ARCHIE'S DREAM: PETROPHYSICS FROM SIDEWALL SAMPLES AND CUTTINGS

-New ways to extract information from sidewall samples and cuttings-

by
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Abstract

In this study it has been shown that it is possible to extract meaningful petrophysical and mineralogical information from small samples such as sidewall samples which can almost always be obtained at low to moderate costs. In principle this technique can also be applied to cuttings when boundary conditions such as a statistically valid sample scheme and a minimum size of the obtained cuttings are adhered to.

The parameters that can be obtained are porosity, permeability, micro-porosity, volume of shale, volume of clay, dispersion and type of clay, all accompanied by an indication of mineralogy and pore geometry. The prediction is based on correlations of plug measurements with image derived parameters. Multiple linear regression was used to define the statistical models needed for prediction. The relations that are found have obvious links with rock properties and can be explained by basic physics. Correlation coefficients for the various petrophysical parameters with their standard errors are presented below.

Parameter	**Corr. Coef.**	**Standard error**
Porosity	0.94	2 P.U.
Permeability	0.89	within a factor 3

The total procedure comprises sample preparation, image collection/processing/analysis and prediction of parameters. In this study a large image data base from a variety of clastic lithologies was build up from which the relations between image parameters and petrophysical parameters were derived to define predictive models. The large image data base ensures generalisation which increases applicability in regions with unknown geology. A separate set of samples with varying lithology from several facies was used as a test to check the validity of the developed models. The results compared well with parameters that were measured on core plugs.

Introduction

At Shell International Exploration and Production in Rijswijk, The Netherlands, research work was carried out with the aim to predict petrophysical parameters from small scale samples like sidewall samples and cuttings. The main driver for this project was the increasing number of deep exploration prospects that exhibit harsh conditions such as high temperature and high pressure (HP/HT). Because of these conditions it is not only difficult but also very costly to retrieve core. Consequently it is hard to obtain accurate calibration points for petrophysical and geological evaluation.

In exploration drilling, cuttings and sidewall samples are acquired routinely to look for oil shows and to judge reservoir quality. Geochemical and paleontological information are normally extracted from these small samples. Qualitative information about mineralogy, grain density, grain-size and pore morphology can be obtained on request, however this is not common practice. The methodology developed in this publication is in essence a quantitative extension of this process.

Contrary to core, which is only taken over the reservoir interval, sidewall samples are taken in reservoir sections as well as in the cap-rock and source rock shales. Shale samples are taken for age-dating and to evaluate cap-rock properties such as sealing potential or to assess source rock properties. Standard petrophysical measurements on cuttings and sidewall samples are cumbersome if not impossible. The samples are very small, and therefore microscopic observation is the only means which can be employed to investigate these samples. Nowadays, imaging techniques have become available, and the next step to use image analysis to quantify rock properties can be taken. The images employed are obtained from SEM (Scanning Electron Microscopy) used in BSE (BackScattered Electron) mode.[1] [2]

Sidewall samples have the advantage that they are retrieved from accurately determined depths. They are therefore ideally suited to investigate anomalies observed on the normal wireline logs. A disadvantage may be the damage caused by the impact of the bullets; samples may be so shattered that the original pore structure and mineral assemblage cannot be revealed to a sufficient extent to apply the methodology described in this publication. The image analysis software can cope with a certain degree of damage, it can be partially corrected for by image processing. When the formation is susceptible to severe damage using conventional sidewall samples, the use of a mechanical sidewall coring tool (MSCT or RCOR) may be considered. This tool drills a 1” core plug from the borehole wall. The plugs can be used in conventional core analysis as well provided that the plugs are intact. Note however that MSCT samples are substantially more costly than standard sidewall samples, which has limited their widespread usage to date.

Cuttings come almost for free as they are routinely collected by the mud logger. A disadvantage of the use of cuttings is the inaccurate depth determination caused by the relatively low frequency of sample collection (generally once every 10 to 30 feet (3 to 10 m)) and the transportation to surface by the mudsystem. One has to rely on the rather crude calculations of the mud engineer to arrive at depths for the collected cutting samples. The presence of clear geological markers will greatly facilitate the tie-in with wireline logs, but the investigation of small scale anomalies using cutting analysis will remain difficult.

