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GEOLOGICAL SURVEY OF ALABAMA

REPRINT SERIES 110

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Reprinted from
Oklahoma Geological Survey
Circular 98, 1996, p. 279-285

Tuscaloosa, Alabama
1996

Heterogeneity in Delta-Destructive Oil Reservoirs: Deposition and Diagenesis of the Carter Sandstone (Upper Mississippian), Black Warrior Basin, Alabama

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INTRODUCTION

More than 85% of the oil produced from the Black Warrior basin is from the Carter sandstone in Lamar and Fayette Counties, Alabama, and >65% of that production is from the North Blowhorn Creek oil unit (Fig. 1A). The Carter sandstone is in the lower Parkwood Formation and is of Chesterian (Late Mississippian) age. Most oil is produced from localized sandstone bodies that were deposited as part of a muddy strand plain that formed by progressive shoaling during delta destruction (Pashin and Kugler, 1992).

Interdeltaic barrier-island deposits have been a primary focus of studies of reservoir heterogeneity (Sharma and others, 1990; Schatzinger and others, 1992), but heterogeneity in muddy strand-plain deposits, such as cheniers and delta-destructive barrier-island arcs, has yet to be analyzed. This paper characterizes heterogeneity in Carter sandstone and examines ways in which muddy strand-plain deposits differ from better-known barrier-island deposits. Investigation of heterogeneity in Carter oil reservoirs in the Black Warrior basin is based on analysis of well logs and cores and has employed stratigraphic, sedimentologic, petrologic, and petrophysical methods. Production and engineering data also were used to evaluate the performance of recovery operations in Carter oil fields.

STRATIGRAPHY AND SEDIMENTOLOGY

Lower Parkwood Lithofacies

The lower Parkwood Formation overlies the Bangor Limestone and is overlain by the interbedded limestone and shale of the middle Parkwood Formation, which locally contains the *Millerella* sandstone at the base (Fig. 2). The lower Parkwood contains shale, siltstone, and sandstone and was divided into three lithofacies by Pashin and Kugler (1992). The shale-and-siltstone facies forms the base of the lower Parkwood and is composed of interbedded gray shale and siltstone with wavy, lenticular, and flaser bedding. Sedimentary structures include current ripples, wave ripples, load structures, graded bedding, and feeding burrows.

In the upper half of the lower Parkwood Formation is the Carter sandstone, which comprises the two remaining lithofacies, the sandstone facies and the variegated facies. The sandstone facies is the principal Carter reservoir rock and is yellowish brown, thick bedded, very fine to fine grained, and moderately to well sorted. Sedimentary structures include current-ripple cross-laminae, horizontal laminae, and planar cross-strata dipping at <5°. In some cores, accumulations of shale pebbles or shells form conglomeratic zones as thick as 4 ft.

The variegated facies typically composes the upper part of the Carter sandstone and is so named for diverse colors and rock types. Sandstone, siltstone, and shale with wavy, flaser, and lenticular bedding predominate in the facies. Much of the sandstone has a mottled texture, and some sandstone is composed of pebble- to cobble-size, intraclastic flat pebbles separated by anastomosing claystone laminae. Root structures and slickensides are abundant, and burrows are present in parts of the facies. Thick beds of gray and red shale are also in the variegated facies and contain slickensides, plant fossils, and pisoidal carbonate nodules (large coated grains resembling pisolites).

Reservoir Architecture

Although Carter cores from the study area exhibit the same general succession of lithofacies, a sandstone-isolith map establishes marked variation in the plan of the sandstone bodies (Fig. 1B). This variation is especially pronounced among the oil fields. In the area containing the South Fairview, Central Fairview, South Brush Creek, and Blowhorn Creek oil units, isolith patterns are

Pashin, J. C.; and Kugler, R. L., 1996, Heterogeneity in delta-destructive oil reservoirs: deposition and diagenesis of the Carter Sandstone (Upper Mississippian), Black Warrior basin, Alabama, *in* Johnson, K. S. (ed.), Deltaic reservoirs in the southern Midcontinent, 1993 symposium: Oklahoma Geological Survey Circular 98, p. 279–285.

