THE NIOBRARA GAS PLAY: EXPLORATION AND DEVELOPMENT OF A LOW PRESSURE, LOW PERMEABILITY GAS RESERVOIR

Charles A. Brown, Chief Res. Eng.
Kansas-Nebraska Natural Gas Co., Inc.

Dr. James W. Crafton, Consultant
Crafton Engineering, Inc.

Presented at The Natural Gas Reservoirs Symposium sponsored by Stanford University with assistance from The American Gas Association.

From: "Analytical techniques and Applications for Natural Gas Reservoirs". American Gas Assoc./Stanford University Joint Symposium February 16-17, 1979 pp. 124-156

INTRODUCTION

The rapid exploitation of low permeability gas reservoirs has been fostered by significant changes in the natural gas industry. The development of tight gas reservoirs such as San Juan Basin, New Mexico; Wattenburg Field, Colorado; Cretaceous development in Montana, and the Devonian Shale in the Appalachian province, is a direct result of the foresight of interstate gas companies.

An overview of another tight gas exploration activity--"The Niobrara Gas Play,"--will illustrate the importance of economics and technology in improving the natural gas supply situation. The integration of geologic, engineering, and economic factors has provided the dynamics for the Niobrara Play. Through the initial efforts of Kansas-Nebraska Natural Gas Co., Inc., the Niobrara Play has rapidly evolved into one of the largest plays in the Rocky Mountain and Midcontinent areas. The present play includes parts of eastern Colorado, western Kansas, and western Nebraska.

HISTORY

In 1912, the Osborne and Dunn Company encountered a strong flow of gas in the Niobrara Formation while drilling the Goodland No. 1 (Section 24-T8S-R40W) near the town of Goodland, Kansas. No completion was attempted, and the well was subsequently plugged and abandoned. In the 1930's and 1940's, several small Niobrara gas wells were drilled in the Goodland Field area by Industrial Gas Company and others for local use only.

The discovery well for the Beecher Island Field in the Niobrara Formation was the Midfields No. 1 (Section 14-T2S-R43W) in Yuma County, Colorado, drilled in 1919 by the Midfields Oil Company. It had estimated flow rates up to two million cubic feet of gas per day. In the 1920's four additional Niobrara wells were drilled in Beecher Island. Connection to a pipeline could not be justified. By 1970 four dry holes had been drilled to deeper formations in the area. Two did have gas shows while penetrating the Niobrara Formation.

In 1971, Kansas-Nebraska, responding to the need for additional gas for their pipeline system, began investigating the potential of the known gas shows in the Beecher Island Field. In 1972, Midlands Gas Corporation, a subsidiary of Kansas-Nebraska, in partnership with Mountain Petroleum Corporation, air drilled six wells in Beecher Island. Five of the wells were completed without stimulation as producers and were connected to Kansas-Nebraska's pipeline south of Wray, Colorado. The wells were capable of averaging 20 MCF per day each. Although significant quantities of gas were found, the production level with the prevailing 35¢/MCF gas price was economically discouraging.

In spite of the poor economics, Kansas-Nebraska had the foresight to continue with a more extensive evaluation of the Niobrara potential during 1973. Many resistivity log anomalies and reported gas shows were found in the Niobrara of eastern Colorado and western Kansas. A lease play could commence only if adequate completion techniques could be developed. In March 1974, Kansas-Nebraska used a new stimulation technique known as the high quality foam fracture process in the Niobrara for the completion of the

Beecher Island State 1-29 (Section 29-T2S-R42W), in partnership with Mountain Petroleum Corporation. The well had a DST rate of only 5.6 MCF per day natural. After the foam fracture treatment, the State 1-29 had an initial potential of 721 MCF per day and was able to sustain a flow rate in excess of 150 MCF per day.

The successful results of the State 1-29 were the key to beginning a large leasing program. Today the play extends north to Chadron, Nebraska, and as far south as Pueblo, Colorado. The major concentration of drilling remains in the original producing area in Yuma County, Colorado, and Cheyenne and Sherman Counties, Kansas. However, several recent discoveries in the expanded exploration area will quickly promote major development drilling programs.

Since the completion of the State 1-29 in 1974, a total of 323 Niobrara wells have been drilled, of which 125 wells are gas producers in more than 30 fields, and 120 wells are dry holes. The remaining 78 wells are in various stages of completion. At this time none of these fields are considered fully developed. It is expected that as many as 170 exploratory and development wells will be drilled in 1979.

Two papers discuss the early development of the Niobrara Play. In 1977, Lockridge reviewed the beginning of what was to become the Niobrara Gas Play in his paper "Beecher Island Field, Yuma County, Colorado."[1] The paper "Niobrara Gas In Eastern Colorado and Northwestern Kansas,"[2] by Lockridge and Scholle presents a further geologic exposition.

GEOLOGY AND GAS ORIGIN

The chalks of the Niobrara Formation were deposited during a major transgression of the Western Interior Cretaceous Sea. The Cretaceous Seaway extended from the Gulf of Mexico to the Arctic Ocean (Fig. 2). To the east of the Seaway was a stable shelf, and on the west mountain building was occurring with subsequent erosion. After the deposition of the Niobrara chalks, a regressive cycle to the west was the source for a large amount of clastic sediments, which is represented in the stratigraphic section by the Pierre shale.

The Niobrara Chalk is a fine-grained limestone composed largely of the minute skeletal plates of floating algae; the skeletal plates are called coccoliths and plates with spines attached are rabdoliths (Fig. 3). When the organisms die, their skeletal remains settle to the sea floor and accumulate. The rate of deposition is extremely slow, varying from 1 to 50 meters per million years, in water depths ranging from 100 to 4500 meters.[3]

The gas production of the Niobrara comes from the uppermost chalk zone of the Smoky Hill member, commonly referred to as the Beecher Island zone. From X-ray diffraction and insolubility test analysis, this interval ranges from 80 to 95% calcite with remaining amounts of quartz and mixed clay minerals. Being a low energy, deep water environment, the Beecher Island zone is fairly continuous over a large portion of eastern Colorado, western Kansas and western Nebraska (Fig. 4).

The Western Interior Cretaceous Basin in which the Niobrara was deposited, was significantly altered by late Cretaceous and Laramide deformation. The predominance of exploratory activity in the Niobrara Gas Play is located on the gradually dipping east flank of the Denver-Julesburg Basin. The basin is bordered by the Front Range to the west, the Las Animas Arch to the south and east, the Chadron Arch to the north and east, and the Hartville Uplift to the northwest.

Regional structural interpretation indicates the absence of major structural closures; however, the gas trapped in highly faulted, low relief structures as revealed by localized, detailed geology (Fig. 5). The fault pattern is attributed to tension faulting over deep basement structures, forming horsts and grabens.[4] The major faults are normal with up to 250 feet of throw and die out into bedding plane faults with many associated compensating faults. With greater drilling density, additional faults are expected to be encountered in Niobrara fields; however, separate fault block reservoirs have not yet been observed.

The gas from the Niobrara is a biogenic gas formed at temperatures of less than 150° Fahrenheit as opposed to thermal-maturated gas created at higher temperatures. The biogenic process is caused by the breakdown of organic matter by anaerobic bacteria, and can be recognized by a high ratio of methane to total hydrocarbon gases, about 93%, and an enrichment of the light isotope Carbon_{12} to Carbon_{13}.[5] Several Niobrara gas samples have been analyzed by the United States Geological Survey confirming the biogenic nature of the gas. The gas heating content averages 985 BTU per cubic foot.

The source rock for the gas is believed to be the Niobrara Formation, itself. As a result of its particular marine origin, the Niobrara is very rich in organic material and, in some areas, is even a low-grade oil shale. The Pierre shale was the overlying seal which permitted the biogenic gas to accumulate in the Niobrara soon after generation.

Drilling and Completion Methods

The drilling and initial completion of a Niobrara well has been standardized during the last several years. The normal drilling procedure is:

1. Set 8 5/8" surface casing through the shallow Ogallala fresh water sands to protect them from contamination. Surface pipe is usually set at 300 feet.

2. Using a rotary rig, drill a 7 7/8" hole with a fresh water mud system to the top of the Niobrara. Change to a low-fluid-loss mud system to drill to approximately 50 feet below the base of the Beecher Island zone.

3. Run the open hole Dual-Induction resistivity log and Compensated Neutron-Formation Density porosity logs.

4. If the well is productive, set 4½" casing and cement. To ensure that the well is prepared for fracture stimulation, the casing with a guide shoe and float collar, has scratchers and centralizers spaced through the potential pay zone. The casing is also reciprocated during the cementing to improve cement coverage.

The standardized procedures permit a well to be ready for production about four days after spudding. This short time results from using the low fluid loss mud to prevent drilling problems in the bentonite stringer just above the Niobrara, and because no completion rig is required. After swabbing the casing out, a logging truck can run the necessary cased-hole correlation logs and the perforating tool.

Log Evaluation

The Dual-Induction Laterolog has become the primary evaluation tool, because its effectiveness is enhanced by the consistently homogeneous porosity of the Beecher Island zone in localized areas. The logs from the Whomble 1-32 (Section 32-T2S-R43W) in the Beecher Island Field are typical of a productive gas well (Fig. 6). The Spontaneous Potential (SP) curve indicates that the Beecher Island zone contains less shale and is more permeable than the surrounding beds. The shallow and deep induction curves show a formation resistivity of 10 to 18 ohms-meter^2/meter. A structurally low well such as the Whomble 1-22 (Section 22-T2S-R44W) near the Beecher Island Field (Fig. 7) has a resistivity response of only 1.7 ohms-m^2/m. Comparatively, the Whomble 1-32 log denotes a significantly higher gas saturation.

