# Effective Reservoir Identification and Controlling Factor Analysis for Mixed Sediments in Saline Lacustrine Basin, Shizigou Area, Qiadam Basin, China*

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## Abstract

The Lower Ganchaigou Formation of Oligocene age in the Shizigou area is characterized as mixed sediments in a saline lacustrine basin. It contains various complex minerals, and the effective reservoirs are difficult to identify from conventional logs due to the complex lithology and pore structures. It is well known that the pore space connected to fractures, solution enhanced bedding planes, and vugs greatly enhance the fluid flow. Characterizing these different pore spaces in carbonates has been a great challenge for petrophysicists and reservoir engineers for many years. In this study, we proposed a new workflow which merges mineral content calculation, porosity calculation, texture analysis, and heterogeneity analysis mainly using electrical borehole image data and spectroscopy data. Also, incorporating the core analysis data as well as production data, the best reservoirs were identified, and the main controlling factors were concluded.

Based on spectroscopy data and XRD data, the different mineral contents can firstly be quantified, and hence porosity can be derived by using the optimized method. Then the textures of the formation can be classified into five different types from resistivity image data: massive, cracked, interbedded, thinly laminated, and deformed. Conductive fractures are evaluated by quantitative parameters including fracture density, aperture and porosity. What's more, conductive heterogeneities (fractures and vugs) are delineated on the image using thresholds on contrast and value, and conductive inclusion surface proportion and conductive inclusion size can be derived. Also, by comparing the minerals, porosity, textures, fractures, conductive heterogeneities with production data, the controlling factors of the productive reservoirs can be identified.

Conventional logs have low vertical resolution and often fail to predict accurately the production potential of these complex reservoirs. Accuracy has been greatly improved since the introduction of microelectrical borehole image logging and subsequent interpretation workflows.

## Summary

In recent years, many high oil production wells have been discovered within the Oligocene Lower Ganchaigou Formation in the Shizigou area of the Qaidam Basin. Some wells could produce about 1000 t/day; however, effective reservoirs are difficult to identify from conventional log responses due to complex lithology and pore structures. This paper proposes a new workflow to identify effective carbonate reservoirs, which merges texture analysis, heterogeneity analysis, mineral content calculation, and porosity calculation mainly using electrical borehole image data and spectroscopy data. More than 40 wells have been processed and analyzed by this method, and it is found that oil or water daily production (without hydraulic fracturing) have good relationship with surface proportion of conductive heterogeneous inclusion appearing on electrical borehole images. Further study reveals that high oil or water production intervals usually have a high surface proportion of conductive heterogeneous inclusion which are usually caused by fractures or vugs. In conclusion, tectonism is the main controlling factor on reservoir quality; sedimentation, and diagenesis are the secondary factors.

## Introduction

Shizigou area is located on the west of the Yingxiongling structure in northwestern Qaidam Basin. The Lower Ganchaigou Formation of Oligocene age in the Shizigou area is characterized as mixed sediments in a saline lacustrine basin and it contains various minerals of clay, quartz, feldspar, dolomite, calcite, anhydrite, halite, etc. Mineral contents are difficult to estimate from only conventional logs, because rocks with different mineral concentration may have similar well log response, and for this reason it is difficult to get accurate porosity which is calculated based on mineral content and concentration.

Pore structure is very complex in this area due to the different types of pore spaces including intercrystalline pores, dissolution pores, fractures, etc. However, it is well known that the pore space connected to fractures, solution enhanced bedding planes, and vugs greatly enhance the fluid flow. Characterizing these pore spaces in carbonates has been a great challenge for petrophysicists and reservoir engineers for many years. Nuclear magnetic tool is expected to be the best data for pore structure analysis, however, due to high salinity formation water (~300 ppk), it can hardly work anymore in the Lower Ganchaigou Formation.

Combining spectroscopy log data, conventional log data and XRD data, mineral content and porosity can be acquired more accurately, and pore structure can be analyzed to some extent using electrical borehole image data. Integrating mineral content, porosity, pore structure as well as production data, the best reservoirs were identified (Figure 1), and the main controlling factors were concluded.

## Mineral Content and Porosity Computation

Gamma ray spectroscopy tool is a wireline device which uses a pulsed neutron source emitting high neutron flux that interacts with the formation nuclei (Radtke et al., 2012). During inelastic scattering interactions and when the neutrons were absorbed by the formation, gamma-ray emission will happen, and the spectroscopy tool could detect the gamma-ray spectra. Both inelastic and capture gamma ray spectra are processed to obtain the elemental concentrations. Using a simultaneous solver approach, a robust petrophysical model is obtained that solves for the minerals (Grau and Schweitzer, 1989; Herron et al., 2011). Correlation with XRD data, mineral concentration could be calibrated and can be used for other wells. Based on accurate mineral contents, the matrix density can be derived by summing up all the mineral contents times their grain density. And combining the matrix density and density log, porosity can be calculated. It shows that mineral concentration and porosity calculated from spectroscopy data agree well with XRD data and core porosity value (Figure 2).

