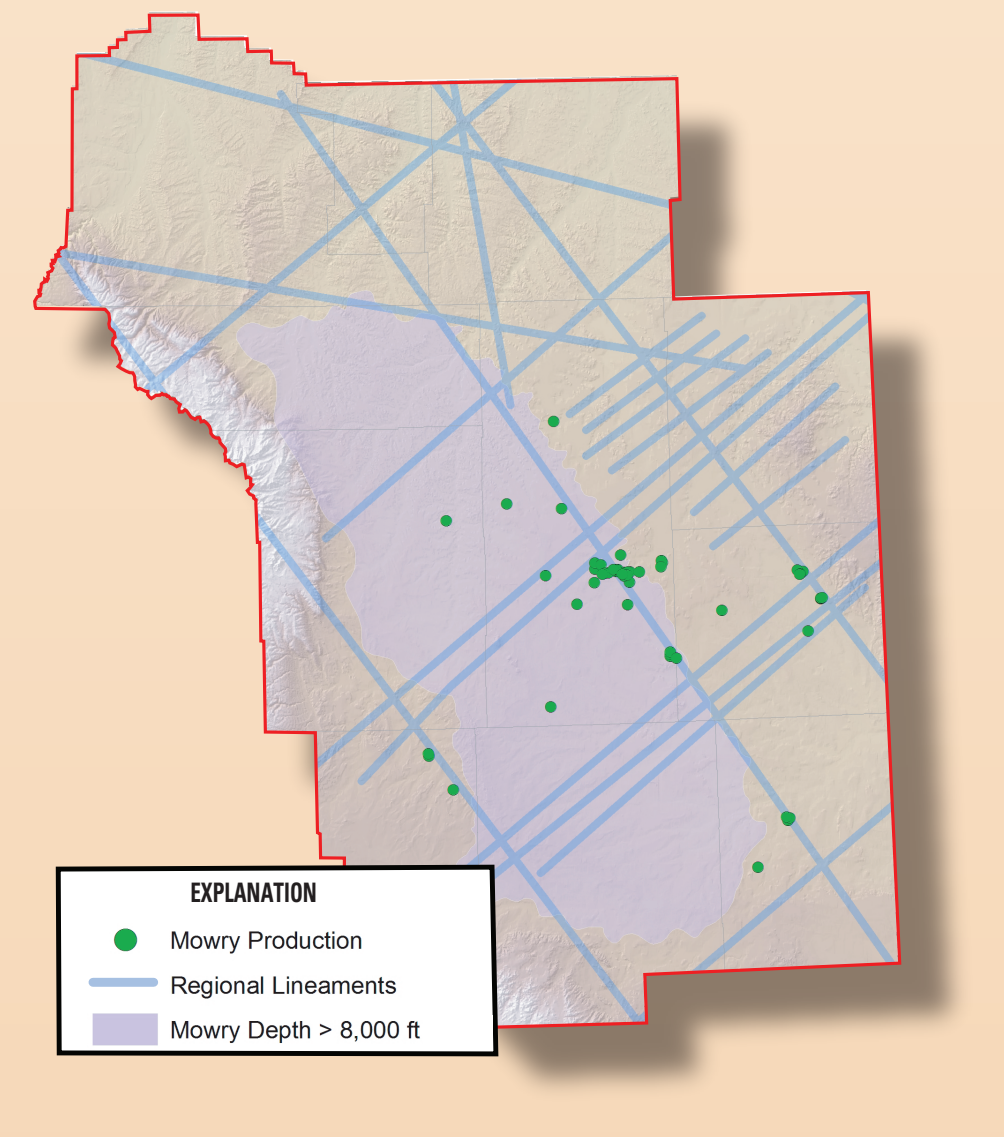

Figure 9. Map showing Mowry Shale production and lineaments.

