INFILL DEVELOPMENT IN CARBONATE WATERFLOODS

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INTRODUCTION

Waterflooding concepts in carbonate reservoirs of West Texas and New Mexico have changed drastically in recent years. The original flood designs for many waterfloods called for peripheral water injection with minimal interior injection. The use of generalized geologic correlations or averages of rock properties in the design and execution of these projects led to delayed and inefficient flood response. Review of these drive projects, particularly with a more precise geologic definition, led to the conclusion that closer-spaced, more regular flood patterns would be necessary to enhance ultimate oil recovery.

GEOLOGIC REFINEMENTS

A significant development which has evolved in recent years has been a better understanding of the geoiogy of carbonate reservoirs. A generalized correlation of the main productive interval and a simplistic net pay map were basically the container definition used in the original flood designs. Detailed geologic studies which have incorporated environmental deposition concepts have identified different types of deposition in the subject reservoirs, and have indicated that porosity-permeability relationships vary markedly among the various environmental rock types. Impermeable lateral barriers extending over several well locations have been identified and mapped. Directional trends of permeability and the presence of discontinuous pay have been established. These geologic refinements have led to the concept that water injected into a pay member will be contained within that pay member; i.e., the impermeable barriers extending over distances of several well locations will prevent extensive crossflow within the reservoir from one pay member into another. Furthermore, inasmuch as the pay members themselves may be discontinuous over long well distances, closer well spacing may be required to connect up the pay between a producer and an adjacent injector to realize maximum flood response.

Figure 1 shows idealized schematics of the "old" and the "new" geologic concepts of such a carbonate

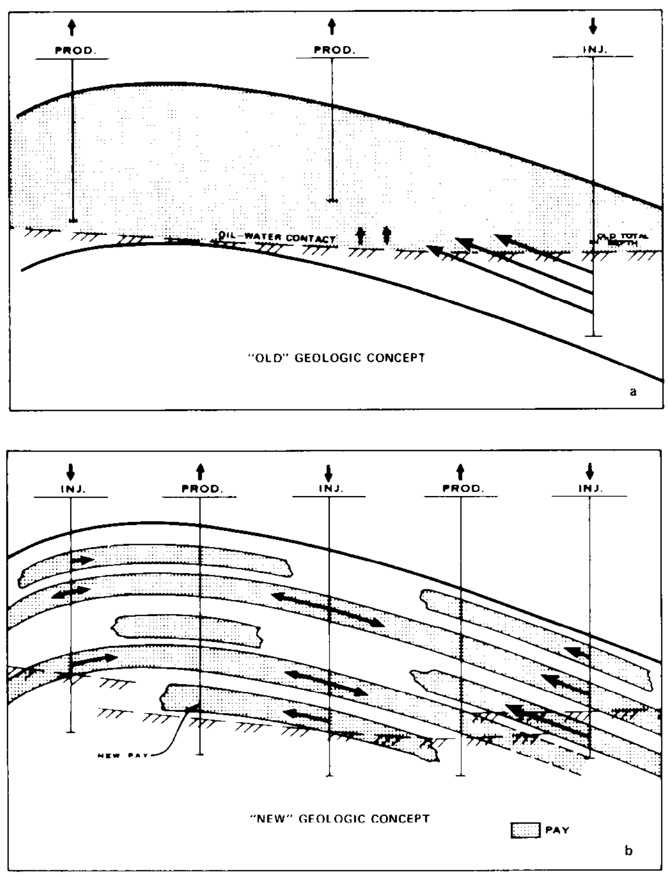


FIGURE 1

reservoir. The figure additionally illustrates the differences between the original peripheral and the current pattern flood design, the latter having been brought about by infill drilling of new producers and injectors, and the conversion of interior existing producers to injectors. For instance it might be noted in Fig. 1a, the water is being injected into the peripheral injector, the assumption being that the drive response would take place updip in the distant producers within basically the entire pay interval. Figure 1b, by contrast, shows (1) greater well density, (2) interior injectors, (3) water injection taking place in different pay members, (4) nonhorizontal oil-water contacts, and (5) pay discontinuity between wells.

An added bonus of infilling has been that water levels (or rather the levels of essentially clean oil production) have been found to be other than horizontal, depending upon rock types. As a result, new deeper pay has been penetrated and is being exploited in several flood projects. As an example, eleven pay members have been correlated and mapped in the Permian San Andres reservoir of Denver Unit (Gaines and Yoakum Counties, Texas) including one deep pay member which had remained essentially unexploited during primary development.

