Scales of lateral petrophysical heterogeneity in dolomite lithofacies as determined from outcrop analogs: Implications for 3-D reservoir modeling

Matthew J. Pranter, Colette B. Hirstius, and David A. Budd

ABSTRACT

Petrophysical data from dolomite outcrops of the Mississippian Madison Formation at Sheep Canyon, Wyoming, exhibit three scales of lateral variability in single rock fabric units. These include a near-random component (nugget effect), a short-range structure, and a long-range cyclic trend (hole effect). The nugget effect is high and accounts for 31–39 and 48–50% of the variance in porosity and permeability, respectively. Short-range lateral variability is reflected by correlation lengths of 6.5–16 ft (2–5.5 m). Laterally, long-range periodicities are equivalent to approximately 10% of the petrophysical variance and have wavelengths of 31 and 140 ft (9.5 and 42.6 m) for porosity and permeability (55 ft [16.8 m] for log_{10} permeability), respectively.

Cross sectional and plan-view petrophysical models and streamline simulations explore the effects of these scales of heterogeneity on fluid flow. Although short-range variability accounts for most of the petrophysical heterogeneity, the longer range trends can significantly affect fluid-flow behavior. Results indicate that breakthrough time and sweep efficiency vary depending on the magnitude of the lateral, long-range, petrophysical variability that exists in a dolomite reservoir. As the component of the long-range periodicity (hole effect) increases from approximately 0 to 25% of the total petrophysical variability, a corresponding increase in breakthrough time and sweep efficiency occurs. However, as the magnitude of the lateral, long-range, petrophysical variability increases beyond 25% of the total petrophysical variability (e.g., from 25 to 50%), a corresponding reduction in breakthrough time occurs because the spatial continuity of permeability is greater. Results indicate...
that heterogeneity caused by lateral petrophysical cyclicity should be incorporated into dolomite reservoir models for hole effect magnitudes that are greater than 10% of the petrophysical variance. To properly characterize and model these scales of variability in a petroleum reservoir, outcrop analogs are essential to provide accurate quantitative descriptions of lateral variability in dolomite rock fabrics.

INTRODUCTION

Accurate reservoir characterization and modeling is essential to successful field development. In carbonate rocks, well, seismic, and core data are typically sufficient to delineate the stratigraphic framework, identify flow units, and characterize lithofacies and petrophysical characteristics close to the borehole. However, these data provide less certain information regarding lateral petrophysical heterogeneity in individual flow units at the subseismic scale. Particularly, for dolomite reservoirs, the distribution of rock properties is a result of depositional and especially diagenetic processes. Outcrop analogs of subsurface carbonate reservoirs provide an understanding of heterogeneity in similar lithofacies and equivalent reservoir flow units that can be used to augment subsurface data sets (e.g., Eisenberg et al., 1992; Kerans et al., 1994).

There have been extensive studies of lateral reservoir-scale petrophysical heterogeneity in carbonate lithofacies in outcrops of the Permian San Andres Formation of west Texas and New Mexico (Kittridge, 1988; Kittridge et al., 1990; Senger et al., 1991; Eisenberg et al., 1992; Lucia et al., 1992; Ferris, 1993; Kerans et al., 1993, 1994; Grant et al., 1994; Wang et al., 1994; Barnaby et al., 1997; Jennings et al., 1998). These studies show that in individual dolomite rock fabrics, approximately 50% of the variance in permeability appears random (the nugget effect, Eisenberg et al., 1994). The balance of the variability is characterized by a short-range correlation structure (typically <20 ft [<6 m]). Two long-range, low-magnitude, periodic features in the permeability data were also observed at scales of 140–180 and >1000 ft (43–55 and >305 m) (Jennings, 2000). Jennings et al. (1998) modeled the combined effects of one short- and one long-range permeability structure on fluid flow. Their results suggested that the long-range periodic permeability structure could be significant relative to fluid flow, even when short-range variability composes most of the petrophysical variance. No other work has been published on lateral petrophysical structures and their effects on fluid flow in dolomites. Critical questions remain unresolved. First, do other or all dolomites exhibit the lateral structures documented in the San Andres Formation outcrops? Second, how do varying degrees of the different scales of lateral petrophysical variability, especially various magnitudes of the long-range periodic permeability structure, affect fluid flow? Third, if the long-range trend does affect fluid flow, at what magnitude, if any, does it become significant to account for this scale of lateral petrophysical variability in subsurface reservoir models?
To address these issues, this study involved petrophysical analyses and modeling of exposures of porous and permeable Mississippian dolomite units at Sheep Canyon, Wyoming (Sheep Mountain; Figures 1, 2). The outcrops at Sheep Canyon are located approximately 5 mi (8 km) northeast of Greybull, Wyoming. The Bighorn River flows to the northeast through Sheep Canyon, and the exposed canyon walls provide a cross sectional view of Paleozoic strata (Figure 2). The Mississippian Madison Formation is the oldest formation exposed in the canyon. Madison dolomite and limestone exposures are analogous to many Paleozoic shelf carbonates and associated reservoirs (Sonnenfeld, 1996; Eberli et al., 2000; Westphal et al., 2004).

