

Advanced surface logging technology for unconventional plays: well-site applications in tight reservoirs

A. Pozzi¹ and F. Casal¹ show examples of unconventional wells where Advanced Surface Logging technologies, applied in real time at the well site, were able to address structural and stratigraphic issues in differing basins with subtly varying sedimentary successions.

Introduction

Recently, significant improvements in Surface Logging technology have led to new methodologies for characterizing reservoirs. Such characterizations add significant value in both drilling and modelling activity and provide highly cost-effective well-site solutions: e.g. the chemical variations within rock sequences can be a powerful tool backing up or even replacing well logs used for well orientation.

In addition, rock facies definition, through trace elements and mineralogy, integrated with mud gas chromatography, LWD/WL logs and production tests, can provide faster and better reservoir understanding.

Such data integration and interpretation can expedite the learning curve, permitting faster and better decision making and allowing more rapid validation of investment decisions.

In the following study, the petroleum provinces of three different sedimentary basins have been characterized through the combination of several techniques, embracing services from basic surface logging technology to on-site geochemistry.

The first basin (Basin-A) is a complex system of depocentres bounded to the north by a major fault zone and constitutes an important unconventional tight gas province.

Most of the Basin-A filling ranges from the Early Eocene to the late Oligocene era, where the origin of sedimentary material varied owing to the combination of tectonic subsidence and global eustasy, has resulted in mostly siliciclastic and volcaniclastic sediments, e.g. basin-plan turbidites. It has a thickness of around 600 m, as shown by a dense network of seismic sections and by hydrocarbon exploration wells.

The main deposits (Oligocene), recently tested with encouraging reservoir quality sands, are interpreted as prograding delta front/pro delta deposits, deposited on to a submarine ramp within a wave dominated delta complex that pro-graded into a sub basin sea.

The main target of two exploration wells, Pilot-1 and Lateral-1 was to prove hydrocarbon charged sands in deep sections that could produce either conventionally or by stimulation.

When clastic sediments are homogeneous and drill cutting texture is destroyed by the cutting action of PDC bits, XRF-

XRD data can be used to identify the most terrigenous sections and, correlated to mud gas data, can reveal potential sweet spots located along the well path and also allow for optimisation of the stimulation strategy.

Furthermore, XRF trace elements used as anoxic proxies, have identified the most organic rich-layers overlaying the Oligocene clinoforms. These were responsible both for hydrocarbon generation and for the pinch-out closure; such characterization became of crucial importance during Lateral-1 geo-steering activity, as a result of GR tool failure (the GR response on Pilot-1 was compromised owing to the presence of radioactive sand layers).

The second basin (Basin-B) is composed of a substantial thickness of sedimentary rocks, consisting of between 20,000 and 40,000 ft of Palaeozoic marine sediments overlaying a Precambrian granitic/rhyolitic basement. The basin is partially deformed and displaced by orogenic uplifts formed mainly during the Carboniferous period. The Mississippian age strata, the object of the study, consists of proximal ramp limestones, shales and siltstones in most parts of the basin. All show evidence of thermal pulses, suggesting several hydrothermal fluid flow episodes related to the tectonic valving. These hydrothermal events primarily impacted the diagenesis of the carbonates rather than the siliciclastics and have led to reservoir development and hydrocarbon entrapment. To better understand diagenesis and interstitial interactions with hydrothermal fluids, an appreciation of the inorganic elemental composition becomes essential, especially regarding trace elements. Once generated, the hydrothermal fluids, as well as the hydrocarbons, followed the fracture systems and precipitated within this system.

The primary goal of two development wells, Pilot-2 and Lateral-2, was to detect fracture systems and porous/permeable zones for optimization of a hydraulic fracturing programme. The integration of several techniques, including XRF-XRD, mud gas chromatography, mud delta flow and image logs were able to identify open and closed fractures, refining the target.

The third basin, (Basin-C) lies on the flanks of a mountain chain. During the Mesozoic, Basin-C was characterized by

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numerous relative sea-level changes, resulting in a complex distribution of sedimentary deposits that include both marine and continental successions.

Basin-C has been targeted for both conventional and unconventional production.

The unconventional targets are of Late-Jurassic marine organic-rich shales developed in a back-arc embayment, where TOC values range from 1 to 8%, and kerogen is mostly of type I/II (locally II-S) or II/III. Basin-C provides opportunities for both shale-oil and shale-gas exploitation owing to its kerogen variability in terms of maturity and type. Additionally, such variability can change within a few kilometres, thus its estimation is of extreme importance both for basin modelling and for selecting the optimum well completion and geo-steering technologies.

To allow assessment of the organic matter characteristics, source rock potentials and inorganic composition of the Late-Jurassic deposit, two geochemical (XRF, XRD, TOC and Pyrolysis) and isotopic mud gas ($\delta^{13}\text{C}_1$ - C3) datasets were analysed. The samples were collected during the drilling of

two exploration wells, Pilot-3 and Lateral-3, and analysed at a lab built within the exploration field (to remove Oil Based Mud OBM contamination, the geochemical samples had to be treated with specialised solvent and glassware not allowed at the rig site).

Methods and Theory

Energy dispersive X-ray fluorescence (ED-XRF) and X-ray diffractometry (XRD)

The analytical methods result in data for 32 elements: 10 major elements reported as oxides in percentage by weight (SiO_2 , Al_2O_3 , Fe_2O_3 , K_2O , CaO , MgO , S , P_2O_5 , TiO_2 , MnO) and 22 trace elements reported as parts per million (Cl, As, Ba, Cu, Ni, V, Mo, Sr, Pb, Zn, Zr, Rb, Th, U, Cr, Co, Nb, Nd, Cs, Ga, Gd and La). Precision error for the major elements is better than 2% absolute and 10% relative, and around 10% relative for abundant trace elements.

