NON STANDARD CORE ANALYSIS AND GEOLOGIC MODEL CONSTRUCTION

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ABSTRACT

For modeling the complex geology at the Pennsylvanian SACROC Unit, new core was obtained by utilizing several new techniques to preserve key features or provide adequate detail on the analysis, including analysis of twelve-inch whole core samples. To maximize the value of new core data for model development and scale-up exercises, a "scale down" exercise was performed on selected samples: twelve inch whole core samples were analyzed then cut into six inch whole cores, two inch whole cores, and selectively plugged. Various analyses were run on each of the smaller samples to quantitatively evaluate the effects of sample size. This analysis showed vertical permeability (Kv) to be sensitive to sample size, in that smaller samples tend to overestimate Kv compared to their longer counterparts, especially in ranges less than 10 millidarcies (mD). The modeling implication is that cores analyzed with standard methods do not adequately sample barriers to vertical flow.

INTRODUCTION

Kinder Morgan CO_2 Company, L.P. ($KMCO_2$) is planning to expand its existing CO_2 flood into a highly complicated Pennsylvanian Reef complex (Canyon Formation and Cisco Formation) at the northern end of the SACROC Unit in the Kelly-Snyder Field of Scurry County, Texas. It is critical in the early stages of flood design to be able to predict fluid flow paths and the flood response since the geology is highly heterogeneous, and the CO_2 is an expensive injectant. The answers to different questions than the ones that are typically posed for reservoirs under primary development scenarios are required for tertiary operations. These different objectives require a new slant on what types of data and analysis are needed to answer these new questions. With that in mind, $KMCO_2$ reviewed their current rock database and found that there were still a few questions the database could not answer. Standard core-collection practices were reviewed to see if there was potential for a process redesign which would allow these questions to be answered. There were several items on which improvements were made. We feel these changes improved the process, reduced risk, and addressed the data collection concerns (Raines and Helms, 2005).

Therefore, $KMCO_2$ planned various core locations to address specific problems in particular portions of the reservoir. The key areas of concern that precluded the exclusive use of existing data included: adequate characterization of vertical permeability (Kv); characterization of core to wireline response; internal continuity of flow units; identification of karst zones; the nature of various significant bedding contacts (i.e. sealing or transmissive); and a detailed look at the phi-K relationships in the Cisco Formation.

BACKGROUND

Reservoir Modeling

High quality core data is an essential component of reservoir modeling, especially in tertiary recovery projects. In order to optimize their design and operation, reservoir and production engineers rely on flow simulations. Flow simulations in turn rely on geologic models, and one of the key components of geologic models is the relationship between porosity and permeability. In tertiary projects, this is especially true in the vertical direction, where density segregation and vertical communication may be of concern. The only way to get a one-to-one representation of the porosity vs. permeability (Phi-K) relationships in the reservoir is through core data. The petroleum industry has long recognized that carbonate reservoirs are highly variable and that larger sample sizes yield more accurate core analysis results in these heterogeneous reservoirs (Pollard and Reichertz, 1952; A.P.I. RP-40, 1960). That is why $KMCO_2$ decided to investigate the influence of core sample sizes on vertical permeability (Kv) measurements.

Data Utilization and Needs

Primary and tertiary development efforts are focused on understanding different aspects of the reservoir, and the majority of cores available for study at the SACROC Unit were taken during primary field development. This fact has two implications: 1. much of the available data pre-dates modern analysis techniques; 2. the modern data that is available was taken with a focus on the data which would be needed for initial field development.

Today, current industry standards for core analysis incorporate a significant time-saving step: a six to eight inch segment is cut from each one-foot length of core. That segment is cleaned, analyzed and used as a proxy for the whole foot, saving up to 50% of the time required for analysis. This is perfectly acceptable since primary projects focus on using permeability to understand deliverability, often in lateral directions only, while all other data is used to quantify volumetrics. Tertiary projects, on the other hand, need to address questions relating to reservoir quality in general, how it varies in specific areas, and where baffles / barriers exist. This information is used to evaluate the feasibility of CO_2 flooding under various development scenarios, optimal production pattern configuration(s), volumes and timing of injectant purchases (CO_2 and water), migration of various phases within the reservoir, communication potential within and between zones, and above all, economic impacts. This type of development has too many moving parts to effectively answer analytically, and the economic risk can be very significant if the wrong approach is taken, so computer modeling (including flow simulation) must be done instead. A reliable simulation model is dependent on having a representative geologic model. The geologic model is tied to both wireline and core analysis data for volumetrics, but core analysis is the only direct way to measure permeability over the entire reservoir and to discern relative contributions from individual zones. Further, if the permeability relationships are properly understood, wireline-based porosity models can be transformed to permeability volumes using Lucia's (1995, 1999) global transforms. Understanding vertical communication within and between zones is also critical to evaluating CO_2 flood designs. The density contrasts between oil, hydrocarbon gas, water, and CO_2 may be very significant, depending on reservoir conditions.

