Key Tools for Black Shale Evaluation: Geostatistics and Inorganic Geochemistry Applied to Vaca Muerta Formation, Neuquen Basin, Argentina*

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Search and Discovery Article #41028 (2012)**
Posted October 8, 2012

*Adapted from oral presentation at AAPG International Conference and Exhibition, Singapore, September 16-19, 2012

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Abstract

The assessment of hydrocarbons in black shales is a new challenge for oil and gas exploration. The detection of hydrocarbon generation potential in black shales and the existence of potential reservoir zones within them, are key features that conventional well logs fail to adequately define. We present a method that allows the integration of chemical data (rapid hand held X-Ray Fluorescence analysis) of cutting, well logs and seismic attributes using Geostistiscal Simulation algorithms.

The Agua del Cajon Block is located in the south margin of Neuquén Basin, Argentina (Figure 1) which has been producing from conventional reservoirs since 1960. The stratigraphic framework (Figure 2) is composed of three source rocks ranging from Jurassic to lower Cretaceous, where the Jurassic Vaca Muerta Formation is the most important (indicated in the figure by an ellipse). The rest of the stratigraphic column is composed of clastic and carbonate beds ranging from Jurassic to Tertiary age. Some of these beds are reservoirs, while claystone, limestone and anhydrite are the most important seals.

Methodology

Data Acquisition

The chemical element analysis was performed using rapid hand-held X-Ray Fluorescence (HHXRF) equipment in a non-destructive registration process. The analysis process consisted of the detection of 32 major chemical and trace elements on 4300 cutting samples from 58 wells. Moreover, analysis of TOC (Rock Eval) and mineralogical X-Ray Diffraction (XRD) was performed on 80 samples of the same wells.

Data Processing and Geochemical Log Construction

This method is based on selection of the best correlations between the chemical elements and the set of wireline logs available in the well, whether recorded or calculated by petrophysical analysis. Then Gaussian co-simulation with Markov model type II was performed using the well log as co-variable and generating *n* realizations (Deutsch and Journel, 1998).

The average value (*E-value*) of the *n* realizations is the expected log of the chemical element. The problem is hard data (XRF analysis data) location because it has a depth uncertainty. Samples are drawn at approximate intervals (best case each 2 meters) and the sampling depth is not exact. The depth of which samples come from is the main source of uncertainty. Additional uncertainty is sample contamination by wellbore collapse, drilling mud chemical composition, etc.

The solution proposed here is to assign each sample a random depth value within the range represented by the sample itself and the samples subset is correlated with a previously selected well log. This operation will select subsets of samples showing better correlation with selected well log. Later we proceed to the execution of 100 realizations for each subset. After running all realizations for all subsets, we calculate the mean, variance and the probability for any given cutoff.

The Heslop curve (Heslop, 2010) showed the best correlation with trace elements like molybdenum, vanadium, nickel and TOC, while the gamma ray curve showed good correlation with potassium, thorium, uranium and zirconium (Figure 3).

This method allows creation of chemical element logs of V, Mo, S, Cr and Ni, useful to assess the potential hydrocarbon generation of source rocks. Moreover, geochemical logs as Zr and Rb (related to clastic episodes) allow identification of areas with better reservoir conditions in black shales.

Vaca Muerta Formation Geochemistry Results

Vaca Muerta Formation rocks can be described as marine organic rich mudstones with a minor siliciclastic component at the base that gradually passes to limestone towards the formation top. From a geochemical point of view, it can be divided in two units, Lower and Upper Vaca Muerta members. The Lower Vaca Muerta Member (lower 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.

The graph of TOC versus S1 + S2 shows the maturity level of the Vaca Muerta bituminous rocks. When we add the molybdenum concentration as a bubble map (Figure 4), we can see that Mo values are higher than 20 ppm when TOC values are greater than 2%. In the cross plot of Figure 5, the regression of TOC versus molybdenum shows a strong correlation of 0.82.

From the comparison of XRD and XRF data, several relationships raise that help to understand the sedimentary history of the Vaca Muerta. One feature of the Lower member is the Zr (Zircon) content, proportionally related to the quartz presence both minerals are common in siliciclastic sedimentary episodes (Figure 6). The other feature is that both Zr and quartz have a proportional correlation with TOC, indicating that the anoxic lower member has and important clastic composition.

Finally, the relationship between Zr and Ca shows an strong negative correlation (Figure 6), interpreted as the gradual passage of environments dominated by clastic sedimentation (high Zr) to environments where chemical (organic) sedimentation prevails (high Ca). A similar relationship is shown in Figure 6 between quartz and calcite, note that mineralogical relationship between quartz and calcite is similar to the geochemical relationship between zirconium and calcium.

The Upper member of the Vaca Muerta Formation has limestones, decreasing zirconium, rubidium and TOC. In the geochemical logs of two wells (Figure 7) the opposite behavior of Zr (black curve) versus Ca (blue curve) can be observed in the vertical direction. Note in the base of Vaca Muerta (Lower member) the increase of molybdenum (and TOC) is accompanied by increasing zirconium concentration.

Tridimensional Modeling of Geochemical Logs

Once we have calculated geochemical logs, three-dimensional models for anoxic facies, chemical element and TOC were made using Sequential Stochastic Simulation. As a result, we obtained 3D models with a resolution 100 m x 100 m in the horizontal plane for 1 m in vertical direction.

As a first step we analyzed the relationship between seismic attributes and different chemical elements. This comparison was made by intervals correlation rather than point to point correlation.

In this way, it was observed that compressional impedance (P imp.) showed low values when the interval has a molybdenum concentration greater than 20 ppm (Figure 8). By contrast, if molybdenum concentration is less than 20 ppm, compressional impedance values increase. This property allows us to define an indicator curve for anoxic and non-anoxic facies, used to populate the interwell space by means of Bayesian Cosimulation (Kelkar and Perez, 2002).

After 100 realizations, a probability 3D model (with 0-1 scale) for anoxic facies was obtained, where two layers for the lower and upper members of Vaca Muerta are shown in Figure 9. The layer belonging to Lower Vaca Muerta is taken to 120 m below the top (layer 120) and the layer for the Upper member is taken 20 m (layer 20) below the top of the formation. The maps of probability for layers mentioned above (Figure 9) clearly shows the difference between anoxic levels of the lower versus the upper member data.

Later, geochemical logs of TOC and chemical elements were simulated through Sequential Gaussian Simulation, conditioned to facies (anoxic/non-anoxic) simulated in the previous step. Thus, with the average of 100 realizations we obtained 3D models for the expected values of TOC and the different chemical elements analyzed.

The bottom of Figure 9 illustrates the maps of sulfur and iron corresponding to layer 120 of Vaca Muerta Lower member. These maps show the *degree of pyritization* (DOP index of Raiswell and Berner, 1985) and the spatial coincidence of their concentrations allow us to identify areas with a greater degree of oxygen absence.

The results of TOC 3D modeling is shown at the top of Figure 10. The Lower member has a TOC average of 3.4% while the upper member has an average 1.1%. In the same way, concentrations of molybdenum and vanadium are greater in the lower member than the upper member (lower part of Figure 10) emphasizing the euxinic characteristics of the environment.