Accuracy, repeatability and precision are guaranteed by 35 certified Reference Materials and internal standard of powdered rock samples used to calibrate the ED-XRF: these

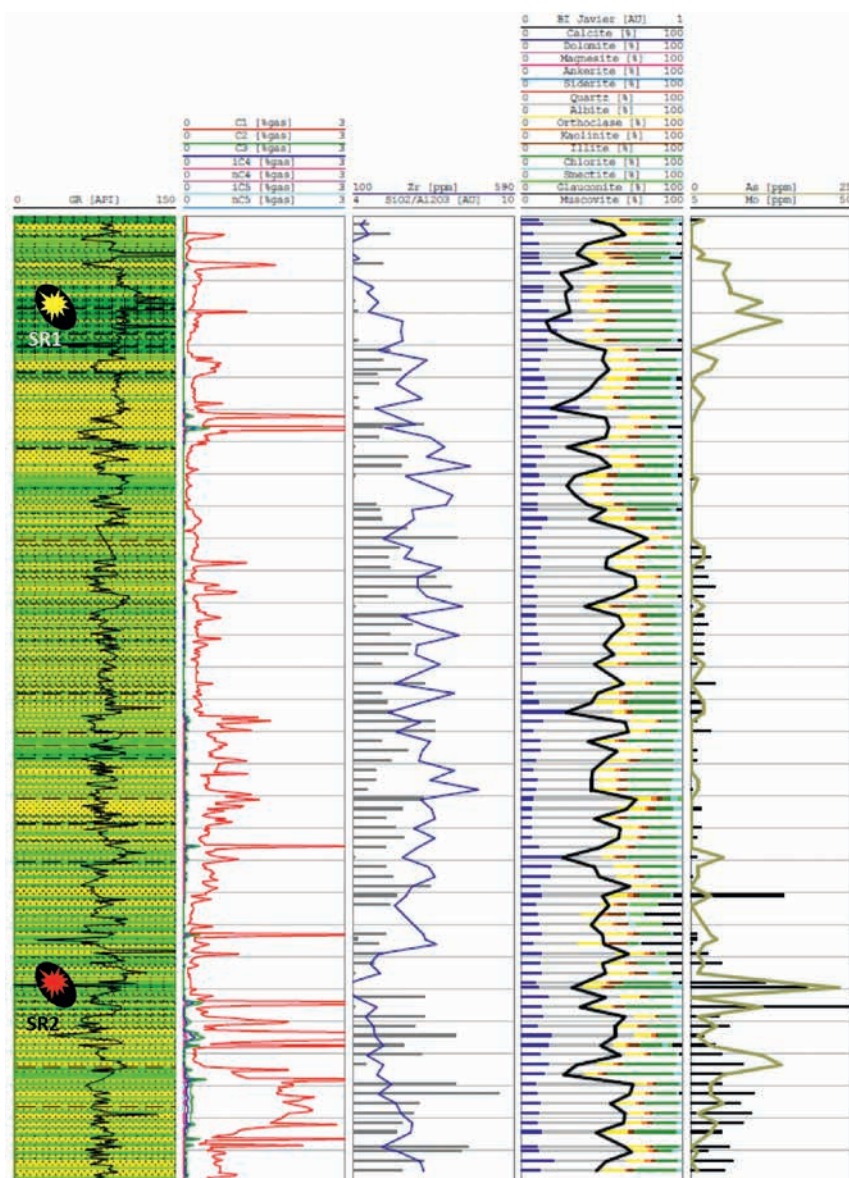


Figure 1 Pilot-1 model – vertical section passing through several bottomset clinoform bodies, where XRF textural proxies seem lined up with mud gas. The anoxic proxies increase the GR resolution for the source rocks (SR1 and SR2) localization. Col.1: Lithology and GR (API), Col.2: Mud Gas (%), Col.3: XRF $\text{SiO}_2/\text{Al}_2\text{O}_3$ and Zr (ppm) as textural proxies, Col.4: XRD Mineralogy (%) and Jarvie B.I., Col.5: XRF As (Arsenic in ppm) and Mo (Molybdenum in ppm) as anoxic proxies.

