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Multi-Scale Flow Zone Determinations

James J. Funk, Shameem Siddiqui, Abdulrazak Al-Sardi, and Mohammad Amin Haque
Saudi Aramco Lab R&D Center
Dhahran, Saudi Arabia

Abstract

The method proposed by Amaefule *et al.* (1993) is frequently used for characterizing flow zones having similar hydraulic properties. The method uses a modified version of the Carman-Kozeny (1939) equation and the mean hydraulic radius concept. The method can be applied on scales from the pore level through the inter-well level. Suitable applications and limitations of the method can be derived from an analysis of the flow zones at these various scales. A large data set of conventional, whole core, and special core analyses on an Upper Jurassic carbonate was used to characterize flow zones based on the Carman-Kozeny model. Size scales for the characterizations extended from approximately 30 pore radii up to well bore size. Small-scale characterizations were based on CT-scan data of porosity distributions in 10,000 voxel slices - 3 mm × 3mm × 10 mm. Plug scale and whole core scale characterizations were based on multi-directional porosity and permeability while wellbore characterizations were based on open-hole flow meter results. Comparisons of cumulative distributions of open-hole flow potential, porosity, permeability, reservoir quality index (RQI), and flow zone indicator (FZI) from the tested scales demonstrate the limitations of normal weighting methods for determining overall reservoir quality.

Introduction

Core porosity and permeability measurements are not only essential to reservoir characterization but can also be used as effective indicators of well productivity and as critical input for stimulation design. The proper selection of flow zones within a particular reservoir has been a subject of interest in both formation evaluation and reservoir modeling. (Stiles, 1949;Testerman, 1962; Worthington, 1991; Nelson, 1994; Douglas, 1996). A combination of open-hole well test data and a hydraulic radius model illustrates how synergistic information can be obtained from routine core analysis data and elements of reservoir layering techniques.

Flow meter data were used as the basis for comparisons with the hydraulic radius model. The model input was obtained at a succession of scales that were decreasing in size. Initial data were obtained for whole core samples collected throughout the productive interval. These were followed by plug samples drilled from the whole core at 0.5-ft spacing. X-ray CT scans performed on the whole core were used to determine fine scale model characteristics.

The hydraulic radius model is based on the relationship of permeability and porosity established in the Carman-Kozeny equation -

$$K = \frac{f^3}{2t\,(1-f)^2 a_v^2} \qquad 1)$$

Reservoir Quality Index (RQI)

Amaefule *et al.* (1993) used this model to define three terms that are convenient for use with routine core analysis data. These are the reservoir quality index (RQI), The normalized porosity (NPI), and the flow zone indicator (FZI). They are defined by:

$$RQI = 0.0314 \times \sqrt{\frac{K}{f}} \qquad 2)$$

$$NPI = \frac{f}{1-f} \qquad 3)$$

$$FZI = \frac{RQI}{NPI} \qquad 4)$$

Manipulation of the equations illustrates how the model provides an esthetical representation of the flow zones based on surface area and tortuosity. Here the model provides a concise summation of flow zone

$$FZI = \frac{.0314}{\sqrt{2t}\, a_v} \qquad 5)$$

Samples characterized by the same flow zone will align along a straight line of slope one (1) in a log-log plot of RQI versus NPI, with the intercept at NPI=1 equal to FZI.

Cumulative Reservoir Properties

The Lorenz coefficient (Craig, 1971) provides a convenient method for observing flow capacity (K*h) as a function of storage capacity (ϕ *h). However the method does not provide a spatial representation of either the flow or the storage capacity. If the total productivity of a well is assumed to be a linear combination of individual flow zones, a simple height weighted summation and normalization of permeability, RQI, or FZI starting at the bottom of the well provides a convenient representation of variations with depth. A large fractional change in a cumulative property over a small depth represents large relative contributions of the property. In such a plot consistent zones are characterized by straight lines with the ***slope*** of the line indicating the overall permeability, RQI, or FZI within a particular depth interval. The ***lower the slope the better the property***. In general these straight lines will coincide with Testerman's (1962) layers. They also provide a convenient comparison with the normalized cumulative plot of an open-hole flow meter test.