In general we can say that the sedimentary evolution of the Vaca Muerta Formation is characterized by a decrease in siliciclastic sedimentation toward the top, accompanied by an increase in carbonate sedimentation in the same direction. Maps of layers 120 and 20 for calcium, zirconium and titanium corresponding to Lower (left column) and Upper Vaca Muerta (right column) clearly show this sedimentary evolution (Figure 11).

Rheological properties of Vaca Muerta rocks were analyzed using the Brittleness Index (BI) derived from dipole sonic logs recorded in the same wells. The resulting brittleness is tightly dependent of TOC and mineralogical content (Figure 12) and shows a generalized increase towards the formation top. Using a multivariate non-lineal regression model (neural network model) between BI curve and seismic attributes, a 3D model for brittleness was obtained. A map of the brittleness average for the Vaca Muerta Lower member illustrates the coincidence between high TOC and low brittleness values (Figure 13). By contrast, in the Upper member, mainly composed of limestones, the brittleness index is greater.

Conclusions

A new methodogy to characterize the Vaca Muerta Formation is presented. Based on inorganic geochemistry from XRF analysis performed on well cuttings, properly calibrated with lab data and geostatistical modeling methodology, it is possible to locate wells at the sweet spot to develop this unconventional resource at an early stage. The results include anoxic facies probability, TOC, sedimentary and brittleness indicators.

This method provides chemical element logs of V, Mo, Cr, Ni (high correlation with TOC) which allows assessing the potential hydrocarbon generation of source rocks. Moreover, other geochemical logs (as Ca, Zr and Ti) allow identification of different sedimentary conditions.

From a geochemical point of view, the Vaca Muerta Formation presents two well different sections: the Lower Vaca Muerta (lower 60-70 m), mainly siliciclastics sediments deposited in an anoxic environment which facilitated organic matter preservation, and the Upper Vaca Muerta, mainly mudstones and limestones with low organic content. Rheological properties of rocks are tightly dependent of TOC and mineralogical content. This is observed vertically in geochemical logs, and aerially in maps. We compared these results with others obtained from independent sources (3D seismic cubes and lab data) and obtained very good matching. Advantages of this method are price, rapidity and practicality, as the only need is cuttings.

References

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Raiswell R., and R. Berner, 1985, Pyrite formation in euxinic and non-euxinic basins: American Journal of Science, v. 285, p. 710-724.

Figure 1. Agua del Cajon Block study area location in Neuquen Basin, Argentina.

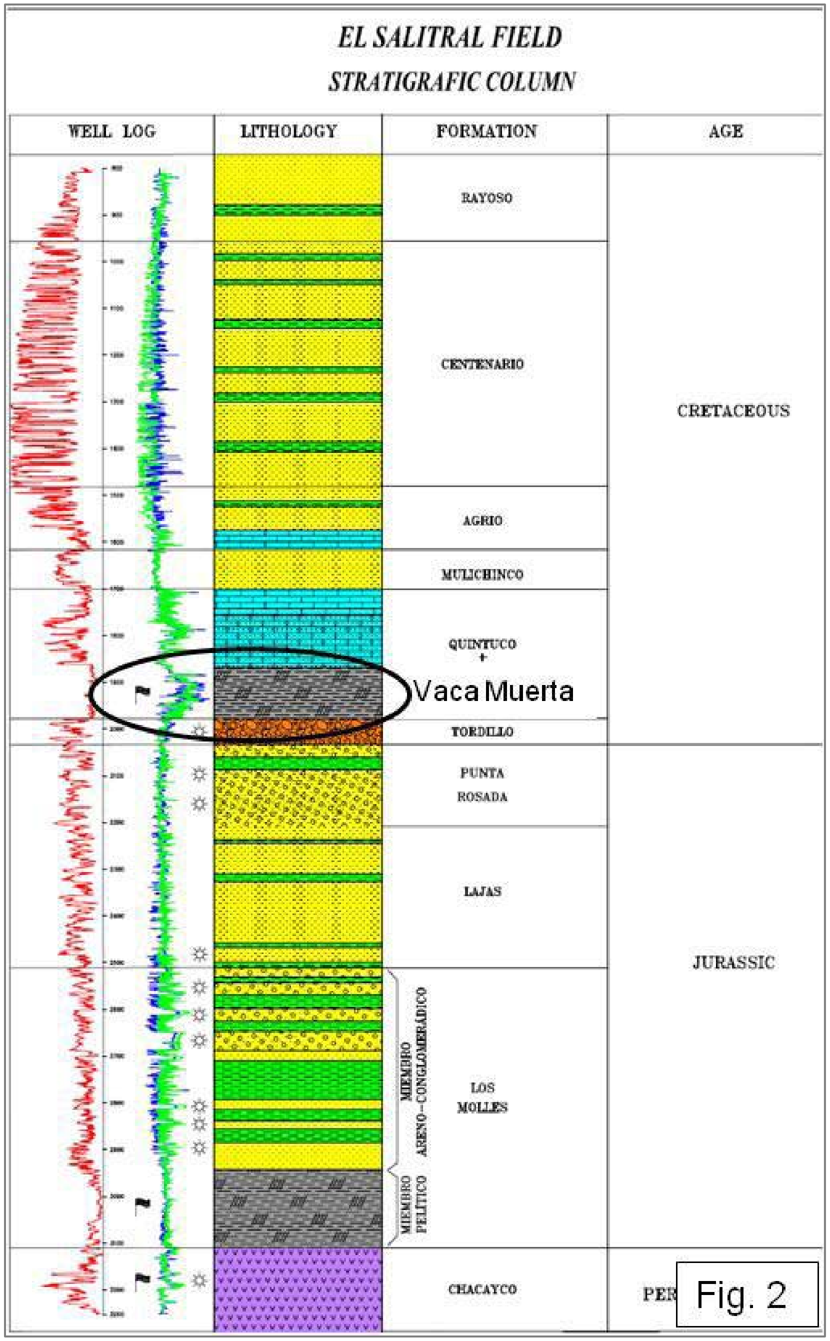


Fig. 2

Figure 2. Stratigraphic column of El Salitral Field area.

