E & P Notes

Sooner Unit, Denver Basin, Colorado: Improved Waterflooding in a Fluvial-Estuarine Reservoir (Upper Cretaceous D Sandstone)

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ABSTRACT

This report summarizes data produced as part of a U.S. Department of Energy (DOE) project to evaluate methods for improving waterflood response in the Upper Cretaceous D sandstone of the Denver basin. Historically poor performance of waterflooding in this widespread reservoir has meant total recoveries averaging less than 20% of original oil in place (OOIP), with considerable variation in local sweep efficiency. Detailed reservoir characterization of the D sandstone in the Sooner unit, integrating well-log, core, seismic, and engineering data, resulted in an updated reservoir model that included delineation of multiple reservoir compartments. This model was used as a basis for a field redevelopment plan whose initial stage involved realigning existing injectors/producers and drilling several infill locations to increase sweep efficiency on a compartment-by-compartment basis. Results of implementation included a 100% increase in daily unit production, an increase in proven reserves of 696,000 bbl oil equivalent to more than 10% of OOIP. On the basis of these results, ultimate recovery from the unit, with implementation of selective infill drilling, is projected at 32.6% OOIP. Success of the project suggests that similar programs might yield significant economic benefits in other D sandstone fields.

INTRODUCTION

The Sooner unit, located in northeastern Weld County, Colorado, along the eastern flank of the Denver basin (Figure 1A), is productive from the Cretaceous D sandstone. The unit composes the major part of Sooner field, originally discovered in 1969 and developed predominantly during the 1980s. Oil and gas are produced from fluvial and estuarine sandstone reservoirs, with the major proportion coming from fluvial channel-fill material. The D sandstone reservoir lies between two shale intervals (Huntsman and Graneros shales) and consists of an upper, a middle, and a lower portion (Figure 1B). Average net pay is 17 ft (5 m) at depths of approximately 6300 ft (1909 m). The field does not have a gas cap or free-water contact. A 1440-ac area, including 17 active wells on 40-ac spacing, was unitized in 1989, and waterflood operations were initiated. Estimates of original oil in place (OOIP) at that time averaged 5.6 Mbbl, with ultimate primary recovery projected at about 0.90 Mbbl (16.1%), of which 0.77 Mbbl had been actually produced. Moderate to excellent reservoir quality and the lack of any water production suggested favorable conditions for good waterflood response. However, based on the history of waterflood performance in nearby D sandstone fields, incremental recovery from the Sooner unit was estimated at no more than 2–3%, or 168,000 bbl. By the end of 1992, with 11 production wells, 4 water injection wells, and 2 gas recycling wells, cumulative oil production was 1.09 Mbbl, and the average daily rate

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M = million, G = billion.

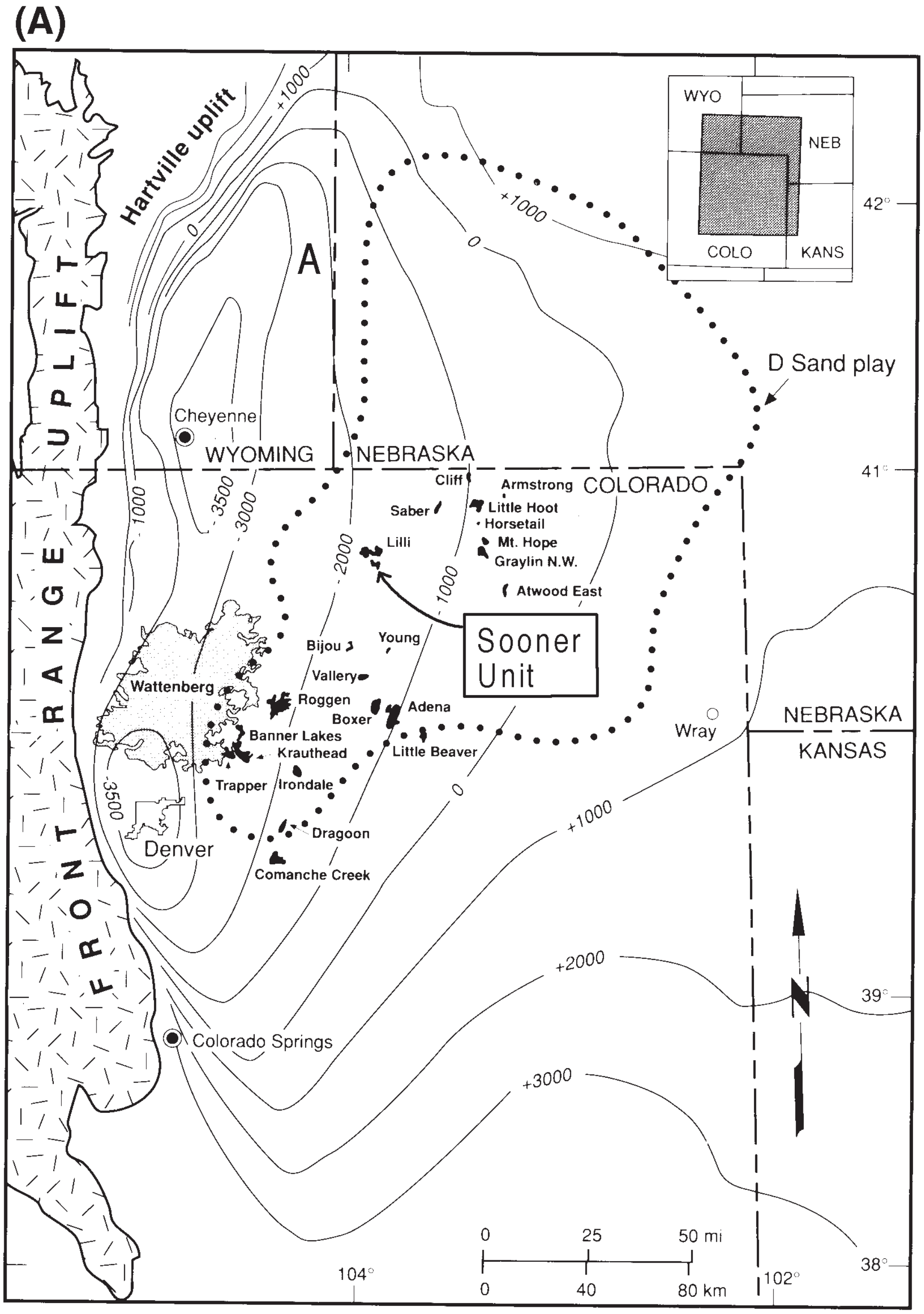
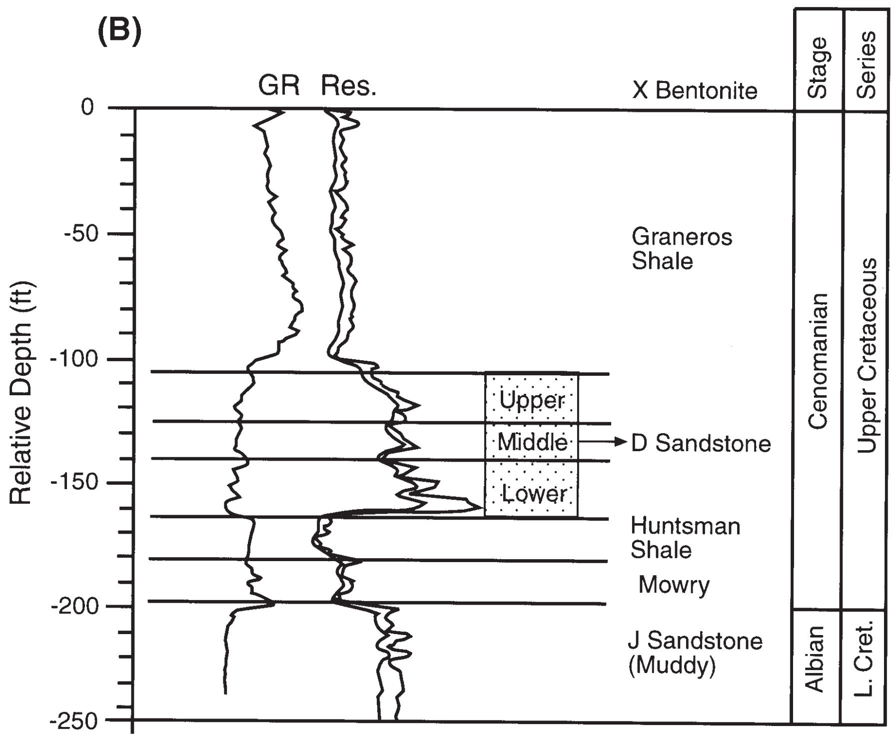


Figure 1—Denver basin, showing (A) outline of the D sandstone fairway trend and location of the Sooner unit, and (B) regional stratigraphic units of the uppermost Lower Cretaceous and overlying Upper Cretaceous. Modified from Hemborg, 1993.

from the total unit was 332 bbl, with 12–15% annual decline. Well test data indicated poor sweep efficiency and early breakthrough.

During 1992–1996, the Sooner unit was the subject of a U.S. Department of Energy, National Petroleum Technology Office, class 1 (fluvial-deltaic deposits) study that sought to identify and, if possible, remedy those factors contributing toward poor waterflood response in the D sandstone. A combination of well-log, core, three-dimensional (3-D) seismic, and engineering analyses yielded an improved reservoir model that suggested realignment of waterflood design, plus the strategic drilling of additional infill wells. Such realignment was based, in part, on the identification of depositional heterogeneity resulting in reservoir



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compartments that constrained fluid flow in various parts of the unit and led to inefficient recovery under existing patterns of injection and production.

These findings were used to design an initial realignment phase that involved converting four wells from production to injection and vice versa, drilling two new production and one new injection well, and cessation of gas recycling. Success of this phase of the project was used to help confirm a total of five additional high-priority infill locations. Initial results of the project, including the two drilled producers, included: (1) a 100% increase in daily unit production; (2) an increase in total developed reserves of 0.696 Mbbl; (3) an increase in estimated OOIP to 6.9 Mbbl; and (4) a projected total recovery, on the basis of full development, to 2.25 Mbbl, or 32.6% of OOIP. Such results suggest that similar projects might be effective in other fields with D sandstone production. In particular, the Roggen producing complex, with total recoveries (primary and secondary) as low as 8.7% from the D sandstone and OOIP estimated at 8–10 Mbbl, would appear an excellent candidate for this type of reevaluation, based on analysis of reservoir heterogeneity.