The Madison Formation is interpreted as a single second-order stratigraphic sequence (approximately 13 m.y. duration) bound at the top and base by regionally extensive, tectonically induced unconformities or sequence boundaries (Figure 3) (Sonnenfeld, 1996). In the Bighorn basin, the second-order sequence is subdivided into six third-order sequences (Sonnenfeld, 1996), each with an estimated duration of 2.2 m.y. (sequences I–VI; oldest to youngest, respectively). Sonnenfeld (1996) further subdivided each third-order sequence into intermediate- and small-scale depositional cycles (Figure 3). Sequence I is interpreted to have been deposited on a ramp profile with updip restricted lagoonal facies overlying and grading downdip into shoreface or shoal grain-supported fabrics that, in turn, overlie and grade downdip into outer and middle ramp mud-supported fabrics (Sonnenfeld, 1996). Sequence I at Sheep Canyon is dominated by the latter two facies tracts.

Early dolomitization by marine waters of sequence I is interpreted to have occurred during the deposition of the upper Madison Formation (Smith et al., 2000; Westphal et al., 2004). Although this study focused on lithofacies of sequences I and II as exposed in Sheep Canyon, specific data, analyses, and modeling related only to lithofacies of sequence I are presented.

**DATA SAMPLING AND VARIOGRAPHY**

To analyze and quantify interwell-scale, lateral petrophysical heterogeneity in the dolomite rock fabrics, a data set from regularly spaced rock samples was acquired along several lateral and vertical transects in sequence I (Hirstius, 2003). The data set consists of 1250, 1-in. (2.5-cm)-diameter core plug samples and their respective petrophysical property measurements. Samples were obtained with a water-lubricated core drill at a 1-ft (30-cm) spacing along four lateral transects and 14 vertical transects. A 1-ft (30-cm) sample
spacing was used based on the results of Eisenberg et al. (1994), who estimated that this spacing was appropriate to capture reservoir-scale variability in dolomite rock fabrics.

The two longest lateral transects are the focus here. These lateral transects (LT1 and LT2) are located at the core of the exposed anticline on both sides of Sheep Canyon (Figures 4, 5). Both transects are in the same bed, one that lies below the maximum flooding surface of sequence 1. The two transects are separated laterally by approximately 300 ft (100 m). Lateral transect LT1 (Figure 4) is located on the northwest face of the canyon and is 483 ft (147 m) in length. Lateral transect LT2 is located on the southeast face of the canyon.
and is 530 ft (162 m) in length. Both LT1 and LT2 targeted the same bioturbated, skeletal dolowackestone-mudstone facies of the transgressive systems tract of sequence 1. This outer ramp facies is one of the most porous of all rock fabrics exposed at Sheep Canyon (Figure 5) (Sonnenfeld, 1996; Smith et al., 2004).

Core plug samples were trimmed to lengths of approximately 1–1.5 in. (2.5–3.8 cm). The outer 0.5–0.75 in. (1.27–1.9 cm) of each sample was trimmed and not used for petrophysical analyses to avoid errors associated with outcrop weathering and sampling methods. Permeability measurements were made using a miniprobe permeameter (MPP). The MPP measures the flow of nitrogen gas through a rock sample at a set range of injection pressures. Flow rates were converted to permeability based on empirical calibrations from a set of standard core plugs with known permeabilities. Calibration of the standard plugs was run daily to account for any changes in atmospheric pressure. Because of the small scale of investigation of the MPP, the geometric mean permeability was calculated using up to four permeability measurements, two on each end of the plug. This was done to minimize the effect of intrasample variability. Further details as to the minipermeameter procedures that were used can be found in Budd (2001). Porosity was measured for each sample using a modification of the bulk-density technique (Singer, 1986).

