SCA2003-40: NEW REPRESENTATIVE SAMPLE SELECTION CRITERIA FOR SPECIAL CORE ANALYSIS

Shameem Siddiqui, Taha M. Okasha, James J. Funk, Ahmad M. Al-Harbi
Saudi Aramco, Dhahran, KSA

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Abstract

To this date there is hardly any specific industry guideline for selecting representative samples for special core analysis (SCAL) tests. No one can deny the importance of SCAL data in the development of appropriate reservoir engineering models. This paper describes some of the effective criteria and tests required for the selection of representative samples for use in SCAL tests. The proposed technique is essential to insure that high quality core plugs are chosen to represent appropriate flow compartments or facies within the reservoir. The absence of a petrophysical input in the selection of SCAL plugs can result in SCAL data being NOT representative of the reservoir or its flow compartments. Often, visual inspection and sometimes, computerized tomography (CT) images are the only techniques used for assessing and selecting native state core plugs for SCAL studies. Although it is possible to measure the effective brine permeability (K_b), there is no routine method for determining the porosity (f) of the SCAL plugs without compromising their wettability. Some of the existing selection criteria involve using the conventional core analysis data (k and f) on 'sister plugs' as a general indicator of the properties of the SCAL samples. However, the uncertainties surrounding the extent of heterogeneity as well as the exact depth of the plugs make it difficult to ascertain plugs as representative of a particular flow compartment. The proposed technique identifies intervals with similar porosity/permeability relationships. It uses a combination of wireline logs, gamma scan, quantitative CT and preserved state brine permeability data to calculate appropriate depth-shifted reservoir quality index (*RQI*) and flow zone indicator (*FZI*) data, which are then used to select representative plug samples from each reservoir compartment.

Introduction

Coring is a very expensive operation. The main goal of coring is to retrieve core samples from the well in order to get maximum amount of information about the reservoir. Core samples collected provide very important petrophysical, petrographic, paleontological, sedimentological, and diagenetic information. From a petrophysical point-of-view, the whole core and plug samples typically undergo the following tests: CT-scan, gamma-scan, conventional tests, special core analysis (SCAL) tests, rock mechanics and other special tests. The data are combined to get information on heterogeneity; depth-shift between core and log data; whole core and plug porosity and permeability; porosity-permeability relationship; fluid content (Dean Stark), Reservoir Quality Index (*RQI*); Flow Zone Indicator (*FZI*), wettability, relative permeability, capillary pressure, stress-strain relationship, compressibility, etc. The petrophysical data generated this way play very important roles in reservoir characterization and modeling, log calibration, reservoir simulation, and overall field production and development planning.

Among all the petrophysical tests, the SCAL tests which include wettability, capillary pressure, relative permeability and capillary pressure determination are very important and time-consuming. A reservoir condition relative permeability test can sometimes run for several months when mimicking the actual flow mechanisms taking place in the field. So, it is very important to design these tests properly and in particular to select the samples that ensure meaningful results. In short, the samples must be 'representative samples,' which can capture the overall variability within the reservoir in a more scientific way. Unfortunately, the most important aspect of all SCAL procedures, the sample selection is one of the least talked about subjects. According to Corbett et al. [2001], the API's RP40 (Recommended Practices for Core Analysis) makes very little reference to sampling and similarly, textbooks on Petrophysics do not have sections on sampling. They [Corbett et al., 2001] made a good review of some of the statistical, petrophysical and geological issues for sampling and proposed a series of considerations. This has led to the development of a method using Hydraulic Units in a relatively simple clastic reservoir [Mohammed and Corbett, 2002].

In this paper some issues related to sample selection criteria, with special focus on carbonate reservoirs will be discussed. A large data set of conventional, whole core, and special core analyses on a well in an Upper Jurassic carbonate reservoir was used to characterize 'representative samples' for special core analysis tests.

Reservoir Quality Index and Flow Zone Indicator

Core porosity and permeability measurements are extremely important for proper selection of flow zones within a particular reservoir. Stiles [1949], Testerman [1962], and Nelson [1994] are among researchers who worked extensively on porosity, permeability and reservoir zonation issues using synergistic information that can be obtained from routine core analysis data and elements of reservoir layering techniques.