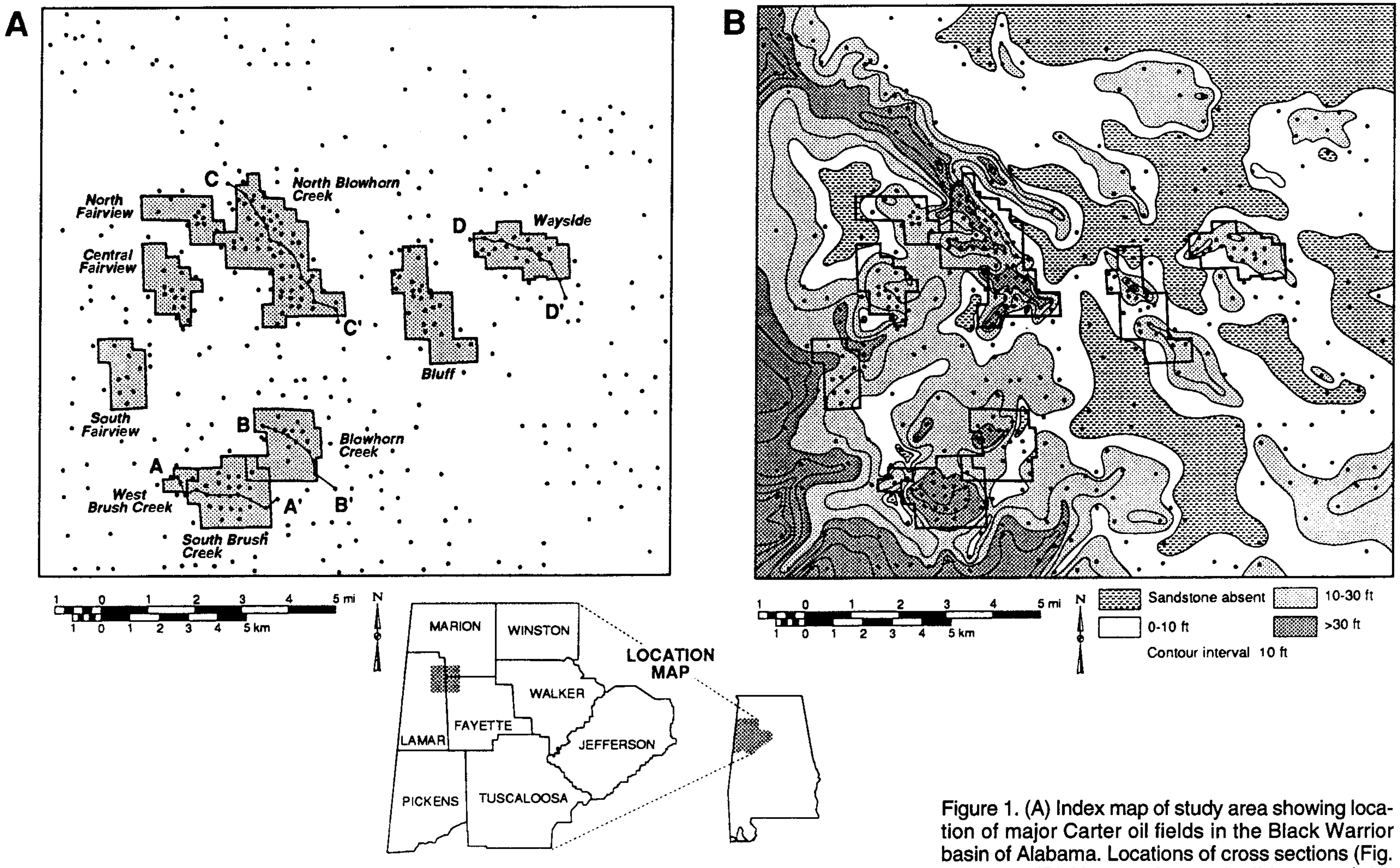

Figure 1. (A) Index map of study area showing location of major Carter oil fields in the Black Warrior basin of Alabama. Locations of cross sections (Fig. 2) given. (B) Net-sandstone-isolith map of the Carter sandstone in parts of Fayette, Lamar, and Marion Counties, Alabama.