The following report presents a summary of information gained from the Sooner unit study. It draws mainly upon data recently presented in Sippel (1993, 1996), as well as previous studies of D sandstone geology, such as those by Hemborg (1993), Sonnenberg (1982, 1987), Allison (1982), and Mossel (1978). The aim is to offer a case study of updated reservoir characterization and resulting improved reserves identification in a mature play where enhanced recovery has had limited success.

SETTING

The Sooner unit lies along the gently dipping eastern flank of the Denver basin, a highly asymmetric structural low whose present form is genetically related to Laramide (Late Cretaceous–early Tertiary) uplift of the Front Range foreland basement block (Figure 1A). During the Cretaceous, the basin formed part of the Western Interior Seaway, acting as a local depocenter for sediments shed mainly from the west.

Along with other fields in its immediate vicinity, the Sooner unit is part of a major D sandstone productive trend stretching from Elbert and Adams counties, Colorado, in the southwest to Morrill and Box Butte counties, Nebraska, on the northeast (Figure 1A). Much of this 150-mi (240-km) trend in Colorado follows the crest of a broad, low-relief basement uplift known as the

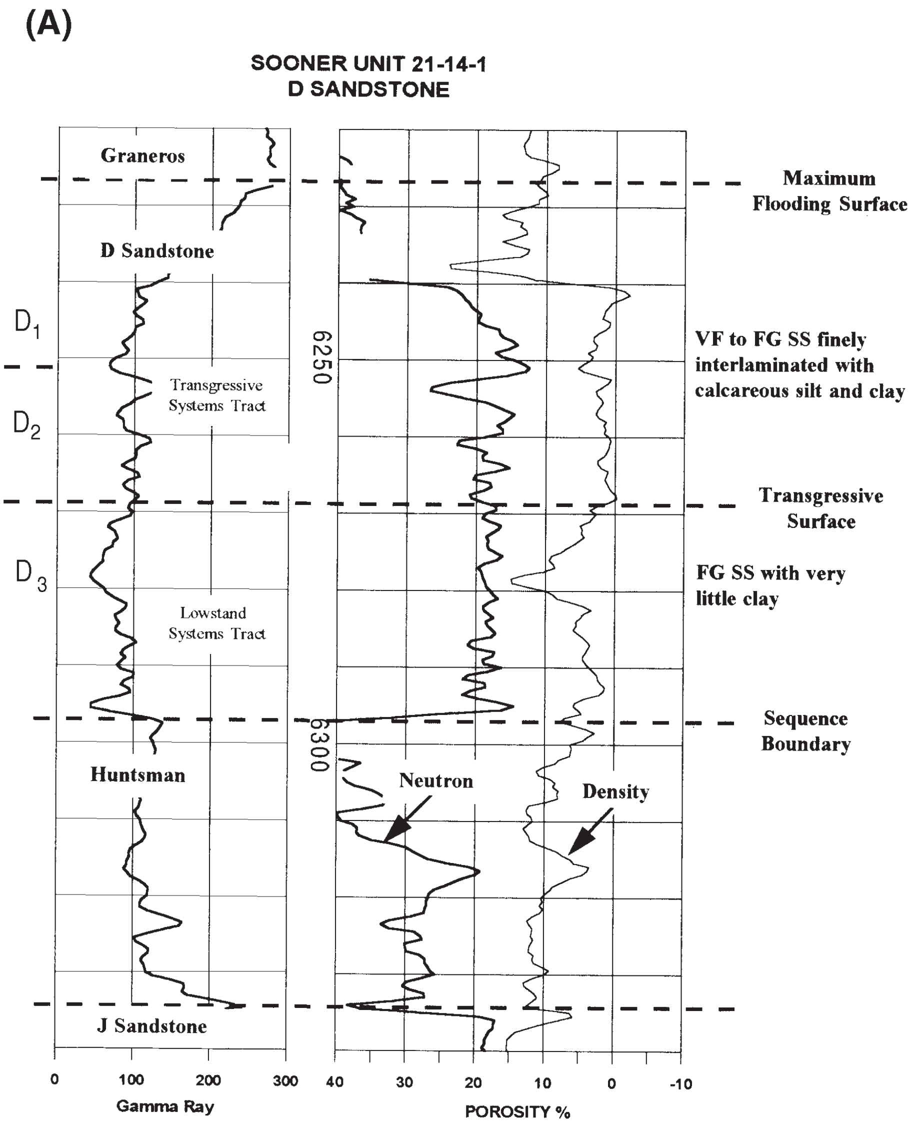
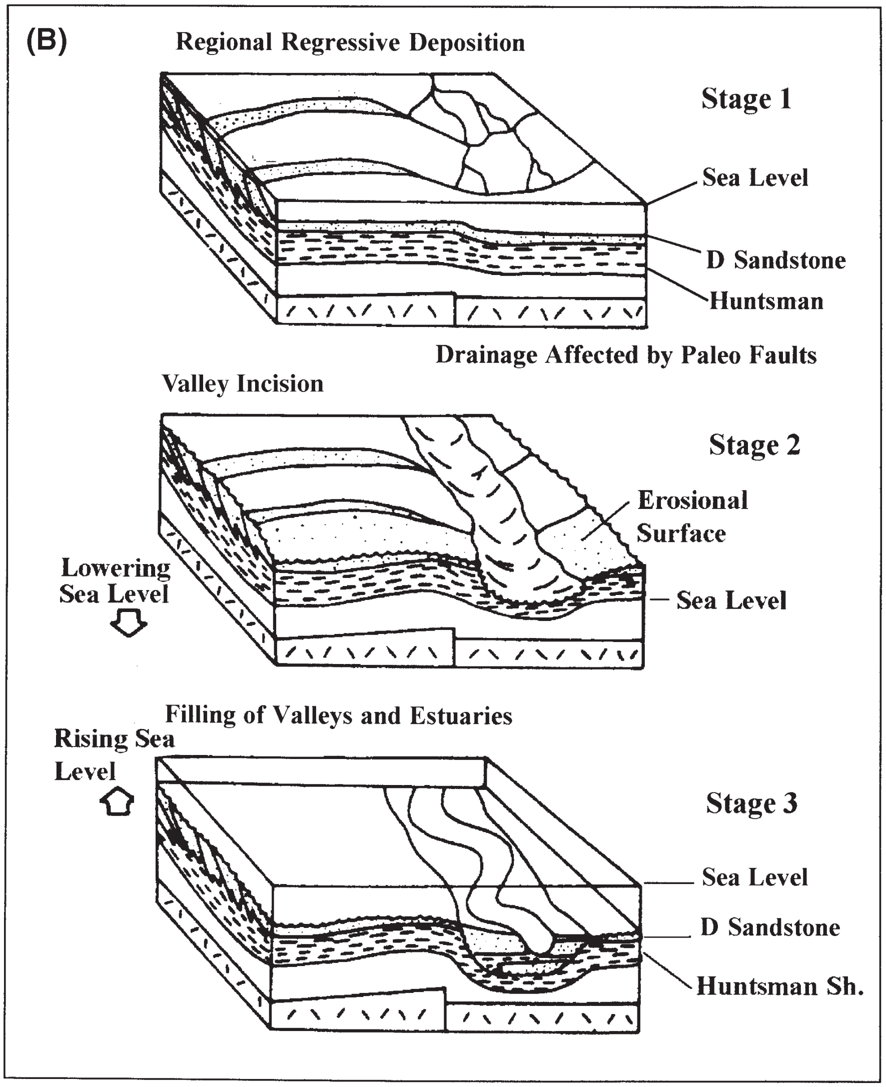


Figure 2—(A) Type log and (B) depositional model, Upper Cretaceous D sandstone interval, Sooner unit. Modified from Sippel, 1996; Sonnenberg, 1987.

Wattenberg high (Weimer, 1984). The Wattenberg high, in turn, is part of a series of northeast-southwest-oriented, fault-bounded uplifts that together comprise the Transcontinental arch, a regional basement feature whose influence on Late Cretaceous deposition has been recognized for some time (Weimer, 1980). In southern and eastern Weld County, the Wattenberg high, composing the southern part of the arch, is evident on regional seismic lines, in patterns of isopach thinning, and in the development of unconformities, particularly at the base of the Niobrara Formation (Weimer, 1984). Tectonism was apparently most active during the Late Turonian (Merewether and Cobban, 1986), but subtle movements took place intermittently throughout the Late Cretaceous, as inferred from local patterns of faulting. Some of this faulting, particularly along the northeastern flank of the Denver basin, may be related to basement-controlled salt solution within the Permian section (Lyons formation).

In the vicinity of the Sooner unit (T8N, R58W), faulting is interpreted to have a north-northwest strike and to have exerted control over channel incision during D sandstone deposition. This type of relationship was earlier proposed by Sonnenberg (1987) for the Zenith field D sandstone reservoir, where paleovalley trends were correlated with the downthrown sides of basement faults (Figure 2). The model shows listric faulting at the level of the Niobrara Chalk above identified basement structures, with no obvious faulting through the D sandstone. A similar model is proposed for



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the Sooner unit and suggests that the Niobrara may have acted basinwide as a more brittle unit within a shale-dominated section. High-angle faults are interpreted at the level of the D sandstone in the Sooner unit, with displacements of no more than 20 ft (6 m) or less. These faults are interpreted on the basis of log and production data for wells with 40 ac spacing. Such structures cannot be resolved either with 2-D (two-dimensional) or 3-D seismic data; thus, their identification and mapping are considered tentative.

REGIONAL CHARACTER OF D SANDSTONE FAIRWAY

The D sandstone fairway is restricted to parts of northeastern Colorado and southwestern Nebraska (Figure 1A), where sufficient sandstone thicknesses exist. This occurrence corresponds broadly with the Transcontinental arch, and it has been proposed that gentle tectonism associated with this feature enhanced development of marginal marine and fluvial environments in an otherwise shale-dominated basinal setting (Sonnenberg, 1987).