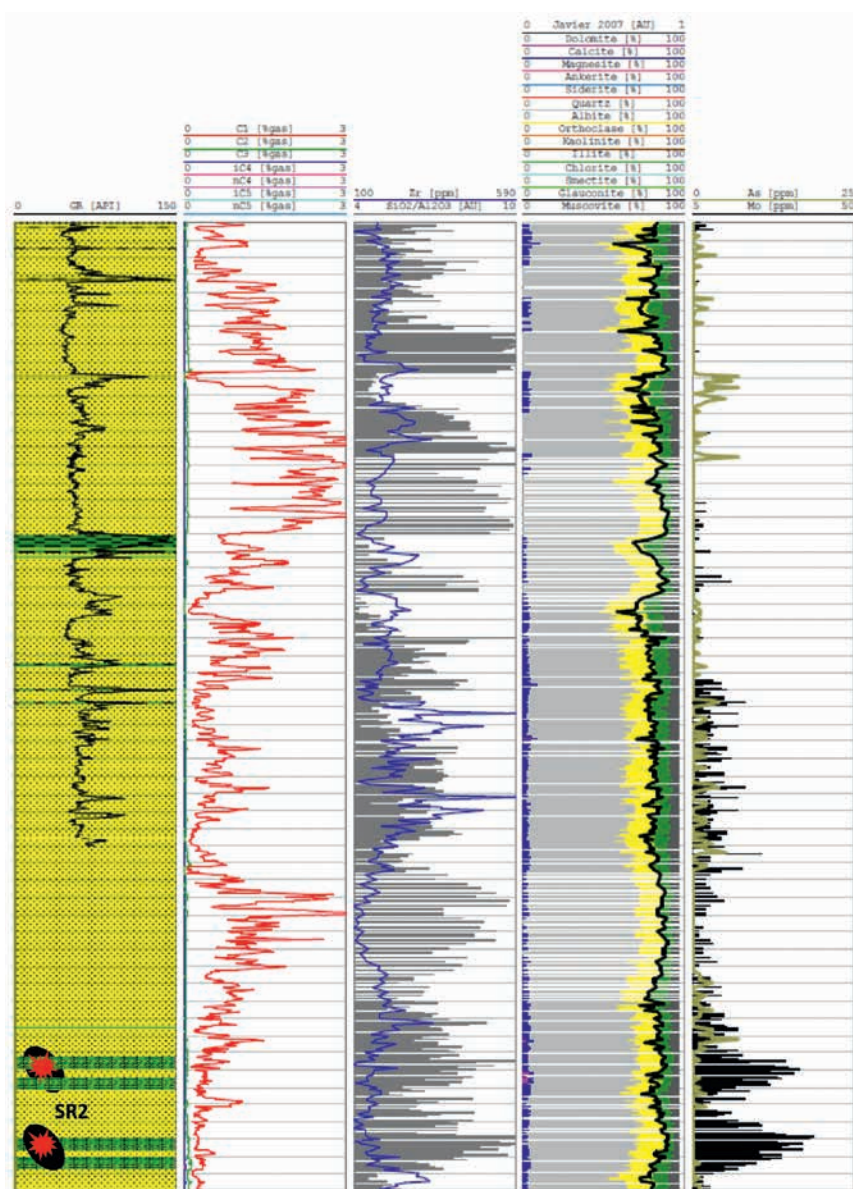


Figure 2 Lateral-1 model – the sampling rate in the lateral section was increased to improve data resolution, the linearity between the textural proxies and the mud gas corroborate the model built in Pilot-1, as well as the anoxic proxies, that define the end of the foreset clinoforms and the landing in the topset environment characterized by SR2. Col.1: Lithology and GR (API), Col.2: Mud Gas (%), Col.3: XRF SiO₂/Al₂O₃ and Zr (ppm) as textural proxies, Col.4: XRD Mineralogy (%) and Jarvie B.I., Col.5: XRF As (Arsenic in ppm) and Mo (Molybdenum in ppm) as anoxic proxies.

35 standards were selected to cover the whole elemental and mineralogical composition of all the sedimentary rocks and of the most frequent volcanic/metamorphic rocks. The calibration accounts also for the matrix effects (absorptions, secondary radiation, etc.) which differ between the several sedimentary rocks (carbonate, clastic and evaporitic) and volcanic-metamorphic rocks.

Low energy X-ray photons characteristics of light elements (Mg, Al, Si, etc.) are sensitive to air pressure and temperature variations. Built-in temperature and pressure sensors compensate every analysis for these atmospheric variations.

The samples were also analysed by XRD to verify with stoichiometry the veracity of the XRF data and to determine the bulk mineralogy.

The XRF and XRD facility that produced the data presented here was granted a laboratory quality system accreditation.

Chemostratigraphy, as applied here, involves the use of major and trace element geochemistry for the characterization and correlation of strata. The elemental composition of sedi-

ments is highly variable owing to the source rock composition, facies, paleoclimate and diagenesis (Ratcliffe et al, 2007). Although data for a total of 32 elements are acquired, chemostratigraphic characterization typically relies on a relatively small number of these elements or ratios of elements (Pearce et al, 2005; Ratcliffe et al, 2006). These key elements and elemental ratios are used to construct a chemostratigraphic framework of formations.

In the following study, several elements and elements ratios have been used to build a chemostratigraphic model within the basins' stratigraphy.

In Basin-A, Chemostratigraphy helped to identify potential petrophysical sweet spots and anoxic layers: the first were considered for the well completion design with the anoxic layers being used to geo-steer the well trajectory.

Being in a siliciclastic environment, the potential sweet spots were used:

- SiO₂/Al₂O₃: Silicon/Aluminum, lithologic ratio was used for siliciclastic rocks classification (after Sprague et al.,

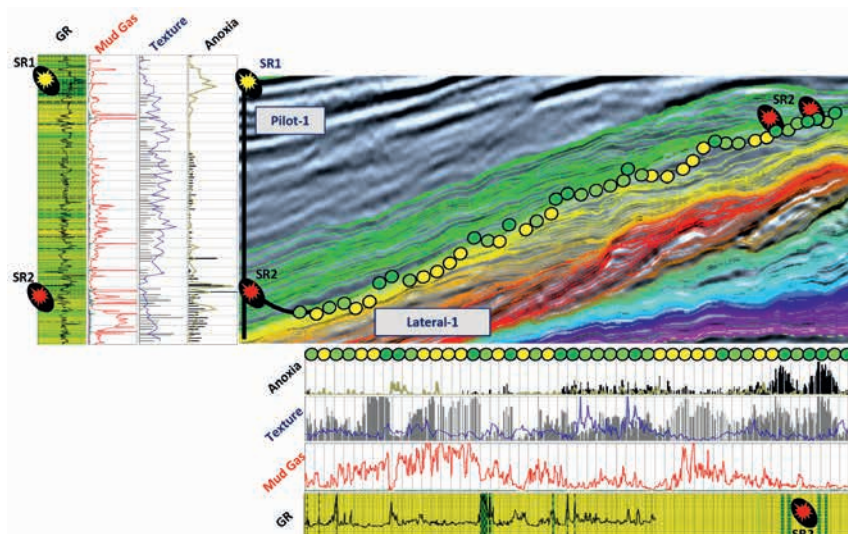


Figure 3 Wells position idealized within the seismic section – Pilot-1 designed to pass through the HST (High-stand System Tract) sequence, while Lateral-1 to pass through the gas sands clinofolds related to the LST (Low-stand System Tract) sequence. In Lateral-1, the anoxic proxies have been perfectly up to the task, defining the end of the foreset clinofolds and the entrance in the topset environment, accordingly to the well programme. The Gamma Ray tool, owing to a failure, did not provide any response in the most important section of the well.

