

Unravelling Paradigms in Vaca Muerta Formation, Neuquén Basin, Argentina: The Construction of Geochemical Wellbore Images by Geostatistical Integration of Geochemistry and Conventional Log Data with Wellbore Resistivity Images*

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Abstract

In this article the problem of paradigm change in the study of unconventional reservoirs is analyzed. A paradigm change involves not only a deconstruction process of category analysis, but also an intellectual and collective effort of scientific community of the whole local oil industry. The ways to do that are rethinking old techniques, incorporating new ones, combining like elements differently, and adding contributions from other disciplines.

We describe a methodology based on the geostatistical integration of organic and inorganic geochemical data, wireline logs and resistivity wellbore images. Geochemical and well log data are used as hard data while resistivity wellbore images are used as soft data. The integration method applied was the Sequential Gaussian Simulation with Type II Markov model using hard and soft data mentioned above.

Well data is from the Cerro Vagón Block, southeast Neuquén Basin, Argentina, where the Vaca Muerta Formation has a thickness of 110 m. Chemical analysis was performed on 45 cutting samples for both organic (destructive pyrolysis analysis) and inorganic (nondestructive X Ray fluorescence analysis with rapid handheld equipment). Moreover, 18 m of core were analyzed for TOC by 12 chip samples irregularly spaced and 180 readings with nondestructive X ray fluorescence analysis, at a distance of 10 cm from each other.

As a result of the stochastic simulation process, several wellbore images were obtained to 1 inch of average vertical resolution involving properties such as density, calcium carbonate and molybdenum concentration together with TOC content. The Vaca Muerta Formation has a pattern of molybdenum and vanadium metals that correlate with TOC and pyrite content and hence, the anoxic level of the sedimentary environment. Pyrite content is precisely estimated by means of high correlation shown by iron and sulfur. Conventional methods for TOC

thickness evaluation (Passey Model, among others) are based on high transit time, low density and high resistivity properties of organic matter. In this case the pyrite concentration decreases the resistivity values and underestimates the real TOC thickness values. High resistivity values are related to calcium carbonate as observed in wellbore images. As a conclusion, a more accurate TOC thickness evaluation can be made with the geostatistical integration of geochemical and wireline log data.

Introduction

The detection of hydrocarbon generation potential thickness and brittleness in black shale are key features to evaluate the production potential. We present a method that involves a paradigm change and it will allow the integration of geochemical data (X-Ray Fluorescence analysis and pyrolysis from cutting and cores), conventional well logs and wellbore image using Geostatistic Simulation algorithms.

A paradigm is a ‘conception of the world’: a set of values and models to determine how to produce taxonomies, i.e. structure, categorize and classify the world (Khun, 1962; Palma, 2012). A ‘technological paradigm’ is based on scientific principles and physical models. It is studied with a specific technology and it has an economic consequence (Dosi, 1982). The prevailing paradigm, the ‘conventional reservoirs assessment’, does not always give answers to shale reservoirs problems, for example the porosity-permeability relationship problem, conventional well logs response to shale reservoirs, etc. We think that the ‘technological paradigm change’ related to shale reservoir evaluation, will consist in staking old techniques, incorporating new technologies, combination of known elements differently and the contribution of other disciplines.

The wells studied are from the Cerro Vagón Block, located in the south margin of the Neuquén Basin, Argentina ([Figure 1](#)). The stratigraphic framework is composed of three source rocks levels ranging from Jurassic to Lower Cretaceous, where the Jurassic Vaca Muerta Formation is the most important (red arrow). The rest of the stratigraphic column is composed of clastic and carbonate beds ranging from Jurassic to Tertiary ages. Some of these beds are sandstone reservoirs with shale, limestone and anhydrite as the most important seals (Larriestra and Merino, 2014).

Materials and Methods

This article is based on soft inorganic geochemistry concept defined by Larriestra (2011, 2013), which can be defined as the spatial modeling of geochemical data which prioritizes the amount of data, their spatial relationship and their relationship with other data types (geological and geophysical data) over the individual chemical analysis accuracy. The method is based on hundreds of chemical analysis from cutting and core samples and their quantitative integration with wellbore image using a geostatistical simulation technique. These processes produce well bore images of geochemical and petrophysical data.