Trapping within the D sandstone fairway involves a local structural component in the western part of the basin, close to the Front Range uplift, but is stratigraphic in areas to the east. Lateral pinch-out of productive sandstones occurs into clay-rich sandstone or siltstone units. Local patterns in reservoir quality are highly complex, due to the close juxtaposition of marine, marginal marine, and nonmarine facies types. Nonreservoir lithologies or overlying shales of the Graneros interval provide the top seal. Gross thickness of the D sandstone interval ranges

Table 1. Reservoir Rock and Fluid Data, Sooner Unit*

Average Depth	6300 ft
Maximum Gross	55 ft
Average Net	17 ft
Permeability to Air	21 md
Dykstra-Parsons Coefficient	0.74
Oil Gravity	41° API
Oil Viscosity	0.36 cp
Mobility Ratio	0.30

*Data courtesy Mark Sippel Engineering, Inc.

up to 100 ft (33 m), but is more commonly 20–60 ft (6–18 m) (Hemborg, 1993). Average reservoir characteristics include 17 ft (5.2 m) of net pay, with porosities of 5–20% and permeabilities of 10–400 md. Wells in many fields have been subjected to artificial fracturing, which is intended to overcome formation damage caused by drilling, to enhance productivity from relatively low-permeability reservoirs, and to exploit any natural fractures that might exist. The main reservoir facies include valley-fill and river-mouth or estuarine bar sandstones. These sandstones display considerable lateral heterogeneity in terms of lithology and reservoir quality (Sonnenberg, 1987). Source rocks include the underlying Huntsman and overlying Graneros shales (Figure 1B), both of which have measured total organic content values of 1 to 3% (Weimer, 1994).

As of 1996, cumulative production from the D sandstone included more than 170 Mbbl oil and 445 Gcf gas from nearly 380 individual reservoirs. Gravity of the produced oil generally ranges from 36–45° API, but condensate of up to 60° API is locally produced (at Sooner unit, gravity is 41° API: Table 1). Reservoirs exhibit gas-cap expansion or gas solution drive. Little or no water is produced from D sandstone reservoirs, even at relatively advanced stages of depletion, suggesting that reservoirs are at or near irreducible water saturation.

Discovery in the D sandstone began as early as 1930, with subsequent exploration and development occurring in several major pulses during the 1950s, 1960s, and 1980s. One of the largest and most productive pools to date, Lilli field, with 4600 ac and more than 55 wells, was discovered as late as 1987. Lilli field lies immediately north of the Sooner unit and displays no evidence of paleovalley incision. Instead, the field produces from subtidal marine bar facies that developed downdip from, and slightly later than (i.e., at a more advanced stage of transgression), the productive valley-fill and estuarine facies at Sooner. Reservoir sandstones at Lilli field are thinner (average 8 ft; 2.4 m) but more continuous than those at the Sooner unit.

D sandstone reservoirs are notorious for poor response under waterflooding. Waterflooding of these reservoirs began in the 1960s, and by 1974, a total of 37 projects were in operation. As shown by the representative fields in Table 2 (all located in the general vicinity of the Sooner unit), primary recovery from the D sandstone averages 15.9%, with an average incremental of only 1.8% under waterflood. Estimated total recoveries rarely exceed 22% OOIP.

Poor performance during waterflooding is interpreted to be a result of several factors: (1) complex reservoir compartmentalization; (2) preferential directions of fluid flow, related to original depositional heterogeneity; and (3) rapid

Table 2. Recovery Data for Fields in Vicinity of Sooner Unit*

Field Name	Township, Range	Area (acres)	OOIP (Mbbl)	Primary EUR Mbbl/ % OOIP	Waterflood Incremental/% OOIP	Recovery Factor Total (%)
Bijou	T4-5N, R59-60W	1180	7410	1400/18.9	170/2.2	21.1
Bijou, West	T4N, R60W	1320	7540	1198/15.9	13/0.2	16.1
Buckingham	T8N, R58W	480	2740	389/14.2	0	14.2
Greasewood	T6N, R61W	240	1235	248/20.0	19/1.5	21.5
Jackpot	T6-7N, R59W	1440	5515	1381/25.0	381/6.9	31.9
Masters	T5N, R60W	360	4070	335/08.2	19/0.5	8.7
Orchard, East	T4N, R60W	360	1237	301/24.3	7/0.6	24.9
Orchard, West	T4N, R60W	200	766	132/17.2	0	17.2
Roggen, NW	T2N, R63W	200	1462	204/14.0	37/2.5	16.5
Roggen, SE	T2N, R63W	1050	6267	496/07.9	56/0.9	8.8
Total		6830	38,242	6084/15.9	702/1.8	17.5

*Data from Sippel, 1996.

lateral facies changes. An additional factor, unexamined at present, may involve completion practices.

STRATIGRAPHY, LITHOLOGY, AND DEPOSITIONAL MODELS

A type log for the Sooner unit and a generalized depositional model, taken from Sonnenberg (1987), are shown in Figure 2A and B, respectively. The D sandstone interval exists between two regional transgressive shales, the Huntsman and Graneros. The boundary between Upper and the Lower Cretaceous deposits is assigned to the top of the J sandstone, a widespread fluvial-deltaic deposit productive in many parts of the Denver basin. The J sandstone is overlain by the black, organic, unburrowed, marine Huntsman shale. The end of Huntsman deposition was marked by rapid regression and establishment of marginal marine environments, in which very fine to fine grained sand, silt, and clay were deposited. Related sandstones of the D interval exhibit numerous marine trace fossils and intense burrowing, and are interpreted as reflective of nearshore deposition in a variety of settings (shoreline, marine bar, delta front). This depositional phase was succeeded by continued regression and development of fluvial-estuarine or shallow bay systems, with valley incision occurring into early-phase deposits and the underlying Huntsman shale. Subsequent eustatic rise in sea level resulted in valley filling, with related deposits exhibiting a fining-upward sequence from point bar/channel sandstones to estuarine/bay-fill material, possibly including sand deposition in tidal or shallow marine bars. Specific age relations remain unresolved between valley fill and surrounding estuarine/bay-fill material. Sonnenberg (1987) postulated that valley-fill deposits postdate marine-influenced sandstones and shales. At Sooner unit, however, estuarine/bay-fill material appears to overlie channel-fill sandstones in a number of locations. Transition is observed between overlying fine-grained estuarine/bay-fill deposits and dark, organic marine Graneros shales.

The type log in Figure 2A includes a sequence stratigraphic interpretation of the D sandstone interval, based on sidewall core and thin section analyses from the Sooner unit 21-14-1 well (Sec. 21, T8N, R58W). This well is located within the central part of the field and shows an upper sandstone part, consisting of two units or sandstone "benches" (D_1 and D_2), and a lower part composed of a single, thicker unit (D_3). Units D_1 and D_2 are typified by very fine grained sandstone, interlaminated with silt and clay and containing abundant evidence of burrowing. Unit D_3 consists of very fine to fine grained, well-sorted, relatively clean sandstones, showing tabular cross-bedding, ripple cross-lamination, rip-up clasts, and flaser bedding. D_3 is interpreted as lowstand systems tract valley fill, floored by an erosional sequence boundary (base of incised channel) and capped by a transgressive surface corresponding to a clay-rich layer marked by higher gamma-ray values and zero porosity (Figure 2A). The overlying transgressive systems tract sandstones, characterized by trace fossils, represent the later stages of valley filling, with increased flooding.

D sandstone deposition is correlated with a Cenomanian regressive event whose effects are widespread within the reconstructed Western Interior Seaway (Weimer, 1984). The three-stage depositional model of Figure 2B, showing succession from shoreline/shallow marine environments to valley incision and aggradation, is a useful approximation for reconstructing events related to the D sandstone interval; however, this model is likely to appear simplified in light of more recent detailed analyses based on abundant core data. Such analyses propose that the interval is a result of small-scale fluvial-deltaic systems developed at the heads of shallow marine bays and estuaries. A large array of subfacies are interpreted for this overall setting, including shoreface, bay-mouth bar, interdistributary bay-fill, delta plain, splay, fluvial channel, rivermouth bar, and distributary channel (Wilson, 1991; Weimer, 1994). Constructing a model based on these interpretations is beyond the scope of the present report, but has apparently been done locally for particular fields (see, for example, Wilson and Thomas, 1985). Such a model, regionalized to D sandstone occurrence, seemed needed to more precisely explain and predict the highly complex patterns of sandstone development and texture observed.

D SANDSTONE RESERVOIRS: SOONER UNIT

D sandstone reservoirs in the Sooner unit can be divided into two intervals, the upper of which includes units D_1 and D_2, the lower including unit D_3 (Figure 2A). Areal and vertical distribution of these three sandstone units are shown on Figure 3A. The upper two benches, corresponding to the upper reservoir interval, occur in elongate sandstone bodies oriented parallel to depositional dip and interpreted as bay-mouth or estuarine-tidal bar deposits. These sandstones range from 2 to 12 ft (0.6–3.6 m) in thickness and from relatively clean quartz arenite to nonreservoir interlaminated