Petrophysical Data

For LT1 and LT2, the range of permeability data is 0.26–300 and 0.28–152 md, respectively (Figure 6), with geometric mean permeabilities of 29.4 and 13.4 md, respectively. For the same transects, the range of porosity data is 9.5–37.6 and 8.5–35.7%, respectively, with arithmetic means of 17.5 and 16.1%, respectively (Figure 6). Petrophysical properties of similar dolomite lithofacies from lower Madison Formation cores (Demiralin, 1991) from the nearby Garland...
field (~20 mi [32.3 km] northwest of Sheep Canyon) are comparable to measurements taken on core plug samples from Sheep Canyon. At Garland field, the ranges of permeability and porosity values of the dolomites are 0.01–200 md and 5–30%, respectively (Demiralin, 1991).

Porosity and permeability values with distance for LT1 and LT2 show a high degree of lateral variability over short distances (e.g., three orders of magnitude for permeability data of LT1) and patterns of lateral cyclicity (Figure 7). The difference in the orders of magnitude of permeability variability for LT1 and LT2 (Figure 7) is possibly caused by permeability anisotropy in the dolomite unit that was sampled.

**Nested Structures and Variogram Models**

To evaluate petrophysical heterogeneity in the dolomite rock fabrics, spatial correlation of petrophysical properties was quantitatively analyzed through variogram analysis. A variogram measures the variation of sample property values with distance and direction and is presented as a graph of data points (experimental variogram) that shows the variance of a property value plotted against the distance between samples (separation distance or lag). Gringarten and Deutsch (2001) provide detailed reviews of variogram theory, terminology, application, and interpretation. In addition, Frykman (2001) presents a summary that describes the variogram definition, calculation, and terminology.

Experimental variograms were calculated for porosity and permeability data from each transect (Figure 8). The porosity and permeability experimental variograms exhibit three scales of variability (near-random, short range, and long range). The near-random variability or nugget effect refers to the nonzero variability at zero lag. Although one may expect the variance to be zero at zero lag, sampling error and short-range variability can cause this variance to be greater than zero. Short-range petrophysical variability occurs at separation distances from approximately 0 to 20 ft (0 to 6 m) and is seen as the increase in variance (γ) with increasing lag away from the nugget (Figure 8). Long-range petrophysical variability is observed at separation distances greater than approximately 20 ft (6 m) as a periodic trend in the petrophysical properties (Figure 8).

Variography for permeability for LT1 and LT2 indicates that near-random variability accounts for
approximately 48 and 50%, respectively, of the data variance (Figure 8A, C). The short-range structure accounts for 52 and 50%, respectively, of the data variance, with a range of 16 ft (4.9 m) for LT1 and 8 ft (2.4 m) for LT2. Long-range variance in permeability exhibits a cyclic trend with wavelengths of approximately 55 ft (16.8 m) for LT1 and LT2 (log10 permeability; Figures 8A, C; 9A).

Variography for porosity depicts similar results as for permeability. The nugget effect accounts for 39% of the variability in LT1 and 31% of the variability in LT2 (Figure 8B, D). The short-range structure of LT1 (61% of the variance) has a correlation range of 16 ft (4.9 m). The short-range structure of LT2 (69% of the variance) has a range of 6 ft (1.8 m). Long-range variability in porosity also exhibits a cyclic trend with wavelengths of approximately 31 ft (9.45 m) for LT1 and 25 ft (7.62 m) for LT2.

Because geostatistical-based reservoir-modeling methods require a variogram value for all distance and direction vectors, the experimental variogram is not used directly in reservoir modeling. Instead, a variogram model or function (e.g., spherical or exponential function) is fitted to the experimental data points (Gringarten and Deutsch, 2001). Variogram models were fitted to the experimental variograms for transects LT1 and LT2. To account for and model each scale of petrophysical variability, nugget-effect, spherical, and hole-effect models were combined to create a nested variogram model. The resultant nested variogram model describes the total variability of permeability or porosity using simple functions that are additive (Isaaks and Srivastava, 1989). In all but one case, a spherical function was used to model the short-range variability, the relatively steep increase in variance at short separation distances on the experimental variogram. The exception was LT2, for which an exponential function was used to model the short-range porosity variability. The periodic character of a hole-effect function was used to model the oscillatory patterns in porosity and permeability observed at greater lags on the experimental variogram. The variogram models represent the

