Outcrop permeabilities within four facies of a single depositional parasequence, upper San Andres Formation (Permian, Guadalupian/Leonardian), Lawyer Canyon, Guadalupe Mountains, Otero County, New Mexico

Malcolm A. Ferris, Charles Kerans, and Sharp, John M., Jr., 1993, pp. 205-210

in:
Carlsbad Region (New Mexico and West Texas), Love, D. W.; Hawley, J. W.; Kues, B. S.; Austin, G. S.; Lucas, S. G.; [eds.], New Mexico Geological Society 44th Annual Fall Field Conference Guidebook, 357 p.

This is one of many related papers that were included in the 1993 NMGS Fall Field Conference Guidebook.

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INTRODUCTION

The Permian (Leonardian-Guadalupian) San Andres Formation is a prolific reservoir rock in the Permian Basin. Predictions of secondary or tertiary oil recovery in this carbonate reservoir have proven difficult. Consequently, studies by the Texas Bureau of Economic Geology, among others, have investigated the details of permeability and porosity distributions on outcrops and their extrapolation to subsurface conditions. Such data are necessary input into numerical models of enhanced oil recovery (e.g., Dagan, 1986; Weber, 1986; Kerans et al., 1991) or ground-water flow and transport. Recent studies on field permeabilities have included welded tuffs (Fuller and Sharp, 1992; Sharp et al., 1993), fluvial sandstones (Davis and Phillips, 1990), Paleozoic fluvial/deltaic sandstones (Fu et al., 1992) and aeolian sandstones (Chandler et al., 1989).

The ability to obtain accurate permeability data rapidly on cores or outcrops is required to develop geostatistical models of reservoir properties. Air minipermeameters have proven an ideal tool for obtaining such data.

GEOLOGIC SETTING

The San Andres Formation outcrop selected for permeability analysis is on the Algerita Escarpment of the Guadalupe Mountains. This was based upon outcrop accessibility, proximity to producing fields in the San Andres Formation and promising pilot studies by Hinrichs et al. (1986) and Kittridge (1988).

San Andres reservoirs are typically in shallow-water platform-top and upper-slope carbonates with laterally extensive facies and generally low recovery efficiencies (Galloway et al., 1983). The site selected in Lawyer Canyon had exposures of a scale comparable to producing fields. In this study, the area of data collection was confined to a single parasequence as defined by Van Wagoner et al. (1988), a single cycle of genetically related and flood-bounded bed sets. This limitation allows a significant number of measurements to be collected at various vertical and lateral separations within each interpreted genetic facies of the parasequence.

King (1942, 1948) and Hayes (1964) provided early descriptions of the Guadalupe Mountains. First identified by Lee (1909), the San Andres Formation is part of a Permian platform composed of stacked upward-coarsening carbonate cycles on the margins of the Delaware and Midland Basins. More recent discussions of the local geology are provided by Silver and Todd (1969), Leary (1984), Sarg and Lehmann (1986) and Kerans et al. (1991). The sequence stratigraphy for the San Andres Formation in the Guadalupe mountains was outlined by Kerans et al. (1991), from which a simplified geologic cross section of the San Andres Formation in Lawyer Canyon is taken (Fig. 1).

Permeability measurements were taken from within the basal parasequence of the upper third-order San Andres sequence. This parasequence was mapped in detail by Kerans and Nance (1989, written comm.) and is subdivided into four facies. Facies 1 is a low-energy, flooded-shelf, sheet-like mudstone bed that thickens downdip from 5 ft in the north to up to 13 ft in the south. This massive facies lacks laminae, perhaps because of bioturbation or subsequent diagenesis, which resulted in recrystallization of the fine mud grains to dolomite microporar. In the outcrop, this facies is fractured at a variety of scales. Many of the smaller fractures are filled by calcite or dolomite.

Facies 2 is a laterally discontinuous, low-energy, draped, shallow-shelf deposit that overlies Facies 1. Facies 2 grades upward from a mudstone and wackestone to a peloid packstone/grain-dominated packstone. Thickness varies from 2 to 6 ft and pinches out between sections A1 and A2 (Fig. 2). This facies contains wavy laminations interspersed with massive zones that show signs of bioturbation. Dolomite microporar replaces and overprints the original texture. Intra-crystalline porosity is observed in these sections (Ferris, 1993, fig. 11B).

Facies 3 is a high-energy, shallow-shelf, ooid-rich grainstone interpreted as a bar creast deposit. This facies caps the mud-rich facies in the northern end of the section (A1—A11). Facies 3 pinches out at the southern end (A19—A20). This facies exhibits trough cross-stratification and planar-tabular stratifications, which indicate reworking by wave and tidal currents. The fabric is largely replaced by dolomite microporar.
FIGURE 1. Simplified geologic cross section of the San Andres Formation along the Algerita escarpment (from Kerans et al., 1991).

