Application of Advanced Reservoir Characterization, Simulation, and Production Optimization Strategies to Maximize Recovery in Slope and Basin Clastic Reservoirs, West Texas (Delaware Basin)

Annual Report

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ABSTRACT

The objective of this Class III project is to demonstrate that detailed reservoir characterization of slope and basin clastic reservoirs in sandstones of the Delaware Mountain Group in the Delaware Basin of West Texas and New Mexico is a cost-effective way to recover a higher percentage of the original oil in place through geologically based field development. Phase 1 of the project, reservoir characterization, was completed this year, and Phase 2 began. The project is focused on East Ford field, a representative Delaware Mountain Group field that produces from the upper Bell Canyon Formation (Ramsey sandstone). The field, discovered in 1960, is operated by Orla Petco, Inc., as the East Ford unit. A CO_2 flood is being conducted in the unit, and this flood is the Phase 2 demonstration for the project.

The depositional model of the East Ford unit was revised on the basis of analysis of pressure and production information and reexamination of the outcrop data. Overbank splays were recognized in outcrop as being the main area of sand storage outside of the channels, not levees. This model has now been applied to the East Ford unit. Deposits flanking the Ramsey 1 and 2 channels are interpreted as consisting of narrow levees and wider overbank-splay sandstones. Deposits at the south end of the field are interpreted to be lobe sandstones in both Ramsey 1 and 2 intervals.

The depositional model provides a way to predict the distribution of siltstones, which are the most important depositional heterogeneities within Bell Canyon reservoirs. Siltstones occur (1) as widespread sheets that bound high-order cycles, (2) as discontinuous drapes along the base of channels or at the tops of sandstone beds, (3) interbedded with thin sandstones in levee deposits, and (4) overlying erosion surfaces associated with channel avulsion. Even thin siltstones can affect displacement operations in reservoirs. Because of the low permeability of siltstones, limited cross flow of fluids will occur between sandstones separated by siltstone.

The 12.2 MMbbl of remaining oil in place in the CO_2 flood area represents the target for enhanced recovery. The CO_2 flood began in July 1995, and production response was observed in December 1998. In 1993 and 1994, before the CO_2 flood began, annual production from the field

was 12,000 to 14,000 bbl of oil. By 1998, annual production had increased fivefold to almost 64,000 bbl. Daily production from the field increased from 30 bbl to more than 100 bbl.

EXECUTIVE SUMMARY

Slope and basin clastic reservoirs in sandstones of the Delaware Mountain Group in the Delaware Basin of West Texas and New Mexico contained more than 1.8 billion barrels (Bbbl) of oil at discovery. Recovery efficiencies of these reservoirs have averaged less than 20 percent since production began in the 1920's, and, therefore, a substantial amount of the original oil in place remains unproduced. Many of these mature fields are nearing the end of primary production and are in danger of abandonment unless effective, economic methods of enhanced oil recovery (EOR) can be implemented. The goal of this project is to demonstrate that reservoir characterization, using outcrop characterization, subsurface field studies, and other techniques, can optimize EOR projects in Delaware Mountain Group reservoirs.

The original objectives of the reservoir-characterization phase of the project were (1) to gain a detailed understanding of the architecture and heterogeneity of two representative fields of the Delaware Mountain Group, Geraldine Ford and Ford West, which produce from the Bell Canyon and Cherry Canyon Formations, respectively; (2) to choose a demonstration area in one of the fields; and (3) to simulate a CO_2 flood in the demonstration area. After completion of the study of Geraldine Ford and Ford West fields, the original industry partner decided not to continue. Orla Petco, Inc., is the industry partner now participating in the project, and the focus has shifted to East Ford field.

Project workers completed Phase 1, reservoir characterization, this year and began Phase 2, the implementation phase. A CO_2 flood is being conducted in the unit, which is the Phase 2 demonstration for the project. The objectives of the implementation phase of the project are to (1) apply the knowledge gained from reservoir characterization to increase recovery from a demonstration area and (2) demonstrate that economically significant unrecovered oil can be recovered by a CO_2 flood.

East Ford field, immediately adjacent to the Ford Geraldine unit, produces from a branch of the same Ramsey sandstone channel. Bell Canyon sandstones exposed in outcrop 25 mi west of the East Ford unit are analogs of slope and basin clastic reservoirs in the Ramsey sandstone, Delaware Basin. The depositional model developed by characterization of Bell Canyon outcrops and by the earlier study of the Ford Geraldine unit guided correlations of the Ramsey reservoir in the East Ford unit. Ramsey sandstones at the East Ford unit are interpreted as having been deposited by sandy high- and low-density turbidity currents that carried a narrow range of sediment size, mostly very fine sand to coarse silt. The sands were deposited in a basin-floor setting by a channel-levee system with attached lobes and overbank splays.

The depositional model of East Ford field was revised this year on the basis of analysis of pressure and production information and reexamination of the outcrop data. Overbank splays were recognized in outcrop as being the main area of sand storage outside of the channels, not levees. Deposits flanking the Ramsey 1 and 2 channels have been reinterpreted as consisting of narrow levees and wider overbank-splay sandstones. Interbedded sandstones and siltstones of the levee deposits can restrict flow between channel and splay sandstones. Deposits at the south end of the field are interpreted to be lobe sandstones in both the Ramsey 1 and 2 intervals.

More than 350 Delaware Mountain Group reservoirs have been discovered in West Texas and southeast New Mexico in sandstones of the Bell, Cherry, and Brushy Canyon Formations. Those fields had produced 340 MMbbl of oil through 1998, but many are mature fields that are nearing the end of primary production. The 1.5 Bbbl of remaining unrecovered oil makes these fields potential candidates for enhanced recovery techniques. The CO_2 flood being conducted in East Ford, a representative Delaware Sandstone field, can serve as a model for other fields in the play.

INTRODUCTION

This report summarizes the results of research conducted during the fifth year of the DOE Class III project "Application of Advanced Reservoir Characterization, Simulation, and Production Optimization Strategies to Maximize Recovery in Slope and Basin Clastic Reservoirs, West Texas (Delaware Basin)." The objective of the project is to demonstrate that detailed reservoir characterization of clastic reservoirs in basinal sandstones of the Delaware Mountain Group in West Texas and New Mexico is a cost-effective way to recover more of the original oil in place (OOIP) by geologically based field development. Because current production from Delaware Mountain Group reservoirs averages less than 20 percent of the original 1.8 billion barrels (Bbbl) of oil in place, a clear opportunity for improved recovery exists.

Phase 1 of the project, reservoir characterization of the East Ford unit (figs. 1, 2), was completed this year, and Phase 2 was begun. The reservoir characterization focused on the main producing interval in the East Ford unit, the Ramsey sandstone in the upper Bell Canyon Formation (fig. 3). Earlier in the project, reservoir characterization was conducted on the Ford Geraldine unit (Dutton and others, 1996, 1997a, 1997b, 1998), which is immediately adjacent to the East Ford unit and produces from a branch of the same Ramsey sandstone channel (fig. 4).

Phase 2, assessment of the effectiveness of CO_2 flooding to improve recovery in a mature Ramsey sandstone field, began this year. The goal is to apply the knowledge gained from the reservoir characterization to increase recovery from the East Ford unit. Orla Petco, the operator of the East Ford unit, began a CO_2 flood in the Ramsey sandstone in July 1995. Orla Petco has made available to the project all the injection and production data generated since the flood was initiated, allowing an excellent opportunity to evaluate the success of the flood and compare the results with predictions made on the basis of the reservoir characterization. The CO_2 flood at East Ford field reached the response phase in December 1998, so evaluation of the flood results could begin as soon as Phase 2 started.

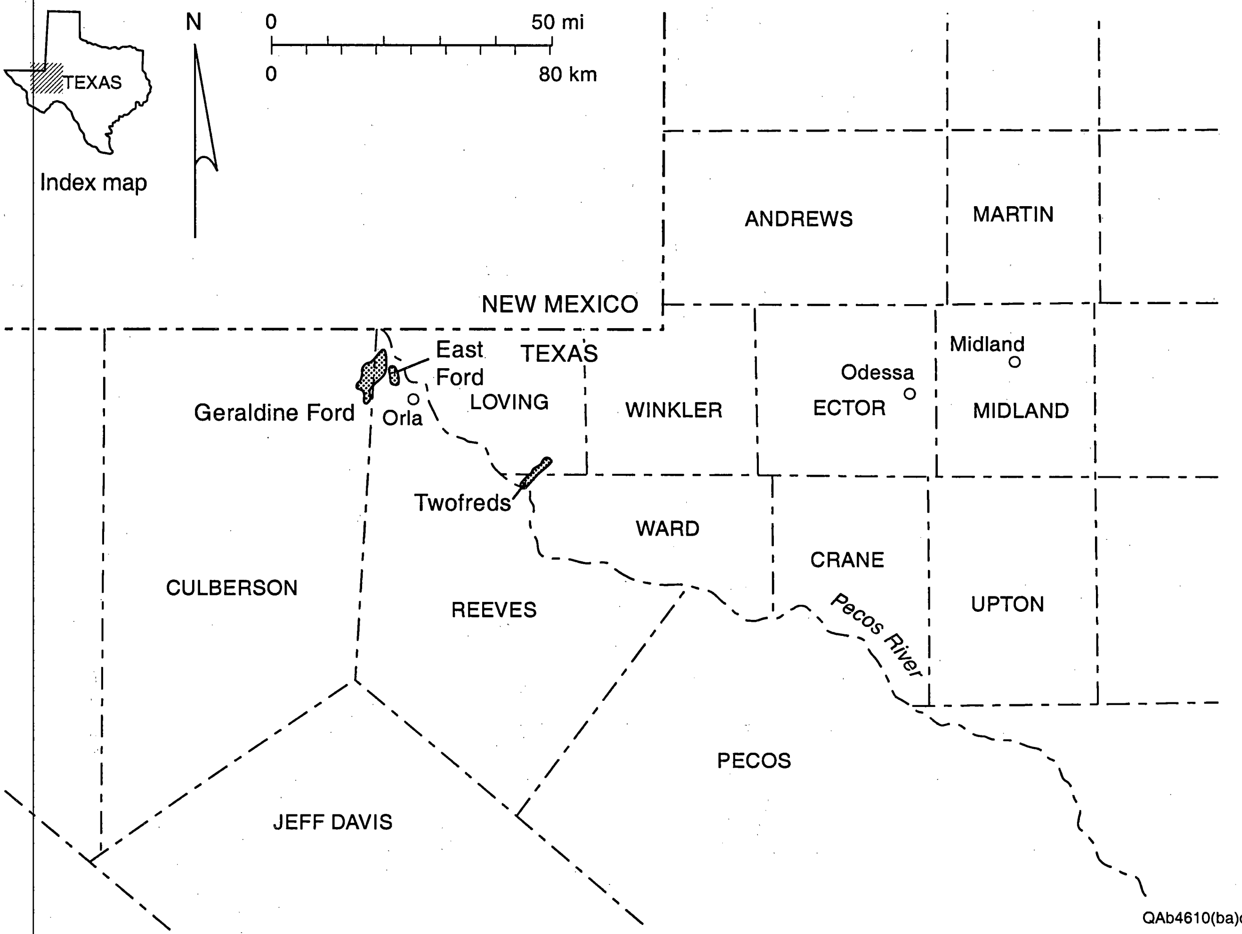

Figure 1. Location of East Ford, Geraldine Ford, and Twofreds fields in West Texas.

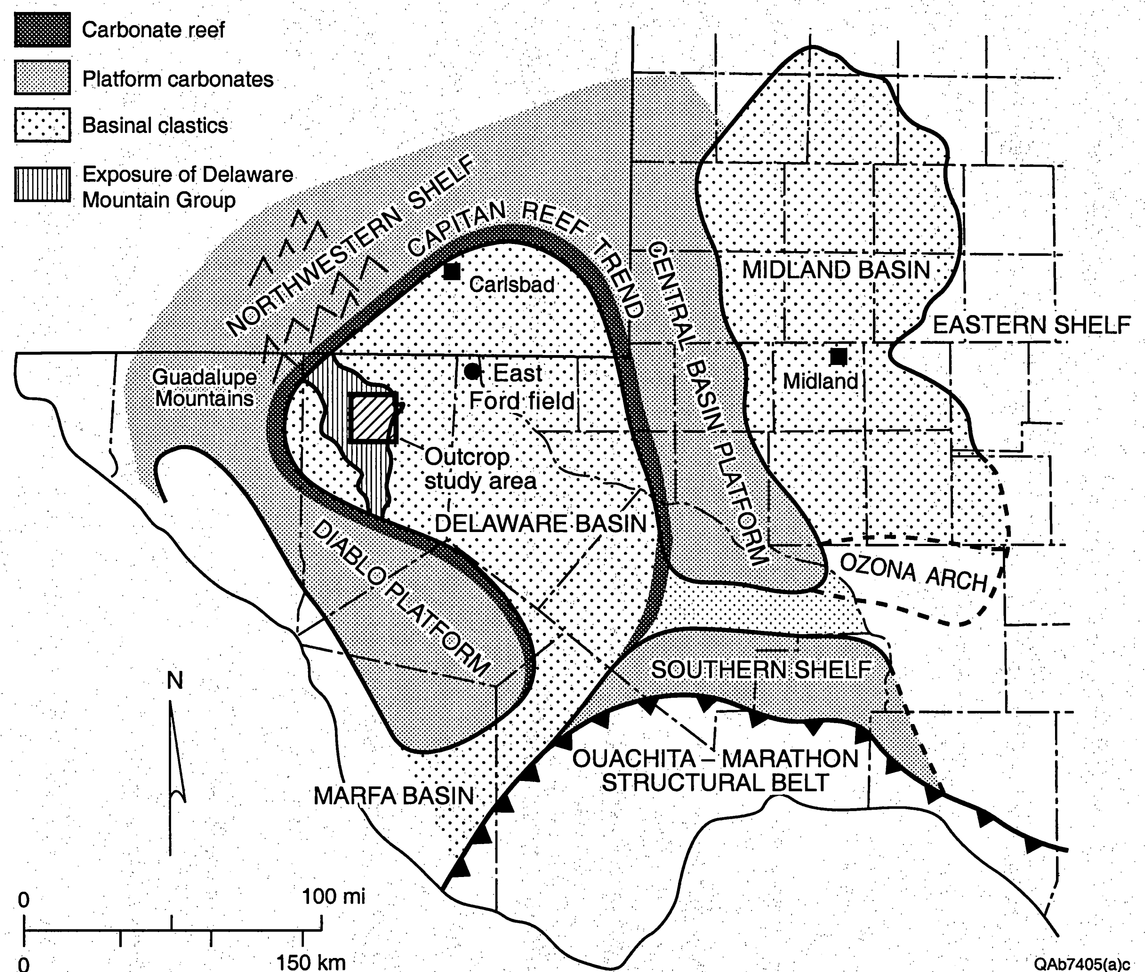

Figure 2. Map showing location of the Delaware Basin and paleogeographic setting during the Late Permian. Present-day exposures of the Delaware Mountain Group and the locations of the outcrop study area and East Ford field are superimposed onto the paleogeographic map. Modified from Silver and Todd (1969).

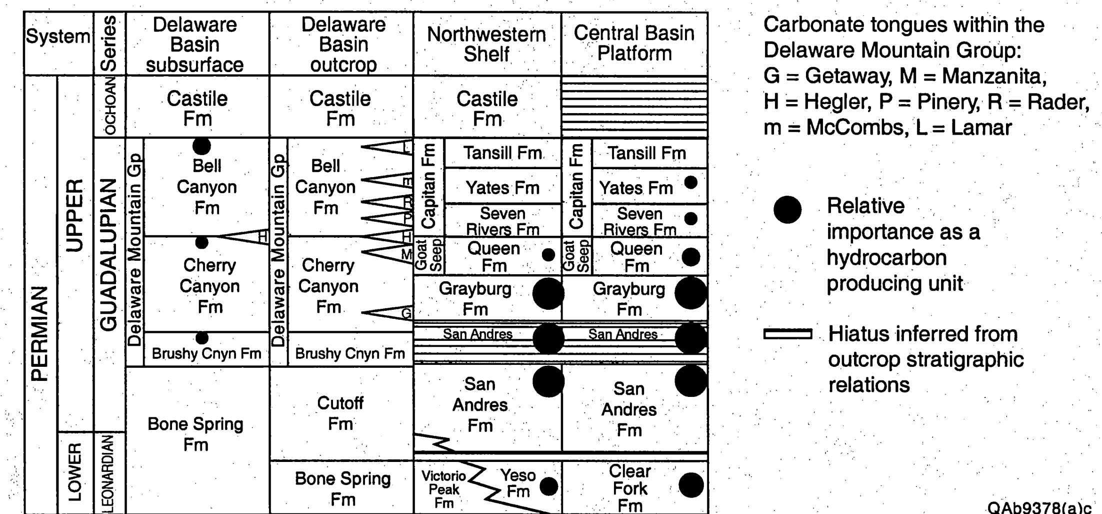

Figure 3. Stratigraphic nomenclature of the Delaware Mountain Group in the Delaware Basin subsurface and outcrop areas and time-equivalent formations on the surrounding shelves. Modified from Galloway and others (1983); Ross and Ross (1987); and Kerans and Fitchen (1995).