## Texture Classification

Electrical images, acquired with wireline after drilling, can provide a high-resolution conductivity image of the reservoir, which responds to rock texture properties. Comparison of the core textures with the micro-resistivity images can help to reveal many features like formation beddings, concretions, and fractures. In the Shizigou area, five types of rock textures were classified based on core and micro-resistivity image: thinly laminated, interbedded, massive, cracked, and deformed (Figure 3). Massive texture looks homogeneous and has no beddings and fractures developed in the core and in micro-resistivity image; cracked texture has open fractures or partially filled fractures or looks cracked on micro-resistivity images; thinly laminated texture has very thin layers developed seen both in the core and micro-resistivity images, which formed in a very quiet environment; interbedded texture has layers of different colors or minerals interbedded with each other; deformed texture has deformed beddings developed. Based on oil shows from mud logging and core observation, cracked texture and deformed texture are more likely to have good oil show.

## Quantitative Evaluation of Fractures

In the tight oil reservoirs of the Lower Ganchaigou Formation, the natural fracture distribution and connectivity generally have a huge impact on fluid flow and accumulation. Characterizing the natural fracture properties (length, aperture, volume) is therefore essential for reservoir evaluation. Open fractures appear as dark sinusoid on borehole electrical images, and it can be evaluated by quantitative parameters including fracture aperture, fracture density, fracture length, and fracture porosity based on the equation proposed by Luthi and Souhaite, 1990. The analysis of this tight oil reservoir shows that high production layers often have many effective fractures developed, and fracture aperture and fracture porosity is higher (Figure 4).

## Heterogeneity Characterization

Carbonate reservoirs usually show high heterogeneities because of fractures and vugs which are quite important for carbonate reservoirs. Conductive heterogeneities of the borehole electrical images should correspond to local changes in porosity relative to the matrix; high conductive heterogeneities correspond to porous and high permeable zones. Hence, delineation of conductive heterogeneities is the key for carbonate reservoir evaluation. Porotex technique can help to delineated conductive heterogeneities using borehole electrical images (Yamada et al., 2013). It includes a series of processing steps. Firstly, the background of the image is computed by removing noncrossing features on images such as vugs, molds, fractures, and concretions. Secondly, conductive heterogeneities will be delineated on the electrical image using thresholds on contrast and value compared to matrix, and geometrical properties of heterogeneities such as conductive inclusion surface proportion and conductive inclusion size can be derived (Figure 5). Thirdly, artificial conductive heterogeneities will be removed, such as induced fractures, break out, and bad image data.

## Case Study

Figure 6 is the evaluation result for one well in this area. This interval contains mainly clay, quartz, feldspar, dolomite, calcite, and anhydrite. The porosity is higher in the intervals of 3914-3916.5 m and 3921.2-3927 m than in other intervals. However, the lower interval has more dolomite and anhydrite and less clay, which is better for fracturing and dissolution. From the image data, it was found that it is interbedded texture for the upper interval and cracked texture for the lower interval, where more fractures are developed, and the fracture aperture and fracture porosity is high. Heterogeneity analysis also shows that the lower interval has high surface proportion and high size of conductive heterogeneous inclusions appeared on electrical image. Combing mineral content, porosity, fracture aperture, fracture porosity, surface proportion, and size of conductive heterogeneous inclusions, 3921.2-3927 m is thought to have better reservoir quality. After perforation of 3921-3927 m, it produced oil about 17 t/day, which agree with our interpretation very well.

## Controlling Factor Analysis

More than 40 wells were processed and evaluated using this integrated solution. Combining with production data, reservoir controlling factors were analyzed. Figure 7 is the cross plot of fluid production per day and conductive heterogeneity surface proportion. We can see two obvious trends in this cross plot, the upper line is mainly water production line and the lower line is mainly oil production line, water production is higher than oil production due to higher phase permeability. And for both lines, production data has good relationship with heterogeneity result. High production intervals usually have high conductive heterogeneity surface proportion, and vice versa. It proves that conductive heterogeneity surface proportion is important controlling factor for carbonate reservoirs, even in this complex mixed sediment carbonate reservoir.

High conductive heterogeneity intervals usually have high dolomite content and have fractures with big fracture aperture and fracture porosity, and vugs along fractures or in cracked texture zones formed by fault. In conclusion, fractures and faults formed by tectonism play a very important role for this complex carbonate reservoir. On one hand, they contribute a lot to reservoir permeability; on the other hand, they are fluid migration pathways and beneficial to dissolution. Sedimentation and diagenesis also influence the reservoir quality, the higher the dolomite content with lower clay content, the higher the reservoir porosity (Figure 8), and it is favorable to be fractured.

## Conclusions

The identification of effective carbonate reservoirs and controlling factors is very important for field exploration and development planning. This paper has demonstrated the implementation of a comprehensive petrophysical evaluation workflow for a complex carbonate reservoir. Mineral concentration and porosity can be calculated from spectroscopy data and density data, and the result matches the core analysis data very well. Rock texture can be recognized from electric borehole image data, and fracture quantitative evaluation and heterogeneity analysis can be implemented using borehole image data. By integration of mineral concentration, porosity, rock texture, fracture quantitative evaluation, and heterogeneity analysis, the effective reservoir can be identified. This comprehensive petrophysical evaluation workflow can also be applied to other carbonate reservoirs.