A final disadvantage is mud contamination, this is valid for both sidewall samples and for cuttings. It is therefore important that detailed information about the applied mud system is available prior to SEM/BSE analysis. To assess the influence of mud contamination, mud samples should be included in the analysis to enable determination of the BSE ‘signature’ of the mud to allow possible corrections.

The minimum required size of reservoir material for SEM/BSE analysis is some 3 x 3 x 3 mm. Preferably 4 to 8 samples of each anticipated lithology are needed in order to arrive at a statistically valid representation. Minimum size is related to the size of the area investigated with the SEM. Experiments showed that a scanned area of some 2 x 2 mm is an acceptable compromise between resolution and representativeness. This compromise captures sufficient variability in image properties to fulfil the requirement of homogeneity at that scale of observation to be representative for the predicted petrophysical parameters. A scanned area of 2 x 2 mm requires a sample size of some 3 x 3 x 3 mm and is consequently considered an absolute minimum for this technique. It is remarked that the developed methodology can only be applied to samples which are considered homogenous at the selected scale of observation, i.e. images of 2 x 2 mm at approximately 1 micron resolution.

The reference data set

In this study, a large sample data base of some 250 siliciclastic samples from different provenances world-wide was build up which served as the reference data set. The sample data base contains samples from fields in the Niger delta, North Sea reservoirs, fields in Central and South Oman, fields in the Netherlands, Australia, Venezuela, Gabon and offshore Brunei and Sarawak.

Lithologies range from coarse clean sandstones via finer grained shaly sands and silts to tight shales. Depositional environments encompass continental deposits and continental shelf, margin and turbiditic deposits. Samples in the data base which origin from river channel deposits are from fields in the North Sea and Sarawak. Braided river deposits are also represented in the data base, samples from a field in Gabon and a field in Australia. Desert deposits are represented by samples from a gas field in the North Sea, and a gas field in the Netherlands. Finally samples from glacial deposits in the Middle East are included as well.

The validation test

The sample set for validation was deliberately kept outside the regression analysis in order to investigate the predictive capabilities. This sample set originates from an alluvial plain deposit in the Middle East. Facies in this well comprise a stack of different lithologies: laminated heterolithics, silt/shale layers a clean sands and a shaly sand. A set of 32 samples was subjected to standard core analysis, prior to SEM/BSE analysis.

SEM/BSE analysis

SEM analysis can be performed in two modes. Firstly conventional SE (secondary electron) analysis can be applied to samples with freshly broken surfaces. SE analysis enables observation of the surface structure of the sample, hence the pore geometry and the pore wall morphology can be inspected in detail. This mode of observation allows clay typing and a qualitative estimation of the clay abundance and it's dispersion in the pore network. The second mode of SEM analysis is BSE analysis (back-scattered electron).

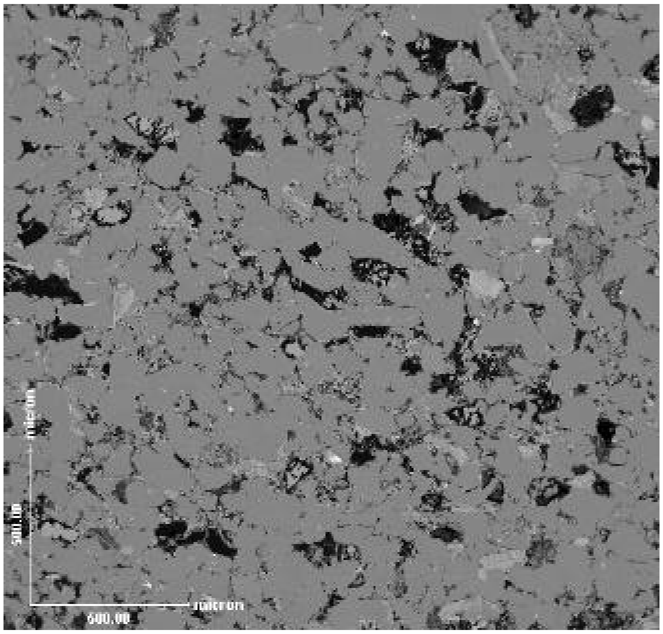

Figure 1. Typical BSE image from a shaly sand.