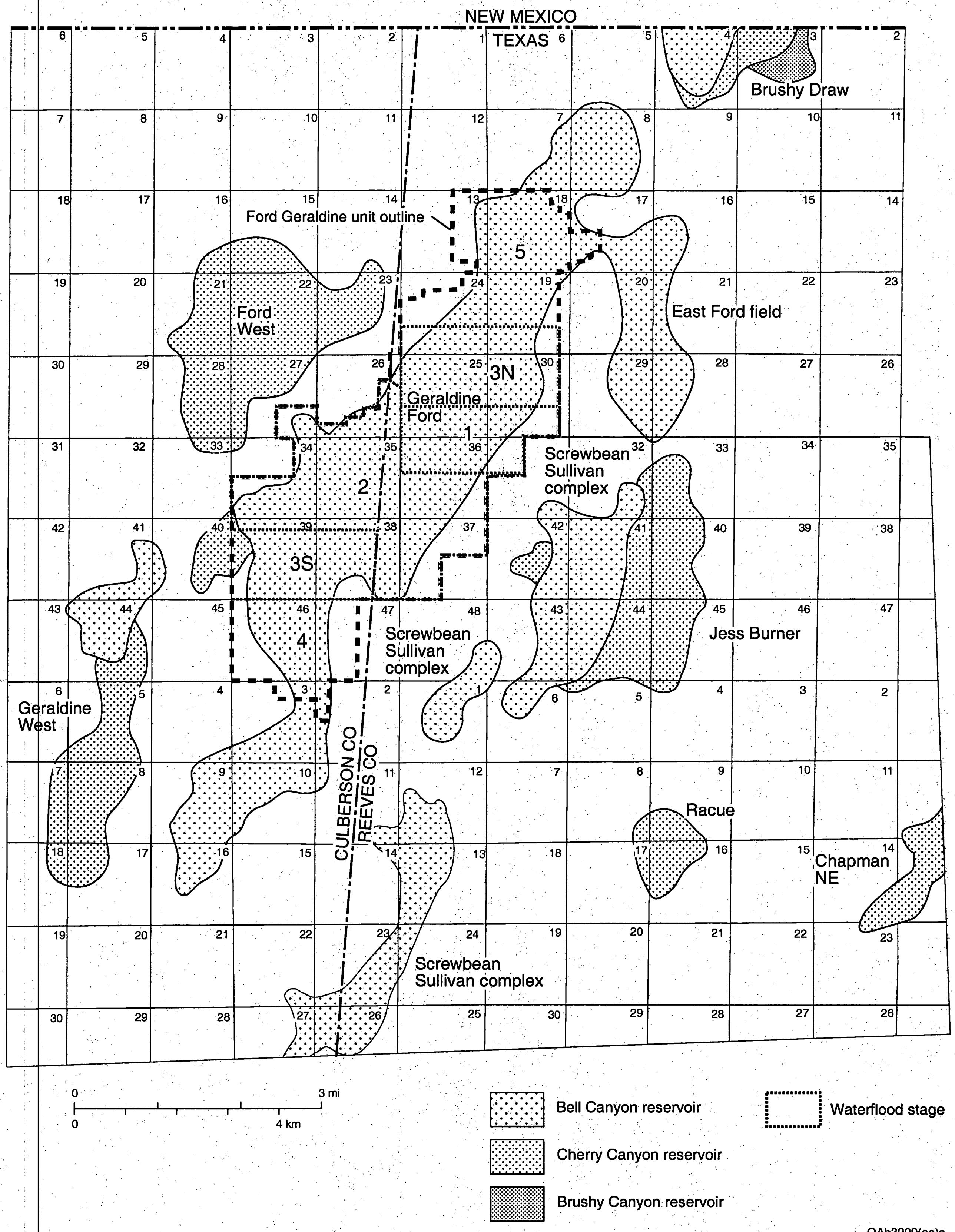

Figure 4. Detailed location map of the East Ford and Ford Geraldine units and other nearby Bell, Cherry, and Brushy Canyon reservoirs.

General Information

The north end of the East Ford unit is located 2.5 mi south of the Texas-New Mexico state line in Reeves County, Texas, approximately 10 mi north of the town of Orla (fig. 1). The unit, which was discovered in 1960, is in Railroad Commission of Texas District 8. The Railroad Commission field name is Ford, East (Delaware Sand). The field was unitized and is operated by Orla Petco, Inc., as the East Ford unit.

Project Description

The goal of this study is to demonstrate that reservoir characterization can optimize Enhanced Oil Recovery (CO_2 flood) projects in slope and basin clastic reservoirs of the Delaware Mountain Group. The project objective is to increase production and prevent premature abandonment of reservoirs in mature fields in the Delaware Basin of West Texas and New Mexico.

Project objectives are divided into two main phases. The original objectives of the reservoir-characterization phase of the project were (1) to gain a detailed understanding of the architecture and heterogeneity of two representative fields of the Delaware Mountain Group, Geraldine Ford and Ford West, which produce from the Bell Canyon and Cherry Canyon Formations (fig. 3), respectively; (2) to choose a demonstration area in one of the fields; and (3) to simulate a CO_2 flood in the demonstration area (Dutton and others, 1997a, 1997b, 1998). After completion of the study of Geraldine Ford and Ford West fields, the original industry partner decided not to continue.

A new industry partner, Orla Petco, Inc., is now participating in the project, and the reservoir characterization phase has expanded to include the East Ford unit. This additional reservoir characterization provided an excellent opportunity to test the transferability of the geologic model and log-interpretation methods developed during reservoir characterization of the Ford Geraldine unit to another field in the Delaware sandstone play. The East Ford unit underwent primary recovery through June 1995. As a result of serious producibility problems—particularly low reservoir energy—primary recovery efficiency at the East Ford unit was less than 15 percent. Unless methodologies and technologies to overcome these producibility problems could be applied, much of the remaining oil in the East Ford unit would not be recovered.

Reservoir characterization of the East Ford unit built upon the earlier, integrated reservoir characterization study of the Ford Geraldine unit (Dutton and others, 1996, 1997a, 1997b, 1998) and the work of Ruggiero (1985). Both units produce from the most prolific horizon in the Bell Canyon Formation, and the reservoir characterization studies of these units provide insights that are applicable to other slope and basin clastic fields in the Delaware Basin. The technologies used for reservoir characterization of the East Ford unit included (1) subsurface log, core, and petrophysical study; (2) high-resolution sequence stratigraphy; (3) mapping of nearby outcrop reservoir analogs; and (4) analysis of production history.

In Phase 2 the knowledge gained during reservoir characterization is being applied to increase recovery from the CO_2 flood in the East Ford unit. In addition, the results of the CO_2 flood are being used to refine and improve the geologic model of the East Ford unit. Comparisons will be made between production from the unit during the CO_2 flood and the predictions that were made during Phase 1. This comparison will provide an important opportunity to test the accuracy of reservoir-characterization studies as predictive tools in resource preservation of mature fields. Through technology transfer, the knowledge gained in the study of the East Ford and Ford Geraldine units can be applied to increase production from the more than 350 other Delaware Mountain Group reservoirs in West Texas and New Mexico, which together contain more than 1.5 Bbbl of remaining oil.

FIELD-DEVELOPMENT HISTORY

East Ford field was discovered in 1960 from reservoirs in the upper Bell Canyon Formation (fig. 3). The field was originally developed on 20-acre spacing at the north end, then drilled on 40-acre spacing throughout the rest of the field (fig. 5). There are currently 44 usable well bores in the field, including 13 producer and 7 injector wells (fig. 5). Approximately half of the East Ford wells are open-hole completions. Most wells were initially stimulated by a small fracture treatment of 1,000 gal of lease oil and 1,000 to 1,500 lb of 20/40 sand (W. A. Flanders, Transpetco Engineering, written communication, 1994). About 5 yr after completion, many of the wells were restimulated by larger fracture treatments, typically 3,000 to 5,000 gal of lease oil and 4,000 to 7,500 lb of 10/20 sand. Most wells were initially completed in the Ramsey sandstone, then as Ramsey production declined, some wells were deepened and completed in the Olds sandstone (fig. 6). Production from the Olds and Ramsey sandstones was commingled.

Oil gravity is 43° (API), and viscosity is 0.775 cp at reservoir temperature. Average current reservoir pressure is 850 psi. An oil-water contact occurs at an elevation of 88 ft above sea level.

Primary recovery in East Ford field began in October 1960 and continued until June 1995. A total of 45 wells were drilled for primary production. Oil production peaked at 965 bbl of oil per day (bopd) in May 1966. Cumulative production by the end of primary recovery in June 1995 was 3,209,655 bbl. An estimated 10 percent of the total production, or 320,966 bbl, was from the Olds sandstone (W. A. Flanders, Transpetco Engineering, written communication, 1994). The estimated 2,888,690 bbl produced from the Ramsey sandstone represents 15.7 percent of the 18.4 MMbbl of OOIP (Dutton and others, 1999c).

Primary production data in the East Ford unit were collected by lease, not by individual well. To map primary oil production, we plotted production for each lease at the geographic center of the wells that produced from the Ramsey sandstone (fig. 7). All production was assumed to be from the Ramsey sandstone. Highest production at the north end of the field occurs along the position of the Ramsey 2 channel, but in the south part of the field the highest

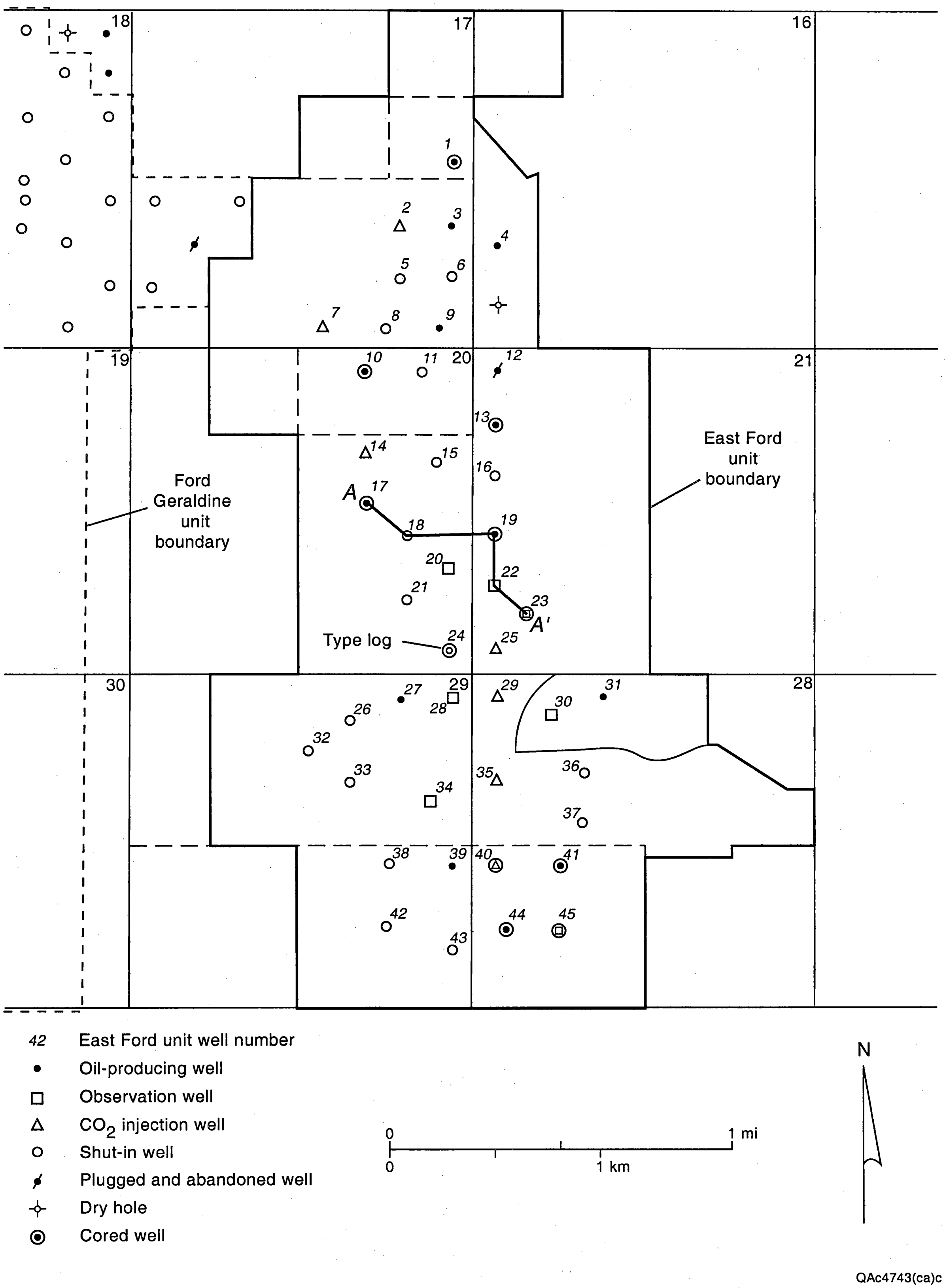

Figure 5. Status of wells in the East Ford unit. Type log shown in figure 6 and cross section A–A′ in figure 22.

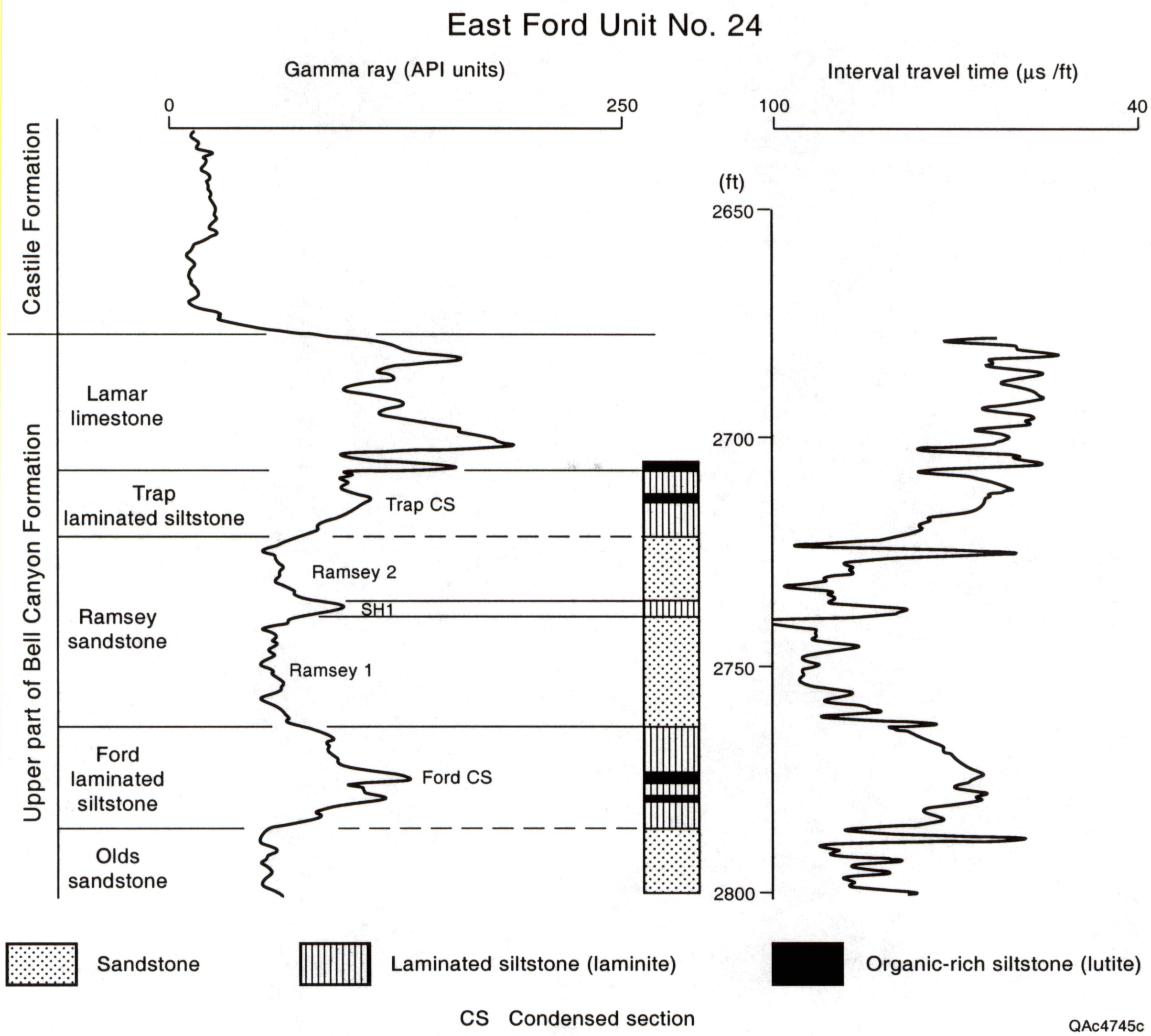

Figure 6. Typical log from East Ford Unit Well No. 24. Well location shown in figure 5.

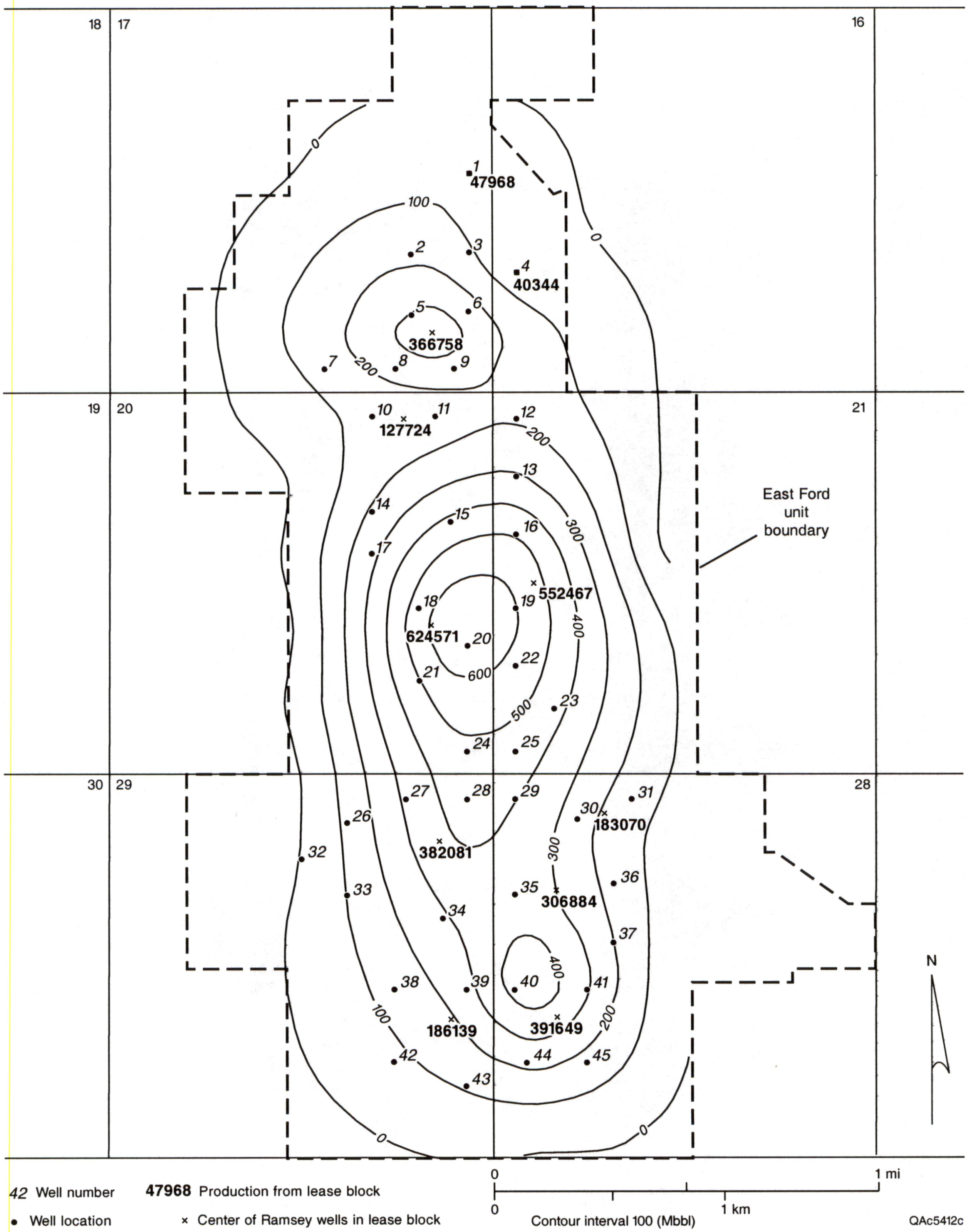

Figure 7. Map of primary oil production from the Ramsey sandstone in the East Ford unit. Production for each lease was plotted at the geographic center of the wells producing from the Ramsey sandstone within the lease.

production is shifted to the east, at the position of the Ramsey 1 channel and lobe (see Revised Depositional Model for East Ford Field, p. 15).