Combining production data, the main controlling factors on reservoir quality were concluded. Tectonism is the most important controlling factor for reservoir quality and oil production, and sedimentation and diagenesis also can help to improve the reservoir quality.

## Acknowledgments

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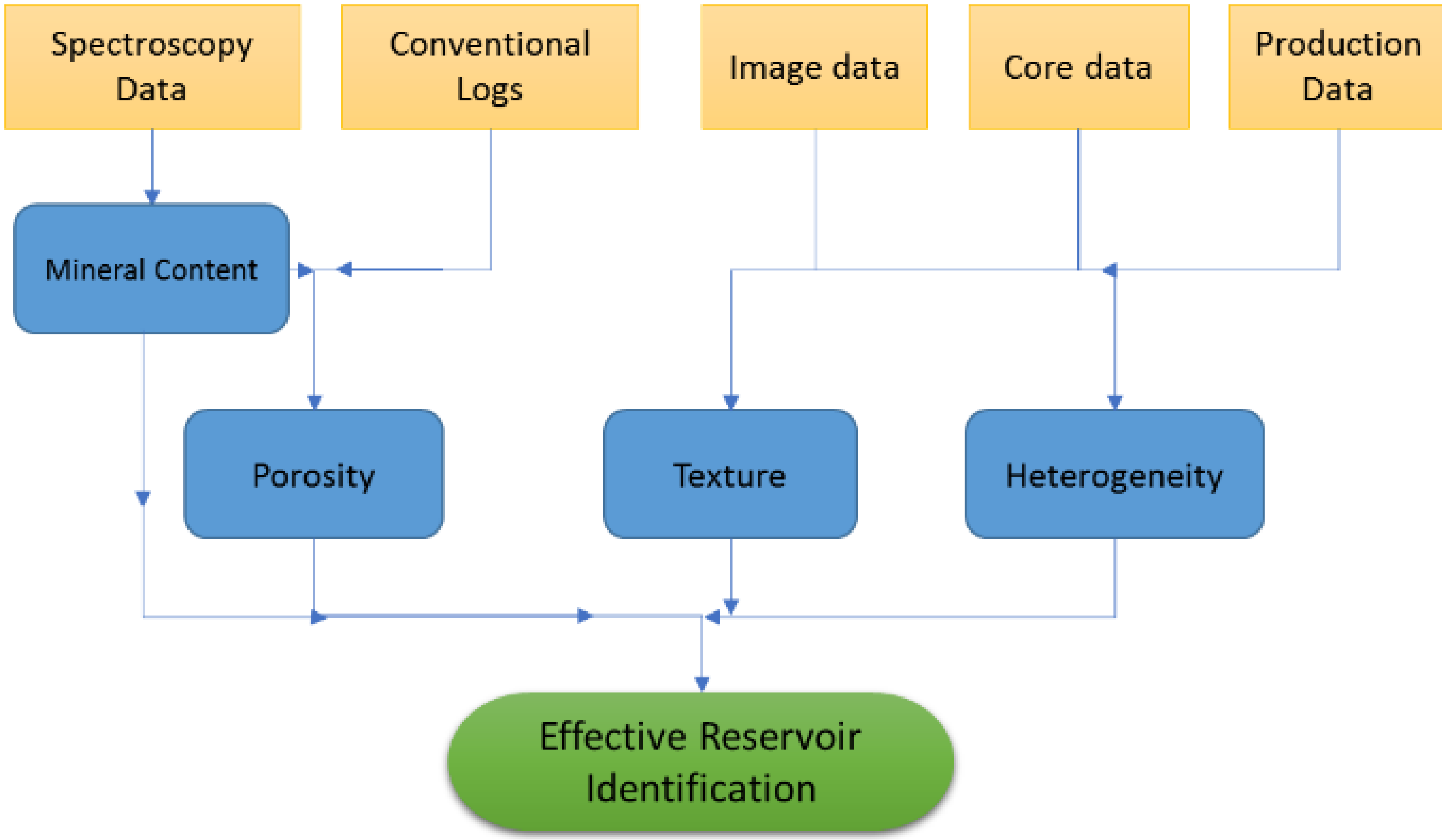


Figure 1. Integrated solution for effective reservoir identification.