2009). The Silicon represents principally the quartz within the sediments, while the Aluminum the clay-prone ones.

- Zr: Zirconium, immobile element not affected by hydrolysis and not related to re-crystallization; typically associated with detrital zircons in siliciclastic or volcanoclastic sediments, usually in linear association with detrital SiO₂. Zr combined with SiO₂ or SiO₂/Al₂O₃ can be used to discriminate detrital quartz from biogenic/recrystallized quartz, because the latter do not contain Zr.

While for the anoxic layers:

- Mo and As: Molybdenum and Arsenic participate in various geochemical processes in the marine environment and become authigenically enriched or depleted in sediments depending on availability of free oxygen during deposition. As a result, the distribution patterns of such elements are extensively used to understand the changes in paleo-redox conditions in both modern marine sediments and ancient rocks.

The enrichment of the redox-sensitive trace elements has significant importance in sedimentological research and is therefore considered to be a tracer of anoxic events through geological time (Tribouillard et al. 2009).

In Basin-B consisting of fractured carbonates, XRF fracture proxies were correlated to image log and mud flow losses to understand fracture permeability and related position within the well path.

When the sedimentary basin is deep enough to trigger hydrothermal phenomena (epi/tele-thermal: from 90 to 200°C) such fractures and faults systems are filled with a variety of mineral species related to the hydrothermal regime, identifiable through positive anomalies in minor and trace elements (Moore and Druckman, 1981), such as Sr, Cl, Ni, S, Mg, Zn, Pb et cetera, depending on the different type of source rock such as crystalline basement, igneous intrusion or surrounding lithology.

This variety of mineral species is often unidentifiable through XRD analysis owing to their trace concentration (XRD analysis has a relatively high limit of detection for trace minerals), thus the only way to identify possible crystalline fractures

is the use of a trace element characterizing such minerals (the XRF analyser, if well calibrated, is able to detect many trace elements).

The following elements are the main tracers of several hydrothermal minerals:

- Sr, Cl and Mg à Interstitial brine and Dolomite/Magnesite
- S, As à Pyrite, Marcasite, Arseno-Pyrite
- S, Zn à Sphalerite
- S, Pb à Galena
- Ni, As, S à Arsenide

There can be no generalisations made regarding minerals and/or elements that are associated with all faults. The type of fracture filling mineralisation will depend directly on the composition of the hydrothermal fluids, and by syn- and post-faulting P/T conditions.

Geochemical identification of fractures can be potentially difficult: when crossing a fracture system, the pattern of geochemical logs can contain abrupt change in profile (positive and abrupt anomalies), which do not relate to changes caused by stratigraphic variations. Other data, such as mud losses, resistivity logs, image logs, can support the interpretation.

In basin-C, XRF anoxic proxies, in particular Molybdenum (Mo), exhibited a linear relationship to the TOC values within the stratigraphy and could be used to characterize the different layers of kerogen. The deeper section of Pilot-3 was drilled to achieve the following:

- To provide confirmation regarding the position of the over-mature organic-rich layers (with highest TOC and Mo values). These layers have been previously identified as the primary source rock (late mature/overmature) responsible for hydrocarbon generation which subsequently migrated to the upper stratigraphic levels and were exploited during the 1980s through conventional techniques. They should therefore be excluded from the lateral production sections as being of no commercial value.
- To evaluate the maturity and type of kerogen in the upper layers which are less thermally developed (immature/early mature). Analysis of the Molybdenum content here closely aligned with the Rock-Eval and Isotopic mud gas data (the theory and methods used are reported below).

Cavity Ring Down Spectroscopy (CRDS)

The equipment was included in the Advanced Mud Gas Logging configuration.

a third isotopic form of carbon that is found in trace amounts in nature. However, it is radioactive with a half-life of 5730 years and thus it is absent from geological accumulations other than very recent sediments.

The ratio of ^{12}C and ^{13}C in compounds varies according to the biological and geological processes that formations have undergone. Their relative ratio is used as proxy for these phenomena. Such variations are generally expressed on a relative scale by comparing the measured ratio with an accepted standard. The international standard is the isotopic ratio of the CO_2 produced by hydrolysis of the carbonate fossil *Belemnitella Americana*.