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 equation and the mean hydraulic radius concept. The method is widely applied on scales from the pore level through the inter-well level. Amaefule et al. [1993], defined three terms that are convenient for use with conventional core analysis data. These are the reservoir quality index (*RQI*), The normalized porosity (*NPI*), and the flow zone indicator (*FZI*). They are defined by:

$$RQI = 0.0314 \times \sqrt{\frac{K}{f}} \quad \text{.....1}$$

$$NPI = \frac{f}{1-f} \quad \text{.....2}$$

$$FZI = \frac{RQI}{NPI} \quad \text{.....3}$$

Where,

RQI = Reservoir quality index (μm),
K = Permeability (md), and
f = Porosity (fraction).

According to Tiab and Donaldson [1996], samples with the same *FZI* values have similar pore throat size, and thus constitute a flow unit. *FZI* is typically calculated using conventional core analysis derived porosity and permeability data on the so-called 'sister-plugs' but that information may not apply to the wettability-preserved actual SCAL plugs. Although it is not so difficult to get the brine permeability data for a SCAL plug, it is almost impossible to determine its porosity without compromising the wettablility state of the sample. CT provides a solution to this problem by allowing the calculation of porosity values without taking the samples out of the brine.

CT-Scanning

Until the early 80's special core analysis samples were chosen using visual inspection. The introduction of Computerized Tomography (CT) in petrophysical analysis revolutionized the sample selection process as it became possible to look at the 'inside of the core plugs' and to select 'good' plugs before using them in long-duration SCAL tests, thus reducing rates of failure. CT is a very powerful tool for detailed characterization and fluid flow visualization for evaluating reservoir rocks in a non-destructive manner. During scanning, the X-ray source and detectors move around the object to cover the entire 360 degrees at each scan location to make a 'slice' of attenuation data. At high X-ray energies, the attenuation becomes mainly a function of the electron density of the materials present in the object being scanned. CT number, the parameter measured by all medical-based CT-scanners, is a relative scale of attenuation coefficients (uses the value of -1000 for air and 0 for water). For a properly calibrated artifact-free system, the CT number varies linearly with the bulk density of a rock [Vinegar and Wellington, 1987]. By using appropriate brine and grain density data, very accurate porosity values can be obtained for every slice of a wettability-preserved SCAL sample [Siddiqui, 2000].

Reservoir Zonation Using Cumulative RQI

The combination of ϕ and k data in terms of reservoir quality index (*RQI*) provides a convenient starting point to address the differences between samples and between reservoir zones. If the total productivity of a well is assumed to be a linear combination of individual flow zones, then a simple summation and normalization of permeability, *RQI*, or *FZI* starting at the bottom of the well provides a convenient comparison with the normalized cumulative plot of an open-hole flow meter test. In such a plot consistent zones are characterized by straight lines with the slope of the line indicating the overall reservoir quality within a particular depth interval. The lower the slope the better the reservoir quality. In general these lines will coincide with Testerman's [1962] layers [Funk et al., 1999]. The equation used for calculating Normalized Cumulative *RQI* (*NCRQI*), in this paper is as follows.

$$NCRQI = \frac{\sum_{x=1}^{i} \sqrt{\frac{K_i}{f_i}}}{\sum_{x=1}^{n} \sqrt{\frac{K_i}{f_i}}} \quad \text{..... 4}$$

where,

n = total number of data

i = number of data points at sequential steps of calculation

By plotting *NCRQI* versus depth it is possible to divide the reservoir into several zones by observing changes in the slope. Consistent *RQI* zones are characterized by straight lines with slope of the line indicating the overall reservoir quality within a particular depth interval. The smaller the slope, the better the reservoir quality. Typically this type of zonation technique works better in carbonate reservoirs where the typical *RQI* vs. *NPI* values [Amaefule et al., 1993] don't line up properly along parallel straight lines.