Data Acquisition

The chemical element analysis was performed using rapid hand-held X-Ray Fluorescence equipment (HHXRF) in a non-destructive registration process. The analysis consisted on detection of 32 chemical major and trace elements, from 80 cutting samples and two cores from

base of the Vaca Muerta Formation. Cores were analyzed by 180 readings at a distance of 10 cm from each other. Finally, all samples were processed for X-ray diffraction and pyrolysis (TOC) destructive analysis.

Data Processing and Geochemical Image Construction

This method is based on the analysis of best correlations between the chemical elements and resistivity data of wellbore images. Additional correlation between density log and image data was performed. Then Sequential Gaussian Cosimulation with Markov model type II was performed, using the image data as covariable (Deutsch and Journel, 1998; Remy et al., 2009). After 30 realizations are run (the minimal number needed to represent a Gaussian variable) the expected value of these is the wellbore image log of the chemical element or property (Nawratil et al., 2012; Larriestra, 2011; Larriestra, 2013).

This method allowed the creation of wellbore images of density, calcium carbonate, molybdenum and total organic content. One source of uncertainty that remains unsolved is the location of each hard data point (geochemical and density log data). Every hard data point is to be compared with wellbore image data composed of 176 curves belonging to wellbore resistivity image. The depth location of each hard data point within the core is well known but matching with the position on the image remains unknown. It is for this reason that we compare the 176 image resistivity curves with the hard data points and the best correlation is selected.

Results

Vaca Muerta Formation Sedimentology and Geochemistry

Vaca Muerta Formation rocks can be described as marine organic rich mudstones with a minor siliciclastic component at the base which gradually passes to limestone towards the top. The lower part of the formation (first 60-70 m) is characterized by clastic sediments deposited in an anoxic environment with high contents of TOC, hydrogen index and anomalous concentrations of molybdenum, vanadium, nickel and chromium (Nawratil et al. 2012; Larriestra and Merino, 2014). These properties are shared with most of black shale environments (Potter et al., 2005, among others).

The graph of TOC versus $S1 + S2$ shows the source rock potential of Vaca Muerta bituminous rocks at Cerro Vagón Block. When molybdenum concentration as a bubble map is added ([Figure 2](#)), the positive correlation of the three variables can be seen. Regression of TOC versus molybdenum concentration shows a strong correlation of 0.82 and molybdenum concentration is a valuable estimator of TOC content.

Detail core high resolution chemostratigraphy is shown in [Figure 3](#). First track shows: potassium (blue), zirconium (brown), and gamma ray (dash line). In the first 12 m measured from the top, the curves show high correlation among themselves and a remarkable stratigraphic cyclicity. In the second track, short, medium and deep resistivity curves are shown in black and calcium concentration is plotted in blue. Again a strong correlation between those curves and a characteristic cyclicity is observed in this section of the Vaca Muerta Formation.

In the third track, the density log (dashed line), molybdenum (orange) and TOC percentage (black dot) are plotted. As it was shown above, the TOC percentage, indirectly measured by molybdenum concentration, shows an inverse behavior with the density log, where high concentration of organic matter is accompanied by low density values. In the fourth track, potassium, thorium and uranium curves are drawn. Both first and second are well correlated with gamma-ray log, while uranium (geochemically related to organic matter and molybdenum) cannot be more frequently detected due to the detection level of the HHXRF equipment. The sixth track shows the core photograph, while the seventh track shows sulfur and iron concentration. The high spatial correlation of these elements is explained by the presence of pyrite, enabling to quantify the volume of this mineral.

The eighth track displays short and deep resistivity curves, TOC percentage (black dots) and pyrite percentage in yellow area. We can see that resistivity lows match very well with pyrite and TOC peaks, behaving inversely to the Passey Model (Passey et al., 1990, among others) where the resistivity is proportional to the content of organic matter. In the ninth track, we can observe the spatial matching between molybdenum (orange) and vanadium (red). The last one is the second most important trace element present in anoxic levels of Vaca Muerta Formation. Finally, the tenth track shows nickel and chromium have the same trend of the others metals showed in the previous tracks.