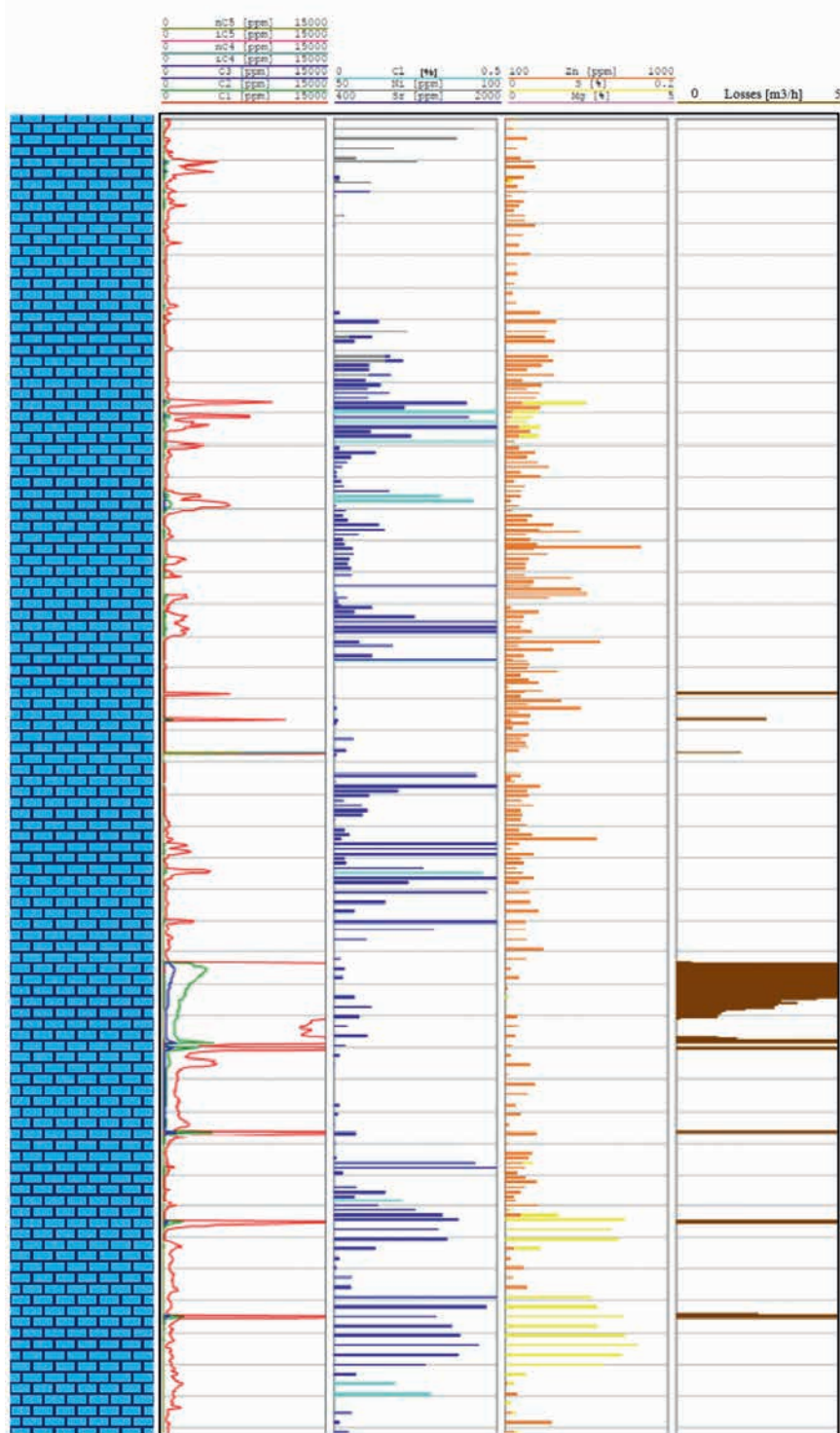


Figure 4 Pilot-2 model – vertical section passing through several fracture/fault systems generated by tectonic movement and related hydrothermal pulses. Col.1: lithology, Col.2: Mud Gas (%), Col.3: XRF Cl (%), Sr and Ni (ppm) as fracture proxies, Col.4: XRF Zn (ppm), S and Mg (%), Col.5: Mud Losses (m3/h).

$$\delta^{13}\text{C} \text{ (‰)} = \frac{[\left(\frac{^{13}\text{C}}{^{12}\text{C}}\right)_{\text{sample}} - \left(\frac{^{13}\text{C}}{^{12}\text{C}}\right)_{\text{standard}}]}{\left(\frac{^{13}\text{C}}{^{12}\text{C}}\right)_{\text{standard}}}$$

Owing to the anomalous characteristics of the standard, almost all measured $\delta^{13}\text{C}$ values are negative; for example, atmospheric CO_2 has a $\delta^{13}\text{C}$ of approximately -8‰.

[illegible]

The primary driver of this functionality lies in the differing reactivity of ^{12}C and ^{13}C . The lighter atom, ^{12}C , requires less energy when participating in reactions when compared to the heavier ^{13}C . The ^{12}C - ^{12}C bonds are subsequently less stable than ^{12}C - ^{13}C bonds and therefore require less energy to be broken. When this factor is related to the alteration of organic kerogen in source rocks, the dominant mechanism of reaction will affect the $\delta^{13}\text{C}$ of the products derived from the original kerogen content. At lower temperatures in the presence of bacteriological action upon kerogen, the breaking of ^{12}C - ^{12}C bonds will be dominant leading to ^{12}C enriched products relative to the source rock. When the thermal decomposition of kerogen takes place in the lower temperature range (without bacterial action), the lower energy ^{12}C - ^{12}C bonds will be preferentially broken, again

Figure 5 Lateral-2 model – lateral section passing through the fracture/fault systems individuated in Pilot-1 in proximity of the high mud losses (more than 5 m³/h), high mud gas and low values of fracture proxies (probable open fractures with low precipitates). Col.1: lithology, Col.2: Mud Gas (%), Col.3: XRF Cl (%) , Sr and Ni (ppm) as fracture proxies, Col.4: XRF Zn (ppm), S and Mg (%) as fracture proxies, Col.5: Mud losses (m³/h)

