DECIPHERING CORE AND LOG POROSITY DIFFERENCES AND EVALUATING THE SCALE DEPENDENCE OF CORE ANALYSES IN A COMPLEX LITHOLOGY

June Gidman, Frank. J. Conner, and Dennis J. Fischer*
Chevron Petroleum Technology Co, La Habra, CA.
* Chevron Overseas Petroleum Inc, San Ramon, CA.

Core porosities from a mixed siliciclastic/carbonate reservoir in offshore West Africa average close to 20%, whereas log porosities average 30% over the same interval. This discrepancy resulted in large uncertainties in estimations of reserves and remaining oil in place. It was assumed that the reservoir was vuggy and that core analysis techniques were underestimating porosity. As a prerequisite to a waterflood feasibility study of the field, it was essential to resolve the core/log porosity differences. Three new wells were cored and great care was taken in developing the core analysis program. Measurements were made at full-diameter, plug, and minipermeameter scales, and quality control steps were incorporated into the program.

The reservoir geology was studied in detail with emphasis on petrophysical characteristics. Minipermeameter data show extreme heterogeneity across slabbed core. Similarly minipermeameter measurements made on each end of routine core analysis plugs show variations up to three orders of magnitude between the two ends. Comparison of full-diameter and plug data shows that plugs underestimate permeability below 80 mD. A power law relationship between full-diameter and plug permeabilities was used to scale-up plug data below 80 mD. Porosity is not scale-dependent, and no significant differences were found between plug and full-diameter data.

Vugs were not significant in the core, but burrow mottling was very common and resulted in heterogeneous rock fabrics. The poorly consolidated silt-filled burrows are surrounded by tight silty dolomite. The outside of the cores and the borehole wall have significant small-scale rugosity that was measured as porosity by the logs. The greatest discrepancies between log and core porosities correspond to intervals of burrow mottling.

Both the core and the log porosity data were "correct." The density log was performing normally, but the surface it was measuring was not representative of the formation.

INTRODUCTION

For the reservoir described here, porosities from logs average close to 30%, whereas core analysis porosities average 21%. Before the rocks were studied in detail, it was speculated that the log data were "correct" and that the reservoir was vuggy and not represented by the core. The field is located in offshore West Africa, and the reservoir is shallow (<2000 ft ss) and composed of Late Cretaceous mixed carbonates and siliciclastics. The field is still on primary production but was to be assessed for waterflood feasibility. The differences between core and log porosities result in large uncertainties in reserves and remaining oil in place.

As part of a waterflood feasibility program, detailed geological work included analysis of modern logs, construction of cross sections, and development of a geologic model for waterflood simulation. (As used here, "geological model" means incorporation of facies, depositional and diagenetic characteristics of the rocks with petrophysical and log data, designation of reservoir zones, and development of porosity and permeability transforms for the simulation.) As part of this study, it was essential to resolve the core-to-log porosity differences.

CORE AND LOG DATA

Three new wells were drilled and cored as part of the study, and the logging suite included neutron-density logs. In addition, the HLS CAST (Circumferential Acoustic Scanning Tool) borehole televiewer was run in two of the wells. The log data were quality controlled and then processed using either the neutron-density crossplot or interpretation of the density log using the formations' average matrix density (2.74 gm/cc). Both of these methods resulted in a significant bias between log and core porosity over much of the reservoir (Figs. 1 and 2).