Heterogeneity Classification

In reservoir characterization heterogeneity specifically applies to the variability that affects flow [Jensen et al., 1997]. One of the commonly used techniques for measuring the static heterogeneities is the Lorenz (sometimes known as the Stile's) Plot, which gives the Lorenz Coefficient, L_c. The technique involves ordering the product of permeability and the representative thickness (kh) in the descending order along with the corresponding porosity-representative thickness product (fh) for a well (or wells). The normalized cumulative values of kh, which also known as the fraction of total flow capacity (between 0 and 1) are then plotted against the normalized cumulative values of fh, which is also known as the fraction of the total volume (between 0 and 1). The L_c is calculated by comparing the area under the curve above a 45° line between (0,0 and 1,1) and 0.5. L_c can theoretically vary between 0 and 1, with 1 representing the highest degree of heterogeneity. Details of the procedure for calculating L_c can be found in the literature [Craig, 1971; Jensen et al., 1997].

The coefficient of variation, C_v is another measure of heterogeneity. It is a dimensionless measure of sample variability or dispersion [Jensen et al., 1997], and is given by,

$$C_v = \frac{\sqrt{Var(x)}}{E(x)} \quad \text{.....} \quad 5$$

where, the numerator is the sample standard deviation and the denominator is the sample mean. C_v is being increasingly applied in geological and engineering studies as an assessment of permeability heterogeneity (Saner and Sahin, 1999). For data from different populations, the mean and standard deviation often tend to change together such that C_v stays relatively constant. Any large changes in C_v between two samples indicate a dramatic difference in the populations associated with those samples [Jensen et al., 1997].

Results

For this study, a well from an Upper Jurassic carbonate reservoir was chosen on which extensive log, and core data were available. The core tubes were gamma-scanned first, from which it was found that the core depths needed to be shifted down by 6.5 ft for the entire cored length to match with the log depths. Then the entire cored section was plugged thoroughly to collect about 375 SCAL plugs, which were kept preserved in brine, and about 180 other plugs, which were leached and dried for conventional core analysis tests.

Brine permeability was run on most of the SCAL plugs under the wettability-preserved condition. The 375 SCAL samples were then CT-scanned (full coverage, about 9 slices per plug) and the raw data were transferred to a SUN workstation for generating statistical data (typically, mean, standard deviation, minimum and maximum CT number) on circular regions-of-interest

representing the core materials. Then appropriate conversion equations were applied to obtain porosity data for each slice of a plug and their average was recorded. The depth-shifted core data were then compared with the logs, which showed a very good agreement between these two independent sets of data (see Figure 1).

Using the CT-derived porosity and brine permeability data on the SCAL plugs, the *RQI, NPI, FZI* and *NCRQI* values were calculated. Figure 2 shows the *NCRQI* values plotted as a function of depth for the SCAL plugs as well as the more continuous conventional core analysis generated *NCRQI* vs. depth data. By closely observing these two sets of data, a total of eight zones were identified within the cored section, each with a different slope, as shown by the solid line segments. For reference, the cumulative production data from a PLT test are also shown and it shows trends similar to what was seen by Funk et al. [1999]. Figure 2 also shows demarcations (dotted horizontal lines) based on original geological facies data.

The SCAL plugs were then subjected to screening based on various heterogeneity and related criteria. Typically plugs with large inter-slice and intra-slice heterogeneities are eliminated from SCAL tests. Figure 3 shows one example each of inter-slice and inter-slice heterogeneities. The image on the left contains an anhydrite nodule in the last three slices, rendering it unsuitable for SCAL tests. The image on the right shows a case of intra-slice heterogeneities where each slice looks alike but there is a large variation of CT numbers within each slice. For eliminating the plugs with inter-slice variations the ratio between the maximum and minimum CT numbers within each plug was calculated and plugs having a ratio of 1.09 or more were discarded. For eliminating the samples with intra-slice variations the plugs with average of the C_v of CT numbers for each slice (standard deviation divided by mean) above 0.08 were eliminated as heterogeneous. Additionally, plugs having a porosity of 5% or less were also eliminated and a final list of 134 plugs was created that were suitable for SCAL studies.