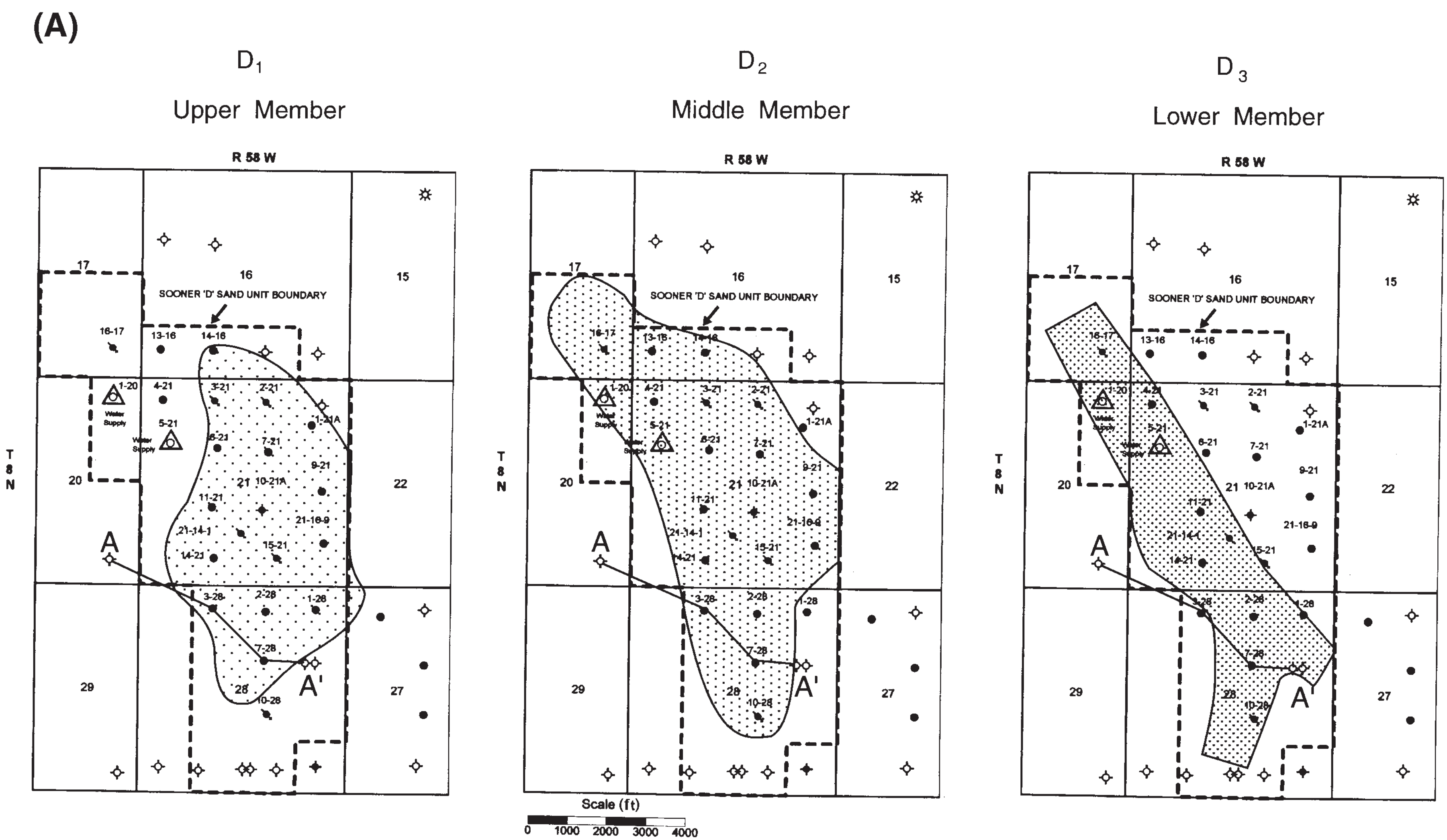
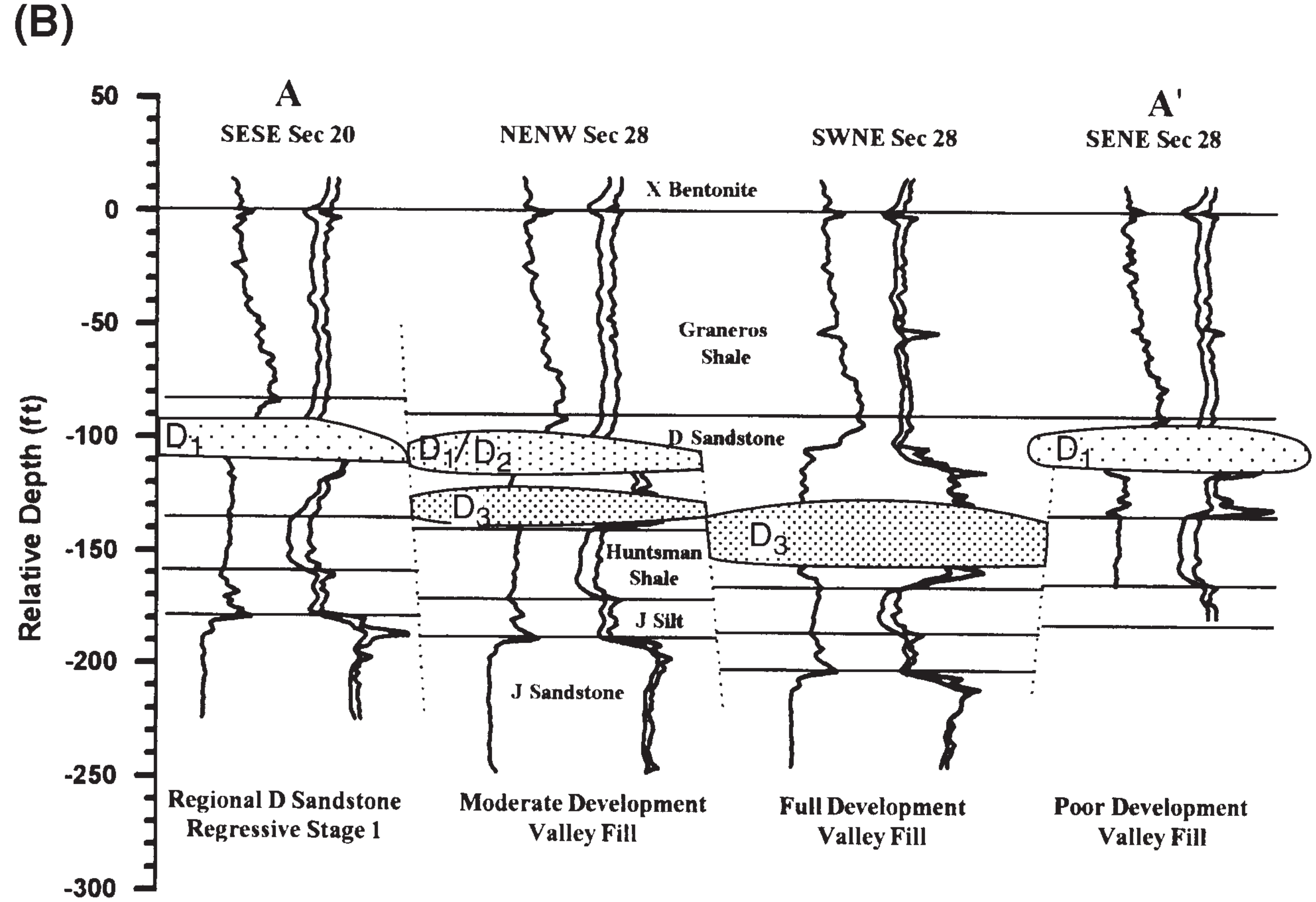


Figure 3—(A) Map distribution of major reservoir sandstone units, Sooner unit. (B) East-west stratigraphic cross section, D sandstone, showing vertical distribution of sandstone units. Datum is a bentonite marker (X bentonite) in the lower Graneros Shale. Data courtesy Mark Sippel Engineering, Inc.



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subarkose and siltstone/shale. As indicated by the field discovery well, the Davidor and Davidor 1 (Sec. 27, T8N, R58W), which produced 32,000 bbl of oil and 1.5 Gcf of gas between 1969 and 1980, cleaner sandstones in this interval can be significant reservoirs in the field. Porosities of up to 24% and permeabilities of 50–150 md characterize the best reservoirs in this interval. Calcite cement, authigenic clays, and quartz overgrowths significantly reduce primary porosity in all but the cleanest examples of this facies. Secondary pore systems are mainly the result of feldspar dissolution. These sandstone reservoirs have proven difficult to map in detail, and their occurrence is still not completely understood.

The underlying D_3 sandstone bench, with a restricted and bifurcated east-west occurrence (Figure 3A), is identified as a lowstand systems tract valley-fill channel facies (Figure 3B). This facies comprises the dominant reservoir in the Sooner unit. Core and thin section study of samples recovered from the Sooner unit 21-14-1 indicate very fine to fine grained, well-sorted sandstones with up to 10% feldspar, low clay content (5% or less), and variable amounts of quartz overgrowth and pore-filling kaolinite. The cleanest, coarsest sandstones occur within a 5–6 ft (1.5 m) interval in the middle part of the unit, and display 15% or more porosity resulting from both preserved primary intergranular and secondary feldspar dissolution pore types. Immediately above and below this interval finer grained sandstones with increased quartz overgrowth cementation and higher clay content occur; porosities are reduced to 3–5% and are mainly the result of feldspar dissolution. The basal and uppermost parts of the D_1 unit display interbedding between very fine grained quartz sandstone and calcareous, clay-rich siltstone containing organic-rich stylolites. The dimensions and orientation of the paleovalley system in the Sooner unit are evident from thinning in the Huntsman shale related to incision of the relevant drainage system (Figure 4). As indicated, the main valley is approximately 0.75 mi (1.2 km) wide and trends north-northwest.