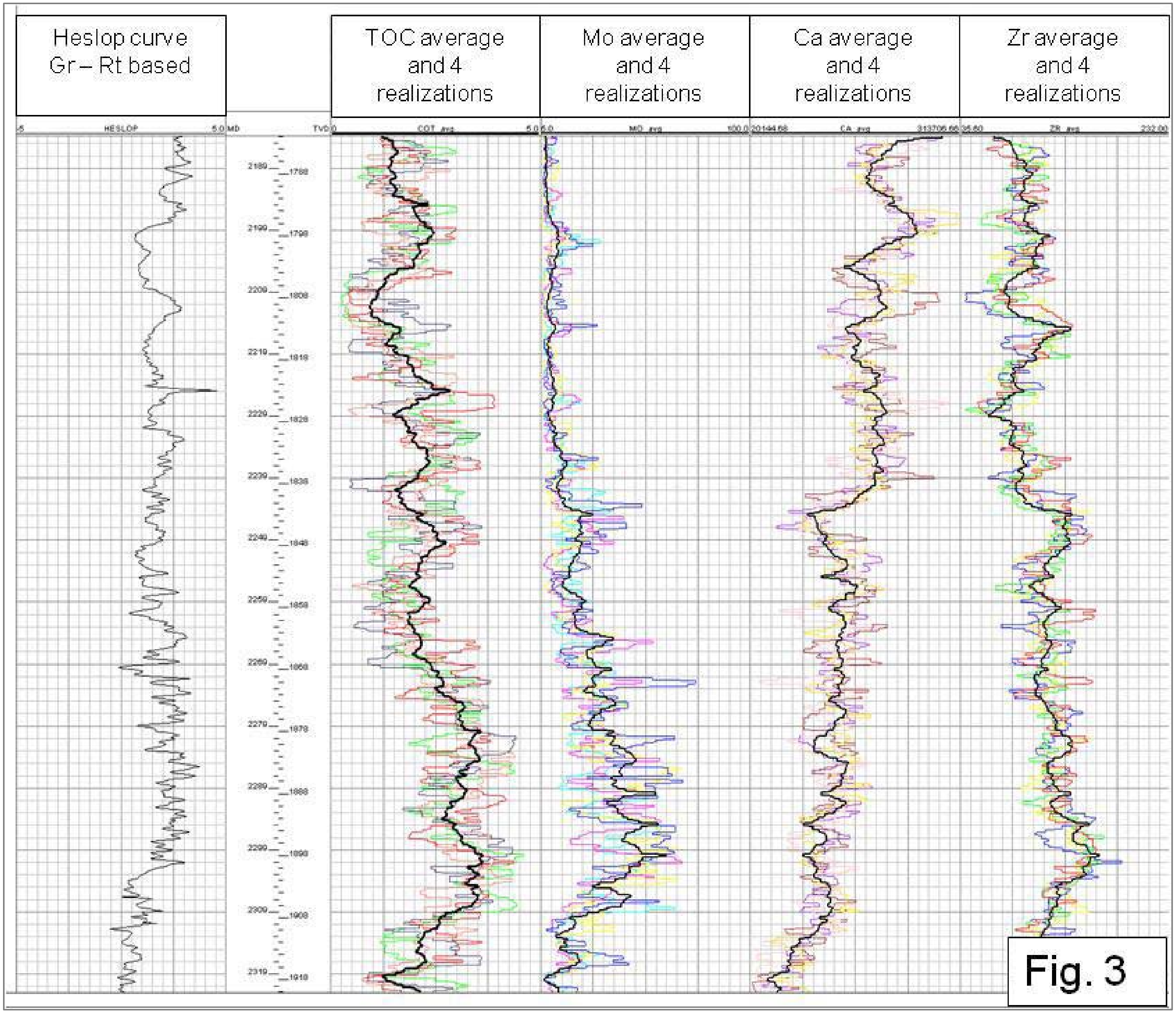


Fig. 3

Figure 3. Example of Heslop curve chemical element log.

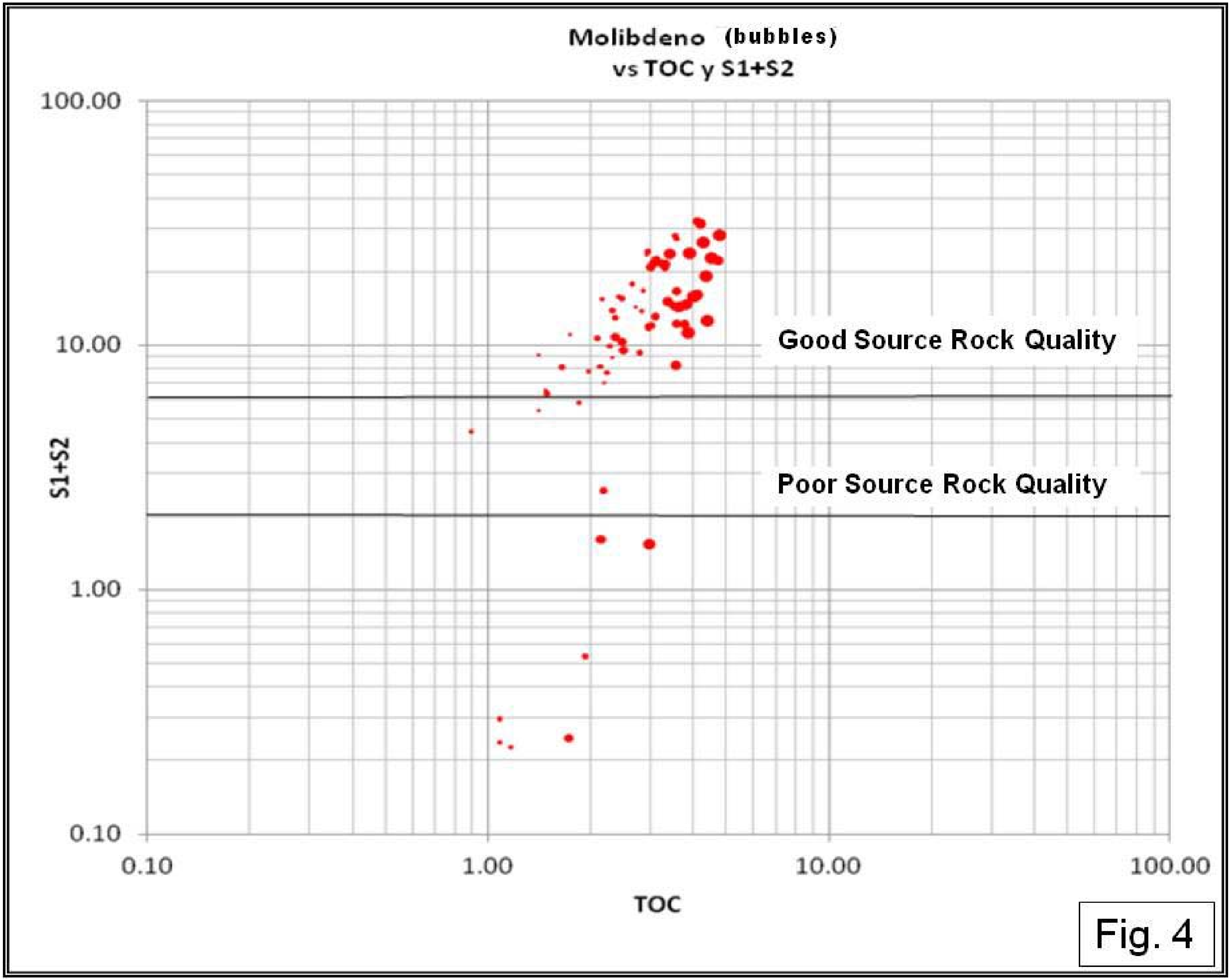


Figure 4. Graph of TOC versus S1 + S2 with molybdenum concentration bubbles, showing the maturity level of the Vaca Muerta bituminous rocks.