In the author's experience, vertical permeability (Kv) is typically the least honored geologic parameter used in flow simulations, simply because a history match frequently cannot be obtained without drastically modifying Kv. Currently, it is not clearly understood if industry standard Kv measurements are adequate for tertiary models, and / or if there is a way to use “modern” Kv data, alone or in conjunction with horizontal permeability (Kh) to accurately infer Kv at the flow unit scale. The size of the sample used in core analysis measurements has been an industry concern for some time (Pollard and Reichertz, 1952; A.P.I. RP-40, 1960). The size of samples from which Kv is derived has a significant impact on scale-up procedures. To address the issues of scale-ability between the twelve inch analysis techniques reported in this paper and standard modern practices, a special "scale-down" exercise was performed, allowing comparisons between twelve-inch whole core (WC), six-inch WC, two-inch WC, and plug data. These results from the scale-up investigation impact how other SACROC Unit core analysis data is used in the geologic model.

PROCEDURES

Coring

Several procedures were implemented to minimize core breakage and maximize core recovery. The first of which was limiting core runs to a maximum length of fifty-eight feet per attempt. The inner barrels of the coring assembly were aluminum sleeves. To ensure fresh personnel on location at all times, two experienced core engineers were required to monitor the coring process 24 hours a day. 897 feet of core was cut with 100% recovery by following these procedures.

Collection

The cores were collected at the well site. The two thirty foot long aluminum inner barrels were removed from the core barrel and laid on the cat walk. The thirty foot long aluminum inner barrels were immediately capped and loaded on a trailer for transportation to the laboratory in Midland, Texas. Once the core reached the laboratory, the aluminum barrels were cut into ten foot lengths. The core was laid out on a table where the drilling mud was wiped off. The core was fit together, labeled with orientation lines, and the depth was marked on the surface of the core. A master orientation line was marked on the core where the core fit together with no rubble zones or spinners. Fifty-seven foot long segments were present, in which no spinners or rubble zones were observed. Individual pieces of core as long as eleven feet without a break were obtained.

Analytical Methods

$KMCO_2$ requested that the core be sampled in twelve inch lengths to identify vertical permeability barriers present at the one foot scale and to capture potential multi-zone communication across barriers. Porosity and permeability measurements were performed on the twelve inch samples. Plugs were drilled in the K-90 horizontal direction and analyzed when the WC samples were too broken for analysis. Thirty-five WC samples were selected and cut into six inch disks. These six inch samples were scattered throughout the entire core. They were selected to represent low, medium, and high permeability zones. Vertical permeability was measured on the six inch disks. The six inch samples were then cut into two inch disks. Porosity and permeability measurements were performed on these samples. Plugs were drilled from selected samples (representing approximately 25 different zones) in horizontal or vertical orientations. Porosity and permeability was measured on the plugs. Horizontal permeabilities for one foot, six inch, and two inch disks are reported as K-0 and K-90. An additional 108 plugs were drilled in the K-90 horizontal direction and Phi-K was measured. However these plugs were taken in a karsted Cisco interval and do not represent the entire reservoir, so they are not included in the following data comparisons.

DISCUSSION

Whole Core Analysis

Twelve inch full diameter data was examined as a stand-alone dataset. Samples that were too broken for analysis are not included in the analysis, nor are Kv datasets. An average Kh was calculated for use in comparisons with other (old) datasets. In the WC samples, full length Kv is approximately half an order of magnitude smaller than the average Kh.

Vertical Permeability

Examining the relationship(s) of Kv to sample length was one of the key drivers for the scale-down study. Though the small scale Phi-K datasets exhibit the same character as WC, direct comparisons to parent samples demonstrate that neither plug data nor two inch WC can be utilized to predict depth specific twelve inch permeability values.

To determine if the differences between large and small sample sets were related to sample size or core analysis methodology (plug and WC are measured in different permeability apparatus), the methods were reviewed. Since the Kv calculated on plugs and the two inch disks is essentially the same, both permitted flow through the same relative percent of their surface areas. Therefore, when Kv is calculated in the laboratory, the differences seen between large and small samples are not due to differences in measurement techniques, or surface area, but are attributable to sample height. This short sample effect is an indication that there is a depositional pattern which results in small scale vertical permeability barriers on the +/- one foot scale. These barriers cannot be characterized with two inch scale samples. These barriers are readily apparent in core analysis when sample sizes of six inch or longer are utilized.

Six inch samples more closely match the depth specific twelve inch sample Kv measurements. The six inch samples do have more variability than the twelve inch samples, but the six inch samples are equally likely to overestimate or underestimate twelve inch Kv data. Arithmetically averaged six inch sample data is similar to the twelve inch data above 1 mD. Below 1 mD, Kv is overestimated by the six inch samples.