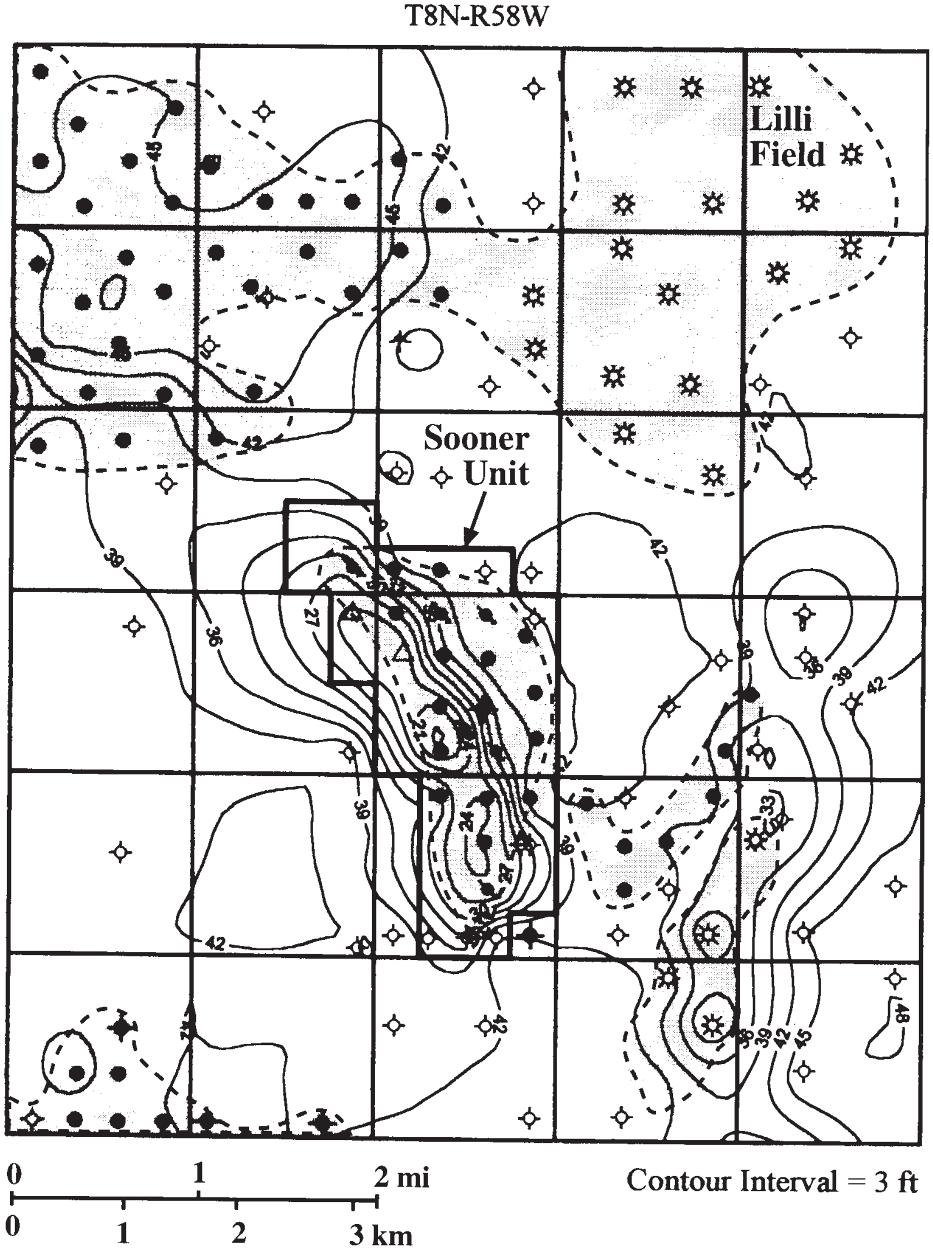


Figure 4—Isopach map, Huntsman shale. Area of pronounced thinning is related to valley incision associated with the D sandstone drainage system. From Sippel, 1996.

Core and well-log information therefore implies a complex distribution of reservoir quality both laterally and vertically in the upper and lower reservoir intervals. Reservoir compartmentalization differs between tidal/bay-mouth bar facies and fluvial channel facies. Bar facies sandstones exist in relatively narrow, lenticular bodies with moderate-to-good continuity and preferential fluid flow parallel to depositional strike. These reservoirs should have limited extent in the dip direction. Fluvial channel sandstone reservoirs are dominantly point-bar deposits that developed in moderate-sinuosity streams. These reservoirs are mainly restricted to deeper parts of the paleovalley system and occur as a series of both separate and overlapping lenticular bodies divided by intervening shale and siltstone channel fill. The precise extent of these bodies is likely to vary considerably. Preferential flow directions should mainly parallel valley strike.

RESERVOIR COMPARTMENTS FROM WELL TEST DATA

Analyses of injection and production data confirm the existence of multiple reservoir compartments in

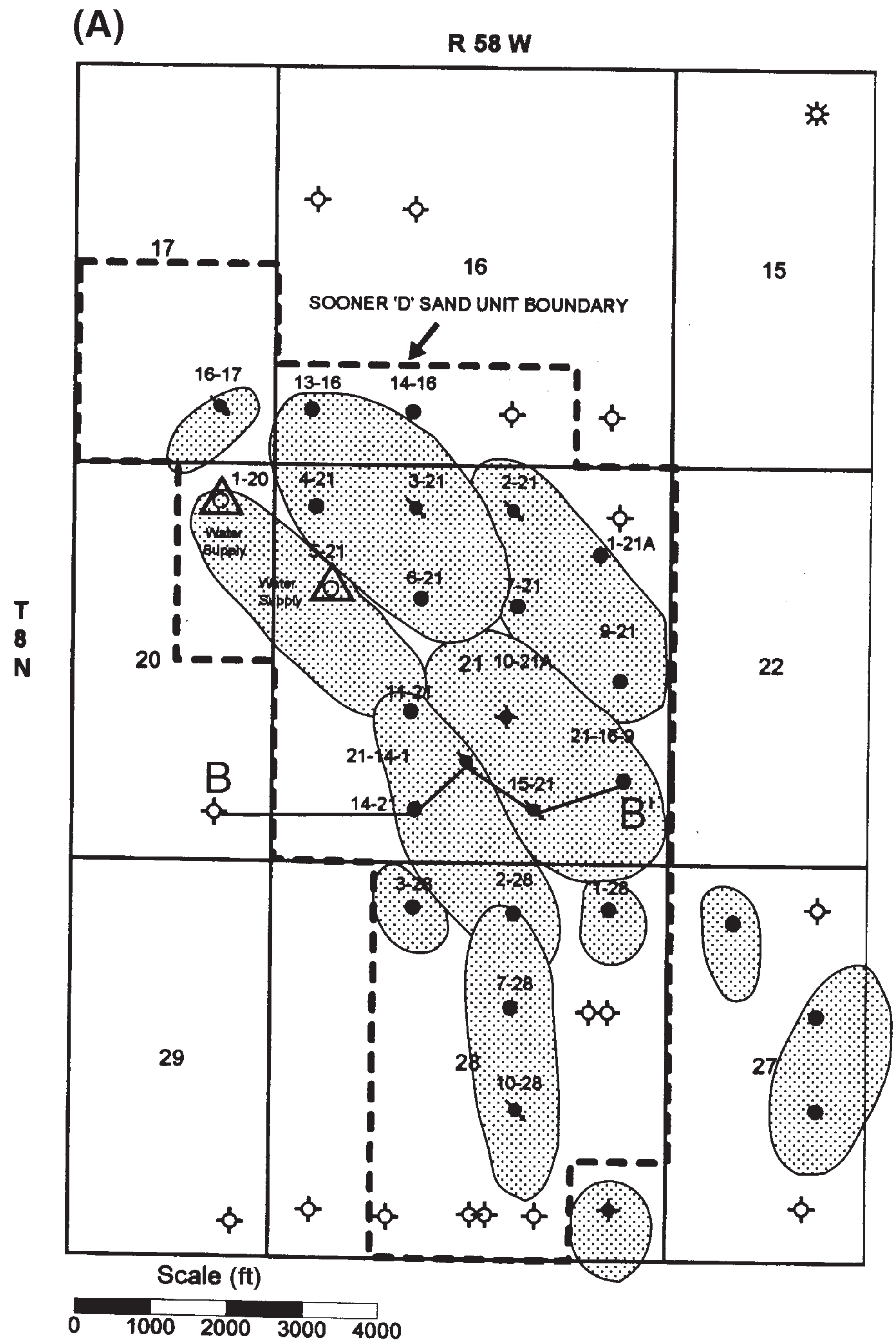
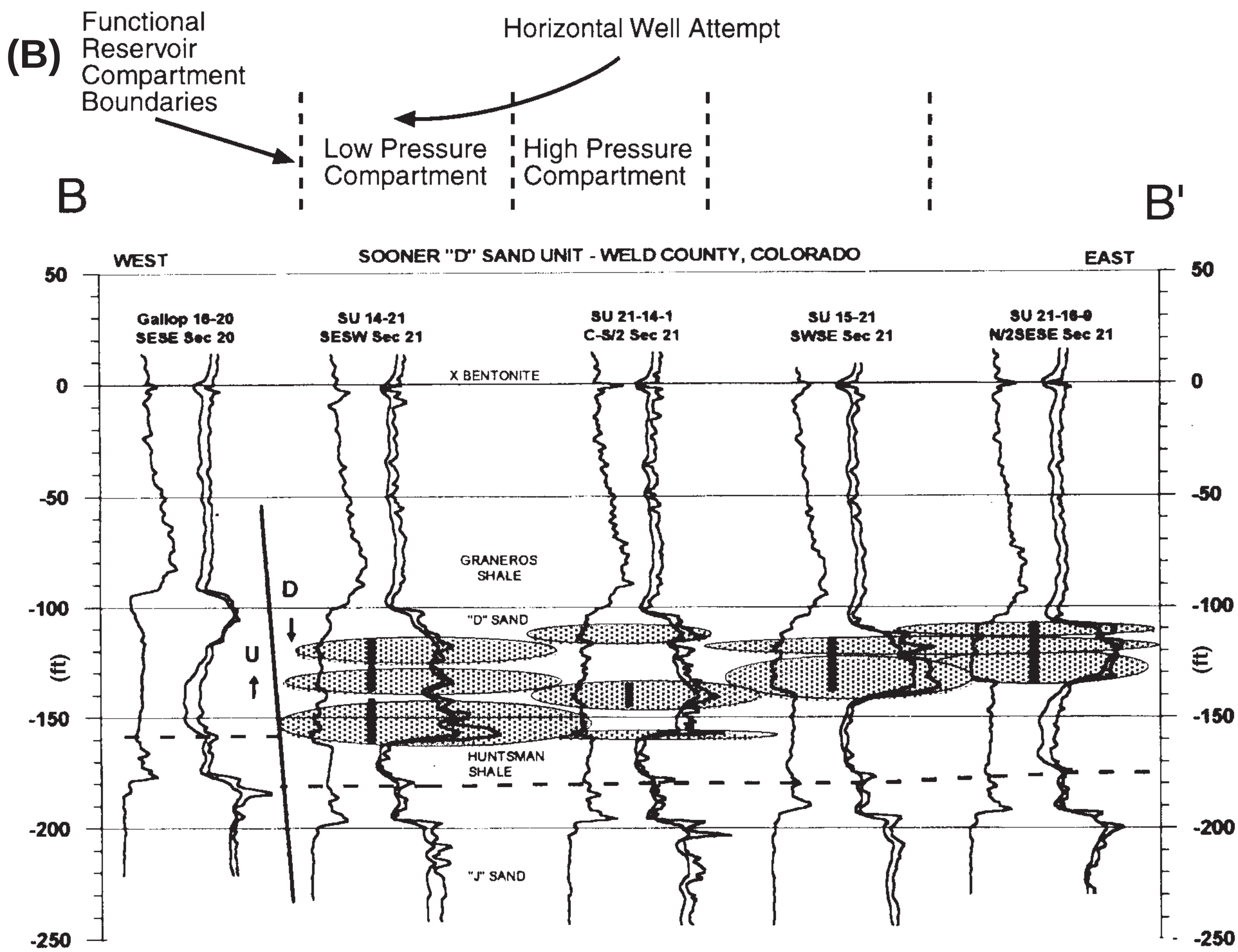


Figure 5—(A) Identified functional reservoir compartments in the D sandstone, Sooner unit. (B) Cross section BB′ through the D sandstone interval, suggesting that reservoir compartments are related to sandstone development. Modified from Sippel, 1996.

the D sandstone. The compartments shown on the map of Figure 5A are considered "functional," in that they are based primarily on pressure transient data and thus group wells on the basis of similar pressures and depletion histories within the overall D sandstone reservoir section. Related data showed considerable differences (200 psi to more than 2000 psi) in static reservoir pressure across the field.



