IN REPLY REFER TO:

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON 25, D.C.

'70 JUN 29 AM 8 15

2871

Benson-Montin-Greer Drilling Corporation
221 Petroleum Center Building
Farmington, New Mexico 87401

JUN 2 5 1970

Attention: Mr. Albert R. Greer

Gentlemen:

Your application of June 10, 1970, filed with the Oil and Gas Supervisor, Roswell, New Mexico, requests preliminary approval of the proposed second expansion of the Canada Ojitos unit area, Rio Arriba County, New Mexico.

The Canada Ojitos unit agreement, No. 14-08-0001-8526, was approved effective June 19, 1963. The unit was formed for the purpose of conducting exploratory drilling operations in an unproven area. The unit area presently contains 35,825.12 acres, more or less, and upon approval of the pending seventh revision of the Niobrara-Greenhorn participating area, 15,026.62 acres within the unit will have been determined as capable of producing unitized substances in paying quantities or necessary for unit operations. The proposed second expansion will add 5,437.53 acres to the unit area consisting of 4,088.74 acres (75.19 percent) of Federal land and 1,348.79 acres (24.81 percent) of fee land. Approval of such expansion subsequent to final approval of the proposed first expansion will increase the Canada Ojitos unit area from 50,841.92 acres to 56,279.45 acres, more or less. Although the lands to be added by the proposed expansion are not presently productive, available geologic data indicates that such lands are underlain by a gas cap associated with the oil productive Niobrara-Greenhorn interval under the present Canada Ojitos unit area. Accordingly, the inclusion of such lands in the unit area is necessary to insure proper control and use of the natural reservoir energy in order to obtain maximum oil recovery. The application advises that Benson Montin-Greer Drilling Corporation will drill and complete a test well in the area to be added by the second expansion within one year after the effective date of the expansion. It is further agreed if such well does not establish the presence of the gas cap under the expanded area, that the unit area will be contracted to eliminate all lands added by the second expansion which are unnecessary for unit operations.

No objection will be offered to the proposed second expansion of the Canada Ojitos unit area if it is accomplished in accordance with the

ILLEGIBLE

applicable provisions of Section 2 of the unit agreement within a reasonable period of time. A minimum of five copies of the application for final approval accompanied by the appropriate joinders should be filed with the Oil and Gas Supervisor, Roswell, New Mexico after such application has been approved by the appropriate officials of the State of New Mexico.

The format of the original exhibits attached to the unit agreement should be followed closely in the preparation of revised Exhibits A and B. The existing tracts should not be renumbered.

Sincerely yours,

W. A. Radlinski

Acting Director

cc:
BLM, Santa Fe
Comm. of Pub. Lands, Santa Fe
N.M.O.C.C., Santa Fe ✓
Roswell (2)

ERW:act:ds:6-17-70

SERIALS:

New Mexico	022268-A	Santa Fe	079285
	0108332		079285-A
	0301697-A		079285-D
	0309390		079285-G
	0309391		079286
	0424837		079286-B
	0554417		079286-E
	0554030		079286-H
NM	8218		079287
	8835		079287-A
	11435		079287-D
			079287-E

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON 25, D.C.

'70 JUN 29 AM 8

2871

Benson-Montin-Greer Drilling Corporation
221 Petroleum Center Building
Farmington, New Mexico 87401

Attention: Mr. Albert R. Greer

JUN 25 1970

Gentlemen:

Your application of June 10, 1970, filed with the Oil and Gas Supervisor, Roswell, New Mexico, requests preliminary approval of the proposed first expansion of the Canada Ojitos unit area, Rio Arriba County, New Mexico.

The Canada Ojitos unit agreement, No. 14-08-0001-8526, was approved effective June 19, 1963. The unit was formed for the purpose of conducting exploratory drilling operations in an unproven area. The unit area presently contains 35,825.12 acres, more or less, and upon approval of the pending seventh revision of the Niobrara-Greenhorn participating area, 15,026.62 acres within the unit will have been determined as capable of producing unitized substances in paying quantities or necessary for unit operations. The proposed first expansion will add 15,016.80 acres to the unit area consisting of 10,746.29 acres (71.56 percent) of Federal land, 559.39 acres (3.73 percent) of State of New Mexico land, and 3,711.12 acres (24.71 percent) of fee land. Upon approval of such expansion, the Canada Ojitos unit area will be increased from 35,825.12 acres to 50,841.92 acres, more or less. Although the lands to be added by the proposed expansion are not presently productive in the Niobrara-Greenhorn interval, the proposed expansion will permit the orderly development of the acreage involved. In addition, such expansion should increase the ultimate oil recovery from the Niobrara-Greenhorn gas injection pressure maintenance project now being conducted within the present unit area as the lands to be added to the unit are indicated by available geologic information as potentially productive from the same interval. The application advises that Benson-Montin-Greer Drilling Corporation will drill and complete a minimum of two wells in the expanded area to test the Niobrara-Greenhorn interval within 18 months after the effective date of the expansion. It is further agreed if such wells are determined as not being capable of producing unitized substances in paying quantities that the unit area will be contracted to eliminate all lands added by this expansion which are not qualified for inclusion in a participating area under the terms of the unit agreement, as amended.

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No objection will be offered to the proposed first expansion of the Canada Ojitos unit area if it is accomplished in accordance with the applicable provisions of Section 2 of the unit agreement within a reasonable period of time. A minimum of five copies of the application for final approval accompanied by the appropriate joinders should be filed with the Oil and Gas Supervisor, Roswell, New Mexico, after such application has been approved by the appropriate officials of the State of New Mexico.

The format of the original exhibits attached to the unit agreement should be followed closely in the preparation of revised Exhibits A and B. The existing tracts should not be renumbered.

Sincerely yours,

W. A. Radlinski

Acting Director

cc:
BLM, Santa Fe
Comm. of Pub. Lands, Santa Fe
N.M.O.C.C., Santa Fe
Roswell (2)

ERW/att:ds:?-17-70

SERIALS:

New Mexico	03453	NM	2975
	0122478		2978
	0122493		2979
	0436721		2980
	0467231		2981
	04995?7		4446
	0499?08		8991
	0510100-A		9371
	0510143		9954
	0556814		10237

ILLEGIBLE

BENSON-MONTIN-GREER DRILLING CORP.

GENERAL OFFICE:
1390 FIRST NATIONAL BLDG.
OKLAHOMA CITY, OKLAHOMA 73102
PHONE 235-0546

221 PETROLEUM CENTER BUILDING
FARMINGTON, NEW MEXICO 87401
PHONE 325-8874

March 7, 1968

New Mexico Oil Conservation Commission
P.O. Box 2088
Santa Fe, New Mexico

Re: CAÑADA OJITOS UNIT
RIO ARRIBA COUNTY

Gentlemen:

We are sending you herewith copy of letter dated March 4, 1968, from the Department of the Interior, Geological Survey, evidencing the Department's approval of the requested fifth expansion of the Niobrara-Greenhorn Participating Area, Cañada Ojitos Unit.

Yours very truly,

BENSON-MONTIN-GREER DRILLING CORP.

BY: Albert R. Greer
Albert R. Greer, President

cc: New Mexico Oil Conservation Commission
Aztec, New Mexico

ney

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON, D.C. 20242

Benson-Montin-Greer Drilling Corp.
221 Petroleum Center
Farmington, New Mexico 87401

MAR 4 1968

Gentlemen:

Your application of October 20, 1967, for the fifth revision (4,637.84 acres), of the Niobrara-Greenhorn participating area, (new total 8,637.84 acres), under the Canada Ojitos unit agreement, Rio Arriba County, New Mexico, No. 14-08-0001-8526, was approved February 27, 1968, by Arthur A. Baker, Acting Director of the Geological Survey, effective as of May 1, 1967.

Enclosed is one copy of the approved application for your records. We request that you furnish all interested principals with appropriate evidence of this approval.

Sincerely yours,

Chief, Conservation Division

Enclosure

BOLACK - GREER, INC.
158 PETROLEUM CENTER BUILDING
FARMINGTON, NEW MEXICO

MAR 7 AM 03

March 4, 1966

To: OWNERS OF INTEREST
CANADA OJITOS UNIT

NEW MEXICO OIL CONSERVATION COMMISSION
SANTA FE, NEW MEXICO

NEW MEXICO STATE LAND OFFICE
SANTA FE, NEW MEXICO

This is to advise you that the Third and Fourth Revisions of the Niobrara-Greenhorn Participating Area in the Canada Ojitos Unit, Rio Arriba County, New Mexico, have been approved by the Acting Director, United States Geological Survey, effective as of November 1, 1964 and April 1, 1965 respectively.

The third revision added the following lands:

Township 25 North, Range 1 West

Section 10: E/2
Section 15: NE/4

The fourth revision added the following lands:

Township 25 North, Range 1 West

Section 23: NW/4, S/2
Section 24: SW/4

Retroactive adjustments in payments for production are now being calculated. These figures, and figures for investment adjustment, will be supplied the affected parties in the near future.

BOLACK-GREER, INC.