In BSE analysis, images from impregnated, polished rock samples are collected and stored for further evaluation The grey-values in BSE images represent atomic density and are calibrated against a set of known standards which then enables quantitative use. Figure 1 presents a typical BSE image from a shaly sand interval in a North Sea reservoir. The impregnating epoxy has a low atomic density (it consists of carbon and hydrogen) and therefore appears dark in the images. As the epoxy is filling the pore space, the dark parts of the images consequently represent the pore network, hence the porosity.[3]

The dark grey areas represent the clays and the medium grey the quartz or dolomites. Brighter areas contain either feldspars or calcites, the brightest areas represent heavy minerals like baryte, siderite, anhydrite etc. [4] In some cases ambiguity can arise, i.e. when minerals have approximately the same atomic density, for example, when dolomite and quartz are present simultaneously. When this happens X-ray elemental analysis, available on most electron microscopes, can help distinguish either of the two.

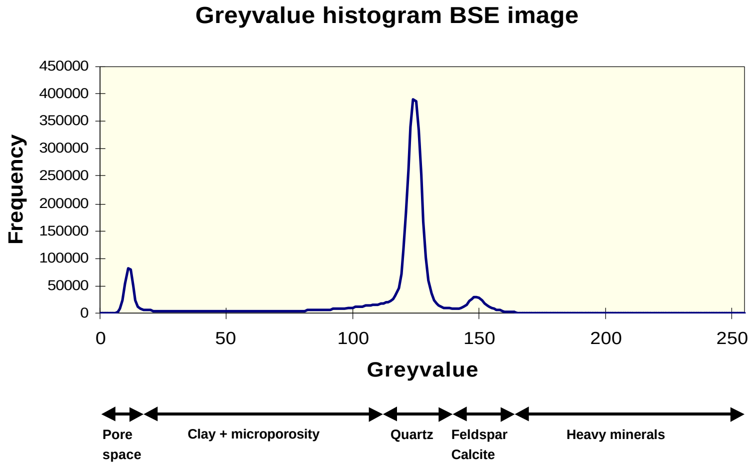

Figure 2. Grey-value histogram from figure 1.

In BSE images the total grey-value range can be divided in sub-ranges representing the various constituents. Figure 2 shows how the total range of grey-values can be subdivided and assigned to the various constituents. Via grey-value discrimination these constituents can be extracted and evaluated quantitatively. The evaluation comprises the measurement of global and local geometric and intensity properties. Global geometric parameters include the total area, the percentage area and the perimeter. Local geometric parameters are area, perimeter and diameter of the individual pore bodies and pore necks. Intensity parameters are the moments of the grey-value distribution function. Correlation analysis between the image derived parameters and the plug analysis parameters of the reference data set then leads to the establishment of predictive models for petrophysical parameters. Parameters that can be obtained are porosity, permeability, micro-porosity and volume of clay. Shale basically consists of a clay matrix with associated micro-porosity and a certain amount of silt sized quartz particles. Therefore V-shale can be obtained by adding fractions of the micro-porosity, clay volume and silt sized quartz and feldspar particles. Compacted, dehydrated clays contain only very little amounts of micro porosity and are known as claystone.

A model based on electron scattering physics was developed to quantify the micro-porosity residing in the clays. The micro-porosity is defined as that part of the pore space with pore diameters below 1 micron, usually residing in the clays. When the clays show high micro-porosities (in the case of illite this can be up to 90% PV) grey-values will be very near the open porosity peak around grey-value 16. On the contrary, when low micro-porosities are present, e.g. in the case of vermiculus kaolinite, grey-values will be near the quartz peak around grey-value 128. The range between 16 and 128 is then linearly mapped between 100% and 0% micro-porosity. The applicability of this linear model is still subject of investigation. The total porosity as determined by SEM/BSE analysis is the sum of the open, effective porosity and the, generally not considered effective, micro-porosity.

Additional information from BSE images.

Analysis of BSE images enables quantitative assessment, which leads to estimation of petrophysical parameters. However, there is more information to be gained from BSE images. Since a BSE image is a record of a cross section through the sample, it will give a similar view as a conventional thin section observed under a petrographic microscope. Therefore BSE images can in essence provide the same information as can be obtained from thin sections. This includes assessment of for instance pore geometry, an important indicator for permeability at larger scales. Another factor greatly influencing permeability is the dispersion of clay minerals and their habitus. As authigenic clays reduce the available primary porosity, especially wen present in pore necks these can have a profound influence on permeability. Moreover, detailed observation of clay morphology can help to reveal the diagenetic history of a reservoir. Similarly, cementation, which can be clearly observed in BSE images, can also aid to assess diagenetic history. Information about the detrital assemblage can also be obtained from BSE images; grain parameters such as size, shape and sorting, each with their own relation to petrophysical parameters, can be evaluated qualitatively. Finally there is another important observation to be made from BSE images; the pore space that can be seen is really effective pore space as it could be invaded by the impregnating epoxy and therewith uniquely classified as effective, accessible porosity.