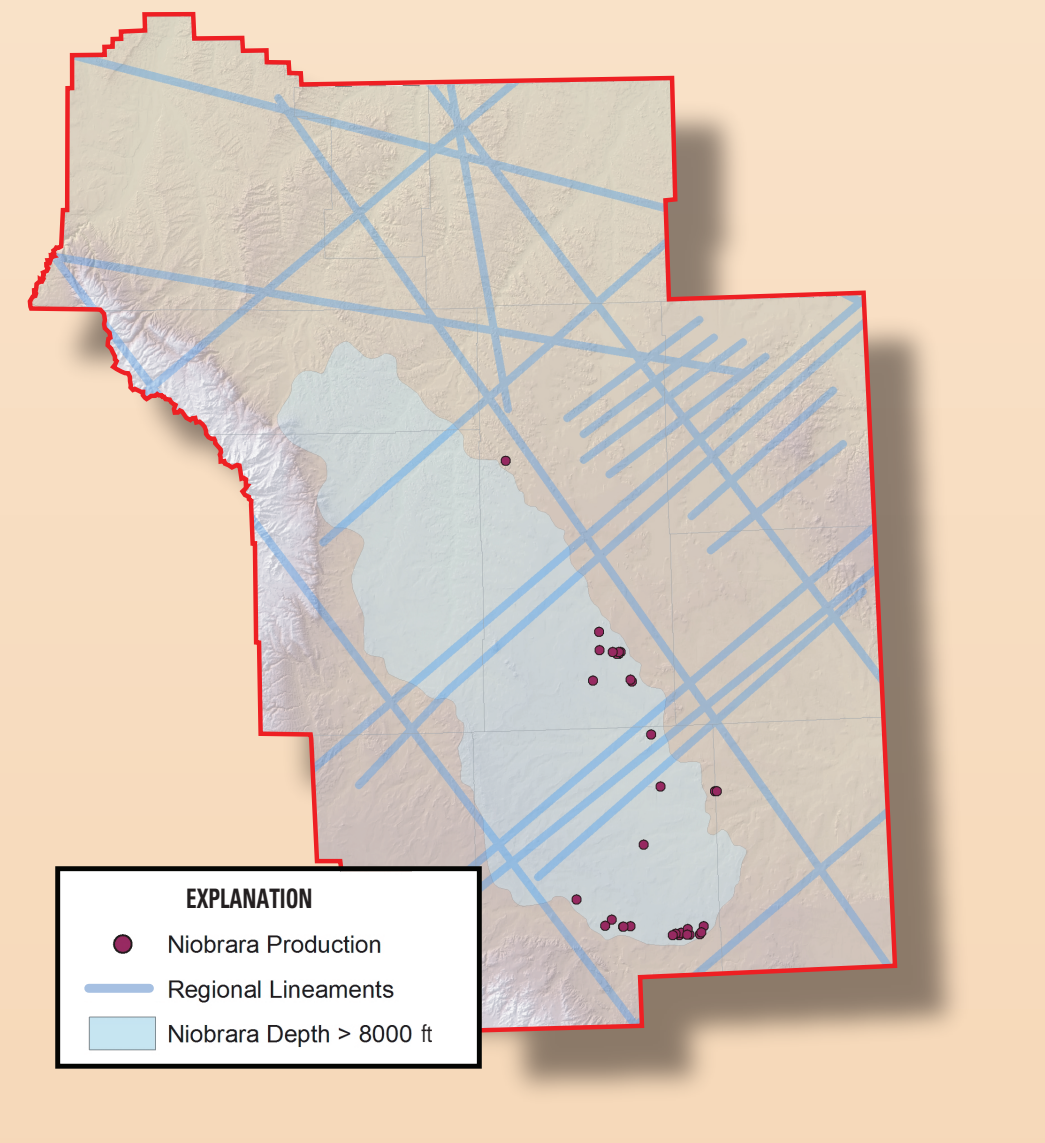

Figure 10. Map showing Niobrara Formation production and lineaments.

Quantitative Analysis of Fractures and Faults

Continuous reservoir production is delivered through a network of fractures and faults, although details of networks are enigmatic because parameters are difficult to obtain and analyze. Intensity is an important parameter to determine fracture or fault connectivity, which control rates and distribution of fluids. Connectivity is best defined by fracture or fault orientation, length (or size), and intensity. (Continued above, next column).