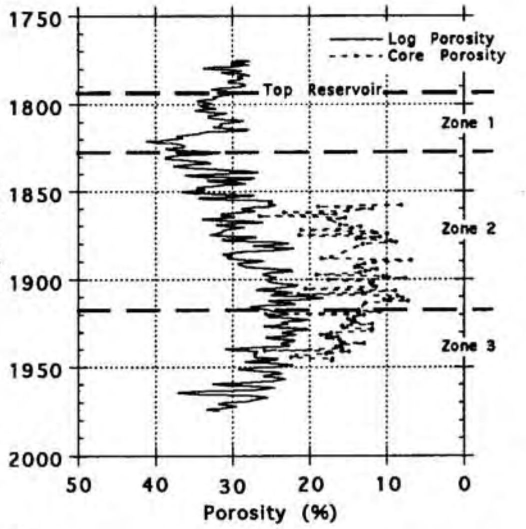


Fig 1

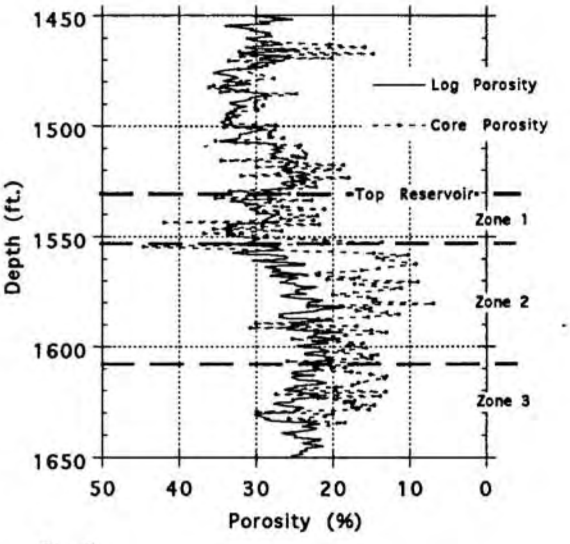


Fig 2

Figs 1 and 2. Porosities calculated from the neutron-density crossplot (Fig 1) and from the bulk density log using a matrix density of 2.74 gm/cc (Fig 2) are approximately 10 p.u. higher than core analysis data. The major discrepancy between core- and log-derived porosities correlates with zone 2.

In 1991 approximately 130 ft of 4-in. diameter core were recovered from three wells. The cores were cut in fiberglass liners and sent to the U.S. for analyses. Since quality of the core data was an important issue, a very detailed core analysis program was written and data checks were incorporated. Archimedes, Boyles' Law, and caliper data were collected. Bulk volume could be estimated from caliper, Boyles' Law, and Archimedes measurements, and pore and grain volumes from Archimedes and Boyles' Law. Comparisons between the results of these techniques were used to identify problematic data and samples that needed to be remeasured. As the data were measured, we received all of the raw measurements and maintained ongoing quality control.

Initially the cores were CT-scanned and visually inspected to select core analysis locations. If the rock was heterogeneous on a scale greater than a core plug or contained centimeter-sized (or larger) pores or vugs, then full-diameter samples were measured; otherwise, one-inch diameter plugs were used. Once full-diameter measurements were complete, plugs were also cut from the centre of the same lengths of core. This allowed direct comparisons between full-diameter and plug analyses for the same section of core.

Permeability measurements were made at both ends of all of the core plugs using an electronic minipermeameter. The electronic minipermeameter is a Chevron research device with an experimentally determined range of 0.003 mD to 10D. Measurements are repeatable to within 2%. The minipermeameter measurements are within 10% of plug permeability measurements based on calibration experiments using 'homogeneous' plugs (Goggin 1993).

Archimedes and caliper data are at ambient conditions and were used largely for quality control, not for correlation with log data. Boyles' Law measurements at 1000 psi better represent petrophysical properties in the reservoir. Both Boyles' Law and Archimedes measurements can underestimate porosity in samples that have surface vugs. The saturated weight of a sample is input into Archimedes porosity calculations and may be underestimated as surface vugs drain. During Boyles' Law analysis the Hassler sleeve can penetrate and reduce the measured volume of surface pores. Unless indicated otherwise, the data shown here are from Boyles' Law analyses.

Quality Control of Core Data

Log data are traditionally quality controlled. Calibrations are recorded before and after logging. Repeat sections are run and records are kept of observations that are made during logging. Core data quality control, on the other hand, is commonly poor on the part of the measuring laboratory and nonexistent on the part of the operator. Whattler (1991) eloquently described these problems and, among other things, he strongly advocates specifying detailed work instructions and collecting all the raw data. In addition to this, we designed a core analysis program that incorporated different measurements of the same sample property. For example, bulk volume by Archimedes, caliper, and Boyles' Law techniques. This added very little to cost and contributed greatly to our ability to identify problem data.

The contractor measuring the core analysis data was aware that the customer was closely scrutinizing all the raw and reported data. Quality control is time-consuming and tedious but it is worth noting some of the results, as there are few examples of this type of effort documented in the literature.