The map of total primary production by lease (fig. 7) gives a somewhat misleading view of where the best production occurs because the leases are different sizes (fig. 8). Production was normalized, therefore, by dividing total production for each lease by the size of the lease. The map of normalized production in bbl/acre indicates that the highest production rates occur on the east side of the unit (fig. 9). High production rates from leases 6 and 9 suggest that there may be some aquifer support to production that is bringing in oil from the water-oil transition zone to the east of those leases.

The highest production generally follows the trend of low-percentage water cut during initial-potential (IP) tests (Dutton and others, 1999b). In the Ford Geraldine unit, the percentage of water produced during IP tests was the single best predictor of eventual total production from a well (Dutton and others, 1997b), and it appears to be a good predictor in the East Ford unit as well.

The East Ford unit did not undergo secondary recovery by waterflooding. In Ramsey sandstone reservoirs in other fields, waterflooding has not been very successful. In the Ford Geraldine unit, waterflooding added only an estimated 4.5 percent of the OOIP to the total recovery by the end of secondary development (Pittaway and Rosato, 1991). Low secondary recovery is not unique to the Ford Geraldine unit; secondary recovery from Twofreds field was only 4 percent (Kirkpatrick and others, 1985; Flanders and DePauw, 1993).

Tertiary recovery in the East Ford unit by CO_2 injection began in July 1995, and production response to the CO_2 injection was observed in December 1998 (fig. 10). In 1993 and 1994, before the CO_2 flood began, annual production from the field was 12,000 to 14,000 bbl of oil. In 1998, annual production had increased to more than 30,000 bbl. In 1999 production had risen to 38,791 bbl. Daily production from the field increased from 30 bbl to more than 100 bbl (fig. 10).

The initial pattern had 8 injectors and 10 producers, but the pattern was changed this year to 7 injectors and 13 producers (fig. 5). As part of the Phase 2 field demonstration, a new well has

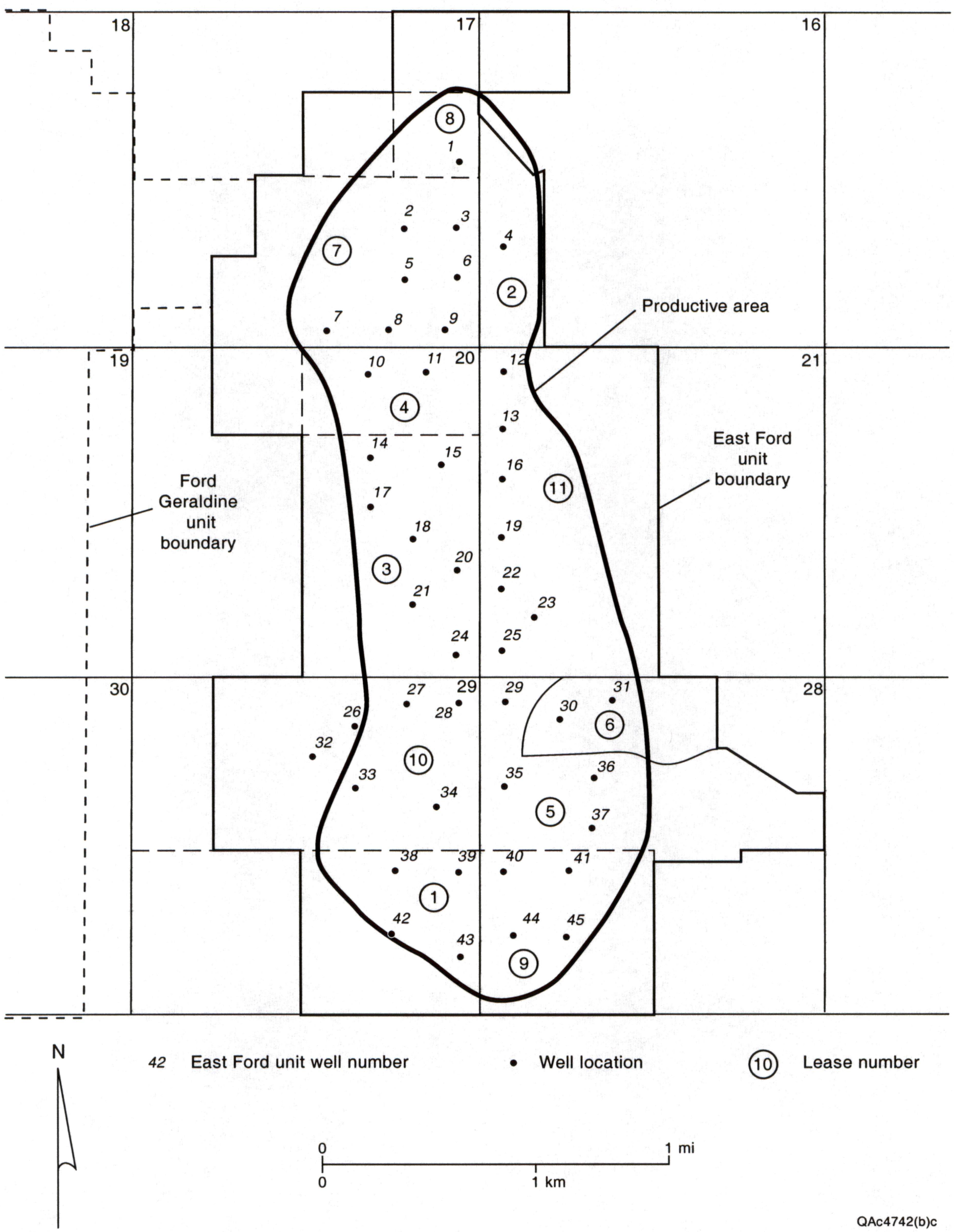

Figure 8. Outline of the producing area of the East Ford unit and individual leases.

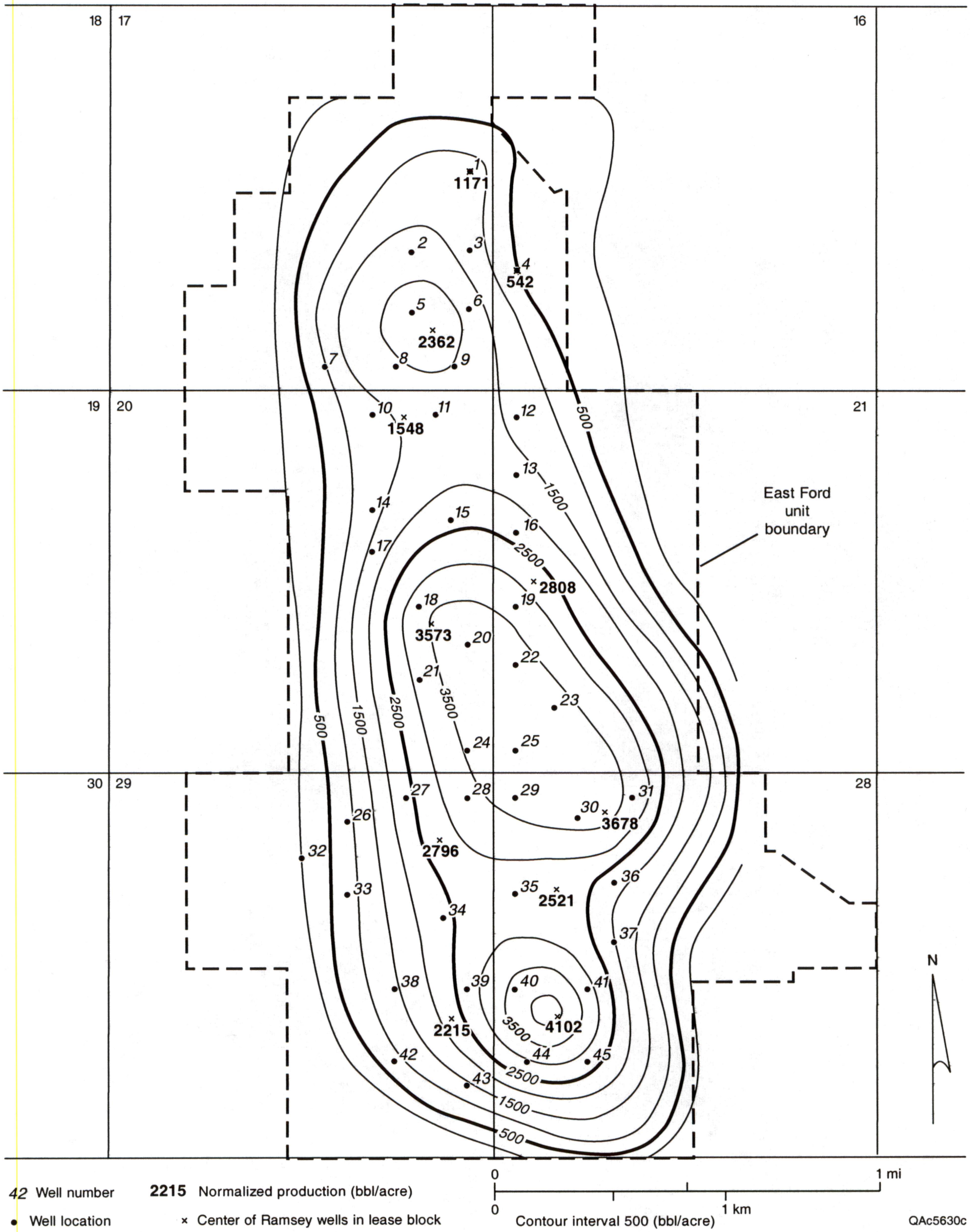

Figure 9. Map of normalized production in the East Ford unit in bbl/acre. Normalized production for each lease was plotted at the geographic center of the wells producing from the Ramsey sandstone within the lease.

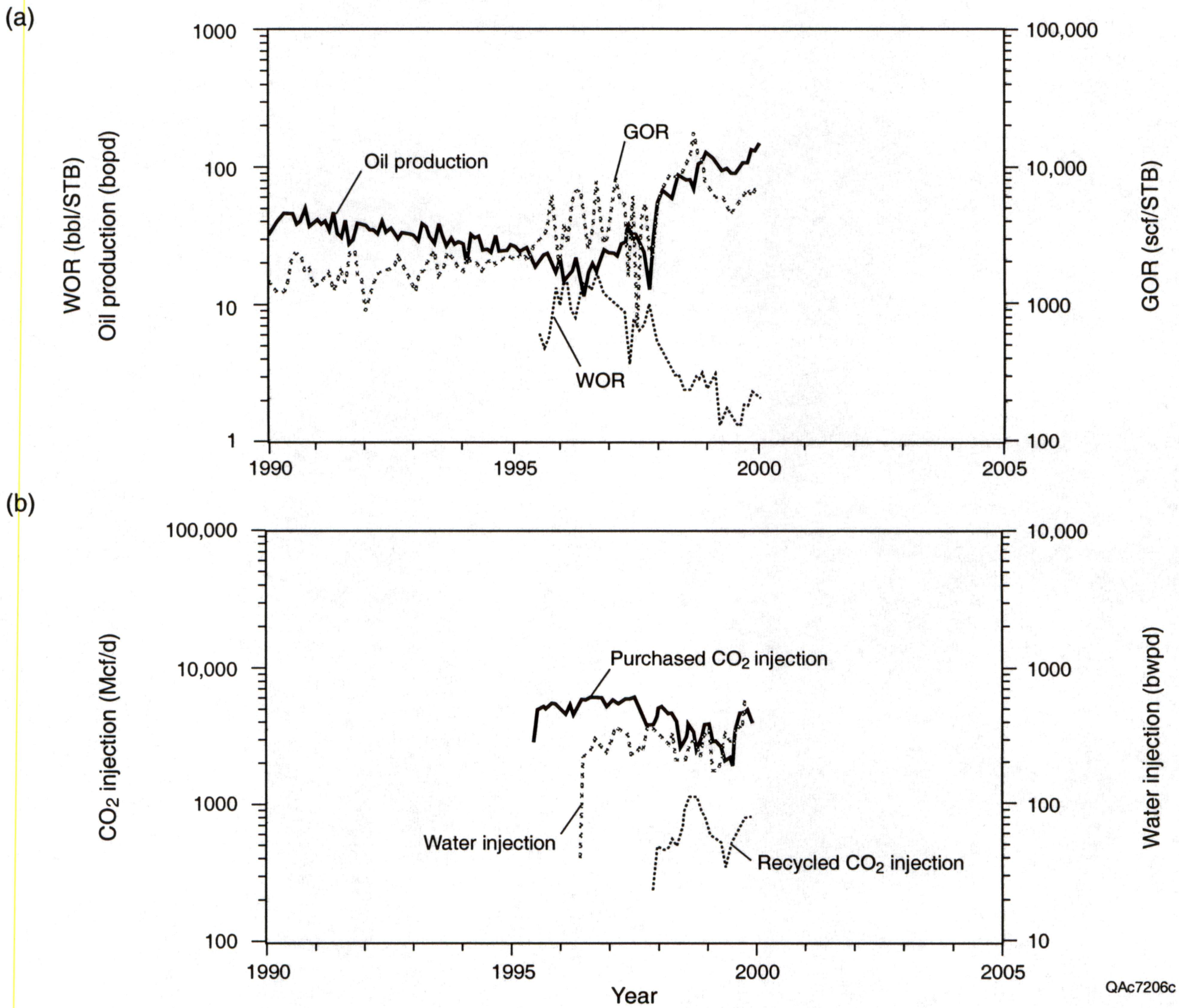

Figure 10. (a) Total field production and (b) injection in the East Ford unit.

been permitted and will be drilled as soon as a rig becomes available. The new well is located just northwest of well 41, which is being replaced because its casing parted during a workover to repair a casing leak.

VOLUMETRIC ESTIMATES

Tertiary recovery potential of the East Ford unit was estimated by determining how much oil remains in the unit and where the remaining oil is located. The map of $S_o \times \phi \times H$ (fig. 11) (Dutton and others, 1999b) was used to estimate OOIP in the East Ford unit and in the area of the CO_2 flood. To calculate OOIP in the East Ford unit, we divided the $S_o \times \phi \times H$ map into 50-ft × 50-ft grid blocks, and the volume of oil in each grid block was summed. The 1,212 acres of the East Ford unit contained an estimated 18,445,101 bbl of OOIP (table 1). The lease outlines were then superimposed on the $S_o \times \phi \times H$ map to calculate OOIP in each lease (fig. 8). Primary production was known for each lease, so remaining oil in place (ROIP) was calculated by subtracting primary production from OOIP (table 1). ROIP for the entire unit is estimated to be 15.2 MMbbl. The percentage of ROIP in most leases is about 82 to 89 percent (table 1), but leases 6, 9, and 11 apparently contain lower percentages of ROIP, from 65 to 78 percent. The lower values may reflect additional oil production from the oil-water transition zone to the east of these leases, making it appear that they have produced a higher percentage of their OOIP, whereas they actually reflect oil entering the leases from the east by aquifer support.

The area influenced by the CO_2 flood is smaller than the total productive area of the East Ford unit. A streamline model developed to determine the optimal injection pattern for the East Ford unit (W. A. Flanders, Transpetco Engineering, written communication, 1994) was used to estimate the size of the CO_2 flood area as 842 acres (fig. 12). The outline of the flooded area was superimposed on the $S_o \times \phi \times H$ map to calculate the OOIP of 14,742,138 bbl (table 2). Although the area of the CO_2 flood is only 69 percent of the total producing area, it contained 80 percent of the OOIP in the unit.

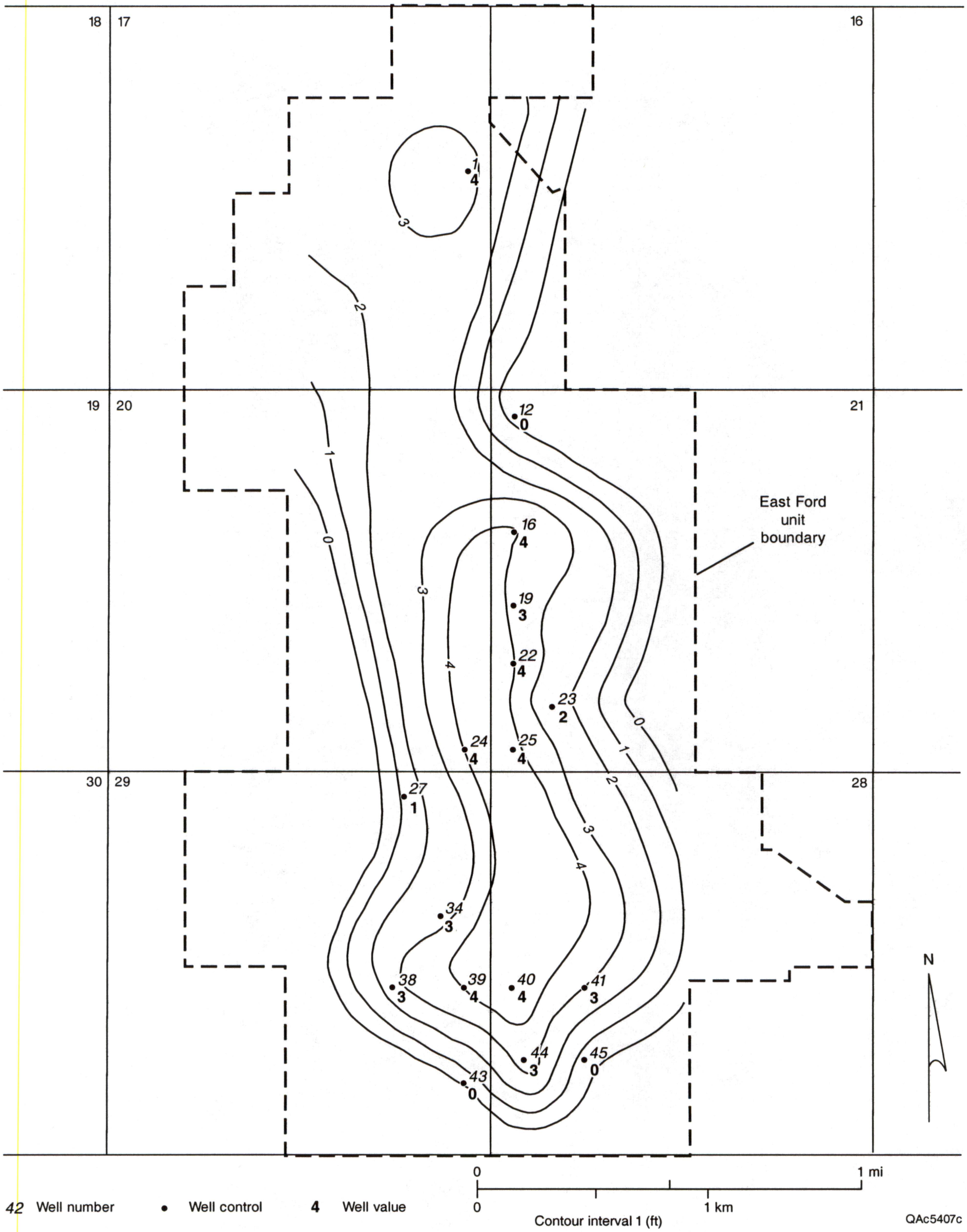

Figure 11. Map of hydrocarbon pore-feet ($S_o \times Ø \times H$) of the Ramsey sandstone in the East Ford unit.