The Dual-Induction Log is an accurate tool in the Niobrara to quantify the amount of water and gas saturation for evaluating productivity and reserves. For localized areas, resistivity cutoffs can be determined as a criterion for setting production casing or abandoning a well. In the Beecher Island Field area, a resistivity of approximately four ohms-m^2/m is used as the cutoff.

If the Niobrara well is logged within a short time after penetrating the Beecher Island zone, the Dual-Induction Log is virtually problem-free. However, most resistivity logs are adversely affected by excessive filtrate invasion, as in the case with wells that are drilled considerably deeper prior to logging. Nevertheless, many of the present Niobrara fields in the play area were identified by old wells having resistivity log anomalies.

The Compensated Neutron-Formation Density Log, which is primarily used for porosity determination, provides a "quick look" at whether or not gas is present. If gas is present near the wellbore, the neutron response indicates a pessimistic porosity value and the density response has an optimistic value. This is called "cross-over." The Whomble 1-32 log shows crossover in the Beecher Island zone (Fig. 8). In contrast, the log from the structurally low Whomble 1-22 does not show crossover, hence no significant gas saturation (Fig. 9).

The Compensated Neutron-Formation Density Log has a relatively shallow depth of investigation. Even productive wells show varying degrees of crossover, because of significant filtrate invasion. This limits the usefulness of the Compensated Neutron-Formation Density Log as the primary indicator of well productivity.

A few operators in the play have used a velocity log to determine a productive well. The effectiveness of the two previously mentioned logging tools eliminates the need for this log.

Fracture Stimulation

Prior to the fracture treatment of the State 1-29 in Beecher Island, the production of Niobrara gas was not economically feasible. It appeared that a fracture treatment process had to be developed which did not require the large volumes of liquid usually needed for the stimulation. Research work At Colorado School of Mines employed a foam-based carrying fluid which was only 30% liquid (water) and 70% gaseous (nitrogen). Rapid after-treatment clean-up and significantly reduced formation damage along the fracture faces prompted Kansas-Nebraska to adopt this process for well stimulation in the Niobrara. These relatively small initial treatments consisted of 17,000 gallons of foam with only 10,000 pounds of sand.

Initially problems were encountered with frequent plugging of the surface flow lines of the conventional hydraulic fracturing equipment. Since the sand and liquid were first mixed, and the nitrogen added later, sand concentrations of eight pounds per gallon were required at the blender to obtain a bottom-hole concentration of 1.5 to 3 pounds per gallon. During 1976, a treatment design which circumvented the problem used the foam to break down the formation, followed by nitrified, gelled water to carry the sand. In some cases, wells could not clean-up the additional treatment water without intermittent build-up periods. Nevertheless, during this time, the typical fracture treatment had grown to 18,000 pounds of sand and 20,000 gallons of fluid.

By 1977 equipment design and operation had been sufficiently improved so that the completely foam-based fracture treatment could again be used.

now with up to 40,000 pounds of sand. The foam quality or gas content was also increased to 80%, improving clean-up and reducing reservoir damage. In addition, another fracture treatment, the gelled water-carbon dioxide fluid system, was performed with encouraging results.

Fracture stimulation design for the Niobrara continues the trend toward larger volume treatments. This trend has been found beneficial in many other reservoirs.[6,7] The variation in Niobrara well quality with water saturation has concealed this improvement.

The Niobrara reservoirs generally have transitional water saturations, dependent on structural position. Well productivity is also dependent on water saturation. A correlation of 24-hour initial potential flow rate versus water saturation for two ranges of fracture treatment size clearly shows the expected improvement in well performance with increased treatment size (Fig. 10). At 35% water saturation the larger treatments ranging in size from 18,000 to 50,000 pounds of sand have initial potentials almost twice as great as the small treatments using less than 18,000 pounds of sand. The long term well performance can also be expected to be better on wells with larger stimulations.

As a result of this comparison, it seemed that further improvement could be achieved in well performance. A massive hydraulic fracture re-stimulation of the Bruder 1-7 (Section 7-T2S-R43W) with 124,000 pounds of sand and 90,000 gallons of foam in May, 1978, yielded a 24-hour potential of 1228 MCF per day, with stabilized production of 100 MCF per day. The initial stimulation with 18,000 pounds of sand, gave an initial potential of 455 MCF per day and stabilization at 45 MCF per day. The initial potential is 2.7 times greater and the well stabilized at rates over twice as large. The restimulation cost, $25,700.00, would have payed out in approximately 9.5 months based on present prices.

For the most recent Niobrara completions, Kansas-Nebraska has used fracture treatments in the range of 55,000 to 204,000 gallons of foam with 80,000 to 300,000 pounds of sand. Early flow rate data from these wells give favorable indications that further improvement can be expected. After optimum fracture treatments have been achieved with sufficient production histories, infill drilling may also be required to further maximize gas recovery.

Testing and Production

A Niobrara well is generally produced for 2 days to remove as much of the fracture fluids as possible. The well is then shut-in for a 30-day build-up period prior to the initial normal sequence four-point test, followed by the twenty-four hour one-point flow test.

The wells produce through the 4½ inch casing, without artificial lift equipment or surface production facilities. They do not produce any significant water to the surface, but minor, apparently water-related problems are appearing. In addition, some wells have exhibited production rate decreases with significantly reduced wellhead pressure. Attempts to explain the anomalous behavior have ranged from pressure sensitive permeability or fractures to fluid migration into the wellbore during production.

Tubing completions or temporary pump installations may be necessary for a few wells for adequate clean-up after the fracture treatment.

The oldest commercial producing well with modern stimulation is the State 1-29 (Section 29-T2S-R43W) in Beecher Island. It has only about 58 months of history, but has produced 138 million cubic feet to year-end 1978. The Eckberg 1-33 in Beecher Island has the largest cumulative production at year-end with 236 million cubic feet. Table 1 shows the cumulative production for the fields connected and producing as of January 1, 1979.

RESERVOIR EVALUATION

Reservoir Properties

The chalk matrix Beecher Island zone of the Niobrara is an underpressured gas reservoir with very high porosity and low permeability. The reservoir is noticeably influenced by its depth of burial with diagenetic changes arising from both mechanical compaction and increased chemical modification.

A satisfactory correlation of porosity versus depth is easily established using data collected from the present Niobrara fields (Fig. 11). The matrix porosity at Goodland Field is 45% at a depth of 950 feet; Beecher Island has 41% at 1600 feet; and the Whisper Field exhibits 33% porosity at 2750 feet. This trend continues on into the deeper Denver-Julesberg Basin.

In-situ permeability established from resistivity gradient analysis compares favorably to permeabilities determined from cores and transient testing. Reduced reservoir permeabilities occur with increased overburden similar to the porosity reduction (Fig. 12). Permeabilities measure 5.0 mds. at Goodland Field, 1.8 mds. at Beecher Island, and 0.3 mds. at Whisper Field. Minor secondary matrix fracturing occurs in localized areas significantly increasing the effective permeability.

Water saturation is a critical reservoir property. The unusual sensitivity of a Niobrara reservoir is attributed to the transitional water saturations observed in virtually every reservoir. The low permeabilities of the Niobrara cause the transition zone between water and gas to be several hundred feet. From an examination of matrix resistivities within a reservoir, wells higher on structure have higher resistivity and lower water saturation than do wells which occur lower on the structure (Fig. 13).

The Niobrara gas pressure gradient ranges from .06 to .24 psi per foot as compared to normal hydrostatic gradient of .43 psi per foot (Fig. 14). At 1000 feet in the Goodland Field, the pressure is only 50 to 60 psia, while in DeNova Field, Washington County, Colorado, the pressure exceeds 700 psia at 2900 feet. In addition to the under-pressured condition, localized areas appear to have independent pressure systems particularly deeper in the play. This erratic pressure condition may arise from pressure seals occurring between reservoirs due to reduced relative and absolute permeability at greater depth. This is accentuated by the local generation of gas, causing nonequilibrium pressure gradients.

By integrating these analyses of the porosity, permeability, transitional water saturation and pressure, a fairway of optimum reservoir development can be defined. In the deeper parts of the basin as the permeability decreases, the thickness of the transitional water saturation zone will increase. Hence, the water saturation at a given structural position will increase. Also, reduced porosity will reduce the total pore volume available. To obtain adequate reserves and sufficient elevation above the water, larger structural closures will be required for commercially productive wells.

The commercial failure of the Alice G. Nay No. 1 (Section 14-T9N-R58W) in Weld County, Colorado, drilled by Excelsior Oil Co., a subsidiary of Kansas-Nebraska, suggests that a depth exists below which no commercial matrix production will be possible regardless of structure size. The Niobrara was encountered at 5422 feet and a completion was attempted. The porosity was 10% with less than ten microdarcies permeability. Between the commercial fields at 2900 feet of depth and the Alice G. Nay No. 1 at 5422 feet, a depth of 3500 feet has been determined as a reasonable commercial production limitation.

