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 New Mexico Geological Society, 56th Field Conference Guidebook, Geology of the Chama Basin, 2005, p. 434-444.

INSIGHTS INTO THE PETROLEUM GEOLOGY AND STRATIGRAPHY OF THE DAKOTA INTERVAL (CRETACEOUS) IN THE SAN JUAN BASIN, NORTHWESTERN NEW MEXICO AND SOUTHWESTERN COLORADO

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Abstract.—Highlights of an integrated study to evaluate the original and remaining Dakota gas resources in the San Juan Basin are presented. Dakota (Cretaceous) reservoirs contain a major stratigraphic gas accumulation with cumulative production of more than 6 TCF, and include braided and meandering fluvial, deltaic, shoreface, and shelf-ridge sandstones in seven distinct reservoir units. Data from 85 measured sections, 32 core descriptions, and 7,000 wells were integrated to construct a regional stratigraphic framework that correlates outcrops with the subsurface over the entire San Juan Basin. In addition, a 3,300-well digital log database was constructed to compute the petrophysical parameters and volumetric potential of each reservoir. Integration of these datasets and the resulting maps provides methods for determining the significance of various depositional trends, reservoir characteristics, and trapping mechanisms for gas production. Volumetric original gas-in-place and recovery factor maps closely approximate geologic and production trends, providing a basis for additional exploration and development opportunities.

INTRODUCTION

The development history of the Dakota began with the discovery of structurally trapped gas around the margins of the San Juan Basin during the 1920's. The first stratigraphic gas field was discovered in 1947, and the Basin Dakota Field was established on 320-acre well spacing in 1961, opening the first significant period of development. The field was later infilled to 160-acre well spacing in 1979, and to optional 80-acre spacing in 2002. Geologic and engineering work is currently underway to determine if greater well density is needed in selected areas.

The Basin Dakota Field currently produces 300 MMCFD from 5,112 wells (IHS Energy Data), many of which are commingled with completions in the Mesaverde Formation. Dakota production is from an approximately 122 m thick interval containing seven reservoir units deposited in various environments. Gas production is dominated by stratigraphy, which is integral to the interpretations and datasets that comprise this basinwide resource assessment.

Previous geologic studies focused on small geographic areas, or were limited by small datasets relative to the size and complexity of the Dakota interval. Inconsistent stratigraphic nomenclature has also been a source of confusion. The primary objective of this study was to provide a reliable geologic model that could be used to derive realistic estimates of volumetric original gas-in-place (OGIP). Figure 1 summarizes the various elements of the workflow used to determine the Dakota OGIP.

The basis for geologic and volumetric mapping is a 7,000-well, subsurface tops database, constructed from a sequence-stratigraphic framework with correlations to 85 Dakota outcrop measured sections. Core descriptions from 32 wells were used to calibrate wireline log facies interpretations. Isopach maps of each Dakota reservoir extend beyond the limits of gas production to include outcrop data around the basin perimeter, providing a basis for regional depositional environment interpretations. Specific facies types were delineated and correlated to gas production, and natural fractures were characterized. A 3,300-well digital log database was compiled and used for core-based petrophysical modeling to determine volumetric parameters. The parameters were then mapped using spatial modeling techniques to better conform to the stratigraphy, validating original and remaining gas estimates. Insights into a few of the most meaningful interpretations and results follow.

SUBSURFACE STRATIGRAPHY

The New Mexico Oil Conservation Division defines the Dakota producing interval in the San Juan Basin as the 400-foot (122 m) section below the base of the Greenhorn Limestone, an excellent chronstratigraphic subsurface marker. The Dakota Sandstone, a formal lithostratigraphic name long established in most of the Western Interior Basin of the U.S., has been used in the San Juan Basin since Dutton's early work (1885). Having both the Dakota Sandstone and the underlying Burro Canyon Formation included

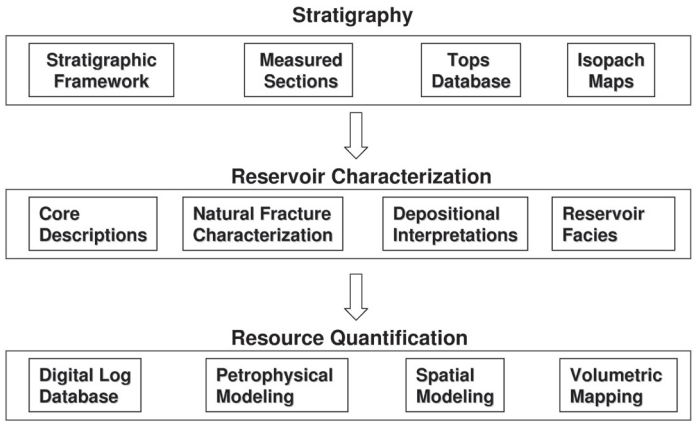


FIGURE 1. Dakota resource assessment workflow and primary study components.

in the Dakota producing interval has led to confusion, especially where exploration and production occurs in the Burro Canyon, but production is reported as from the Dakota producing interval.

The Dakota contains several sandstone beds separated by shales. For at least 50 years, San Juan Basin subsurface geologists have informally lettered these Dakota interval sandstones from the top down as they were encountered in drilling. This practice has been inconsistent and confusing because Dakota sandstone beds wedge out and merge within the basin and different geologists and companies have used the letters differently, especially in separate parts of the basin. Table 1 lists the inconsistent usage of lettered beds from all published papers in which this nomenclature has been used. Formal lithostratigraphic member names have been defined from outcrops around the San Juan Basin by Owen (1966), Landis et al (1973), Aubry (1988), and Owen and Owen (2005, in this guidebook). Only recently have some subsurface geologists (for example, Owen and Head, 2001) begun to correlate the formal outcrop members of the Dakota into the subsurface to replace the numbered sandstones. Table 2 lists these formal members and those of adjacent formations. Note that the informal "Dakota main body" of previous usage has been formally named as the White Rock Mesa Member of the Dakota Sandstone (Owen and Owen, 2005, this guidebook).

Key surfaces used in sequence-stratigraphic analysis, (Figure 2) especially marine-flooding surfaces and sequence-bounding unconformities, are also recognizable on outcrops, and well logs and can be used to define stratigraphic units. In the Dakota producing interval, many of these surfaces coincide with formal lithostratigraphic boundaries, so this subdivision was used in this study. The Burro Canyon is bounded by the K1 and K2 sequence-bounding unconformities, the Encinal Canyon is topped by the initial marine-flooding surface, the Oak Canyon is truncated by the K3 sequence-bounding unconformity where the White Rock Mesa overlies it and by the K3 correlative conformity or a locally scoured surface where the Cubero overlies it. The White Rock Mesa is topped by a series of marine-flooding surfaces. The Cubero, Paguate, and Twowells are topped by marine-flooding surfaces. The Clay Mesa and Whitewater Arroyo marine shale tongues have gradational upper boundaries, so they were combined with the overlying sandstones into what was informally designated the Paguate interval and the Twowells interval. This gave us 6 (or 7, if the White Rock Mesa and Cubero are mapped separately) intervals for isopach mapping and correlating on cross-sections (Table 3). Two prominent bentonites, the A bentonite in the Oak Canyon, and the X bentonite near the base of the Twowells interval, serve as critical key beds that can be used as datums on cross-sections. Other marine-flooding surfaces occur at the top of other parasequences, especially in the Cubero and Twowells interval. Other bentonites occur in the Twowells interval and the Graneros Shale, including an excellent bentonite datum for structural mapping at the top of the Graneros Shale. These bentonites,

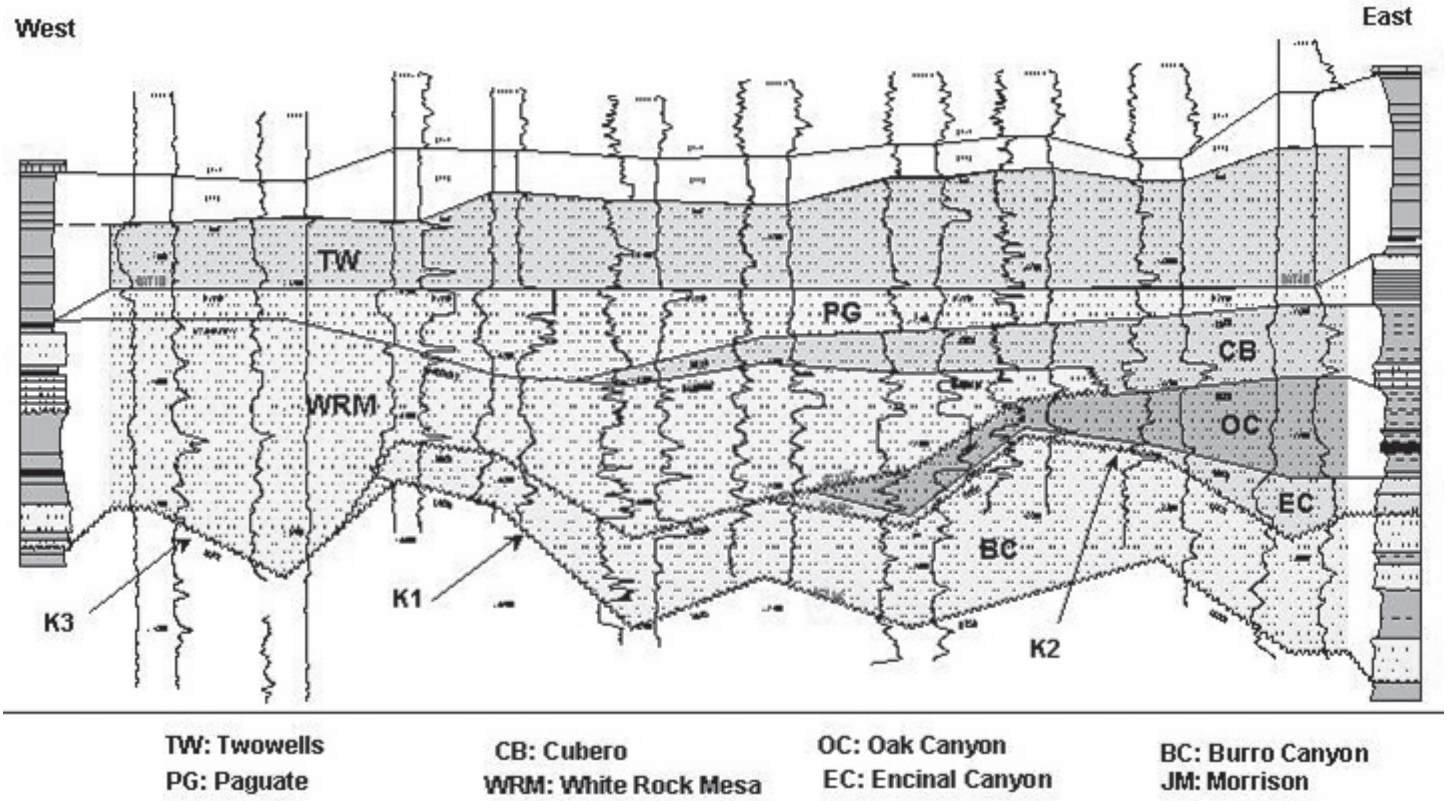


FIGURE 2. Dakota producing interval stratigraphic cross-section from the Four Corners in the west to the Chama Basin (Heron Dam) in the east (216 km. or 134 mi.), with outcrop sections on each end and well logs in between. Note westward erosional truncation of all lower Dakota and Burro Canyon as well as K-2 and K1 unconformities by K3 unconformity. Also note westward onlap of upper shoreface parasequence of Cubero on White Rock Mesa fluvial wedge. This cross-section is a summary of approximately 100 wells between outcrops. See Plate 7A for a color version of this figure.