Most of TOC estimation methods using common logs assume that organic matter volume is sensitive to density (R_{ho} is inversely related to TOC) and sonic wave transit time logs (direct relationship between DT and TOC). Moreover, in all TOC estimation methods a direct relationship between TOC and resistivity is assumed. Because the Vaca Muerta Formation is more bituminous marl than a typical organic shale, resistivity peaks are more related to calcium carbonate than to organic matter content. High pyrite content has influence in lowering resistivity response of interbedded organic shale, and the Passey Model (Passey et al., 1990) must be used with caution. Instead, molybdenum and vanadium concentration are valuable tools for direct TOC estimation. Due to uranium and molybdenum geochemical affinity, the combination of density and gamma ray logs is a better method to TOC evaluation in Vaca Muerta Formation, when only conventional well logs are available.

Wellbore Images

As it was mentioned above, the geostatistical model was built in the core interval (1210 m to 1240 m), combining well log data (density) and geochemical data (TOC) both used as hard data, with the wellbore resistivity images used as soft data. After that, the model was expanded to the entire Vaca Muerta Formation and the upper part of Quebrada del Sapo Formation.

The first step in the wellbore image construction was made with the geostatistical combination by simulation of the density log and wellbore image data. [Figure 4](#) shows result of simulation process and the justification of used data, both hard and soft. We can observe curve spatial matching of resistivity (third track), density (black curve, fourth track) and calcium (blue curve) together with one of the 176 curves of wellbore resistivity image (black) in the sixth track. The measure correlation of 0.72 units was obtained between resistivity image curve shown in the sixth track, with the density log shown in the fourth track. This correlation was used to perform 30 realizations of density data, then the expected value (average of realizations) was calculated. In the eighth track, the expected value is the more probable density image after the process described here. We can see high density values (colors yellow to red) related to calcium carbonate (blue curve in sixth track) and it is

shown as light brown color on the wellbore resistivity image. Low density values (magenta to blue color) of the density image is related to organic shale intervals, as can be seen by the spatial correlation with molybdenum and TOC values shown on the fourth track.

The second step involves the creation of TOC wellbore images using the density image previously calculated as soft data and TOC pyrolysis derived as hard data. After 30 realizations, the expected value of TOC wellbore image is shown in the ninth track. Moreover, the pyrite curve calculated with sulfur and iron concentrations is drawn on the same track. We can see the matching of high TOC values (color green to red) with pyrite peaks, while low TOC values (blue) are related to pyrite troughs. The first 4 meters of bottom core show high density and low TOC values and this fact is related to episodes of clastic sedimentation.

Model Propagation and Validation

The model built in the core interval was applied to the rest of Vaca Muerta and the upper part of Quebrada del Sapo formations. As a result, we obtained wellbore images of density and TOC for the entire formations, whose values were compared with geochemical data from cuttings (TOC, trace elements) not included in the geostatistical modeling (blind test). [Figure 5](#) shows wellbore density and TOC images on the right, crossplot for blind test on the left and the well logs and geochemical data in the center of the figure. The first result is the inverse correlation between the wellbore density image and cuttings TOC values shown in the crossplot of DEN_S_AVE versus TOC (upper left of [Figure 5](#)). Moreover, the crossplot (left center) shows the correlation between molybdenum and TOC image values where the lineal trend of both properties is clear. In the same way, the crossplot in bottom left shows the correlation of vanadium and TOC image. Obviously we cannot expect a perfect correlation in every case due to different rock volumes represented for each type of data (geochemical from core and cutting, wireline logs and wellbore images) and the complexity of sedimentary processes, but the results shown here are remarkable.

Conclusions

This article is a demonstration of the paradigm change effect, as we made new applications of known logging methods but used them differently, included the inorganic geochemistry and finally the used geostatistics to deal with uncertainty.