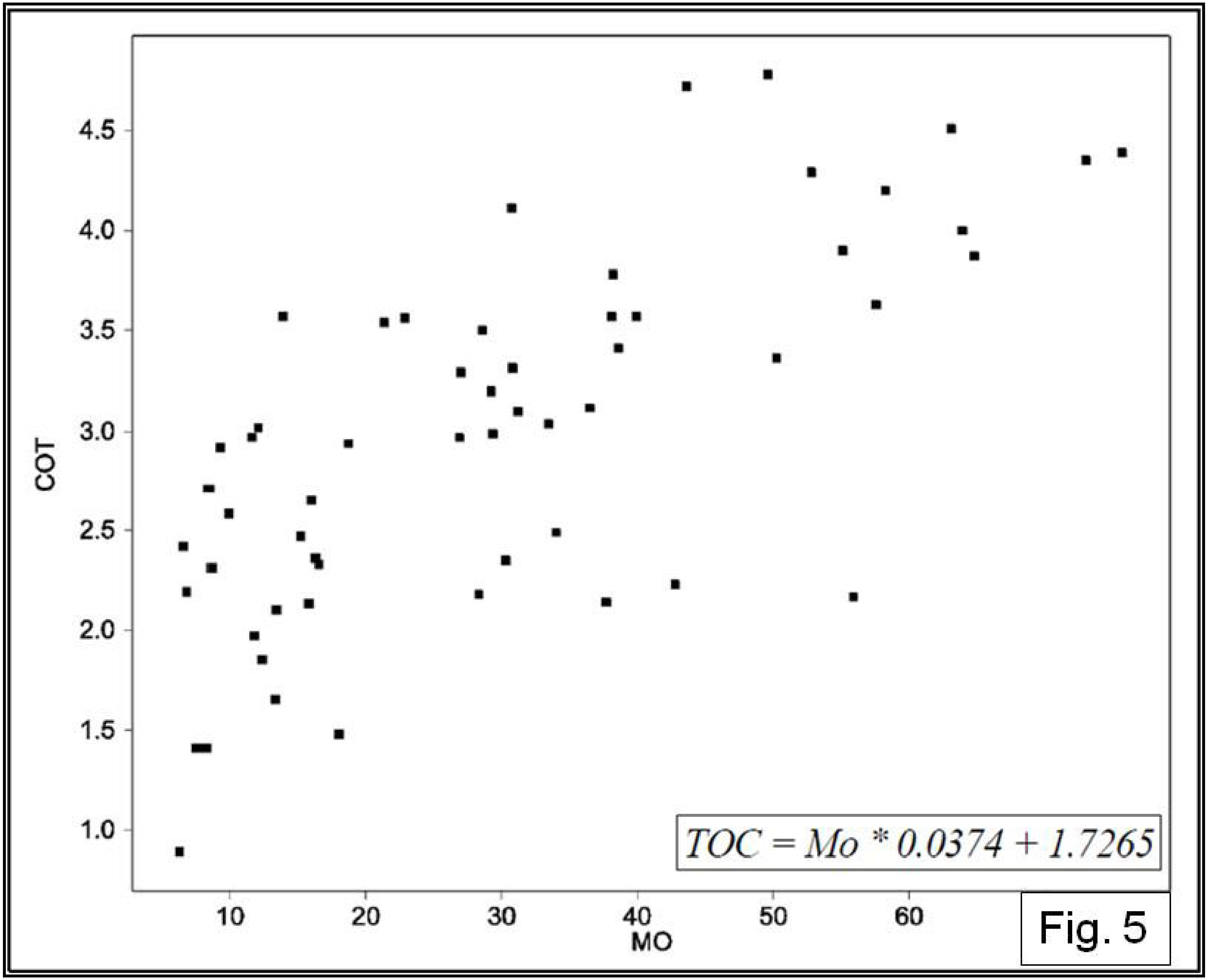


Fig. 5

Figure 5. Cross plot of the regression of TOC versus molybdenum.

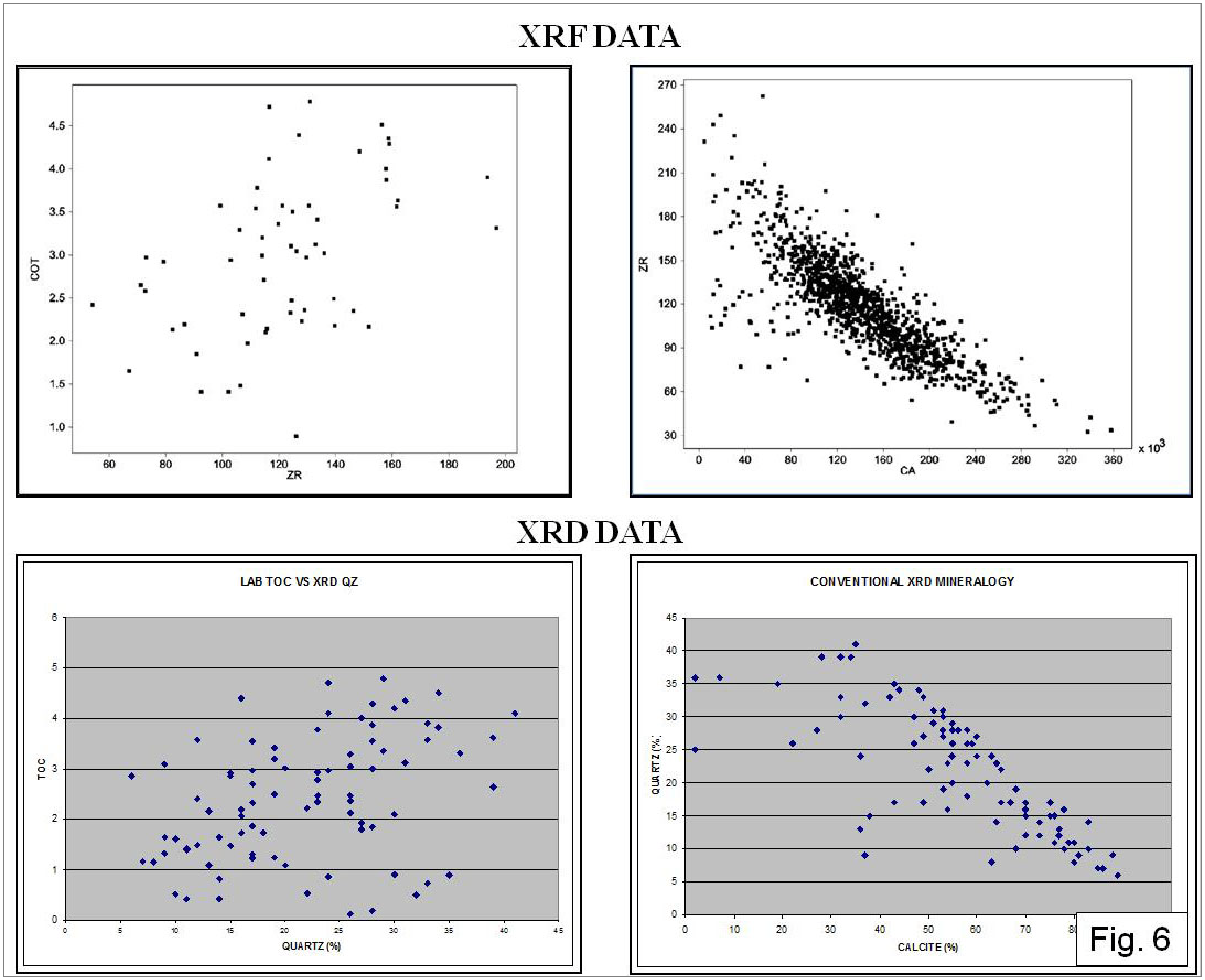


Figure 6. Graphs of XRD and XRF data.