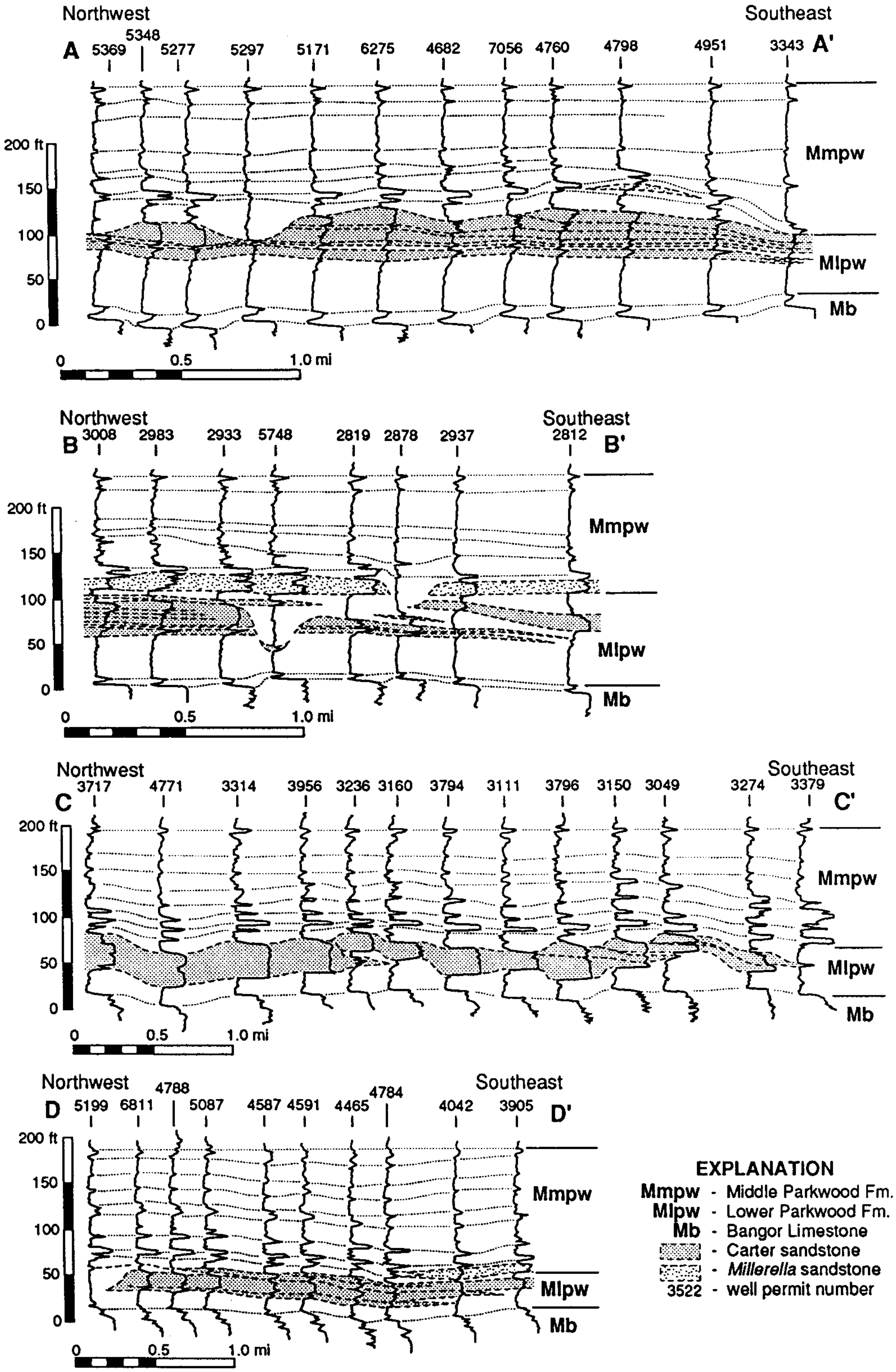

Figure 2. Resistivity-log cross sections of the Carter sandstone and associated strata in parts of Fayette, Lamar, and Marion Counties, Alabama. See Figure 1A for locations.