Figure 4 is the classic *RQI* versus *FZI* plot [Amaefule et al., 1993] for the suitable plugs, which are also classified according to the zone using different symbols. It also shows six diagonal lines, each pair of which representing a range of *FZI* values. Upon close examination a total of five bin sizes were chosen to group the core plugs into different *FZI* ranges. These are 0 to 1 inclusive, 1 to 2 inclusive, 2 to 3 inclusive, 3 to 4 inclusive, and greater than 4. Table 1 shows the SCAL plugs listed according to these *FZI* bin sizes as well as the zones identified previously. In order to make a representative composite core plug for say Zone 1, one can have several choices of *FZI* ranges. Once an *FZI* range is selected, one composite plug for each zone should be sufficient for conducting representative SCAL tests. It is also possible to mix plugs with different *FZI* values but within the same zone in order to get an idea about the overall variations possible within the zone. It may be noted that in this particular case Zones 6 and 8 have the steepest slope and they contribute almost nothing to the production. Therefore testing samples from these two zones can be avoided.

The use of the so-called sister plugs is common in making inferences about the behavior of the plugs used for SCAL tests because of unavailability of some critical data such as porosity and permeability. It was found that while porosity data didn't vary so much for the short distance (typically within one foot between the SCAL and the corresponding 'sister' conventional plug sample), the permeability varied sometimes by one or two orders of magnitude. This is evident in Figure 5, where the Lorenz plots are generated for the SCAL and conventional core analysis plugs on which permeability data were available. Results showed a large difference between the

two Lorenz coefficient values, with the coefficient for the SCAL plugs having a value of 0.57 compared to the coefficient for conventional plugs having a value of 0.72. Although some of the difference may be due to the sampling or experimental bias, one should be careful in using sister plug data in serious calculations especially when permeabilities and overall heterogeneities are concerned.

Conclusions

1. A set of guidelines has been established to select the 'representative' core plug samples for special core analysis tests based on a combination of reservoir zonation, heterogeneity analysis and application of *RQI* and *FZI*-based techniques.

2. This research finds CT-scanning to be an extremely useful tool for quantifying heterogeneities within small plugs.

3. Samples picked up from a zone based on the normalized cumulative *RQI* based technique demonstrated here have a better chance of representing that zone than samples picked up at random from the entire cored section.

4. Using the properties of the sister plugs, especially for permeability and heterogeneity, may lead to strange results.

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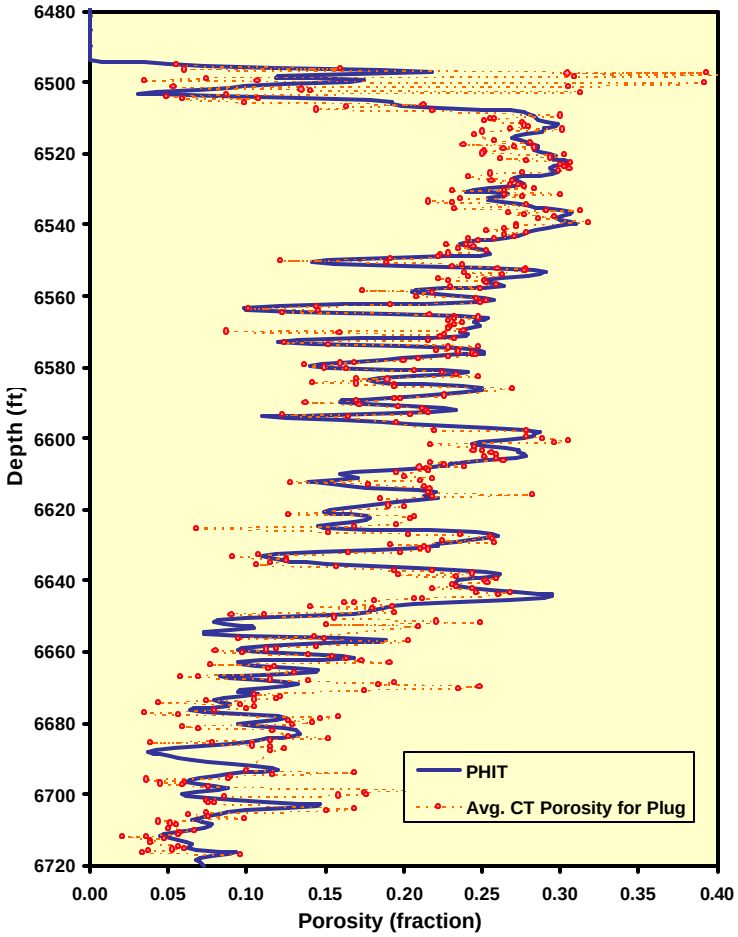

Figure 1: CT-derived SCAL plug porosity data compared against the logs show a very good agreement between the two independently derived sets of data.