Table 1. Volume of original oil in place (OOIP) in the East Ford unit. Oil volumes are in stock-tank barrels.

Lease no.	Area (acres)	OOIP	Primary production	ROIP	ROIP/OOIP (%)
1	84	1,307,025	186,139	1,120,886	86
2	74	361,882	40,344	321,538	89
3	175	3,484,483	624,571	2,859,912	82
4	83	1,013,064	127,724	885,340	87
5	122	2,579,520	306,884	2,272,636	88
6	50	614,927	183,070	431,857	70
7	155	2,249,600	366,758	1,882,842	84
8	41	777,984	47,968	730,016	94
9	95	1,117,527	391,649	725,878	65
10	137	2,395,441	382,081	2,013,360	84
11	197	2,543,647	552,467	1,991,180	78
Total unit	1,212	18,445,101	3,209,655	15,235,446	82

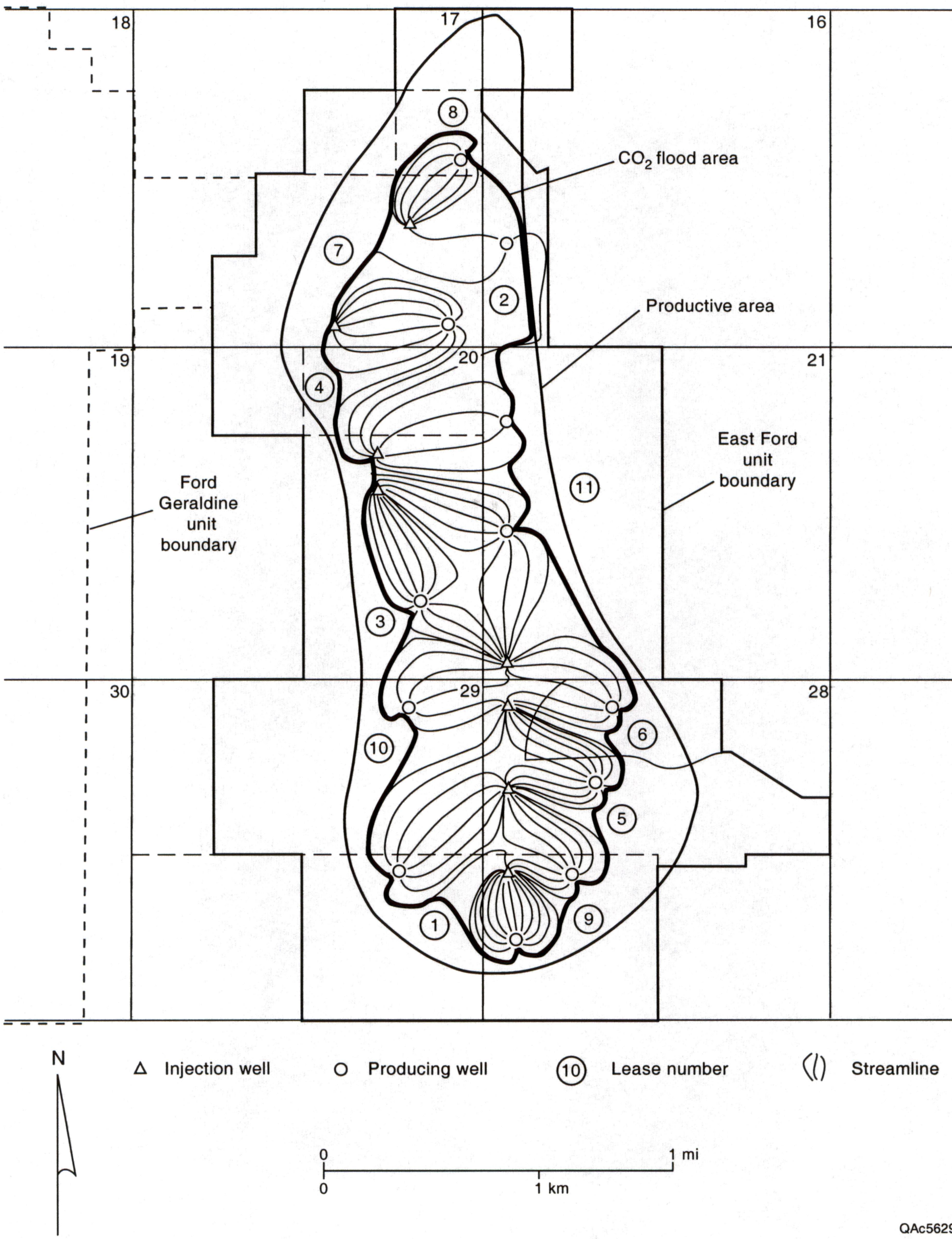

Figure 12. Outline of the CO_2 flood area within the East Ford unit, superimposed on a streamline-pattern model of the flood.

Table 2. Volume of original oil in place in the CO_2 flood area within the East Ford unit. Oil volumes are in stock-tank barrels.

Lease no.	Area (acres)	OOIP	Primary production	ROIP	ROIP/OOIP (%)
1	55	1,120,062	159,513	960,549	86
2	40	153,690	17,134	136,556	89
3	169	3,402,474	609,871	2,792,602	82
4	83	1,017,090	128,232	888,858	87
5	82	2,054,109	244,376	1,809,732	88
6	28	430,576	128,187	302,389	70
7	123	1,811,034	295,257	1,515,776	84
8	13	276,153	17,027	259,127	94
9	38	771,981	270,549	501,432	65
10	120	2,304,745	367,615	1,937,130	84
11	91	1,400,226	304,122	1,096,104	78
Total area	842	14,742,138	2,541,882	12,200,256	83

The flooded area within each lease and the OOIP in the flooded area were estimated from the streamline and $S_o \times \phi \times H$ maps (table 2). To estimate primary production from the flooded area of the lease, we multiplied primary production from each lease by the ratio of OOIP in the flooded area to OOIP in the total lease (table 2). The flooded area contained an estimated 14.7 MMbbl of OOIP. ROIP was then calculated by subtracting primary production in the flooded area from the OOIP in the flooded area (table 2). The average percentage of ROIP after primary production in the areas to be flooded was 83 percent (table 2). The 12.2 MMbbl of ROIP in the CO_2 flood area represents the target for tertiary recovery.

DELAWARE SANDSTONE DEPOSITIONAL MODEL

Reservoir displacement operations such as CO_2 flooding are sensitive to geologic heterogeneities in a reservoir. Siltstones, commonly interbedded with reservoir sandstones in Delaware fields, are the geologic features in this play that have the greatest effect on tertiary recovery (Dutton and others, 2000). Because of the low permeability of siltstones, limited cross flow of fluids will occur between sandstones separated by siltstone. A depositional model for Bell Canyon sandstones was developed from outcrop characterization (Barton, 1997; Barton and Dutton, 1999) and subsurface data from the Ford Geraldine unit (Dutton and Barton, 1999; Dutton and others, 1999a). This depositional model was applied to the East Ford unit (Dutton and others, 1999b, 1999c). Because no cores from East Ford were available for viewing, facies were interpreted on the basis of sandstone thickness and log response. Analysis of the response to CO_2 injection in the East Ford unit, however, has provided additional information on potential flow restrictions between wells that has caused us to refine the depositional interpretation of the field this year.

Bell Canyon Facies in Outcrop

The outcrop study focused on a stratigraphic unit in the Bell Canyon Formation that is analogous to, but older than, the Ramsey sandstone (Barton and Dutton, 1999). The interval is the uppermost high-order cycle below the McCombs limestone (fig. 3). The scale and position of this stratigraphic unit are analogous to those of the Ramsey interval, the uppermost high-order cycle below the Lamar limestone (fig. 3). This unit shows complex stacking patterns and facies changes that are interpreted to be formed by a system of channels and levees that have attached lobes and overbank splays (fig. 13).

Six facies were identified in the outcrop study area in Culberson County, about 25 mi west of the East Ford unit (fig. 2). Facies 1 is a massive organic-rich siltstone; facies 2 is an organic-rich, laminated siltstone; facies 3 is a laminated siltstone; facies 4 is composed of thin-bedded sandstones and siltstones that are graded or that display partial Bouma sequences (Bouma, 1962); facies 5 is a structureless sandstone; and facies 6 is a large-scale, cross-laminated sandstone (Barton and Dutton, 1999).

Facies 1, a massive, organic-rich siltstone, lacks the extremely fine, parallel lamination of facies 2 (Barton, 1997). It ranges in thickness from 0.5 inch to 1 ft and occurs as a relatively thin, discontinuous drape at the top of a sandstone bed or at the base of a channel. Contact with other facies varies from abrupt to gradational, gradational contacts occurring at the top of graded and ripple-laminated sandstone beds. The organic-rich siltstones are interpreted to record the fallout from suspension of silt and organic matter from a turbulent sediment gravity flow. The facies is similar to the E division of the Bouma sequence.

Facies 2 is a dark-gray to black, finely laminated, organic-rich siltstone that is commonly referred to as lutite (Williamson, 1978, 1979). Facies 2 displays gradational contacts with facies 3 and occurs at the top of upward-fining, or at the base of upward-coarsening, successions of laminated siltstone (Barton, 1997). Facies 2 is interpreted to have been deposited by the settling out from suspension of marine algal material and airborne silt. The presence of fossils and

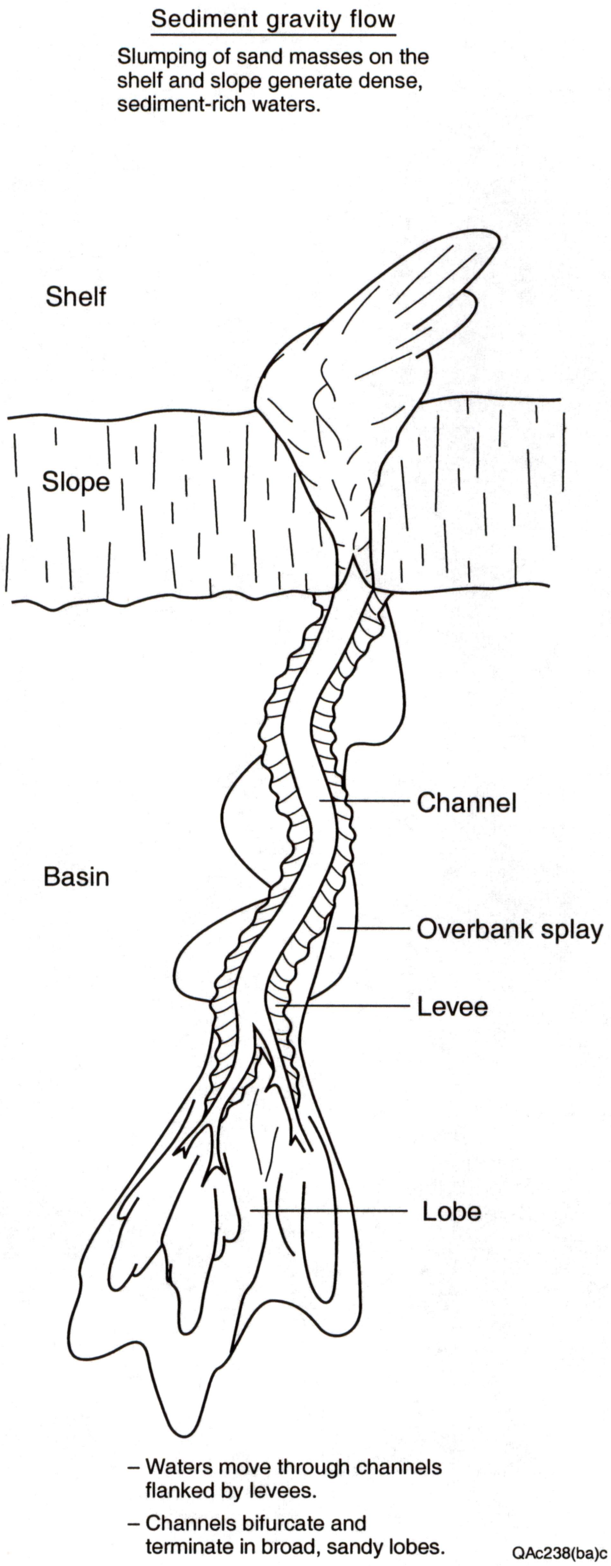

Figure 13. Depositional model proposed for the Ramsey sandstone in the East Ford unit (after Barton, 1997; modified from Galloway and Hobday, 1996).

volcanic ash beds suggests that it was deposited during a prolonged period of sediment starvation, when coarser particles were prevented from entering the basin (Gardner, 1992).

Facies 3 is a laminated siltstone that is similar to facies 2 but contains considerably less organic matter; it is commonly called laminite (Williamson, 1978, 1979). The dominant sedimentary structure is extremely even, parallel lamination produced by the regular alternation of dark, organic-rich siltstone laminae that are less than 1 mm thick, with tan to light-gray siltstone laminae that are less than 1 to 3 mm thick. The laminated siltstones occur as laterally extensive sheets that mantle underlying deposits. Facies 3 is interpreted to record regular fluctuations in the settling from suspension of marine algal material and airborne silt.

Facies 4 consists of thin-bedded sandstones and siltstones that display abundant current laminations (fig. 14). Sandstone beds are 1 inch to 1 ft thick and commonly display erosional bases. Most individual beds grade upward from sandstone at the base to siltstone at the top. The most common sequence of stratification types is similar to the BC or BCD division of the Bouma sequence (Bouma, 1962), in which beds begin with a horizontally laminated or ripple-drift, cross-laminated sandstone and pass upward into a wavy-laminated siltstone. The sequence of stratification types and abundance of ripple-drift cross-lamination indicate that facies 4 was deposited from waning, turbulent, sediment gravity flows (Barton, 1997).

Facies 5 and 6 are clean sandstones having no interbedded siltstones; facies 5 is a structureless sandstone, and facies 6 is a large-scale, cross-laminated sandstone. The paucity of lamination, presence of floating clasts, and abundance of water-escape and load structures suggest that the facies 5 sandstones were rapidly deposited from high-density sediment gravity flows (Lowe, 1982; Kneller, 1996). The scale, form, and occurrence of the cross-laminations in facies 6 suggest that the sands were deposited from confined, highly turbulent sediment gravity flows (Barton and Dutton, 1999).

Figure 14. Photograph of a levee deposit composed of thin-bedded sandstones and siltstones in the Bell Canyon Formation, Culberson County, Texas (from Barton and Dutton, 1999).

Depositional Interpretation

Stratigraphic relationships indicate that the Bell Canyon sandstones studied in outcrop were deposited in a basin-floor setting by a system of leveed channels having attached lobes and overbank splays (figs. 13, 15). Individual channel-levee and lobe complexes stack in a compensatory fashion and are separated by laterally continuous, 3-ft-thick laminated siltstones. These siltstones are interpreted to have been deposited by the settling of marine organic matter and airborne silt during periods when coarser particles were prevented from entering the basin.

Lobe sandstones, as much as 25 ft thick and 2 mi wide, are composed of massive or structureless sandstones (facies 5), and they display a broad tabular geometry. Lobe sandstones were deposited by unconfined flow at the mouths of channels (fig. 15b). In a prograding system, lobe facies would have been deposited first and then overlain and partly eroded by the channel-levee-overbank-splay system.

Channels are largely filled with massive and cross-stratified sandstone (facies 6). Channels mapped in outcrop range from 10 to 60 ft in thickness, with most being 20 to 40 ft thick. Channel widths are 300 to 3,000 ft, giving aspect ratios of 10 to 100. In updip areas, channel positions remained relatively fixed. As a result, individual channels are highly amalgamated and form a body that has larger dimensions than that of any single channel (fig. 16) (Barton and Dutton, 1999). Downdip the spacing of the channels expands (fig. 17). The expansion reflects migration of the channel laterally during the initial stages of channelization (fig. 15c) and channel avulsion or bifurcation, or both, during later stages (fig. 15d).

Flanking the channels on both sides are wedges composed of thinly bedded sandstone and siltstone (facies 4) that are interpreted to be levees. The width of levee deposits mapped in outcrop varies (figs. 16, 17). Many levee deposits are about 500 ft wide, but some are as wide as 0.5 mi (Barton, 1997). The levees rapidly thin away from the channel, decreasing in thickness from 20 to 3 ft over the distance of a few hundred feet to 0.5 mi (Barton and Dutton, 1999). Sandstone-bed thickness and sandstone content (net to gross) also decrease in a similar fashion. Near the channel margin, sandstone beds in the levees are several feet thick, whereas

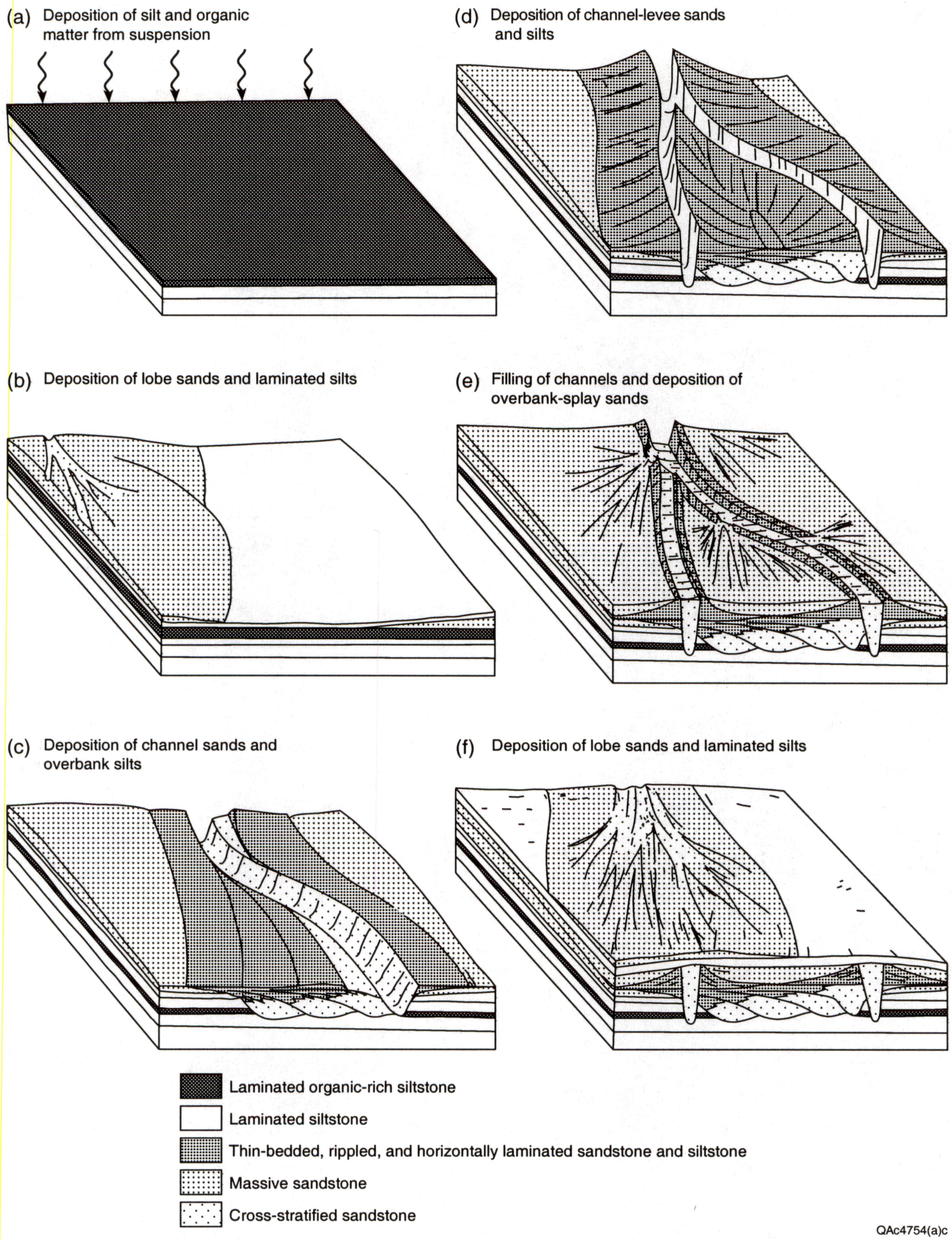

Figure 15. Depositional model proposed for the Bell Canyon sandstone, showing deposition in submarine channels with levees, overbank splays, and attached lobes (from Barton and Dutton, 1999). The model was developed from outcrop study of a high-order cycle in the upper Bell Canyon Formation.