BY: Albert R. Greer, Vice-President

MAILING LIST ATTACHED

CAÑADA OJITOS UNIT
MAILING LIST

ATLAS CORPORATION
NATIONAL BANK OF TULSA BUILDING
TULSA, OKLAHOMA

MRS. M. A. BARTON
BOX 2154
SANTA FE, NEW MEXICO

R. L. BAYLESS
BOX 1541
FARMINGTON, NEW MEXICO

TOM BOLACK
1010 NORTH DUSTIN
FARMINGTON, NEW MEXICO

ALICE BOLACK
1010 NORTH DUSTIN
FARMINGTON, NEW MEXICO

BENSON-MONTIN-GREER DRILLING CORP.
221 PETROLEUM CENTER BUILDING
FARMINGTON, NEW MEXICO

BURK ROYALTY COMPANY
800 OIL AND GAS BUILDING
WICHITA FALLS, TEXAS

F. H. CARPENTER
BOX 608, SOUR LAKE, TEXAS

LOUISE G. CARPENTER
BOX 608, SOUR LAKE, TEXAS

THOMAS D. CHACE
BOX 2072
SANTA FE, NEW MEXICO

FRANK O. ELLIOTT
BOX 703
ROSWELL, NEW MEXICO

J. V. FRITTS
ROSWELL, NEW MEXICO

GENERAL AMERICAN OIL CO. OF TEXAS
MEADOWS BUILDING
DALLAS, TEXAS

ALBERT R. GREER
221 PETROLEUM CENTER BUILDING
FARMINGTON, NEW MEXICO

F & S DRILLING COMPANY
TRI STATE INSURANCE BUILDING
TULSA, OKLAHOMA

LESTER C. HOTCHKISS
4949 NORTH VAN NESS BOULEVARD
FRESNO, CALIFORNIA

WALTER HOWARD
LINDRITH, NEW MEXICO

GAYLE HUDGENS
BOX 1898
HOBBS, NEW MEXICO

JACK LONDON, JR.
1390 FIRST NATIONAL BUILDING
OKLAHOMA CITY, OKLAHOMA

ESTATE OF T. H. McELVAIN
c/o FORREST MILLER
220 SHELBY, SANTA FE, NEW MEXICO

ADELINA MAESTES
LLAVES, NEW MEXICO

MONTIN-HARBERT PIPELINE CONSTRUCTION CO., INC.
1390 FIRST NATIONAL BUILDING
OKLAHOMA CITY, OKLAHOMA

MOUNTAIN STATES NATURAL GAS CORP.
BOX 1362
TULSA, OKLAHOMA

SKELLY OIL COMPANY
BOX 4115, STATION A
ALBUQUERQUE, NEW MEXICO

JOE E. SMITH
8285 WHITE ROAD
BEAUMONT, TEXAS

STANLEY J. STANLEY
1702 CHACO
FARMINGTON, NEW MEXICO

VIRGIL L. STOABS
1320 EAST COOPER
FARMINGTON, NEW MEXICO

SUNRAY DX OIL COMPANY
BOX 1416
ROSWELL, NEW MEXICO

TEXOTA OIL COMPANY
110 - 16th STREET
DENVER, COLORADO

571

BOLACK - GREER, INC.
158 PETROLEUM CENTER BUILDING
FARMINGTON, NEW MEXICO

June 7, 1965

New Mexico Oil Conservation Commission
P.O. Box 2088
Santa Fe, New Mexico

Attention: Mr. J. E. Kapteina

Gentlemen:

With reference to your letter of April 22nd, we are sending you herewith an executed counterpart of the Canada Ojitos Unit Agreement.

If you need any additional information, please advise.

Yours very truly,

BOLACK-GREER, INC.

BY: ______________________
Albert R. Greer
Vice-President

ARG:nej

1964 AUG 14 AM 7 36

Drawer 1857
Roswell, New Mexico 88201

August 13, 1964

Bolack-Greer, Inc.
158 Petroleum Center Building
Farmington, New Mexico

Attention: Mr. Albert R. Greer

Gentlemen:

Your letter of August 5 advises that Bolack-Greer, Inc., as unit operator of the Canada Ojitos unit area, Rio Arriba County, New Mexico, has determined unit well No. 2-18 to be incapable of producing unitized substances in paying quantities from the Niobrara-Greenhorn formation.

Unit well No. 2-18, in the NW¼NE¼ sec. 18, T. 25 N., R. 1 E., was completed November 30, 1963, for a pumping potential of 15 barrels of oil per day from the Niobrara-Greenhorn formation 5,278 to 5,848 feet.

This office concurs with your determination that unit well No. 2-18 is incapable of producing unitized substances in paying quantities under existing conditions.

Sincerely yours,

(Orig.Sgd.) CARL C. TRAYWICK

CARL C. TRAYWICK
Acting Oil and Gas Supervisor

cc:
Washington (w/cy ltr.)
Farmington (w/cy ltr.)
NMOCC-Santa Fe (ltr. only)
Accounts

State of New Mexico
Oil Conservation Commission

P. O. BOX 871
SANTA FE

August 9, 1963

Re: Case No. 2871
Order No. R-2544
Applicant:
BOLACK-GREER, INC.

Mr. William J. Cooley
Verity, Burr, Cooley & Jones
Attorneys at Law
152 Petroleum Center Building
Farmington, New Mexico

Dear Sir:

Enclosed herewith are two copies of the above-referenced Commission order recently entered in the subject case.

Very truly yours,

A. L. Porter, Jr.

A. L. PORTER, Jr.
Secretary-Director

ir/

Carbon copy of order also sent to:

Hobbs OCC x
Artesia OCC ______
Aztec OCC x
OTHER ______________________

BENSON-MONTIN-GREER DRILLING CORP.

ENGINEERING AND GEOLOGICAL REPORT INCLUDED IN APPLICATION FOR PRELIMINARY APPROVAL OF THIRD EXPANSION OF THE CANADA OJITOS UNIT

JANUARY 22, 1981

INDEX TO
ENGINEERING AND GEOLOGICAL REPORT
INCLUDED IN APPLICATION DATED
JANUARY 22, 1981
FOR PRELIMINARY APPROVAL OF THIRD EXPANSION OF THE
CANADA OJITOS UNIT

ENGINEERING AND GEOLOGICAL REPORT ACCOMPANYING APPLICATION FOR PRELIMINARY APPROVAL OF THE THIRD EXPANSION OF THE CANADA OJITOS UNIT

JANUARY 22, 1981

A

The third expansion of the Canada Ojitos Unit is proposed to test the possibility that the presently producing reservoir underlying the Canada Ojitos Unit extends westward beyond its present boundary and is capable of supporting wells which can produce in "paying quantities".

The initial Canada Ojitos Unit has previously been expanded (first and second expansions) and undergone one contraction. The first and second expansions and the one contraction were for lands along the south and east sides. The area along, and adjacent to, the west side remains untested.

General description of the Canada Ojitos Unit and the West Puerto Chiquito Pool, within which it lies, is given in papers of the Four Corners Geological Society and in AAPG bulletins. Copies of two of these papers are included herein for reference as to these general features (Sections B and C herein). Detailed engineering and geological data are in the files of the U.S.G.S., the Oil Conservation Division and the State Land Office. Additional data have been presented in conjunction with applications for formation, and expansion, of the Niobrara-Greenhorn participating area within the Canada Ojitos Unit.

The possibility of the Canada Ojitos Unit reservoir extending beyond its west boundary can be seen from the colored contour map enclosed (Section D herein). The best fracturing and locations of the better wells appear to coincide with areas showing a change (flexure) of dip:

(Blue color) - from the initial dip of the outcrop to east side of blue color of about 3000'/mile in blue color area;

(Green color) - change from blue area to dip of about 400'/mile;

(Brown area) - change from green area to dip of about 200'/mile;

(Gray area) - change from brown area to about 100'/mile.

It is apparent that another flex could occur in the general area of the west side of the gray shaded area; and that if so, the productive area could extend west beyond the Canada Ojitos Unit west boundary.

We would not anticipate high capacity wells here: but at the present price of oil, low capacity wells might still be profitable to operate; and the farther west the downdip row of wells can be extended, the more efficient can be the recovery of oil from the reservoir.

This possibility existed - and was recognized - when the westernmost wells were drilled some 10 or 12 years ago; but economics at that time of anticipated productivities left no room for wells of lower capacity than had theretofore been encountered to be commercial. Since that time drilling costs have increased about threefold; but oil prices have increased about tenfold, so it now makes economic "sense" to explore what appears to be a marginal area, in an effort to locate additional recovery wells farther downdip and thereby be able to more efficiently produce the reservoir.

The exploration plan is to drill wells in this expansion area and to expand the existing participating area as a result of this drilling to include any additional lands capable of "production in paying quantities"; and to exclude from the expanded unit area (by later contraction) lands not proven to be capable of production in paying quantities.

It is impossible to forecast accurately which lands will be commercially productive and which will not: however, a reasonable choice of expansion area can be supported by selecting boundaries of the third expansion area as follows:

North:

By the boundary of the Jicarilla Reservation (same as Canada Ojitos Unit). It should be noted also that the main producing interval (Zone "C") in the south part of Canada Ojitos Unit apparently is missing north of this line.

East:

By the Canada Ojitos Unit boundary.

South:

By westward extension of the Canada Ojitos Unit boundary in this area (apparent south limit of production).

West:

This boundary is chosen at 1 to 2 miles from location of the last probable synclinal "flex" of the formation (west edge of gray-shaded area on colored contour map).