Five percent of the samples were seriously in error and had to be remeasured. In the first draft report, 25% of the data differed from the original raw data. The mistakes were largely transcription errors that in turn produced calculation errors. In the subsequent draft report, a third of these errors had been corrected, but new ones appeared. The majority (95%) of the errors resulted in small variations in the end numbers; for example, 0.2 porosity percent or 0.02 gm/cc grain density difference. The remaining 5% gave vastly different data. We ultimately ended up with satisfactory data, but the process illustrated the need for, among other things, informed customers in the operating companies.

RESERVOIR GEOLOGY

The rocks are mixed siliciclastics and carbonates with a strong diagenetic overprint and range from mudstone through dolomitic siltstone to silty dolomite, with no carbonate-free siliciclastics and no siliciclastic-free carbonates. Siliciclastic grains are almost entirely coarse silt and rarely very fine sand. The cores are bioturbated throughout, and well-preserved primary sedimentary structures are extremely rare. The reservoir rocks were subdivided into lithofacies based on lithology, carbonate content, and estimated differences in reservoir quality. In general the rocks can be grouped into siliciclastic-dominated (mudstone, argillaceous siltstone and siltstone) and carbonate-dominated (mottled siltstone and silty dolomite) lithofacies. The more siliciclastic-rich facies also occur in the overlying formation.

Mottled siltstone is the most common lithofacies in the reservoir. Rocks of this lithofacies have brown mottles of poorly cemented siltstone surrounded by light gray silty dolomite. The mottles are an inch or so in diameter and are cross-cutting *Thalassinoides* burrows. Most porosity and permeability is confined to the poorly cemented siltstone burrow fills. The surrounding gray silty dolomite is tight. The mottles are most distinctive where the rock is oil filled, because the porous burrow-filling siltstone is oil stained; whereas, the surrounding silty dolomite is not. The outer surface of much of the mottled siltstone core is irregular and gives the impression of being vuggy. Much of this surface roughness was caused during coring by washout of poorly consolidated siltstone from within burrows. Intervals of this lithofacies can be as much as 40 to 50 ft thick.

Vuggy Intervals

Initially it was suspected that vuggy intervals were common in the reservoir and might in part explain the discrepancy between core and log porosity. From examination of the cores and logs, including a borehole televiewer (HLS CAST) log in two of the recent wells, we concluded that there was little vuggy porosity.

Vuggy intervals make up only a minor portion of the cores. The vugs are either dissolved shells or dissolved anhydrite nodules. The most permeable rocks are those that contain many large dissolved shells. The dissolved anhydrite nodules tend to form only isolated vugs that do not contribute significantly to permeability. In the three recent wells, less than 4% of the section contained large, connected shell-moldic vugs. The shelly layers are typically a few inches thick and are not likely to be laterally continuous between wells. While these are locally significant, vugs in general do not explain the consistent differences between core and log porosities through almost the entire reservoir.