Figure 5. Outcrop descriptions from Sheep Canyon for sequences I and II that show the stratigraphic positions of the lateral transects (LT1, LT2, LT3, and LT4) and the interval of sequence I that was used for the framework in the reservoir modeling (Figure 11). Porosity, cyclicity (CS = composite sequence, 3rd = third-order sequence, IS = intermediate-scale cycle, SS = small-scale cycle), lithology, and depositional texture are shown. Modified from Sonnenfeld (1996) and Smith et al. (2004).
experimental variograms reasonably well for lag distances less than 100 ft (30 m). At greater distances, the model functions do not represent the variance. It is possible that longer range petrophysical trends exist that are not totally captured by the lateral transects. The presence of longer range cyclic trends could explain the difference between the standard model function and the experimental data at greater lags.

For visualization of the long-range porosity features, a more complex nested structure was constructed for transect LT1 (Figure 9B). For LT1, the variance of porosity values depicts a repetitive increase and decrease for seven cycles about an average sill to a lag distance of 240 ft (72.2 m). A combination of a spherical model, representing the variability at short lag distances, and hole-effect models were used to represent the cyclic behavior of variance with greater lag distances (Figure 9B).

The experimental and nested model variograms of LT1 depict a cyclic pattern of porosity with a wavelength of 31 ft (9.45 m). A larger cyclic trend might also exist with a wavelength that is much longer than the lateral transect, such that only a portion of a larger cycle is depicted. This is suggested by the pattern of minimum (or maximum) variance in each 31-ft (9.45-m) wavelength (dashed lines in Figure 9B). In the San Andres Formation, where the lateral transects were much longer, gradual trends with wavelengths up to 2700 ft (823 m) have been observed in dolomite outcrops (Jennings et al., 1998). Therefore, more than one scale of long-range cyclicity could be present but unsampled in the Madison outcrop.

**HETEROGENEITY MODELING**

Two-dimensional cross sectional and plan-view petrophysical models were constructed using data obtained from the Madison Formation at Sheep Canyon and data from the San Andres Formation to investigate the effects of short- and long-range petrophysical variability.
on fluid flow. For the plan-view models, only data from the Madison Formation were used.

The framework for the cross sectional models replicates the stratigraphy of sequence I at Sheep Canyon (Figure 5). The plan-view models were specifically constructed for the porous dolowackestone lithofacies of sequence I. Multiple, unconditioned permeability simulations were run for the cross sectional and plan-view models using different nested variogram structures for each rock fabric in the models. These permeability models were created to incorporate the different scales of variability through the use of a nugget effect, a short-range model (spherical or exponential), and a long-range model (hole effect). Single-phase streamline simulations of each petrophysical model scenario were conducted to assess the relative effect of the different scales of variability on fluid flow.

**Model Setup and Facies Distribution**

Sequence I at Sheep Canyon is composed of alternating intervals of dolomite and limestone (Sonnenfeld, 1996). Regionally, however, this sequence is primarily dolomite (Westphal et al., 2004); thus, all lithofacies

---

**Figure 7.** Distribution of petrophysical data (points) for lateral transects LT1 (A, B) and LT2 (C, D). The solid black trend lines on each plot depict a five-point moving average for the data. Approximately two and three orders of magnitude of variability exist for permeability data of LT2 and LT1, respectively.
were modeled with petrophysical properties of dolomites. This also ensures that the model results are applicable to dolomitized sequences in general instead of the specifics of one outcrop. A cross sectional model was constructed using bedding thickness values based on the outcrop descriptions of Sonnenfeld (1996) but without structural dip (Figure 10) to avoid any effect on fluid flow caused by the anticlinal structure. The facies model is subdivided into lower, middle, and upper zones, each with distinct lithofacies assemblages. The lower zone of the facies model is a 43-ft (13.1-m)-thick dolowackestone. The middle zone is a 36-ft (11-m) zone of thinly interbedded dolopackstones and dolowackestones. The upper zone is a 34-ft (10.4-m) interval of thinly interbedded dolograinstones and dolowackestones. This vertical profile is a reflection of deposition through sequence I (Smith et al., 2004) (Figure 5). Cross sectional model dimensions are $113 \times 3000$ ft ($34.4 \times 914.4$ m). Vertical dimensions replicate the thickness of sequence I at Sheep Canyon, and the length of the model was selected to represent a reasonable well spacing for a carbonate reservoir. The framework for the cross sectional model was divided into a $1 \times 1$-ft ($30 \times 30$-cm) grid with 333,900 cells. This high-resolution grid was used to ensure that the model results capture the petrophysical variability observed in the outcrop data.