B

PUERTO CHIQUITO MANCOS, WEST

(Oil)

T. 25-27 N., R. 1 E., R. 1 W., NMPM
Rio Arriba County, New Mexico

By: Albert R. Greer
Benson-Montin-Greer Drilling Corporation

GEOLOGY

Regional Setting: Eastern flank, San Juan Basin

Surface Formations: Cretaceous, Lewis Shale and Tertiary, Ojo Alamo Sandstone

Exploration Method Leading to Discovery: Surface and subsurface geology

Type of Trap: Stratigraphic, fractured shale

Producing Formation: Cretaceous, Niobrara interval of Mancos Shale

Gross Thickness and Lithology of Reservoir Rocks: Approximately 150 feet total of three separate zones within an overall section of approximately 250 feet of fractured shale

Geometry of Reservoir Rock: Apparently (from interference tests) a jigsaw pattern of tight, low permeability, blocks interconnected by a high capacity fracture system. Tight blocks are measured in terms of tens of acres of reservoir volume

Other Significant Shows: Cretaceous, Dakota Sandstone gas and distillate (low volume)

Oldest Stratigraphic Horizon Penetrated: Jurassic, Morrison Formation

DISCOVERY WELL

Name: Bolack-Greer No. 2 Bolack (present operator: Benson-Montin-Greer Drilling Corp.)

Location: NE SW (1785' FSL and 2120' FWL) sec. 13, T. 25 N., R. 1 W., NMPM

Elevation (KB): 7,090 feet

Date of Completion: July 23, 1963

Total Depth: 6,022 feet

Production Casing: 5½" at 5,976 feet with 150 sacks of cement

Perforations: None (open hole)

Stimulation: 100 gallons acid and sand-oil fractured with 85,620 gallons oil and 111,000 lbs sand

Initial Potential: 95 BOD (pump)

Bottom Hole Pressure: 1,620 psig at datum of + 1,195 feet

DRILLING AND COMPLETION PRACTICES

Surface Casing: 400 feet of 10¾" cemented to surface

Intermediate Casing: 7 5/8" set within 500 feet of pay zones with enough cement to cover Mesaverde Group

Production Casing (Liner): 5½" cemented back up into intermediate casing, hole below intermediate drilled with gas if available, or air, or air and nitrogen

Stimulation: Sand-oil fracture with 200,000 to 500,000 lbs of sand, 200,000 to 500,000 gallons of lease crude, injection rates of 50 to 100 barrels per minute

NOTE: Above approximates conditions for majority of wells drilled in sixties and early seventies

RESERVOIR DATA

Productive Area:

Proved (as determined geologically): Approximately 50,000 acres within participating area of unit

Unproved: Several thousand acres within pool boundaries outside of unit

Approved Spacing: 320 acres

No. of Producing Wells: 11 (4 injection, 7 observation or temporarily suspended)

No. of Abandoned Wells: None

No. of Dry Holes: None following discovery well, 2 prior to discovery well

Average Net Pay: Indefinite, probably less than 50 feet

Porosity: Indefinite, fracture porosity probably on order of 1 percent

Permeability: Unknown (transmissibility, from interference tests, ranges up to 6 darcy-feet)

Water Saturation: Unknown, probably quite low

Initial Field Pressure: 1,620 psig at + 1,195 feet datum

Type of Drive: First 15 years, primarily gravity drainage, with some liquid expansion initially; pressure maintained essentially constant by gas injection from fifth to fifteenth year (1968 to 1978); final stages of depletion will include solution gas drive and gas "cycling" by gas injection

Gas Characteristics and Analysis: Sweet, primarily solution gas with some gas cap gas; CO_2 and N_2 0.3 percent; methane through hexanes 26 percent; heptanes +46 percent

Oil Characteristics and Analysis: Sweet, 39° to 40° API gravity, yellow-green

Associated Water Characteristics and Analysis: No produced water

Original Gas, Oil, and Water Contact Datums: Gas-oil, approximately + 1,600, no bottom water

Estimated Primary Recovery: See "Field Commentary"

Type of Secondary Recovery: See "Field Commentary"

Estimated Ultimate Recovery: See "Field Commentary"

Present Daily Average Production: 750 BOD (December, 1977)

Market Outlets: Oil: pipeline to Shell's system for most part, some trucked to Bloomfield; gas: all but small volume is gathered and injected in reservoir. None sold.

FIELD COMMENTARY

The Puerto Chiquito Mancos, West field is located about fifteen miles north of Regina, New Mexico. It underlies lands of the Santa Fe National Forest, the Jicarilla Indian Tribe, and fee and state ownership. Geologically it is located on the eastern flank of the San Juan Basin.

Production is from Niobrara age rocks of the Mancos Shale. The structure is essentially a monocline, dipping west into the basin. Areas of highest capacity wells occur along synclinal flexes in the otherwise uniform dip. The dip of the beds decreases progressively from the outcrop (one to five miles east of the pool boundary) to the western limits of established production. The magnitude of the dip changes from approximately 3,000 feet per mile at the outcrop to approximately 100 feet per mile at the western edge.

The reservoir consists of fracture porosity in the more brittle zones within the Niobrara interval. Lithology of these zones has been investigated and reported on by London (1972); the reservoir rock being primarily shale with varying amounts of dolomite and calcite. Three such zones have been identified which persist throughout the area of the field. Production in the south part of the field for the first fifteen years has been primarily from the lower zone; whereas production from the north part of the field for the first fifteen years has been primarily from the upper two zones. For purposes of local identification the zones have been labeled A, B and C; with the upper two sometimes called "Alto" and "Bajo."

Because of the common pool boundary and similar log characteristics, both the Puerto Chiquito Mancos, East and West pools and type log are shown on the same, accompanying plate.

Some 98 percent of the field's first fifteen years of production (approximately 6 million barrels) is from the Canada Ojitos Unit lying wholly within the Puerto Chiquito Mancos, West pool. This part of the reservoir has been under a pressure maintenance program from the fifth through the fifteenth year of production (1968 to 1978). General reservoir characteristics have been described by Gorham and others (1977); and in more detail, particularly as to the gravity drainage aspect by Greer (1969).

No estimate is made for ultimate recovery. There are a number of factors which bear on ultimate recovery. The chief one is the time of operation of the pressure maintenance project which is a "cost-sensitive" operation. The chief cost items are those attendant to gathering, handling, and compressing of produced gas, and the purchase of "make-up" gas. For the initial phase of the depletion process (gravity drainage of the high capacity fracture system) per-well oil production rates have been high with low gas-oil ratios. Pressure maintenance by gas injection has been quite successful, both physically from the standpoint of oil recovery, and economically. For the first eight years of pressure maintenance the prices of gas were low and the costs of the pressure maintenance project likewise small compared to value of produced oil.

However, for the second phase of the depletion cycle (gravity drainage of the "tight" blocks with gas cycling to move the oil to the wellbores) the economics will be less attractive; per-well oil production rates will be comparatively low, gas-oil ratios high, and the handling of large volumes of produced gas and purchases of make-up gas will be more expensive. Even so, if the economics of this phase of the depletion process can be profitable, the author anticipates a long future life—albeit at low production rates compared to the past—with a significant future ultimate recovery. Under consideration for this phase of the depletion cycle is a gasoline plant to process the "cycled" gas; this could have a bearing on the economics and extension of producing life (and ultimate recovery) of the reservoir.

Although the pressure maintenance project has been successful—evident, for example, from several million barrels of production at solution gas-oil ratios—it makes difficult the forecasting of future and ultimate production. For in addition to the complicating factor of the economics of the second phase of depletion as described above, is the fact that downdip oil recovery wells continue to produce at high rates until the gas-oil contact—as it migrates downdip—reaches them. Then, in a matter of months, the oil production rate for a well will decrease from several hundred barrels a day to a few tens of barrels a day, so analysis of production decline rates is of little help in forecasting reserves. By the same token, reservoir pressure data is of little help, for if it is maintained constant, it has no relation to production.

The final stage of depletion will be the "blow-down" when produced gas is marketed and the last vestiges of oil are claimed. (The depletion process is a combination of solution gas drive with free gas "sweeping" the fractures.) This free gas which has been maintaining pressure and increasing oil recoveries will have played a quadruple role: In phase one it maintained pressure and allowed the gravity drainage depletion process of the high capacity fracture system to function effectively. In phase two (cycling) it will have swept the oil, which drained primarily by gravity from the tight blocks, along the high capacity system to the wellbores. In phase three (blow-down) it will sweep the fractures of oil produced from the tight blocks by solution gas drive along the fracture system to the wellbores, and ultimately it will come out of "storage" and be marketed.