We demonstrated that it is possible to integrate different types of data to improve the TOC thickness evaluation, under a strict sedimentary model and geochemical concept. Clearly the integration tool is the geostatistic and the imagination is the limit. With regard to the evaluation of organic matter, it is necessary to make some observations on conventional methods of TOC assessment. In the area studied in the Neuquén Basin, the Passey Model is not the most appropriate because of the Vaca Muerta pyrite and calcium carbonate content modify deeply the resistivity log response. However, Holmes et al. (2013) propose an interesting method to evaluate pyrite content using logs and we tried to use it but it was an unsuccessful test. Therefore, we conclude that the best indirect method for the evaluation of TOC content for the Vaca Muerta Formation is the non-destructive chemicals analysis looking for molybdenum, vanadium and the quantitative integration with the rest of available data.

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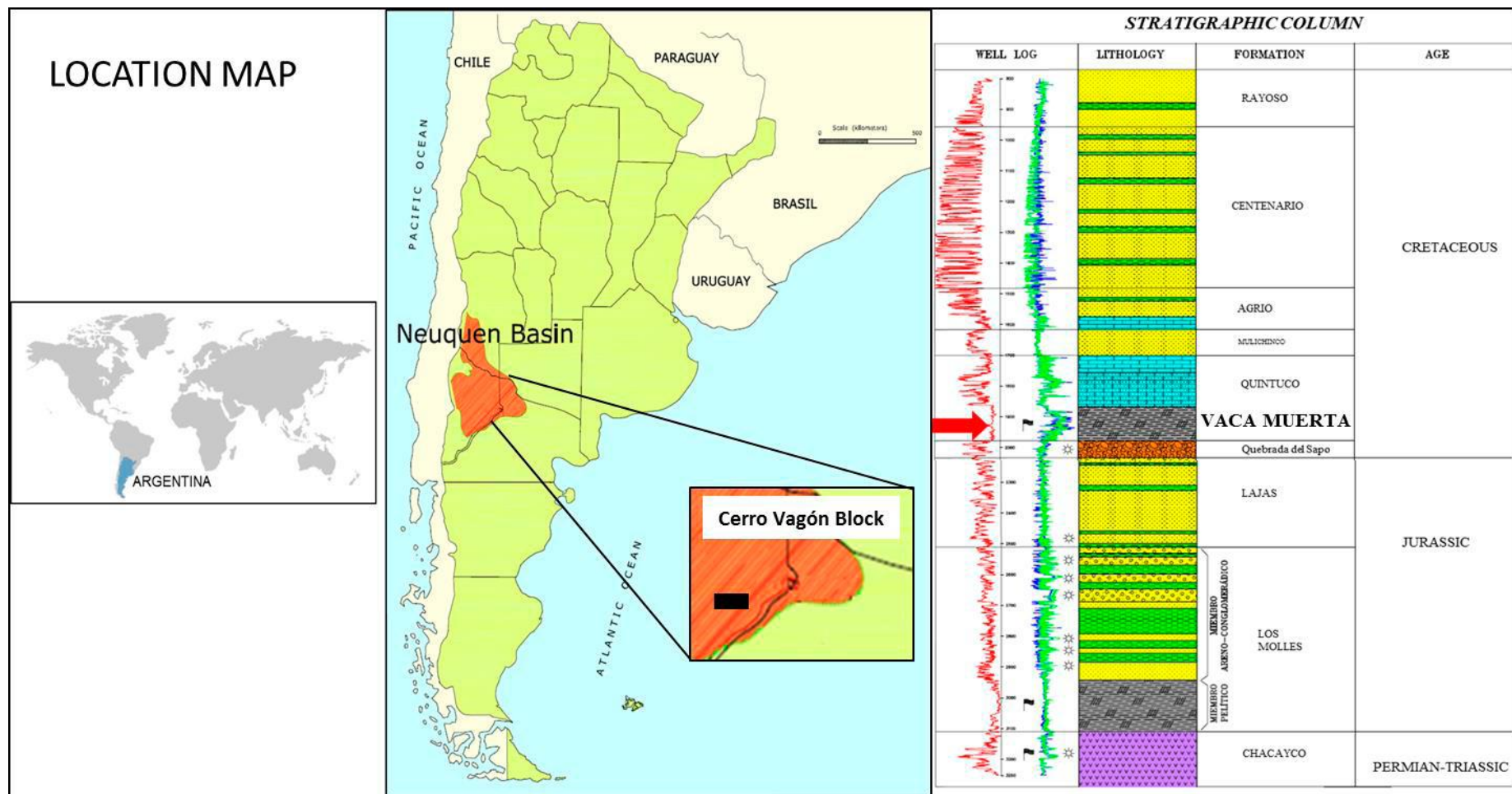


Figure 1. Study area location map and stratigraphic column of Neuquén Basin.