TABLE 1. Correlation of formal member nomenclature with published informal lettered subsurface units.

Formal Members	Black (1978)	Black & Hiss (1974)	Bowman (1978)	Storhaug (1978) & Berg (1979)	Weidler (1978)	Ridgley (1987)
Twowells[1]	A (upper) B (lower)	A	none	A	A	none
Paguate[1]	C	B	A	none	B	C
Cubero[2]	D	C	none	D	D	B
Oak Canyon[2]		C	none	none	none	B
Encinal Can.		D	none	none	none	A
Jackpile[3]	none	D	none	none	none	none

[1] Mancos Shale members (Whitewater Arroyo Shale Tongue and Clay Mesa Shale Tongue) are included with overlying lettered sandstone.

[2] Upper shale unit of Oak Canyon Member is included with overlying lettered sandstone.

[3] Morrison Formation member.

[4] Ridgley followed standard outcrop procedure and lettered units from the bottom up.

where thick enough, are prominent high gamma-ray peaks and low resistivity (high conductivity) troughs on well logs.

A west-east cross-section (Figure 2) from the Four Corners to the Chama Basin with outcrop sections on each end and well logs in between illustrates the complex stratigraphic relationships in the Dakota producing interval. Note that the K3 unconformity erosionally truncates all of the underlying intervals and the K2 and K1 unconformities from east to west.

PETROLEUM GEOLOGY

Dakota Gas Stratigraphic Traps

The San Juan Basin is considered by many to be a prime example of a continuous, basin-centered gas accumulation, with updip water and downdip gas. While the areal extent of the Basin Dakota Field is defined by updip water production, stratigraphic complexities demonstrate that Dakota reservoirs are more compartmentalized than was previously thought, with large and small scale lithologic seals to gas migration. Within the field, well performance is largely controlled by the reservoir stratigraphy of the productive sandstone units and localized fracturing.

The Dakota interval is at the bottom of a large Upper Cretaceous gas accumulation which includes, in ascending order, the Dakota, Gallup (Tocito), Mesaverde, Pictured Cliffs, and Fruitland formations (Figure 3). Dakota gas is most prolific along the flanks of the structurally deepest part of the basin, and its commercial limits are defined by an irregular updip "waterline" (Figure 4). In the western portion of the basin, cross-sections

TABLE 2. Idealized "layer cake" lithostratigraphy of the Dakota Sandstone and adjacent units in the eastern San Juan Basin, New Mexico. Some of these units intertongue and others are truncated at unconformities, so not all are present at a single locality.

Lithostratigraphic Name	Original Reference
Greenhorn Limestone Member of Mancos Shale	Gilbert, 1896
Graneros Shale Member of Mancos Shale	Gilbert, 1896
Twowells Sandstone Tongue of Dakota Sandstone	Pike, 1947; Owen, 1966
Whitewater Arroyo Shale Tongue of Mancos Shale	Owen, 1966
Paguate Sandstone Tongue of Dakota Sandstone	Landis et al., 1973
Clay Mesa Shale Tongue of Mancos Shale	Landis et al, 1973
Cubero Sandstone Tongue of Dakota Sandstone	Landis et al., 1973
White Rock Mesa Member of Dakota Sandstone1	Owen & Owen, 2005
Oak Canyon Member of Dakota Sandstone	Landis et al., 1973
Encinal Canyon Member of Dakota Sandstone	Aubrey, 1988a
Burro Canyon Formation	Stokes and Phoenix, 1948
Jackpile Sandstone Member of Morrison Formation	Owen et al., 1984
Brushy Basin Shale Member of Morrison Formation	Gregory, 1938

1 Formerly "Dakota main body".

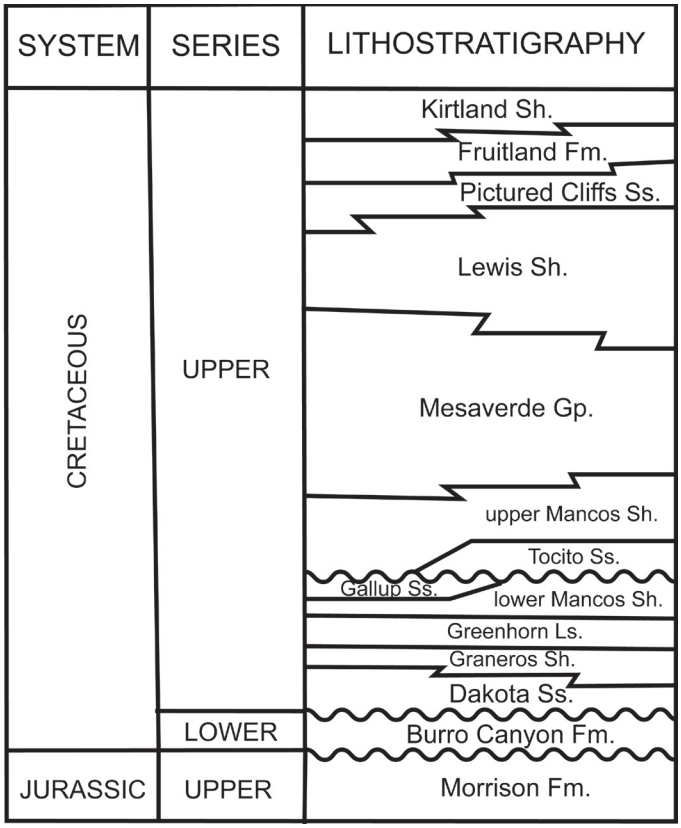


FIGURE 3. Generalized stratigraphic column of Cretaceous and uppermost Jurassic section of San Juan Basin, NM and CO.

TABLE 3. Sequence-stratigraphic based units in the Dakota producing interval.

Interval	Boundaries	Lithostratigraphic Unit	Remarks
Twowells interval	MFS5 to MFS4	Twowells Ss. Whitewater Arroyo Sh.	Contains C bent. Contains X bent.[1]
Paguate interval	MFS4 to MFS3	Paguate Ss. Clay Mesa Sh..	X
Cubero Interval	MFS3 to MFS2	Cubero Ss. underlying sh., locally	X
White Rock Mesa Interval	MFS2 to SBK3	White Rock Mesa Member (ss., sh., and coal)	X
Oak Canyon Interval	SBK3 to MFS1	Oak Canyon Member (sh. with ss., locally)	Contains A bent.
Encinal Canyon Interval	MFS1 to SBK2	Encinal Canyon Member (ss.)	X
Burro Canyon Interval	SBK2 to SBK!	Burro Canyon Fm. (ss., cgl., and mudstone)	X

[1] The B bentonite of Owen and Head (2001).

show the stratigraphy is generally continuous between gas and water productive wells across the waterline, and log resistivity can be used to discriminate pore-filling gas from water. Field limits in the southern and eastern portions of the basin are defined by stratigraphic pinchouts, and by water-filled fractures in high-resistivity rocks which extend well beyond the limits of commercial gas production.

The Basin Dakota Field can be subdivided into three large stratigraphic compartments based on the extent and quality of the primary reservoirs (Figure 5). The boundaries between the

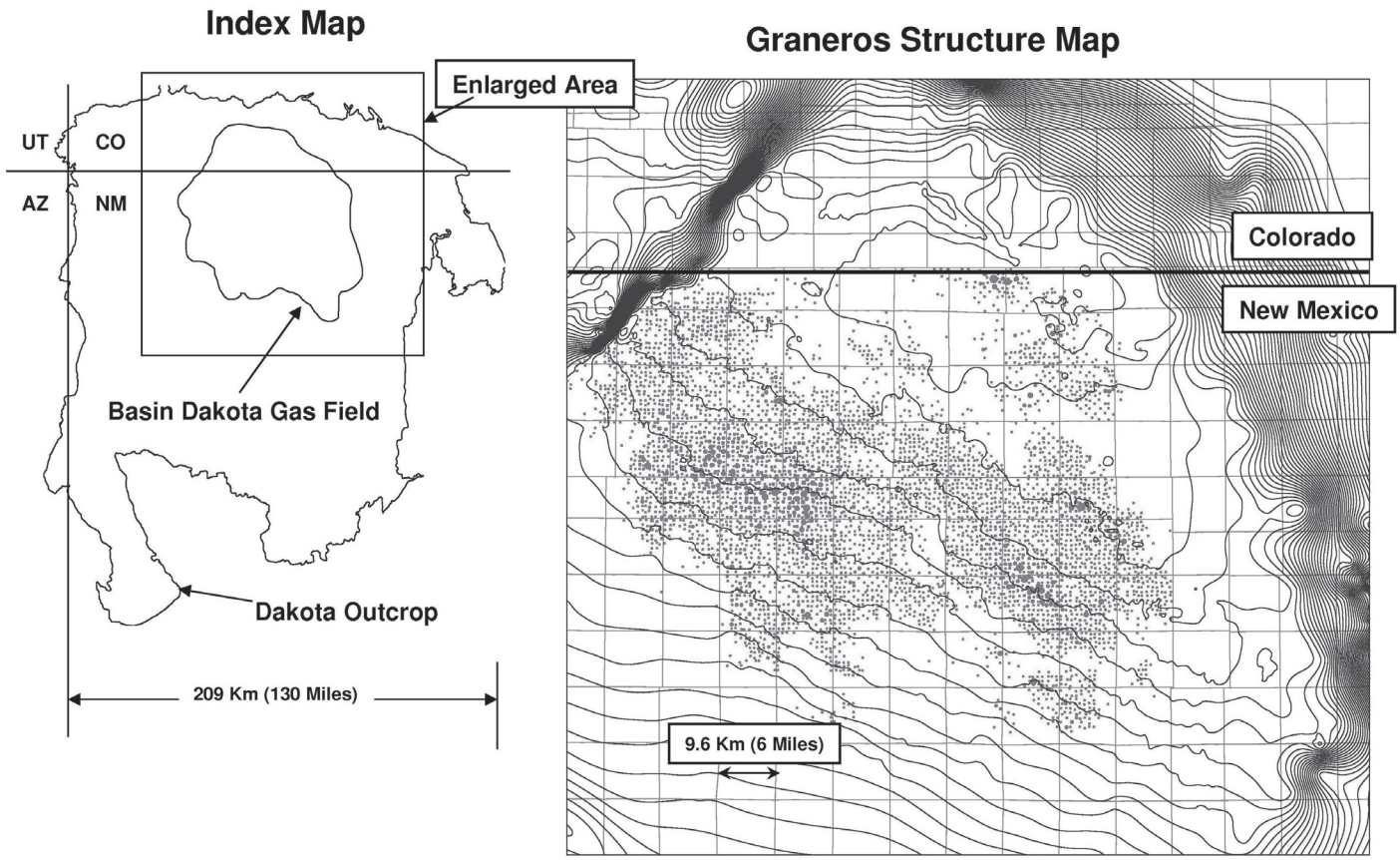


FIGURE 4. Structure-contour map of northern San Juan Basin on top of Graneros Shale with Basin Dakota Field gas production bubbles. Contour interval is 400 feet (122 m). Field limits are defined by updip waterlines.