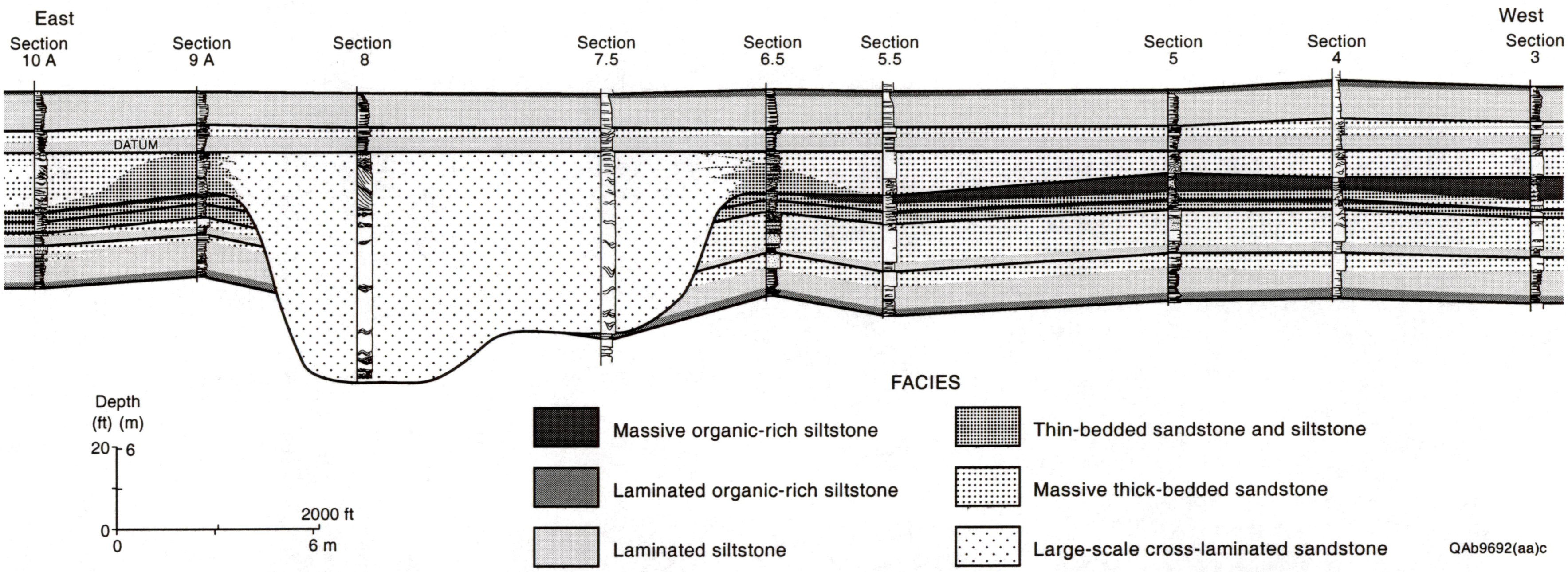

Figure 16. Northeast-southwest strike cross section showing amalgamated channels that form a single body 60 ft thick and 4,000 ft across in Bell Canyon sandstones at Willow Mountain outcrop, Culberson County, Texas (from Barton and Dutton, 1999). Narrow levee deposits are composed of interbedded siltstones and thin sandstones. The levees are onlapped by overbank-splay deposits composed of massive sandstones.

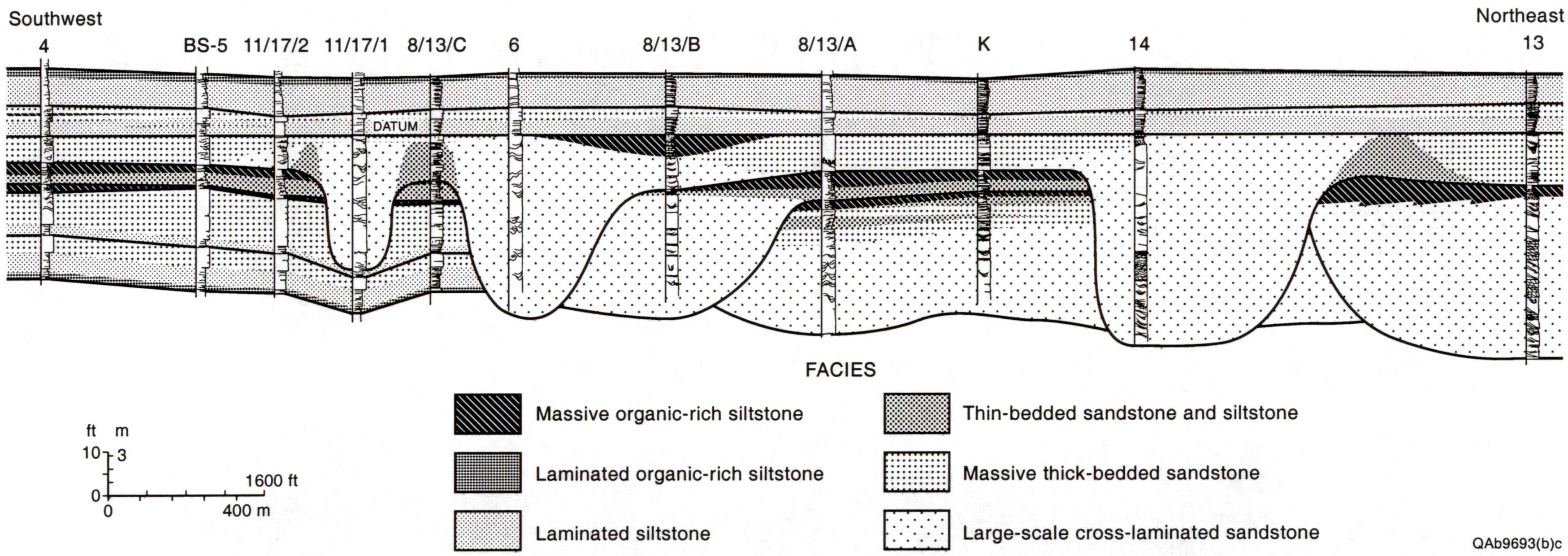

Figure 17. Southwest-northeast strike cross section showing laterally and vertically offset channels in Bell Canyon sandstones at Willow Mountain outcrop, Culberson County, Texas (from Dutton and others, 1999a). Section located 0.6 mi basinward of section in figure 16.

several hundred feet away they are several inches to a foot thick. Sandstone content decreases from about 70 percent near the channel margin to less than 10 percent where the levees pinch out. Levee deposits form a volumetrically small component of the system, about 10 percent, but are important in a reservoir because they form the topography that defines the geometry and connectivity of overbank splays (M. Barton, personal communication, 1999).

The levee deposits are onlapped by massive sandstones (facies 5) that display a broad, tabular to irregular geometry. The massive sandstones are 3 to 25 ft thick and as much as 3,000 ft wide (Barton, 1997). These massive sandstones are interpreted as overbank splays that filled topographically low interchannel areas (fig. 15e). Volumetrically they contain much of the sandstone in the system (fig. 16). The somewhat irregular geometry of the overbank splays is related to the underlying topography. Stratigraphic relationships suggest that the splays formed during the final stages of channel filling (Barton and Dutton, 1999).

Depositional Heterogeneities in Bell Canyon Sandstones

The depositional model developed from outcrop provides a way to predict the distribution of siltstones in Bell Canyon deposits. Siltstones provide the most important depositional heterogeneity within Bell Canyon reservoirs because of the grain size and permeability contrast between sandstone and siltstone facies. Siltstones occur (1) as widespread sheets that bound high-order cycles, (2) as discontinuous drapes along the base of channels or at the tops of sandstone beds, (3) interbedded with thin sandstones in levee deposits, and (4) overlying erosion surfaces associated with channel avulsion (Dutton and others, 2000).

Widespread laminated siltstone sheets can form low-permeability boundaries between producing sandstones. In the East Ford unit, the Ramsey reservoir sandstone is divided into upper and lower sandstone intervals (Ramsey 1 and Ramsey 2) that are separated by a 1- to 3-ft-thick laminated siltstone (SH1 siltstone) throughout the field (fig. 6). The SH1 siltstone represents a break in sandstone deposition within the Ramsey interval, when laminated siltstone was deposited over a widespread area. Cross flow of fluids between the Ramsey 1 and 2 sandstones will be limited because of the SH1 siltstone. CO_2 injected only into the Ramsey 2 sandstone interval, therefore, probably will not penetrate the Ramsey 1 sandstone.

The base of Bell Canyon sandstone channels is commonly marked by a concentration of rounded siltstone clasts and, rarely, by a drape of massive, organic-rich siltstone (Barton and Dutton, 1999). Siltstone drapes at the base of channels were also observed in outcrops of Brushy Canyon (Harms, 1974) and Cherry Canyon (Barton, 1997) sandstones (fig. 18). Siltstones also occur interbedded with thin sandstones within the levee deposits that flank both sides of channels and gradually thin and taper away from the channel (fig. 19). Levee deposits would be likely to restrict flow between channel and splay sandstones.

Finally, in the interchannel areas (fig. 17), individual beds or bedsets are commonly overlain by thin, discontinuous, massive, organic-rich siltstones. The massive, organic-rich siltstones are as much as 4 inches thick and pinch out toward the channel (fig. 17) (Barton and others, 1998).

All of these siltstone beds have the potential to disrupt displacement operations in Delaware sandstone reservoirs. There may be limited cross flow of fluids between a well in an overbank-splay deposit and a well in a channel deposit because of interbedded siltstones in the levee, as well as a possible siltstone-pebble lag or thin siltstone drape along the base of the channel. A well equivalent to measured section 10A in figure 16, for example, might have limited cross flow with a well equivalent to measured section 8.

REVISED DEPOSITIONAL MODEL FOR EAST FORD FIELD

The Bell Canyon strata mapped in outcrop form a complex deposit composed of channel, levee, lobe, and overbank-splay facies (figs. 16, 17). It is difficult to interpret such complex facies relationships in a subsurface reservoir from log data alone. Because of the narrow range of grain sizes in Ramsey sandstones and the absence of detrital clay, log patterns are generally not diagnostic of facies. In a field like East Ford, which has no cores, facies interpretations must

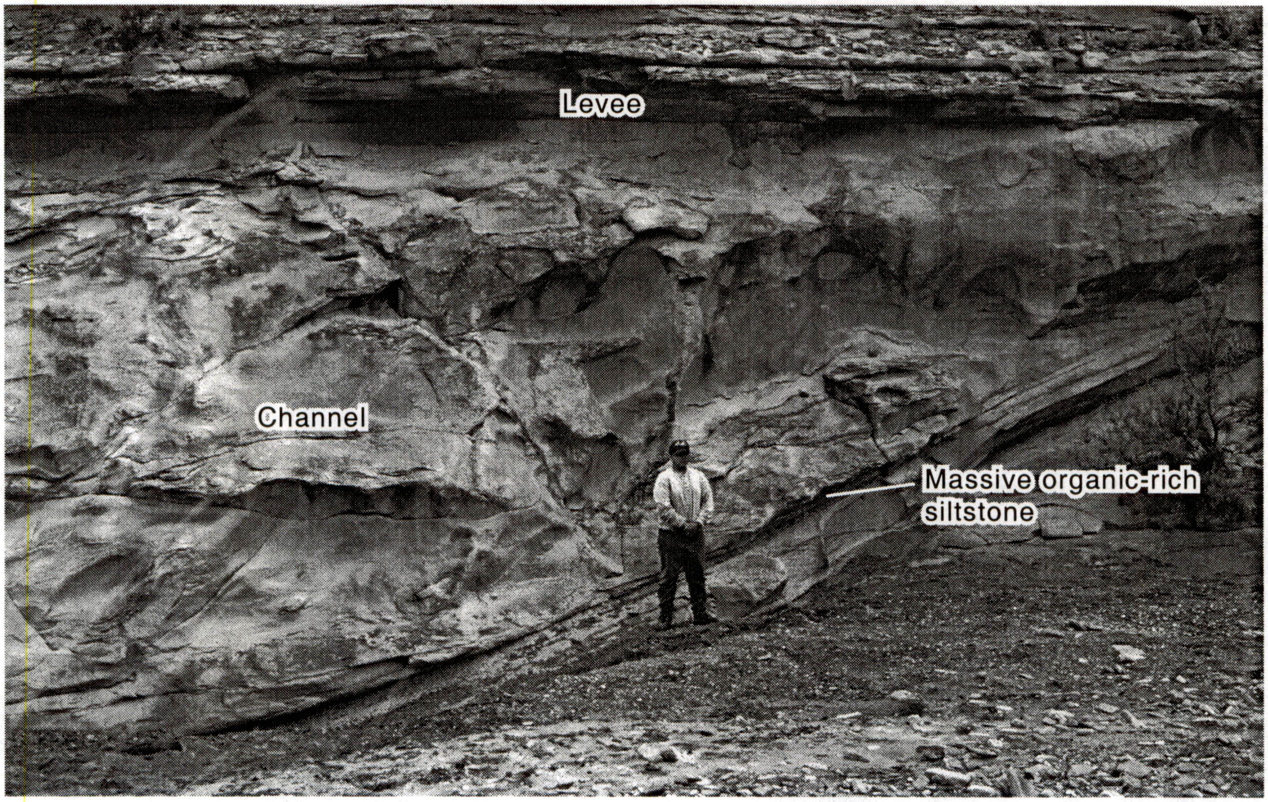

Figure 18. Photograph of channel in the Cherry Canyon Formation at Willow Draw outcrop, Culberson County, Texas. The base of the channel is marked by a concentration of rounded siltstone clasts and a drape of massive, organic-rich siltstone (from Dutton and others, 2000).

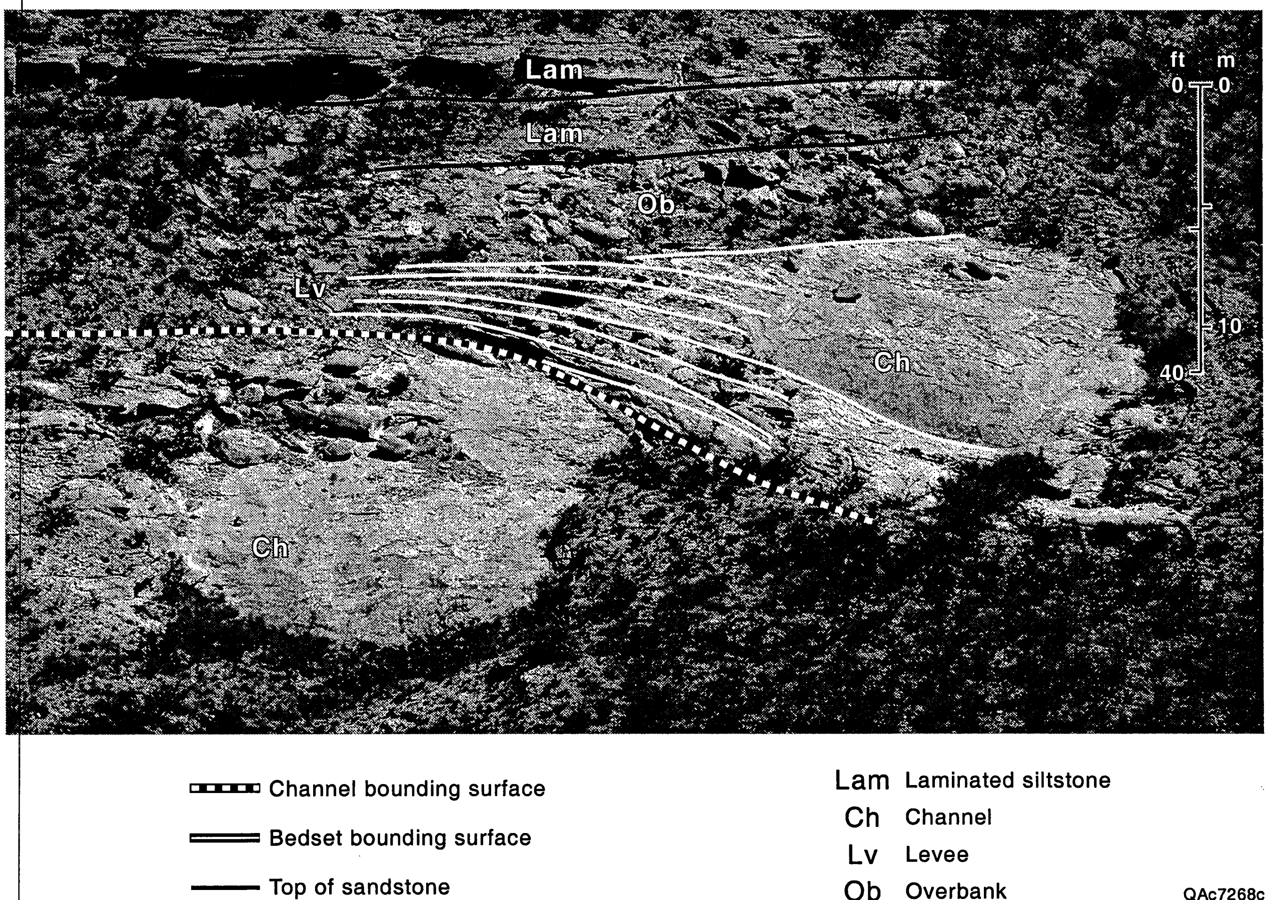

Figure 19. Photograph of channel and levee deposits at Willow Mountain outcrop, Culberson County, Texas (from Dutton and others, 1999a). The two channels are vertically stacked in an offset fashion.

be based on all available information, including sandstone thickness, pressure response, log patterns, and petrophysical properties, and be guided by the outcrop model. Although we will use all available data, it is likely that the model developed for a subsurface reservoir will be less complex than what can be observed in outcrop.