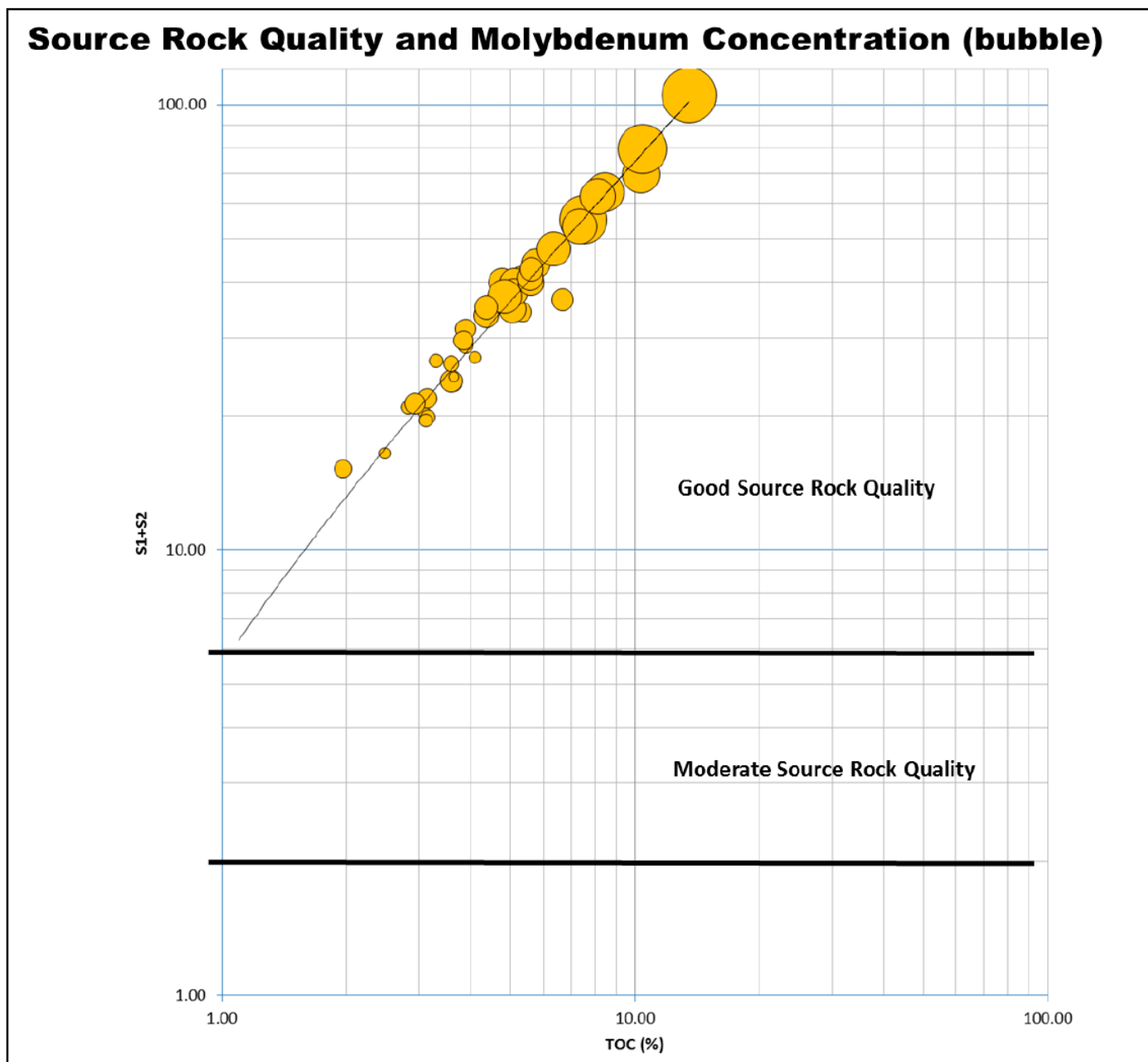


Figure 2. Vaca Muerta Formation source rock quality crossplot (TOC vs. S1+S2) and molybdenum concentration.