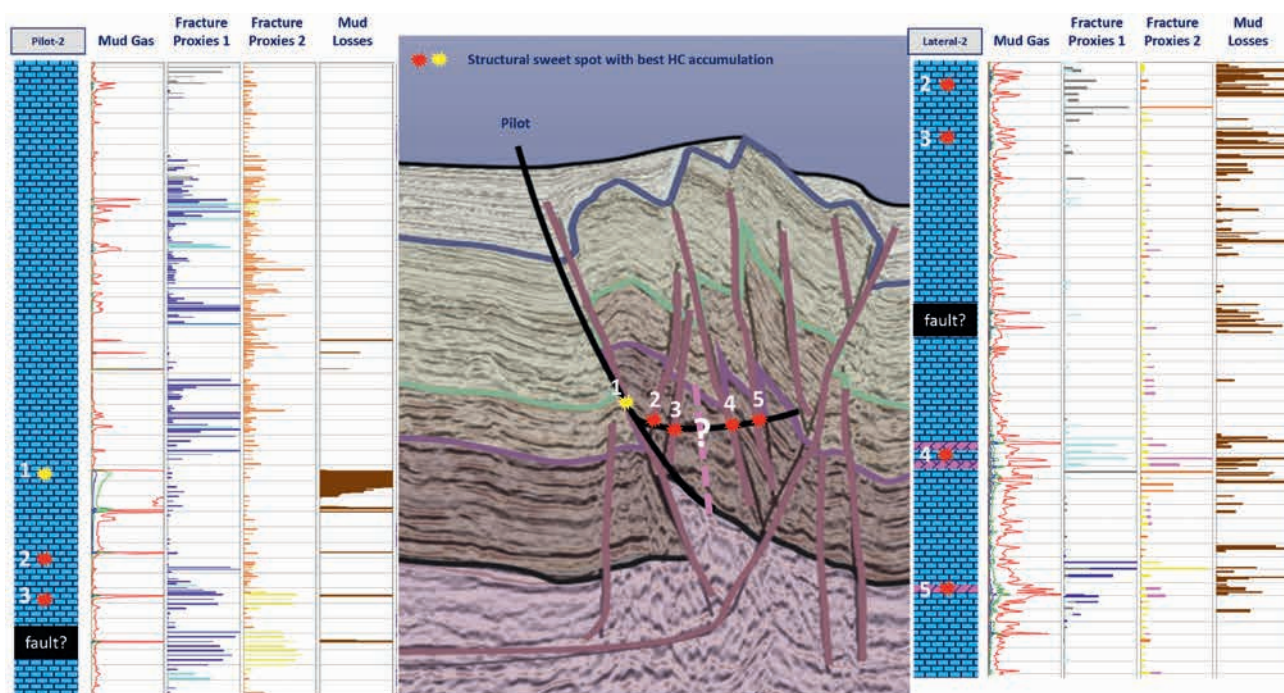


Figure 6 Wells position idealized within the seismic section – Pilot-2 designed to reach the pop-up structure and investigate the lower section of the Mississippian deposits interested by several fracture/fault systems. Lateral-2, with a KOP (Kick off Point) close to the pop-up limit, designed to investigate all the fracture/fault systems within the pop-up structure.

leading to ^{12}C enrichment in derived products. As temperature increases the remaining kerogen, now relatively richer in ^{13}C , will be broken down giving relative enrichment of products with ^{13}C . Thus, as a source rock's thermal maturation proceeds, initial products will be relatively enriched with ^{12}C while later stage, more mature products, will exhibit relative enrichment in ^{13}C . These chemical characteristics can be seen to result in a number of factors in the geological setting.

Bacterial processes are more selective than thermogenic ones, the breaking of ^{12}C - ^{12}C bonds will be preferentially favoured resulting in products highly enriched in ^{12}C .

Thermal maturation will generate products initially enriched in ^{12}C , then as maturation proceeds, a reverse of this trend towards ^{13}C enrichment will occur.

Products will contain features reflective of their sources, e.g. a ^{13}C -rich source rock will generate a greater number of ^{13}C -rich hydrocarbons, when subjected to equivalent conditions, i.e. temperature, time, pressure etc, of a source rock with a lower initial ^{13}C content.

For the above reasons, $\delta^{13}\text{C}$ values can provide information about both the hydrocarbon source and the processes undergone.

It should be noted that in general, lighter isotopes are also more mobile than the heavier ones, resulting in fractionation effects while migrating (Prinzhofer, 2003).

A complete characterization of the hydrocarbon isotopic profile should include evaluation of the $\delta^{13}\text{C}$ ratios for all components. The present study (in Basin-3) covers the mud gas isotopic measurements and relevant interpretation models for only the light hydrocarbons C1, C2 and C3.

Although Isotope-Ratio Mass Spectrometry (IR-MS) is the more commonly utilised laboratory tech-

nique, the wellsite conditions greatly limit the use of this approach owing to its fragility and instability under field conditions.

Case studies

Basin-A

Wells: Pilot-1 and Lateral-1

Targets: gas charged sands in proximal clinoforms bodies (foreset), to evaluate the best completion: conventional or by stimulation (unconventional)

Surface Logging Technology: ED-XRF, XRD, Mud Gas Chromatography

SiO₂/Al₂O₃ and Zr combined with mud gas provided:

- the KOP (kick off point) in Pilot-1;
- the main potential sweet spots in Lateral-1.

Observing their trends and integrating with the anoxic proxies, was possible:

- to identify the two source rocks within the stratigraphy of Pilot-1: SR 1 (the upper) characterized by an increase of Arsenic (As), probable vicarious of Iron (Fe) in Pyrite under redox conditions; and SR2 by Mo (Molybdenum);
- to assist the geo-steering strategy in Lateral-1, recognizing the entrance in the topset clinoforms environment (end of the well) and replacing the GR owing to a failure in the last section of the well.