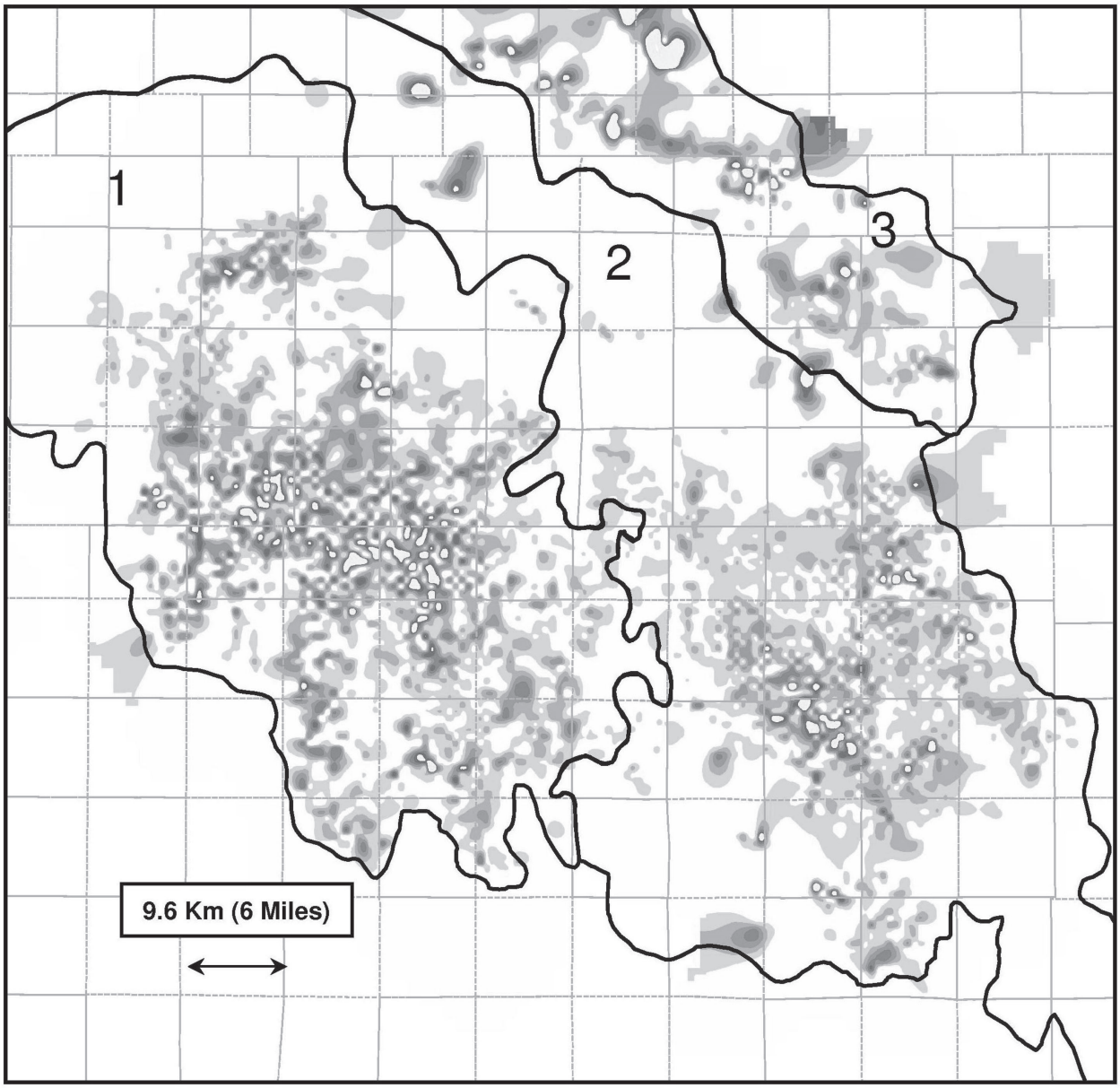


FIGURE 5. Basin Dakota Field ultimate gas recovery map with outlines of three compartments defined by large-scale variations in stratigraphy and original reservoir pressure. White areas have lowest gas reserves.

compartments are defined by lateral facies transitions from sandstone to shale, particularly in the marine reservoirs. The original bottom-hole reservoir pressure generally is uniform for each of the three compartments, but there are significant differences between them, demonstrating they are not in communication with one another. For example, the pressure boundaries conform to the stratigraphic extent of the Paguate sandstones in the west and north, and to the extent of the Twowells-Cubero-Oak Canyon sandstones in the east. As described below, these reservoir units dominate Dakota gas production, and each one grades laterally into impermeable marine shales.

The central, deepest portion of the basin is underdeveloped due to the combination of poor reservoir quality and a relative lack of natural fracturing (Buller River Associates, 1999). With the exception of the Burro Canyon, the Dakota produces gas with very little water, and depends on natural fracturing and hydraulic stimulation to produce commercially.

Gas Reservoirs

The Dakota is characterized as a "tight-gas" formation with highly variable reservoir stratigraphy, in the lateral as well as the vertical sense. Matrix porosity and permeability of most reservoirs are very low due to silica cementation (except Burro Canyon), so productivity is closely related to the amount of natural fracturing. Cleaner, silica-cemented sandstones tend to be more brittle and fracture prone than clay-rich, bioturbated sandstones, so various facies maps are necessary for understanding and predicting pro-

ductivity. However, because all prospective reservoirs are simultaneously completed, individual zone contributions are difficult to determine.

Upper Dakota delta-shoreface reservoirs of the Twowells, Paguate and Cubero (Figure 2) are extensive and their respective maps correlate closely with production, so they are the main focus of this paper. High-resistivity distributary channels-fills have very different lithologic and production characteristics from shoreface sandstones (GeoQuest, 1997). These three reservoir units were sourced by extensive marine shales above marine-flooding surfaces which also form vertical and lateral stratigraphic seals.

The middle portion of the Dakota is productive from discontinuous fluvial channels within the coastal-plain deposits of the White Rock Mesa (formerly, "Dakota main body"). Gas contribution is less than in higher marine units, and is dependent upon reservoir quality, fracture density, and proximity and type of source rock. Thin coals and carbonaceous shales probably sourced much of the gas, but overlying marine shales also charged the channel-fill sandstones. This is particularly true in areas lacking marine sandstone. The White Rock Mesa coastal-plain reservoirs terminate at productive Cubero shoreface-marine facies.

Near the base of the Dakota, Burro Canyon and Encinal Canyon braided fluvial reservoirs are distinctively different from the rest of the Dakota, and were not included in our resource assessment due to development risks associated with water production. Gas contribution is minor relative to the rest of the section, but these units are important exploration targets in selected areas. The Burro Canyon is of particular geological interest, and is discussed below.

Dakota matrix permeabilities (except for the Burro Canyon) are in the microdarcy range, while porosities range from 4% to 12%. It is evident from cores and logs that most of the original matrix was altered by diagenetic quartz overgrowths in siliceous rocks, and by dolomitic cement in the shaley rocks (Reservoirs, Inc., 1997). Fracture density is related to lithology: cleaner sandstones are more likely to be fractured than clayey or silty sandstones (Buller River Associates, 1999). Because permeability (hence productivity) is directly related to fracture density, much of the best Dakota production is from siliceous deltaic-distributary facies rather than argillaceous marginal-marine facies.

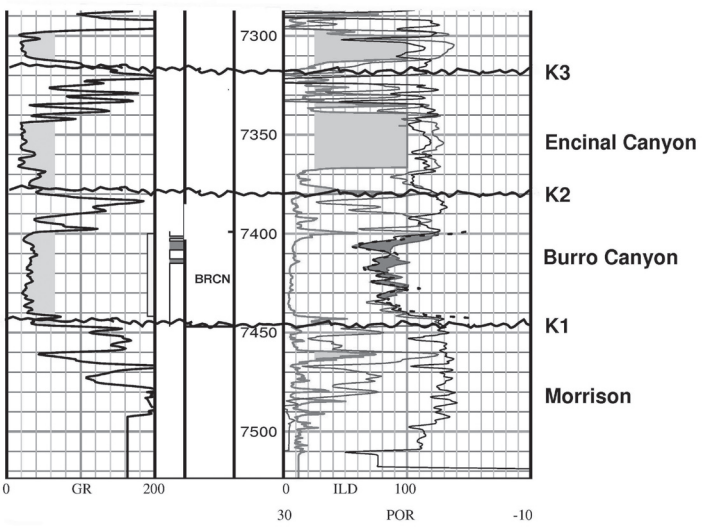


FIGURE 6. Burro Canyon type log showing low-resistivity, high-porosity reservoir with gas effect. Green mudstones and the K2 unconformity cap this reservoir. See Plate 7B for a color version of this figure.

Incised Valley-Fill Reservoirs

Geologically and economically, the Burro Canyon is distinctly different from overlying Dakota reservoirs. Gas occurs in conventional buoyancy traps with gas-water contacts within valley incisements into Morrison mudstones. Reservoirs are highly compartmentalized and vary in size from several acres to several tens of acres. Some completions may produce significant gas volumes for long periods of time with very little water, but most others produce little or no gas with enormous quantities of water. The best reservoirs are excellent flow units with maximum matrix porosity of 25% and millidarcy permeability. Where it is gas-saturated, the Burro Canyon yields obvious drilling breaks and gas shows on mudlogs, as well as gas effect on porosity logs (Figure 6). Most commercial completions are in low-resistivity contrast pays due to high porosity and conductive clays, resulting in overly pessimistic water-saturation calculations in gas-productive zones. Reservoir pressures typically are up to 1,000 psi higher than those measured in the Dakota reservoirs above the Burro Canyon. Many Burro intervals can be successfully completed by perforations alone.

Sidewall-core analyses reveal dramatic differences in permeability between the Burro Canyon and upper Dakota reservoirs. A comparison of properties such as capillary-injection pressure and pore-throat size indicates that Dakota sandstones are generally several orders of magnitude "tighter" than the Burro Canyon sandstones (Reservoirs, Inc, 1997). This contrast in permeability provides an effective vertical pressure seal, even where "tight" Dakota sandstones are in direct contact with the underlying Burro Canyon. This contact is typically at the K2 or K3 unconformity and forms the base of the Cretaceous basin-centered gas column. An explanation for the permeability contrast is that kaolinite clay coating on sand grains and/or early gas saturation in the Burro Canyon might have prevented the diagenetic cementation which is pervasive in upper Dakota reservoirs. Because of the uncertainty in predicting prospective areas and trap sizes, the Burro Canyon was not included in the Dakota resource assessment, but it remains an important exploration target.