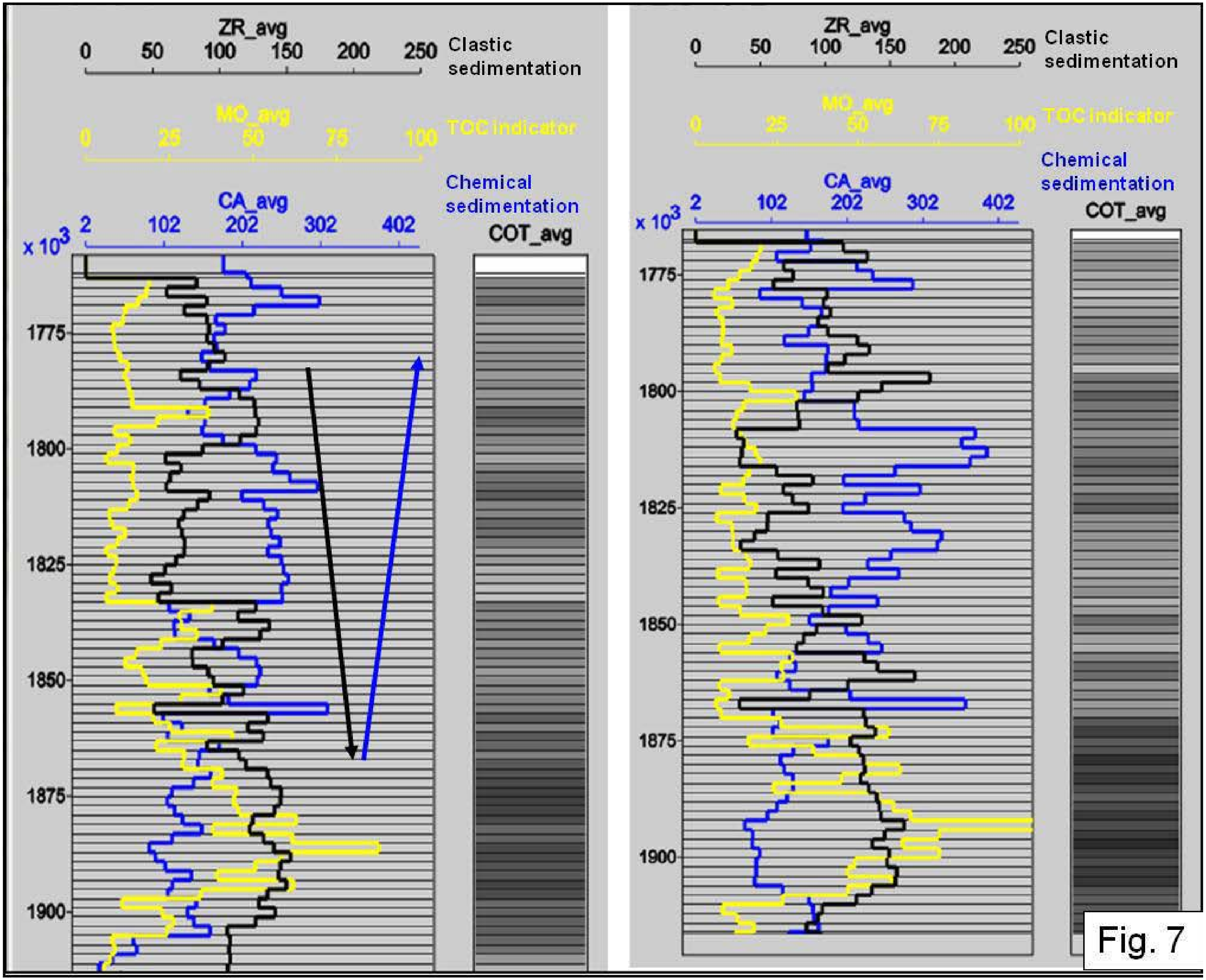
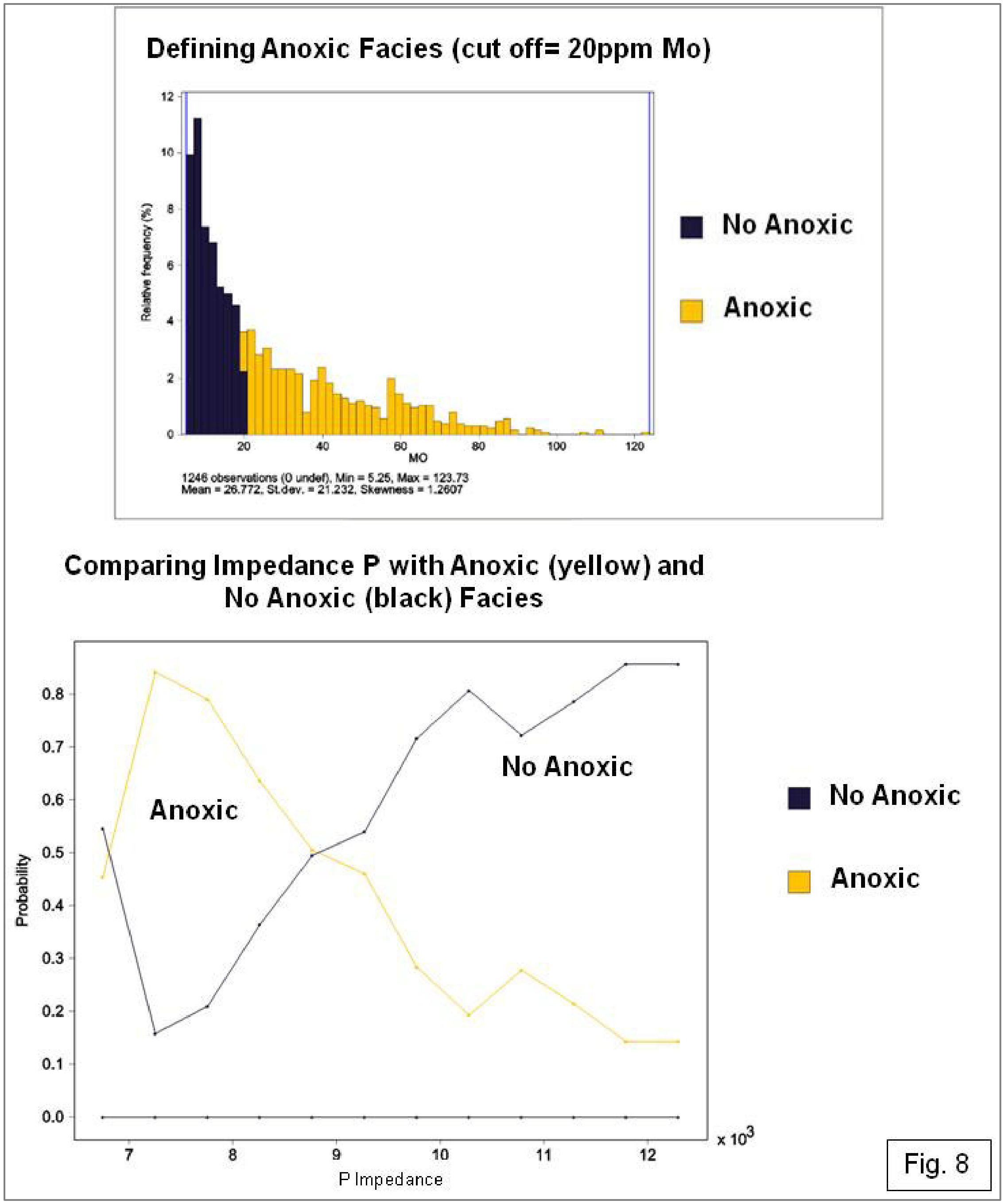


Figure 7. Geochemical logs of two wells.