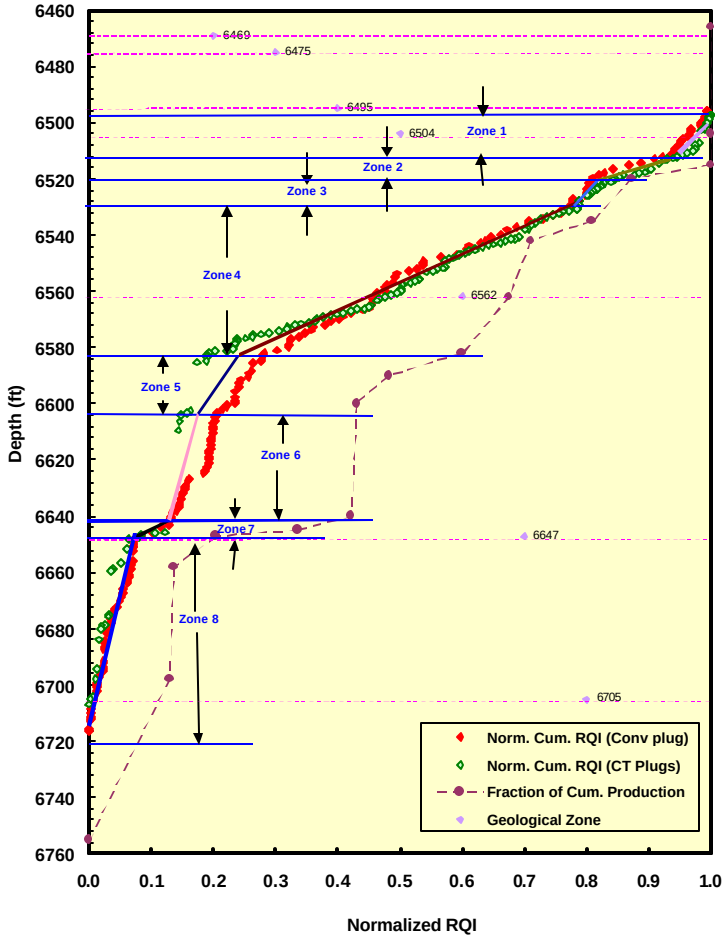

Figure 2: Normalized Cumulative *RQI* vs. depth for the SCAL and conventional core analysis plugs showing the existence of eight distinct zones within the cored section (shown by solid line segments). The cumulative production data and the geological zone markers (dotted horizontal lines) are also shown for reference.

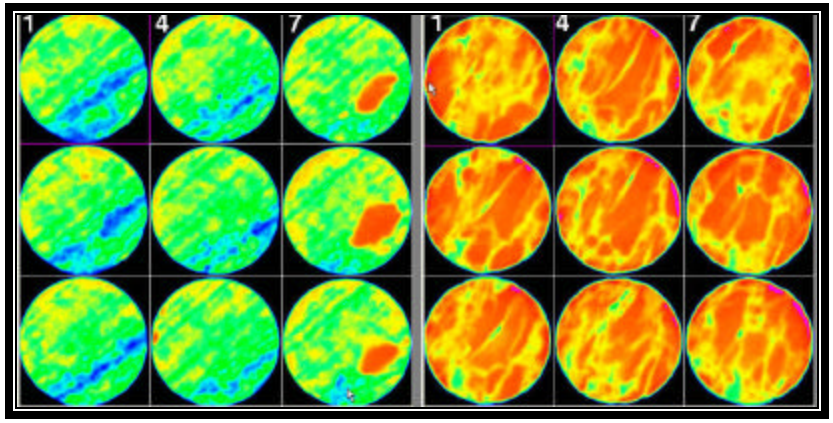

Figure 3: CT-Scan slices showing case of inter-slice heterogeneity (left image), and intra-slice heterogeneity (right image). The image on the left shows the presence of a distinct anhydrite nodule in the last three slices, making it unsuitable for SCAL tests. The image on the right shows large variations within each slice, with relatively small channels available for flow and therefore unsuitable for SCAL tests.