Numerous studies have shown (Slack, 1981; Anna, 1986a, 1986b, Marrs and other, 1984; Martinsen and Marrs, 1985; Maughan and Perry, 1986; Mitchell and Rogers, 1993) that the pervasive regional structural orientation in the PRB is Northwest to Southeast and Northeast to Southwest. Different orientations may exist, especially when associated with local stress systems, but they are minor contributors to the regional fracture and fault connectivity patterns. Fracture and fault lengths are difficult to measure although partial length distributions can be expanded through statistical methods and used to eliminate censoring and bias from mapping. Conventional wisdom associates large fracture density with an increase in reservoir permeability, which may be true locally, but only if fracture length improves the connectivity of a given network (often called percolation theory). Most locally generated fractures are connected by a regional system that enhances reservoir permeability. Sweet spots, therefore, should be determined first by mapping regional structural trends and second by mapping local features such as fractures related to folding. Mapping regional trends should be done at different scales (such as for lineament mapping, fault size calculations using seismic methods, and outcrop mapping). Each method should contain size distributions, which are then plotted with the cumulative number of faults/fractures per unit area (fig. 11).

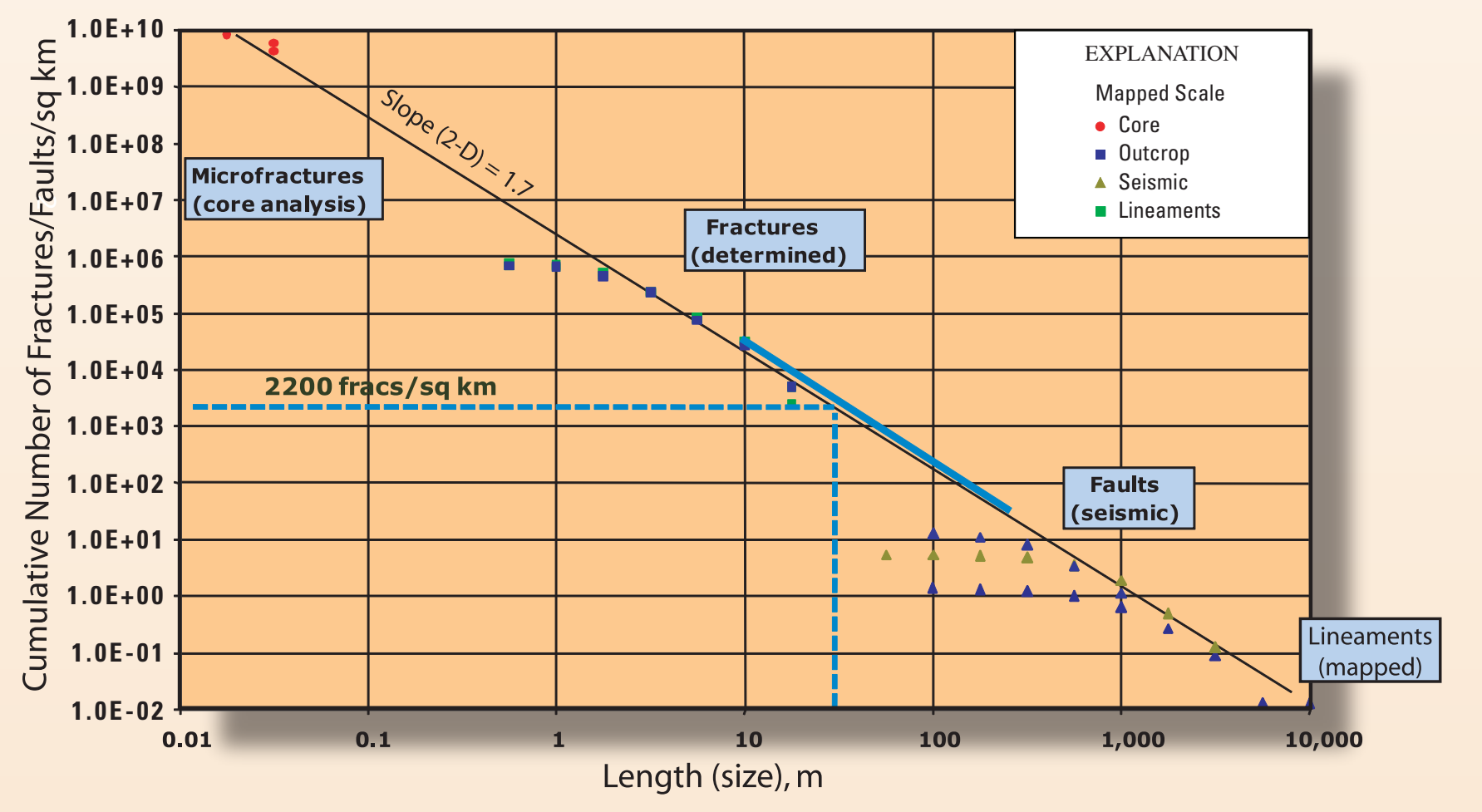

Figure 11. Composite size distributions of faults, fractures (fracs), and lineaments at all scales. Symbols represent various mapped areas.