lobate to concentric. In the North Blowhorn Creek oil unit, by contrast, the reservoir is in the terminus of a linear sandstone body with an irregular southwest margin and a comparatively smooth northeast margin. Bluff field was established in a linear series of lensoid sandstone bodies that extend southeastward from the North Blowhorn Creek sandstone axis, and the Wayside oil unit was established in one of several lensoid sandstone bodies near the northeast limit of the Carter sandstone.

Internally, all Carter sandstone bodies in the study area are made up of imbricate, clinoformal sandstone lenses, but the lithologic characteristics and spatial arrangement of those lenses differ greatly among the fields (Fig. 2). In the South Brush Creek and West Brush Creek oil units, well logs have a serrate, coarsening-upward log signature reflecting vertical gradation of the shale-and-siltstone lithofacies into the sandstone lithofacies. Clinoformal sandstone beds dip gently toward the northwest and southeast, and the sandstone is truncated by a scour surface that is overlain by shale of the variegated facies. The Carter sandstone in the Blowhorn Creek oil unit is a continuation of that in the South Brush Creek oil unit, and channels locally truncate the full thickness of the sandstone. Oil in the Blowhorn Creek oil unit is produced from the *Millerella* sandstone, which also is truncated by a channel.

In the North Blowhorn Creek oil unit, the size of imbricate sandstone lenses decreases southeastward toward the terminus of the reservoir (Fig. 2). The sandstone lithofacies forms the axis of the sandstone body and typically has a blocky resistivity pattern. Southwest of the axis, sandstone and shale of the variegated lithofacies predominates, and resistivity logs typically have a serrate pattern. In Bluff field, the oil reservoir comprises isolated sandstone lenses that define four separate Carter and *Millerella* pools. The Wayside oil unit, by comparison, was developed in a single lensoid sandstone body. Depositional dip of the imbricate sandstone lenses is gentler than in the other oil fields. The sandstone generally has a serrate resistivity signature, except at the western end of the sandstone body, where the sandstone is thickest and has a blocky resistivity signature.

Depositional Systems

Lower Parkwood lithofacies have been interpreted to represent open-marine to backshore environments (Pashin and Kugler, 1992). The shale-and-siltstone lithofacies represents a muddy, storm-dominated shelf on the basis of wave ripples, graded bedding, and load structures. Predominance of horizontal laminae and gently dipping planar cross-strata in the sandstone lithofacies is characteristic of shoreface and foreshore environments. By contrast, root structures and pisoidal carbonate in the variegated facies signify vegetation and soil formation in backshore environments. The variety of isolith patterns and stratigraphic architecture (Figs. 1,2) demonstrates that Carter beach systems were diverse. Moreover, the change of sandstone-body geometry from lobate bodies in the southwest to thin, isolated lenses in the northeast records systematic evolution of the strand plain.

The lobate geometry and serrate, coarsening-upward resistivity signature of the Carter sandstone in the South Brush Creek oil unit and adjacent areas (Figs. 1,2) signify sedimentation in a cuspate delta. Truncation of the top of the sandstone suggests subaerial degradation of the beaches as the delta prograded farther seaward. Similar degraded beaches are present in the Doce Delta of Brazil (Dominguez and Wanless, 1991). The Carter reservoir in the Blowhorn Creek oil unit apparently accumulated at the distal fringe of the cuspate delta. The shale-filled scours are interpreted as tidal channels that were part of the cuspate delta, because the uppermost Carter sandstone lenses extend above the scour structures.