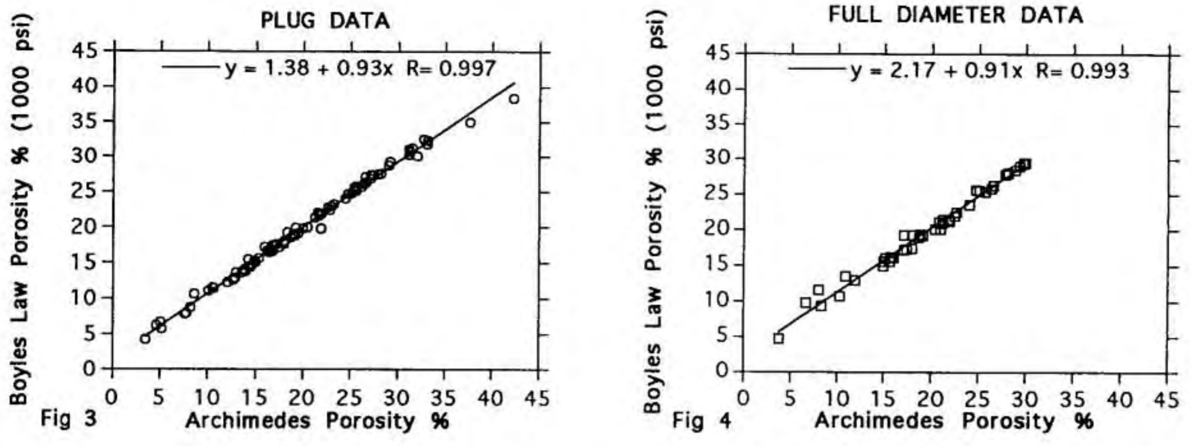
Reservoir Zonation

Based on the predominant rock type, the reservoir was subdivided into three zones: an upper clastic zone, a carbonate zone, and a lower clastic zone. The upper clastic zone and the carbonate zone are productive; the lower clastic zone rocks are mostly nonreservoir quality. The carbonate zone is the thickest zone of the productive reservoir, between 30 and 100 ft thick over the field. It is characterized by low gamma and contains predominantly mottled siltstones with some indurated siltstones. This zone shows the most significant core/log porosity discrepancies.

COMPARISON OF ARCHIMEDES AND BOYLES' LAW POROSITY

Figures 3 and 4 show correlations between Archimedes and Boyles' Law (1000 psi) helium porosities for both plug and full-diameter samples from the three new wells. The high-porosity samples are mostly siltstones and indurated siltstones, and were not heterogeneous enough to warrant full-diameter analyses.

Most of the Archimedes and Boyles' Law porosities are within 0.5 p.u. (porosity units) of each other. Some of the higher porosity plug samples have Archimedes porosities over 1 p.u. higher than Boyles' Law values. These samples are the least cemented and most compressible of the siltstones; hence the greater impact of stress when measured by Boyles' Law. Some of the low-porosity full-diameter samples have Boyles' Law values over 1 p.u. higher than Archimedes. These samples were probably incompletely saturated during measurement of Archimedes data.



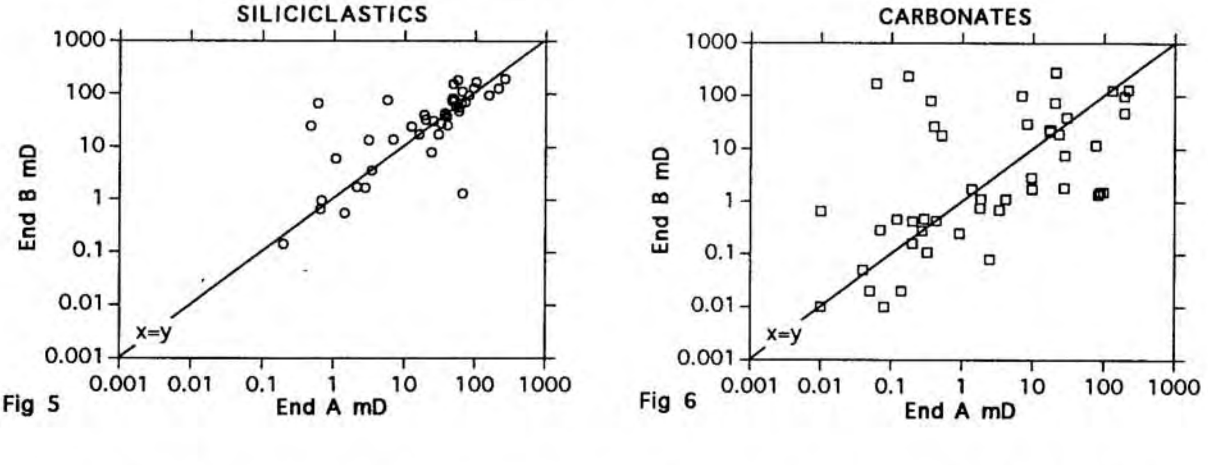
Figs 3 and 4. Comparison of Boyles' Law and Archimedes porosities for the plug data (Fig 3) and full diameter data (Fig 4)

PERMEABILITY MEASUREMENTS AT DIFFERENT SCALES

Permeability data were collected at three scales: full diameter, one-inch plug, and electronic minipermeameter.