Horizontal Permeability and Porosity

Beginning with the 2" disk experiments, Kh was added to the scale-down investigation. Measurements were taken in the same K-0 and K-90 directions as the original twelve inch samples. The Phi-K relationships of the SACROC 37-11 plug Kh, WC Kh, and the two inch disk Kh data are similar.

Horizontal plug permeability data underestimates Kh when compared to depth specific WC data until the plug permeability values exceed 1 mD. Even above 10 mD, plug data tends to slightly underestimate depth specific WC Kh. The capability to accurately measure low permeability values (.01 – 1.00) on plug and WC samples is the same. Again sample size is the key factor in the permeability differences between small and large samples.

Plug porosity, two inch WC porosity, and twelve inch porosity measurements are similar (+/- 3%). This indicates that porosity is scalable from plug scale or two inch scale to the twelve inch sample equivalent.

Old, Modern, and New Core Data

Phi-K trends of old and modern core analysis were compared to the SACROC 37-11 using a standard permeability vs porosity plot. Samples ranging in size from 1” to 18” were utilized in these comparisons. The Phi-K relationships did not appear to be influenced by sample length. When modern plug, two inch, six inch and twelve inch sample data from the SACROC 37-11 was plotted on a standard permeability vs porosity plot, the Phi-K relationships were very similar. The similarity between trends exhibited by the different sample sizes indicates that an intrinsic Phi-K relationship exists in the Cisco and Canyon Formations. Since this apparent Phi-K relationship exists, we were able to use a standard permeability vs porosity plot as a screening tool.

Core analysis was performed in the 1950's on a large number of wells in the SACROC Unit. The average Kh and Kv data from the SACROC 37-11 was compared to data from several old wells (1950's vintage). Approximately 2/3 of the old wells exhibited Phi-K relationships which were similar to the Phi-K relationship seen in the SACROC 37-11. Approximately 1/3 of the old wells exhibited Phi-K relationships which did not correlate with the SACROC 37-11 Phi-K plots. Plug analysis data was available from several of these older wells. The old plug analysis data did not correlate with the new WC data in any of the wells reviewed. Even when the old plug analysis is compared to old WC analysis from the same well, analyzed by the same laboratory in the same time frame, the data exhibits very different Phi-K relationships. Different analytical techniques are probably the cause of the discrepancies in the data.

A few SACROC Unit wells were cored in the 1980's and analyzed using modern core analysis techniques. The core analysis data from these wells matches the Phi-K relationships exhibited in the SACROC 37-11.

Before any core analysis data is used in a reservoir model, it should be compared against modern vetted core analysis data to insure the data follows the same trends. The data should not be included in the reservoir model if it exhibits different trends than the modern vetted data.

CONCLUSIONS

- New procedures resulted in 100% recovery of 897' of continuous core.
- Scale down analysis shows Kv to be sensitive to sample size. Samples less than 6" in height tend to overestimate Kv at the 12" scale.
- Phi-Kv is similar for modern plug, 2", 6", and 12" datasets, but Kv subsets do not match their parent samples in lower Kv ranges.
- Old plug data (1950's) never matched the Phi-K relationships seen in modern data.
- When averaged, 2" Kv datasets match parent samples above 10 mD and 6" Kv datasets match above 1 mD.
- Measurement variability between small and large Kv samples is a result of sample height.
- In well 37-11 there is a basic cyclicity that results in vertical barriers at the 6" to 12" scale that affect the gross Kv. To model flow units, sample heights must be greater than 6".
- 37-11 plug and WC Phi-Kh relationships are similar. However, depth specific plugs tend to underestimate 12" WC Kh.
- Porosity values on all 37-11 datasets were consistent and adequate for model construction.
- Core data should not be trusted until it has been vetted.

TERMINOLOGY

flow unit - self-contained reservoir interval, through which fluids migrate (typically in a lateral direction)
history match - the process used in flow simulations to match actual oil well performance, typically by specifying either pressure or oil rate and allowing the simulation to calculate all other production streams
K-0 - Kh measured in direction #1, (perpendicular to the slab face) as indicated by the orientation lines marked on the core surface
K-90 - Kh measured perpendicular to K-0 (parallel to the slab face)
Kh - horizontal permeability
K-max - maximum horizontal permeability
K-min - minimum horizontal permeability
Kv - vertical permeability
modern core analysis – fluids removed from the core by solvent extraction prior to Phi-K measurements
scale-up - process by which very fine resolution data is converted into a coarser equivalent during flow simulation exercises
spinner – two ends of core which have been grinding against each other making smooth surfaces which do not fit together
whole core (WC) - full diameter core cylinder of any length

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