The proximity of the formation outcrops and excessively low pressures which cause insufficient gas reserves have led to the upper limitation of 1000 feet. From these reservoir conditions, areas of favorable exploration are defined (Fig. 15). The exploration fairway is anticipated between 1000 feet on the east side and 3500 feet on the west side.

Evaluation Methods

Attempts have been made to interpret well performance employing traditional methods. One very common empirical method is the rate versus time plot. Such a plot has been prepared for the Eckbert #1-22 (Section 22-T2S-R43W), Beecher Island Field, Colorado (Fig. 16). The traditional method of straight-line exponential production decline shows that subsequent interpretations with additional production data seem to indicate persistently increasing gas recovery, or that the exponential decline analysis is pessimistic. This curvature of the rate-time graph is primarily caused by the stimulation.

The material balance calculation was also attempted. This method results in the graphical cumulative production versus pressure decline graph (Fig. 17). In the early life of a well, the observed shut-in well pressure declines much more rapidly than the reservoir average pressure does. Until the two decline at about the same rate, this method indicates a very steep decline or too little recoverable reserves. These erratic results only confirmed that considerable additional production and pressure data must be obtained to permit adequate stabilization of the pressure curve.

The commonly used traditional methods of reserves analysis were consistently pessimistic when used in evaluating the Niobrara reservoir when compared to a numerical simulation of the reservoir behavior. A simulator[7] which includes the linear flow and pressure losses in the fracture was used, with a history-matching step to more realistically characterize the production and pressure behavior of the fracture and reservoir.

The State 1-29 was one of several wells investigated with the simulator. Its four years of production and pressure data recorded from the meter charts was averaged over weekly intervals primarily to yield more convenient time increments for the program. Since geologic data and well tests did not indicate sealing boundaries, the history-matching process was begun with a drainage extent equivalent to 640 acres. The large drainage area was selected to ensure that the match would not be adversely affected. Good agreement between the observed and calculated rates and pressures was obtained by varying fracture length, and reservoir or fracture permeability (Fig. 18). The final match of the State 1-29 was obtained with an effective fracture radius of 325 feet. This was consistent with other independent methods generally used to determine fracture length.

The existence of drainage boundaries generally cannot be anticipated unless they have significantly influenced the production behavior. For this reason, relatively short forecasts were made for the Niobrara wells. A six-year forecast of production of the State 1-29, or ten years of producing life, show that the well can be expected to recover 274 million cubic feet of gas. At the end of the forecast period it will be producing about 70 MCF per day against 160 psia bottom-hole pressure.

The State 1-29 simulations have shown that even with the small fracture treatment in four years the pressure at the outer boundary of a 640-acre area had dropped three pounds. That corresponds to a twelve pound reduction in reservoir average pressure in the same area.

In a further attempt to define the behavior of each well, other evaluation methods have been used. Where data permitted, the analysis suggested by Gringarten, Ramey and Raghaven[8] for the detection of faults and fractures was undertaken. Also, the traditional Horner plot[9] was constructed. In no case were any sealing boundaries detected, even with tests lasting up to 90 days. The results indicated that at least one well had several different highly conductive fracture planes as opposed to the single plane normally arising from the fracture treatment.

Although insufficient production data has been recorded to evaluate the new large fracture treatments, it is possible to anticipate their effectiveness by using the simulator. For the properties obtained from the Eckberg 1-22 match, simulations were made for four years production with 200 feet, 800 feet and 1,490 feet fracture radii. The increasing gas recovery with increased treatment size or fracture length can be shown graphically (Fig. 19). This reaffirms results in reservoirs such as the Cotton Valley Formation in east Texas and the Wattenberg Muddy "J" in Colorado.[10,11]

Economics

An indication of the economic feasibility of drilling a Niobrara well can quickly be investigated based on the 10-year history-projection for the State 1-29. The present cost of a well is estimated at $68,000. The price of new gas is estimated at $2.11/MCF with a 10%/yr escalation. A net revenue interest of 85% and monthly operating costs of $225 with 7%/yr escalation are assumed. The calculated undiscounted net cash flow would be $662,000 before federal income tax, and discounted at 20%, the Net Present Value is $209,900. Payout of the well would occur in approximately 1.2 years.

CONCLUSIONS

With the active support and participation of the natural gas companies, such as Kansas-Nebraska Natural Gas, it is possible to explore, develop and evaluate previously unproducible supplies of natural gas. The Niobrara Gas Play which was first discovered in 1912 and extends over parts of three states is such a source. It was made possible by the combination of two critical ingredients:

1. an adequate economic incentive in the form of an increased wellhead price for gas sold in interstate commerce, and
2. technologically more effective completion methods.

Since the inception of the play, information regarding the geology, petrology, and reservoir mechanics has been collected and analyzed in great detail. Although some questions remain unanswered, several important conclusions about the Niobrara Gas Play and low permeability reservoirs in general can be made:

1. The Niobrara is a unique chalk reservoir producing biogenic gas generated in-situ and flowing from the matrix which has extremely high porosity and very low permeability. The reservoirs are shallow structural traps which consistently exhibit transitional water saturations.

2. Successful, efficient, problem-free completion methods and in-field evaluation guidelines have significantly reduced drilling and completion time and minimized cost.

3. Improvements in fracture stimulation techniques and increased treatment sizes continue to improve Niobrara well performance in a manner consistent with that observed in other low permeability reservoirs.

4. To adequately predict the performance of a fractured Niobrara well with relatively short production histories requires the use of sophisticated simulation, testing and evaluation procedures. These rigorous methods will yield realistic appraisals of productivity and, in time, reserves for Niobrara wells.

All these factors combine to yield an exploratory and development venture in the Niobrara Gas Play which is economically very attractive.

REFERENCES

1. Lockridge, J.P.: "Beecher Island Field, Yuma County, Colorado," R.M.A.G. - Exploration Frontiers, Denver, Colorado, (1977) p. 271.

2. Lockridge, J.P., and Scholle, P.A.: "Niobrara Gas In Eastern Colorado and Northwestern Kansas," R.M.A.G. - Energy Resources of the Denver Basin, Denver, Colorado, (1978) p. 35.

3. Scholle, P.A.: "Current Oil and Gas Production from North American Upper Cretaceous Chalks," U.S. Geol. Survey Circular No. 767, 51 pp.

4. Tremain, G.: Personal Communications, 1979.

5. Rice, D.D.: "Origin of and Conditions for Shallow Accumulations of Natural Gas," Wyoming Geological Assn. Guidebook, (1975) p. 267-270.

6. Holditch, S.A., Jennings, J.W., Neuse, S.H., and Wyman, R.E.: "The Optimization of Well Spacing and Fracture Length in Low Permeability Gas Reservoirs," presented at the 53rd Annual Fall Mtg., SPE, Houston, Texas, (October 1-3, 1978) SPE Paper No. 7496.

7. Crafton, J.W. and Harris, C.D.: "Direct Finite Difference Simulation of a Gas Well with a Finite Capacity Vertical Fracture," presented at the 4th Symposium on Numerical Simulation of Reservoir Performance SPE, Los Angeles, California, (February 19-20, 1976) SPE Paper No. 5736.

8. Gringarten, A.C., Ramey, H.J., Jr., and Raghavan, R.: "Applied Pressure Analysis for Fractured Wells," Trans. AIME, (1975) 259, p. I-887.

9. Horner, D.R.: "Pressure Build-up in Wells," Proc, Third World Petroleum Congress, E.J. Brill, Leiden, (1951) II, p. 503.

10. Jennings, A.R., Jr., and Sprawls, B.T.: "Successful Stimulation in the Cotton Valley Sandstone--A Low Permeability Reservoir," presented at the 50th Annual Fall Mtg., SPE, Dallas, Texas, (Sept. 28-Oct. 1, 1975) SPE Paper No. 5627.