Deltaic Reservoirs

Differences in facies interpretations from wireline logs and cores in several portions of the basin suggest a strong influence by marginal-marine deposition. The most striking example is in the Paguate, where northwest-trending, marine-shoreface sands were incised by a lobate paleodelta complex in the western portion of the Basin Dakota Field (Figure 7). The primary features of the paleodelta are distributary channels which prograded northward,

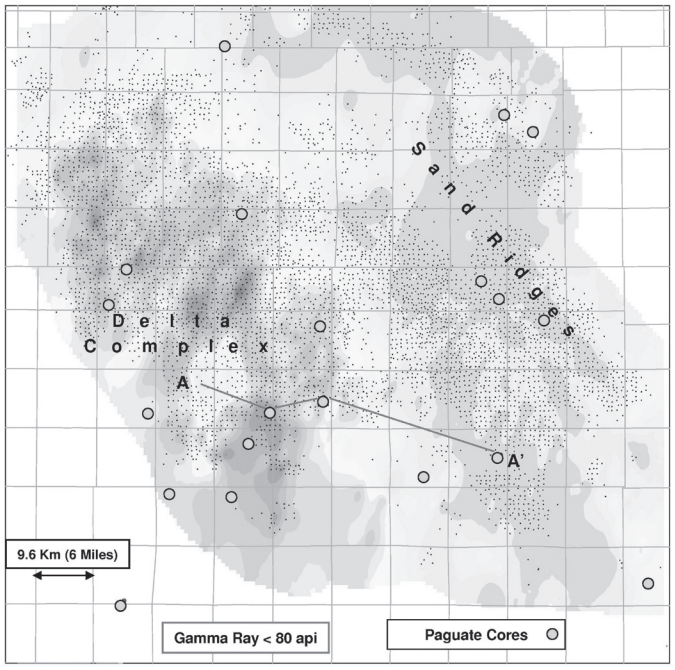


FIGURE 7. Paguate interval net sandstone isopach map showing northeast-prograding delta complex flanked by northwest-trending shoreface sand ridges built by longshore drift. Note distributary channels that form meander belts up to 3 miles (4.8 km) wide. Darker areas are distributary thicks and lighter gray areas are thin swales between sand ridges. See Plate 8A for a color version of this figure.

removing lower, muddy Paguate shoreface rocks during relative sea-level drop. The channels were subsequently backfilled with distributary and estuarine sandstone, making them much cleaner, and therefore more fracture-prone than their marine equivalents (GeoQuest, 1997). Log characteristics include a pronounced resistivity increase and a clean, blocky gamma-ray signature. This makes the filled channels easy to distinguish from clay-rich, low-resistivity, funnel-shaped shoreface facies (Figures 8 and 9). The effects of pressure solution in channel sandstones are obvious, with near total elimination of original porosity by quartz cementation and styolite development.

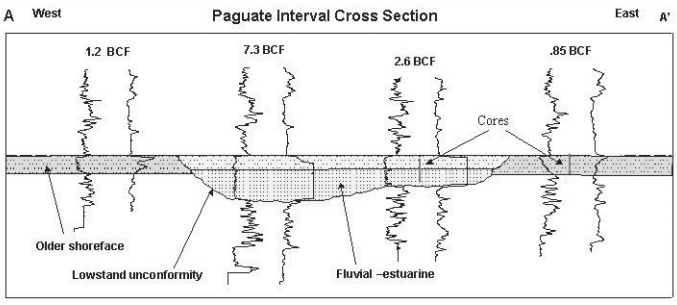


FIGURE 8. Paguate stratigraphic cross-section A-A' perpendicular to delta complex in Fig. 7. Lowstand distributary channel-fill facies filled eroded older shoreface deposits. Note contrasting log characters of blocky distributary and coarsening-upward shoreface, as well as location of two key cores. Also note higher gas recoveries from distributary sandstones. See Plate 8B for a color version of this figure.

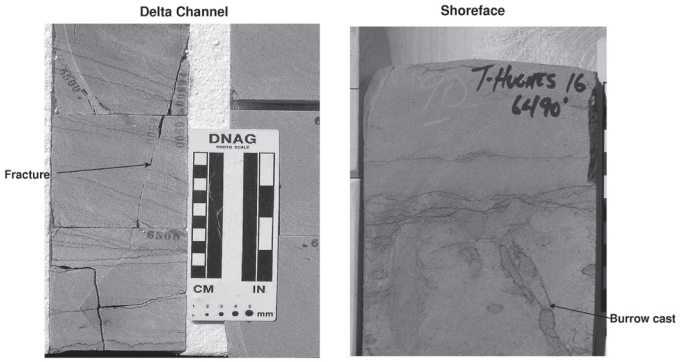


FIGURE 9. Photographs of core slabs from well in Figure. 8 showing cross-bedded and fractured distributary channel-fill sandstone (left) to muddy, bioturbated shoreface sandstone (right).

The Paguate dominates Dakota gas production in the western portion of the basin, as evidenced by the excellent correlation between Paguate sandstone thickness and well performance. The channel-fills are relatively thick and much more prolific than the marine facies. Marginal-marine facies also occur along the coastal extent of the White Rock Mesa and Oak Canyon intervals, with similar evaluation and productivity contrasts relative to equivalent marine facies (Figure 10).

Shelf-Ridge Reservoirs

Because of their similar depositional environments, Dakota marine members (Twowells, Paguate, Cubero and Oak Canyon) are difficult to distinguish in outcrops, cores and log signatures. Bentonites and marine-flooding surfaces were the keys to proper correlation. The shoreface intervals of these units are the most homogeneous and predictable reservoirs within the Dakota, and because of their great extent, the majority of gas production in the eastern and northern portions of the basin is attributed to them (Figure 11). The best reservoir quality is found in the middle-shoreface environment, because upper-shoreface deposits were seldom preserved due to erosion associated with shoreface ravinement during subsequent sea-level rise (GeoQuest, 1997).

The Twowells is the most widespread and productive marine unit, with several prominent northwest-trending linear shelf sand-ridges (Figure 12). Each sand ridge is a regressive, shoreface sandstone with a characteristic funnel-shaped, coarsening-upward log profile capped by a marine-flooding surface (Figure 13). Sand ridge gas production correlates to reservoir quantity and quality, which is found in thicker trends along depositional strike. Of interest is that the Twowells is the earliest Cretaceous northwest-trending shelf ridge, and the much later Mesaverde and Pictured Cliffs marine sand trends have very similar orientations. Dakota marine facies successions integrated with log signatures and trace fossils were interpreted as wave-dominated and wave-influenced, progradational shoreline complexes (GeoQuest, 1997, Figure 14). These ridges are very fine-grained, shaly sandstones that are extensively bioturbated, indicating that they were deposited in the middle and outer shoreface, not in the inner shoreface or littoral zone.

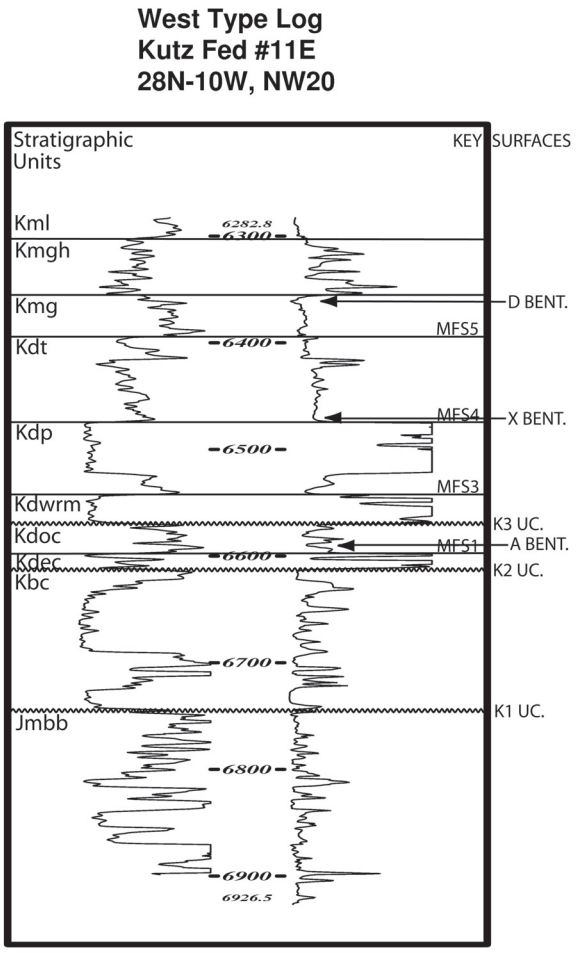


FIGURE 10. West type log of Dakota producing interval with stratigraphic units and key surfaces labeled. Kml = lower Mancos Sh.; Kmgh = Greenhorn Ls. Member of Mancos Sh.; Kmg = Graneros Sh. Member of Mancos Sh.; Kdt = Twowells interval of Dakota Ss. (includes Whitewater Arroyo Sh. Tongue of Mancos Sh.); Kdp = Paguate interval of Dakota Ss. (includes Clay Mesa Sh. Tongue of Mancos Sh.); Kdwrm = White Rock Mesa Member of Dakota Ss.; Kdoc = Oak Canyon Member of Dakota Ss.; Kdec = Encinal Canyon Member of Dakota Ss.; Kbc = Burro Canyon Fm.; Jmbb = Brushy Basin Member of Morrison Fm.; MFS = marine-flooding surface; UC = unconformity; BENT. = bentonite. At this western location, no Cubero Ss. Tongue of Dakota Ss. (Kdc) is present, so that the Paguate interval onlaps the White Rock Mesa Member. (compare to Figure 11).