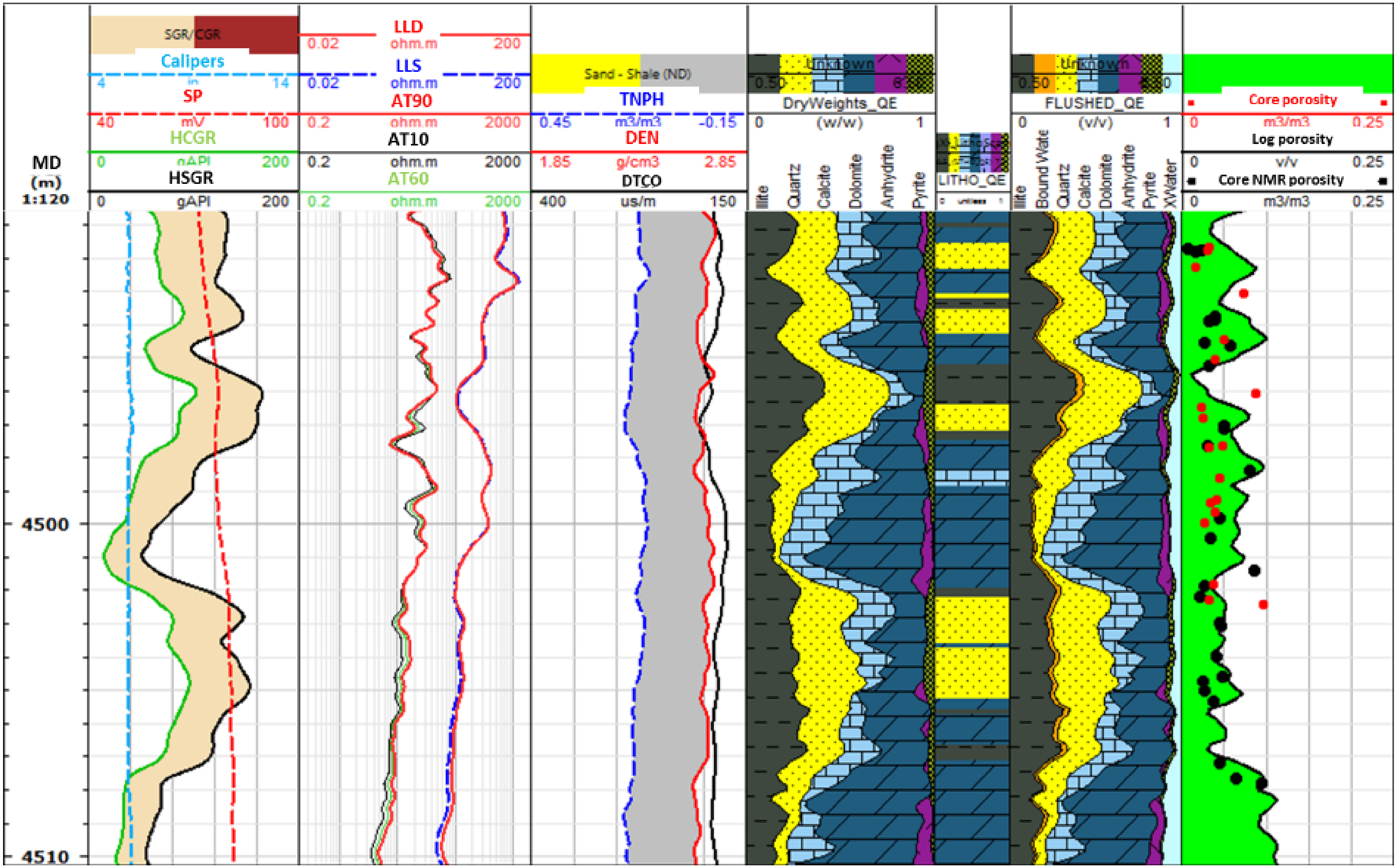


Figure 2. Comparison between computed porosity and core porosity (Point data is core data and continuous data is computed from spectroscopy data).