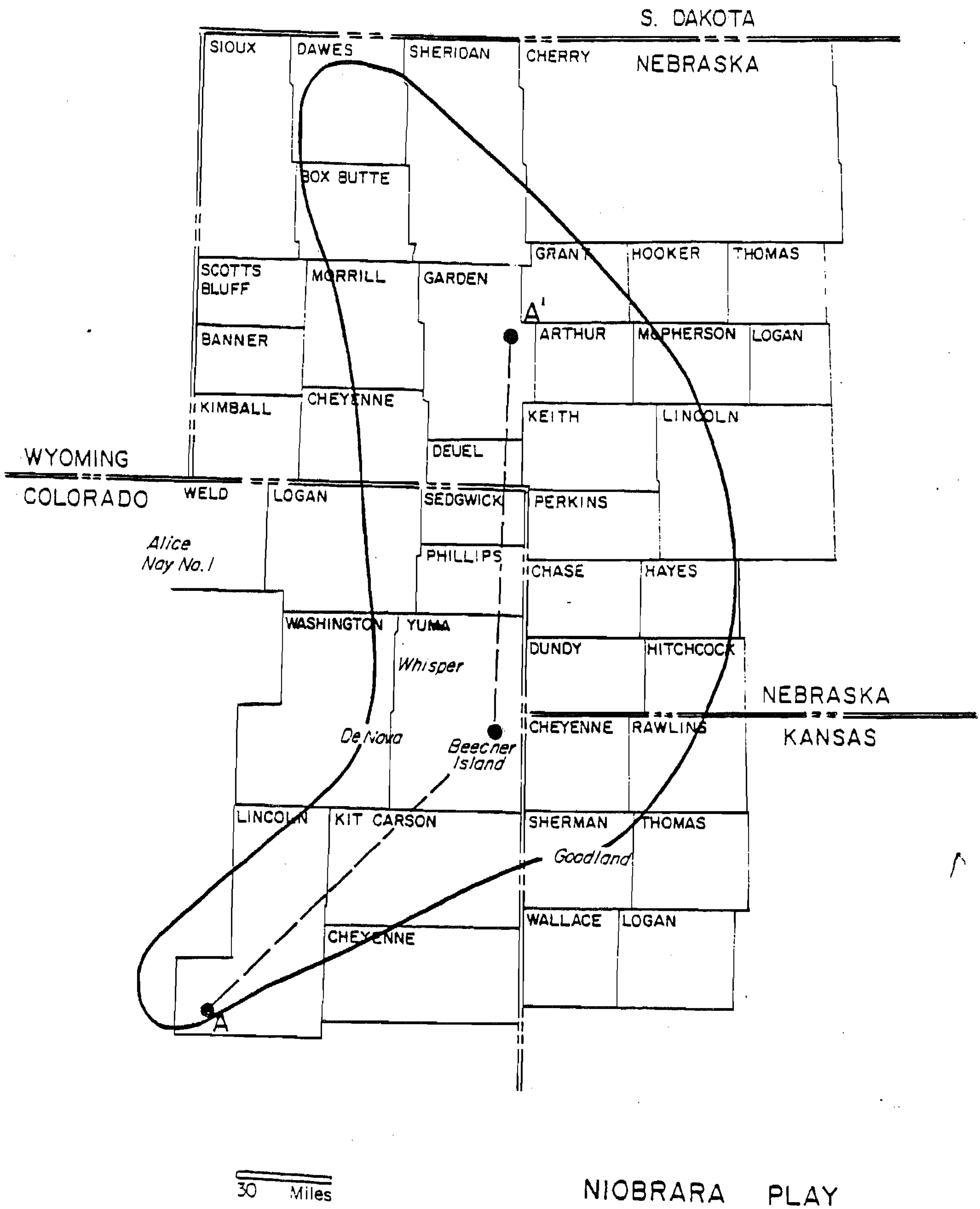
11. Fast, C.R., Holman, G.B. and Covlin, R.J.: "A Study in the Application of MHF to the Tight Muddy 'J' Formation, Wattenberg Field, Adams and Weld Counties, Colorado," presented at the 50th Annual Fall Meeting, SPE, Dallas, Texas, (Sept. 28-Oct. 1, 1975) SPE Paper No. 5624.

TABLE I

NIOBRARA PLAY

Producing Field Data
All Volumes in MCF at 14.73 psia

Field	Number of Wells Connected	Date of Initial Production	Cumulative Production as of Dec. 31, 1978
Beecher Island	27	9/72	2,084,659
Whisper	2	7/75	58,754
Republican	7	5/76	165,251
Vernon	9	5/76	180,221
Shout	3	6/76	62,798
Cherry Creek	2	8/77	12,470
Phuma	5	12/77	47,295
Waverly	6	2/78	107,686
Buckboard	3	2/78	23,123
Mildred	9	8/78	88,005
Schramm	3	9/78	12,908
Armel	3	12/78	1,525