Analysis: Statistical evaluation of the reference data set

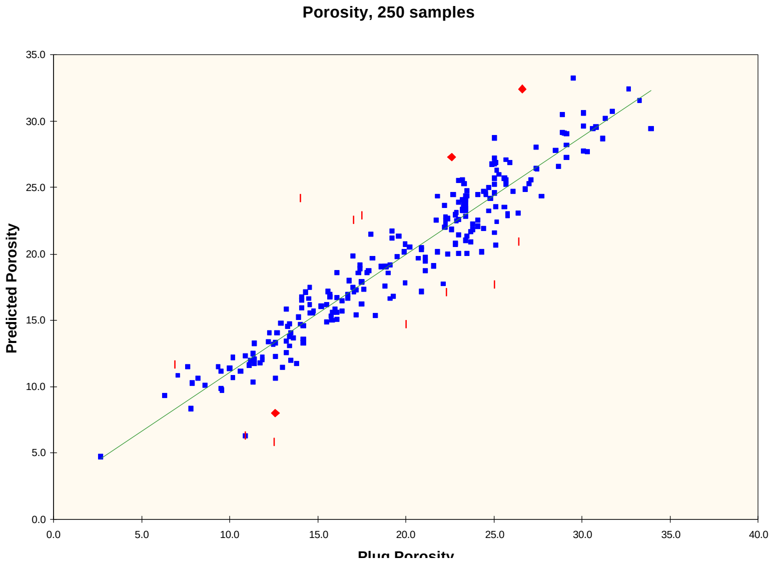

Figure 3. Cross-plot of plug porosity and predicted Image Analysis porosity.

The total number of samples from the reference data set used in the definition of the model for prediction of porosity was 253. Multiple linear regression was used to determine which image parameters showed a relationship with porosity measured on core plugs using the conventional buoyancy method. A linear model was devised which uses the open, effective porosity and the micro-porosity, therefore the this porosity is based on a total porosity concept, which is in line with density porosity as derived from wireline logs. The correlation coefficient between the two image derived parameters and the plug porosity is 0.94. Standard error based on a normal distribution function of the residuals is approximately 2 porosity units which is used to indicate the accuracy of the estimation. The cross-plot of plug porosity versus predicted porosity is shown in Figure 3. The diamond points are presenting samples with errors larger than 2 times the standard error, i.e. outside the ± 2σ range around the fit line.

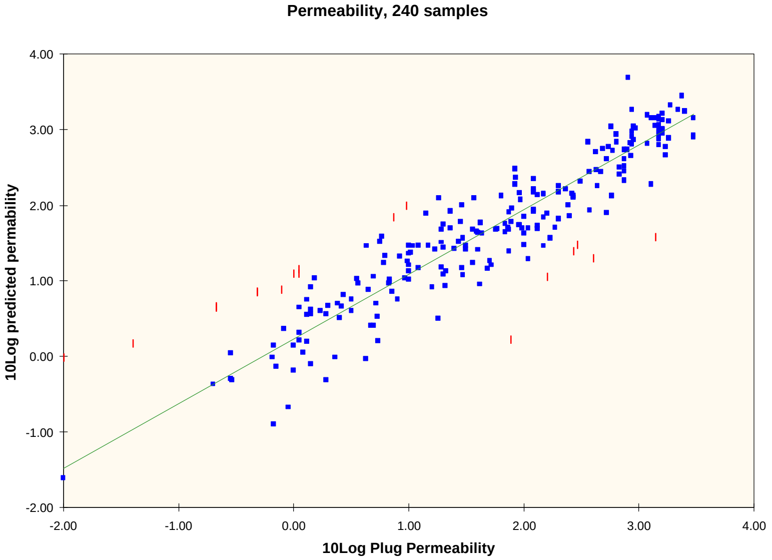

Figure 4. Cross-plot of unstressed plug permeability and predicted Image Analysis permeability.