The Carter sandstone in the North Blowhorn Creek oil unit has been interpreted as a spit-style beach system by Pashin and Kugler (1992) (Figs. 1,2). They suggested that the irregular southwest margin of the sandstone body and the southward decrease in size of the imbricate sandstone lenses delineate spit arms. Bluff reservoirs apparently formed in a string of beaches extending southeast from the axis of the North Blowhorn Creek spit. The localized geometry of the Carter reservoir in the Wayside oil unit is suggestive of the small, arcuate beaches that form in areas of high tidal range (Hayes, 1979). Indeed, localized sandstone bodies in the Wayside area apparently accumulated along the margin of an estuarine tidal embayment where no sand was deposited. Thick sandstone with a blocky log signature adjacent to the embayment may reflect reworking by tide- and storm-generated currents.

PETROLOGY, DIAGENESIS, AND PETROPHYSICAL PROPERTIES

The Carter sandstone is dominantly very fine grained to fine-grained, moderately well sorted quartzarenite. Heterogeneity in the Carter sandstone is influenced by grain-size distribution, intrabasinal framework grains, and authigenic minerals. Volumetrically important authigenic minerals are quartz, kaolinite, and carbonate minerals, including nonferroan and ferroan calcite, ferroan dolomite–ankerite, and siderite (Kugler and Pashin, 1992). The distribution of diagenetic components in some oil units is related directly to depositional facies, but the present distribution and composition of authigenic minerals and the nature of compactional features resulted from burial diagenesis. Carbonate-cemented sandstone, which is associated with the margins of reservoir zones and with shell accumulations, forms baffles and barriers to fluid flow. Pressure-solution seams also form effective barriers to flow and mark the lower limit of oil-stained sandstone in several cores. Deformed intraclasts and wispy microstylolites increase tortuosity of fluid flow.

The pore system in the Carter sandstone consists of effective macropores between framework grains and ineffective micropores between detrital and authigenic clay particles. In general, shoreface and foreshore deposits of the sandstone facies have a well-interconnected pore system, whereas backshore deposits of the variegated facies contain the most authigenic clay and carbonate and thus have a poorly interconnected pore system. The primary pore system was modified to some extent during burial. Some aluminosilicate framework grains, such as feldspar, were dissolved and redistributed as kaolinite; redistribution did not enhance porosity significantly. Authigenic carbonate is common in Carter sandstone but occludes all pores only in the vicinity of shell accumulations; secondary porosity related to dissolution of carbonate is scarce. Of all the factors affecting the pore system, dispersed and laminated clays have the most detrimental effects on reservoir properties.

A weak correlation exists between porosity and permeability ($R^2 = 0.52$) in the Carter reservoir of the North Blowhorn Creek oil unit. Capillary-pressure data indicate that pore-throat size distribution is typically polymodal, reflecting the mixture of micropores and macropores and, hence, the distribution of authigenic and detrital clay minerals. Order-of-magnitude variation of permeability in some shoreface and foreshore sandstone may be related to grain-size variation. This variation affects sweep efficiency during water flooding, because fluids are channeled preferentially through high-permeability zones.

DISCUSSION: PRODUCTION PERFORMANCE AND RESERVOIR HETEROGENEITY

To sustain or increase oil production in the Black Warrior basin of Alabama, five Carter oil fields have been unitized for water flooding, gas injection, or a combination of the two processes. Production patterns of oil and water correlate well with depositional features and petrophysical parameters, reflecting progressive evolution of the Carter strand plain and subsequent burial diagenesis. In the North Blowhorn Creek oil unit, for example, the distribution of original oil in place corresponds favorably with sandstone-isolith patterns (Fig. 3A). Most of the oil extracted in the northern part of the oil unit has been from shoreface and foreshore sandstone northeast of the sandstone-body axis; production from backshore and recurved-spit deposits behind the axis is minimal (Fig. 3B). Oil production in the southern part of the unit is variable, reflecting segmentation of the reservoir by imbricate sandstone lenses (Fig. 2, cross section C–C′; Fig. 3B). Similar patterns are visible in the cumulative volume of injected water (Fig. 3C). Although similar amounts of water have been injected in the northern and southern parts of the field, cumulative water production is exceptionally high in the southern part of the oil unit (Fig. 3D), signifying early breakthrough. Injected fluids channeled through high-permeability thief zones and fractures may have bypassed some producible oil where breakthrough occurred early; similar relationships exist in the other oil units.