REFERENCES

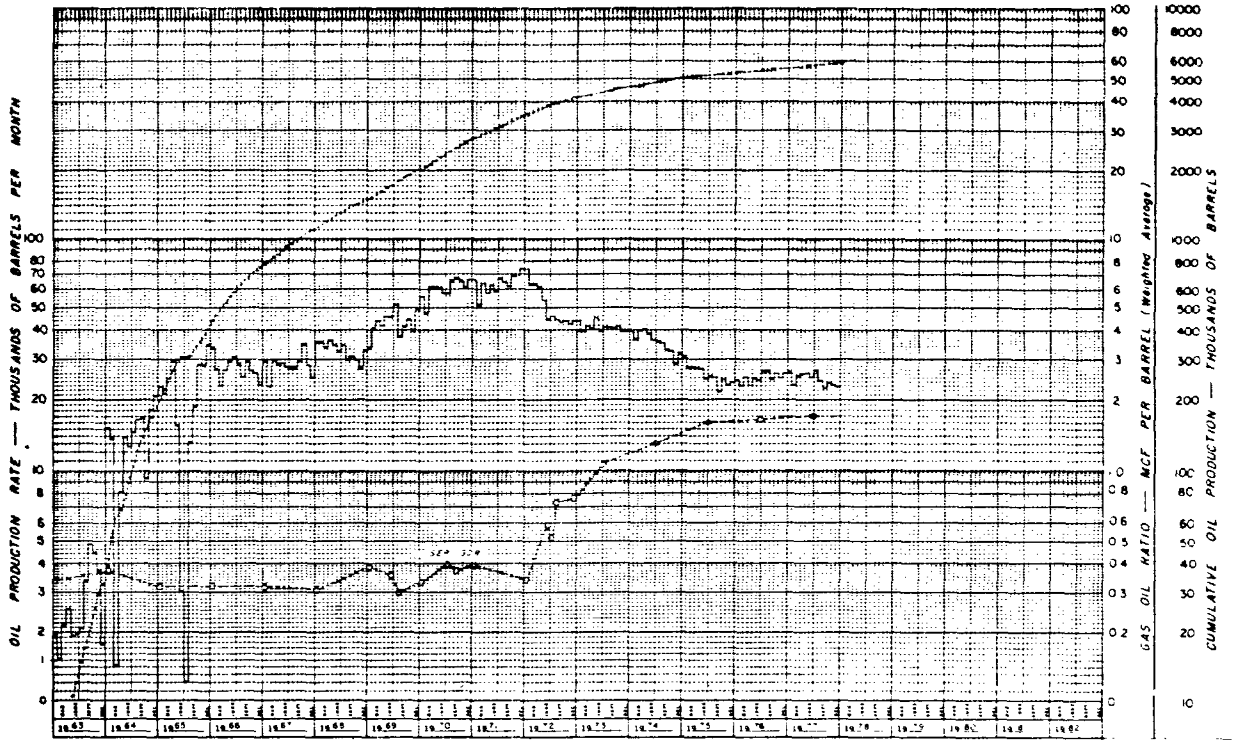
Greer, A. R., 1969, Oil recoveries under gravity drainage depletion and pressure maintenance as dependent on physical reservoir characteristics and as affected by well spacing, fractured shale reservoirs, Niobrara Member of the Mancos Shale Formation, West Puerto Chiquito Pool, Rio Arriba County, New Mexico, exhibit in Case 3455 before the New Mexico Oil Conservation Commission.

Gorham, F. D., Woodward, L. A., Callender, J. F., and Greer, A. R., 1977, Fracture permeability in Cretaceous rocks of the San Juan Basin, *in* San Juan Basin III: New Mexico Geol. Soc., 28th Field Conf. Guidebook, p. 235-241.

London, W. W., 1972, Dolomite in flexure-fractured petroleum reservoirs in New Mexico and Colorado: Am. Assoc. Petroleum Geologists Bull., v. 56, p. 815-821.

Operator's files.

State of New Mexico records.



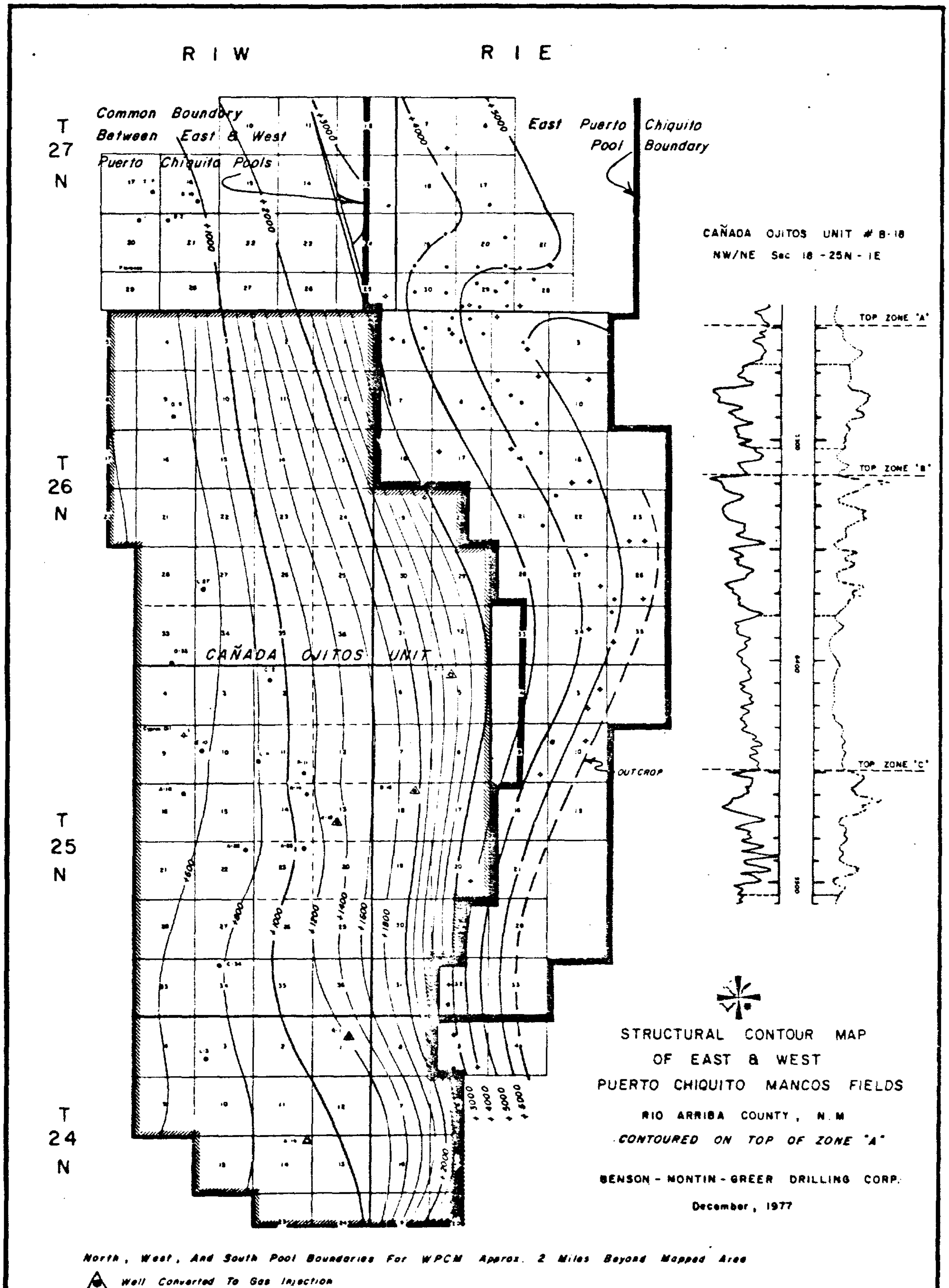
PRODUCTION HISTORY

WEST PUERTO CHIQUITO – MANCOS

Year	Number of Wells at Year End: Producing	Injection	Observation* or shut in	Oil Production (barrels): Annual	Cumulative
1962	2	-	-	1,426	1,426
1963	2	-	-	31,601	33,027
1964	4	-	-	159,135	192,162
1965	3	-	2	238,942	431,104
1966	4	-	2	340,141	771,245
1967	7	-	3	347,789	1,119,034
1968	8	1	3	396,511	1,515,545
1969	8	1	3	519,922	2,035,467
1970	8	1	4	732,118	2,767,585
1971	10	3	7	769,573	3,537,158
1972	9	3	8	638,160	4,175,318
1973	9	3	8	511,566	4,686,884
1974	8	4	8	438,692	5,125,576
1975	6	4	10	321,875	5,447,451
1976	9	4	7	309,652	5,757,103
1977	11	4	7	314,713	6,071,816

* Observation wells (for pressure data): shut in or suspended.

NOTE: Gas production figures omitted because of gas injection program. Weighted average gas-oil ratio of produced oil and gas is shown on production graph.


R 1 W
R 1 E
T 27 N
T 26 N
T 25 N
T 24 N
Common Boundary Between East & West Puerto Chiquito Pools
East Puerto Chiquito Pool Boundary
CAÑADA OJITOS UNIT
OUTCROP
CAÑADA OJITOS UNIT # B-18
NW/NE Sec 18 - 25N - 1E
TOP ZONE 'A'
TOP ZONE 'B'
TOP ZONE 'C'
STRUCTURAL CONTOUR MAP
OF EAST & WEST
PUERTO CHIQUITO MANCOS FIELDS
RIO ARRIBA COUNTY, N. M
CONTOURED ON TOP OF ZONE 'A'
BENSON - MONTIN - GREER DRILLING CORP.
December, 1977
North, West, And South Pool Boundaries For WPCM Approx. 2 Miles Beyond Mapped Area
Well Converted To Gas Injection

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Fractures in Cretaceous Rocks from Selected Areas of San Juan Basin, New Mexico—Exploration Implications[1]

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Abstract Fracture reservoirs are present in the Verde, Boulder, West Puerto Chiquito, and East Puerto Chiquito oil fields of the San Juan basin, New Mexico. Brittle, competent siltstone and carbonate-rich interbeds within Cretaceous shale intervals are fractured in areas of maximum curvature along the Hogback monocline.

Surface observations indicate that there are usually three sets of fractures along limbs of folds. Open fractures trend parallel with fold axes and occur on convex sides of folds. Dip fractures and oblique fractures are commonly tight.

Exploration for traps with fracture reservoirs should focus on areas of maximum curvature of folds where brittle interbeds can be expected in the subsurface. Monoclines are common along the margins of many basins in the Rocky Mountain region and provide many exploration targets, as they probably formed at relatively low confining pressures, thus facilitating fracture of brittle rocks in the Cretaceous System.