FIGURE 2. Original 16 measured geologic sections in parasequence 1, upper San Andres Formation, Lawyer Canyon study site, as mapped by Kerans and Nance (1989, unpublished). Depositional texture, grain types and sedimentary structures shown with interpretations of genetic-facies lateral continuity.
Primary porosity is retained, but dissolution and cementation disrupt the grain-dominated fabric and fill some of the primary pores and fractures.

Facies 4 is a low-energy, shallow-water, shelf facies, of packstone and wackestone textures. It is transitional between Facies 2 and 3 and is interpreted as a bar-flank deposit. A gradual transition occurs upwards from a mud- to a grain-dominated facies, typified by increasing grain size. The deposits show intermittently preserved, wavy to parallel lamina tions. Replacement of the fabric by dolomite microspar caused an increase in the intercrystalline porosity of the mud-supported fabric but did not change the interparticle porosity (Ferris, 1993, fig. 11D). For more detailed discussion of the facies, the reader should consult Kerans et al. (1991) or Ferris (1993).

DATA COLLECTION

Permeability data were collected with a mechanical field permeameter (MFP) and augmented by permeabilities estimated from core plugs. Permeabilities were calculated from steady-state flow and pressure values as recorded from flow tubes and dial gauges, respectively, on the device. The MFP was described by Goggin et al. (1988) based upon published designs for air flow permeameters (Dykstra and Parsons, 1950; Eijpe and Weber, 1971).

In this study, the weathering rind was chiseled off the outcrop at measuring points and the permeameter nozzle positioned inside the chiseled area. This avoided problems described by Kittridge (1988) and Ferris (1993). A set of three to five measurements was taken at each point for redundancy.

The permeability data were collected in four distinctly scaled grids, incorporating the measured geologic sections provided by Kerans et al. (1991) and covering an outcrop of the first parasequence for almost half a mile. Sample grids ranged from the largest, Grid A, which considered the entire lateral distance of the study area, to Grid D, which is a 2- by 4-ft outcrop of Facies 3 sampled at a 1-in. scale. All data are contained in Ferris (1993, Appendix A) and the permeabilities were calculated using the equation of Goggin (1988).

RESULTS

Permeability data were contoured (Fig. 3) for the largest grid (Grid A) and analyzed using geostatistical theory. Fig. 3 is a kriged contour map of permeabilities over the outcrop delineated in Fig. 2. In general, the population of MFP-measured permeabilities has a log-normal distribution (Fig. 4). Two major regions are delineated, one of low (<10 md) permeabilities, which is overlain by regions of higher (10-100 md) permeabilities. The former region corresponds to Facies 1, the mud-dominated facies. The bed of mud-dominated fabric at the bottom of this, and presumably other parasequences, indicate their importance in channeling fluid flow. Laterally continuous zones or "streaks" of higher (>100 md) permeability with dimensions of 35 to 376 ft (Fig. 3) were observed to be disrupted and less continuous in the finer-scaled grid sampling.

Geostatistical analysis follows techniques developed by Krige (1943) for estimation of ore reserves and subsequently extended for hydrogeology by many workers (e.g., Fogg, 1986; Gelhar, 1986). Our goal in this analysis is to determine the spatial correlation structure of per-
meabilities (i.e., if we know the permeability at one point, how well can we predict its value some distance away?).

For this purpose we used a variogram analysis, plotting variance of data separated by equal distances (or lags) (for details of the analysis, see Ferris, 1993). Both horizontal and vertical variograms were constructed for all four grids (scales of 100 ft, 10 ft, 1 ft and 1 in.). Variogram parameters are given in Table 1. Data for Grid A show a nested, horizontal correlation structure with permeabilities correlated at ranges of 254 and 748 ft. Grid B has a range of 22 ft. For both Grid A and Grid B, the vertical correlation ranges are much less, which reflects the effects of bedding inhomogeneity. Grid C (1-ft sample grid), on the other hand, shows equal correlation structure vertically and horizontally. Grid D data, like those for Grids A and B, show greater ranges horizontally, suggesting a structure at scales of less than 1 ft.

The nugget (the inherent heterogeneity at any point) was remarkably consistent at all scales. This indicates that the inherent randomness (or white noise) of the permeability may be due to diagenetic effects that cross facies (fracturing and pore-filling by carbonate cements). Application of power-law theory to the scale-based variograms resulted in a superpositioned variogram (Fig. 5). Calculation of the best-fit line through the points had a slope of 0.155 and a y-intercept (the characteristic variance) of —0.761. Based on the power-law equation of \( g = g(0) \cdot h^{-d} \) the slope corresponds to the fractal codimension for the population of permeability data and the y-intercept corresponds to the characteristic variance of the population for a baseline lag distance (analogous to the nugget and calculated for \( h = 1 \) ft for simplicity, since \( \log(1) = 0 \)). Therefore, the fractal codimension \( (1-d) \) is found to be equal to 0.07, an order of magnitude lower than that suggested by Hewett and Berhens (1990) and Mandelbrot (1983) for natural phenomena.