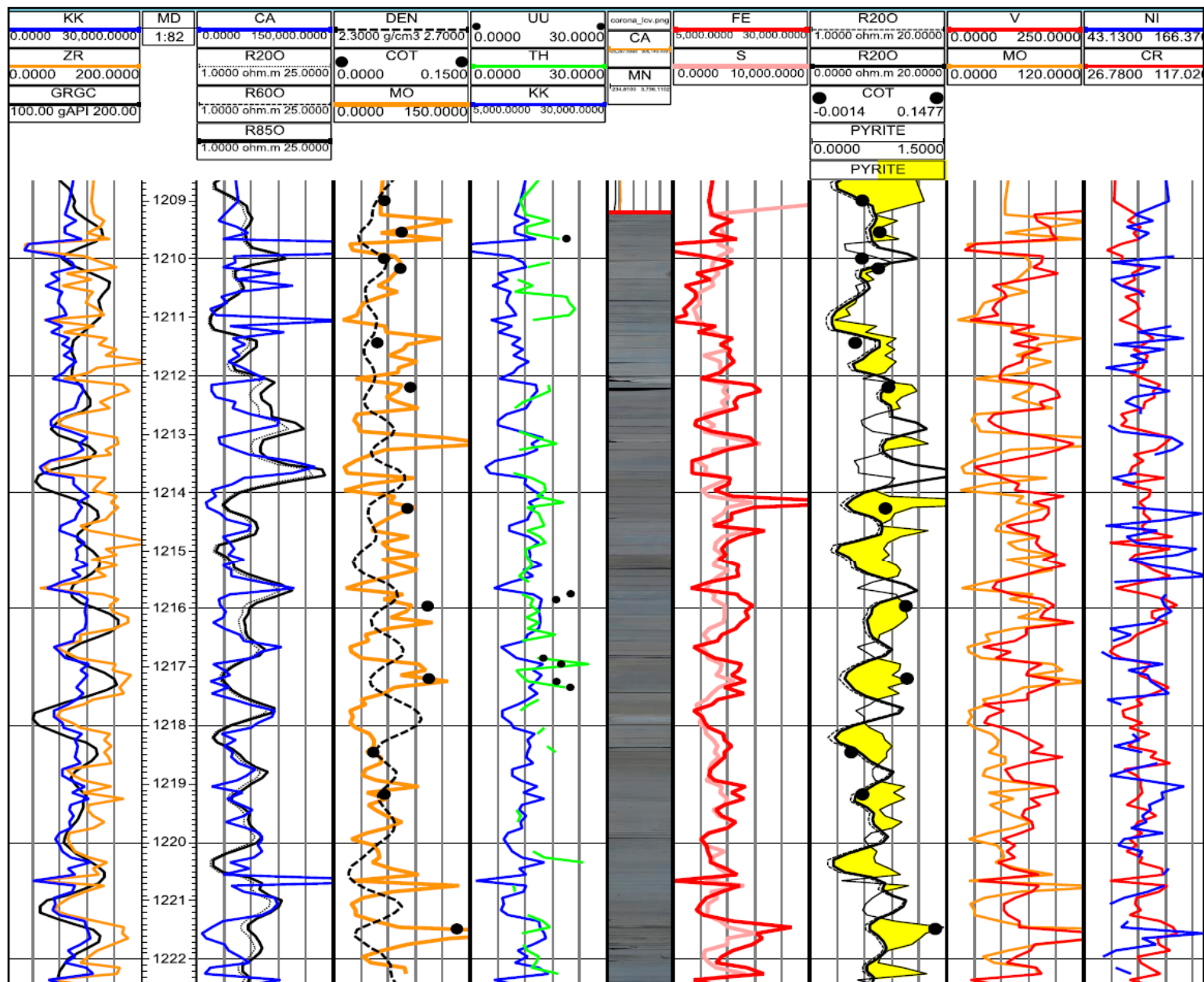


Figure 3. Vaca Muerta Formation core chemostratigraphy. Spatial correlation between TOC-molybdenum, calcium-resistivity, sulfur-iron, pyrite-resistivity, molybdenum-vanadium and nickel-chromium are shown.