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The cross section of Figure 5B suggests that these compartments are related to specific patterns of sandstone development and faulting. Individual compartments typically have a length-to-width ratio of 2:1 and are oriented parallel to the axis of the main paleovalley system (compare Figure 4), supporting the conclusion that they are geologically constrained. Well test data indicate flow anisotropy is consistent throughout the reservoir section, with preferential fluid movement in the north-south or northwest-southeast direction. Faults within the D sandstone section are interpreted to have similar orientation and may have acted as seals.

One part of the DOE project involved an attempt to drill a horizontal well from the SU 10-21A well, connecting several functional compartments. Mechanical problems, including hole collapse within the unstable Graneros Shale section, prevented successful completion of this attempt. However, drilling encountered a distinct permeability (fault?) barrier 254 ft (77 m) southwest of the vertical well bore, confirming predictions. Selective use of horizontal drilling, possibly employing coiled tubing as a protection against hole collapse, is still considered an excellent, untested approach to enhanced recovery in D sandstone reservoirs.

SEISMIC DATA

In October 1992, a 7.7 mi^2 (19.7 km^2) 3-D seismic survey was performed that included the Sooner unit and immediate surrounding areas. Data from this survey were interpreted with an aim to identifying specific seismic attributes that might be successfully integrated with well-log, core, and

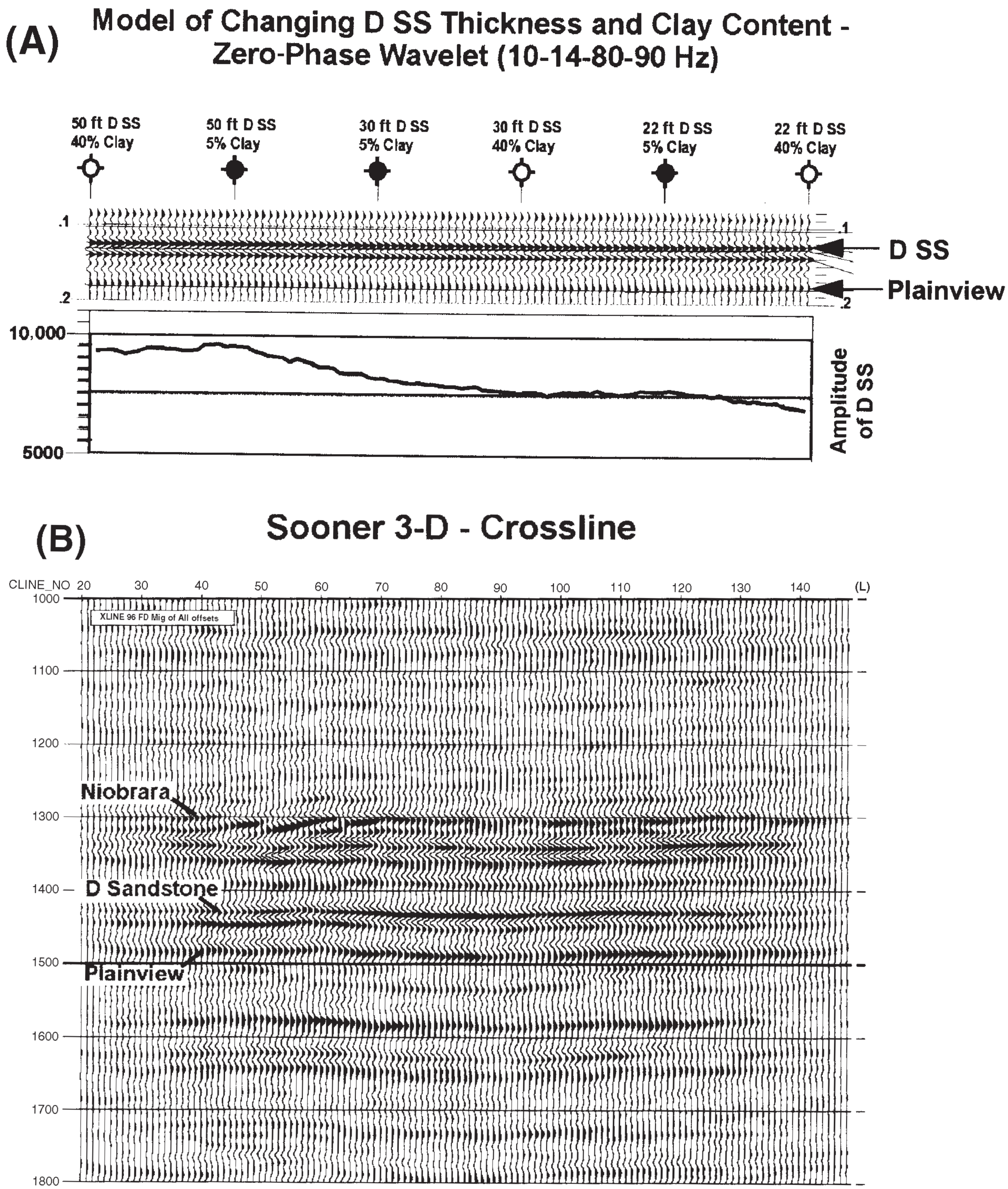


Figure 6—(A) Synthetic seismogram for the Sooner unit, showing amplitude increase associated with thickness and clay content of the D sandstone interval. (B) 3-D seismic section from the Sooner unit survey showing variable amplitude along D sandstone reflection. Modified from Sippel, 1996.