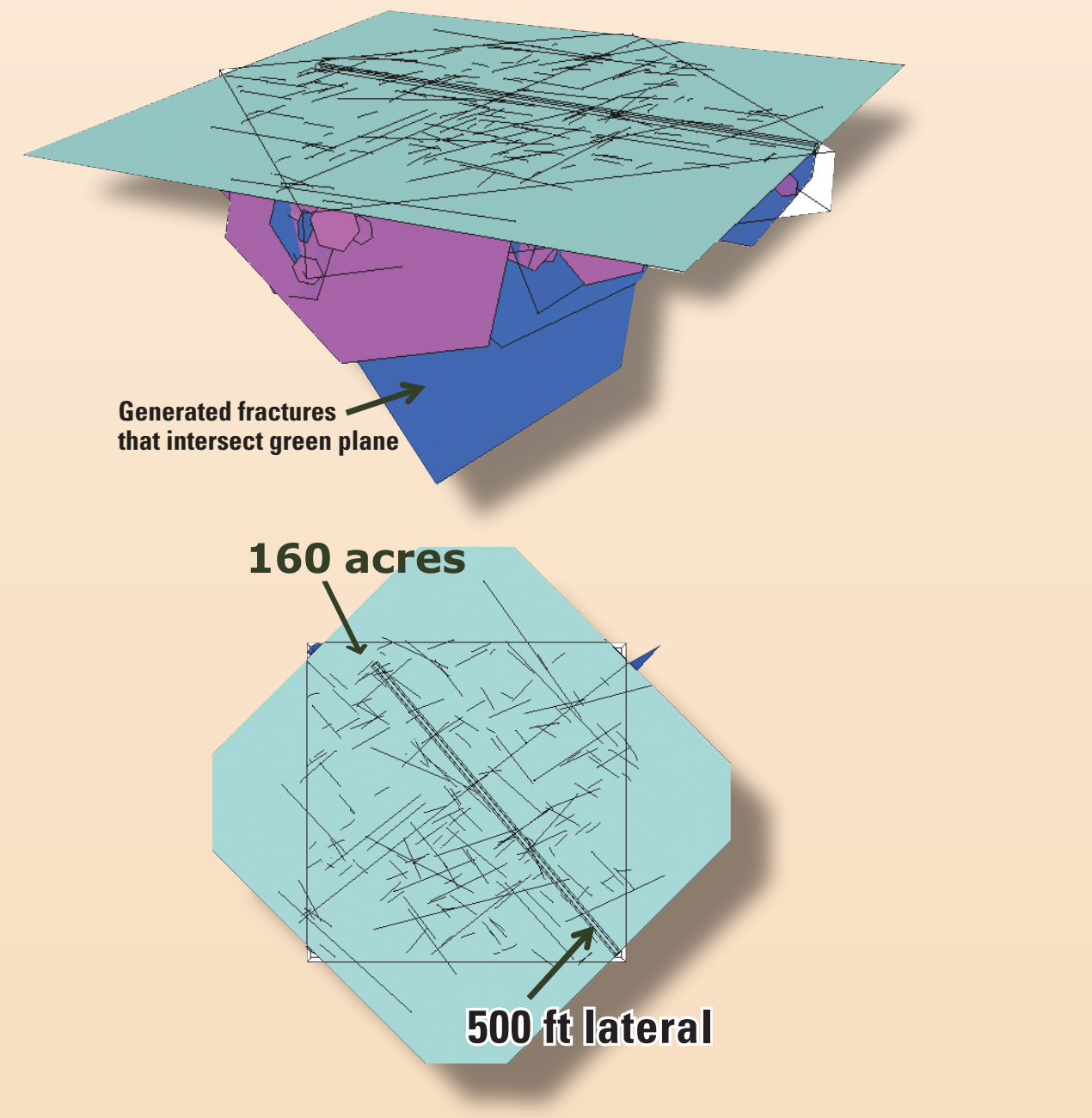

Figure 12. 3-D model of a fracture-generated volume and resulting intersections.

A complimentary approach to analyze fractures and faults is to develop a discrete fracture network (DFN) model. The procedure is to determine model input parameters of fracture set orientation, length, and intensity from lineament maps, seismic lines, and (or) outcrop measurements. Orientations are taken directly from maps, whereas length distributions are determined by (1) mapping fracture, fault, or lineament lengths at various scales, (2) plot lengths on a cumulative frequency chart (similar to fig. 11), and (3) determine the correct slope from the chart and use its value as input into the DFN model. Intensity is calculated as the number of fractures or the total length of fractures per unit area. Model results can be compared to fracture maps or formation micro-imager (FMI) logs.

For example, figure 12 shows an application of the DFN to a hypothetical field area with 160 acre spacing. The DFN was constructed with 400 fractures per 160 acres (an equivalent to 2,200 fractures per km^2 as marked on figure 11) Fracture spacing from fractures that intersect the simulated 500 ft lateral in the DFN model could be compared to a FMI log. A close match gives confidence that the DFN fracture network represents the real fracture network. If not, input parameters are revaluated. Results are used to calculate drainage volumes and area, the number of potential reservoir compartments, and migration pathways.

A systematic approach, such as burial history modeling, geochemical analysis, and quantitative fracture evaluation, will elevate geologic understanding, reduce risk, and enhance success in fractured shale reservoir plays.

References