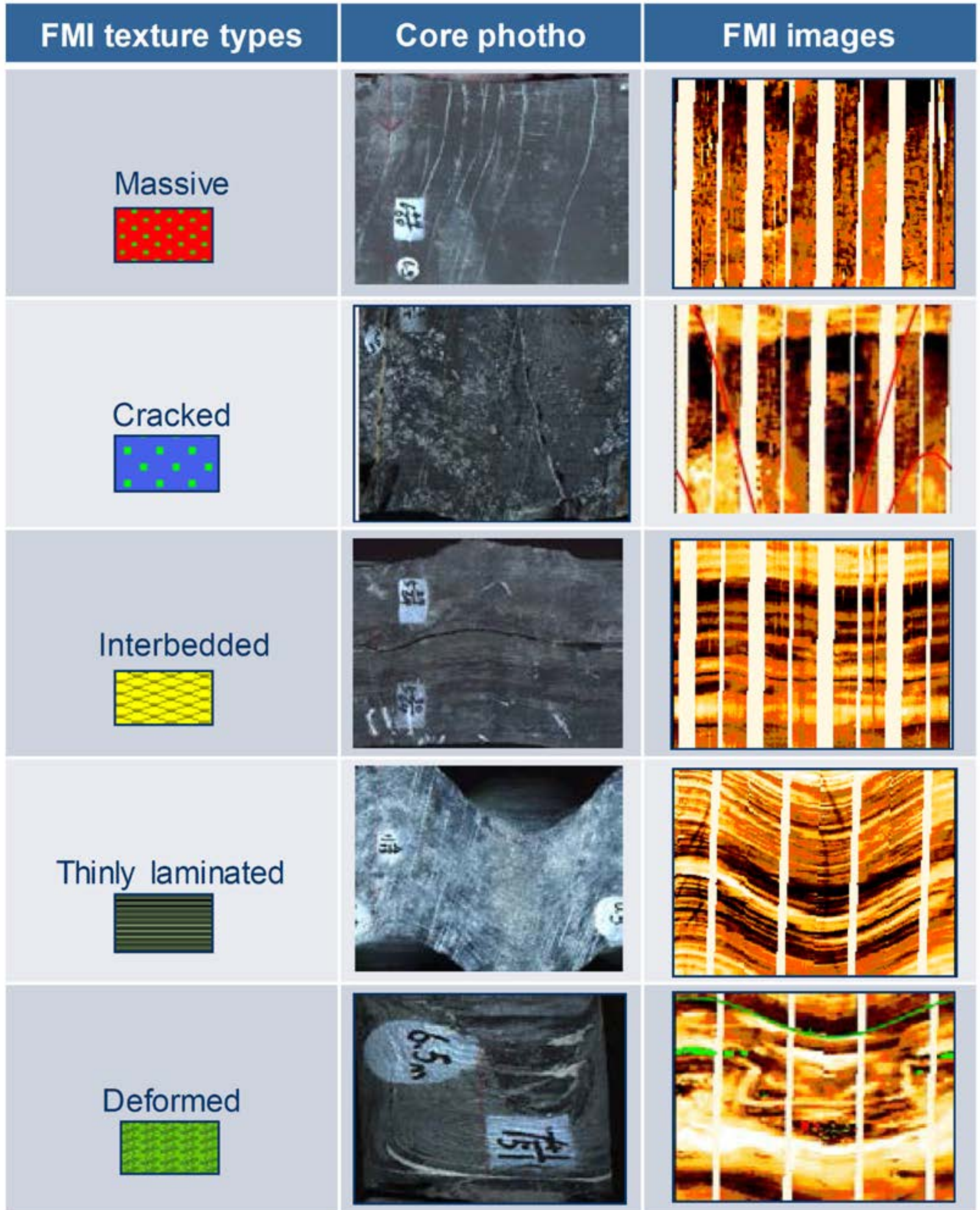


Figure 3. FMI texture classification.