NIOBRARA PLAY
REFERENCE MAP
FIGURE 1

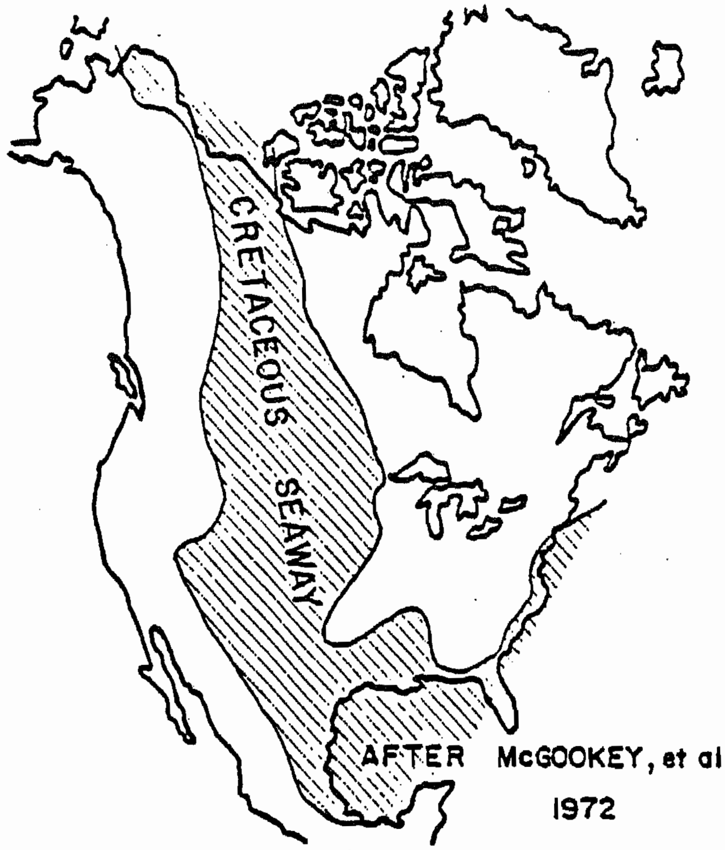


Figure 2

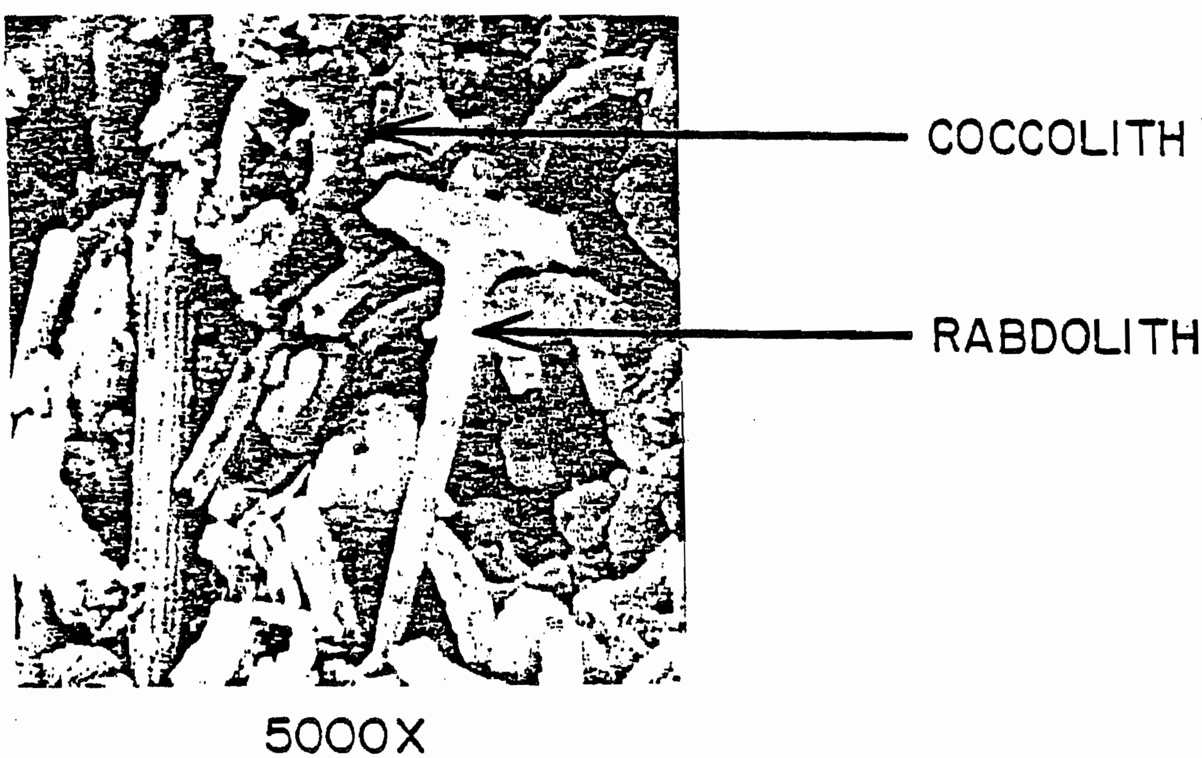


Figure 3

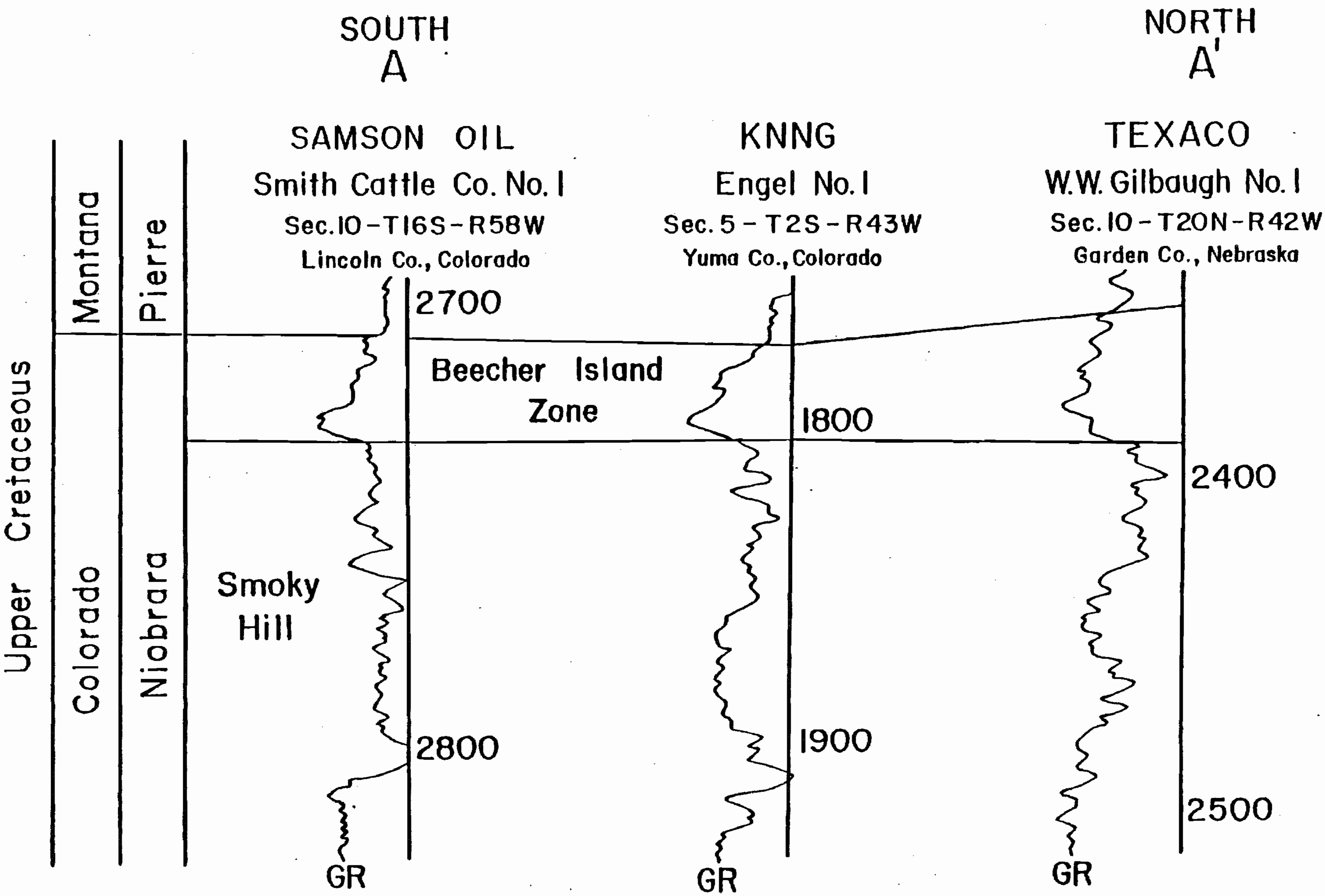

SOUTH
A
NORTH
A'
SAMSON OIL
Smith Cattle Co. No. I
Sec.10-T16S-R58W
Lincoln Co., Colorado
KNNG
Engel No. I
Sec. 5 - T2S - R43W
Yuma Co., Colorado
TEXACO
W.W. Gilbaugh No. I
Sec. 10 - T20N - R42W
Garden Co., Nebraska
Upper Cretaceous
Montana
Colorado
Pierre
Niobrara
Beecher Island Zone
Smoky Hill
2700
2800
1800
1900
2400
2500
GR
GR
GR