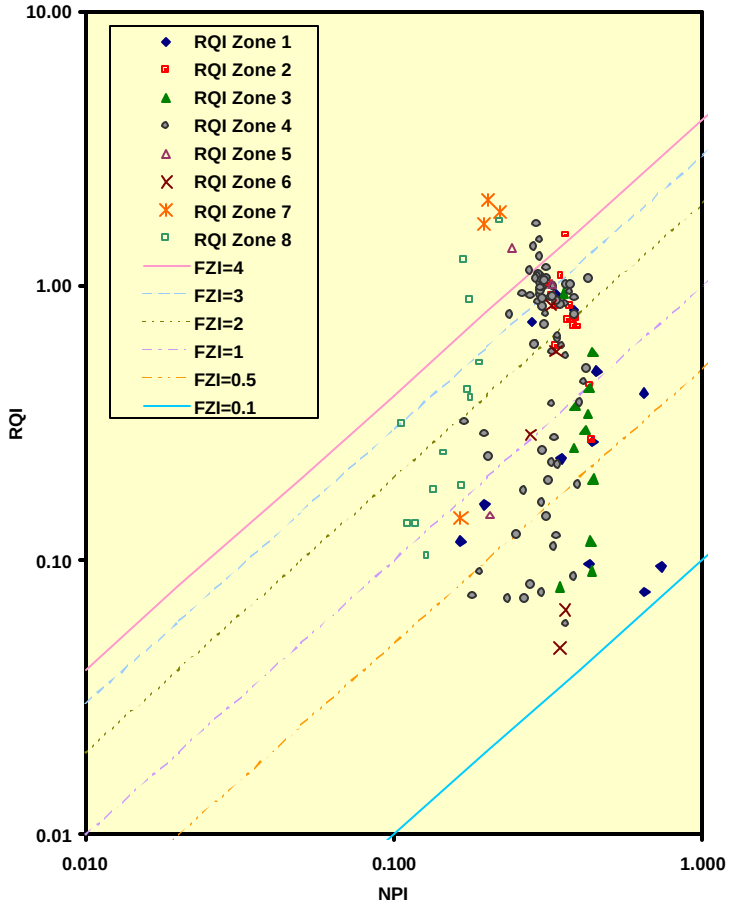

Figure 4: *RQI* versus *NPI* plot for the small subset of plugs suitable for SCAL tests after eliminating the heterogeneous or low-porosity plugs. The diagonal lines correspond to six *FZI* values.

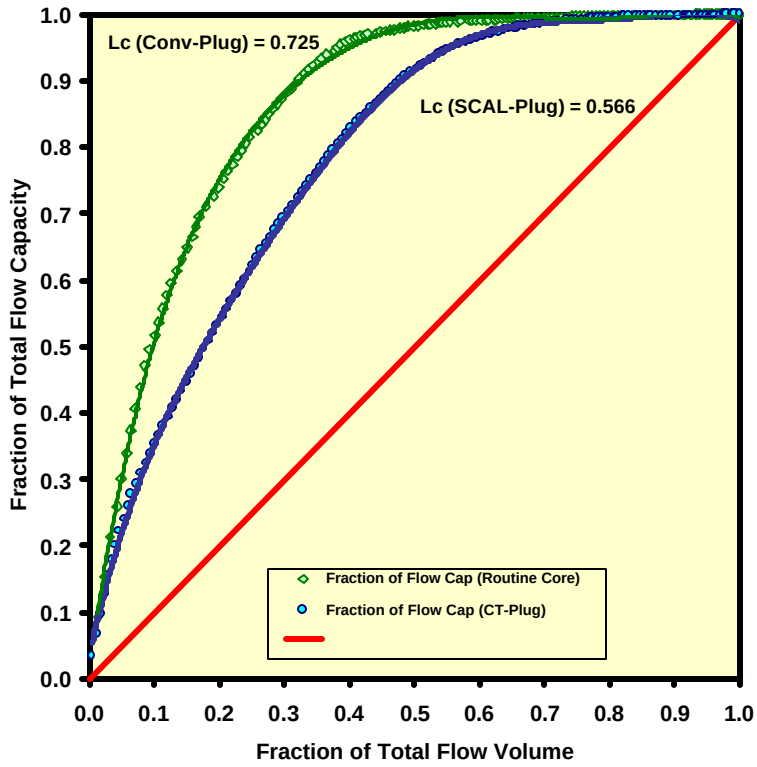

Figure 5: Lorenz plots illustrating the difference between the sister plugs used for SCAL and conventional core analysis tests.