Procedures

Flow Meter Measurements

Single phase, raw turbine meter flow data were taken following the cleanup of an open-hole completion. Data were obtained from a well that had complete core recovery over the productive zone. Flow meter data were calibrated and normalized over the cored interval and plotted as fraction of flow from the base of the productive interval to the top.

Whole Core and Conventional Measurements

Whole core and conventional measurements were made on cleaned and dried samples. Porosity values were determined by the Boyle's Law method, while permeability values were absolute gas permeabilities determined at ambient conditions under steady-state flow.

Whole core measurements were performed on samples 2-5/8 inch in diameter and 0.4 to 0.7 ft. in length. The whole cores covered the complete cored interval. Whole core permeability was determined in perpendicular horizontal directions and in the vertical direction.

Plug measurements were made on 1.5-inch diameter samples 2.0 inches in length. Plug samples were drilled perpendicular to the vertical axis of the whole core at a set-sampling interval of 0.5 ft.

X-ray CT Scans

X-ray CT scans were taken at 1.0 in spacing throughout the complete interval using the whole cores. Scans were performed using a Technicare DeltaScan-100 CT scanner at 120 KV and 25 mA. The 256 × 256 binary image data were processed on a Sun Ultra-60 workstation using VoxelCalc image processing software running on PV-Wave. Calibration of bulk densities was made using standard carbonate scans and measured whole core bulk and grain densities.

Results

Flow Meter Flow Zone Indicators

Cumulative property correlations were used in an effort to match the flow meter performance. Figure 1 shows the comparative results for whole core permeability, reservoir quality index (RQI), and flow zone indicator (FZI). Figure 2 shows results from plug characterizations of the same cumulative reservoir properties.