The plan-view models of the dolowackestone lithofacies are $248 \times 248 \times 1$ ft ($75.6 \times 75.6 \times 0.3$ m). Each cell in the plan-view models is $4 \times 4$ ft ($1.2 \times 1.2$ m); thus, each plan-view model includes 3844 cells.

**Petrophysical Modeling**

Sequential Gaussian simulations (Deutsch and Journel, 1998) were used to create the permeability models for each facies. Permeability models were created for the dolowackestone lithofacies based on variogram models,

---

**Figure 8.** Experimental variograms of permeability ($\log_{10}$) and porosity for LT1 (A, B) and LT2 (C, D). The nugget and short-scale components of variability are highlighted in (A). The gray shaded area on (A) indicates the approximate lag distance for short-scale permeability ($\log_{10}$) variability for LT1. The approximate amplitude of the long-range cyclic trend is also highlighted in (A).
histograms of permeability, and statistical analysis of data from LT1 and LT2. Permeability values ranged from 0.01 to 300 md, with a mean of 39.3 md, a median of 25.8 md, and a standard deviation of 41.8 md. A nested variogram was used with a combination of nugget-effect, short-range, and long-range structures. Short-range permeability variation in the dolostone was modeled with a spherical variogram with ranges of 16 ft (4.9 m) horizontally and 5 ft (1.5 m) vertically. Long-range variability was modeled with a hole-effect variogram to incorporate the cyclic petrophysical patterns.

The spatial correlation and property variability of the dolopackstone and dolograinstone lithofacies were based on data collected by Eisenberg et al. (1994) and Jennings (2000) for similar lithofacies in the Permian San Andres Formation, Guadalupe Mountains, New Mexico. Permeability of the dolograinstone lithofacies ranged from 0.0 to 41.5 md, with a mean of 3.5 md and median of 20.1 md. A spherical variogram model was used with a 10-ft (3.0-m) horizontal range, a 5-ft (1.5-m) vertical range, and a 70-ft (21.3-m) range for the hole-effect variogram (Eisenberg et al., 1994; Jennings, 2000). Permeability of the dolopackstone lithofacies ranged from 0.270 to 374.0 md, with an average of 24.7 md and a median of 9.9 md (Eisenberg et al., 1994). An exponential variogram model was used with correlation lengths of 5 ft (1.5 m) horizontally and vertically and a 90-ft (27.4-m) range for the hole-effect variogram.

Six two-dimensional cross sectional permeability models were generated to compare the resulting permeability distributions based on the different nested structures and the corresponding streamline simulations. Four of these models that represent the range of variability are presented. Two-dimensional cross sectional models (CS1–CS4; Figure 11) show the distribution and continuity of permeability for the different nested structures. Model CS1 was created with a nested structure with an equal contribution of nugget effect and short-range variability (spherical or exponential), but no long-range hole effect. Models CS2–CS4 were generated with nested structures with hole-effect magnitudes equivalent to 10, 25, and 50% of the petrophysical variability. Correlation lengths for each facies were kept constant for all simulations.

Four plan-view permeability models were built with hole-effect magnitudes equivalent to 0, 10, 25, and 50% of the permeability variability (PV1–PV4; Figure 12). Because information regarding horizontal petrophysical anisotropy for these dolomites does not currently exist, the models were generated using isotropic conditions with a range of 16 ft (4.9 m) in the x- and y-directions.

**Streamline Simulations**

Streamline simulations were used to assess the relative effects of the different scales of petrophysical variability on fluid flow. The simulation models included two wells.
that penetrated the entire thickness of each model. In the cross sectional models, an injection well is located on the western edge (left side) of the model, and a production well is located on the eastern edge (right side). For the plan-view model, an injection well is in the southwest corner, and a production well is in the northeast corner. In this study, horizontal to vertical petrophysical anisotropy was not quantified. However, Jennings (2000) recognized that horizontal to vertical anisotropy does exist within and between similar dolomite rock fabrics of the San Andres Formation, especially at scales that are larger than rock fabric units or high-frequency cycles. For samples from the San Andres Formation at Lawyer Canyon, New Mexico, contrasts between vertical and horizontal permeability are greater between cycles than laterally within cycles (Jennings, 2000). In addition, stratification associated with high-frequency cycles results in petrophysical anisotropy. To account for this, the cross sectional streamline simulations were run with a 10:1 horizontal/vertical permeability anisotropy ratio. Because of the marginal covariant relationship between porosity and permeability and the interest to evaluate the effect of permeability variability on fluid flow, porosity was held constant at 20% for all simulations.