Table 1: The final grouping of the SCAL plugs according to various FZI bin sizes and zones

FZI Range: 0 to 1						FZI Range: 1 to 2						FZI Range: 2 to 3						FZI Range: 3 to 4						FZI Range: >4					
Plug No.	Zone	Avg. CT Poro	k_b (md)	RQI	FZI	Plug No.	Zone	Avg. CT Poro	k_b (md)	RQI	FZI	Plug No.	Zone	Avg. CT Poro	k_b (md)	RQI	FZI	Plug No.	Zone	Avg. CT Poro	k_b (md)	RQI	FZI	Plug No.	Zone	Avg. CT Poro	k_b (md)	RQI	FZI
1004	1	0.394	2.3	0.076	0.12	1016	1	0.313	75.5	0.488	1.07	1025	1	0.219	121.2	0.739	2.63	1037	2	0.258	309.4	1.087	3.13	1042	2	0.264	626.2	1.529	4.26
1006	1	0.424	3.8	0.095	0.13	1031	2	0.278	143.7	0.714	1.85	1029	1	0.252	218.4	0.925	2.75	1039	2	0.239	251.6	1.019	3.25	1147	4	0.216	281.5	1.134	4.12
1011	1	0.392	65.4	0.405	0.63	1032	2	0.280	164.1	0.760	1.96	1030	1	0.276	184.4	0.811	2.12	1071	4	0.231	273.9	1.081	3.60	1151	4	0.229	496.5	1.462	4.92
1012	1	0.306	22.6	0.270	0.61	1034	2	0.302	57.7	0.434	1.01	1033	2	0.269	153.4	0.750	2.04	1091	4	0.248	248.6	0.994	3.01	1152	4	0.221	425.1	1.377	4.85
1015	1	0.141	2.0	0.117	0.71	1041	2	0.284	143.8	0.707	1.79	1036	2	0.246	211.1	0.920	2.83	1098	4	0.229	200.1	0.927	3.12	1156	4	0.229	374.5	1.269	4.26
1023	1	0.164	4.2	0.159	0.81	1044	2	0.251	93.1	0.604	1.80	1040	2	0.271	196.0	0.845	2.28	1113	4	0.229	241.3	1.019	3.43	1165	4	0.225	646.0	1.682	5.78
1026	1	0.301	2.9	0.097	0.23	1053	3	0.306	102.3	0.574	1.30	1043	2	0.251	183.9	0.849	2.53	1117	4	0.230	215.7	0.961	3.21	1172	5	0.194	367.8	1.366	5.67
1027	1	0.258	14.4	0.234	0.67	1076	4	0.292	58.5	0.445	1.08	1047	3	0.262	235.6	0.942	2.65	1127	4	0.192	118.6	0.781	3.29	1270	7	0.181	623.0	1.840	8.30
1045	2	0.304	23.4	0.275	0.63	1079	4	0.296	74.8	0.499	1.19	1066	4	0.300	341.0	1.058	2.46	1132	4	0.217	184.2	0.915	3.30	1271	7	0.163	468.1	1.682	8.64
1046	3	0.294	26.7	0.299	0.72	1084	4	0.265	82.4	0.553	1.53	1067	4	0.265	269.0	1.001	2.78	1135	4	0.233	228.5	0.983	3.23	1272	7	0.169	715.1	2.044	10.07
1048	3	0.279	37.9	0.366	0.94	1085	4	0.254	105.5	0.640	1.88	1069	4	0.237	149.5	0.789	2.54	1136	4	0.229	276.7	1.093	3.69	1275	8	0.181	541.7	1.719	7.79
1049	3	0.306	12.2	0.198	0.45	1094	4	0.245	34.3	0.372	1.15	1072	4	0.279	229.0	0.900	2.33	1137	4	0.238	323.2	1.157	3.70	1286	8	0.149	120.1	0.891	5.07
1050	3	0.301	54.6	0.423	0.98	1115	4	0.253	110.9	0.657	1.94	1074	4	0.233	187.3	0.890	2.93	1139	4	0.230	222.9	0.978	3.28	1288	8	0.144	222.6	1.232	7.30
1051	3	0.305	2.6	0.092	0.21	1116	4	0.259	95.9	0.604	1.72	1083	4	0.272	276.6	1.000	2.67	1140	4	0.229	254.6	1.047	3.53						