Basin-B:

Wells: Pilot-2 and Lateral-2

Target: Fractures permeability and related position within the well path

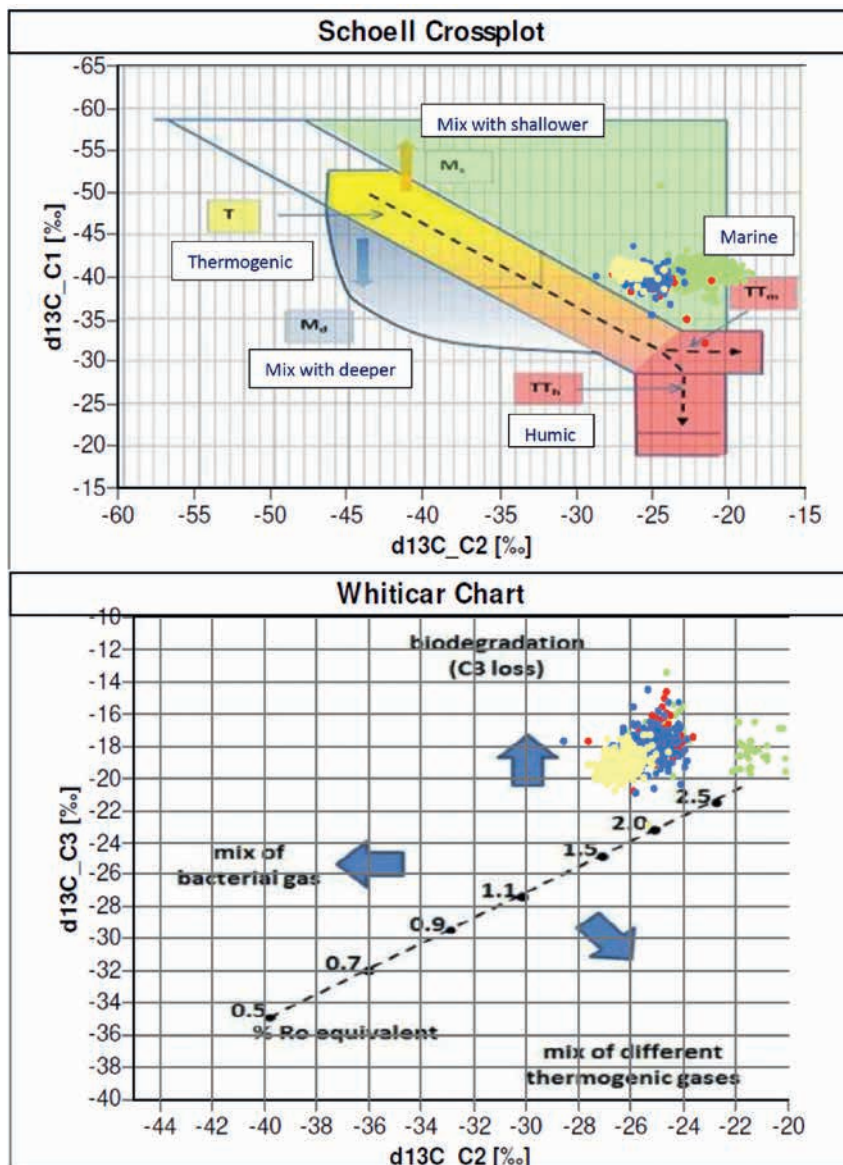


Figure 7 Lateral-3 – (above) Schoell Crossplot represents the thermogenic gas trend of the several sections of Lateral-3: The green section, deeper (KOP area), is characterized by more thermogenic gas than the following shallower sections. Indeed these latter sections are composed by more mixing with shallower gas owing to a more immature kerogen. In Whiticar Chart (below) the same trend is compared to the equivalent Vitrinite reflectance (Ro%). The following Rock-Eval results, will corroborate the interpretation.

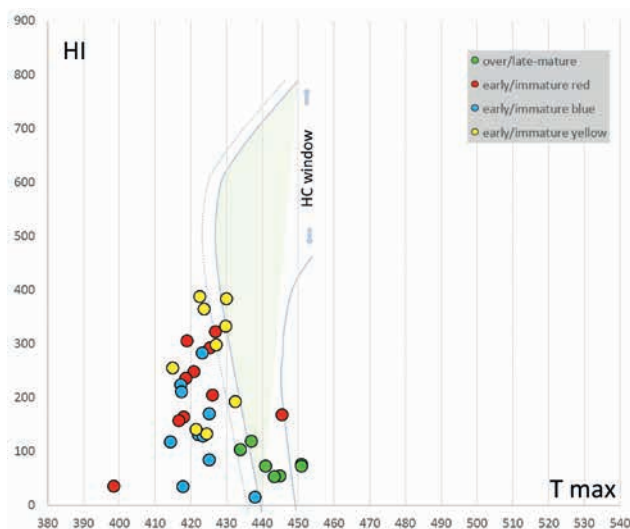


Figure 8 Lateral-3 – Crossplot HI (Hydrogen Index) versus T max (°C) from Pyrolysis. The responses confirm the higher maturity of the green section, which entirely fall in the Hydrocarbon window. Less maturity for the remaining sections, ideal for the fracking stimulation.

Surface Logging Technology: ED-XRF, Mud Gas Chromatography, Mud delta flow

In Basin-B mud gas data combined with mud losses provided:

- a conspicuous harbinger during the entrance in the pop-up domain in Pilot-2, target of the well;
- the identification of the several fracture/fault systems, main target for the hydraulic stimulation in Lateral-2.

Their integration with the XRF fracture proxies revealed:

- a brine/sulphate (Sr, Cl and S) composition of the fracture precipitates in Pilot-2: probably owing to the nearby detachment surface, a listric fault visible in the seismic interpretation of Figure 6;
- a slight change of precipitates composition in Lateral-2 fractures: brine/sulphate mixed to dolomitic (Mg) / Arsenide (Ni). According to the XRF proxies, fractures 2 and 3 (Figure 6), both present in the two wells, in Lateral-2 (thus above their position in Pilot-2) changed composition owing to a probable slight acid/alkaline reducing environment

usually characterized by high CO₂ fugacity. Such mechanisms are not so relevant from their intrinsic point of view but can be a valid instrument for the reservoir zonation: especially if, during the production tests, the different fracture systems gave different responses.

Basin-C

Wells: Pilot-3 and Lateral-3

Target: Kerogen type and maturity in organic-rich sweet spots.