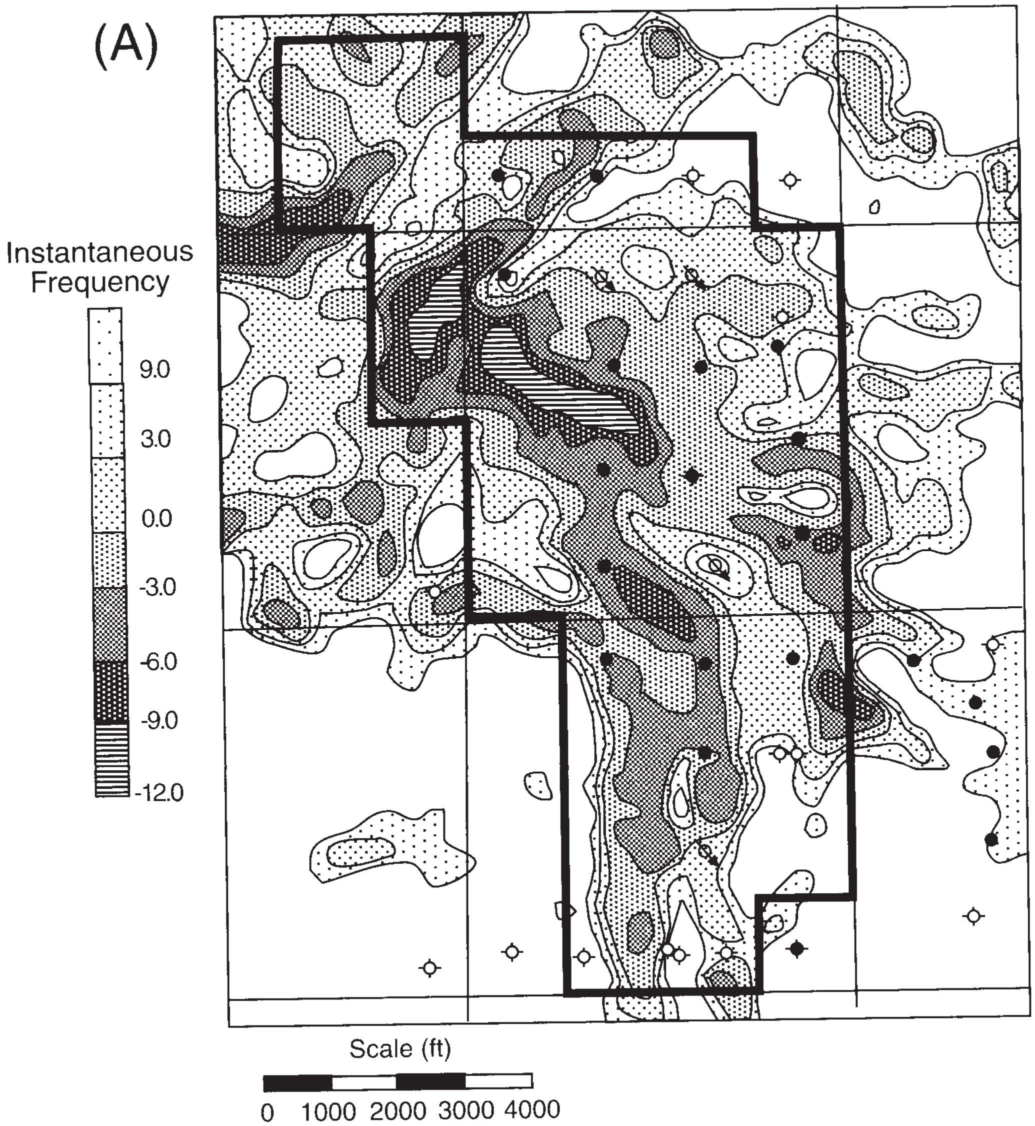
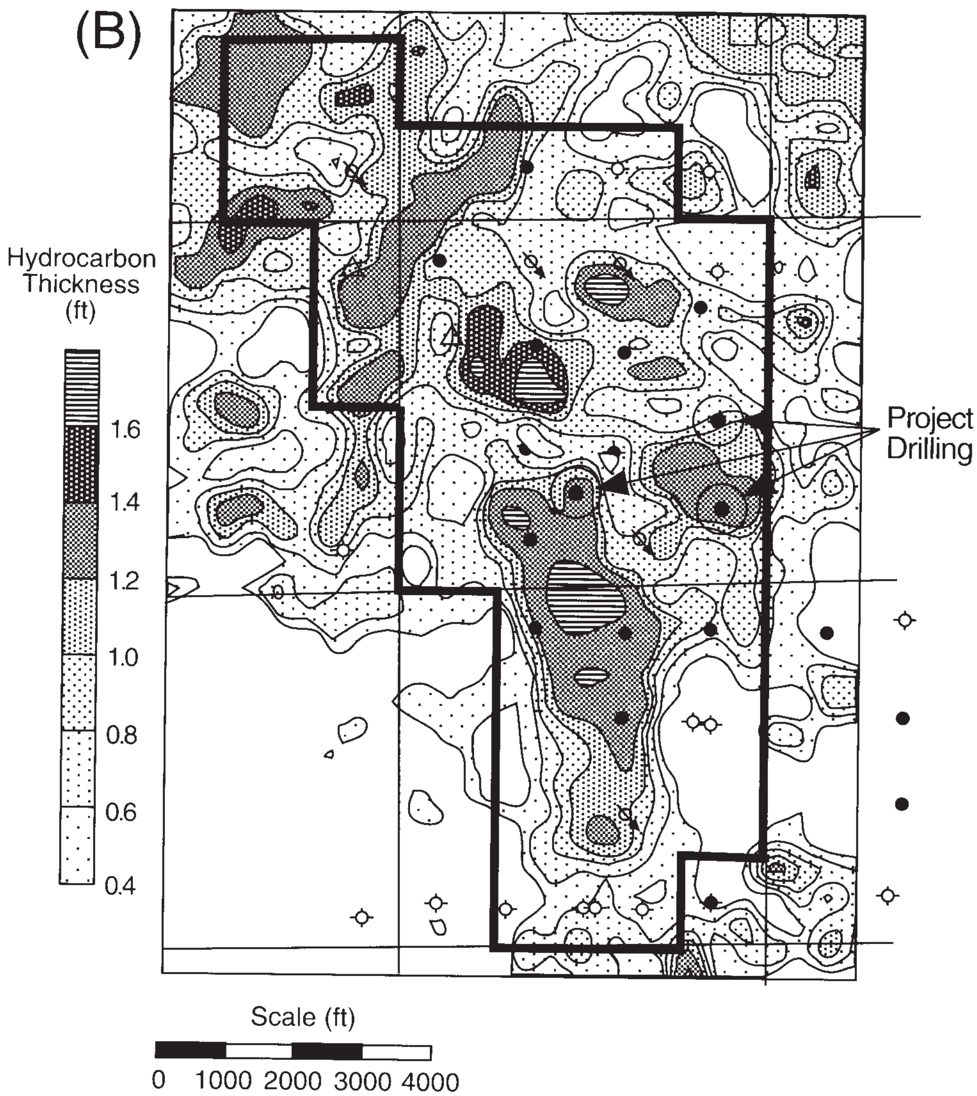


Figure 7—(A) Instantaneous frequency map for the Huntsman Shale time horizon, showing the scale and orientation of the incised D sandstone paleovalley system. Negative frequencies are associated with valley incision. (B) Hydrocarbon-ft map derived from seismic-attribute correlations with well-log data. Data courtesy Mark Sippel Engineering, Inc.

production information to identify low-risk, high-potential infill locations. Good-quality sonic and density logs were found sufficient to construct synthetic seismograms, calibrating seismic data with formation boundaries.

Previous studies had confirmed a distinct positive event associated with the contact between the Graneros Shale and the D sandstone (Plybon, 1983; Plybon and Oldham, 1985; Sonnenberg, 1987). Figure 6A shows a synthetic seismogram for the Sooner unit, indicating an increase in amplitude associated with a thickening D interval, with peak amplitudes related to the presence of cleaner, clay-poor sandstones at the top of the interval. This can be compared with the actual 3-D line of Figure 6B, which exhibits significant amplitude variation in the D sandstone event. Analysis of the full data set revealed that D sandstone amplitude and isochron maps provided acceptable delineation of the valley-fill system, but were unable to resolve areas of good reservoir development. This is because moderate to good reservoir sandstones, including valley-fill facies, do not always correlate with D sandstone gross thickness maximums.

Sandstone architecture within the D interval could be identified only at frequencies of 125 Hz or higher. Acquisition of such data was prohibitively expensive within the financial limits set for the project Instead, a range of seismic attributes was investigated and found to be of relative utility. Two of the resulting maps are given in Figure 7. Instantaneous frequency data for the Huntsman shale (Figure 7A) nicely reveal the scale, orientation, and complexity of the paleovalley system in the Sooner unit at a level of detail previously unavailable through well data



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alone. Comparison of these data with a map of hydrocarbon pore-ft distribution, based on integrated seismic-attribute and well-log information, suggests a fairly close correlation, with some exceptions. Such data appear to confirm the conclusion from geologic study that reservoir-quality sandstones (both valley-fill and overlying estuarine/bay-fill facies) are largely confined to within the limits of the paleovalley system.

FIELD REDEVELOPMENT: PLAN AND RESULTS

On the basis of the D sandstone reservoir characterization study, it was determined that maximum recovery of remaining moveable oil at the Sooner unit, within the limits of economic efficiency, could be achieved by injection by reservoir compartment, using unconventional well-spot patterns. To test this approach, a combination of infill drilling and realignment of selected producers and injectors was implemented. Realignment of existing injection/production patterns consisted of converting the two gas-recycling wells to production status (recycling was observed to have no significant impact on reservoir performance) and changing two producing wells (SU 1-20 and 5-21) to water injectors. In addition, four other wells with marginal production were shut in. Finally, three additional wells were drilled: one injection well (SU 21-14-1) and two producers (SU 9-21 and SU 21-16-9) (Figure 8). These producers were drilled in a north-south alignment in the easternmost functional reservoir compartment (see Figure 5). Their locations were intended to take advantage of the determined preferential flow direction. Based on seismic

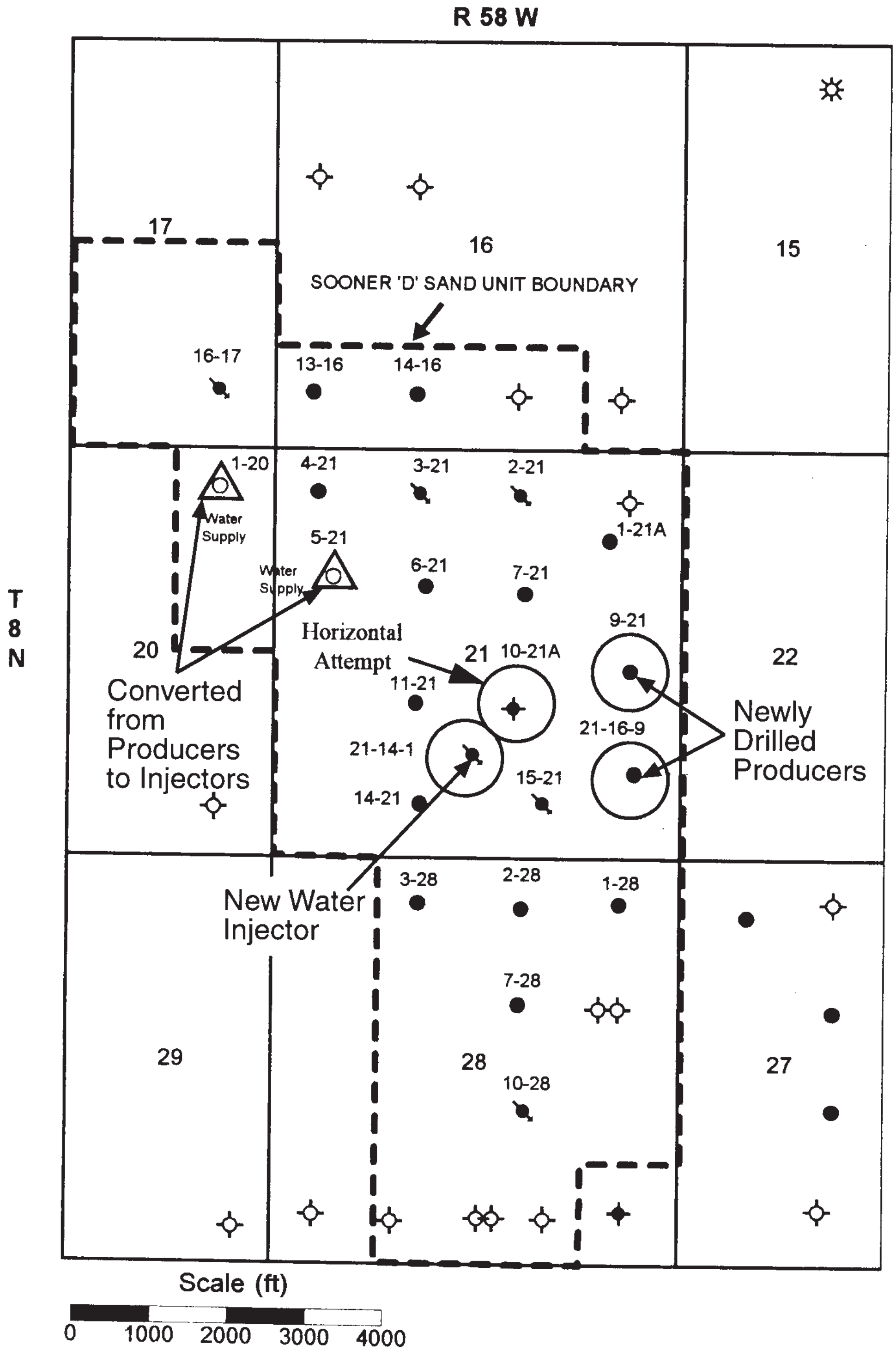


Figure 8—Realignment of injector/producer wells and infill wells drilled during the duration of the Sooner unit DOE study. Modified from Sippel, 1996.

attribute data, the SU 21-16-9 location was predicted to have approximately 29 ft (8.8 m) of net pay. The well actually logged 26 ft (7.9 m) of net pay and was completed at a rate of 220 bbl per day. This well, plus the 9-21 infill producer, more than doubled daily production from the unit to 400 bbl, and increased total proven reserves by 696,000 bbl.