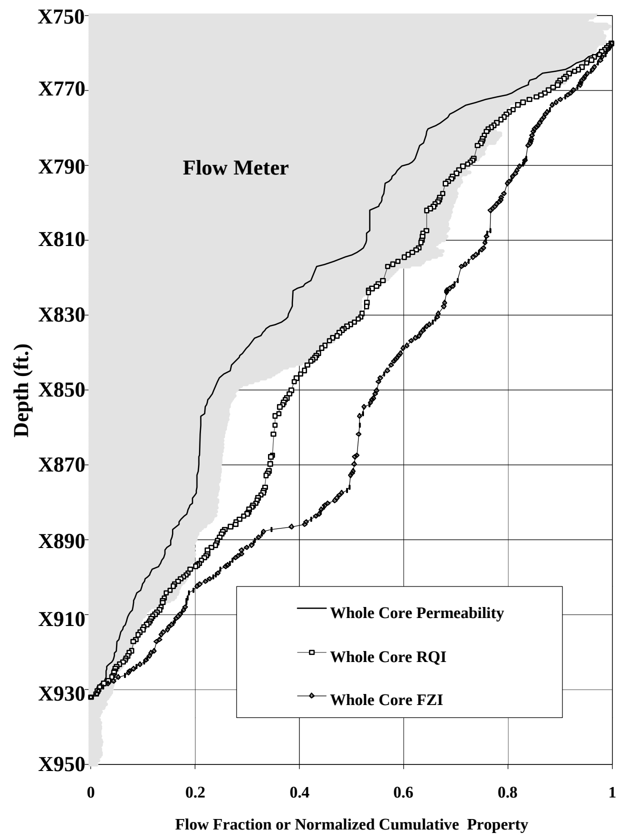

Figure 1: Flow Meter and Whole Core Correlation

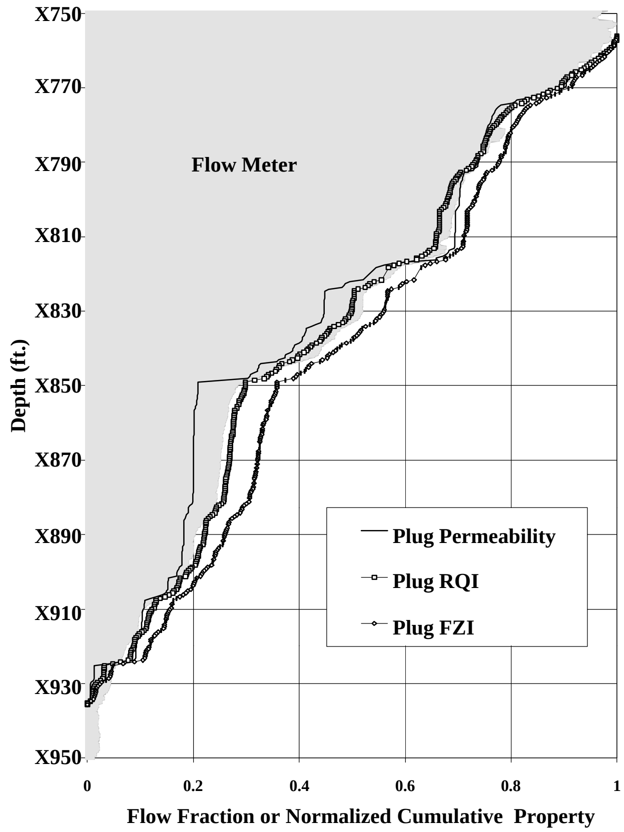

Figure 2 Flow Meter and Plug Correlations

Summary Statistics

Summary statistics from whole core and plug sample analyses are listed in Table 1. Histograms for porosity and permeability are shown in Figures 3 & 4. Lorenz coefficient plots are shown in Figure 5.

Table 1 Whole Core and Plug Sample Statistics

	Porosity (%)		Permeability (md)			
	Whole Core	Plug	Whole Core			Plug
			Vertical	Horizontal Max	Horizontal 90°	
Mean	22.32	23.02	55.18	126.88	83.26	84.77
STD	7.16	6.82	13.30	4.20	4.81	18.32
Skewness	-0.51	-0.84	0.19	0.06	0.09	0.40
CV	0.32	0.30	4.42	1.98	2.27	4.52
N	202	354	199	198	198	324