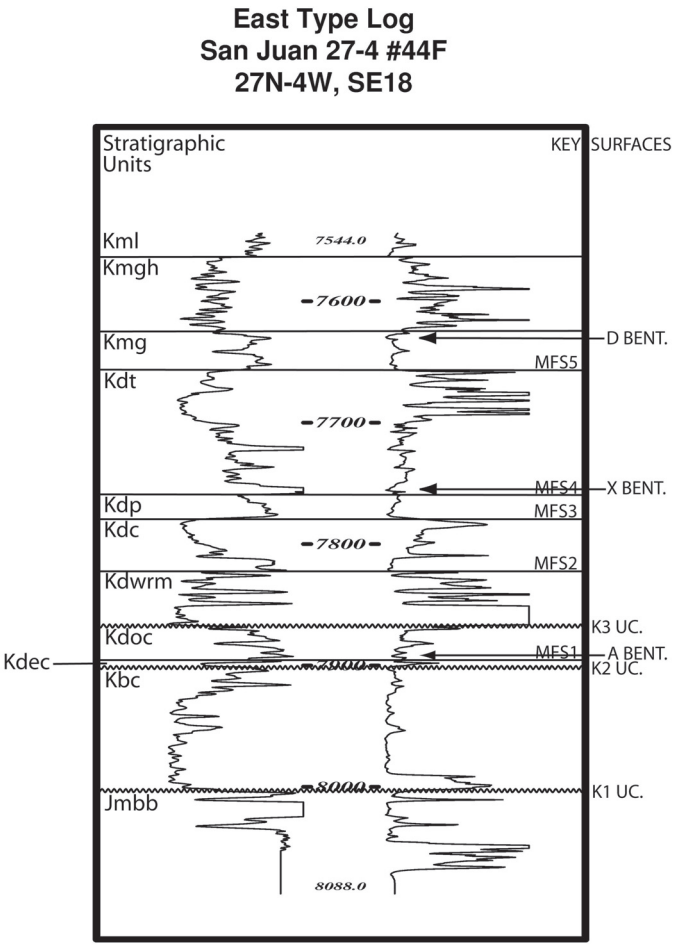


FIGURE 11. East type log of Dakota producing interval with stratigraphic units and key surfaces labeled. See Figure 10 for explanation of abbreviations. All stratigraphic units in the Dakota producing interval are present in this log, including the Cubero Ss. Tongue of Dakota Ss (Kdc). The very small thickness of Kdec in this log is atypical. The thin, shaly nature of the Paguate interval is typical of a WNW-trending area from the southernmost Chama Basin on the east, through the area of this well, to an area north of the Paguate delta shown in Figure 7.

Volumetric Mapping

Given the excellent correlation between Dakota gas production and stratigraphy, there should also be high confidence in estimates of original gas-in-place (OGIP). This is the basis for past and future reserve accountablility. Spatial modeling techniques were utilized to validate volumetric estimates by using the stratigraphy to control data extrapolation and gridding of each reservoir. The resulting volumetric maps closely resemble the stratigraphy, and correlate closely to existing production trends.

The digital log database consists of 3,300 wells with gamma-ray and resistivity logs, but only 880 wells with usable density (porosity) logs. A type-log with the petrophysical variables used to compute the volumetric potential of each unit is shown in Figure 15. It was necessary to use the larger dataset (net sand thicknesses) to "guide" the gridding of the smaller volumetric (porosity-dependent) dataset. This was accomplished by establishing a regional correlation coefficient between gross sandstone thickness and bulk volume hydrocarbon feet (BVH-H) for each reservoir unit. Variograms were used to determine reservoir anisotropy (depositional) orientations, and the resulting models used net sandstone grids to extrapolate porosity-dependent variables such as BVH-H.

The BVH-H grids for each reservoir (except Burro Canyon and Encinal Canyon) were combined and integrated with engineering data to produce a Dakota OGIP map. The trend geometry of this map closely approximates both stratigraphic and production trends, particularly those associated with the lobate Paguate and linear Twowells complexes described above (Figures 16 and 17).

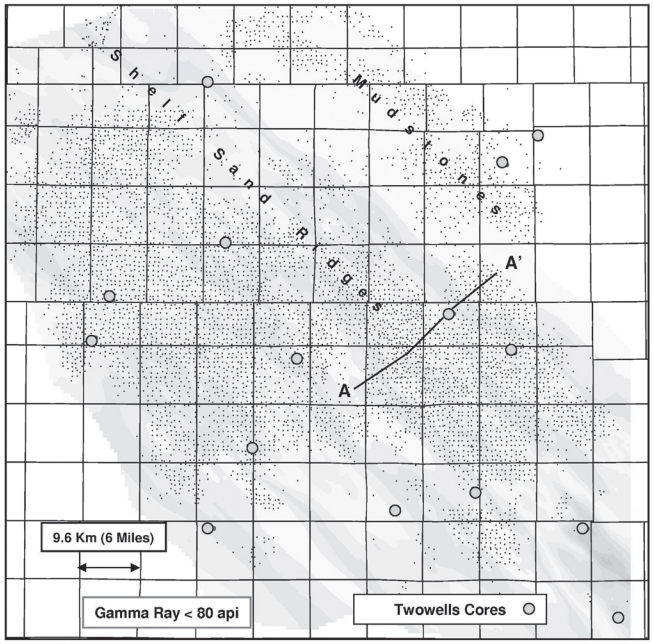


FIGURE 12. Twowells interval net sandstone isopach map showing prominent northwest-trending, shelf-sandstone ridges. Light gray areas are shelf-ridge sandstone thicks and dark gray areas are thin, shaly swales between ridges. The white area to the northeast labeled mudstones marks the terminus of Twowells sandstones in the San Juan Basin; Twowells parasequences are composed of mudstones in this area and to the northeast. Crossbedding in sandstone outcrops of similar Twowells ridges indicate a southeasterly to southerly paleocurrent flow (Owen et al., 1978). See Plate 9A for a color version of this figure.

CONCLUSIONS

It was necessary to integrate data and interpretations from a variety of projects, including subsurface and surface stratigraphy, core analyses, outcrop sections and petrophysics, to understand the petroleum geology of the Dakota interval and estimate gas reserves. The Dakota is a stratigraphic gas play, and correlation of surface and subsurface data provides a reliable framework for sand thickness maps which include much of the well control in the basin. Calibration of log responses to cores and outcrops provides valuable insight into a variety of depositional facies and trends and their significance to natural gas production.

Gas production is dominated by the reservoir stratigraphy of large-scale marginal-marine and marine depositional trends in the middle and upper portions of the Dakota producing interval. Contribution from lower Dakota fluvial facies is less predictable due to compartmentalization and higher water saturations. Reservoirs typically have low permeability and porosity, and are dependent upon natural fracturing to produce. Cleaner delta-channel-fill facies tend to be more densely fractured, and are better producers.

Reservoir pressure maps reveal significant differences in average bottom-hole pressure between the three most productive areas of the Basin Dakota Field. The boundaries between the three areas correlate to extensive marine shales which define the distal limits of the primary reservoir trends. The perimeter of commercial gas production is defined by updip water in all directions.

A non-traditional approach using spatial modeling techniques was used to extrapolate data and construct geologically reasonable reservoir sandstone and volumetric maps. Good agreement between production, reservoir, and volumetric trends validate the results, confirming accurate resource assessment estimates.

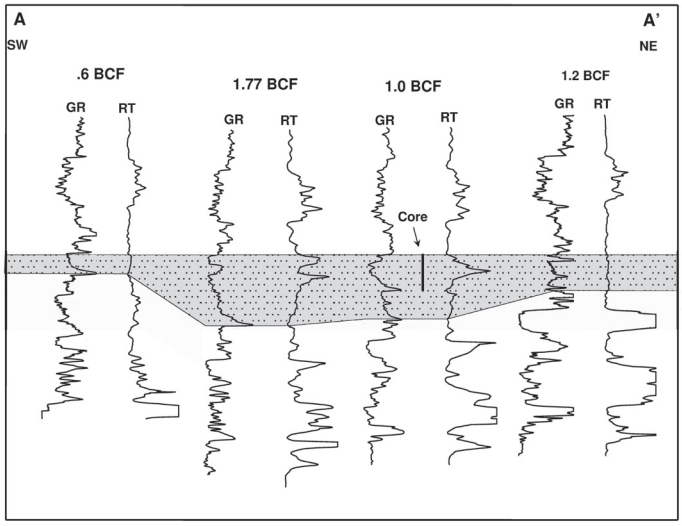


FIGURE 13. Twowells stratigraphic cross-section A-A' perpendicular to shelf-sandstone ridge trend in figure 12. Note thin, silty sandstone in swale in the left well and mudstone parasequences in the right well.

ACKNOWLEDGMENTS

We appreciate the work of Kevin Kohles in creating the formation tops database used during the early part of this study, and the excellent core descriptions and interpretations of Steve Sturm, which helped us determine reservoir properties and reconstruct depositional environments. Glen Christiansen and Will Sawyer did much of the petrophysical modeling and mapping. Donald E. Owen, Jr. was an able assistant who obtained logs, entered data, and prepared some of the illustrations. Bill Connelly, Mike Dawson and Spencer Lucas kindly reviewed this paper for us,

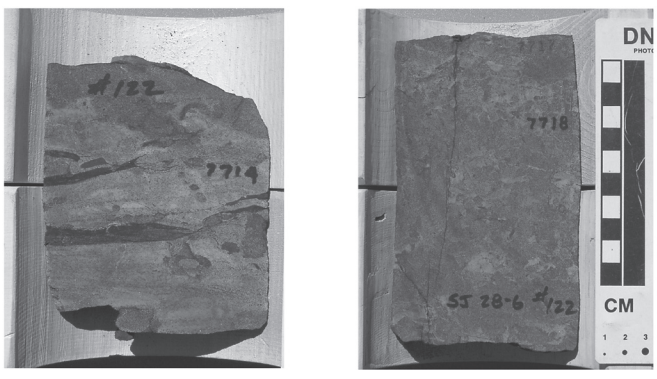


FIGURE 14. Photographs of core slabs of burrowed (left) and bioturbated (right) Twowells middle-shoreface silty sandstones.