Comparison of Full-Diameter, Plug, and Minipermeameter Data

Minipermeameter measurements were made at both ends of the core plugs. Figures 5 and 6 show comparisons between the two end measurements for the siliciclastic and carbonate facies. The siliciclastics have few values below 1 mD, and the values measured at each end are similar as the data fall close to the x=y line.



Figs 5 and 6. Minipermeameter measurements at each end of a plug from the siliciclastic lithofacies (Fig 5) are fairly similar and fall close to the x=y line while those from the carbonate lithofacies (Fig 6) are widely variable. The carbonate data scatter reflects the heterogeneity of these rocks.

The carbonate data show more scatter because of their greater heterogeneity and were replotted to show the variation between the measurements at the two ends of the plugs (Fig. 7).

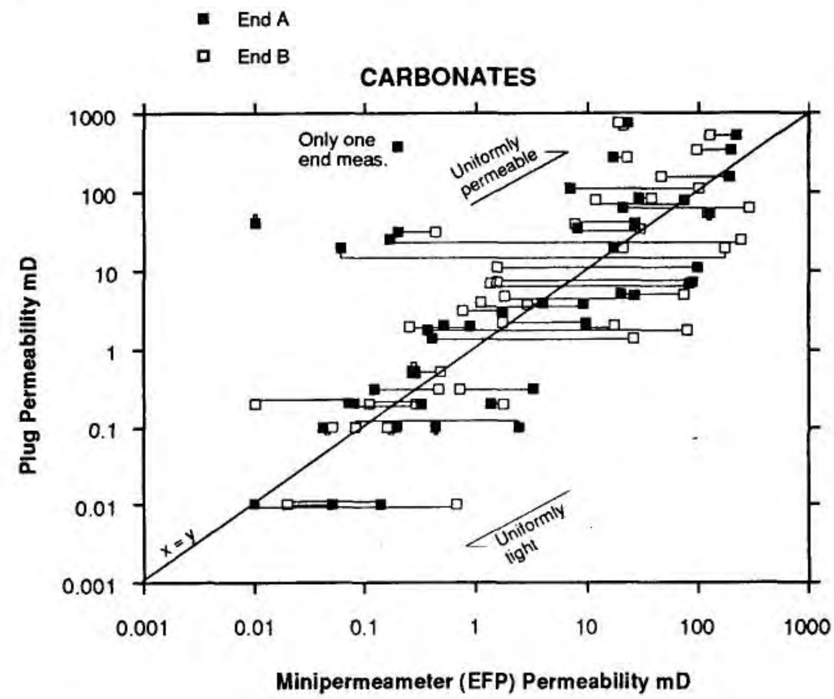
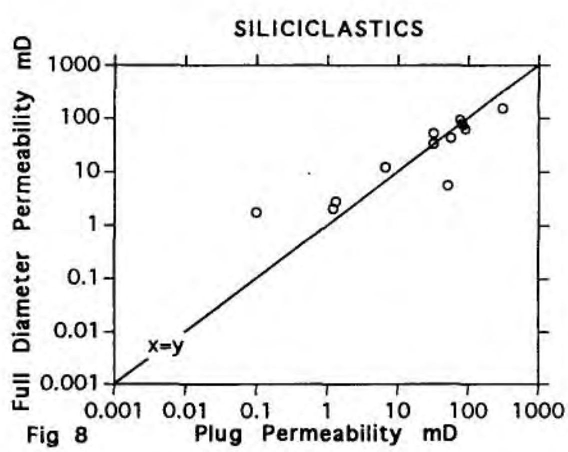
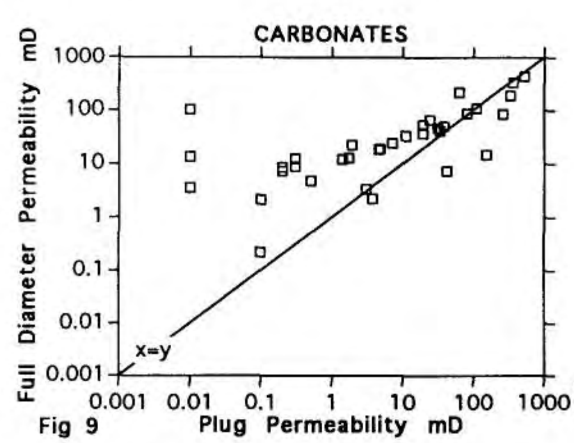


Fig 7. Comparison between the minipermeameter data measured on each end of a plug and the equivalent plug analysis permeability.