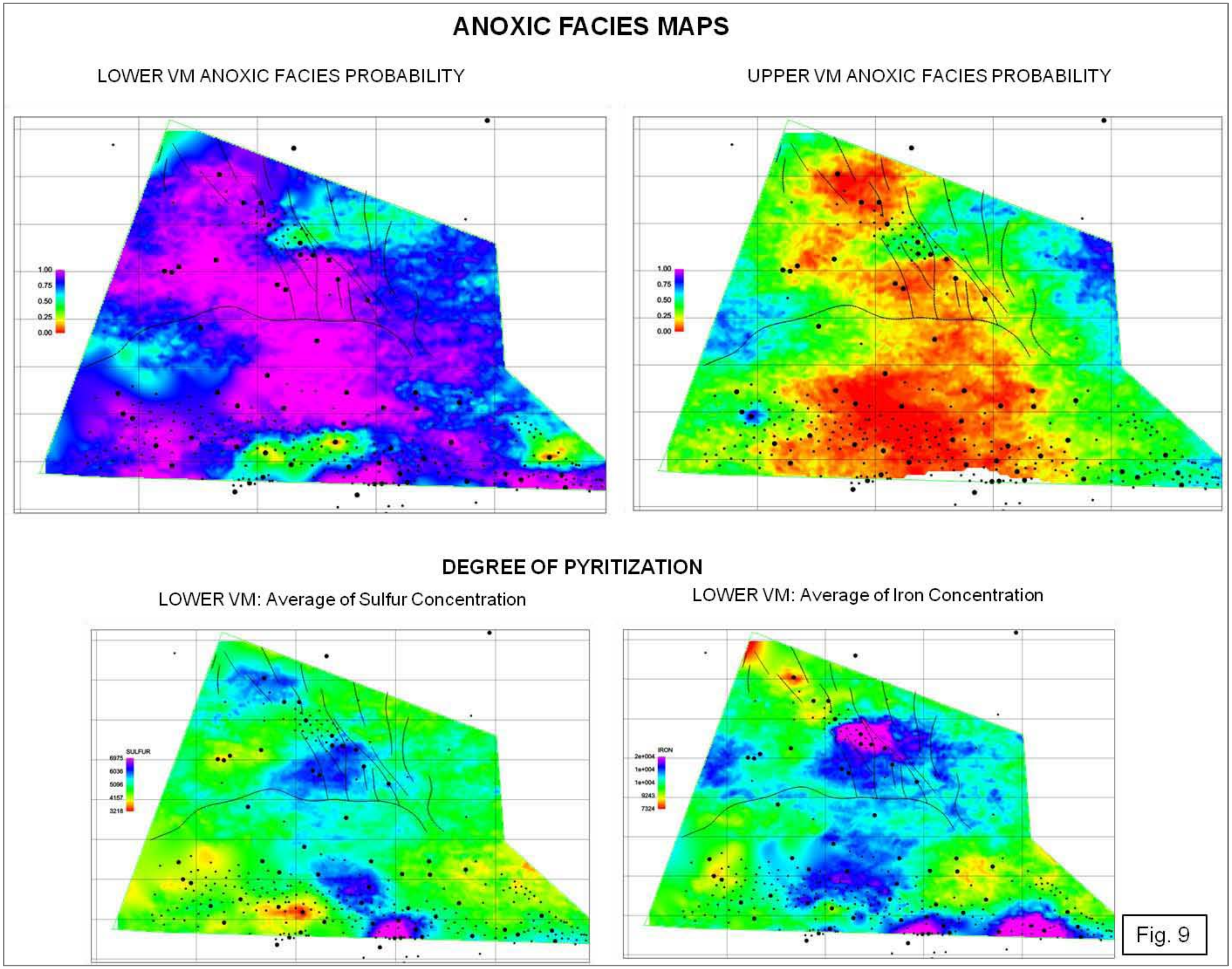
Defining Anoxic Facies (cut off= 20ppm Mo)

1246 observations (0 undef), Min = 5.25, Max = 123.73
Mean = 26.772, St.dev. = 21.232, Skewness = 1.2607

Comparing Impedance P with Anoxic (yellow) and No Anoxic (black) Facies

Fig. 8

Figure 8. Indicator curve for anoxic and non-anoxic facies.


ANOXIC FACIES MAPS

LOWER VM ANOXIC FACIES PROBABILITY

UPPER VM ANOXIC FACIES PROBABILITY

DEGREE OF PYRITIZATION

LOWER VM: Average of Sulfur Concentration

LOWER VM: Average of Iron Concentration

Fig. 9

Figure 9. Anoxic facies maps for the Lower and Upper members of Vaca Muerta Formation, from 3D probability model.