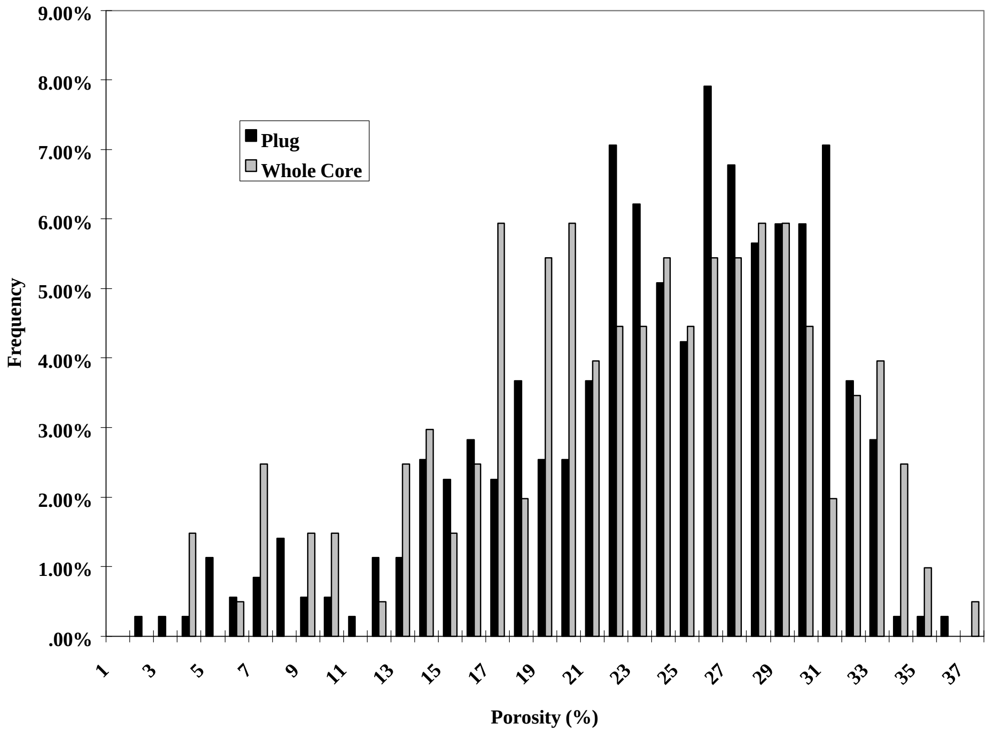

Figure 3 Porosity Histogram

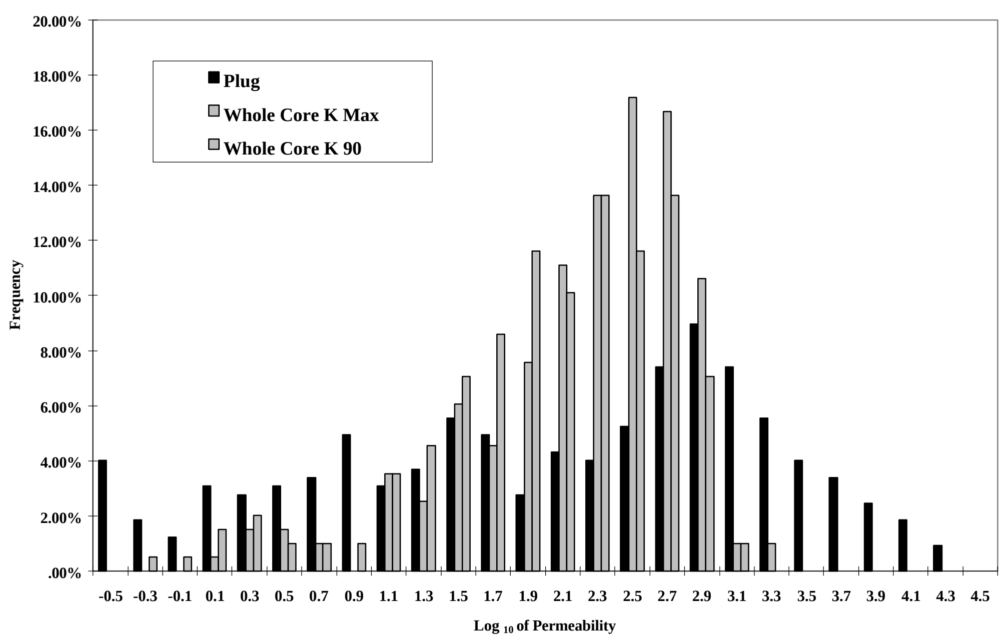

Figure 4 Permeability Histogram

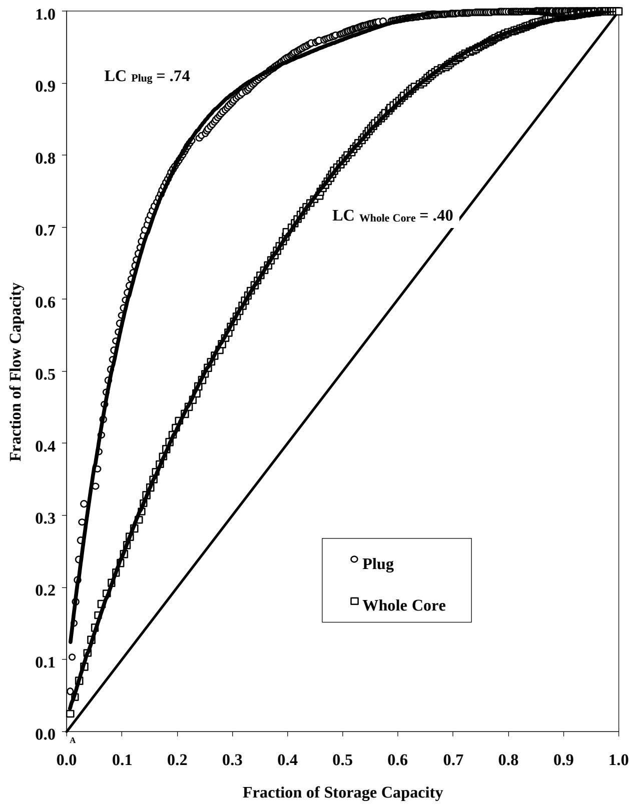

Figure 5 Lorenz Coefficients for Whole Core and Plug Data

X-ray CT Scans

Two CT scan slices were selected from a one-foot whole core interval. The raw CT numbers from each voxel (volume element) of these slices were converted to bulk densities and then to porosities using the data from calibration standards and from the bulk and grain density data for the plugs from the same depth. Based on the FZI data for the depth at which the slice was taken, the porosities were converted to permeabilities using an empirical equation of the following form:

$$K = a f^{b} \qquad 6)$$

Where, *a* is the coefficient and *b* is the exponent derived by fitting a trendline through the plug porosity and permeability data corresponding to the same flow zone. The porosity and permeability distributions are given in Figures 6 and 7. Included in Figures 6 and 7 are the plug sample porosity and permeability distributions for the interval covered by the CT scans. Each plug sample represents approximately 14% in the frequency distribution. X-ray CT images and CT number profiles through selected slices and whole intervals are shown in Figures 8 and 9.

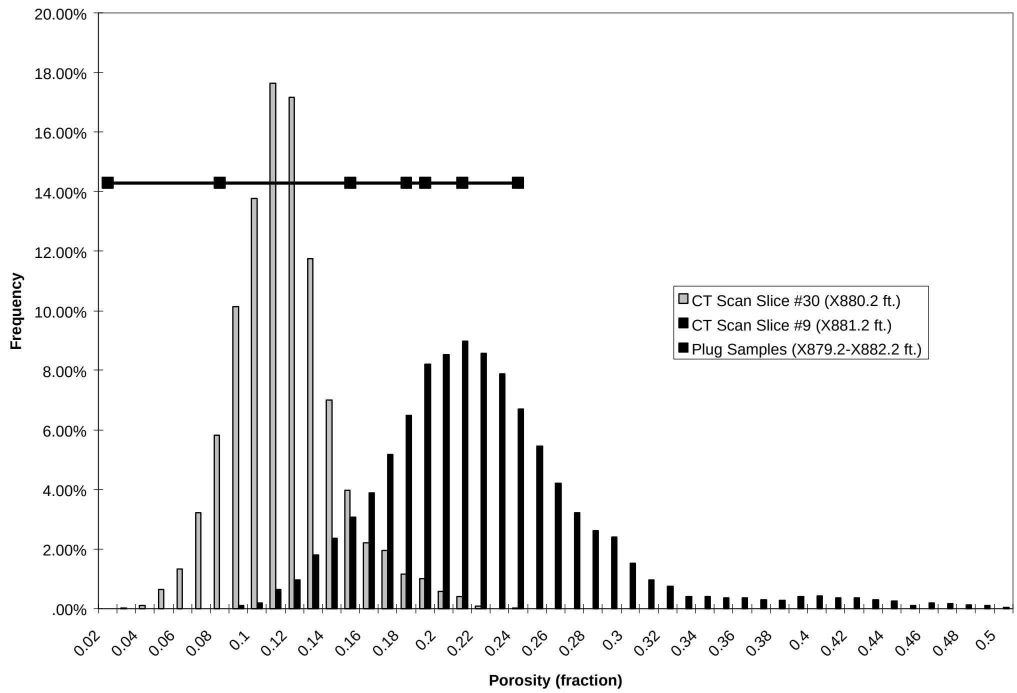

Figure 6 CT Scan Porosity Distributions

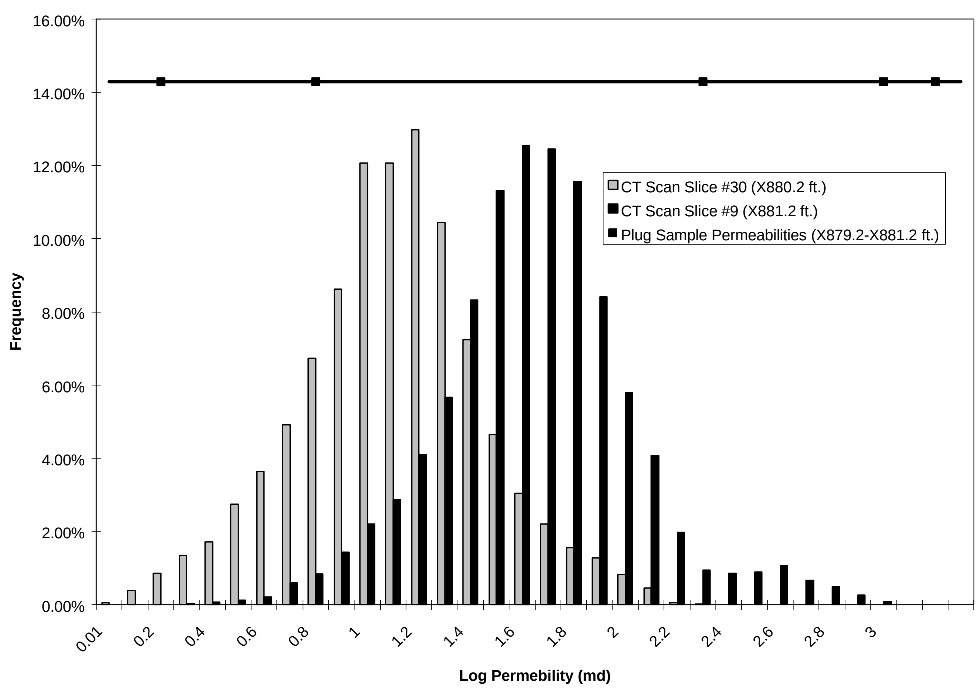

Figure 7 CT Scan Calculated Permeability Distributions

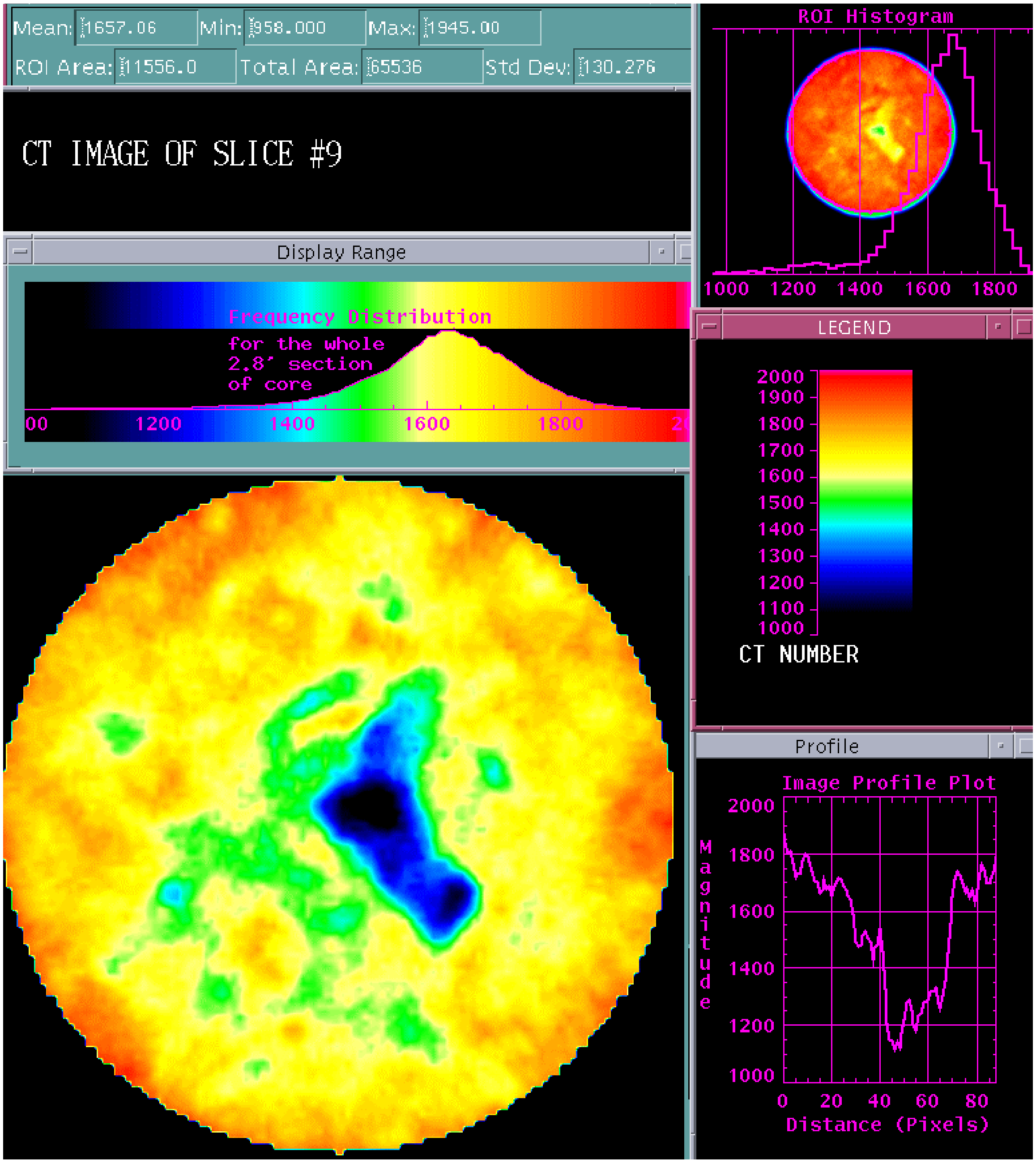

Figure 8 CT Scan Slice #9 (X881.2 ft.)