The greatest differences between the two ends are for samples that fall within the middle of the permeability range. The high-permeability samples appear more uniformly permeable and presumably have less carbonate; in other words, they are more like the siliciclastics. The low-permeability samples are more uniformly tight at the scale of measurement captured by a plug. The plugs that are in the middle of the distribution are heterogeneous, and permeability from one end to the other can vary by up to three orders of magnitude.





Figs 8 and 9. Full-diameter permeability compared to data measured on a plug cut from full-diameter for siliciclastic (Fig 8) and carbonate (Fig 9) lithofacies.

Figures 8 and 9 show crossplots of plug versus full-diameter permeabilities for the siliciclastic and carbonate facies. For the siliciclastics, the data tend to fall close to the x=y line. This indicates that the scale of heterogeneity in these rocks is low and that a plug is an adequate sample size for permeability measurement. By contrast, most full-diameter carbonate samples have higher permeabilities than the plugs cut from them, and the values only start to come close to the x=y line at values above about 80 mD.

Thirty-two of the thirty-five carbonate samples in Figure 9 are mottled siltstones and the other three are silty dolomites. The discrepancy between full-diameter and plug data results from heterogeneity of the mottled siltstones. To evaluate the heterogeneity of a typical mottled siltstone sample, 24 minipermeameter measurements were made on the slabbed surface from a length of core that had been measured by full-diameter analysis (Fig. 10). The full-diameter sample measured 12.2 mD, the plug 1.4 mD, and the minipermeameter values ranged between 0.003 and 104 mD, with an arithmetic mean of 10.3 mD. High and low values are adjacent and less than an inch apart. Eighteen of the twenty-four minipermeameter measurements are lower than the full-diameter value of 12.2 mD. This indicates that, with these small-scale measurements, there is a 3:1 chance of measuring low permeability for these mottled siltstones.

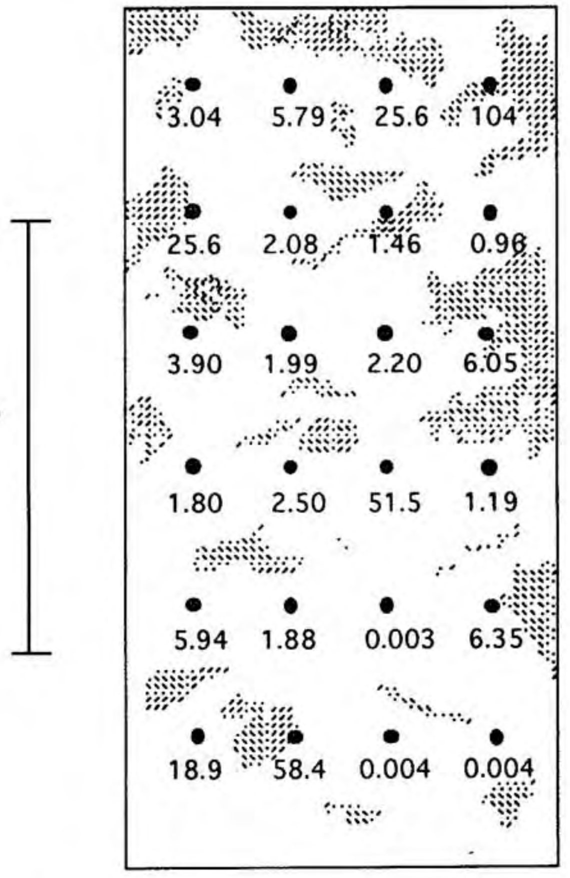
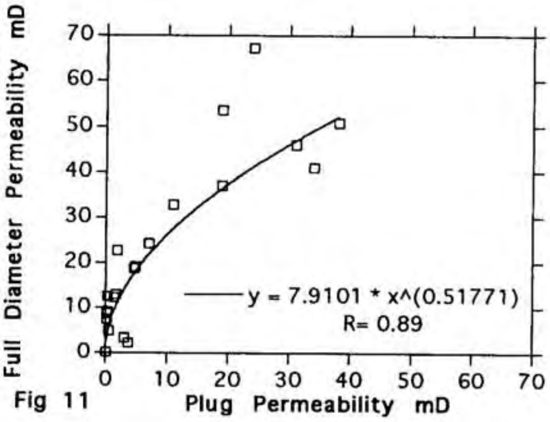