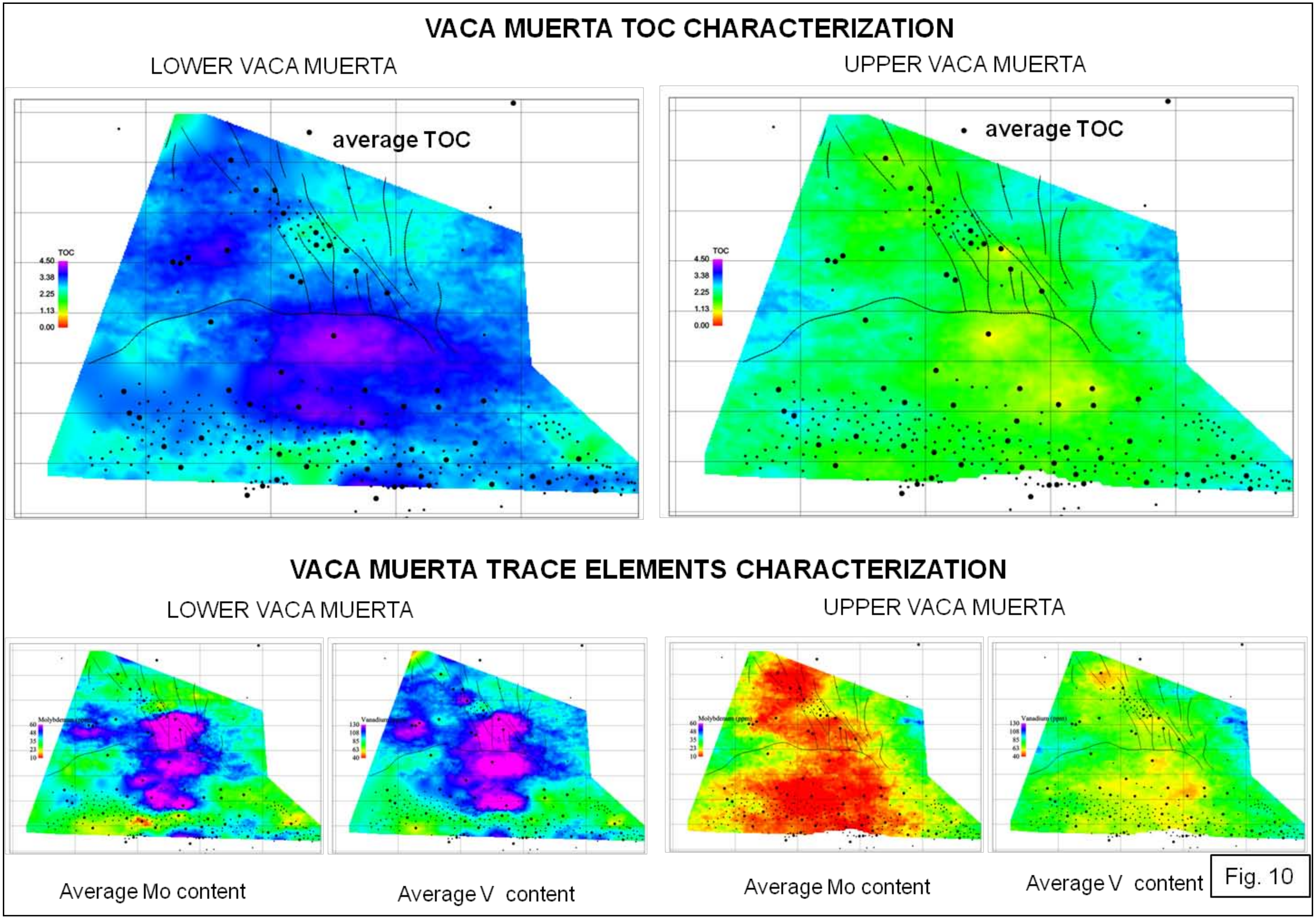


Figure 10. TOC and trace elements characterization facies maps for the Lower and Upper members of the Vaca Muerta Formation, from 3D probability model.

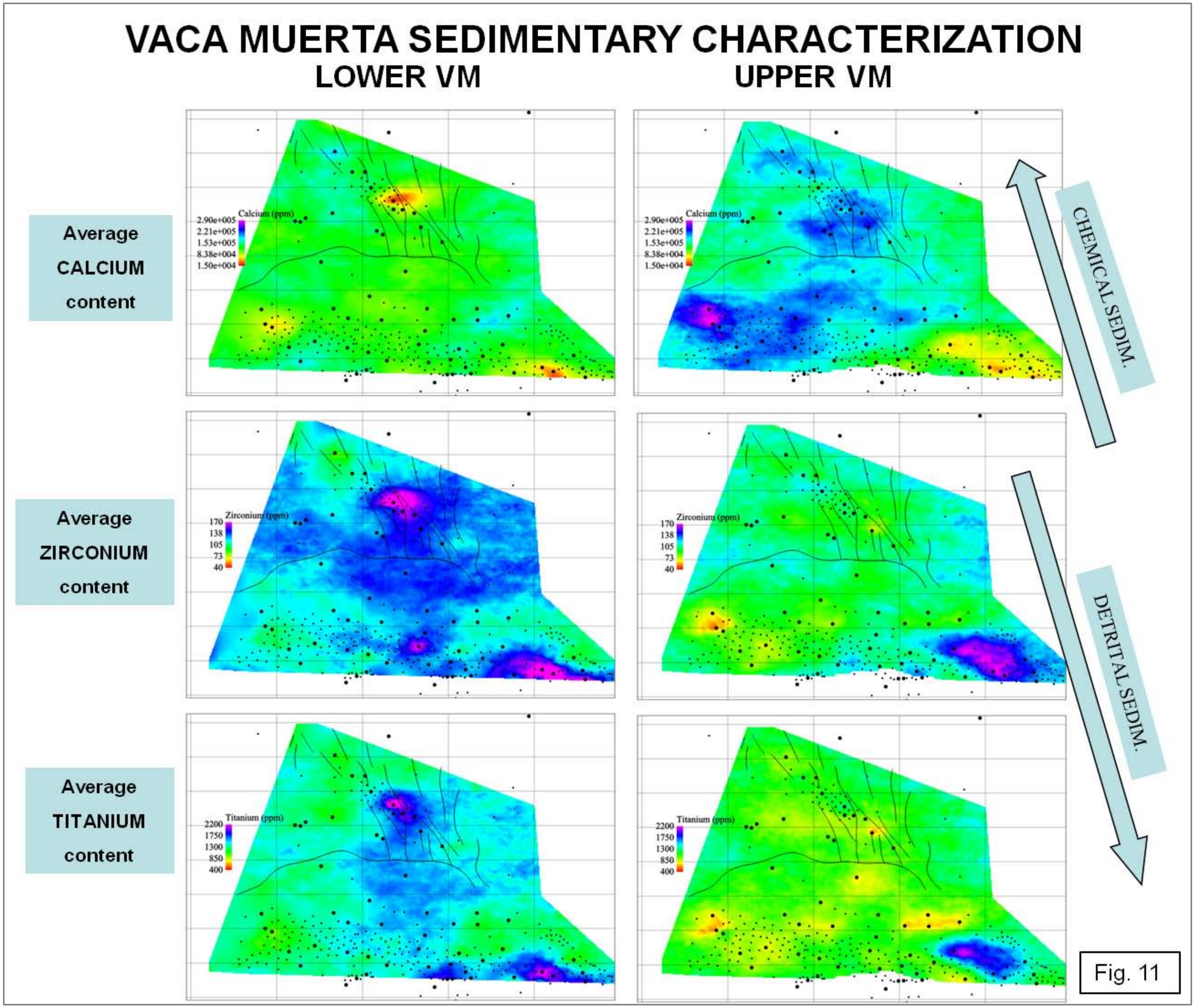


Figure 11. Sedimentary characterization facies maps for the Lower and Upper members of the Vaca Muerta Formation, from 3D probability model.