INTRODUCTION

A single fracture 1/25 in. (1 mm) wide crossing a well bore in an oil reservoir can provide permeability sufficient to produce between 7,000 and 10,000 bbl of oil per day, depending on pressure and oil viscosity (Daniel, 1954). Also, the height of the fracture as it is intersected by the well bore is an important factor. Kostura and Ravenscroft (1977) noted that the role of fracturing in creating and enhancing reservoirs is one of the more elusive and challenging problems facing petroleum geologists; they anticipate considerable attention on this subject because of the significant reserves remaining to be found in fractured reservoirs.

Oil production from Cretaceous rocks is primarily, if not entirely, from fracture permeability and porosity in the Verde, Boulder, West Puerto Chiquito, and East Puerto Chiquito fields (Fig. 1) along the margins of the San Juan basin (Arnold, 1974). In many other producing areas in the San Juan basin reservoir permeability is aided by fractures.

The principal factors involved in development of fracture permeability and porosity are the radius of curvature during flexure folding, rock type, temperature, confining pressure, and rate of strain. Open fractures tend to develop where tensional joints form at places of maximum curvature of beds (i.e., where there is greatest rate of change of dip, not necessarily where the dips are steepest). The following sequence is generally in order of increasing ductility and therefore decreasing brittle behavior: quartzite, dolomite, sandstone, limestone, and shale (Stearns and Frieuman, 1972). Bedding thickness influences competence; Harris et al (1960) suggested that density of joints is greater in thin beds.

Murray (1968) has shown in a quantitative fracture study that fracture porosity and fracture permeability can be related mathematically to bed thickness and structural curvature. Also, he found that fracture porosity varies directly as the product of bed thickness times curvature and that fracture permeability varies as the third power of this product.

Among the critical questions concerning fracture reservoirs are the following. When and how did the fractures originate? Are they of regional extent or confined to local structures? Are the original fracture trends in older rocks propagated upward into younger strata? When did hydrocarbons migrate into the fractures? How might fractures in the subsurface be predicted in exploration?

Although we do not have all the answers, we hope to stimulate interest through a discussion of our observations and interpretations of subsurface data from the Verde and East and West

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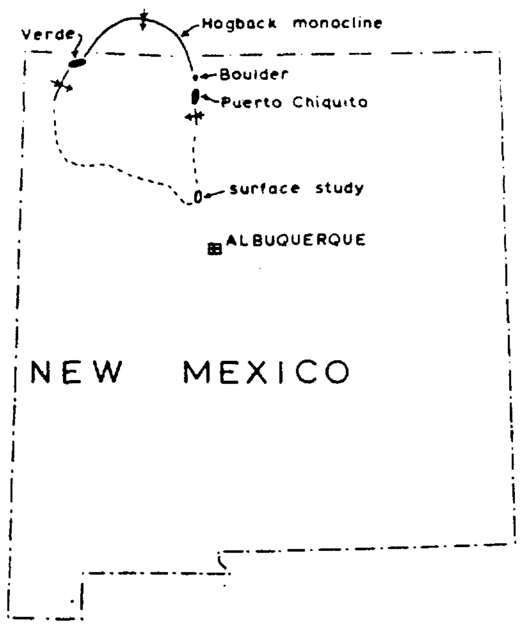

FIG. 1—Index map showing outline of San Juan basin (Hogback monocline and dashed line) and localities noted in text.

Puerto Chiquito fields and surface work on the eastern edge of the San Juan basin. Work on the Verde field is by Gorham, on the Puerto Chiquito fields by Greer, and on the surface by Woodward and Callender.

Speer (1957) discussed the Verde field during the early stage of development and recognized it as a fracture reservoir. Mallory (1977, p. 7) reported that fractured shale reservoirs in northwestern New Mexico yielded 17.4 million bbl of oil since discovery of the Verde field.

VERDE OIL FIELD

The Verde discovery well was drilled in the SE ¼, Sec. 14, T31N, R15W, NMPM, and was completed in September 1955. The initial well was a wildcat guided by surface anticlinal nosing along the Hogback monocline. During early development of the field the productive zone was considered to be the Gallup Sandstone, but subsequent work has shown the producing zone to be in the Niobrara Member of the Mancos Shale. Although only siltstone and indurated black shale were encountered in the so-called Gallup section, pipe was set as a result of shows and lost circulation and the well was completed pumping 180 bbl/day of 42° API gravity oil. During the following 3 years, 100 wells were drilled and completed in the producing interval by various operators with spacing of 40 to 80 acres (16 to 32 ha.) per well.

Stratigraphy

The stratigraphy of Upper Cretaceous rocks of the San Juan basin has been summarized by Molenaar (1977); therefore, only a brief summary of the stratigraphic sequence (Fig. 2) other than that of the producing interval is given here. Rocks exposed in the field area are Upper Cretaceous formations, which consist of the Cliff House Sandstone (uppermost unit of the Mesaverde Group) in the northwest part of the field and a normal sequence of younger Cretaceous beds culminating with the Fruitland Formation in the southeast.

In the Verde field, the Niobrara producing interval is a fractured reservoir having very little or no known effective porosity or permeability, except that associated with fractures, in the entire Niobrara-Carlile section. The producing zone is not exposed at the surface in the field area. The Niobrara interval consists of black, hard, indurated, fissile, calcareous marine shale and thin, hard, quartzitic siltstone beds; the siltstone beds are primarily at the base of the Niobrara, although they occur randomly throughout the interval. Subsurface samples and electric-log correlations from the Horseshoe Canyon area indicate that the primary zone of interest in the Verde area includes the basal Niobrara, the Niobrara-Carlile

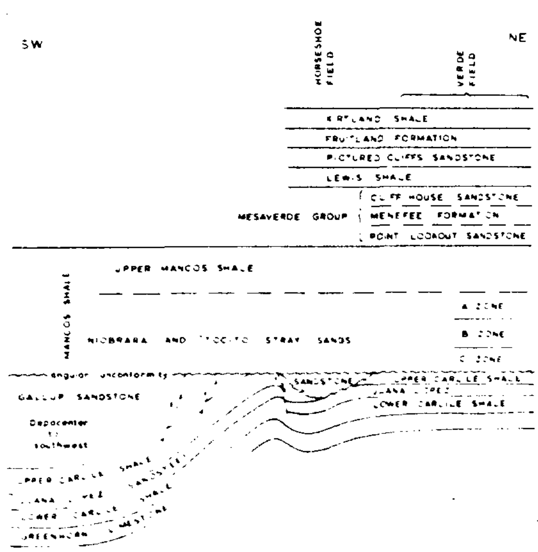

FIG. 2—Diagrammatic cross section showing subsurface relations of Cretaceous rocks in vicinity of Verde field, northern San Juan basin.

unconformity, and the thin upper Carlile shale and siltstone interval above the Juana Lopez (Sanostee). A study of electric logs from thoughout the Verde area indicates that the primary producing interval is generally lithologically consistent throughout. No association is apparent between variations in siltstone content, calcite content, or other observable stratigraphic phenomena and quality of wells or oil reserves. The Niobrara interval of the lower Mancos Shale was subdivided by most operators into the A, B, and C zones, with the C zone being the basal zone of production (Fig. 2). The overall A-B-C zone approaches 1,200 ft (366 m) in thickness. The top of the C zone was where most operators set pipe and then drilled open hole for 200 to 300 ft (61 to 91 m). With only a few exceptions, most of the oil production was obtained from fractures in the C zone, which also has most of the siltstone interbeds. It is stressed that the C-zone lithology is generally consistent over the entire field area, which includes the peripheral dry holes. Therefore, the siltstone in the C zone, although important, cannot be the only factor controlling commercial oil production.

Structure

The Verde field is located on the Hogback monocline on the northwest flank of the San Juan basin in T30, 31N, R14, 15W, NMPM, San Juan County, New Mexico. Surface dips are essentially south and southeast, ranging from 4 or 5° in the Cliff House Sandstone in the northwest part of the field to 23 and 25° in the southeast part of the field where the Pictured Cliffs Sandstone is exposed as a hogback. The monocline is sinuous there, as it is folded to form a south-plunging anticlinal nose (Fig. 3).