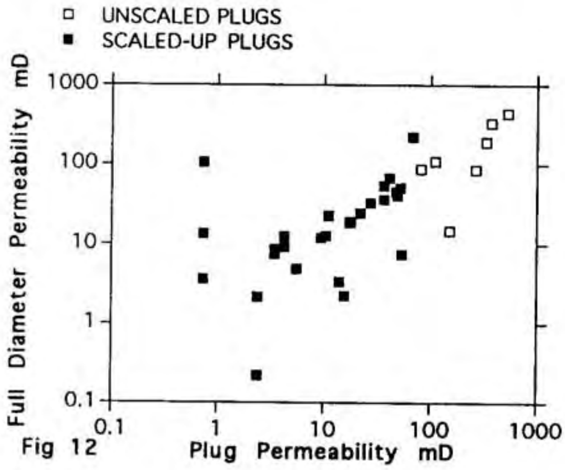
Fig 10. Minipermeameter measurements illustrate the permeability heterogeneity of mottled siltstones.

The size of the full-diameter samples was estimated to capture the extent of the macroscopic heterogeneity, and therefore the resulting data should adequately represent the rock. Permeability in the mottled facies is limited to the porous silty mottles, and the carbonate-cemented areas are tight. As the amount of carbonate increases, there is less and less chance that a plug can be cut that would not include a tight carbonate streak running across it somewhere within its length. Therefore, there is an increased chance that the plugs would measure very low permeability. There is also probably a sampling bias in that, to get a good cylindrical plug, there is a tendency to avoid the more friable, permeable areas of the rock. In summary, judging by the distribution shown in Figure 10, there is an 88% probability that, for full-diameter carbonate samples with less than 80 mD permeability, the equivalent plug cut from it will have lower permeability.

Scale-Up of Permeability Data

The majority of the core data are based on core plug measurements that are shown to be biased toward low permeability in the heterogeneous carbonates. For the carbonates, the greatest discrepancy between plug and full-diameter data is for samples with less than 80 mD. Figure 11 shows a crossplot of the low-permeability samples with values that fall at the minimum of 0.01 mD, plus one outlier removed. The equation was used to scale-up the low-permeability plugs, and the results are shown in Figure 12.





Figs 11 and 12. Correlation between full diameter and plug permeabilities for carbonate samples below 80 mD (Fig 11) can be used to scale up low permeability plug data (Fig 12).

For reservoir simulation purposes this relationship can be used to scale-up the low-permeability data derived for the mottled siltstones occurring mainly in zone 2.

POROSITY MEASUREMENTS AT DIFFERENT SCALES

Full-diameter and plug porosities are crossplotted for the siliciclastic and carbonate lithofacies in Figures 13 and 14. As for permeability, the siliciclastic data fall very close to the x=y line, indicating that both types of data are valid and that plug-sized samples are sufficiently large to capture their low degree of heterogeneity.