In the reservoir characterization of East Ford field that was done earlier in the project (Dutton and others, 1999b, 1999c), Ramsey sandstones were interpreted as having been deposited in a channel-levee system with attached lobes. The deposits at East Ford formed a complex about 2,500 to 4,000 ft wide, dimensions similar to those of the system that was studied in outcrop (Barton and Dutton, 1999). Channel deposits in East Ford field were interpreted to be approximately 1,000 to 1,500 ft wide and 15 to 30 ft deep. Levee deposits were interpreted to be the main sandstone deposits outside of the channels, thinning away from the channels over a distance of about 1,000 to 1,500 ft. Lobe sandstones, deposited at the mouths of the channels, formed broad, tabular deposits that were partly incised and replaced by prograding channels.

The depositional model of East Ford field was revised this year on the basis of analysis of pressure and production information and reexamination of the outcrop data. Overbank splays were recognized in outcrop as being the main area of sand storage outside of the channels, not levees. This model has now been applied to East Ford field, which is interpreted as being similar to the updip outcrop section (fig. 16). Deposits flanking the Ramsey 1 and 2 channels have been reinterpreted as consisting of narrow levees and wider overbank-splay sandstones (figs. 20 through 22). Interbedded sandstones and siltstones of the levee deposits can restrict flow between channel and splay sandstones. Deposits at the south end of the field are interpreted to be lobe sandstones in both Ramsey 1 and 2 intervals (figs. 20, 21).

Influence of Geologic Heterogeneity on East Ford Production

Analysis of pressure and production data suggests that communication between some injector and producer wells is restricted. Tests conducted this year indicate that the restrictions

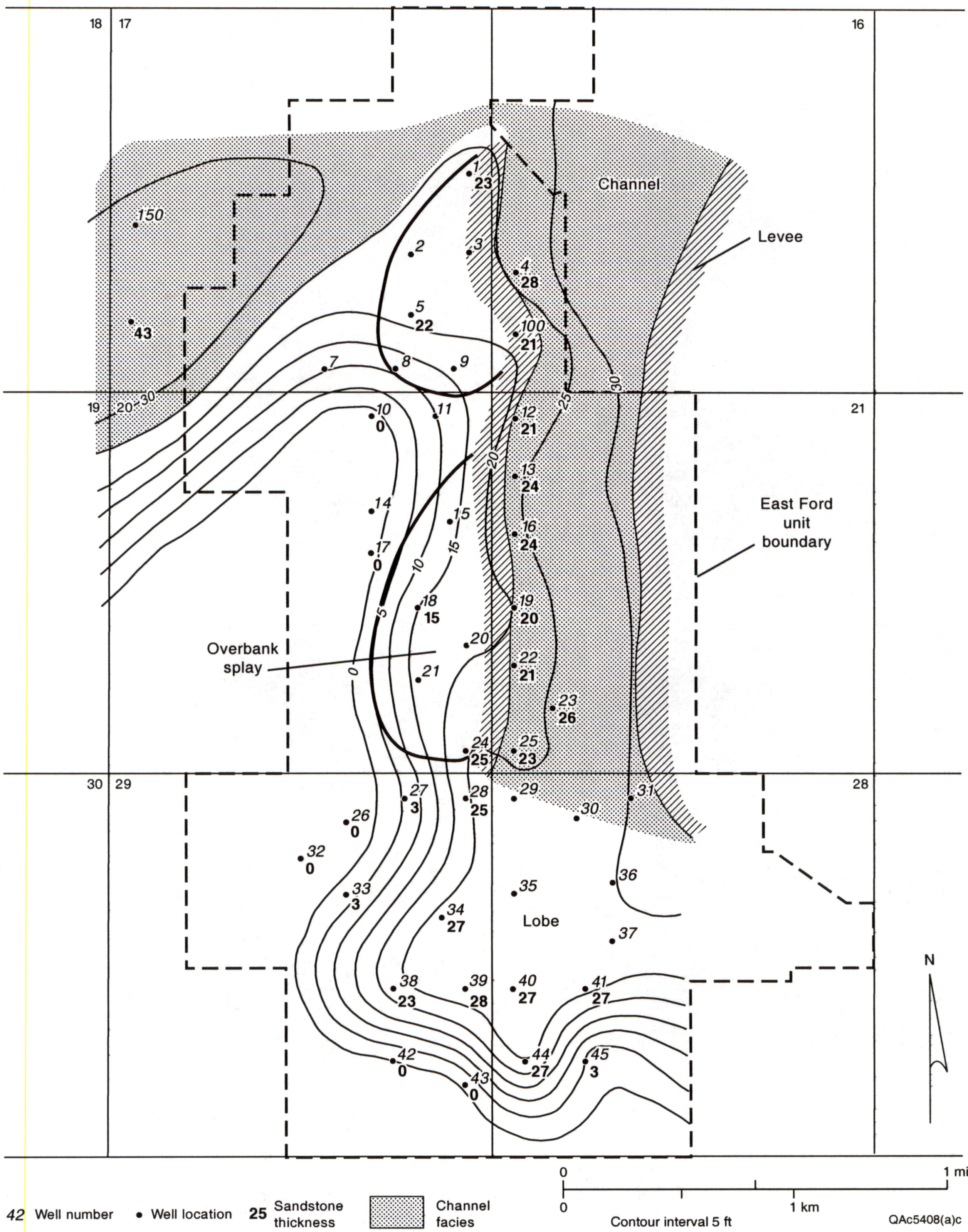

Figure 20. Isopach map of the Ramsey 1 sandstone in East Ford field, with interpreted facies distribution shown.

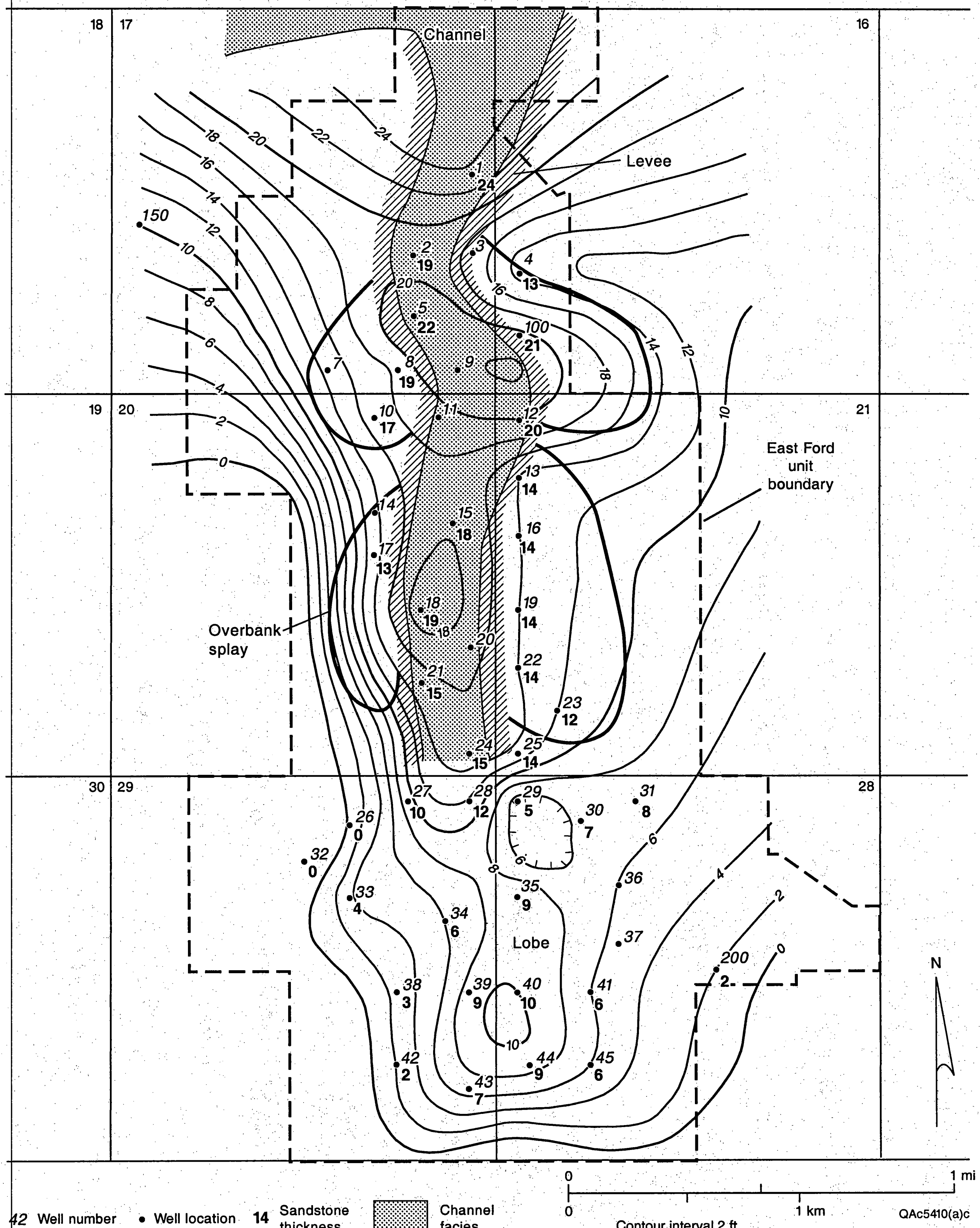

Figure 21. Isopach map of the Ramsey 2 sandstone in East Ford field, with interpreted facies distribution shown.

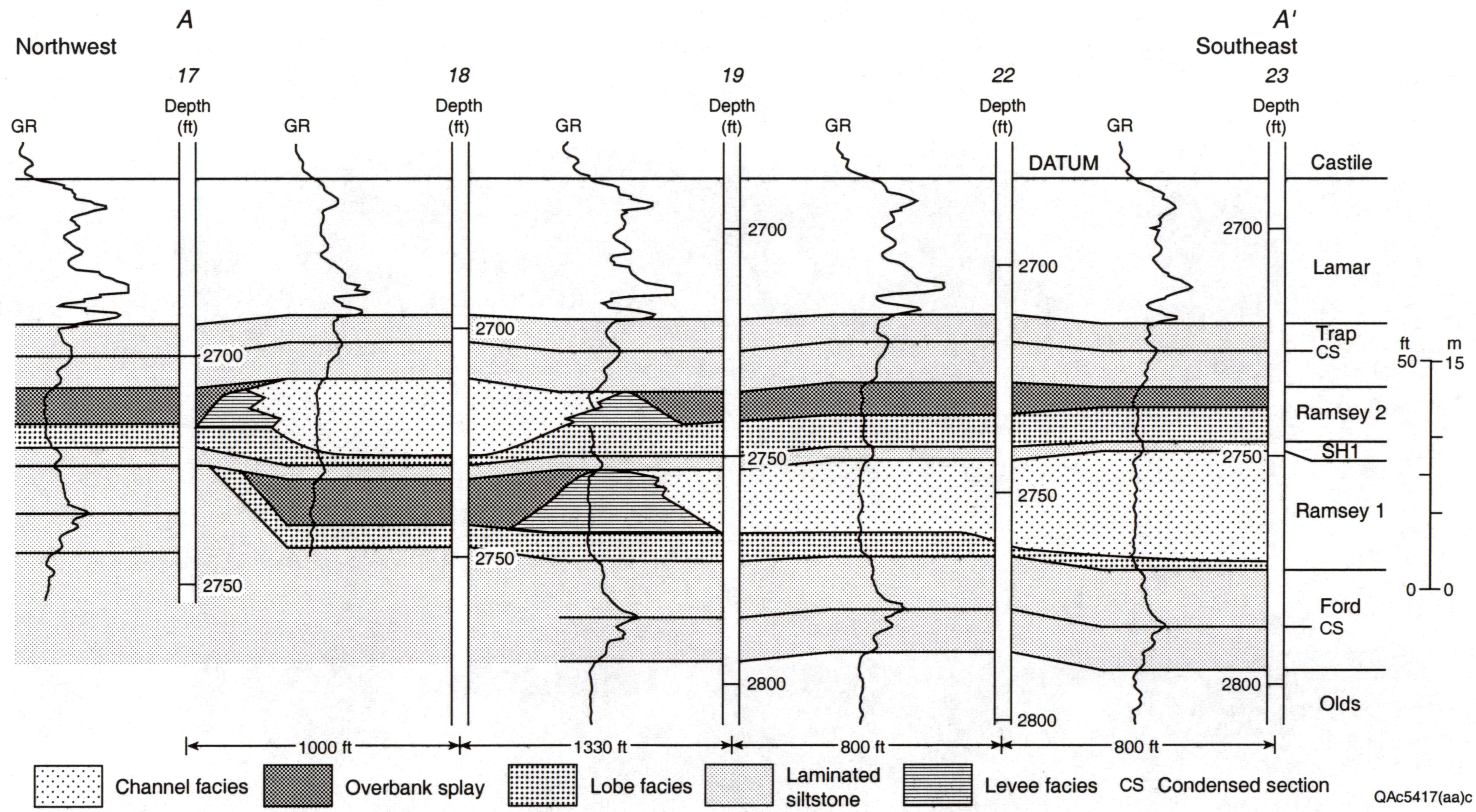

Figure 22. Northwest-southeast strike cross section A–A′ of the central part of the East Ford unit. Line of section shown in figure 5.

were probably not the result of paraffin formation or damage caused by corrosion chemicals. Instead, geologic heterogeneity may explain the apparent flow restrictions. For example, production from well 9 remains low at about 20 bbl/d despite injection of CO_2 into well 7 (fig. 5). Well 7 is apparently located within a compartment in the Ramsey 2 sandstone that has only limited communication with the channel sandstone penetrated by well 9. This compartment may occur in an overbank-splay sandstone with good porosity and permeability. The flow restriction is interpreted as being caused by interbedded sandstones and siltstones of the levee deposits that separate the channel and splay sandstones (fig. 21). Well 10 was converted into a producing well, and it appears to be located in the same splay as well 7.

Wells 14 and 17 are interpreted as being in a different splay sandstone that is not in pressure communication with the splay to the north (fig. 21). Communication between wells in this southern splay and wells in the channel also appears to be restricted by levee deposits. Well 17 was converted to a producing well, and wells 14 and 17 apparently penetrate the same splay. The depositional model suggests that each separate splay sandstone, as well as the channel sandstone, must contain both injector and producer wells to be produced effectively.

Poor production response observed in well 4 suggests that a barrier restricts communication between this producing well and injector well 2 (fig. 5); the barrier may be caused by geologic heterogeneity. Initial geologic interpretations suggested the presence of a channel–levee boundary between wells 3 and 4 in the Ramsey 2 sandstone. To overcome this restriction, well 3 was brought into production. Production from well 3, however, quickly became a mirror image of well 4, about 15 bbl/d, approximately the same amount of water, and little gas. Well 3 was then shut in to run a pressure buildup test. The test indicates the presence of a flow barrier approximately 65 ft away. The nature of the barrier is unknown; it could be a low-permeability levee deposit or it may have been caused by deposition of solids in the formation over a long production time. The low volume of CO_2 produced in well 3 suggests that the barrier occurs between wells 2 and 3 and not between wells 3 and 4. This evidence has caused us to remap the Ramsey 2 levee so that it passes between wells 2 and 3 (fig. 21).

It is more difficult to explain the pressure relationship among wells 18, 21, 24, and 25 (fig. 5). The pressure in well 24 is high, responding to the injection of CO_2 in well 25. The pressure is lower in wells 21 and 18, as if a discontinuity were limiting communication between those wells and well 25. Well 24 is interpreted as occurring in the Ramsey 2 channel, whereas well 25 is probably in an overbank splay or levee deposit (fig. 21). These wells are located near the south end of the Ramsey 2 channel, where levees probably were low and poorly developed (fig. 15f). In this situation, good communication could exist between well 24 in the channel facies and well 25 in a splay (fig. 21). It is not clear, however, why wells 18 and 21 have not responded to injection in well 25, other than their greater distance away.

Horizontal Fractures

Another source of production problems in the East Ford unit is horizontal (or "pancake") fractures that were created in some of the wells during fracture stimulation. Evidence is insufficient for us to say that all wells have horizontal fractures, but it is clear some of them do. Wells that were initially completed open hole in the Ramsey 2 and later deepened into the Ramsey 1 were able to recover cores of the Ramsey 1 sandstone, suggesting that a horizontal fracture had been created in the Ramsey 2. In deeper Delaware fields where this has been done, only frac sand was recovered from the Ramsey 1, suggesting that a vertical fracture had been created. Wells that were deepened in the East Ford unit, but not cored, drilled as if they were cutting formation, not frac sand, and the cuttings were from the formation and not frac sand. Tracer surveys on injection wells and some production wells also indicate some horizontal fractures.

The new well to be drilled in the unit will be logged with a density tool to measure the density of all the layers above the Ramsey sandstone. With this information, overburden pressure at the reservoir can be calculated and used to determine the pressure at which horizontal fractures will form. The goal is to design a fracture treatment for well 3 that stays below the pressure that can cause horizontal fracturing. We will then be able to determine whether the flow restriction that occurs 65 ft from well 3 is caused by a levee or whether it is due to deposition of solids. If it is caused by solids deposition, it should be possible to treat past the damage. If the restriction appears to be caused by a levee, another buildup test will be done.

DELAWARE SANDSTONE PRODUCTION

The technology developed during this project for increasing recovery from slope and basin clastic reservoirs is applicable mostly to other Delaware Mountain Group oil fields. Since the 1920's, approximately 379 Delaware Mountain Group reservoirs have been discovered in West Texas and southeast New Mexico in sandstones of the Bell, Cherry, and Brushy Canyon Formations (fig. 3). The locations of the largest fields, those having individual production of more than 100,000 bbl, were mapped (figs. 22 through 25), and cumulative production data were tabulated by producing formation (tables 3 through 8) (Dutton and others, 2000).

The 102 largest Delaware sandstone reservoirs in Texas produced 226.8 MMbbl through December 1998 (tables 4, 6, 8; figs. 23 through 25). Production from all 220 Delaware sandstone reservoirs in Texas has been 235.8 MMbbl. The 80 largest fields in New Mexico (>100,000 bbl) had produced 102.2 MMbbl through December 1998 (tables 3, 5, 7; figs. 23 through 25). Production from all 159 Delaware sandstone reservoirs in New Mexico has been 104.2 MMbbl.