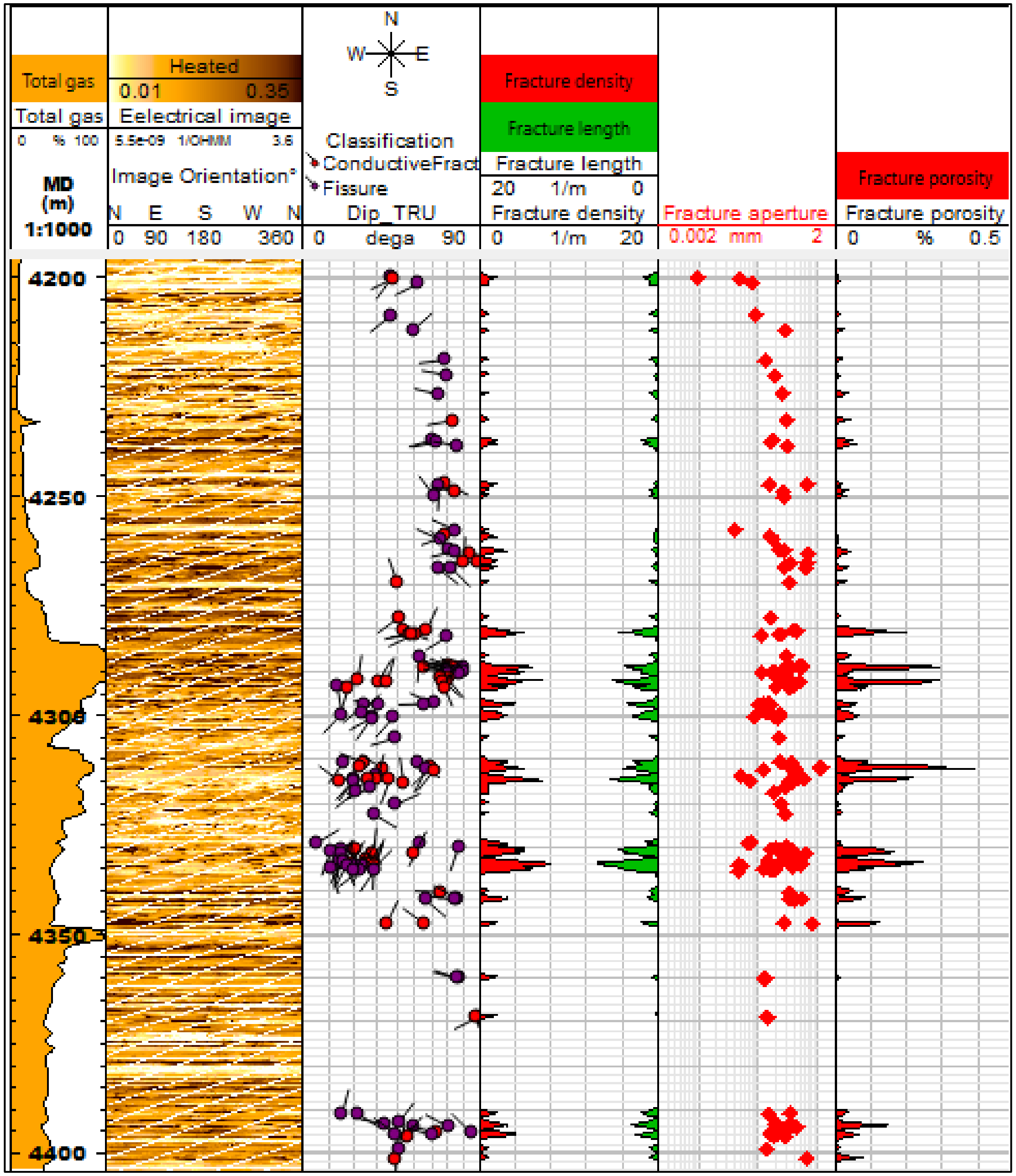


Figure 4. Fracture quantitative evaluation.

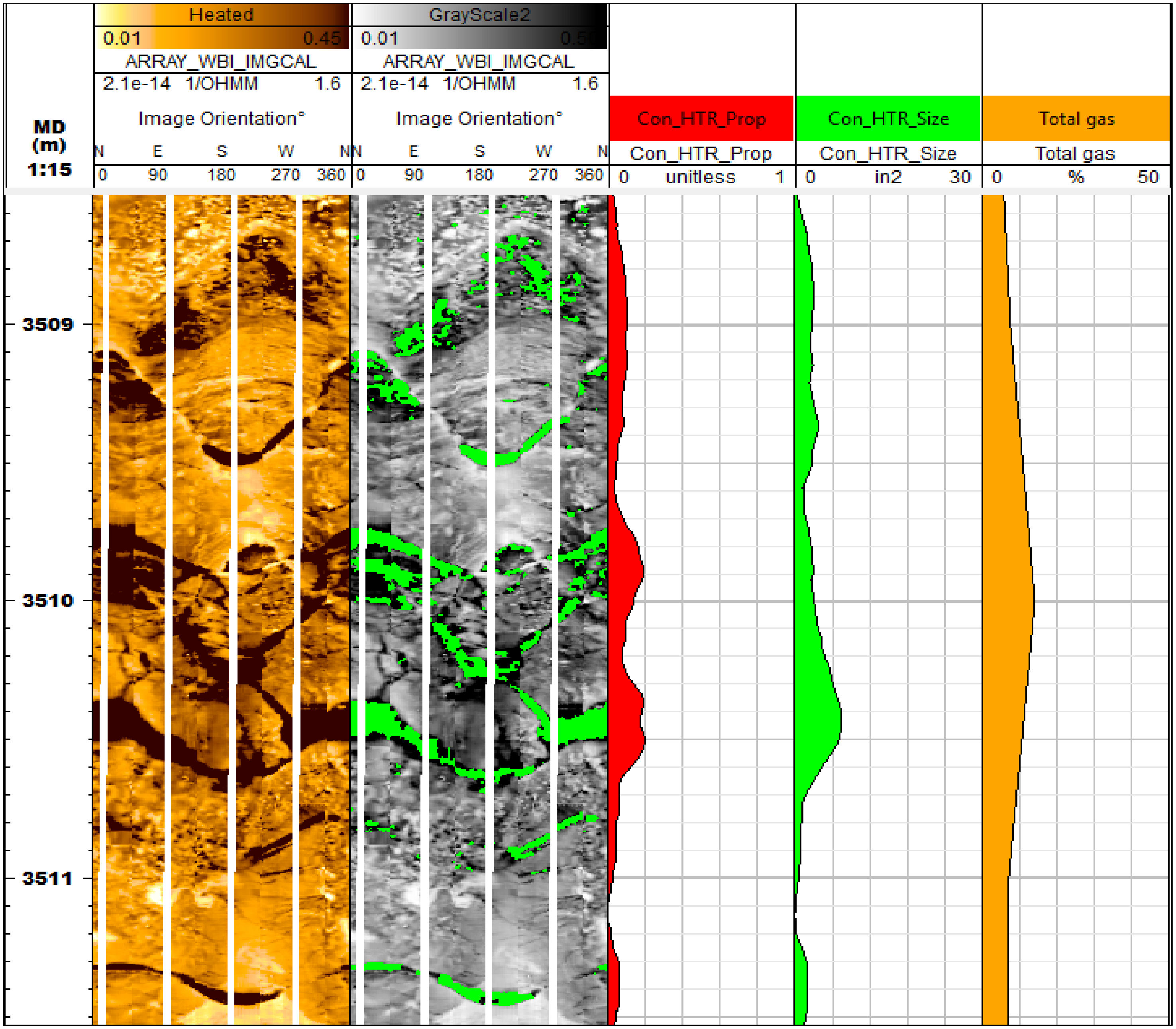


Figure 5. Heterogeneity analysis result.