Evidence that the field is a fractured reservoir is simple, complete, and conclusive. The producing interval in one of Pubco's wells was cored. The well selected was in the area of maximum

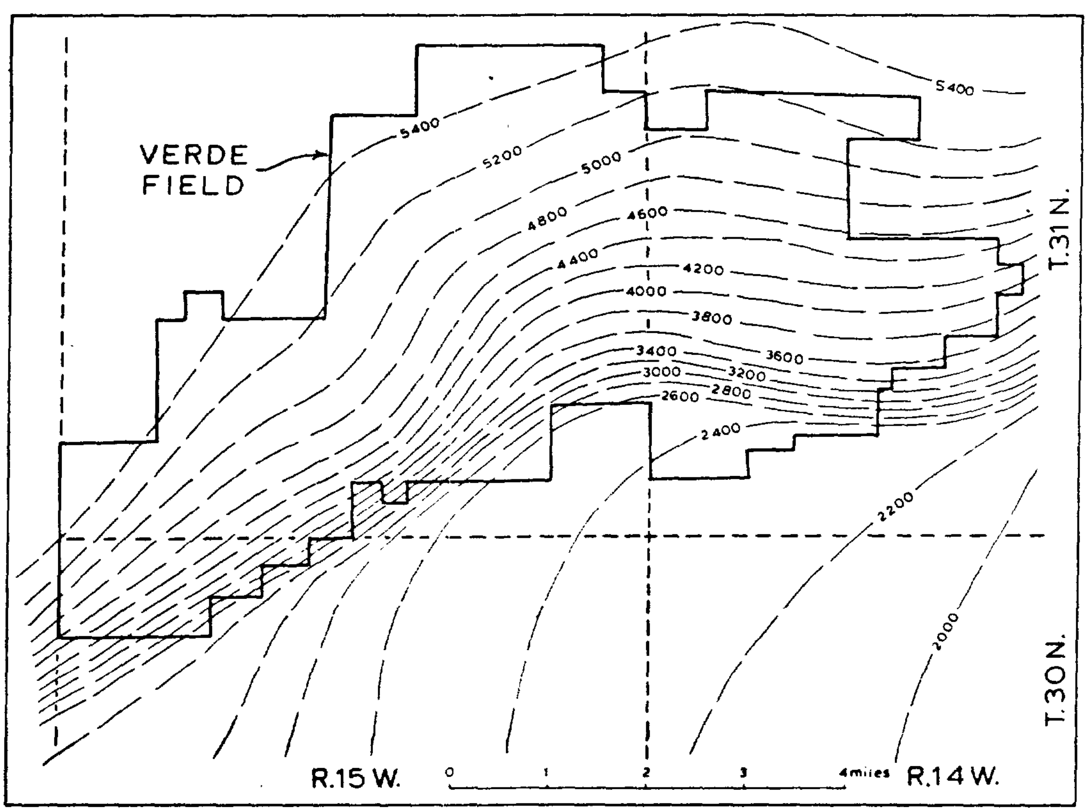

FIG. 3—Generalized structure contour map of Verde field, modified from Hayes and Zapp (1955). Structure contours on top of Point Lookout Sandstone of Mesaverde Group. C.I. = 200 ft (60 m).

flexure. After production casing was set on top of the C zone and cemented in place, the well was drilled with oil 15 ft (4.6 m) below the casing shoe and the core barrel was put on; 42 ft (12.4 m) of core was cut and recovered; it consisted of hard, indurated, fissile black shale with intercalated hard, quartzitic siltstone beds that ranged from 1 in. to several feet in thickness. Analysis of the siltstone in the shale matrix showed porosities and permeabilities far below those required to produce gas, much less oil.

"Concrete" evidence of the fractured reservoir was recovered. There were no problems interpreting fractures in the core. The entire core was laced in a dendritic pattern of fracture "casts" consisting of oil-well cement and lost-circulation material which had filled the natural fractures. Because coring had not begun until after drilling 15 ft (4.6 m) below the casing shoe, we could conclude that in this zone one would not expect to obtain cement-filled fractures unless (1) production casing was set too low or in the fracture system and the cement dropped into the zone cored, or (2) although not as likely, but still possible, the cement and lost-circulation material came from the adjacent lease operated by a company that drilled through the producing zone, set casing, cemented, and perforated. Incidentally, their wells, as a result of their completion practice, usually had initial potentials and ultimate production substantially lower than wells completed by other operators who made open-hole completions. The fractures in the core, as represented by oil-well cement, measured in thickness from 1¾ in. (4.5 cm) wide to hairline cracks. The large fractures were either almost vertical or within 20° of vertical; smaller fractures branched out from them in a festoon or dendritic pattern. One large fracture was represented by a cement slab 7½ ft (2.3 m) long, 1½ in. (3.8 cm) thick, and equally thick from one side of the core to the other. Also surprising was the fact that almost the entire core was intact, being broken only at approximately 8 to 10-ft (2.4 to 3.0 m) intervals when it was removed from the core barrel.

Although poor to average production related to fracture permeability was determined in wells as far southwest as the southwestern corner of T31N, R15W, commercial production from fractures seems to disappear on the east edge of the field in T31N, R14W, perhaps owing to loss of brittle interbeds. In our opinion the commercial oil-filled fractures are confined in large degree to areas of (1) maximum convex curvature, (2) abrupt change in strike direction along the monocline from generally northeast to due east and back to the northeast on the eastern edge of the producing area, and (3) thin, brittle, siliceous siltstone in an indurated Niobrara shale matrix. Of particular interest is the fact that the eastern edge of the field terminates on the crest of the plunging nose of the Barker Creek anticline, where most geologists would suspect strong fracturing. Field evidence from other areas (Harris et al, 1960; Stearns and Friedman, 1972) indicates that the strongest fracturing is located on the flanks of the folds where maximum curvature occurs and not necessarily on the crests of the anticlines or the troughs of the synclines.

The best wells (over 100 BOPD) in the Verde field are located mostly in the syncline crossing the hogback or at the major change in the strike of the hogback. Using the cross section of Hayes and Zapp (1955) shown in Figure 4, it can also be demonstrated that most production came from wells drilled near the Lewis Shale–Cliff House surface contact northwest of the steepest part of the monocline; upon reaching the C zone of the Niobrara, however, the best wells intersected the pay zone at the point of maximum curvature, or about halfway through the arc formed by the monocline at that level, assuming parallel folding. This structural position on the monocline appears to be the most important empirical relation for the best production or fracture abundance. However, the angle of incidence between the borehole and the fracture system reaches a maximum at the greatest dip, and thus more fractures will be encountered with the same depth of penetration. Next in importance is an abrupt change in strike of the producing zone, and third is the presence of brittle, thin beds of siliceous or quartzitic siltstone. Although the presence of these brittle rocks is mandatory for fracturing, they are present in varying degrees at the base of the Niobrara and are capped by overlying ductile soft shales throughout the Rocky Mountains. Most of the

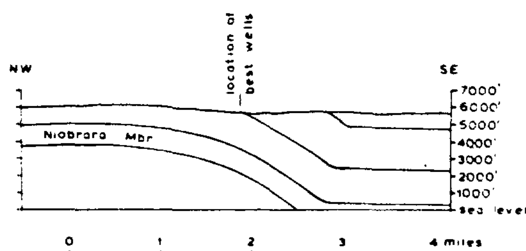

FIG. 4—Northwest-southeast structure section illustrating locations of most productive wells with respect to curvature across Hogback monocline at Verde field (modified from Hayes and Zapp, 1955). Elevations are in feet.

fractured shale reservoirs known are located lithologically near the contact or in the area of change of deposition from nearshore shale and siliceous or quartzitic siltstone stringers to seaward limestone-dolomite stringer facies. These zones of favorable, brittle facies usually are not parallel with the trends of the folds, and thus only those segments of folds with brittle interbeds will develop fracture reservoirs.

Reported initial potentials of the individual wells indicate a tabular high-potential area about 4 mi (6.4 km) long (east-west) and 1.5 mi (2.4 km) wide (north-south) centered in the southwestern part of T31N, R14W. This shape at first glance might indicate a possible direct association with siltstone or "reservoir" content. Although so associated in part, the high-potential of the area is also directly associated with its structural position and, to a large degree, with well completion practices. Completion practices appear to have been particularly important in the south-central part of T31N, R15W, where low potentials are reported but where the better wells are located in the proper structural position.

Completion Practices

Operators in the field followed these methods: (1) pipe was set on top of the fractured zone and drilling was with cable tools or with oil as drilling fluid and was completed in open hole with tubing run to the base of the production string or near total depth in the open hole; (2) pipe was set above the fractured zones as in 1, but a liner was set in the open hole with tubing set to total depth; or (3) production casing was set in the fractured zone, cemented, then perforated.

Of the three methods described or variations thereof, method 1 was by far the most satisfactory. Of particular interest was the observation that while drilling with cable tools through the oil-reservoir fracture zone and to total depth, little or no oil or fluid entry was noted on several of the interior locations. Following a modest or high oil fracture treatment (without sand), all of these wells had almost unlimited oil entry at casing swab rates exceeding several thousand barrels of oil per day. Because the initial bottom-hole pressure permitted the oil, with little or no associated gas, to rise in the casing only to about 400 ft (122 m) from the surface, all wells were completed by pumping with units designed to exceed slightly the allowable production, which was below 70 bbl per well per day. At least two hypotheses were advanced at the time as to why these wells had no fluid entry while drilling with cable tools in open hole, but had high fluid entry rates on being slightly treated. The first and perhaps the more plausible explanation was that, as demonstrated in one well, cement dropped below the guide shoe into the fracture system. Because its weight far exceeded bottom-hole pressure, it thus temporarily plugged the fractures until the time of artificial fracturing. Another explanation is that cable tool drilling or rotary drilling with oil created a thin, impermeable plaster composed of drilling fluid and cuttings that had to be broken hydraulically. Completion practice 1 usually resulted in production rates and recovery 100% greater than that achieved by practice 3. Method 2, a variation of 1, was considered by some operators to be an improvement as subsequent caving, which could cause tubing to get stuck or might limit fluid entry, was prevented.

In this particular reservoir, no open-hole cleanout problems occurred during the life of the wells, as long as the wells had initially been cleaned out properly. We were not aware of any particular benefits in expense savings or increased production as a result of setting a liner in the open hole. Completion practice 3, conventionally used in sandstone and carbonate reservoirs, had no application to this reservoir. In addition to large amounts of mud and lost-circulation material being plastered into the fractures while drilling, at completion the cementing process, in most wells, effectively sealed the fractures so that even after heavy or large fracturing only modest wells or dry holes resulted. These poor results may have been due in part to uncertainty as to the selection of perforated intervals, although the best fractures appeared to be associated with increases in resistivity amplitude or zones of greater siltstone content.