The non-stressed, air permeabilities measured on 243 plugs were used in the definition of the model for the prediction of permeability from image data. In order to enable multiple, linear regression the data set was linearised by taking the 10Log of the permeabilities. The predictive model is based on a Carman-Kozeny [5] [6] [7] approach, as the Carman-Kozeny theory is based on a geometric model, which jives well with the geometric data we extract from BSE images. The model we use contains three parameters we can derived from the images; the open, effective porosity, the specific surface area of the pore space and an additional topological parameter; the pore body/pore neck aspect ratio. The specific area of the pore space is obtained by the taking the ratio of the perimeter and the area of the effective porosity observed in BSE images. The pore network as seen on BSE images can be divided in constrictions (pore necks) and areas (pore bodies). The geometric properties of these can be obtained via image analysis from which the average pore body/pore neck aspect ratio can then be worked out. Micro-porosity is not included in this model, as it is not considered to contribute to flow at rates normally observed in reservoir rock. The correlation coefficient is 0.89 with a standard error of 0.53. Since the data was linearised, the standard error has to be converted back leading to a standard error of approximately a factor 3. This means that in the ± 1σ range the permeability can be predicted within the boundaries of 3 times larger and 3 times smaller. Note that the permeability ranges in total over 6 orders of magnitude. Figure 4 presents the cross-plot of plug permeability and image analysis derived permeability. The diamond points are considered outliers as they plot outside the ±2σ range.

Analysis: Results from the validation test

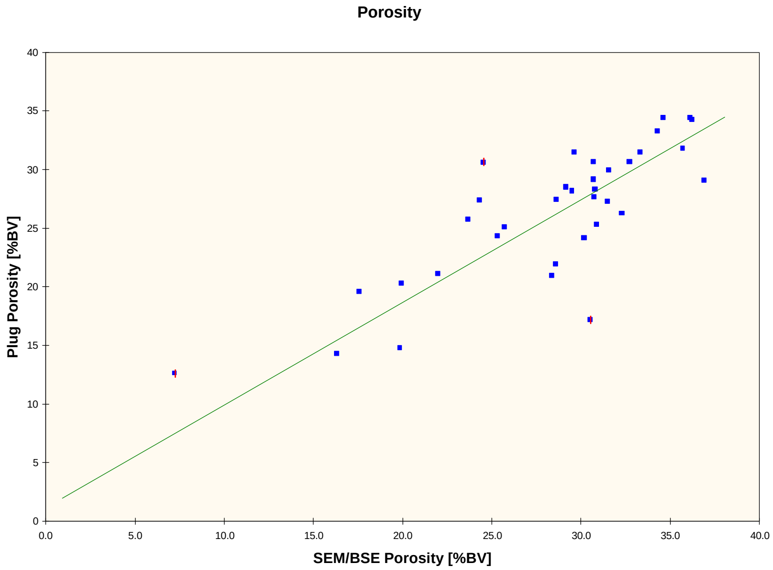

Figure 5. Cross-plot of the Image Analysis predicted and measured porosity of the validation set.

Porosity was predicted from BSE images for 32 samples in the data set used for validation. Statistical analysis revealed a correlation coefficient of 0.87 between the predicted and the measured porosity. Figure 5 presents the cross-plot of the porosity predicted from image analysis parameters and porosity measured from plugs. The three outliers are marked as diamonds, these samples will be evaluated in discussion section, where an explanation for the deviation of the trendline (in green) will be given.

Permeability was estimated on the same 32 samples as were used for porosity. Also in this case 3 outliers were found which are marked diamond in the cross-plot presented in figure 6. It is remarked that 2 of these outliers were found in the porosity estimation as well.

Discussion.