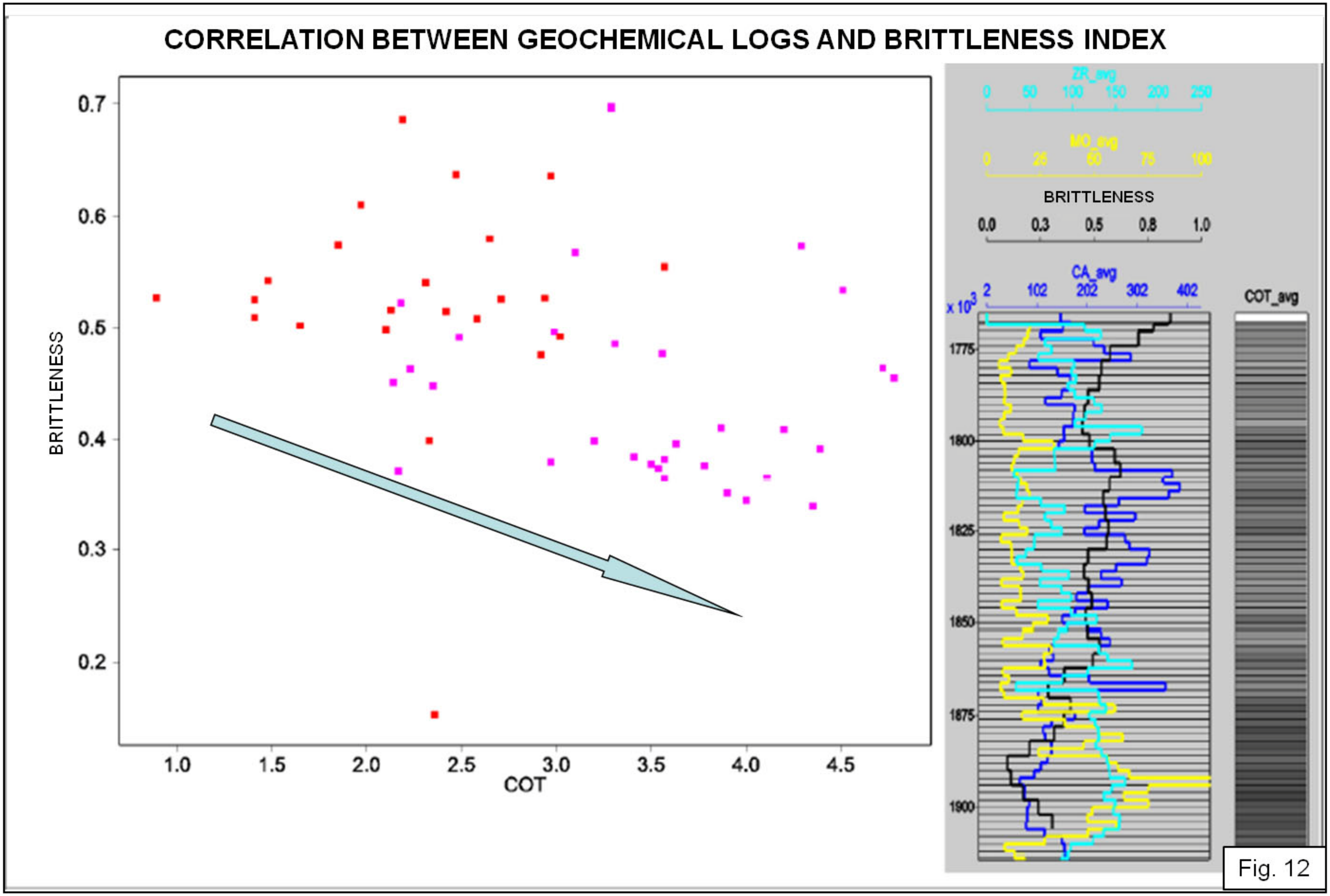
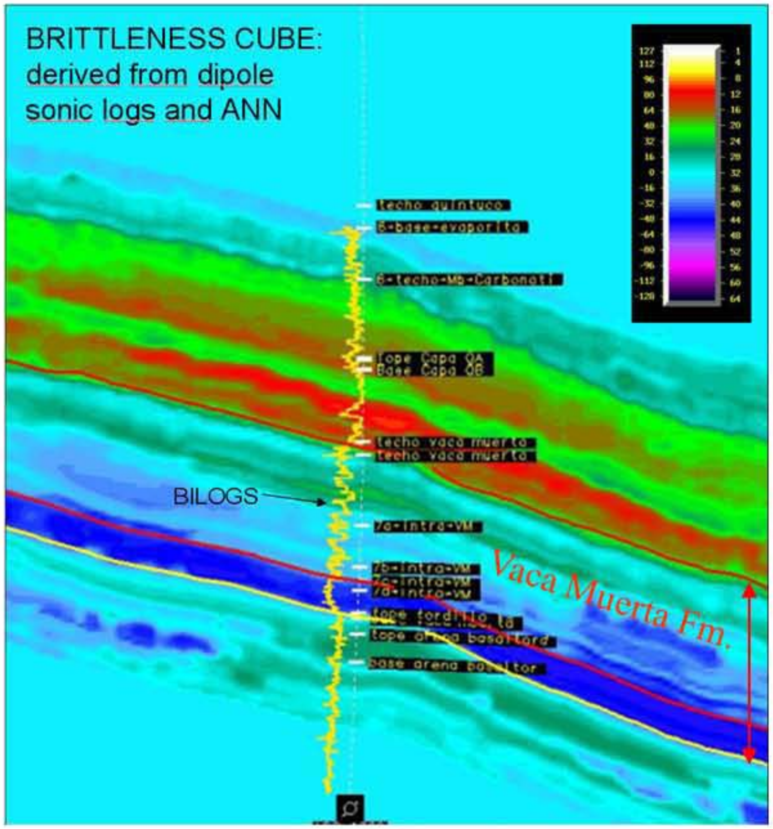
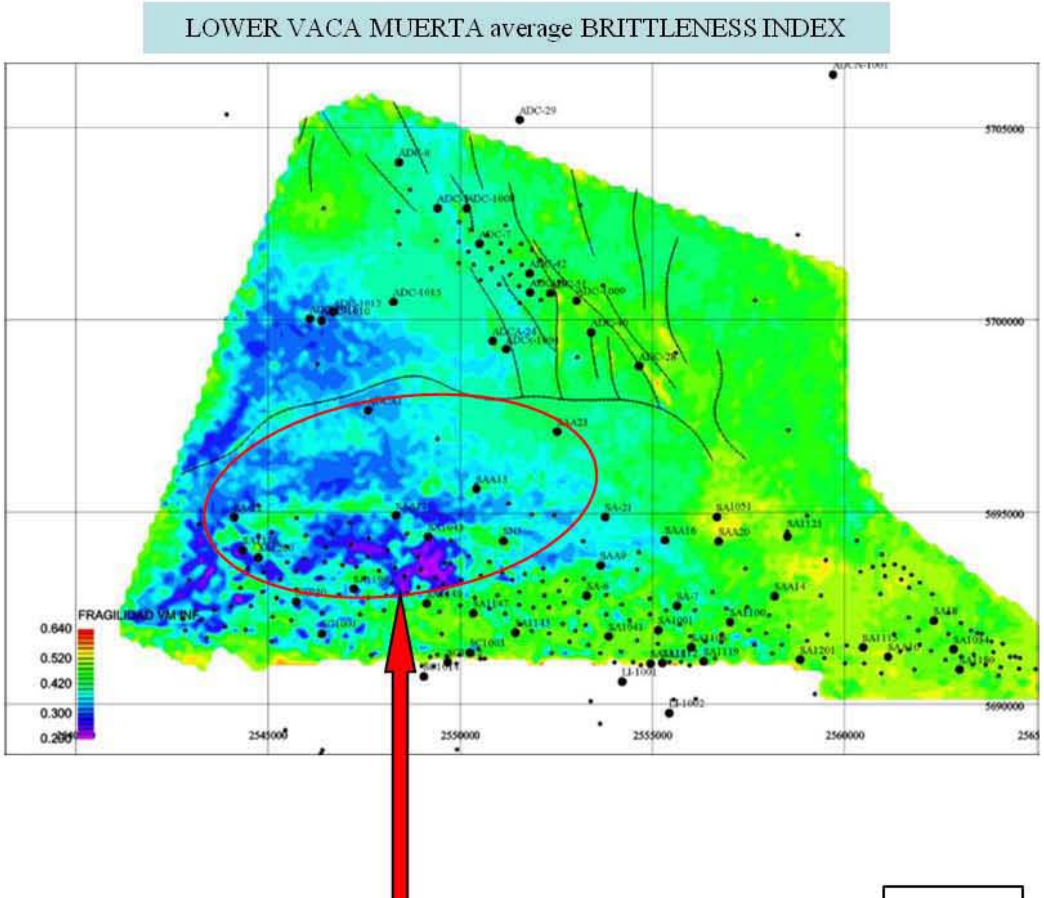


Fig. 12

Figure 12. Correlation between geochemical logs and brittleness index.

VACA MUERTA BRITTLENESS CHARACTERIZATION





LOW BI – HIGH TOC

Fig. 13

Figure 13. Brittleness characterization of Vaca Muerta Formation.