Figure 4

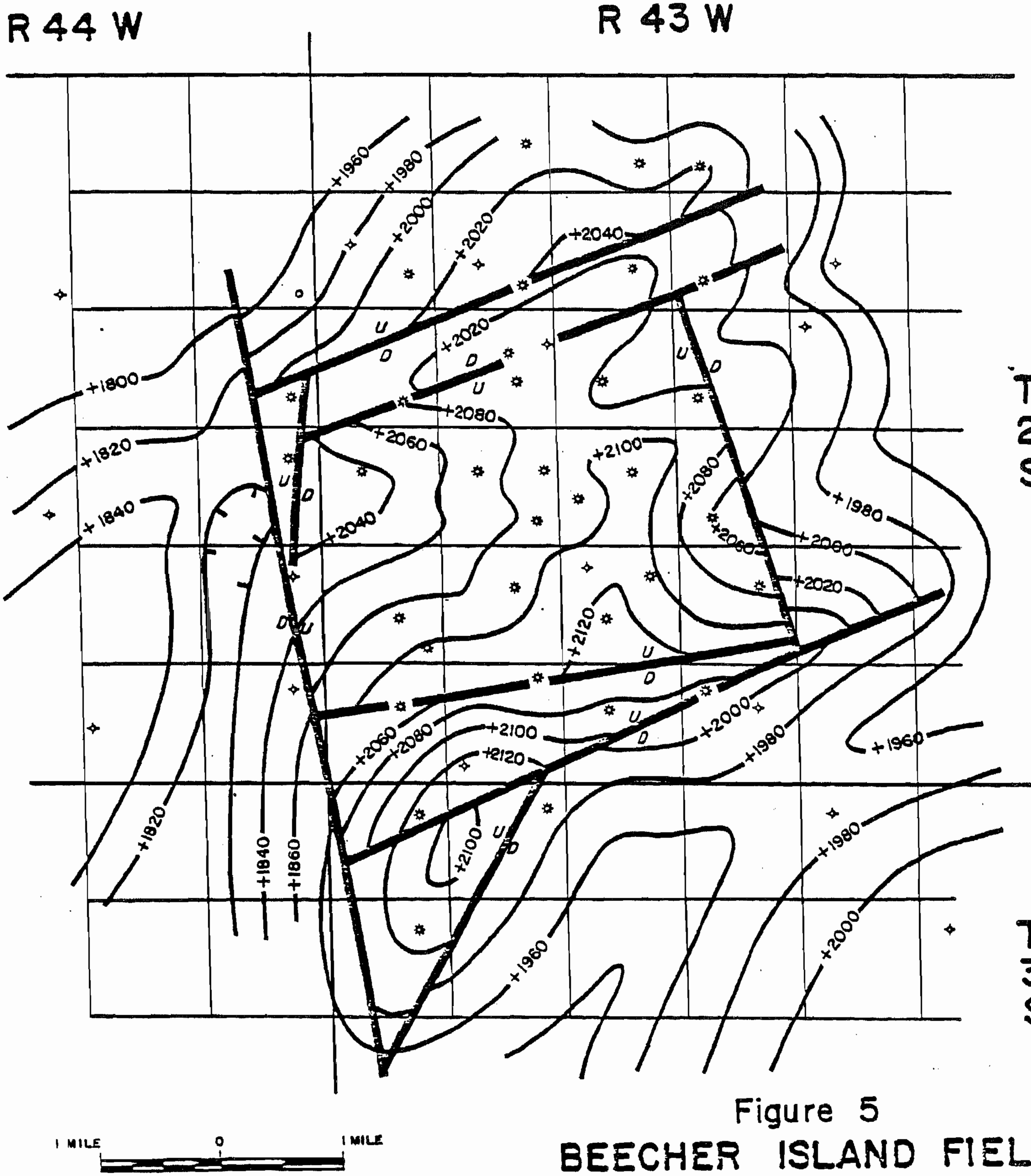


Figure 5
BEECHER ISLAND FIELD
YUMA CO., COLORADO
C. I. = 20'
After Tremain
1979

WHOMBLE 1-32

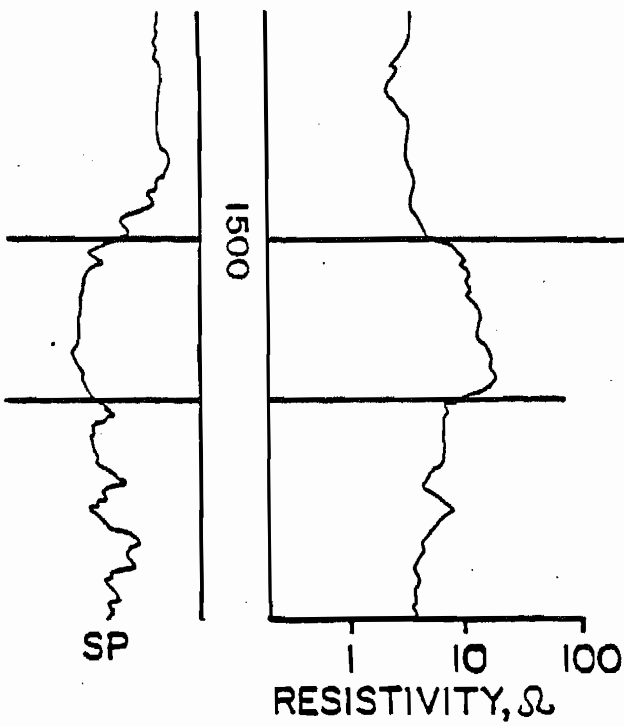


Figure 6

WHOMBLE 1-22

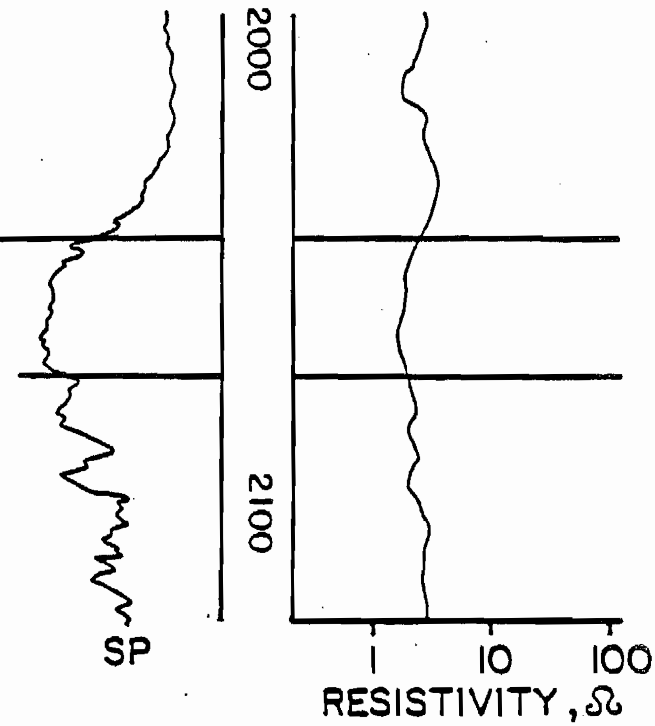


Figure 7

WHOMBLE 1-32

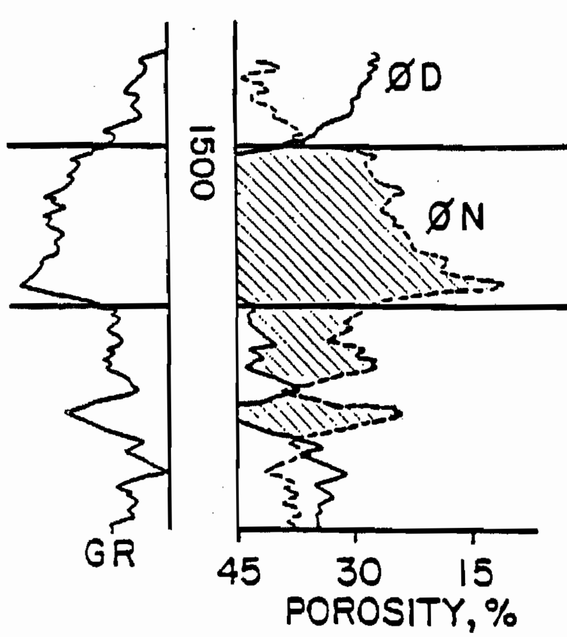


Figure 8

WHOMBLE 1-22

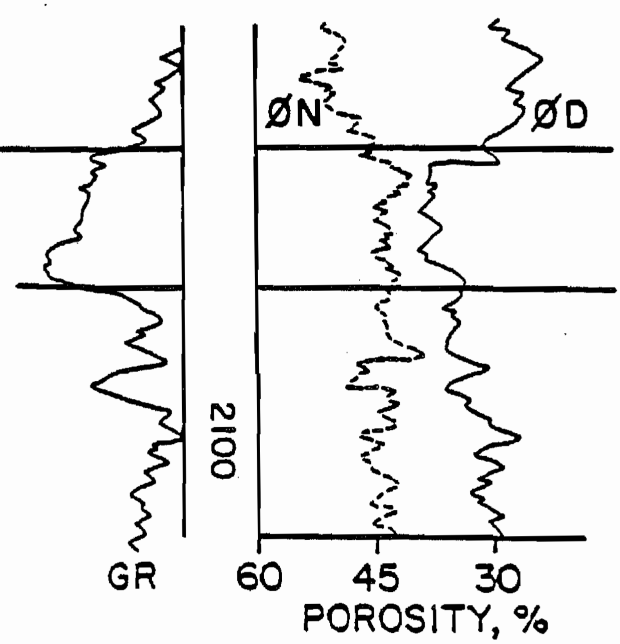


Figure 9

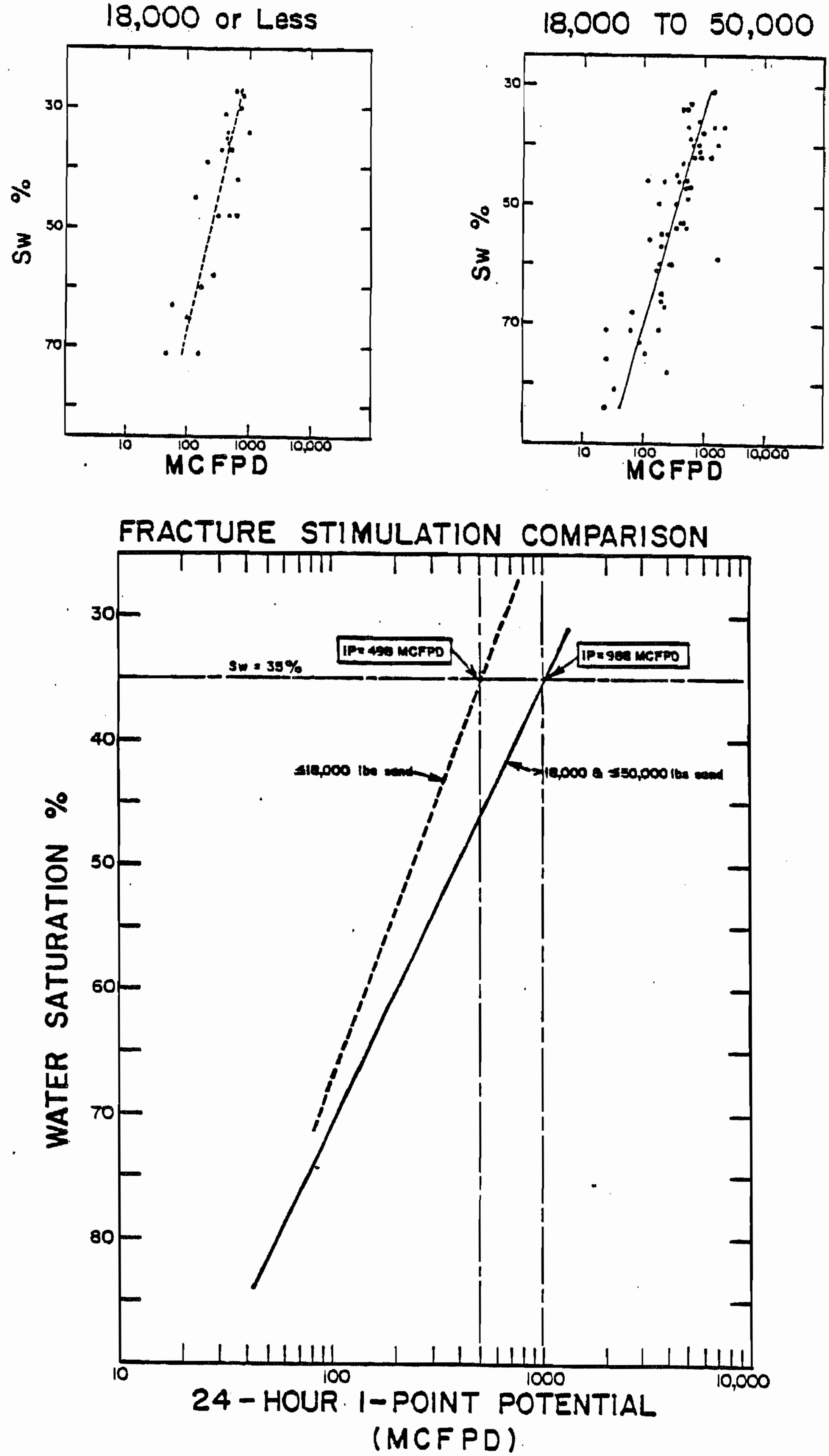

18,000 or Less
Sw %
30
50
70
10
100
1000
10,000
MCFPD
18,000 TO 50,000
Sw %
30
50
70
10
100
1000
10,000
MCFPD
FRACTURE STIMULATION COMPARISON
IP= 498 MCFPD
IP= 988 MCFPD
Sw = 35%
≤18,000 lbs sand
>18,000 & ≤50,000 lbs sand
WATER SATURATION %
30
40
50
60
70
80
10
100
1000
10,000
24-HOUR 1-POINT POTENTIAL
(MCFPD)