Surface Logging Technology: ED-XRF, Cavity Ring Down Spectroscopy, Rock-Eval.

The Schoell cross-plot for Lateral-3 (Figure 7, above) shows how the gas maturity follows the TVDSS (True Vertical Depth Sub Sea): deeper the depth, the more mature the gas. In the plot, the dataset is grouped in the 'marine origin'

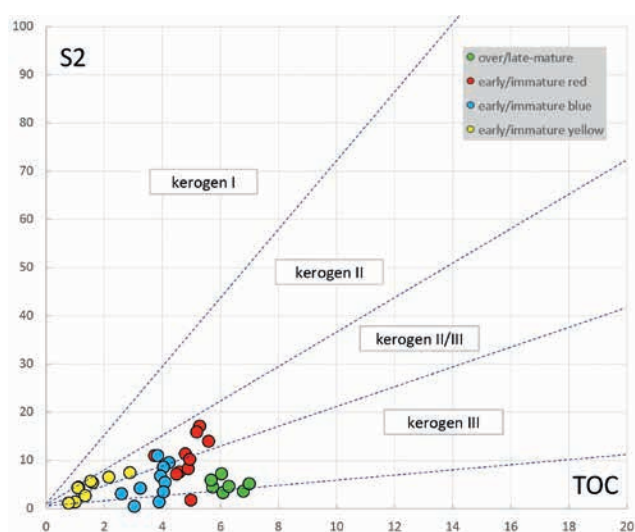


Figure 9 Lateral-3 – Crossplot S2 (Potential Hydrocarbon in mg/g of rock) versus TOC (%). The background lines delimit the kerogen types. Only type III for the late mature green zone (deeper) and mixed II/III for the other immature/early-mature zones (shallower).

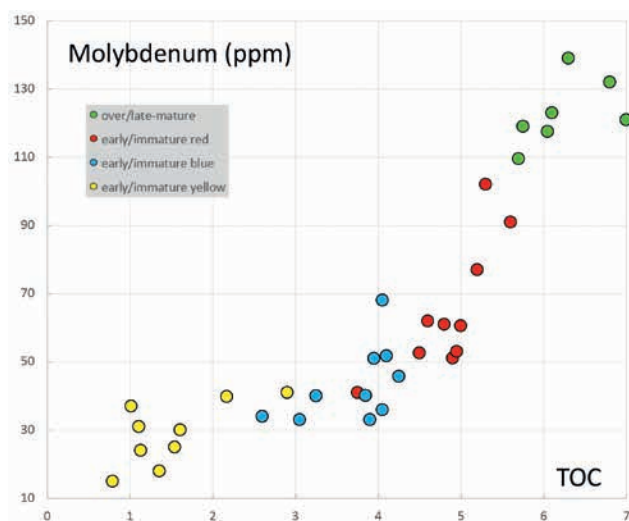


Figure 11 Lateral-3 – Crossplot Mo (Molybdenum in ppm) versus TOC (%). The linear correlation between TOC and Mo suggests a probable authigenic enrichment of Molybdenum in marine organic-rich sediments during anoxic deposition.

zones, confirming the environmental pattern of the reservoir: distal ramp/open basin. This plot, combined with Whiticar chart, can contribute to assess Source Rock (SR) maturity during the hydrocarbons generation. In Whiticar plot, all the sections follow the same linear trend according to depth and environmental pattern, where the deeper overmature/late mature SR is represented by the green points, and the shallower early mature/immature SR by the others (red, blue and yellow). Whiticar chart has been developed according to a particular basin, thus the equivalent % Ro reported in the plot has to be intended as trend and not in absolute value. Different source rocks can generate hydrocarbons with different isotopic signature. For this reason, the Whiticar chart is intended to be an indication of maturity. By calibrating the method with the isotopic data collected from a specific basin, the chart can be used in a quantitative way for SR maturity.

In Basin-C mud gas isotopic data combined with Rock-eval and XRF data (Molybdenum) provided:

- a complete reservoir characterization, from fluids (isotopes mud gas) to rocks composition (XRF and Rock-Eval), distinguishing the no productive zones (overmature/late-mature kerogen) from the productive ones (early-mature/immature), in terms of unconventional exploiting;
- a correlation between the organic (TOC-Pyrolysis) and inorganic (Molybdenum) data, useful for the next wells in geo-steering decisions: XRF Molybdenum analysis is faster, more repeatable, and always available on site, than Rock-Eval analysis, because the OBM (Oil Based Mud) does not influence XRF Molybdenum detection;
- a conspicuous contribution to the reservoir modelling, adding important information for the refinement of the exploration activity (maturity and kerogen assessment).

Conclusions

Advanced Surface Logging technology can give highly effective support during unconventional drilling and modelling activity and provides cost-effective solutions for well-site applications. In particular, the following study has presented how the well-site geochemistry, integrated with the other disciplines was able to provide:

- recognition of petrophysical sweet spots in siliciclastic bodies (e.g. Basin-A), through the combination of XRF textural proxies and mud gas data analysis;
- completion optimization within fractured carbonates by correlating XRF fracture proxies (hydrothermal mineralisation) with mud gas data and high-resolution mud loss monitoring, thereby enabling definition of the carbonate facies and prediction of the optimum hydraulic fracturing zones;
- identification of the optimum organic facies to be stimulated in terms of maturity and kerogen type in a distal shale basin (e.g. Basin-C), using C1, C2 and C3 mud gas isotopes correlated to Rock-Eval and XRF-derived anoxic environment indicators, contributing to basin model construction (still in explorative phase).

Surface Logging, because of the application of well-site geochemistry, is shown to have an enormously beneficial impact on

unconventional plays, bringing significant benefits, and avoiding the uneconomic deployment of expensive downhole tools.

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