It further became apparent from this work that several individual pay members were discontinuous and would not be flooded at the 40-acre well spacing existing in many of these reservoirs. This gave rise to the concept of "continuous" and "discontinuous" pay, and provided an incentive for infill drilling on a 20-acre spacing basis. For instance, for the San Andres reservoir of the Wasson Field, approximately 85 percent of the pay is estimated to be continuous between two adjacent wellbores at 40-acre well spacing."Discontinuous" pay would be the balance of the net pay which would not be connected between two adjacent wellbores. In such a reservoir, if one were to drill infill wells at a spacing closer than that which had existed previously, some of the "discontinuous" pay would become "continuous" in the sense that a larger percentage of the total net pay would be correlatable between closer-spaced adjacent wellbores in the new development pattern. In the case of the Denver Unit, at 20-acre spacing, 90 percent or more of the pay is estimated to be continuous between two adjacent wellbores. It is this incremental increase in pay continuity, along with other pattern modifications discussed later, which have provided the enhancement in additional oil recovery.

RESERVOIR ENGINEERING REFINEMENTS

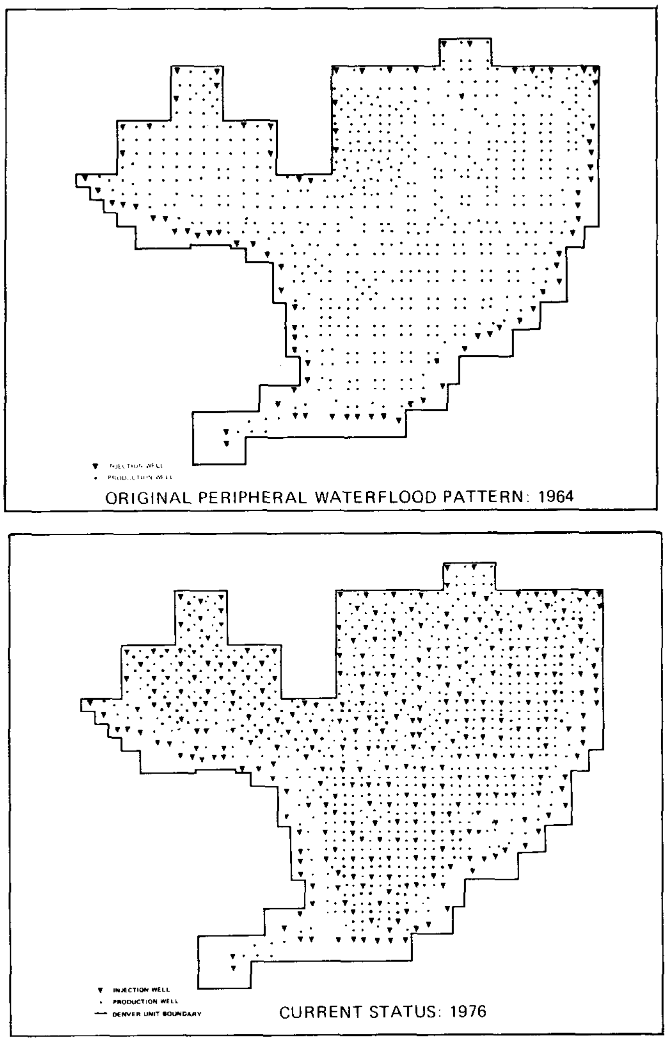
Associated with improved geologic understanding have come refinements in the methods of predicting flood performance. The numerical simulator has played an important role in the reservoir analysis of infill drilling programs where it has been employed to study various flood pattern arrangements.

Numerous operators have used 2-D and 3-D simulation models of field elements to quantify additional waterflood recovery. A detailed discussion of these mathematical models is beyond the scope of this paper. However, analyses of the production functions and related profitability data have indicated that the inverted nine-spot pattern was preferable to the other pattern arrangements studied in the case of the Denver Unit. The inverted nine-spot, therefore, was the basic pattern used in the design of the infill development program in the Denver Unit which, to date, has comprised the drilling of 326 new producers, 42 new injectors, 17 purchased wellbores, and 78 conversions of existing producers to injectors; i.e., a total of 463 wells. Figure 2 illustrates the original peripheral injection design and the current flood pattern in the Denver Unit project. Current well count is 806 producers with a Unit oil production rate of 150,000 BOPD, and 306 injectors with a Unit water injection rate of 430,000 BWPD.