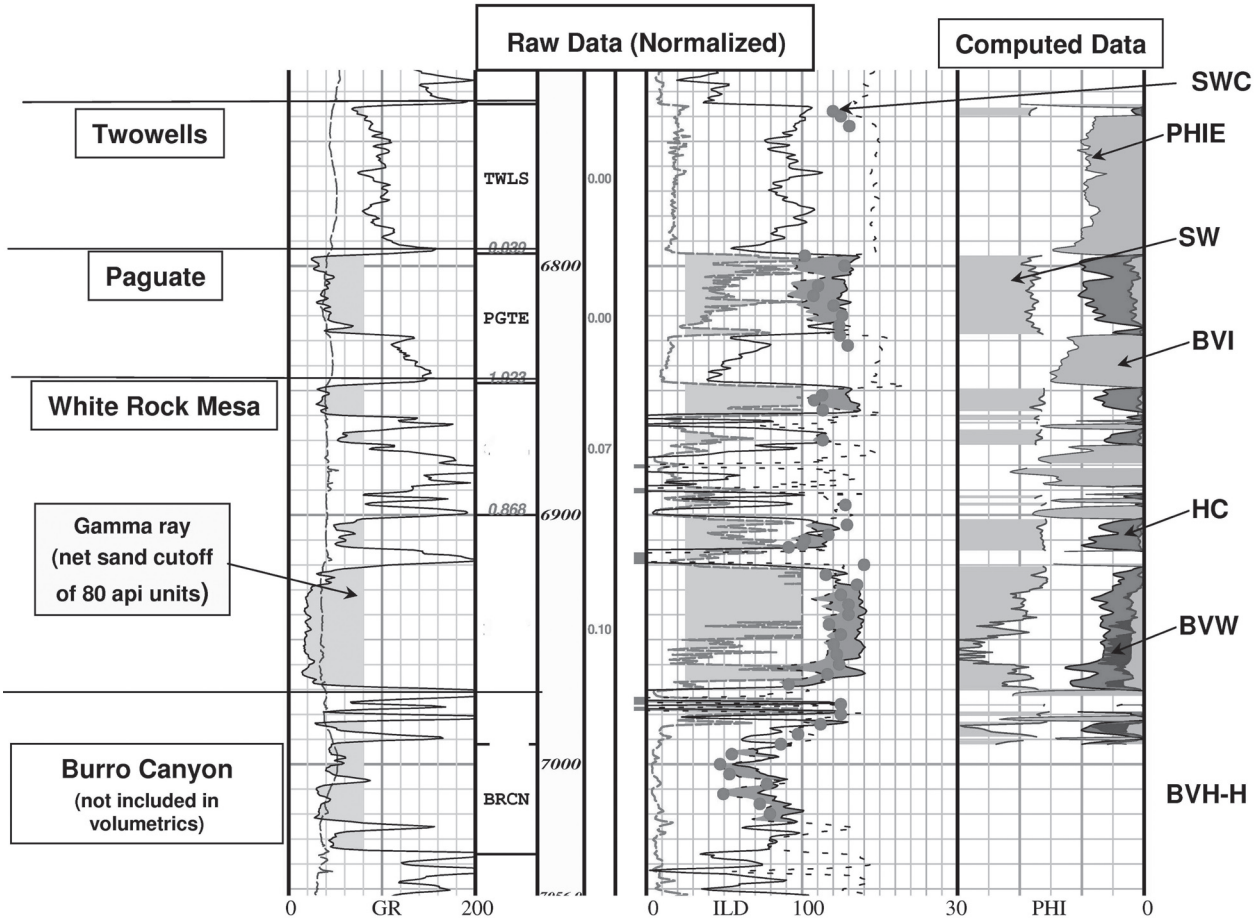


FIGURE 15. Petrophysical type log with raw data on left and computed volumetric parameters on right. SWC = sidewall cores; PHIE = effective porosity; SW = water saturation; BVI = immovable water; HC = hydrocarbons; BVW = moveable water; BVH-H = bulk volume hydrocarbon feet. See Plate 9B for a color version of this figure.

sharing their extensive San Juan Basin experience.

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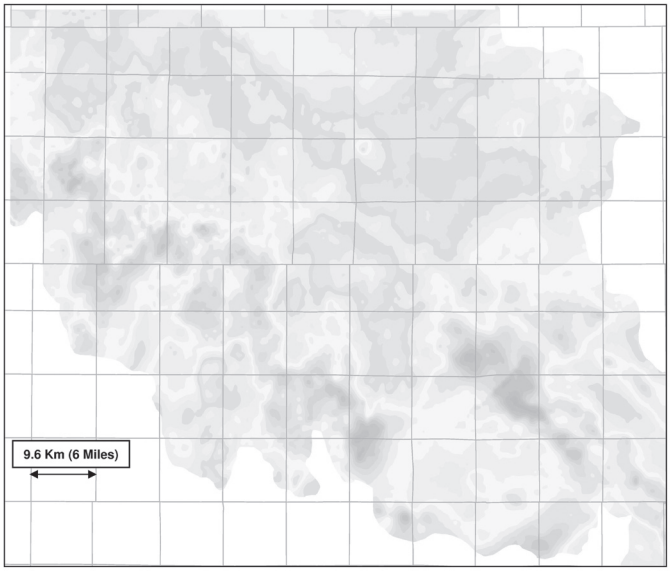


FIGURE 16. Basin Dakota Field volumetric gas-in-place map. Darkest gray areas represent higher amounts of gas in place. See Plate 10 for a color version of this figure.

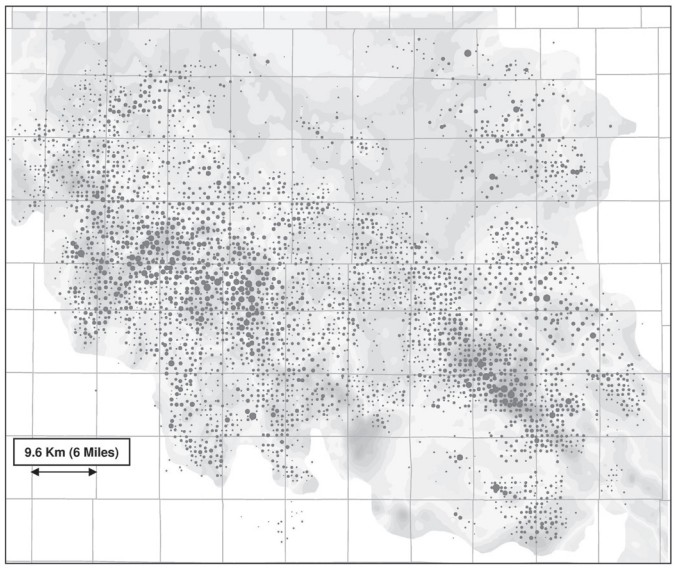


FIGURE 17. Basin Dakota Field original gas-in-place map with well production bubble overlay. Darker gray areas represent higher amounts of gas in place, and bubble size is relative to gas production. See Plate 11 for a color version of this figure.

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PLATE 7: PETROLEUM GEOLOGY OF THE DAKOTA INTERVAL CROSS-SECTION AND BURRO CANYON TYPE LOG

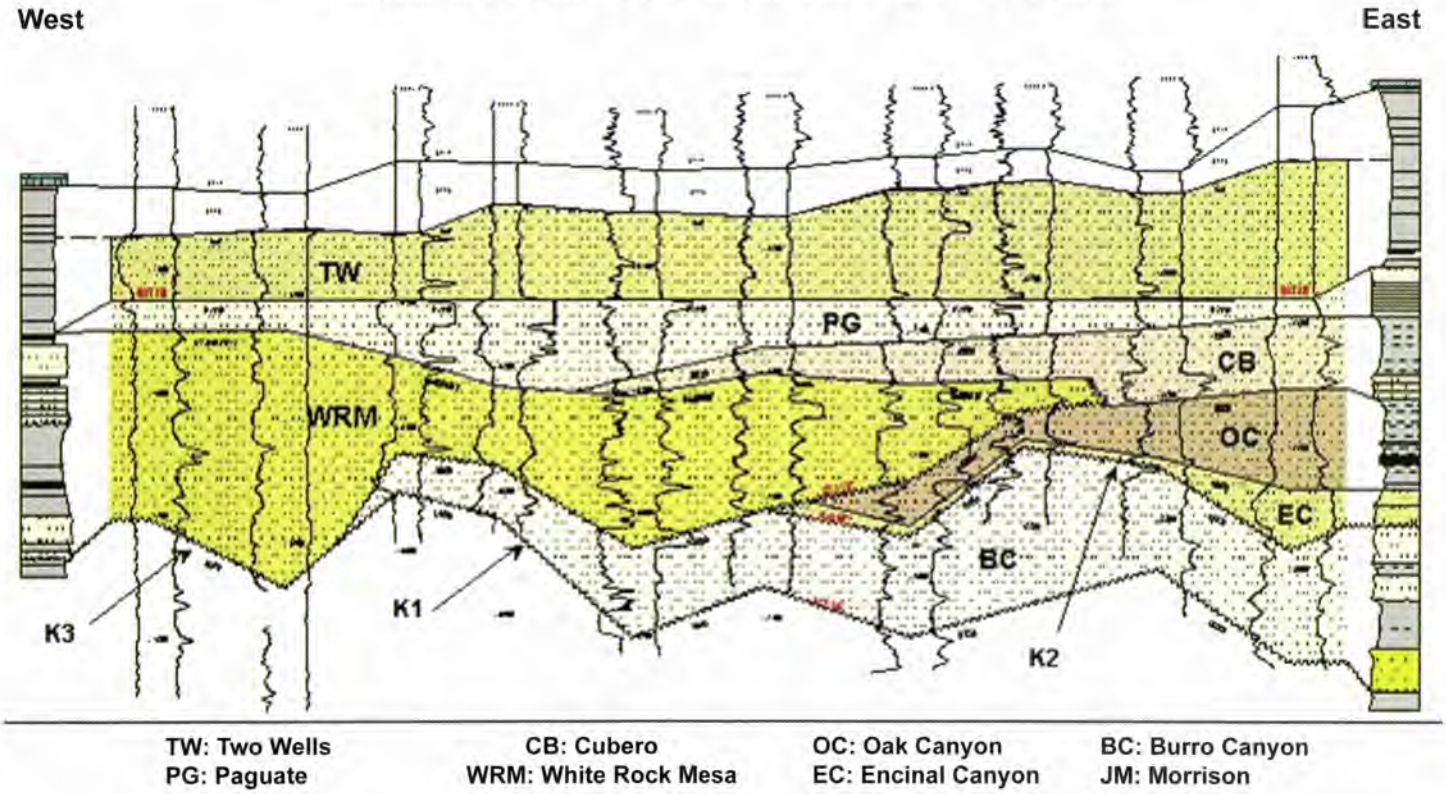


PLATE 7A. Dakota producing interval stratigraphic cross-section from the Four Corners in the west to the Chama Basin (Heron Dam) in the east (216 km. or 134 mi.), with outcrop sections on each end and well logs in between. Note westward erosional truncation of all lower Dakota and Burro Canyon as well as K-2 and K1 unconformities by K3 unconformity. Also note westward onlap of upper shoreface parasequence of Cubero on White Rock Mesa fluvial wedge. This cross-section is a summary of approximately 100 wells between outcrops (see Head and Owen, this volume).

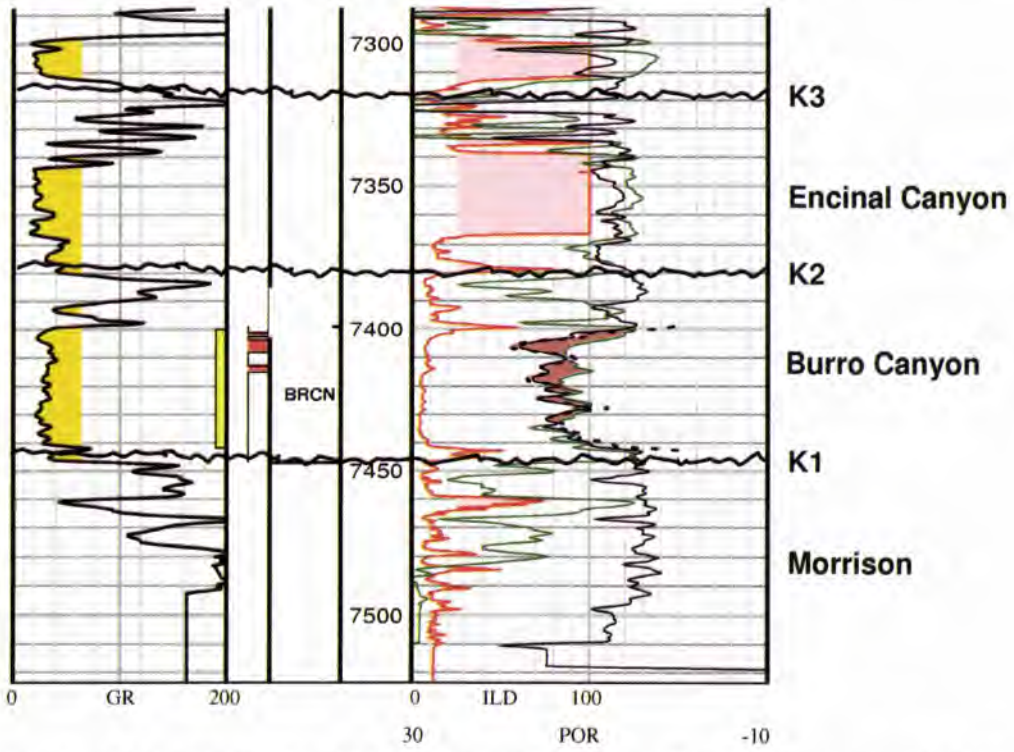


PLATE 7B. Burro Canyon type log showing low-resistivity, high-porosity reservoir with gas effect. Green mudstones and the K2 unconformity cap this reservoir (see Head and Owen, this volume).