1052	3	0.303	4.2	0.117	0.27	1123	4	0.247	82.4	0.574	1.75	1086	4	0.279	173.2	0.783	2.03	1141	4	0.239	276.7	1.069	3.41						
1054	3	0.299	35.5	0.342	0.80	1128	4	0.145	15.0	0.320	1.89	1087	4	0.264	196.0	0.855	2.38	1144	4	0.226	270.2	1.085	3.71						
1055	3	0.276	18.3	0.256	0.67	1159	4	0.169	9.6	0.237	1.16	1088	4	0.271	245.4	0.946	2.55	1145	4	0.224	254.2	1.058	3.67						
1059	3	0.256	1.7	0.081	0.23	1163	4	0.164	13.9	0.289	1.47	1089	4	0.258	190.4	0.853	2.45	1153	4	0.236	257.7	1.038	3.37						
1062	4	0.277	2.1	0.087	0.23	1198	6	0.251	84.9	0.578	1.72	1090	4	0.242	200.0	0.902	2.82	1164	4	0.207	184.1	0.937	3.59						
1063	4	0.284	10.1	0.188	0.47	1210	6	0.217	18.0	0.286	1.03	1093	4	0.228	175.1	0.870	2.94	1197	5	0.245	259.5	1.022	3.15						
1064	4	0.232	1.4	0.076	0.25	1289	8	0.119	3.9	0.179	1.32	1095	4	0.235	123.9	0.720	2.34												
1065	4	0.265	0.9	0.058	0.16	1318	8	0.105	1.9	0.135	1.14	1099	4	0.224	84.7	0.611	2.12												
1080	4	0.286	40.8	0.375	0.94	1326	8	0.143	5.0	0.186	1.12	1100	4	0.223	83.9	0.609	2.12												
1092	4	0.241	9.2	0.194	0.61	1331	8	0.127	7.7	0.246	1.69	1125	4	0.253	199.0	0.881	2.60												
1096	4	0.253	12.8	0.223	0.66	1364	8	0.099	1.9	0.136	1.23	1138	4	0.233	190.0	0.897	2.95												
1104	4	0.238	5.0	0.144	0.46							1146	4	0.232	164.3	0.835	2.76												
1105	4	0.231	6.2	0.162	0.54							1155	4	0.246	208.4	0.914	2.80												
1114	4	0.252	3.8	0.123	0.36							1199	6	0.245	179.3	0.850	2.62												
1118	4	0.250	19.6	0.278	0.84							1317	8	0.096	9.5	0.312	2.95												
1120	4	0.218	1.5	0.081	0.29							1323	8	0.159	44.0	0.523	2.76												
1122	4	0.209	6.7	0.178	0.68							1324	8	0.148	26.4	0.419	2.41												
1133	4	0.233	14.8	0.250	0.82							1360	8	0.151	23.5	0.392	2.21												
1143	4	0.159	1.3	0.091	0.48																								
1149	4	0.152	0.9	0.074	0.41																								
1154	4	0.245	12.7	0.226	0.70																								
1157	4	0.210	1.1	0.072	0.27																								
1158	4	0.200	3.1	0.124	0.49																								
1167	4	0.248	3.2	0.112	0.34																								
1169	4	0.190	1.0	0.072	0.31																								
1171	5	0.170	3.7	0.146	0.71																								
1200	6	0.256	0.6	0.048	0.14																								
1204	6	0.264	1.2	0.066	0.18																								
1274	7	0.142	2.9	0.143	0.87																								
1290	8	0.113	1.2	0.104	0.81																								

Background Color Legend

Zone1
Zone2
Zone3
Zone4
Zone5
Zone6
Zone7
Zone8