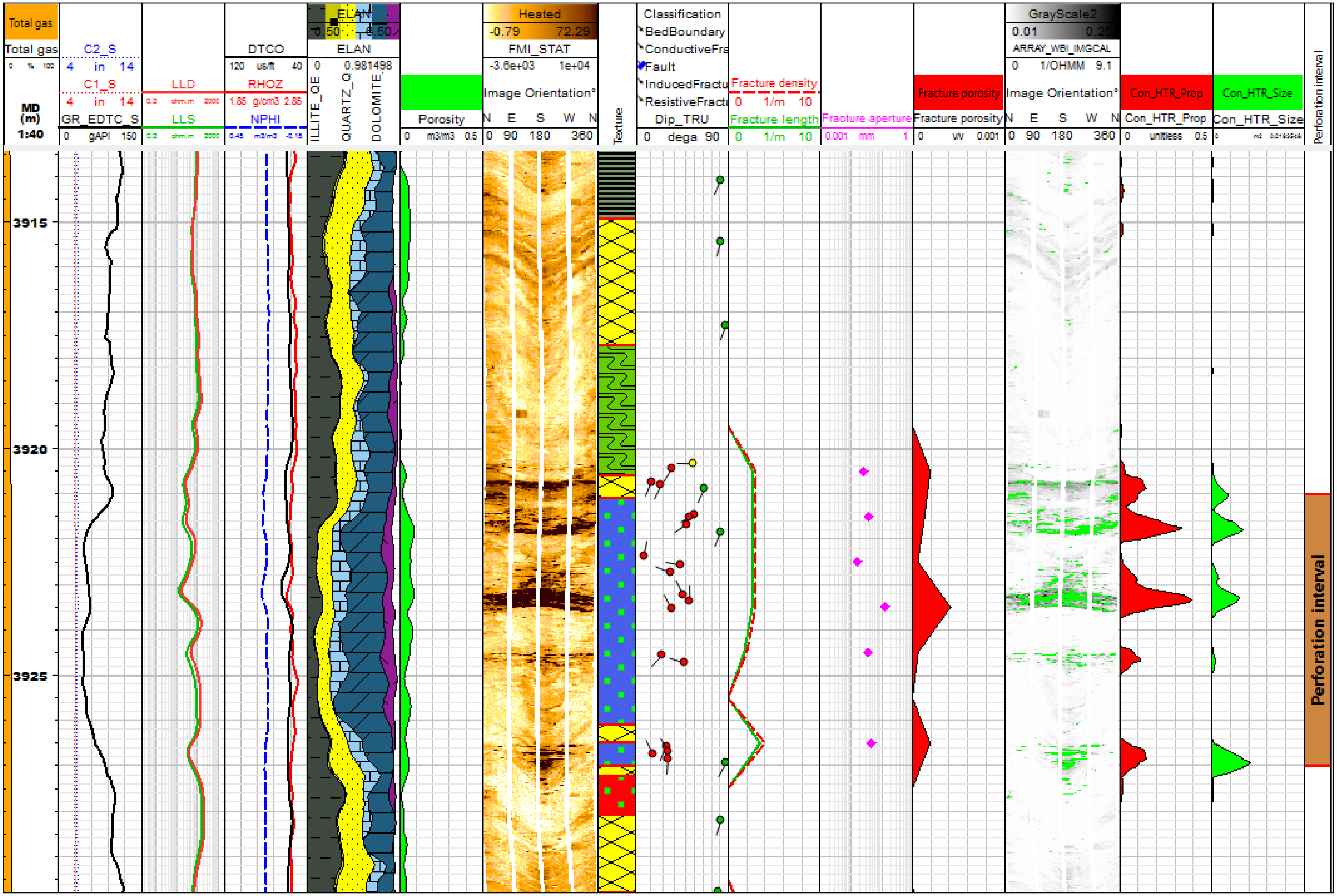


Figure 6. Reservoir evaluation composite plot.