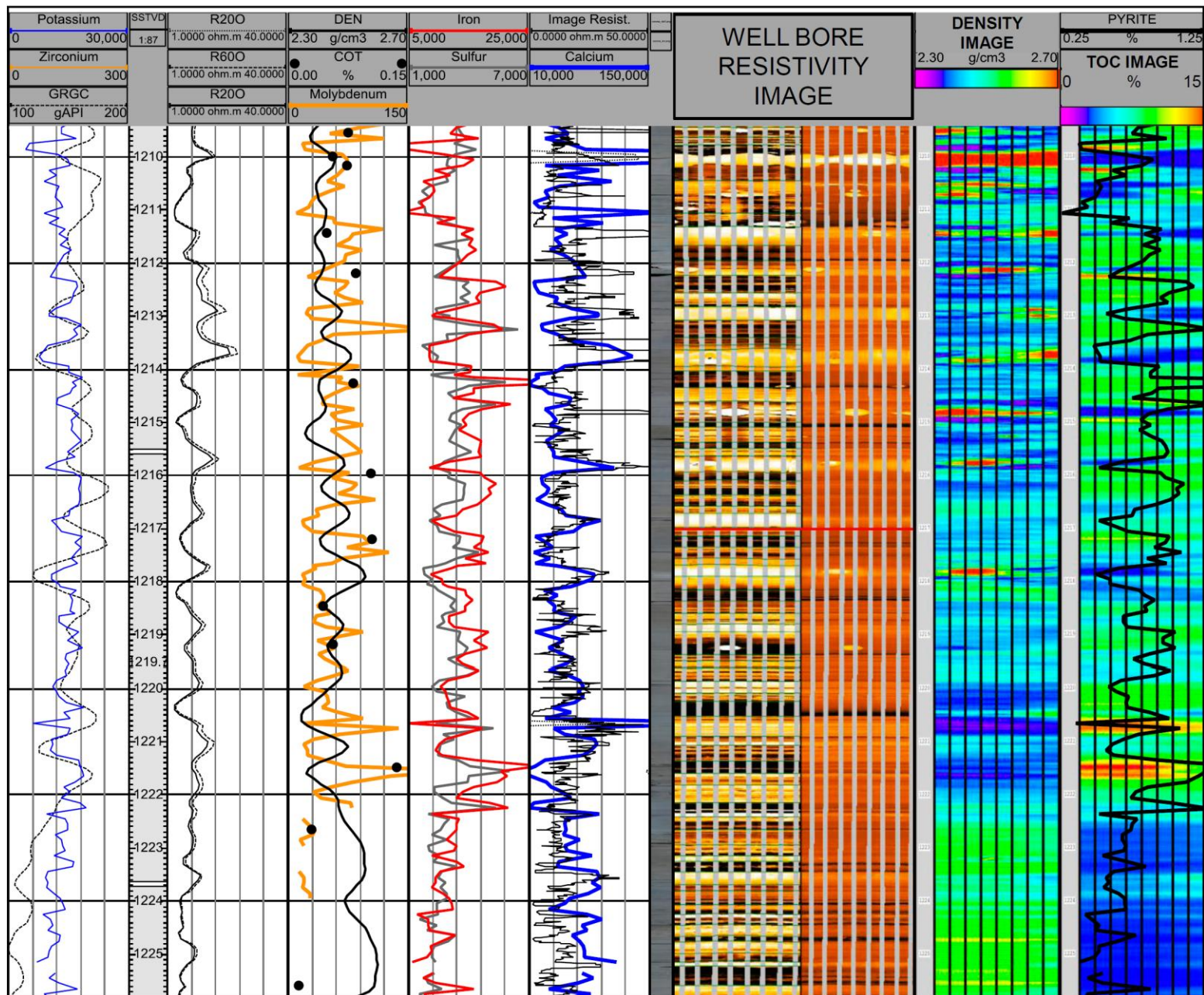


Figure 4. Geostatistical model with core data: density and TOC images from sequential Gaussian co-simulation.