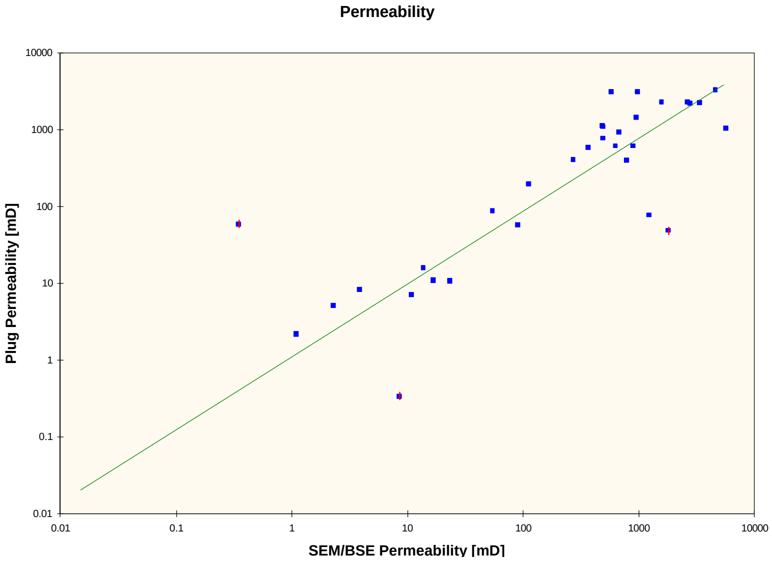

Figure 6. Cross-plot of Image Analysis predicted permeability and plug measured permeability of the validation set.

Although the IA predicted porosity shows a good overall agreement with the plug porosity of the reference data set (ref fig.3), the images of the individual plugs were closely examined in an attempt to explain some of the scatter. In the cases where the porosity predicted from image analysis is lower than the measured plug porosity, abundant local cementation was found. In all cases the cementation was found to be uniformly distributed over the BSE images. Next, the original samples were inspected in the SEM. Some areas showed abundant cementation while other places are fully without cementation; at those places a clean sandstone was found. This is a clear example of heterogeneity at the plug scale while at the scale of the BSE images the sample can be considered homogeneous. This observation led to the conclusion that heterogeneity on the plug scale exists which is not captured in the BSE images. In order to explain this we have to take a closer look at the scales on which plug porosity and image analysis porosity are determined. The plug porosity is normally obtained from a plug of 2.5 cm (1”) diameter and 3 cm (1.25”) height. The whole plug is involved in the analysis, that is 100% of some 15 cm^3, this is a full 3D observation.

BSE images however are obtained from a section, in essence a 2D observation. In this study 4 BSE images of each sample were used, each image comprising an area of 2 x 2 mm. This sums up to 0.16 cm^2 for each sample. As the total area of a horizontal section through a plug is some 5 cm^2, we can easily calculate that BSE analysis involves about 3% of the total area. This leads to the conclusion that in our porosity prediction we use 3% of a 2D observation to estimate porosity that was measured on 100% of a 3D observation. The least to be said that it is remarkable that this methodology works so well, albeit by the grace of the homogeneity requirement. So far we have discussed and explained to some extent underestimation of porosity, i.e. those points falling below the trend line in figure 3. An equal amount of points fall above the trend line; porosity estimated by image analysis is higher than the porosity measured on plugs. Also in this case heterogeneity caused by local cementation was diagnosed. Furthermore, the BSE images showed that most of the pores are filled with clay minerals (dark grey material), indicating shaly samples. Furthermore, cracks are present along the grain boundaries through the pore filling clays. These cracks occur when the sample is cleaned. Some clay types have the property of swelling when taking up fresh water as was used in the cleaning procedure of these samples. The swelling causes the cracks to propagate through the clay areas. These cracks have been filled with epoxy in the sample preparation procedure. They are now mistakenly classified as effective pore space thus increasing the predicted porosity. Especially samples with high clay content, such as shaly sandstones, will suffer from this effect as it was encountered a number of times. In addition, the detailed inspection of the samples with high estimates of porosity also confirmed the presence of heterogeneity as was concluded from the samples with low estimates of porosity.

Conclusions

- Petrophysical parameters can be predicted from small scale samples such as cuttings and sidewall samples using SEM/BSE image analysis techniques. An essential assumption is that the samples are considered representative for the lithology they originate from.
- Porosity and permeability can be predicted using multiple linear regression techniques. In addition, SEM/BSE analysis gives an image similar to a conventional thin section, providing information about mineralogy, pore geometry and clay mineralogy/distribution. Based on normal distributions of the residuals of the predicted parameters, the accuracy of the predictions is ± 2% BV for porosity and within a factor of 3 for permeability.
- The predicted results will be affected by small scale heterogeneities and improper sample preparation techniques. To minimise these effects the samples should be carefully inspected visually for homogeneity and appropriate measures have to be taken to maintain representativity. In addition, rigid cleaning procedures with respect to formation water salinity should be followed carefully to avoid clay swelling effects that may lead to overestimation of porosity when this technique is used.
- The minimum sample size required for SEM/BSE analysis is circa 3 x 3 x 3 mm to ensure a statistically meaningful representation.

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