Other operators in the Permian Basin have infilled on five-spot or line-drive arrangements. The choice of one pattern arrangement over another has been dictated by the existing well locations in the various leaseholds when they were unitized at flood initiation, the directional permeability trends prevalent in the particular reservoir, and the related infill development economics.

ADDITIONAL OIL RECOVERY

The operators of the Permian Basin carbonate waterfloods basically agree that three major components have contributed to the enhancement in additional oil recovery by infill drilling and attendant pattern modifications. These are: pay continuity improvement, areal sweep efficiency improvement, and vertical sweep efficiency



INFILL DEVELOPMENT
DENVER UNIT
WASSON SAN ANDRES FIELD
1964-1976
FIGURE 2

improvement. The improvement in pay continuity at closer well spacing was discussed earlier. The quantification of this component has been derived from relating the pay continuity percentage improvement from say, 40-acre spacing to 20-acre spacing, to the oil-in-place contained in the individual pay members.

The quantification of areal sweep efficiency improvement generally has been obtained by 2-D modeling. For instance, Fig. 3 illustrates the pattern uniformity realized by infilling in the case of the Denver Unit.

The quantification of vertical sweep efficiency improvement has been obtained by 3-D modeling.

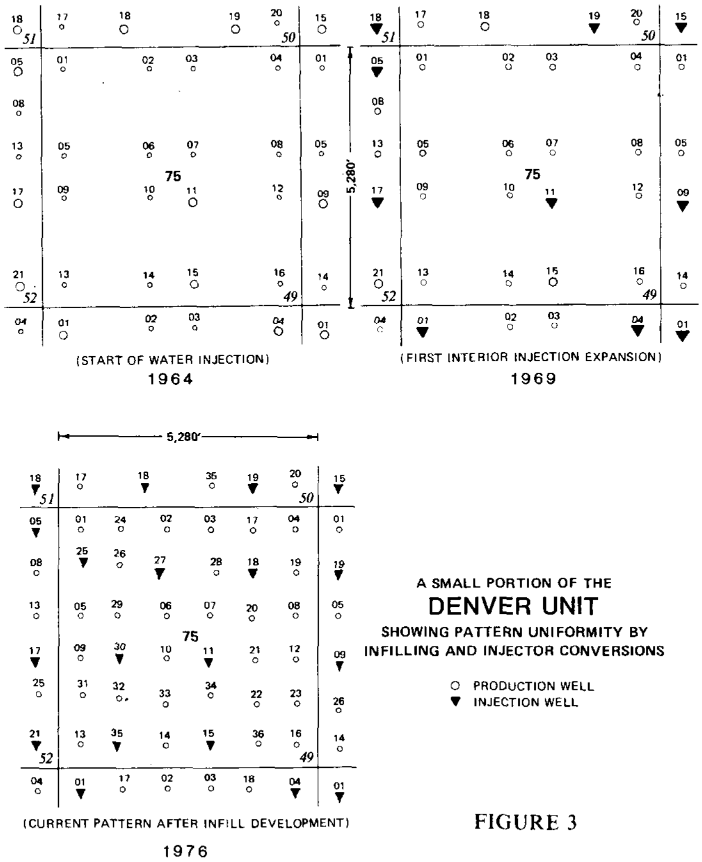


FIGURE 3

Also, changes in operating strategy have enhanced the vertical sweep. For instance in the Denver Unit, the operating policy has been to attempt to distribute the injected water in accord with each pay zone's porosity-thickness product. This has been accomplished as follows: (1) Cemented liners have been installed in openhole producers converted to injection, and the zones to be flooded have been selectively perforated. (2) All new producers and injectors have been cased through the zones of interest and selectively perforated rather than openhole completed, which had been the practice during primary development. (3) Treating pressures during acid stimulation jobs have been kept below formation fracturing pressures in order to maintain zonal isolation. (4) Water injection rates have been kept below fracturing pressure levels.