PLATE 8: PETROLEUM GEOLOGY OF THE DAKOTA INTERVAL
PAGUATE INTERVAL

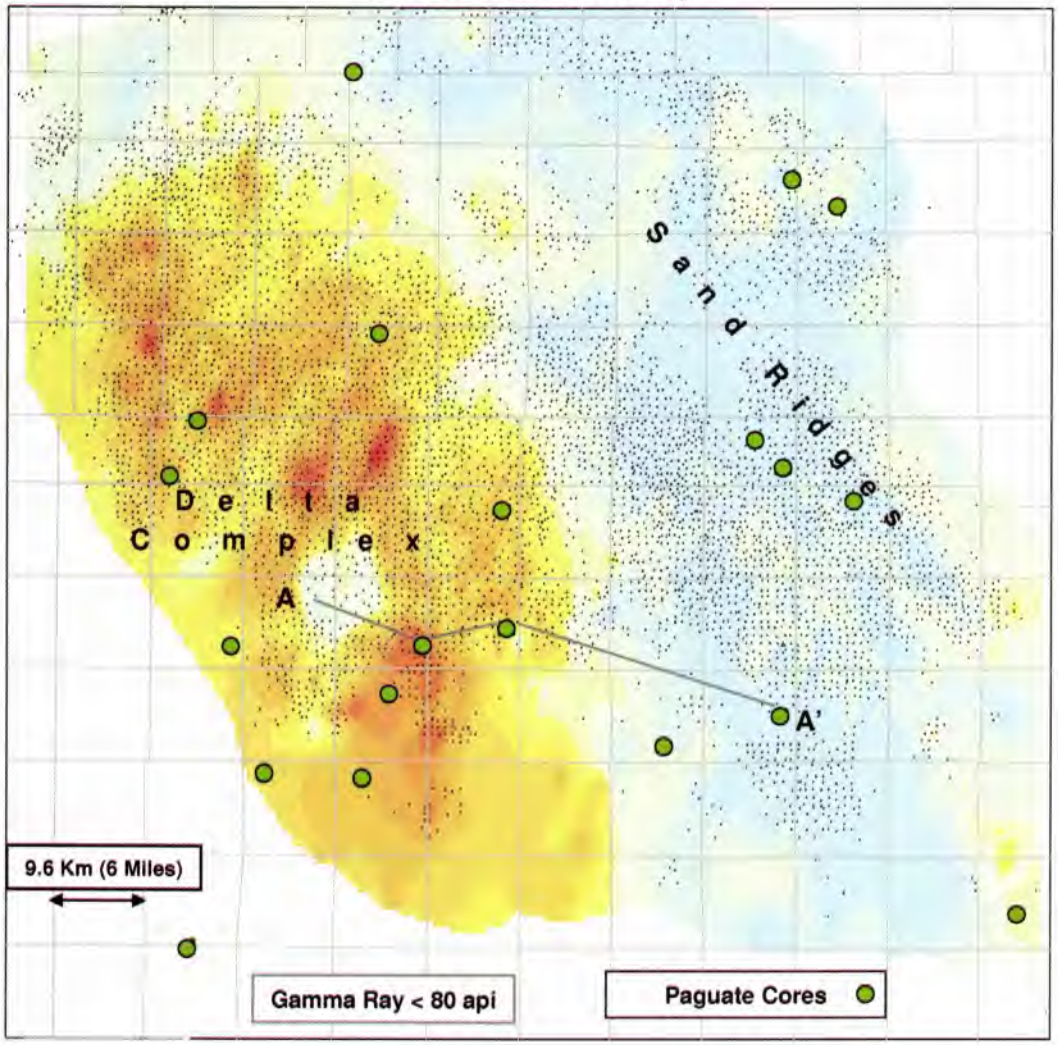


PLATE 8A. Paguate interval net sandstone isopach map showing northeast-prograding delta complex flanked by northwest-trending shoreface sand ridges built by longshore drift. Note distributary channels that form meander belts up to 3 miles (4.8 km) wide. Darker areas are distributary thicks and lighter gray areas are thin swales between sand ridges.

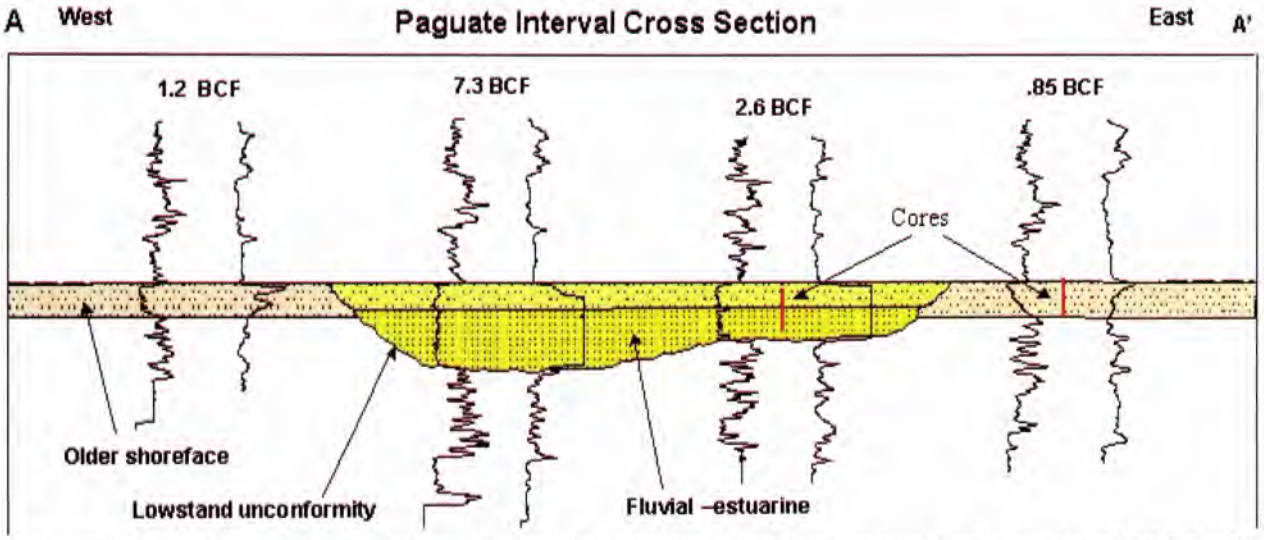


PLATE 8B. Paguate stratigraphic cross-section A-A' perpendicular to delta complex in Plate 8A. Lowstand distributary channel-fill facies filled eroded older shoreface deposits. Note contrasting log characters of blocky distributary and coarsening-upward shoreface, as well as location of two key cores. Also note higher gas recoveries from distributary sandstones.

PLATE 9: PETROLEUM GEOLOGY OF THE DAKOTA INTERVAL TWOWELLS INTERVAL AND DAKOTA PETROPHYSICAL TYPE LOG

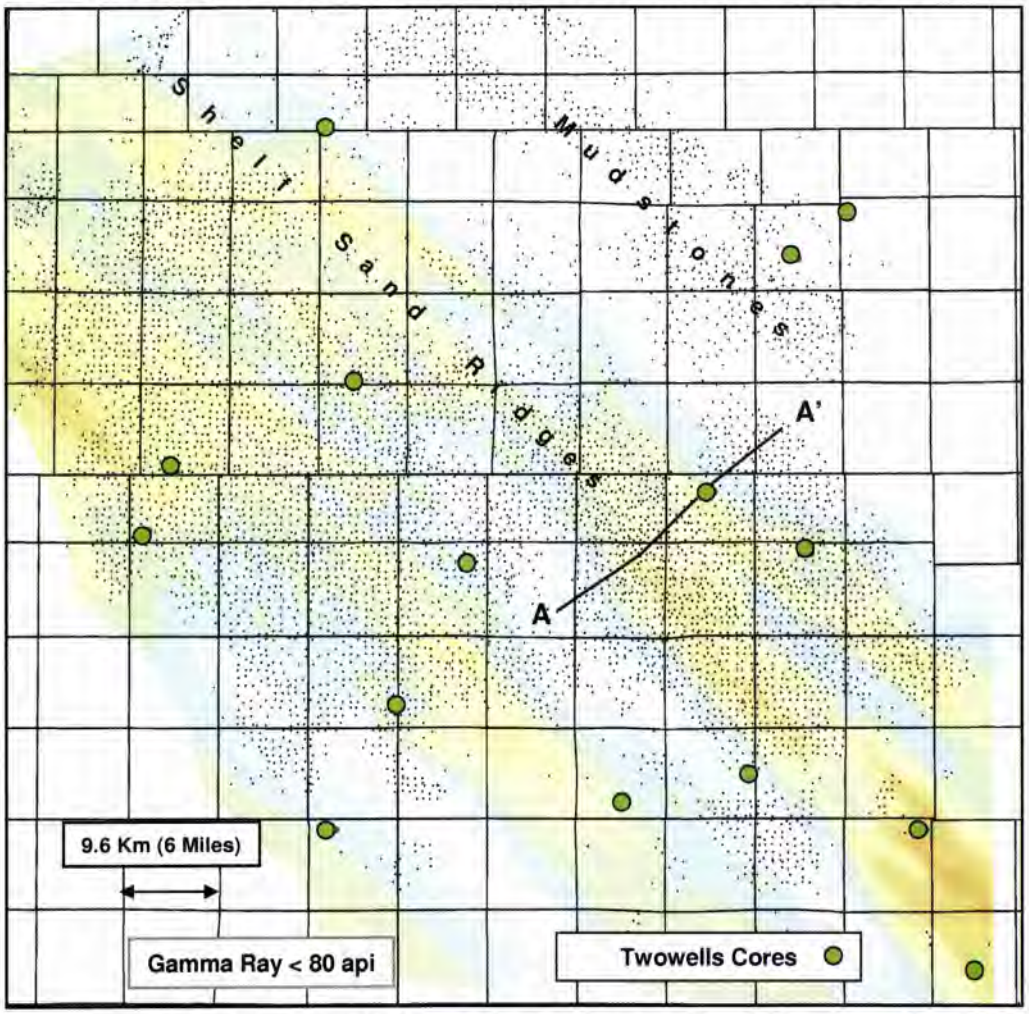


PLATE 9A,. Twowells interval net sandstone isopach map showing prominent northwest-trending, shelf-sandstone ridges. Yellow areas are shelf-ridge sandstone thicks and blue areas are thin, shaly swales between ridges. The white area to the northeast labeled mudstones marks the terminus of Twowells sandstones in the San Juan Basin; Twowells parasequences are composed of mudstones in this area and to the northeast. Crossbedding in sandstone outcrops of similar Twowells ridges indicate a southeasterly to southerly paleocurrent flow (Owen et al., 1978).