CONCLUSIONS

Analysis of permeability distributions (ignoring fractures) in this single shallowing upward sequence of the San Andres Formation reveals certain trends:

1. A generally low-permeability (<10 md), mud-dominated facies is overlain by a region of higher permeabilities (<10 md to <100 md). Streaks of higher permeability (>100 md) in the upper region are not continuous at small (1-ft to 1-in.) scales.

2. An inherent randomness (heterogeneity) of the permeability was observed at all linear scales covered in this study, from inches to hundreds of feet.

3. The analysis of horizontal and vertical variograms supported the visual observations of the existence of continuous heterogeneity across the range of scales.

4. The distribution of permeability within genetically defined depositional facies reflects the correlation range and mean permeabilities based on the fabric textures of the facies.

5. The heightened degree of heterogeneity at the small (inch-spaced) scale of investigation in this study is an indication that more information is required for determination of the controls of permeabilities at dimensions of less than a square foot. Heterogeneities within the generally highly permeable bar-crest facies indicate that values do vary widely within the space of an inch, creating low-permeability baffles and high-permeability conduits. Small-scale continuity and prevalence of the occurrence within a formation can be most significant in determining the capacity of a reservoir to retain trapped fluids.

6. The application of power-law theory to the variogram database on linear-scale samples produced a result for the fractal codimension that was an order of magnitude below the range proposed by other researchers for natural phenomena.

This study shows that it is reasonable to accept the conclusions of anisotropy and the scale dependence of the permeability, at least for this particular shallowing-upward parasequence of the upper San Andres Formation.

ACKNOWLEDGMENTS

We appreciate the reviews of Dr. Brenda Kirkland-George and Mr. Andy Czebieniak on earlier versions of this manuscript. This study is part of an integrated research effort carried out by a team of geoscientists in the Bureau of Economic Geology's Reservoir Characterization Laboratory. Numerous individuals have contributed, including G. E. Fogg.

<p>| TABLE 1. Variogram results for scale-based sample grids. |</p>
<table>
<thead>
<tr>
<th>Sample</th>
<th>Horizontal (θ = 0°)</th>
<th>Vertical (θ = 90°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRID A (100-foot scale)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nugget ( (C_{00}) )</td>
<td>0.2</td>
<td>0.16</td>
</tr>
<tr>
<td>range ( (r_{11}) )</td>
<td>253.5 feet</td>
<td>13.0 feet</td>
</tr>
<tr>
<td>sill ( (C_{11}) )</td>
<td>0.305</td>
<td>0.95</td>
</tr>
<tr>
<td>range ( (r_{22}) )</td>
<td>748.3 feet</td>
<td>N.A.</td>
</tr>
<tr>
<td>sill ( (C_{22}) )</td>
<td>0.497</td>
<td>N.A.</td>
</tr>
<tr>
<td>GRID B (10-foot scale)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nugget ( (C_{00}) )</td>
<td>0.32</td>
<td>0.2</td>
</tr>
<tr>
<td>range ( (r_{11}) )</td>
<td>22.2 feet</td>
<td>4.0 feet</td>
</tr>
<tr>
<td>sill ( (C_{11}) )</td>
<td>0.57</td>
<td>0.44</td>
</tr>
<tr>
<td>range ( (r_{22}) )</td>
<td>N.A.</td>
<td>10.2 feet</td>
</tr>
<tr>
<td>sill ( (C_{22}) )</td>
<td>N.A.</td>
<td>0.71</td>
</tr>
<tr>
<td>GRID C (1-foot scale)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nugget ( (C_{00}) )</td>
<td>0.16</td>
<td>0.165</td>
</tr>
<tr>
<td>range ( (r_{11}) )</td>
<td>2.1 feet</td>
<td>2.1 feet</td>
</tr>
<tr>
<td>sill ( (C_{11}) )</td>
<td>0.22</td>
<td>0.34</td>
</tr>
<tr>
<td>GRID D (1-inch scale)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nugget ( (C_{00}) )</td>
<td>0.26</td>
<td>0.35</td>
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<tr>
<td>range ( (r_{11}) )</td>
<td>9.0 inches</td>
<td>2.0 inches</td>
</tr>
<tr>
<td>sill ( (C_{11}) )</td>
<td>0.42</td>
<td>0.57</td>
</tr>
</tbody>
</table>
H. S. Nance, E. Kasap, S. D. Hovorka, W. M. Fitchen, M. A. Ferris and F. Wang. Funding for this project was from industry sponsors Agip, Amoco, ARCO, British Petroleum, Chevron, Conoco, Exxon USA and Exxon Production Research, Fina, JNOC, Marathon, Mobil, Phillips, Shell, Texaco, Total and Unocal. The Department of Energy supplied matching funds for portions of this research under ANNEX I to DE-FG22-89BC14403 and DE-AC22-89BC14470. We also acknowledge the U.S. Forest Service and in particular Jeanie Milburn, for helpful cooperation. Roger Reisch of the National Park Service is also thanked for his hospitality. Manuscript preparation was supported by the Owen-Coates Fund of The Geology Foundation, The University of Texas at Austin. Rosemary Brant assisted in editing the manuscript.

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