Figure 10

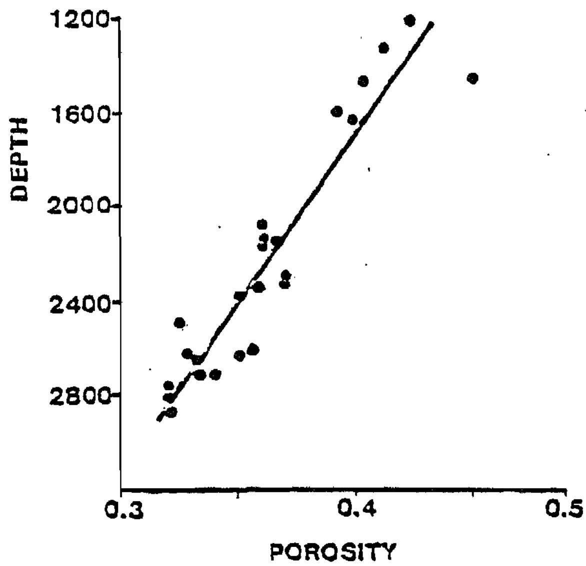


Figure 11

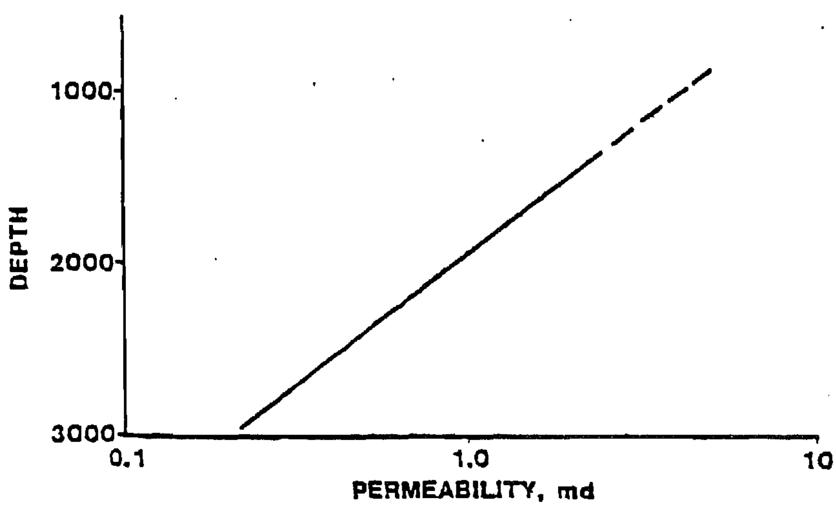
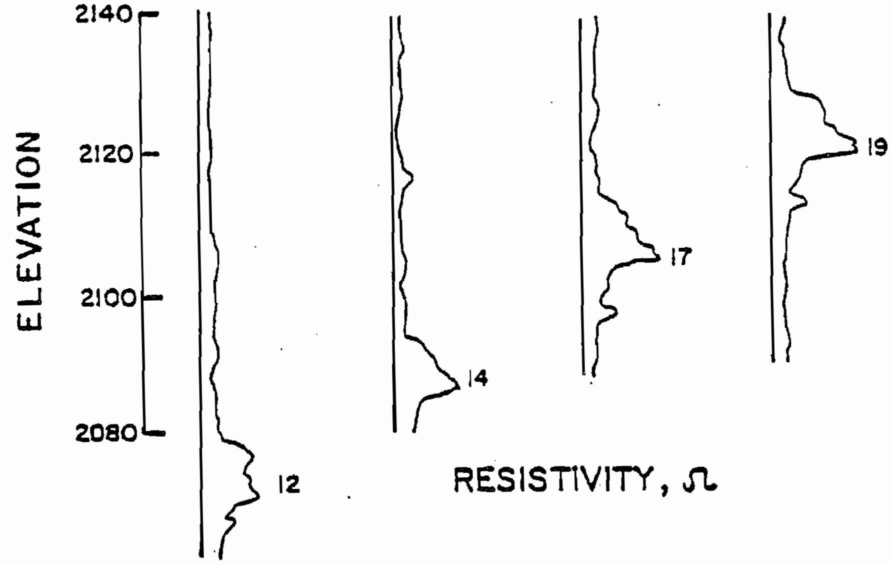


Figure 12



BEECHER ISLAND FIELD

Figure. 13

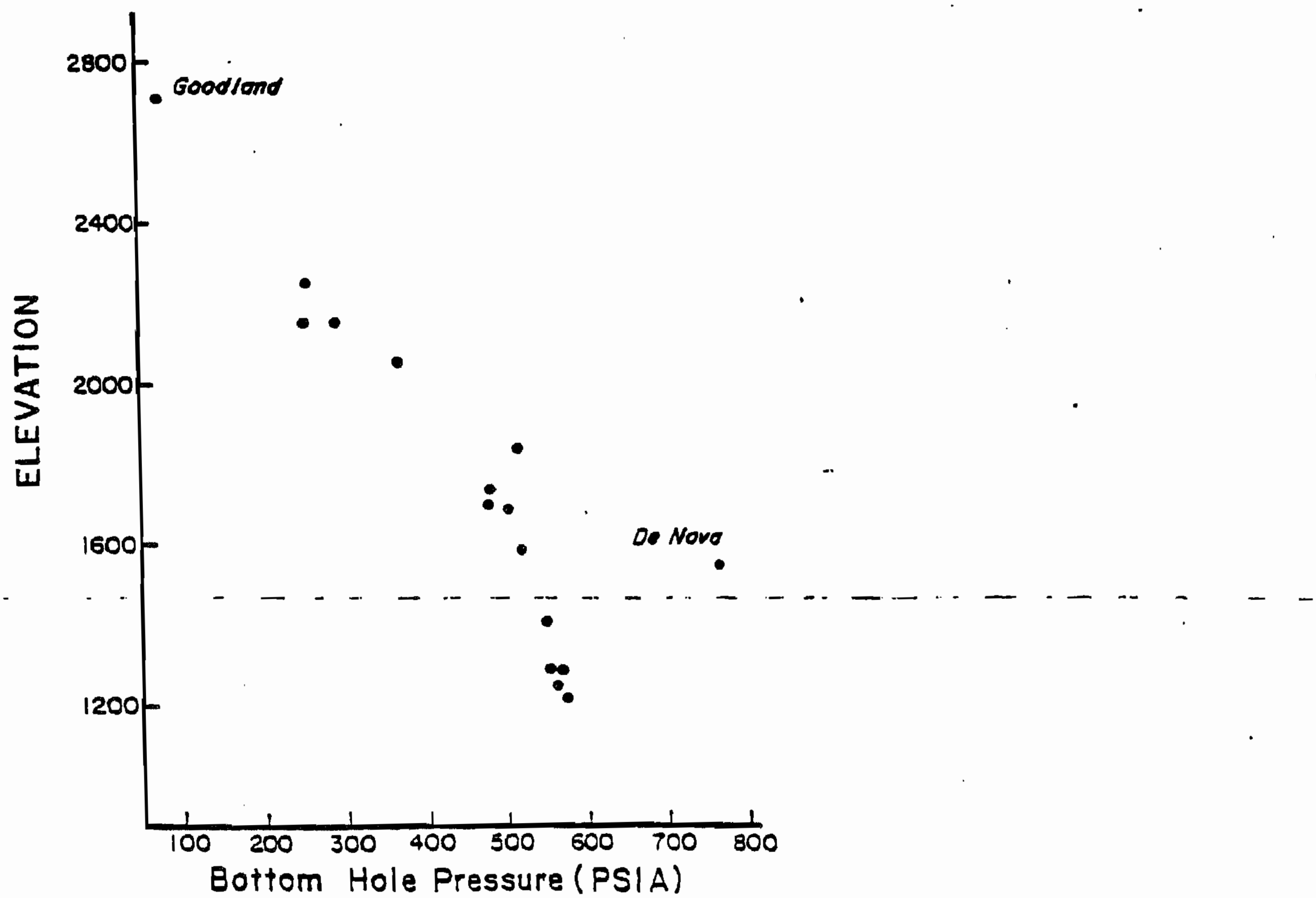
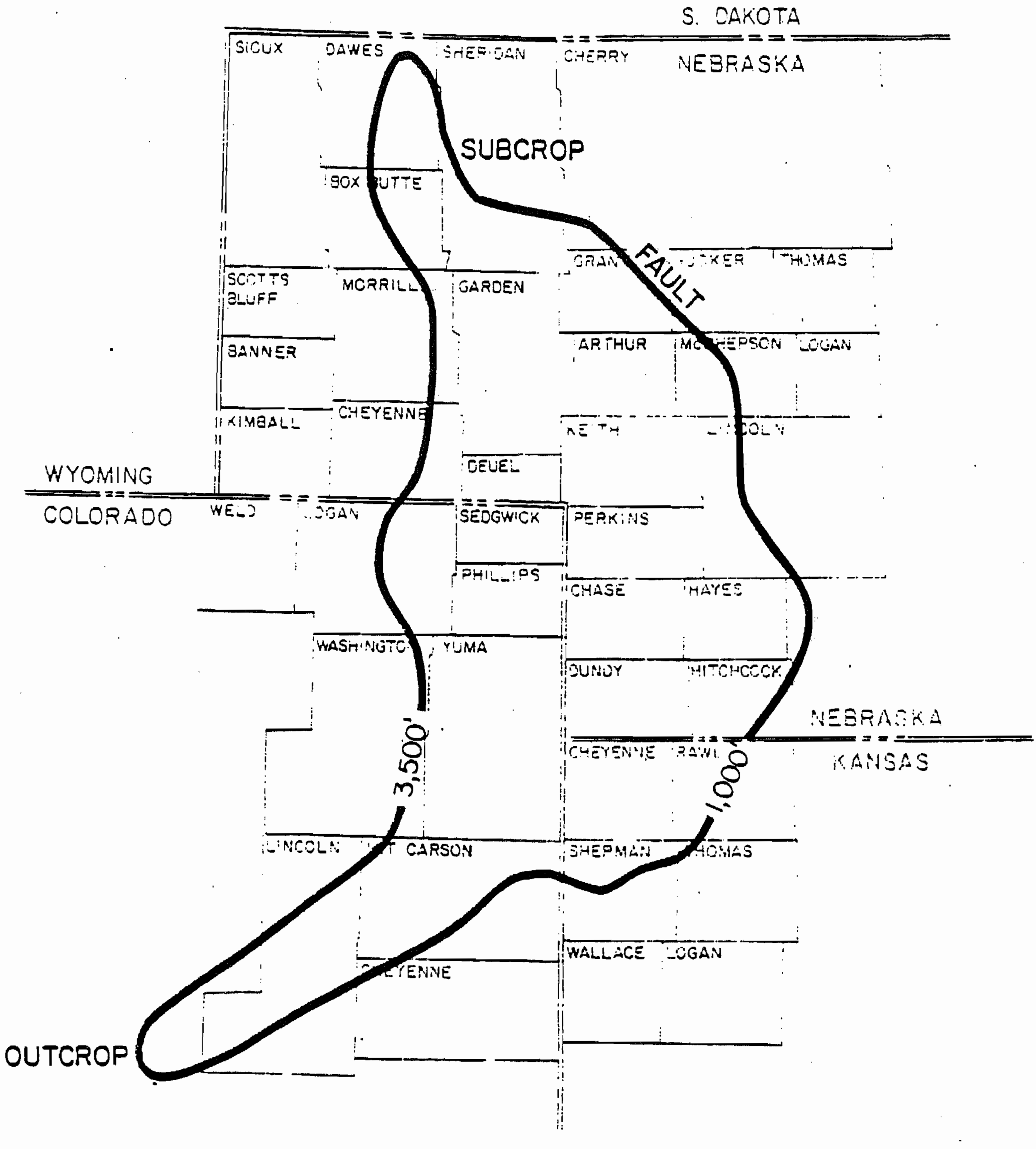