The impermeable barriers extending laterally over distances of several well locations have prevented extensive crossflow within the reservoir from one permeable layer to another. Injection profile analyses bear this out, inasmuch as the percentage of the total water volume being injected into each pay zone is now more nearly proportional to the oil-in-place contained in the individual pay members than had been the case previously, as illustrated by Fig. 4. Water breakthrough problems, to date, have also been minimal. Additionally, recent test wells drilled in the Denver Unit at very close spacing (10-acres per well) in a mature portion of the flood have proven that all individual pay zones are being flooded, although the flood fronts are advancing at different rates. Crossflow between pay members is not taking place within the reservoir, as interpreted from varying bottomhole shut-in pressures obtained during production tests of individual pay zones in the same wellbore.

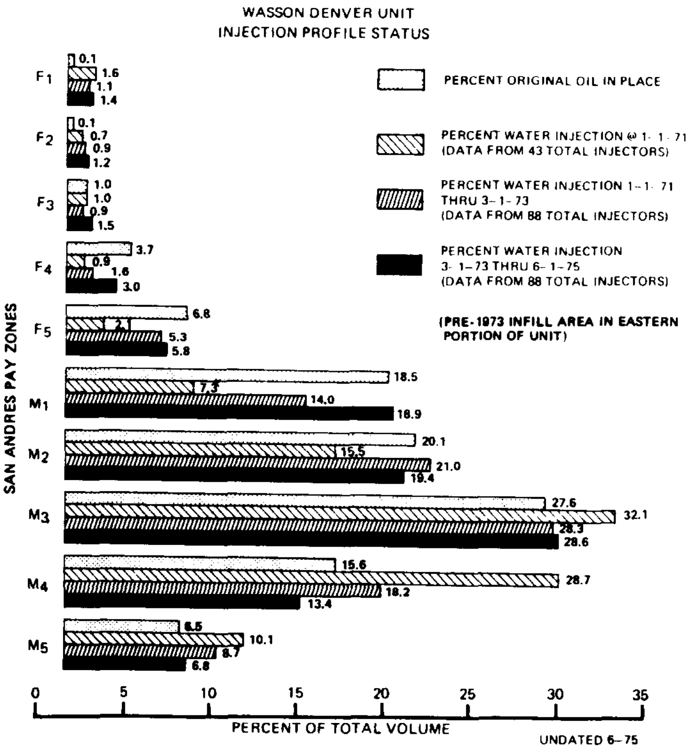


FIGURE 4

The estimated ultimate recovery efficiency for the Denver Unit project might be cited to illustrate the enhancement in oil recovery attributable to infill development. At flood initiation, it was estimated that the ultimate recovery (primary and supplemental) without infilling would be 620 million barrels or 29.4 percent of the original oil-in-place of 2.11 billion barrels (16.8% primary plus 12.6% supplemental). With the Unit having undergone 20-acre infill development, the ultimate recovery efficiency is now estimated to be 32.5 percent of the original-oil-in-place (16.8% of primary plus 15.7% supplemental); i.e., an ultimate oil recovery of 685 million barrels. The incremental 65 million barrels has been comprised of the following:

Pay continuity improvement	25 million barrels
Areal sweep efficiency improvement	20 million barrels
Vertical sweep efficiency improvement	20 million barrels
	65 million barrels

Thus, each of the three components is estimated to add approximately one percent of the original oil-in-place to the additional oil recovery. This order of magnitude of additional oil recovery by infilling would be generally applicable to other carbonate waterfloods in the Permian Basin which have undergone or are currently undergoing infill development. For example, in the Wasson San Andres Field, there are seven operating waterfloodUnits of which six have carried out infill development. The ultimate oil recovery (primary and supplemental) currently estimated for the entire field is approximately 1.43 billion barrels or 33 percent of the original oil-in-place of 4.36 billion barrels. Should the flood response with infill development continue to be favorable, the ultimate recovery efficiency could be revised upwards by a few percent of the original oil-in-place.

CONCLUSION

Infill development to improve flood patterns and reduce well spacing from 40 acres to 20 acres per well has added substantially to supplemental oil reserves in the carbonate waterfloods of the Permian Basin.

BIBLIOGRAPHY

1. Ghauri, W.K., Osborne, A.F., and Magnuson, W.L.: Changing Concepts in Carbonate Waterflooding - West Texas Denver Unit Project - An Illustrative Example, *Jour. Petr. Tech.*, June 1974.
2. Ghauri, W.K.: Innovative Engineering Boosts Wasson Denver Unit Reserves, *Petr. Eng.*, Dec. 1974.

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