Reservoir Performance

The Verde field produced 7,474,136 bbl of 39° API sweet, paraffin-based crude oil prior to depletion. Pubco's two sections, located in the center of the field and in the high potential area, produced 952,533 bbl prior to depletion, or 744 bbl per acre. The reservoir behavior during production was a classic example of gravity drainage with only modest help from solution gas. As the field was produced, the structurally higher wells were depleted first and then the next line of wells, until the bottom tier was reached. Bottom-hole pressures through the life of the field confirmed gravity drainage as the producing mechanism, with a steady pressure drop directly related to depletion. Although no interference tests were conducted, it was observed that almost the entire field depleted as a unit; the structurally higher wells were depleted first, followed tier by tier downdip until total-field depletion had occurred. Excellent overall fracture connection was thus proved, which had in fact been easily observed during initial development. Although the operators attempted to obtain 80-acre (32 ha.) spacing, their request was not granted by the New Mexico Oil Conservation Commission and the field in part was developed on a 40-acre (16 ha.) spacing pattern. In retrospect, had the field been developed along the structurally lower tiers of wells only, with the wells perhaps spaced 0.25 mi (0.4 km) apart, the overall economics of the field would have been substantially better, and total oil recovery based on the reservoir behavior described would probably have been identical.

EAST AND WEST PUERTO CHIQUITO FIELDS

In the course of the drilling of wells in the East and West Puerto Chiquito fields (Fig. 5), Rio Arriba County, New Mexico, Benson-Montin-Greer Drilling Corp. (B-M-G) obtained information and conducted tests which revealed some interesting reservoir characteristics. These fields produce from fractured rocks in the Niobrara Member of the Mancos Shale. Brief summaries of the tests and conclusions are set out in the following, with interpretations and hypotheses.

Commercial oil production resulted from wells drilled on a structural nose in the shallow (2,000 to 4,000 ft; 610 to 1,220 m) East Puerto Chiquito pool and along strike of the monocline with "synclinal flexing" in the deeper (5,000 to 7,000 ft; 1,524 to 2,134 m) West Puerto Chiquito pool. Both reservoirs are in areas of folds; our postulate is that folding caused the fracturing which resulted in reservoirs being sufficient for commercial production. London (1972) investigated the lithology of the producing interval in West Puerto Chiquito with particular emphasis on content of calcite and dolomite in the reservoir rock. London concluded that the percentage of dolomite, which is more brittle than calcite, can have significant effects on whether the rocks fracture. One might then draw the conclusion that a relatively high dolomite content is just as essential as flexure, or whatever other deformation might be partly responsible for the reservoir's existence.

General Reservoir Characteristics

Interpretation of test data, together with information from cores and logs, shows that the individual reservoirs are relatively thin; from the standpoint of oil production, the porosity is all fracture porosity; and each reservoir comprises individual fracture "blocks" of low permeability (lower order of fracture development), but joined and interconnected to a high-capacity fracture system.

The greater part of the volume of the reservoir is probably formed by these fracture blocks and a relatively small part by the high-capacity connecting fracture system. Accordingly, in drilling a well, one may expect to penetrate not the fracture system but rather one of the fracture blocks. This is apparently what has happened in West Puerto Chiquito. Only some wells encounter natural production, and these natural-production rates have never been high enough to indicate direct communication with the high-capacity fracture system. Only after sand-fracture treatments connected the well bores to the fracture systems were wells developed capable of producing at high rates.

The reservoirs ("tight" blocks and high-capacity fracture system) are confined to relatively thin zones which are identifiable on electric logs as more resistant than surrounding beds. Although vertical fractures have been found in cores through these zones, they apparently do not continue far into the more plastic shales above or below. In the Verde field, in contrast, fractures extending for considerable vertical distances have been found. In the Puerto Chiquito fields, communication has been measured over long distances horizontally (miles), whereas vertical communication has not been found in beds as close as 100 ft (30 m) apart. In fact, an absence of communication between zones in a single well bore has been determined. With minor exceptions, commercial production has been limited to zones which are not only electrically resistant, but which extend over long distances and can be correlated between wells.

Some other isolated zones have produced some oil, without artifical fracturing, at initial rates as high as 20 BOPD; but generally these zones deplete rapidly and apparently are not connected with commercial reservoirs. The presence or absence of these isolated zones does not have a relation to commercial productivity of the main identifiable commercial zones.

Three characteristic zones of the Niobrara from which most of the production originates are present over the greater part of both East and West Puerto Chiquito fields. These zones are similar to those described for the Verde field. The main contributing zones in East Puerto Chiquito are the upper two (A and B); whereas in West Puerto Chiquito, most of the production in the south part of the pool is from the lower zone (C), with production in the north part from A and B.

Well Spacing

Under a New Mexico Oil Conservation Commission order, in East Puerto Chiquito the spacing is 160 acres (64 ha.) per well, and in West Puerto Chiquito it is 320 acres (128 ha.) per well. However, in view of the extensive communication found in West Puerto Chiquito, the wells in the

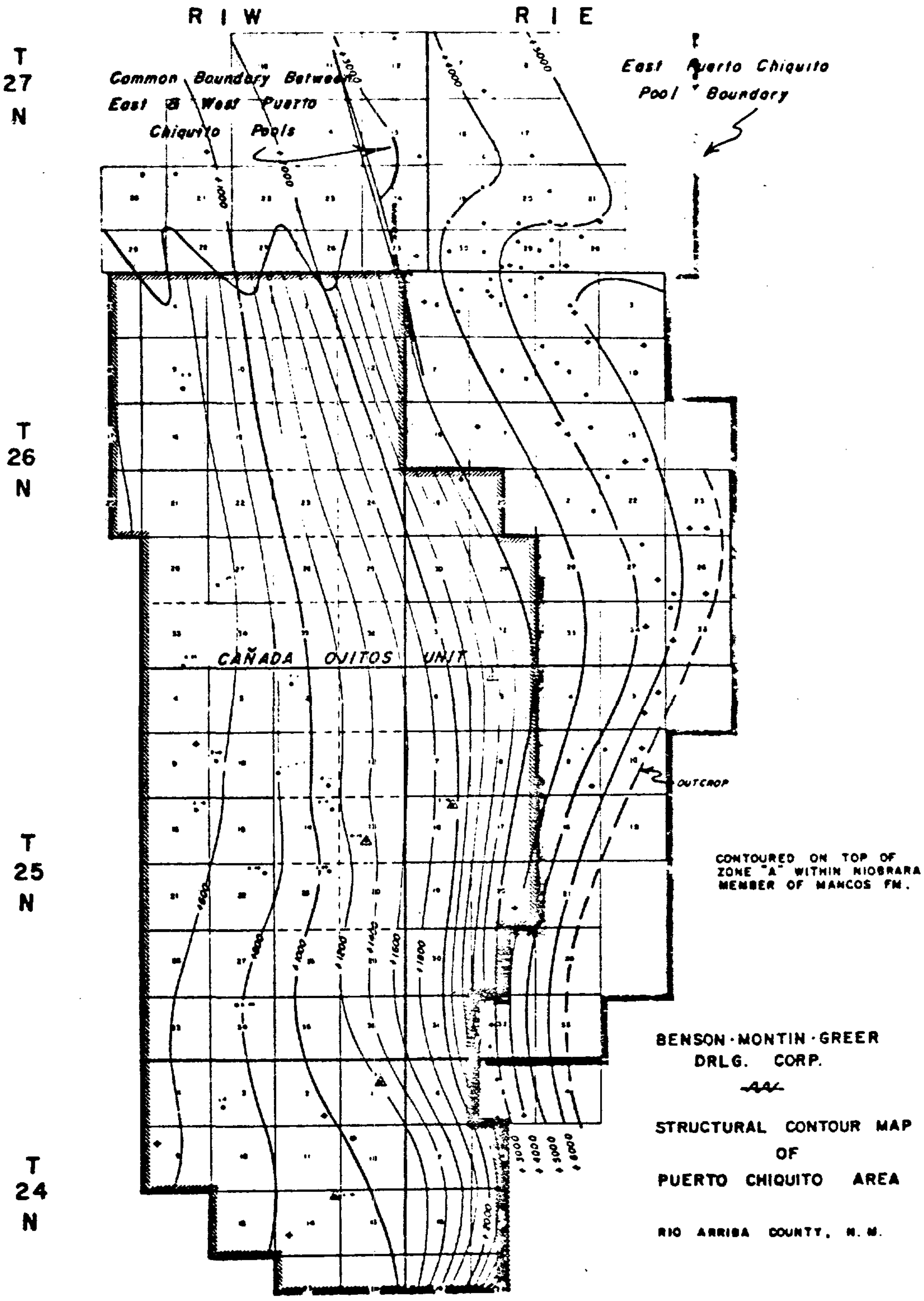

FIG. 5—Structure contour map on top of "A" zone of Niobrara Member of Mancos Shale, Puerto Chiquito area, New Mexico (from Arnold, 1974). C.I. = 1,000 and 200 ft (300 and 60 m).

Canada Ojitos unit there (from which most of the production in West Puerto Chiquito originates) are more widely spaced. Pressure maintenance by gas injection has been continuously carried on since August 1968. Gas injection wells are located on the updip side of the reservoir and oil recovery wells on the downdip side; the resultant spacing of the oil recovery wells is approximately one well per four sections (10.4 sq km). The wells appear to be efficiently draining these large areas; single well recoveries have exceeded 10 times the average recovery of wells in the nearby Boulder-Mancos pool, which was drilled on 80-acre (32 ha.) spacing and which had much better reservoir characteristics and potential for production.