The long-term results of this first stage of field redevelopment are suggested by the production history graph of Figure 9A. Estimated ultimate

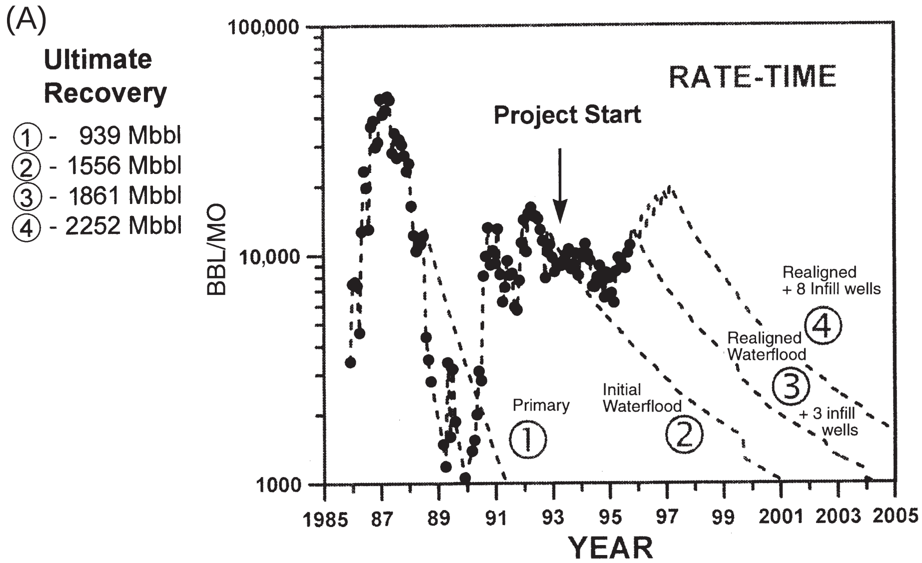
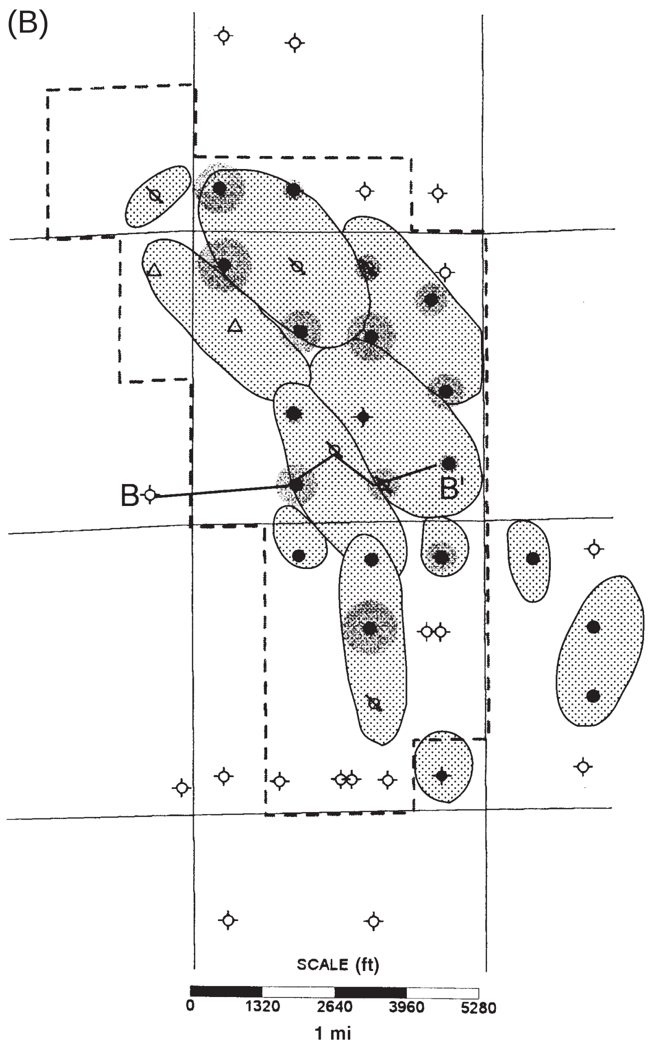


Figure 9—(A) Production history, Sooner unit, showing projected ultimate recoveries for each stage of field development. (B) Bubble map illustrating oil drainage areas after waterflooding, as of December 1995. Bubbles represent estimated areas of drained reservoirs, based on cumulative secondary production and hydrocarbon pore volume. Data courtesy Mark Sippel Engineering, Inc.

recoveries are included on this graph for each stage of field development. Note that curve 3, corresponding to the first stage of redevelopment, predicts total secondary recovery equal to that during primary production, and an 8.4% increase over recovery estimated for initial waterflood operations. The distribution of drained reservoir as a result of waterflooding through December 1995 (curve 2 of Figure 9A) is suggested by the map of Figure 9B. This map depicts the estimated drained-reservoir area for each well, based on cumulative production and hydrocarbon pore volume. As shown, substantial undrained parts of the reservoir in each compartment appear to exist.



CONCLUSIONS

The success of the initial stage of the Sooner unit redevelopment suggests that the principal reason for poor waterflood performance in other D sandstone fields relates to the existence of multiple reservoir compartments in productive valley-fill and marginal marine/shallow marine sandstones. Strategic infill drilling based on 3-D seismic data and reconfiguration of injector/producer patterns based on delineation of reservoir compartments appears to offer an efficient means to maximize productivity and economics. The reservoir model developed for this study also implies that well density should be higher normal to the axis of the identified paleovalley system.

Remaining D sandstone reserves within the regional productive fairway are in the range of 40 to 100 Mbbl, based on field data. Much of this resource may well prove recoverable by methods similar to those employed in the Sooner unit.

REFERENCES CITED

Allison, D. A., 1982, Sooner field, *in* M. C. Crouch III, ed., Oil and gas fields of Colorado, Nebraska, and adjacent areas: Rocky Mountain Association of Geologists, v. 1, p. 473–475.

Hemborg, H. T., 1993, Denver basin plays—D sand, *in* C. L. Hjellming, Atlas of major Rocky Mountain gas reservoirs: New Mexico Bureau of Mines and Mineral Resources, p. 111–112.

Merewether, E. A., and W. A. Cobban, 1986, Biostratigraphic units and tectonism in the mid-Cretaceous foreland of Wyoming, Colorado, and adjoining areas, *in* J. A. Peterson, ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: AAPG Memoir 41, p. 443–468.

Mossel, L. G., 1978, Hydrocarbon accumulations in the "D" sand, Adams and Arapahoe counties, Colorado, *in* J. D. Pruit and P. E. Coffin, eds., Energy resources of the Denver basin: Rocky Mountain Association of Geologists, p. 75–81.

Plybon, S. C., 1983, Seismic-stratigraphic investigation of the D sandstone at Masters field, Weld County, Colorado: M.S. thesis 2781, Colorado School of Mines, Golden Colorado, 165 p.

Plybon, S. C., and D. W. Oldham, 1985, Seismic-stratigraphic analysis of Lanyard–Lost Creek field area, Denver basin, Colorado; application to exploration and field delineation (abs.): AAPG Bulletin, v. 69, no. 5, p. 861.

Sippel, M. A., 1996, Advanced secondary recovery project for the Sooner "D" sand unit, Weld County, Colorado: Final Report Submitted to U.S. Department of Energy (DOE), report no. DOE/BC/14954-14, 85 p.

Sippel, M. A., R. W. Pritchett, and B. A. Hardage, 1993, Integrated reservoir management to maximize oil recovery from a fluvial-estuarine reservoir: a case study of the Sooner unit, Colorado, *in* K. S. Johnson, ed., Deltaic reservoirs in the southern mid-continent: Oklahoma Geological Survey, p. 288–292.

Sonnenberg, S. A., 1982, The Lanyard field, a structural-stratigraphic trap, Denver basin, Colorado: The Mountain Geologist, v. 19, no. 3, p. 63–72.

Sonnenberg, S. A., 1987, Tectonic, sedimentary, and seismic models for the D sandstone, Zenith field area, Denver basin, Colorado; AAPG Bulletin, v. 71, no. 11, p. 1366–1377.

Weimer, R. J., 1980, Recurrent movement on basement faults, a tectonic style for Colorado and adjacent areas, *in* H. C. Kent and K. Porter, eds., Colorado geology: Rocky Mountain Association of Geologists, p. 23–35.

Weimer, R. J., 1984, Relation of unconformities, tectonics, and sea-level changes, Cretaceous of Western Interior, U.S.A., *in* J. S. Schlee, ed., Interregional unconformities and hydrocarbon accumulation: AAPG Memoir 36, p. 7–37.

Weimer, R. J., 1994, Sequence-stratigraphic concepts applied to integrated oil and gas field development, with case histories (abs.): AAPG Bulletin, v. 78, no. 9, p. 1447.

Wilson, K. M., 1991, Cretaceous "D" sandstone delta, Denver basin, Colorado; ancient analog for shallow water bayfill sequences (abs.): AAPG Bulletin, v. 75, no. 3, p. 694.

Wilson, K. M., and J. B. Thomas, 1985, Depositional environments and diagenesis of D sandstone, Wild Horse field, Weld County, Colorado (abs.): AAPG Bulletin, v. 69, no. 5, p. 871.

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