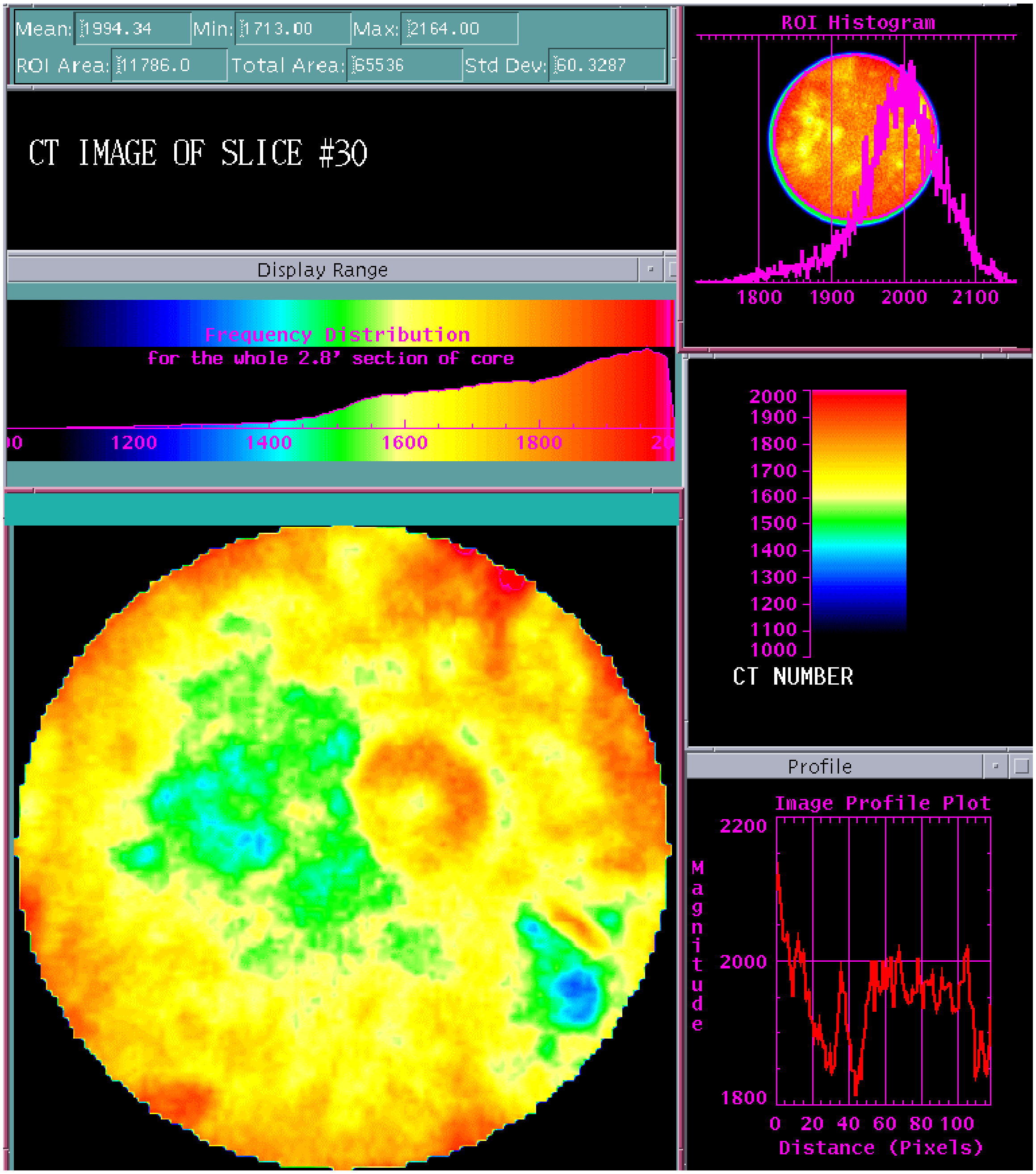

Figure 9 CT Scan Slice #30 (X880.2 ft.)

Discussion

Based on the flow meter data the best model match is achieved with cumulative distributions of plug reservoir quality index (RQI). Although plug data is often assumed to be non-representative for well in-flow performance calibration this is obviously not the case in this particular well. While whole core data does follow the general trend of the in-flow performance it does not capture the contrast in permeability layers, especially in the range of (X880 ft.). The plug data does capture this relation.

The use of cumulative flow zone indicators (FZI) rather than RQI actually degrades the model match. This indicates that the added porosity dependence of NPI used to convert RQI to FZI, is unnecessary. Part of this can be attributed to the grain volume based-specific surface term included in the original Carman-Kozeny formulation. As Nelson (1994) demonstrates, the NPI porosity dependence is eliminated and RQI and FZI are equivalent when the grain volume based specific surface area term (a_v) is replaced with specific surface area based on pore volume.

Although the porosity characteristics of this reservoir are captured easily with either the whole core or plug data, the permeability character is not. The plug permeability histogram clearly shows both low and high ranges of permeability. The whole core permeability has averaged these ranges as indicated by the almost uniform log-normal distribution of whole core permeability. The loss of variability is also apparent in the Lorenz calculations. The Lorenz coefficients for the whole core data are almost one-half that of the plug data.