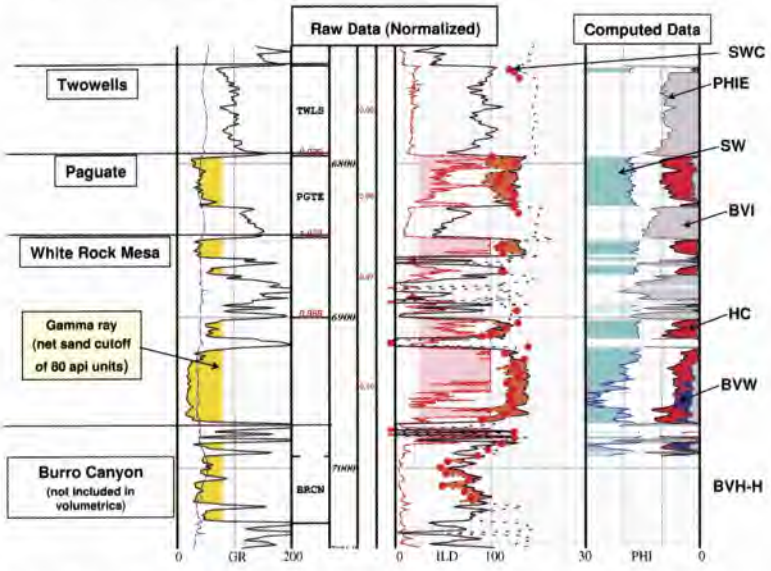


PLATE 9B. Petrophysical type log with raw data on left and computed volumetric parameters on right. SWC = sidewall cores; PHIE = effective porosity; SW = water saturation; BVI = immovable water; HC = hydrocarbons; BVW = moveable water; BVH-H = bulk volume hydrocarbon feet.

PLATE 10: PETROLEUM GEOLOGY OF THE DAKOTA INTERVAL VOLUMETRIC GAS IN PLACE

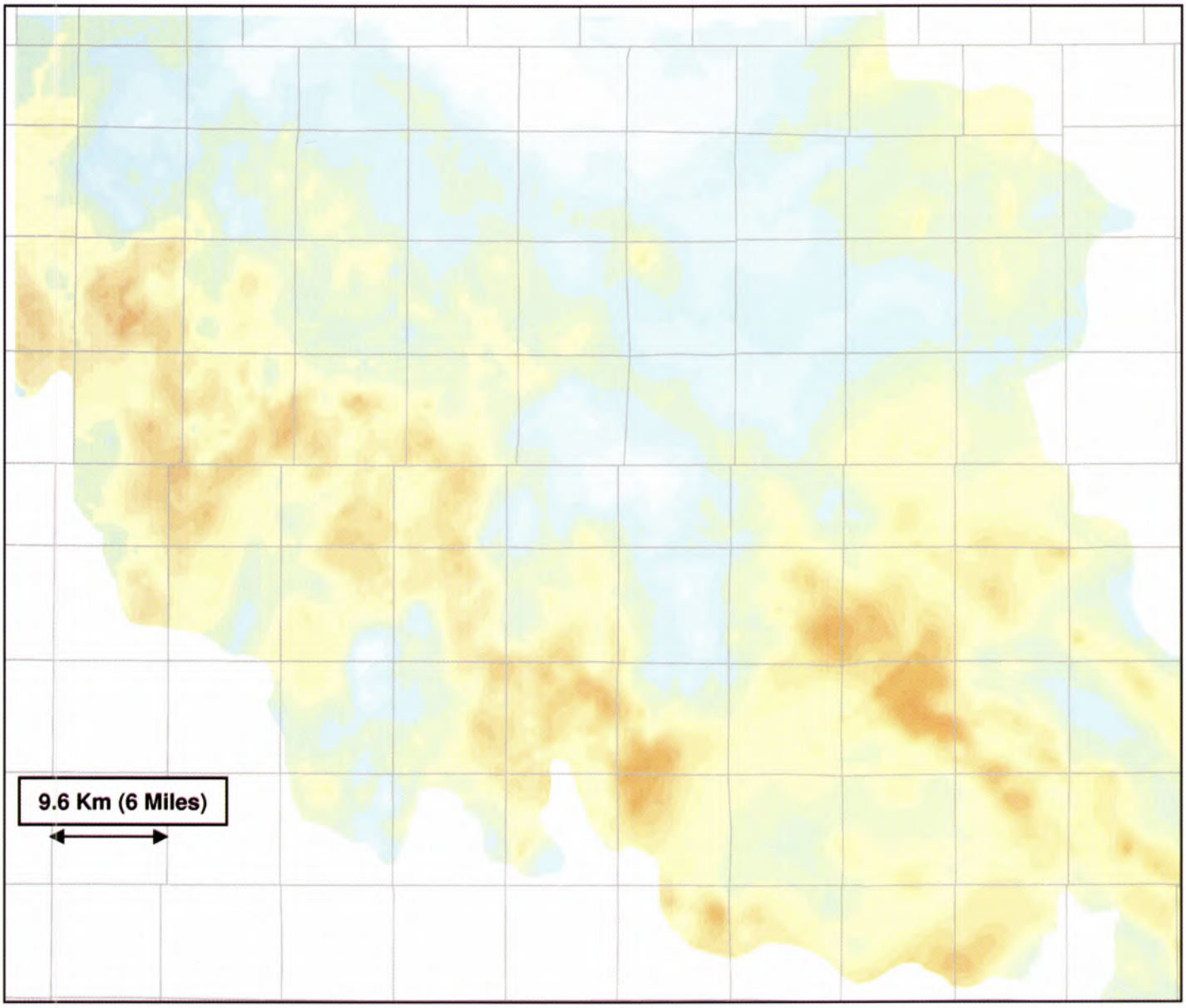


PLATE 10. Basin Dakota Field volumetric gas-in-place map. Warmer colors represent higher amounts of gas in place.

PLATE 11: PETROLEUM GEOLOGY OF THE DAKOTA INTERVAL VOLUMETRIC GAS IN PLACE WITH GAS PRODUCTION

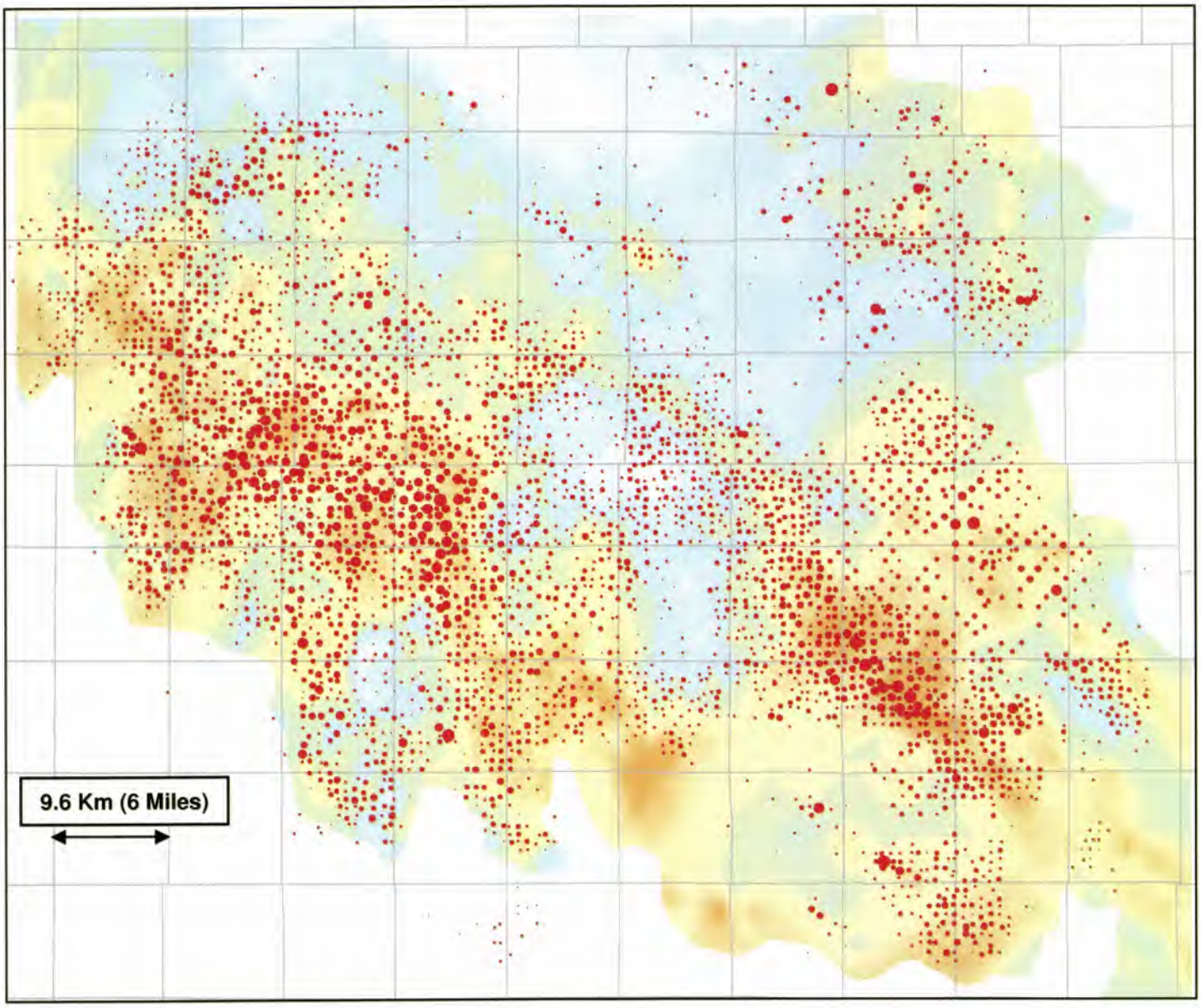


PLATE 11. Basin Dakota Field original gas-in-place map with well production bubble overlay. Warmer colors represent higher amounts of gas in place, and bubble size is relative to gas production.