Greatest production in Texas is from reservoirs in the Bell Canyon Formation (fig. 26a); the 63 largest Bell Canyon reservoirs (>100,000 bbl) in Texas (table 4; fig. 23) have produced 178 MMbbl of oil. The 36 largest Cherry Canyon reservoirs (table 6; fig. 24) have produced 48.3 MMbbl, and the 3 largest Brushy Canyon reservoirs (table 8; fig. 25) have produced 0.5 MMbbl. In New Mexico, the Brushy Canyon is the largest producing interval of the Delaware Mountain Group (fig. 26b). The 38 largest Brushy Canyon fields (>100,000 bbl) (table 7; fig. 25) had produced 44.8 MMbbl through December 1998. The 16 largest Bell Canyon reservoirs (table 3; fig. 23) have produced 30.7 MMbbl, and the 26 largest Cherry Canyon reservoirs (table 5; fig. 24) have produced 26.7 MMbbl.

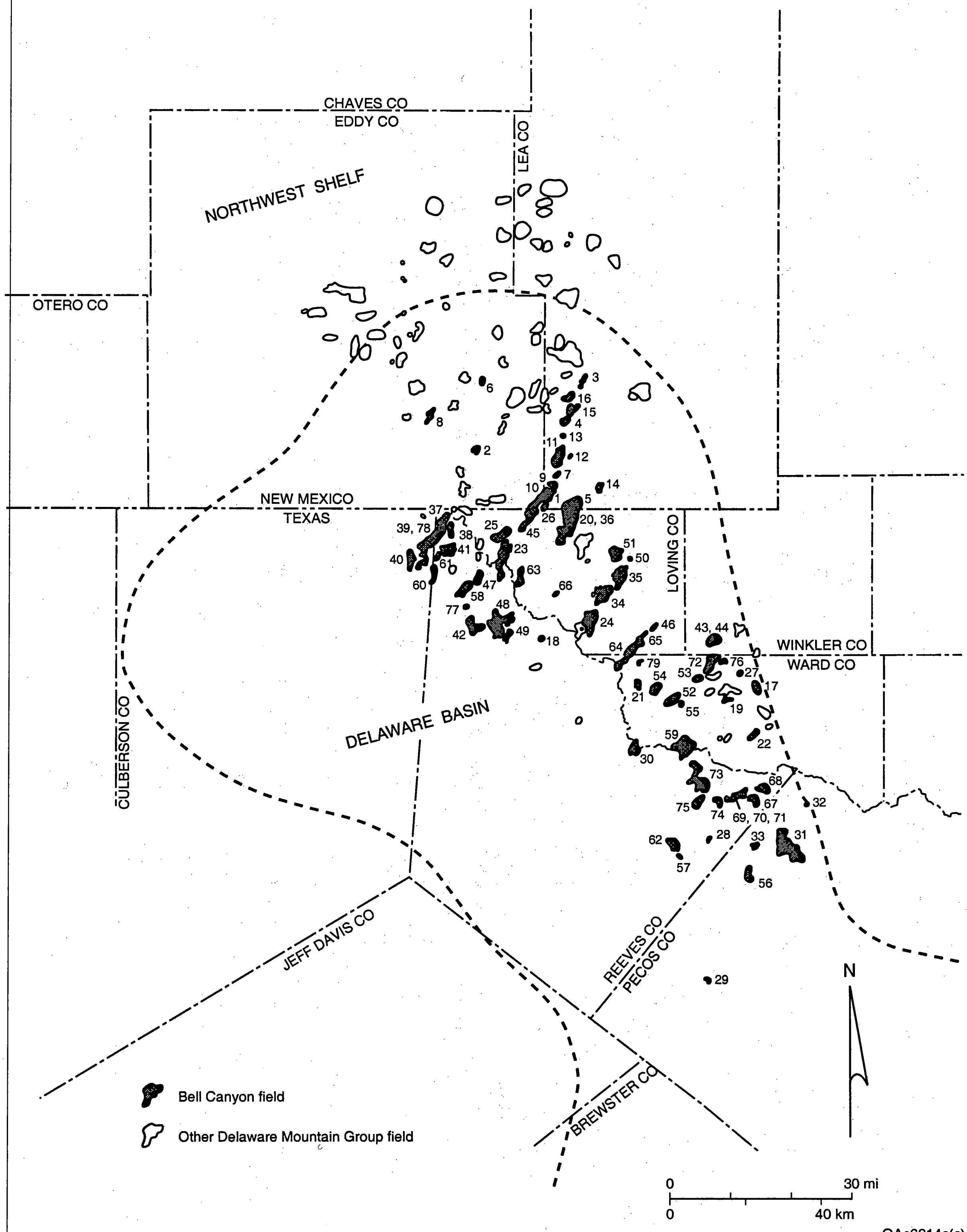

Figure 23. Location of the 79 largest fields (cumulative field production >100,000 bbl) producing from the Bell Canyon Formation in the Delaware Basin, Texas and New Mexico. Fields are identified in tables 3 (New Mexico) and 4 (Texas). Field outlines and locations are approximate and are based on information from Grant and Foster (1989), Kosters and others (1989), Basham (1996), Lewis and others (1996), and the Railroad Commission of Texas (1998).

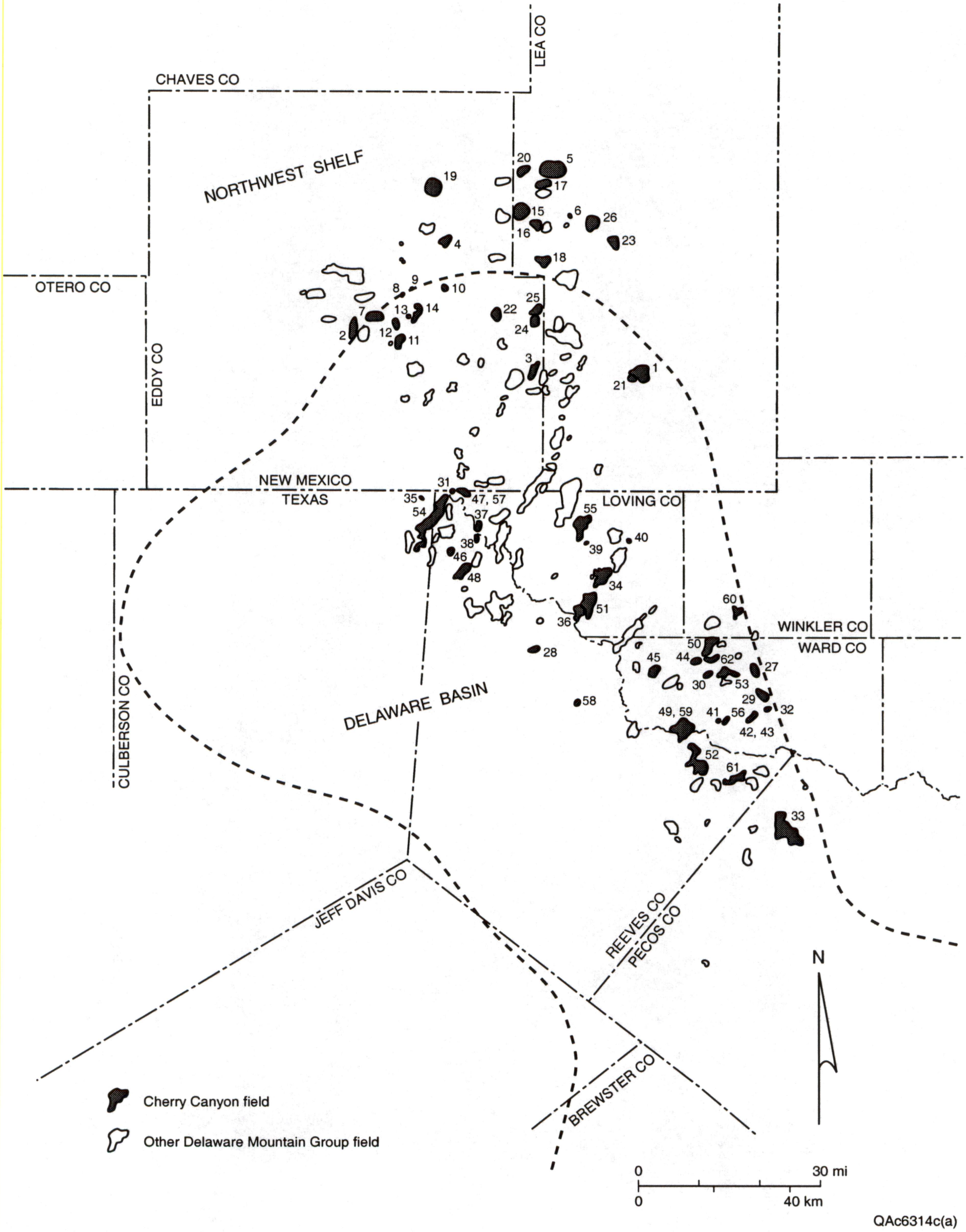

Figure 24. Location of the 62 largest fields (cumulative field production >100,000 bbl) producing from the Cherry Canyon Formation in the Delaware Basin, Texas and New Mexico. Fields are identified in tables 5 (New Mexico) and 6 (Texas). Field outlines and locations are approximate and are based on information from Grant and Foster (1989), Kosters and others (1989), Basham (1996), Lewis and others (1996), and the Railroad Commission of Texas (1998).

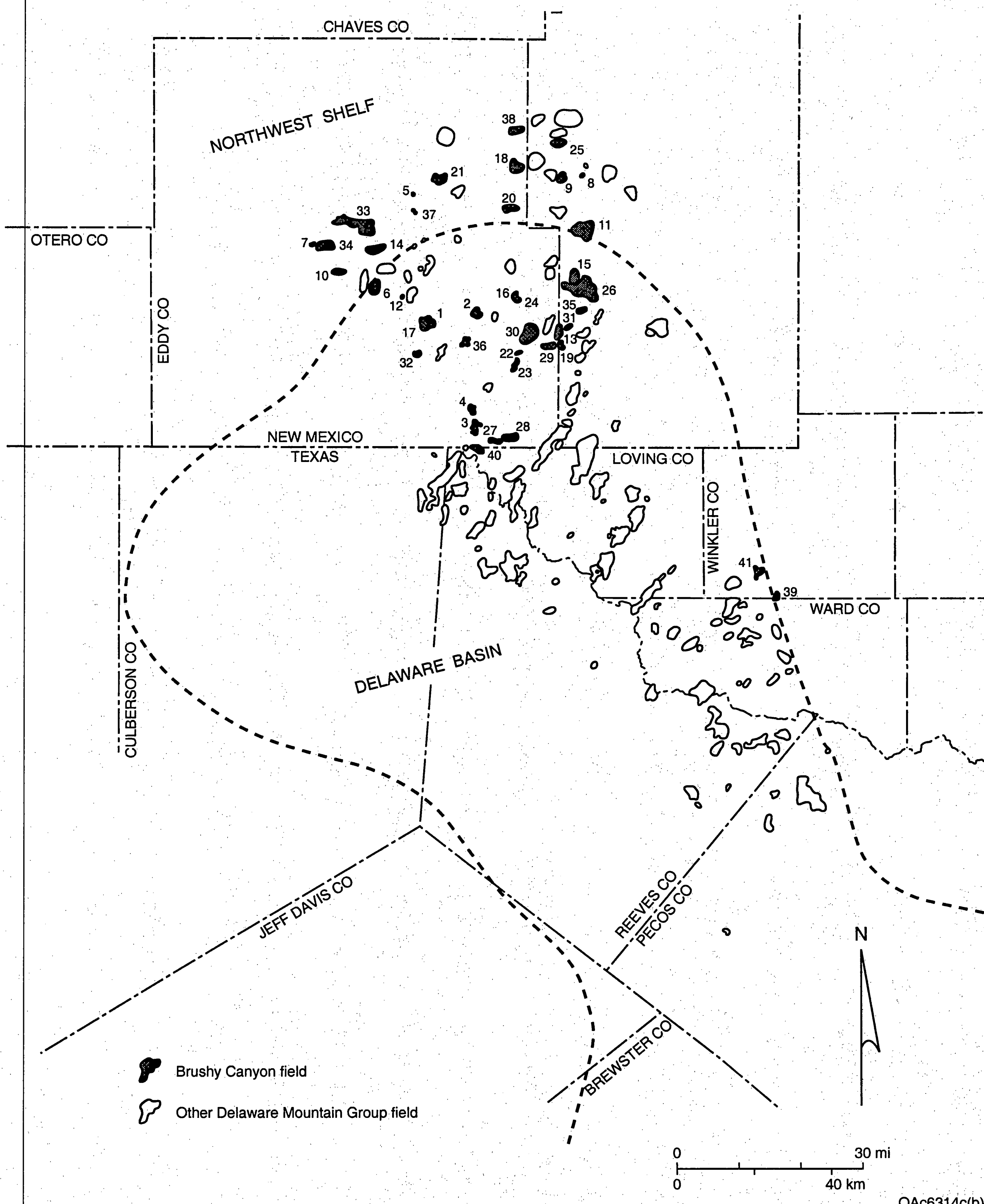

Figure 25. Location of the 41 largest fields (cumulative field production >100,000 bbl) producing from the Brushy Canyon Formation in the Delaware Basin, Texas and New Mexico. Fields are identified in tables 7 (New Mexico) and 8 (Texas). Field outlines and locations are approximate and are based on information from Grant and Foster (1989), Kosters and others (1989), Basham (1996), Lewis and others (1996), and the Railroad Commission of Texas (1998).

Table 3. Cumulative production from oil fields in New Mexico producing from the Bell Canyon Formation. Field numbers refer to figure 23.

Field no.	Field	Producing formation	County	Wells	Cumulative production (bbl)*
1	Battleaxe	Delaware	Lea	4	324,432
2	Corral Canyon	Delaware	Eddy	15	659,990
3	Cruz	Delaware	Lea	20	991,262
4	Double X	Delaware	Lea	32	1,313,206
5	El Mar	Delaware	Lea	62	6,140,725
6	Forty Niner Ridge	Delaware	Lea	3	165,732
7	Jennings	Delaware	Lea	3	176,173
8	Malaga	Delaware	Lea	13	585,154
9	Mason, East	Delaware	Eddy	26	1,362,191
10	Mason, North	Delaware	Lea	59	4,333,116
11	Paduca	Delaware	Eddy-Lea	20	12,927,101
12	Paduca, East	Delaware	Lea	2	110,823
13	Paduca, North	Delaware	Lea	3	191,061
14	Salado Draw	Delaware	Lea	8	758,813
15	Triple X	Delaware	Lea	6	297,313
16	Triste Draw	Delaware	Lea	6	332,211
Total 16					30,669,303

*Only fields having production >100,000 bbl through December 31, 1998, are listed. Data from New Mexico Tech Petroleum Recovery Research Center, GO-TECH data base of New Mexico petroleum data.

Table 4. Cumulative production from oil fields in Texas producing from the Bell Canyon Formation. Field numbers refer to figure 23.

Field no.	Field	Producing formation	County	Depth (ft)	Discovery	Wells	Cumulative production (bbl)*
17	Abraxas	Bell Canyon	Ward	4,740	Oct-96	14	265,344
18	Dixieland	Bell Canyon	Reeves	3,855	Apr-48		350,829
19	Lion	Bell Canyon	Ward	4,965	Oct-44	1	135,702
20	Mason	Bell Canyon	Loving	3,900	1937	5	3,013,160
21	Monroe	Bell Canyon	Ward	4,600	1931	29	4,137,371
22	Pyote, South	Bell Canyon (4950 Sand)	Ward	5,037	Aug-60	2	102,310
23	Tunstill	Bell Canyon	Reeves	3270	Aug-47	123	12,116,607
24	Wheat	Bell Canyon	Loving	4300	1925	157	22,479,476
25	Zuni	Bell Canyon	Loving	3466	Jan-90	28	864,046
26	Battleaxe	Delaware	Loving	4,187	Oct-63	2	167,789
27	Block 17, Southeast	Delaware	Ward	5,003	Feb-56	26	1,645,170
28	Cable	Delaware	Reeves	5,250	Apr-78	2	124,006
29	Chancellor	Delaware Sand	Pecos	5,092	Mar-54	2	328,323
30	Collie	Delaware	Ward	4,725	Nov-81	85	3,242,157
31	Coyanosa	Delaware SD	Pecos	4,793	Dec-59	13	1,280,886
32	Coyanosa, N	Delaware	Pecos	4,809	Oct-66	31	3,212,444
33	Coyanosa, W	Delaware 5200	Pecos	5,386	Jun-62	8	532,612
34	Dimmitt	Delaware	Loving	4,608	May-57	6	220,690
35	Dimmit, Northeast	Delaware SD	Loving	4,350	Jun-82	34	727,686
36	El Mar	Delaware	Loving	4,532	Jan-59	165	18,479,103
37	Ford	Delaware SD.	Reeves	2,642	Apr-56		4,139,470
38	Ford East	Delaware Sand	Reeves	2,730	Sep-63	52	3,235,237
39	Geraldine	Delaware 3400	Culberson	3,454	Apr-82	37	1,580,498
40	Geraldine, W	Delaware 2435	Culberson	2,437	Mar-67	10	386,287
41	Jess Burner	Delaware 3800	Reeves	3,802	Aug-82	175	386,287
42	Ken Regan	Delaware	Reeves	3,350	Jul-54	125	4,170,537
43	Little Joe	Delaware	Winkler	5,034	Jun-65	8	1,689,653
44	Little Joe	Delaware 4990	Winkler	5,002	Dec-66		254,557
45	Mason, N	Delaware Sand	Loving	4,055	Jul-52	58	6,685,477
46	Meridian	Delaware	Loving	4,993	Jun-61	10	817,535
47	Olds	Delaware	Reeves	3,029	Jan-58	29	1,323,395
48	Orla, South	Delaware Sand	Pecos	3,562	Jun-53		1,044,747
49	Orla, Southeast	Delaware	Reeves	3,643	May-59	8	373,204
50	Pinal Dome	Delaware	Loving	5,032	Mar-55	4	189,328
51	Pinal Dome, Central	Delaware	Loving	4,974	May-84	18	353,672
52	Quito	Delaware Sand	Ward	4,934	Apr-53	6	2,443,365
53	Quito, East	Delaware	Ward	5,124	Jun-54	2	151,830
54	Quito, West	Delaware	Ward	4,732	May-55	58	4,864,348
55	Regan-Edwards	Delaware, Upper	Ward	4,757	Jan-57	3	286,892
56	Rojo Caballos	Delaware	Pecos	5,253	Jul-62	16	1,070,413
57	Rojo Caballos, NW	Del.	Pecos	5,246	Apr-82	7	187,207
58	Sabre	Delaware	Reeves	2,968	Jun-58	51	5,797,262
59	Scott	Delaware Gas	Ward	4239		1	5,560

Table 4 (cont.).