Because the geologic processes that form a sandstone reservoir operate at multiple scales, heterogeneity in petrophysical and other engineering properties in the reservoir also is scale dependent. Knowledge of controls on reservoir heterogeneity becomes increasingly important at smaller scales as field development progresses from primary production through a variety of improved-recovery techniques. This is especially apparent in the Carter oil reservoirs of the Black Warrior basin. Carter reservoirs are unusually heterogeneous for beach deposits, because they are localized and shaly. Imbricate sandstone lenses present a critical megascopic heterogeneity in the Carter sandstone, and the arrangement of those lenses differs in each producing oil unit, reflecting environmental variability within the delta-destructive strand plain. Mesoscale heterogeneity within the sandstone lenses is controlled in part by the transition from shoreface to backshore facies. Porosity and permeability contrasts inherent in this facies transition, moreover, have been amplified by diagenetic factors operating at a microscopic scale, which include the development of authigenic clay minerals and carbonate cement.

Although Carter oil reservoirs in Alabama were deposited as part of a single strand-plain system and were subjected to similar diagenetic conditions during burial, these reservoirs are morphologically diverse and have correspondingly diverse production characteristics. Therefore, these reservoirs must be characterized on a field-by-field basis. In each oil unit, the success of recovery operations depends on the ways that problems related to specific depositional and diagenetic heterogeneities are addressed. Continued success necessitates careful evaluation of the sedimentologic, petrologic, and petrophysical characteristics of individual sandstone bodies to gain the fullest understanding of controls on oil production and the methods that can best be applied to improve recovery.

ACKNOWLEDGMENTS

This research is part of a larger study of heterogeneity in Carboniferous sandstone reservoirs of