Anna, L.O., 1986a, Geologic framework of the ground water system in Jurassic and Cretaceous rocks on the Northern Great Plains, in parts of Montana, North Dakota, South Dakota, and Wyoming: U.S. Geological Survey Professional Paper 1402–B, 36 p.

Anna, L.O., 1986b, Structural influence on Cretaceous sedimentation, northern Great Plains, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region: Tulsa, American Association of Petroleum Geologists Memoir 41, p. 173–192.

Byers, C.W., and Larson, D.W., 1979, Paleo-environments of Mowry Shale (Lower Cretaceous), western and central Wyoming: American Association of Petroleum Geologists Bulletin, v. 63, no. 3, p. 354–375.

Davis, H.R., Byers, C.W., and Pratt, L.M., 1989, Depositional mechanisms and organic matter in Mowry Shale (Cretaceous), Wyoming: American Association of Petroleum Geologists Bulletin, v. 73, no. 9, p. 1103–1116.

Dershowitz, W.S., Elben, T., and Doe, T.W., 1999, Size, shape, and spatial pattern of conductive fractures in heterogeneous and fractured reservoirs, *in* Annual Technical Conference and Exhibition, Houston, Tex., Oct. 1999: Society of Petroleum Engineers Paper SPE 56516.

Fett, T., 1991, Fracture evaluation in the Austin Chalk: Houston Geological Society Bulletin, v. 34, no. 3, p. 40–44.

Fox, J.E., 1993, Stratigraphic cross sections G–G′ through L–L′, showing electric logs of Upper Cretaceous and older rocks, Power River Basin, Wyoming: U.S. Geological Survey, Oil and Gas Investigations Chart OC–136.

Higley, D.K., Pantea, M.P., and Slatt, R.M., 1997, 3-D reservoir characterization of the House Creek oil field, Powder River Basin, Wyoming: U.S. Geological Survey Digital Data Series DDS–33.

Hunt, J.M., 1979, Petroleum Geochemistry and Geology: San Francisco, W.H. Freeman and Co., 617 p.

IHS Energy Group, 2006, Petroleum Information/Dwights petroROM Rocky Mountain Region Production Data on CD-ROM: IHS Energy Group, 15 Inverness Way East, D205, Englewood, Colo. 80112, U.S.A.