Field no.	Field	Producing formation	County	Depth (ft)	Discovery	Wells	Cumulative production (bbl)*
60	Screwbean	Delaware	Culberson	2548	May-58	16	895,721
61	Screwbean, N.E	Delaware	Reeves	2519	Mar-61	35	1,212,743
62	Toro	Delaware	Reeves	5158	Feb-61	11	1,040,066
63	Tunstill, East	Delaware	Loving	3652	Aug-59	33	2,822,502
64	Twofreds	Delaware	Loving	4895	1957	94	14,349,910
65	Twofreds, E.	Delaware	Loving	4940	Apr-67	7	204,052
66	Ver-Jo	Delaware	Loving	4136	Nov-58		140,754
67	Waha	Delaware	Reeves	4800	Sep-60	10	1,461,101
68	Waha, North	Delaware Sand	Reeves	4917	Dec-60	45	6,675,203
69	Waha, West	Delaware	Reeves	5034	Jul-61	25	2,475,265
70	Waha, West	Delaware 5500	Reeves	5508	Jul-63		188,618
71	Waha, West	Delaware 5800	Reeves	5833	Jul-63		187,399
72	War-Wink	Delaware 5085	Winkler	5091	Oct-66	8	200,613
73	Worsham	Delaware Sand	Reeves	4932	Jul-60	33	1,632,039
74	Worsham, South	Delaware Sand	Reeves	5050	Jun-61	7	607,075
75	Worsham, SW	Delaware	Reeves	5135	Jun-63	6	350,038
76	Block 17	Lamar Lime	Ward	5,014	Dec-63	3	288,466
77	Chapman, S	Olds	Reeves	2,931	Nov-65	7	306,050
78	Geraldine	Ford	Reeves	2,557	Jul-57	368	25,823,430
79	W W W	Ramsey	Ward	4875	Nov-84	12	471,463
Total 63							178,035,322

*Only fields having production >100,000 bbl through December 31, 1998, are listed. Data from Railroad Commission of Texas 1998 Oil and Gas Annual Report.

Table 5. Cumulative production from oil fields in New Mexico producing from the Cherry Canyon Formation. Field numbers refer to figure 24.

Field no.	Field	Producing formation	County	Wells	Cumulative production (bbl)*
1	Antelope Ridge	Cherry Canyon	Lea	2	254,593
2	Carlsbad	Cherry Canyon	Eddy	3	305,180
3	Sand Dunes	Cherry Canyon	Lea	10	895,705
4	Big Eddy	Delaware	Eddy	1	106,344
5	Corbin, West	Delaware	Lea	44	2,357,355
6	Crazy Horse	Delaware	Lea	2	116,951
7	Esperanza	Delaware	Eddy	7	1,184,584
8	Fenton	Delaware	Eddy	5	118,183
9	Fenton, Northwest	Delaware	Eddy	20	717,215
10	Golden Lane, South	Delaware	Eddy	10	433,284
11	Herradura Bend	Delaware	Eddy	22	865,558
12	Indian Draw	Delaware	Eddy	22	3,124,878
13	Indian Draw, East	Delaware	Eddy	10	431,508
14	Indian Flats	Delaware	Eddy	12	559,804
15	Lusk	Delaware	Lea	3	236,272
16	Lusk, East	Delaware	Lea	7	429,765
17	Querecho Plains, North	Delaware	Lea	3	179,625
18	Salt Lake	Delaware	Lea	1	290,954
19	Shugart	Delaware	Eddy	6	1,596,122
20	Young, North	Delaware	Lea	8	463,043
21	†Bell Lake, East	Delaware	Lea	3	138,272
22	†Cabin Lake	Delaware	Lea	36	2,510,980
23	†Lea, Northeast	Delaware	Lea	43	2,455,873
24	†Livingston Ridge	Delaware	Eddy	45	4,092,636
25	†Lost Tank	Delaware	Eddy	43	2,225,049
26	†Quail Ridge	Delaware (Abolished)	Lea	16	624,444
Total 26					26,714,177

*Only fields having production >100,000 bbl through December 31, 1998, are listed. Data from New Mexico Tech Petroleum Recovery Research Center, GO-TECH data base of New Mexico petroleum data.

†Some production from Brushy Canyon Formation included.

Table 6. Cumulative production from oil fields in Texas producing from the Cherry Canyon Formation. Field numbers refer to figure 24.

Field no.	Field	Producing formation	County	Depth (ft)	Discovery	Wells	Cumulative production (bbl)*
27	Abraxas	Cherry Canyon	Ward	6,922	Mar-96	39	521,402
28	Aylesworth	Cherry Canyon	Reeves	3,940	Sep-56	4	122,188
29	Block 16	Cherry Canyon	Ward	5,981	Oct-69	2	396,577
30	Block 18	Cherry Canyon	Ward	6,306	Jul-85	12	239,700
31	Brushy Draw	Cherry Canyon	Loving	5,090	Dec-82	9	473,871
32	Caveat Emptor	Cherry Canyon	Ward	6,268	Jul-88	14	255,610
33	Coyanosa	Cherry Canyon	Pecos	5,860	Aug-65	3	157,123
34	Dimmitt	Cherry Canyon	Loving	6,226	Aug-80	162	8,089,834
35	Ford West	4100 (Cherry Canyon)	Culberson	4,143	Apr-63	68	2,942,954
36	Hubbard	Cherry Canyon	Loving	5,286	Jun-82	29	1,054,577
37	Jeanita	Cherry Canyon	Loving	4,562	Dec-63	20	537,853
38	Matthews	Lower Cherry Caynon	Reeves	4,444	May-84	24	880,265
39	Myrtle -B-	Cherry Canyon	Loving	66,446	Oct-84	7	223,767
40	Pinal Dome	Cherry Canyon	Loving	6,485	Apr-84	45	1,293,441
41	Pitzer, N	Cherry Canyon	Ward	6,400	Oct-64	5	194,216
42	Pyote, South	Cherry Canyon (6100 Sand)	Ward	6,113	Mar-60	5	660,265
43	Pyote, South	Cherry Canyon (6450 Sand)	Ward	6,457	Dec-61	10	183,333
44	Quito, East	Cherry Canyon	Ward	6,493	Sep-83	12	325,908
45	Quito, West	Cherry Canyon	Ward	6,182	Apr-80	3	130,274
46	Racue	Cherry Canyon	Reeves	3,798	Dec-64	1	126,893
47	Red Bluff	Cherry Canyon	Loving	4,894	Dec-83	9	275,266
48	Sabre	Cherry Canyon	Reeves	3,870	Oct-76	3	102,192
49	Scott	Cherry Canyon	Reeves	6134	Aug-78	26	928,222
50	War-Wink	Cherry Canyon	Ward	6037	Jun-65	100	2,222,608
51	Wheat	Cherry Canyon	Loving	6610	Jul-73	49	1,938,885
52	Worsham	Cherry Canyon	Reeves	6288	Oct-67	9	146,539
53	Caprito	Delaware Middle	Ward	6,164	Dec-74	70	5,251,172
54	Geraldine	Delaware 4000	Culberson	3,953	Apr-62	1	174,773
55	Grice	Delaware	Loving	4,510	Oct-56	101	10,012,318
56	Pitzer, S	Delaware	Ward	6,390	Aug-64	7	370,098
57	Red Bluff	Delaware,Lower	Loving	5,878	May-83	5	194,125
58	Sand Lake	Delaware	Reeves	4,161	Nov-83		110,032
59	Scott	Delaware	Pecos	6222	Jan-83	100	5,031,098
60	University Blk 21	Delaware SD.	Winkler	7235	Jan-54	3	217,304
61	Waha, W.	Consolidated Delaware	Reeves	6504	Sep-74	29	2,386,907
62	War-Wink, South	Delaware	Ward	6288	Nov-79	1	104,025
Total 36							48,275,615

*Only fields having production >100,000 bbl through December 31, 1998, are listed. Data from Railroad Commission of Texas 1998 Oil and Gas Annual Report.

Table 7. Cumulative production from oil fields in New Mexico producing from the Brushy Canyon Formation. Field numbers refer to figure 25.

Field no.	Field	Producing formation	County	Wells	Cumulative production (bbl)*
1	Loving, East	Brushy Canyon	Eddy	49	1,065,497
2	Nash Draw	Brushy Canyon	Eddy	18	1,020,279
3	Brushy Draw	Delaware	Lea	116	5,728,077
4	Brushy Draw, North	Delaware	Lea	11	108,245
5	Burton, East	Delaware	Lea	6	147,968
6	Carlsbad, South	Delaware	Lea	8	291,192
7	Catclaw Draw	Delaware	Eddy	4	152,744
8	Gem, East	Delaware	Lea	4	107,136
9	Geronimo	Delaware	Lea	9	447,264
10	Happy Valley	Delaware	Eddy	11	531,911
11	Hat Mesa	Delaware	Lea	19	1,383,467
12	Herradura Bend, East	Delaware	Eddy	47	1,147,544
13	Ingle Wells	Delaware	Eddy	80	5,035,125
14	La Huerta	Delaware	Eddy	8	133,839
15	Livingston Ridge, East	Delaware	Lea	33	1,660,608
16	Los Medanos	Delaware	Eddy	36	2,311,855
17	Loving, South	Delaware	Eddy	8	135,619
18	Lusk, West	Delaware	Lea	30	2,250,857
19	Mesa Verde	Delaware	Eddy, Lea	8	576,367
20	Parallel	Delaware	Eddy	3	457,383
21	Parkway	Delaware	Eddy	33	2,473,297
22	Poker Lake, South	Delaware	Eddy	6	207,850
23	Poker Lake, Southwest	Delaware	Eddy	16	632,157
24	Quahada Ridge, Southeast	Delaware	Eddy	6	211,893
25	Querecho Plains	Delaware	Lea	6	148,027
26	Red Tank, West	Delaware	Lea	61	2,937,256
27	Ross Draw	Delaware	Eddy	6	132,191
28	Ross Draw, East	Delaware	Eddy	8	471,037
29	Sand Dunes, South	Delaware	Eddy	11	345,899
30	Sand Dunes, West	Delaware	Eddy	78	4,763,225
31	Triste Draw, West	Delaware	Lea	12	379,575
32	Willow Lake	Delaware	Eddy	11	153,293
33	†Avalon	Delaware	Lea	35	3,395,279
34	†Catclaw Draw, East	Delaware	Eddy	4	926,277
35	†Diamondtail	Delaware	Lea	6	222,175
36	†Cedar Canyon	Delaware	Eddy	5	428,547
37	†Scanlon	Delaware	Eddy	9	170,045
38	†Shugart, East	Delaware	Eddy	17	2,101,204
Total 38					44,792,204

*Only fields having production >100,000 through December 31, 1998, are listed. Data from New Mexico Tech Petroleum Recovery Research Center, GO-TECH data base of New Mexico petroleum data.

†Some production from Cherry Canyon Formation included.

Table 8. Cumulative production from oil fields in Texas producing from the Brushy Canyon Formation. Field numbers refer to figure 25.

Field no.	Field	Producing formation	County	Depth (ft)	Discovery	Wells	Cumulative production (bbl)*
39	Delstrat	Brushy Canyon	Ward	7,675	Aug-58	2	157,970
40	Red Bluff	Brushy Canyon	Loving	6,078	Jun-84	2	163,672
41	University Blk 21	Brushy Canyon	Winkler	7,800	Nov-78	5	151,542
Total 3							473,184

*Only fields having production >100,000 bbl through December 31, 1998, are listed. Data from Railroad Commission of Texas 1998 Oil and Gas Annual Report.

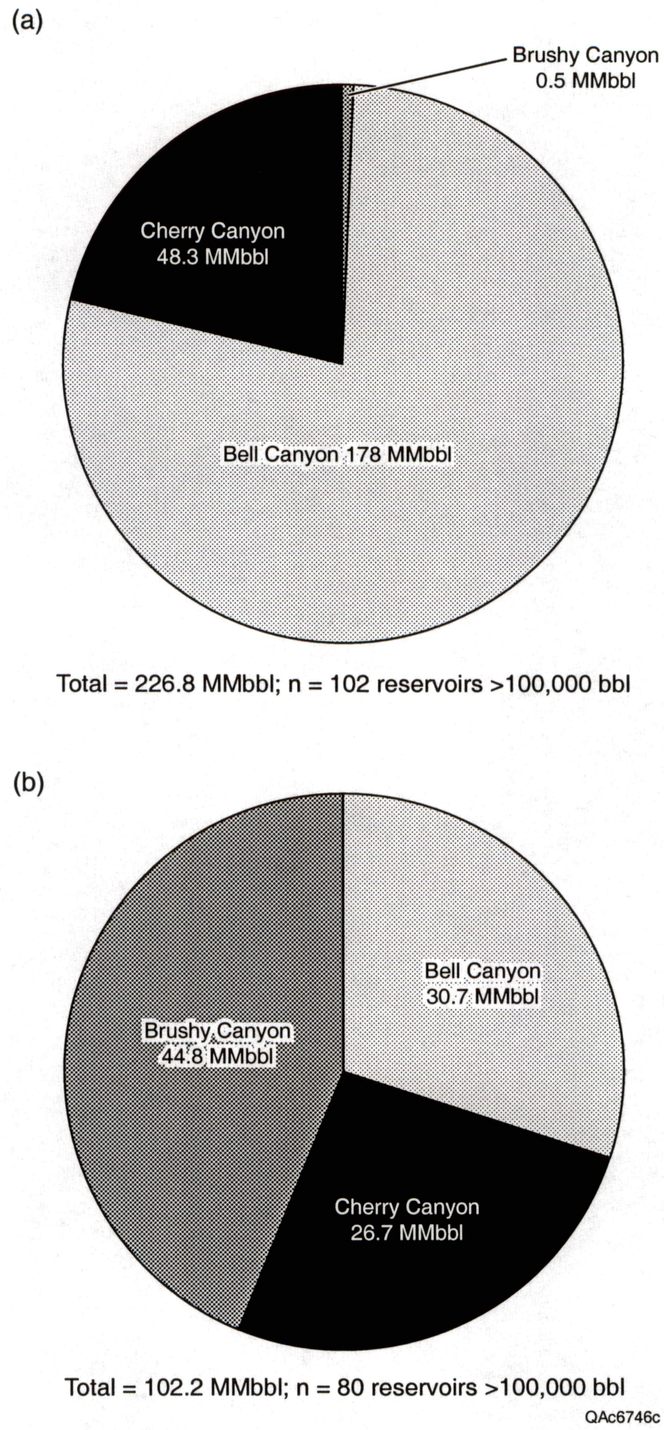

Figure 26. (a) In Texas, the Bell Canyon Formation is the largest oil-producing interval of the Delaware Mountain Group. (b) In New Mexico, the Brushy Canyon Formation is the most prolific interval in the group.

Delaware Mountain Group reservoirs in Texas and New Mexico contained more than 1.8 Bbbl of OOIP (M. Holtz, BEG, personal communication, 1994). Many of the Delaware sandstone fields are nearing the end of their economic primary recovery and are candidates for secondary and tertiary recovery operations. Two mature fields that produce from the Ramsey sandstone, Geraldine Ford and Twofreds (fig. 1), have undergone primary, secondary, and tertiary recovery, thus providing estimates of recovery potential for reservoirs in this play. In the Ford Geraldine unit, areas 1 and 2 (fig. 4) have undergone the most extended, sustained recovery operations, so the analysis of recovery is limited to those two areas.

Under primary recovery operations from 1956 through 1969, areas 1 and 2 of the Ford Geraldine unit produced 16.6 percent of OOIP (table 9). Twofreds field produced 9.1 percent of OOIP during actual primary recovery operations from 1957 through 1963, and 12.9 percent would ultimately have been produced under primary recovery (Kirkpatrick and others, 1985; Flanders and DePauw, 1993).

Secondary waterflooding and tertiary CO_2 flooding increased recovery from Twofreds field to about 28 percent and from the Ford Geraldine unit areas 1 and 2 to about 37 percent (table 9). Most of the improvement in recovery was due to the tertiary CO_2 operations; waterflooding in Delaware sandstone reservoirs has not been very successful. For the Ford Geraldine unit as a whole, waterflooding added an estimated 4.5 percent of OOIP to the total recovery beyond what would have been produced by extended primary production (table 9) (Pittaway and Rosato, 1991). Poor secondary recovery in the Ford Geraldine unit was attributed to high initial water saturation combined with good primary performance (Pittaway and Rosato, 1991). Secondary recovery from Twofreds field was only 4.0 percent of OOIP (table 9) (Kirkpatrick and others, 1985; Flanders and DePauw, 1993). Poor waterflood recovery at Twofreds field was attributed to poor sweep efficiency caused by (1) high mobile water present when the flood started, (2) insufficient filtration of the injected water, and (3) water injection above the formation parting pressure (Flanders and DePauw, 1993).

Table 9. Recovery from the Ramsey sandstone, Ford Geraldine unit and Twofreds field, in percentage of original oil in place.

	Ford Geraldine (Areas 1 and 2)	**Twofreds**
Produced during primary recovery (%)	16.6	9.1
Estimated ultimate recovery under primary production (%)		12.9
Produced during secondary (waterflood) recovery (%)	10.1	7.5
Recovery attributed to waterflood (%)	4.5	4.0
Produced during primary and secondary recovery (%)	26.7	16.6
Produced during tertiary (CO_2 flood) recovery (%) (through 12/31/98)	10.2*	11.6**
Total recovery (through 12/31/98) (%)	36.9	28.2
Original oil in place (MMbbl)	39.2	51

*Through 12/31/95
*Through 12/31/98

In contrast, under tertiary CO_2 flooding, Twofreds field produced almost 12 percent of OOIP (Flanders and DePauw, 1993), and Ford Geraldine unit areas 1 and 2 produced about 10 percent of OOIP (Dutton and others, 1999a) (table 9). Many other mature Delaware sandstone fields that are nearing the end of primary production are potential candidates for CO_2 flooding.

CONCLUSIONS

The research effort this year focused on (1) reservoir characterization of the Ramsey sandstone reservoir in the East Ford unit and (2) evaluation of the CO_2 flood. CO_2 injection in the East Ford unit began in July 1995, and production response was observed in December 1998. Tertiary recovery potential of the East Ford unit was estimated by determining how much oil remained in the unit after primary recovery and where the remaining oil was located. The 1,212-acre East Ford unit contained an estimated 18.4 MMbbl of OOIP, and 15.2 MMbbl remained unproduced after primary recovery. The ROIP in the flooded area, 12.2 MMbbl, represents the target for tertiary recovery. Extended CO_2 floods in Twofreds field and part of the Ford Geraldine unit resulted in production of 10 to 12 percent of OOIP.

The depositional model of the field was refined on the basis of well pressure and production data and reevaluation of outcrop information. Overbank splays, which had been recognized in outcrop, are now interpreted as being the main area of sand storage outside of the channels. Deposits flanking the Ramsey 1 and 2 channels have been reinterpreted as consisting of narrow levees and wider overbank-splay sandstones. Interbedded sandstones and siltstones of the levee deposits apparently restrict flow between channel and splay sandstones. Two overbank-splay sandstones have been interpreted as occurring on the west side of the East Ford unit. Because wells located in splay sandstones have only limited communication with wells in channel sandstones, splay and channel sandstones must contain both injector and producer wells to be produced effectively.

The technology developed during this project for increasing recovery from slope and basin clastic reservoirs is applicable to other Delaware Mountain Group oil fields. Since the 1920's, approximately 379 Delaware Mountain Group reservoirs have been discovered in West Texas and southeast New Mexico in sandstones of the Bell, Cherry, and Brushy Canyon Formations. Those fields have produced more than 340 MMbbl of oil through December 1998, but 1.5 Bbbl remains.

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