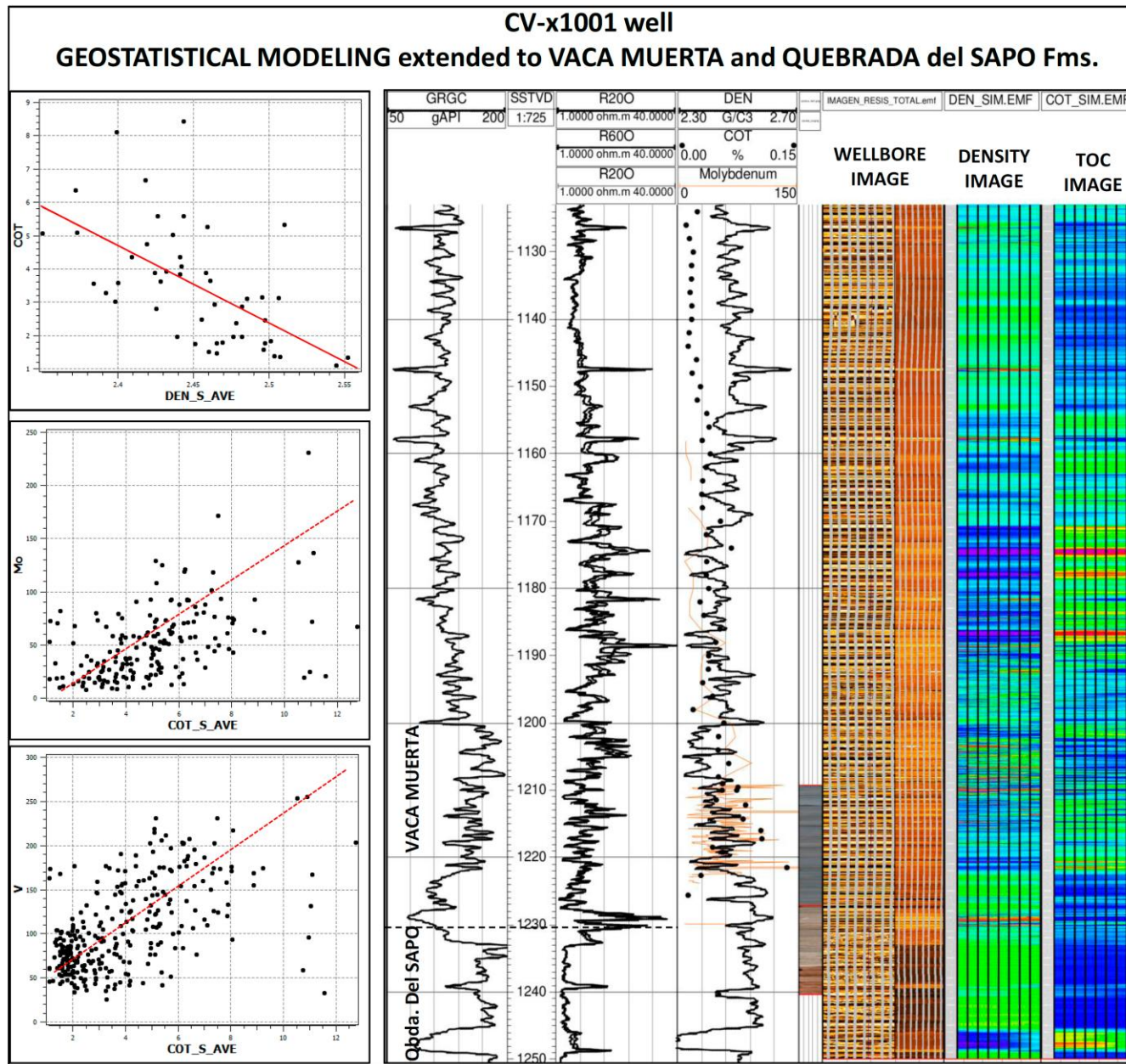


Figure 5. Geostatistical model extension to Vaca Muerta and upper Quebrada del Sapo formations. Crossplot of density and TOC images with geochemical data.