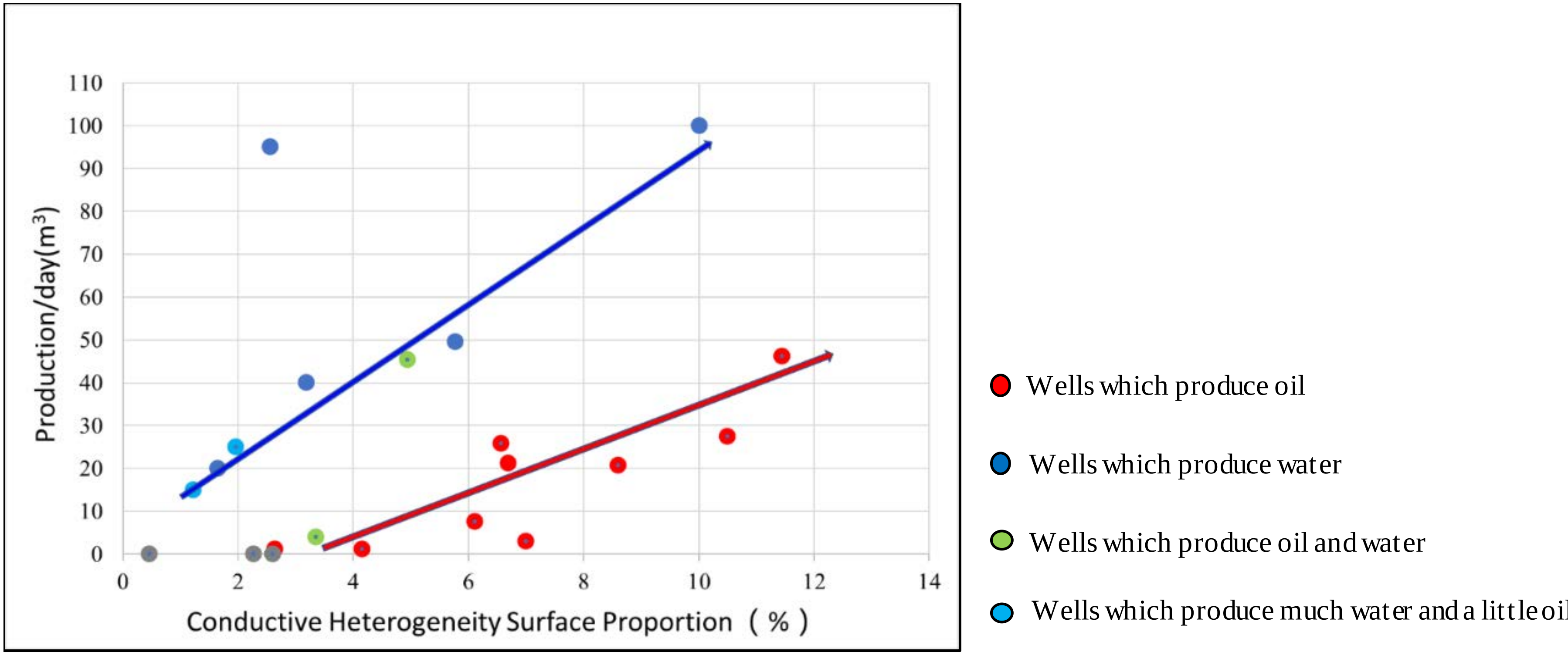


Figure 7. Relationship between daily fluid production and conductive heterogeneity surface proportion.

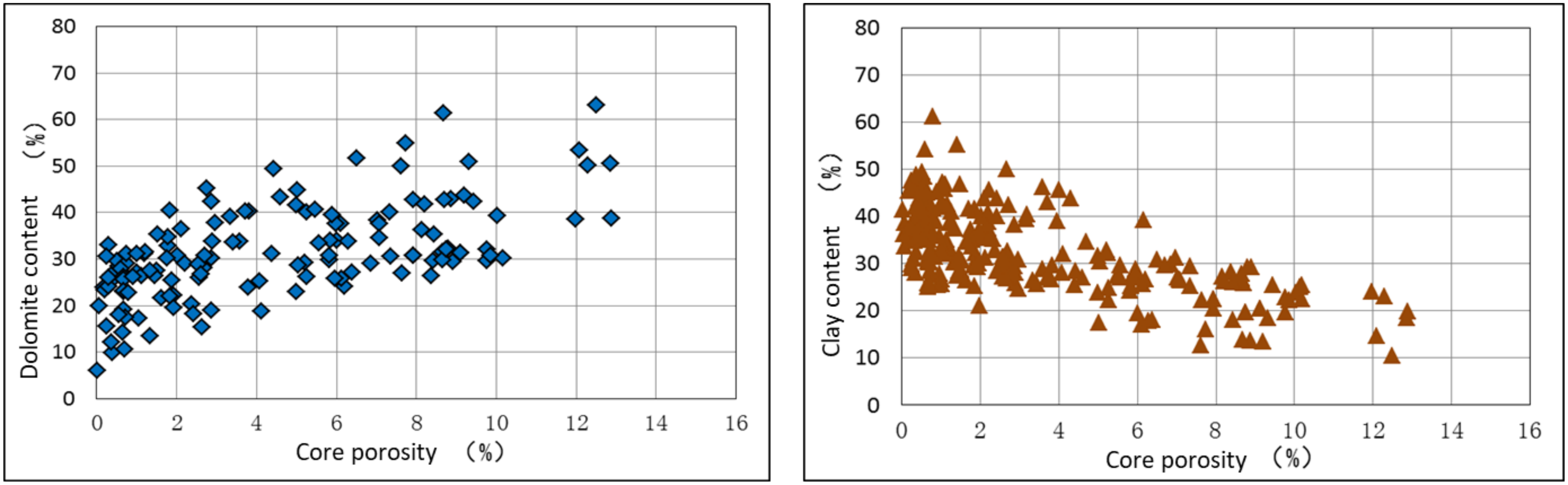


Figure 8. Relationship between core porosity and dolomite content and clay content.