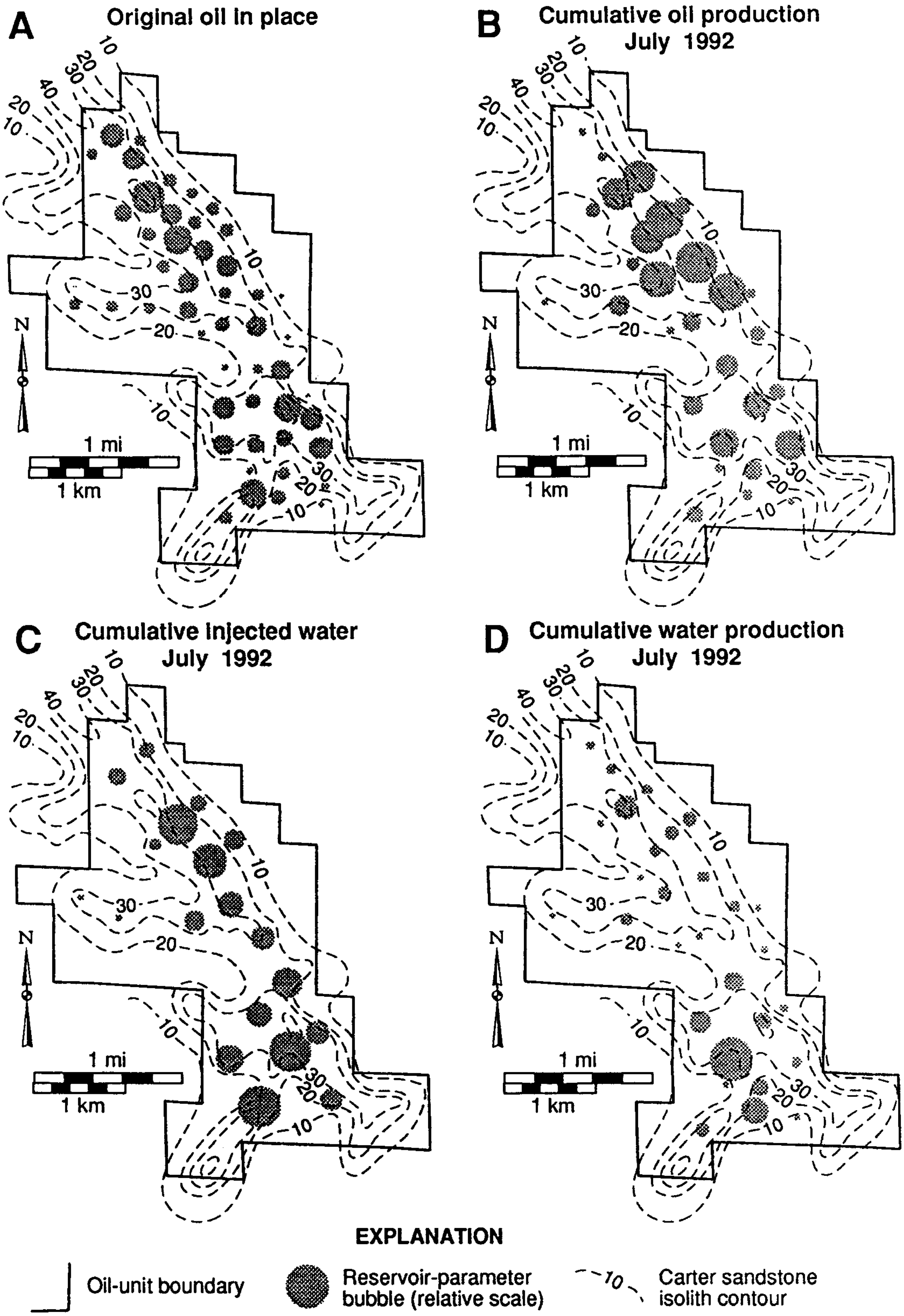

Figure 3. Bubble maps showing the relationship of key production parameters to sandstone-isolith patterns in the North Blowhorn Creek oil unit, Black Warrior basin, Alabama.

the Black Warrior basin. Support for this research was provided by the U.S. Department of Energy, Bartlesville Project Office, under contract DOE/ BC/14448.

REFERENCES CITED

Dominguez, J. M. L.; and Wanless, H. R., 1991, Facies architecture of a falling sea-level strandplain, Doce River coast, Brazil, *in* Swift, D. J. P.; and others (eds.), Shelf sand and sandstone bodies: International Association of Sedimentologists Special Publication 14, p. 259–281.

Hayes, M. O., 1979, Barrier island morphology as a function of wave climate and tidal regime, *in* Leatherman, S. P. (ed.), Barrier islands—from the Gulf of St. Lawrence to the Gulf of Mexico: Academic Press, New York, p. 1–27.

Kugler, R. L.; and Pashin, J. C., 1992, Reservoir heterogeneity in Carter Sandstone, North Blowhorn Creek oil unit and vicinity, Black Warrior basin, Alabama: U.S. Department of Energy, Bartlesville, Oklahoma, Fossil Energy Report DOE/BC/14448-9, 92 p.

Pashin, J. C.; and Kugler, R. L., 1992, Delta-destructive spit complex in Black Warrior basin: facies heterogeneity in Carter sandstone (Chesterian), North Blowhorn Creek oil unit, Lamar County, Alabama: Gulf Coast Association of Geological Societies Transactions, v. 42, p. 305–325.

Schatzinger, R. A.; Szpakiewicz, M. J.; Jackson, S. R.; Chang, M. M.; Sharma, Bijon; and Tham, M. K., 1992, Integrated geological-engineering model of Patrick Draw field and examples of similarities and differences among various shoreline barrier systems: U.S. Department of Energy, Bartlesville, Oklahoma, Fossil Energy Report NIPER-575, 146 p.

Sharma, Bijon; Honarpour, M. M.; Szpakiewicz, M. J.; and Schatzinger, R. A., 1990, Critical heterogeneities in a barrier island deposit and their influence on various recovery processes: Society of Petroleum Engineers, Formation Evaluation, v. 5, p. 103–112.