Integrated Exploration Systems, 2002, PetroMod1D-Express program, (downloaded 9/21/2002, at *http://www.ies.de/*).

Marrs, R.W., Martinsen, R.S., and Raines, G.L., 1984, Regional structure and facies control in the Powder River Basin, Wyoming and Montana, interpreted from satellite imagery *in* International Symposium on Remote Sensing of Environment, Third Thematic Conference, Remote Sensing for Exploration Geology, Colorado Springs, Colo., April 16–19, 1984, Proceedings: Colorado Springs, Colo., Environmental Research Institute of Michigan, p. 25–34.

Martinsen, R.S., and Marrs, R.W., 1985, Comparison of major lineament trends to sedimentary rock thicknesses and facies distribution, Powder River Basin, Wyoming, *in* International Symposium on Remote Sensing of Environment, Fourth Thematic Conference, Remote Sensing for Exploration Geology, San Francisco, Calif., April 14, 1985, p. 9–19.

Maughan, E.K., and Perry, W.J., Jr., 1986, Lineaments and their tectonic implications in the Rocky Mountains and adjacent plains region, *in* Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain Region, United States: American Association of Petroleum Geologists Memoir 41, p. 41–56.

Merewether, E.A., Cobban, W.A., Matson, R.M., and Magathan, W.J., 1977, Stratigraphic diagrams with electric logs of Upper Cretaceous rock, Powder River Basin, Natrona, Converse and Niobrara counties, Wyoming: U.S. Geological Survey Oil and Gas Investigations Map, OC–75.

Mitchell, G.C. and Rogers, M.H., 1993, Extensional tectonic influence on Lower and Upper Cretaceous stratigraphy and reservoirs, southern Powder River Basin, Wyoming: The Mountain Geologist, v. 30, no. 2, p. 55–68.

Neuzil, C.E., 1986, Groundwater flow in low-permeability environments: Water Resources Research, v. 22, no. 8, p. 1163–1195.

Nixon, R.P., 1973, Oil source beds in Cretaceous Mowry Shale of northwestern Interior United States: American Association of Petroleum Geologists Bulletin, v. 57, no. 1, p. 136–161.

Slack, P.B., 1981, Paleotectonics and hydrocarbon accumulation, Powder River Basin, Wyoming: American Association of Petroleum Geologists, v. 65, no. 4, p. 730–743.

Surdam, R.C., Jiao, Z.S., and Martinsen, R.S., 1994, The regional pressure regime in Cretaceous sandstones and shales in the Powder River Basin, *in* Ortoleva, P.J., ed., Basin Compartments and Seals: American Association of Petroleum Geologists Memoir 61, p. 213–233.

Wenger, W.J., and Reid, B.W., 1961, Characteristics of petroleum from the Powder River Basin, Wyoming: U.S. Bureau of Mines Report of Investigations 5723, 14 p.

Publishing support provided by:
Denver Publishing Service Center
Manuscript approved for publication Dec. 6, 2008

For more information concerning this publication, contact:
Team Chief Scientist, USGS Central Energy Resources
Box 25046, Mail Stop 939
Denver, CO 80225
(303)236-1647

Or visit the Central Energy Resources Team site at:
http://energy.cr.usgs.gov/

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this information product, for the most part, is in the public domain, it also contains copyrighted materials as noted in the text. Permission to reproduce copyrighted items for other than personal use must be secured from the copyright owner.

For sale by U.S. Geological Survey Information Services
Box 25286, Federal Center, Denver, CO 80225
1-888-ASK-USGS

This and other USGS products are available on the World Wide Web at:
http://store.usgs.gov/

This report is available at:
http://pubs.usgs.gov/of/2008/1367

Suggested citation:
Anna, L.O., and Cook, T.A., 2008, Assessment of the Mowry Shale and Niobrara Formation as continuous hydrocarbon systems, Powder River Basin, Montana and Wyoming, American Association of Petroleum Geologists Section Conference, July 9, 2008, Denver, Colo.: U.S. Geological Survey Open-File Report 2008–1367, 1 sheet.