Progression to the finer scale of X-ray CT data indicates a similar trend seen in the progression from whole core to plug data. The distribution of both porosity and permeability within a single CT slice illustrates the difficulty in obtaining a single representative porosity and permeability sample. It also illustrates the difficulty in obtaining a representative whole core measurement even within a one-foot interval. Although plug sample porosity and permeabilities scan the range of values captured in CT scans separated by one foot, a single 0.5 ft weighted average for permeability or porosity would not equal the whole core measured values.

Conclusions

Critical questions on the scaling of petrophysical data must be considered reservoir dependent and the results from this heterogeneous carbonate reservoir may reflect a somewhat extreme case pointing to a preference of plug data over whole core data. In summary however, some key points have been identified.

1. The values of permeability determined from whole core are not necessarily more representative of the reservoir than those determined from plug samples, even in heterogeneous carbonates.

2. The best scaling with the use of Carman-Kozeny model is achieved when the concept of pore volume based specific surface is used.

3. The incorporation of CT porosity distribution data is key to understanding the scale of petrophysical property variations so that proper scale factors can be applied.

Acknowledgments

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Nomenclature

h Height (ft.)of a interval represented by a point measurement

a Coefficient of the power-law fit of the porosity vs. permeability data within the same flow zone

b Exponent of the power-law fit of the porosity vs. permeability data within the same flow zone

K Permeability, md

$\mathbf{a_v}$ Specific surface area per unit grain (solid) volume

ϕ Porosity, percent

τ Tortuosity in Carman-Kozeny equation, dimensionless

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