Oil-Producing Mechanism

B-M-G has attempted to take full advantage of the efficient gravity-drainage mechanism in producing its wells in both the East and West Puerto Chiquito pools. Because of the higher formation volume factor and consequent shrinkage, with its attendant adverse effects on recovery, pressure maintenance by gas injection was instituted for the West Puerto Chiquito oil. The main purpose of the gas injection was to maintain pressure so that the gravity-drainage mechanism could operate under optimum conditions. It was not intended to "sweep" the reservoir with gas.

To avoid channeling and to assure gravity drainage, the producing rates of the recovery wells were restricted considerably below their producing abilities. The "gravity-drainage potential" of the reservoir was estimated from interference tests and production rates were set accordingly. B-M-G considers the pressure maintenance operation to have been successful.

Pressure Buildup, Drawdown, and Interference Tests

A high degree of communication was found in wells in both the East and West Puerto Chiquito pools. On interference tests in West Puerto Chiquito, measurable pressure changes occurred in observation wells within 24 hours of commencement of production of wells as far as 1.5 mi (2.4 km) away. In East Puerto Chiquito, reservoir pressure increase caused by fracture treatment of a well was observed in an observation well 1 mi (1.6 km) from the well being treated.

In West Puerto Chiquito overall reservoir transmissibilities were measured by interference tests to be in the range from 2 to 10 darcy-feet. Individual well transmissibilities were found to be much lower, however. Reasonable interpretation of the data permits only one conclusion as to general reservoir geometry: there is a series of individual "fracture blocks" with transmissibilities ranging from 0.02 to 0.4 darcy-feet which are connected as in a jigsaw puzzle through a high-capacity network. Areal sizes of the individual fracture blocks were calculated to be on the order of 30 to 70 acres (12 to 28 ha.).

Drainage of Tight Fracture Blocks

Because of the apparent geometry of the reservoir and the fact that a substantial amount of oil might be contained in the low-permeability fracture blocks, a question arises whether an effort should be made to deplete these fracture blocks as well as the high-capacity fracture system through gravity drainage. The answer depends on the rate at which oil can drain from these tight blocks and the economics of continuing gas injection. Because this determination cannot be made until the oil has first been produced from the high-capacity system, it cannot be made early in the life of the reservoir.

To answer this question, B-M-G continued to produce a suitable well after the high-capacity system was essentially swept (i.e., the gas to oil ratio increased from an initial 300 to about 10,000). After reaching the 10,000 to 1 GOR, this well has produced approximately 100 BOPD for 3 years with no further increase in GOR. This suggests that if all of the fracture blocks in the reservoir are of this quality, it should be feasible to continue gas injection for some time after the main fracture system has been depleted (other wells have been shut in when their GOR reached about 2 Mcf/bbl).

Reservoir Volume

Per-acre reservoir volume of fractured reservoirs is a difficult physical characteristic to measure. The only suitable means found by B-M-G was through analysis of interference tests. Two reliable interference tests were conducted, which, in conjunction with other data, placed a value of 1,500 to 2,000 bbl of oil in place per acre for the part of the reservoir influencing the tests (about 5,000 to 10,000 acres; 2,000 to 4,000 ha.).

The first test was conducted at a time when the pressure was above the bubble point (oil was undersaturated), and for this test the accuracy of the calculation was limited by the indefinite ~~volume~~ value of the compressibility of the fractured shale reservoir rock. From this test a range of 1,000 to 2,500 bbl of stock-tank oil per acre was estimated. At the time of the second interference test the pressure was below the bubble point, eliminating the error due to the indefinite value of the compressibility of the fractured shale, for the compressibility of the oil was now much higher; this test showed 1,600 bbl per acre for approximately

2,000 to 3,000 acres of test area. This figure was estimated to be within 20% of the true value, which is considered close agreement for the two widely different conditions under which parts of the same reservoir were tested.

Undoubtedly, a large part of the reservoir has a much lower volume of pore space per acre, as indicated by lower capacity wells. Data for these other areas are not available; we have been able to hypothesize only about their physical characteristics.

Recovery of the oil in place will depend on how much of the reservoir is susceptible to gravity drainage and whether proper advantage is taken of it. Recovery estimates range from 6% of oil in place for those parts of each reservoir produced through the solution-gas mechanism to 10 times as much for the parts depleted by gravity drainage.

SURFACE OBSERVATIONS

Under ideal conditions with isotropic rocks three sets of joints may develop, with two closed or tight sets forming conjugate shears intersecting at an angle of about 60° that is bisected by the greatest principal stress direction and with the third set parallel with the greatest stress and perpendicular to the smallest stress (de Sitter, 1956, p. 123-125). The latter set of joints may be open. Field studies of joints by Harris et al (1960) and Stearns and Friedman (1972) have shown that the density and orientation of joints in folded beds are directly related to where they occur on the folds; however, neither of these studies fully explained the origin of the joints. Thus, an empirical relation exists that is useful in petroleum exploration, even though the mechanics are not fully understood.

Our observations of joints in surface exposures along the eastern side of the San Juan basin indicate that joint trends in older rocks are not necessarily reflected in overlying strata and that regional joints are probably related to deformational events such as the Laramide orogeny and development of the late Cenozoic Rio Grande rift. Also, we do not find a consistent orientation of the joints with respect to bedding attitude, as suggested by Stearns and Friedman (1972).

We measured the orientations and density of joints in the Dakota Formation on a south-plunging anticline-syncline pair in the San Ysidro quadrangle. This area was chosen because exposures are much better than in the Niobrara interval. Our findings were as follows:

1. At any one place there are usually three sets of joints, and they are perpendicular to bedding.
2. Open joints trend parallel with the axis of the fold and occur in thick competent beds on the convex side of the fold. Areas of maximum curvature are where open fractures develop. The implications of this fact are far reaching and merit further discussion. Crests of anticlines are not necessarily favorable places for open fractures to develop; the corollary is that synclines are not necessarily unfavorable places for open fractures to form if the convex side of the fold is considered.
3. Dip joints or oblique joints are more commonly tight than are strike joints.
4. Density of joints is greatest in thin beds.

REGIONAL FRACTURE TRENDS

Joint trends in the San Juan basin have not been quantitatively characterized in the literature. Kelley and Clinton (1960, p. 19-22) provided a regional perspective for fracture patterns of the Colorado Plateau. They concluded that the joints of the central San Juan basin are heterogeneous, although northeast (N10 to 60°E) and northwest (N15 to 75°W) trends are most common, as they are in much of North America (Thomas, 1976). The predominant trend appears to be northeast, between N45°E and N60°E (Kelley and Clinton, 1960). Pervasive fracture trends of similar orientation have been described elsewhere in the Colorado Plateau by Kelley and Clinton (1960), Wise (1969), Shoemaker et al (1974), and Goetz et al (1975).

In a study of regional jointing in the Comb Ridge–Navajo Mountain area west of the San Juan basin, Hodgson (1961) concluded that the joints there are not genetically related to folding, but form by a fatigue mechanism resulting from earth tides. Hodgson further suggested that joints form early in the history of the sediment and are produced in each layer of overlying rock as soon as it is strong enough to fracture; thus, the older joint trends control development of joints in younger strata.

The major unsolved problems of many regional fracture analyses are the age of fracturing and the orientation of stress fields that produce fracturing. These questions remain unanswered for the San Juan basin and are in large part beyond the scope of this paper. However, work by several investigators suggests that the following observations are important:

1. Precambrian foliation trends and age-province boundaries are predominantly northeastward beneath the San Juan basin (Kelley, 1955; L. T. Silver, personal commun., 1977).
2. Northeast-trending fault zones with major displacements of Precambrian age have influenced later Phanerozoic fracture trends (Shoemaker et al, 1974); in a similar way, fracture sets

of Precambrian age have been reactivated and extended into overlying sediments (J. M. Potter, written commun., 1977).

3. Laramide compression and right-shift of the Colorado Plateau (Woodward and Callender, 1977) probably generated both northeast-northwest conjugate joint sets and northeast-trending extensional fractures.

4. Neogene extension of the western United States (Atwater, 1970), which produced mainly north-trending fracture patterns, has not had a significant effect on fracture trends in the Colorado Plateau, excluding its margins; this is perhaps explained by the divergence of north trends from the basement grain of the region.

CONCLUSIONS

The Verde oil field, one of the first of its kind to be discovered in northwestern New Mexico, is a fracture-reservoir trap along a monoclinal flexure; it is lithologically controlled only to the extent that brittle competent interbeds capable of fracture are present.

When exploring for fracture permeability, it should be kept in mind that fractures tend to be best developed where flexures have maximum curvature; if the axial surface of the fold is inclined, then the hinge will migrate laterally with depth. Open fractures are best developed parallel with the trend of the fold; therefore, monoclines or limbs of folds are attractive targets. Although fractures tend to be perpendicular to bedding, they have greater lateral than vertical continuity. The basic tools used in exploration for fracture permeability are structure contour maps and lithofacies maps showing brittle interbeds in dominantly shaly sequences.

Monoclines are common along the margins of many basins in the Rocky Mountains; because of their locations along basin margins, they probably formed at relatively low confining pressures, thus facilitating fracture of brittle rock in the Cretaceous System. In view of the many hundreds of miles of monoclinal flexures exposed in Cretaceous rocks in basins of the Rocky Mountain region, a new look at this type of trap is surely warranted.

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