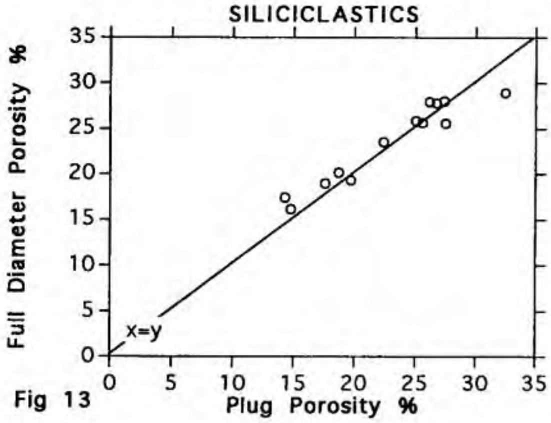


Fig 13

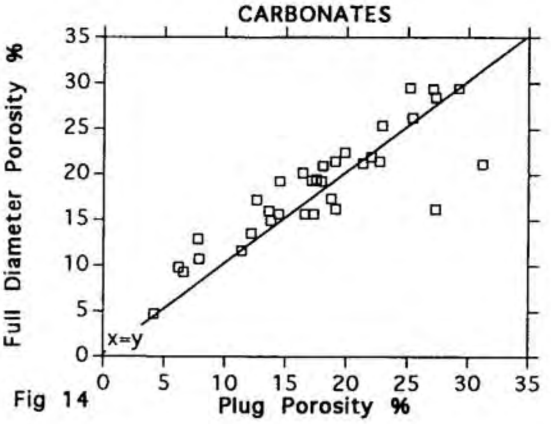


Fig 14

Figs 13 and 14. There is little difference between full-diameter and plug porosities for the siliciclastic samples (Fig 13). The full diameter porosities are generally higher than equivalent plug values for the carbonates.

Full-diameter porosities for most carbonate samples are higher than equivalent plug values. In looking at the core, there could be a number of reasons for this. First there is the possibility of sampling bias described above, i.e., a tendency to avoid friable areas when cutting a plug. Second, several of the full-diameter samples from the mottled facies have surface roughness caused by washout of the poorly cemented silty burrow fills. Some of this would be occluded by the Hassler sleeve during full-diameter core analysis, but some would probably be measured. The plugs are cut and trimmed, and include none of this surface roughness/porosity. Third, there are several samples that contain isolated, centimeter-sized molds. These molds are sufficiently scattered that they are less likely to be sampled by a plug than by a full-diameter sample. Finally it is relatively easy to make a right cylinder out of a plug, whereas some of the full-diameter samples are more irregular in shape and some have chips of rock missing. In summary, the full-diameter data might be biased high and the plug data might be biased low.

Excluding the two outliers seen in Figure 14, differences between full-diameter and plug porosities range from -2.9 to +5.1 p.u. with an average of +1.6. There is no clear relationship between the magnitude of the difference and the amount of porosity. In calculating porosity or porosity-dependent parameters, a sensitivity analysis could be made for the carbonate facies using the average difference between full-diameter and plug data of 1.6 p.u.

WHY CORE AND LOG POROSITIES DIFFER

The significant bias between core porosities and those derived from interpretation of the density or neutron-density logs, correlates with the occurrence of mottled siltstone lithofacies. When unslabbed, the new cores appeared to be vuggy on their outer surfaces. When the cores were CT-scanned and later slabbed, it was clear that these "vugs" did not extend into the rock but were, in fact, caused by drilling-induced erosion of poorly cemented siltstone that had filled burrows. The borehole televiewer images show that the burrows also washed out in the borehole, creating very small-scale rugosity.

The density log reads only a few inches away from the borehole and is very influenced by near-wellbore effects. The density tool pad is too large to conform to the small-scale rugosity. The washed-out burrows may have been filled with drilling mud or may have been empty. Either way the tool would record a bulk density lower than that of the host rock. The extent to which the bulk density is reduced depends upon the extent of the rugosity, which in turn reflects the intensity of burrowing.

SUMMARY

This study illustrates that it is not sufficient to simply collect data. Until the rocks were studied in detail, it was not clear why the core and log data provided conflicting porosity information. When two sets of data conflict, it is common to assume that one set of information is correct and the other in error. In the case described here, both the log and core data were "correct"; however, the log data were not representative of the formation.

The principal reservoir lithofacies is mottled siltstone in which permeability and oil are confined to poorly cemented, siltstone-filled burrows, surrounded by tight dolomite. The major difference between core- and log-derived porosity coincides with the occurrence of these rocks. Vugs do not account for the porosity bias. The mottled siltstones are heterogeneous, and there is a tendency for plugs to underestimate permeability, especially for samples below 80 mD. For these rocks a relationship between plug and full diameter permeability was used to scale-up the low-permeability data. The differences between full-diameter and plug porosities can be used as input to sensitivity analyses.

During drilling, the poorly cemented siltstone burrow fill washed out, leaving small-scale rugosity on the borehole wall. The density logging tool read this rugosity and hence density-derived porosities are too high.

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