Fluid flow through each permeability model was quantitatively assessed using breakthrough time (BTT) and volume drained at breakthrough time. Breakthrough time is the amount of time it takes the injected fluid to reach the producer. It is different for each scenario because of the permeability distribution. More qualitative assessments were made by visually comparing the resulting streamlines, the spread of the injected fluid front, and the sweep efficiency of the front.

### MODELING RESULTS

Three distinct zones are apparent on the cross sectional permeability models because of the distribution of lithofacies (Figure 11). The upper and middle portions of the model (thinly bedded dolograinstones-dolowackestones and dolopackstones-dolowackestones) have lower average permeability than the lower portion of the model (thick, porous dolowackestones). Permeability in the resulting cross sectional models exhibits values that range from 0.01 to 300 md (Figure 11). In model CS1, the relatively greater permeability heterogeneity compared to the other models is caused by the nugget-effect and short-range components of the variogram (Figure 11A).

Model CS2 incorporates a hole-effect component with a magnitude equal to 10% of the permeability variance (Figure 11B) and, therefore, exhibits an additional scale of heterogeneity compared to model CS1. As the contribution of the hole effect increases in each successive model (e.g., CS3 and CS4), the short-range patterns become less distinct, and the permeability continuity becomes more evident (Figure 11C, D).

The plan-view models depict similar patterns of permeability heterogeneity as the cross sectional models (Figure 12). Given the scale of the plan-view model, these changes are more easily discernable. As the contribution of the hole effect increases (PV2, PV3, PV4), the long-range permeability continuity associated with the hole effect becomes more evident (Figure 12B–D).

The streamline simulation results for the cross sectional (Figure 13) and plan-view (Figure 14) models
indicate that as the magnitude of the hole effect increases from 0 to 25%, the BTT becomes longer (Table 1). In addition, the reservoir volume drained at BTT, a measure of sweep efficiency, also becomes higher as the magnitude of the hole effect increases to 25% (Table 1). However, an increase in the magnitude of the hole effect from 25 to 50% results in shorter BTT. This trend is directly related to lower permeability.

Figure 11. Permeability distributions for the cross sectional models of sequence I at Sheep Canyon. Permeability distributions resulting from a progressive increase in the magnitude of the hole effect are shown for (A) CS1 (0% hole effect), (B) CS2 (10% hole effect), (C) CS3 (25% hole effect), and (D) CS4 (50% hole effect).
heterogeneity and, thus, the lower degree of tortuosity. As a result, a corresponding decrease occurs in the volume drained at BTT because of the more direct fluid-flow paths from the injector to the producer.

Model CS4 (50% hole-effect magnitude) is the exception, in that it does not conform to the trend of higher sweep efficiency with longer BTT (Figure 13D; Table 1). This simulation depicts the shortest BTT

Figure 12. Plan-view permeability models of the basal porous skeletal dolowackestone facies (Figure 5). Permeability distributions resulting from a progressive increase in the magnitude of the hole effect are shown for (A) PV1 (0% hole effect), (B) PV2 (10% hole effect), (C) PV3 (25% hole effect), and (D) PV4 (50% hole effect).
(2720 days) as well as the highest sweep efficiency (greater volume drained). This is most likely the result of the highly correlative, long-range, hole effect that dominates the distribution of permeability.