Figure 14



MAP OF NIOBRARA FAIRWAY
FIGURE 15

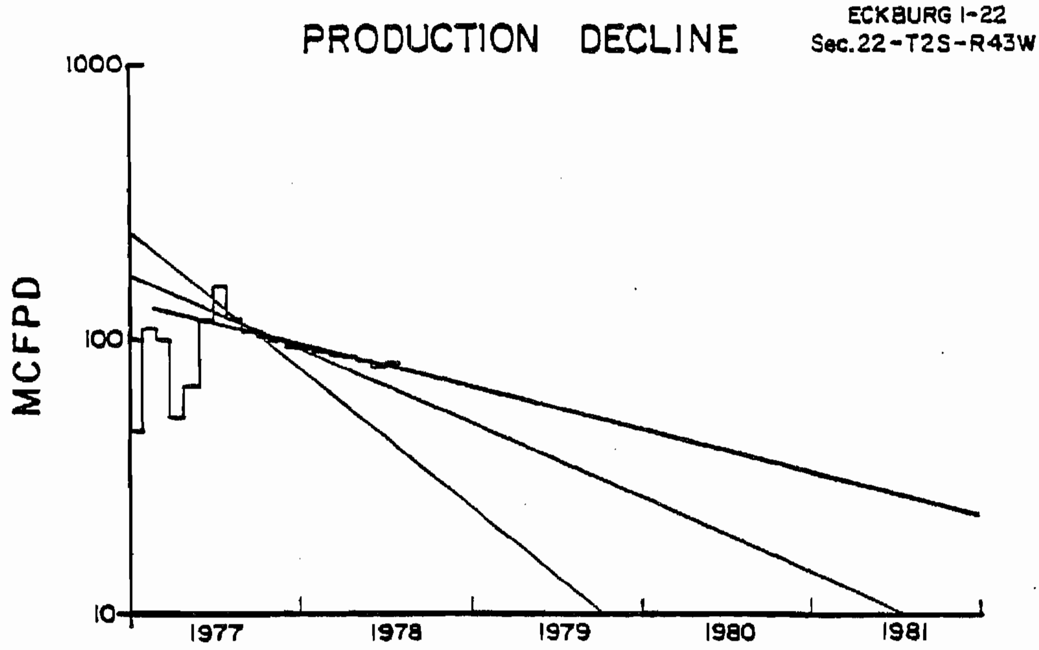


Figure 16

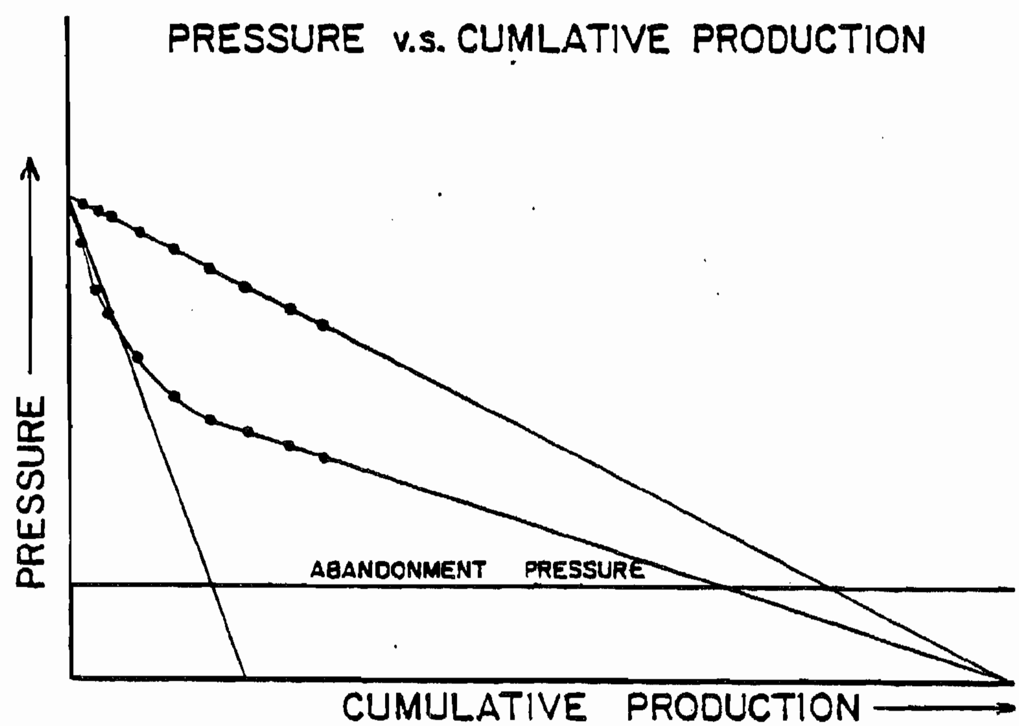


Figure 17

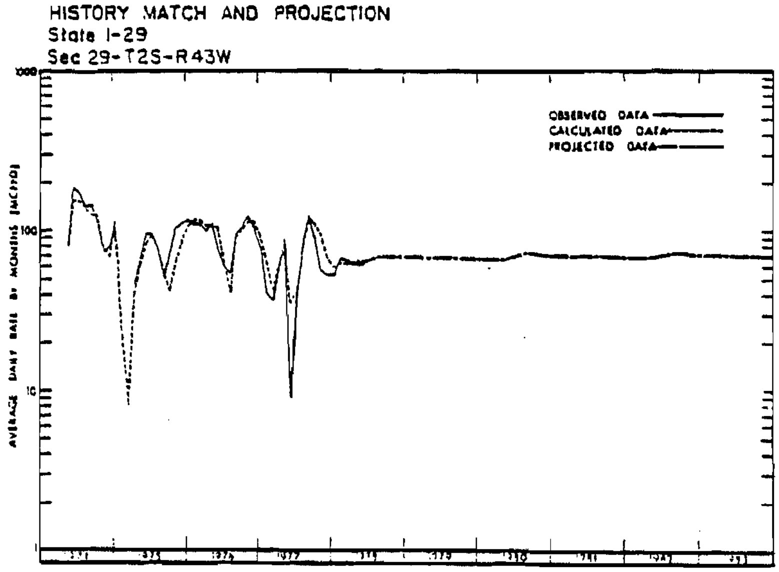


Figure 18

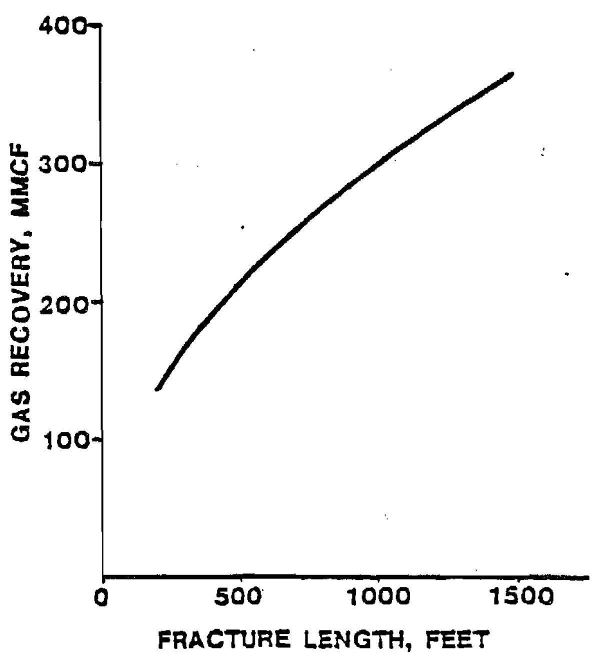


Figure 19