**DISCUSSION**

The petrophysical modeling and streamline simulation results are directly related to the changes in the short- and long-range permeability structure. With up to 25% hole effect, the permeability distribution exhibits relatively smaller regions of baffles and conduits (Figure 13A–C). Because the dominant permeability variability is primarily attributed to the nugget effect and the short-range variance, a relatively higher permeability heterogeneity exists. The higher permeability heterogeneity results in a more tortuous pathway that lengthens the overall BTT; however, a larger area of the reservoir is contacted by the injected fluid, yielding the relatively higher sweep efficiency (Table 1). As the magnitude of the long-range structure increases
Figure 14. Streamline simulation results for plan-view models PV1 to PV4. Time from injector (TFI) is displayed at breakthrough time (BTT) for plan-view models (A) PV1 (0% hole effect), (B) PV2 (10% hole effect), (C) PV3 (25% hole effect), and (D) PV4 (50% hole effect). Time from injector is the amount of time for injected fluid to reach locations in the model for the given boundary conditions. The corresponding BTTs are shown and presented in Table 1.
beyond 25%, the small-scale heterogeneity becomes less distinct (Figure 11D), and the permeability continuity becomes more evident. This leads to a more direct or less tortuous pathway through which fluids travel. As a result, BTT and sweep efficiency are reduced because of the more direct flow paths (Figure 13; Table 1).

Streamline simulations (Figures 13, 14) suggest that BTT, sweep efficiency, and appearance of injected fluid fronts in dolomite reservoirs are affected when the magnitude of a long-range cyclic structure is greater than 10% of the lateral permeability variance. With this type of long-range structure, a more tortuous pathway exists through which the fluids must travel, thus affecting BTT, sweep efficiency, and the appearance of the injected fluid front.

Whereas this study investigates the effect of different hole-effect magnitudes on fluid flow, Jennings et al. (1998) compared three permeability scenarios in dolomites: one that included a short-range structure, one that included a long-range structure, and one that combined both short- and long-range structures. Like Jennings et al. (1998), our results also conclude that the long-range cyclic structure in dolomites, as observed in the supporting outcrop data, could be significant even when short-range variability composes most of the variance. Variography from the petrophysical data at Sheep Canyon shows that the hole effect is equivalent to approximately 10% of the total variance. Other authors have reported larger magnitudes of the long-range petrophysical variance in other lithofacies (Jennings et al., 1998).

These findings show that multiple scales of variability exist in dolomite rock fabrics of the San Andres and Madison formations and potentially other or all dolomites. The geologic origin of this variability is the subject of ongoing studies. One hypothesis is that it is related to a self-organizing process associated with dolomitization (Pranter and Budd, 2004). In addition, these results suggest that subsurface characterization and modeling of dolomite reservoirs should account for heterogeneity associated with these long-range lateral periodicities if they are greater than 10% of the petrophysical variance.

CONCLUSIONS

Dolomite lithofacies sampled at Sheep Canyon, Wyoming, exhibit three scales of lateral petrophysical variability in single rock fabric units. Similar to the San Andres Formation, these include a nugget effect, a short-range structure, and a long-range cyclic trend (hole effect). The nugget effect accounts for approximately 35 and 50% of the porosity and permeability variance, respectively. The short-range porosity variance was modeled with an exponential and spherical variogram model with horizontal ranges from 6 to 16 ft (1.8 to 4.9 m), and permeability was modeled with a spherical variogram model with horizontal ranges from 8 to 16 ft (2.4 to 4.9 m). The long-range variability is equivalent to approximately 10% of the total variance and was modeled with a hole-effect variogram model.

Streamline simulation models that include low to moderate magnitude (0–25%), long-range cyclic structures have longer BTTs and higher sweep efficiencies relative to models that include higher magnitudes of the cyclic structure (>25%). For lower magnitudes of the long-range permeability trend, the permeability distributions exhibit more small-scale heterogeneity. This permeability heterogeneity creates a more tortuous pathway for fluids, resulting in a longer BTT and higher sweep efficiency. Reservoir models that incorporate hole-effect magnitudes that are greater than 25% of the total variance result in shorter BTTs and lower sweep efficiency. As the magnitude of the long-range structure increases, the small-scale heterogeneity becomes less distinct, which leads to more direct, continuous pathways for fluid flow. Although near-random and short-range variability account for most of the heterogeneity, the long-range structure can significantly affect fluid-flow behavior.

These results suggest that it is important in subsurface characterization and modeling of dolomite reservoirs to account for heterogeneity associated with multiple scales of variability in dolomite rock fabrics, and that analog outcrop data are critical to address the
issues regarding lateral variability. In addition to the San Andres and Madison formations, other dolomite formations of various ages should be evaluated to further quantify these multiple scales of variability and to address the geologic controls on their origin.

REFERENCES CITED


Kittridge, M. G., 1998, Analysis of areal permeability variations—San Andres Formation (Guadalupian), Algerita Escarpment, Otero County, New Mexico: Master’s Thesis, University of Texas at Austin, Austin, Texas, 361 p.


