PS Log Features for the Characterization of Igneous Rocks in the Pre-Salt Area of Santos Basin, SE Brazil*

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Search and Discovery Article #11264 (2019)**
Posted December 11, 2019

*Adapted from poster presentation given at 2019 International Conference and Exhibition, Buenos Aires, Argentina, August 27-30, 2019
 DOI:10.1306/11264Oliveira2019

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Abstract

Well drilling in Santos Basin, with objectives in the Pre-Salt area, usually requires the use of impregnated bits, which generate very small drill cuttings and drill-bit metamorphism (DBM) artifacts. These altered drill-cuttings complicate the identification of igneous rocks while drilling and this can lead to misinterpretations of the reservoir thickness. To reduce this uncertainty, three methods for identification of igneous rocks were developed: (1) Igneability feature, using density (DEN) and photoelectric factor logs (PE); (2) Fe-Al-Ca and (3) Si-Al features which use the geochemical log. The Igneability feature indicates the presence of mafic igneous rocks. We obtain this feature by crossing both logs in the same track using the following scales: DEN 2-3 g/cm^3 and PE 12-2 barn/electron. When PE log is to the left of DEN, it strongly indicates the presence of mafic igneous rock. With this feature it may be possible identify the mafic igneous rock is intrusive or extrusive through the relation distance between this logs, where the first will show a wider separation in relation to the second, and through the pattern of the curves which will have a higher variation in the extrusive rocks. The Fe-Al-Ca feature is used to distinguish mafic igneous rocks intercalated with limestones and clay-rich zones within the limestones. To use this feature the three logs are used in the same track with the scales: Al 0-0.12; Ca 1-0; Fe 0.12-0. These logs should be analyzed in pairs. First the interaction between Al and Fe, then Ca and Fe. When Fe is on the right in relation to Ca, there is an indication of limestone. When Fe is on the left in relation to Al, there is an indication of basic igneous rock. The Si-Al feature indicates the presence of aluminosilicates suggesting the occurrence of igneous or siliciclastic rocks. This feature was also used to identify the presence of lithic sandstones, which are difficult to distinguish from igneous rocks during drilling operations in Santos Basin. To use this feature the two logs are used in the same track with the scales: Si 0-0.3; Al 0.12-0. When Al is leftward in relation to Si, the feature indicates the presence of aluminosilicates. The use of these three methods combined can support a detailed interpretation of lithology and stratigraphy of the well, anticipating results that would only be possible after laboratory analysis of sidewall core samples.

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LOG FEATURES FOR THE CHARACTERIZATION OF IGNEOUS ROCKS IN THE PRE-SALT AREA OF SANTOS BASIN, SE BRAZIL.

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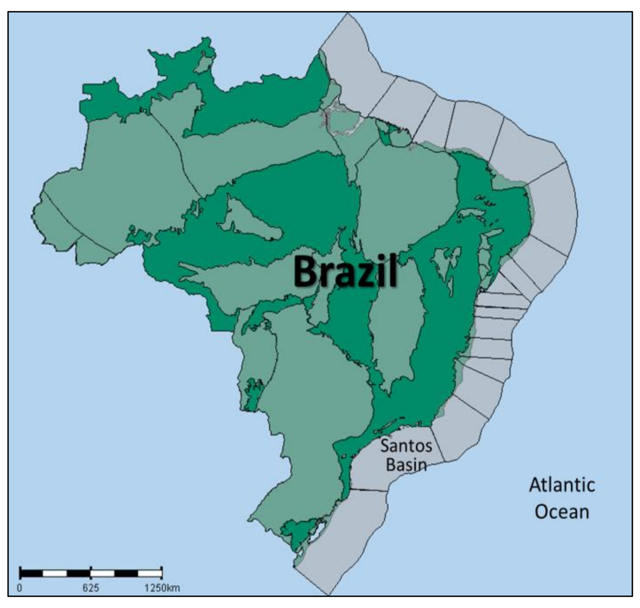

Figure 1. Localization of Santos basin in Brazil

Introduction

Santos Basin is located in the southeast portion of Brazil and currently represents the main Brazilian oil producer (Souza & Sgarbi, 2019). In this context, the deep water carbonatic Pre-salt reservoirs are the main ones (Riccomini et al., 2012). There are some complications during the drilling of the Pre-salt reservoirs in the Santos Basin, such as the need to use turbine impregnated drill bits, which leave the drill cuttings in a small size, making it difficult for the wellsite geologist to identify the lithologies.

In some oil fields in the deep water portion in Santos Basin several occurrences of igneous rock were observed during the well drilling. Due to the bit type, the extremely fine fragments and the very dark shade of igneous rocks, carbonates and siliciclastics make it difficult to identify the lithologies.

The presence of igneous bodies in the reservoir zone directly affects the thickness of the reservoir. In this scenario, it is very important to identify and characterize these bodies by indirect methods, such as LWD and wireline logs, fluorescence and x-ray diffraction, due to the difficulty of identification on drill cuttings for better reservoir´s understanding.

Method

The methodology consisted in observing variations of the different kind of data previously mentioned in each lithology of the Pre-salt. From this evaluation, it was possible to separate specific responses for the following lithologies: mafic igneous, carbonate, siliciclastic, silicified carbonates, contact metamorphism carbonates and anhydrites.

Some features were created such as Igneability (Oliveira et al., 2018), Fe-Al-Ca and Si-Al. Appropriated scales were stablished where the curves used in each feature were inverted in the same track to indicate the exact rock we want to identify. Visual separation of the lithologies through a hatch would indicate the presence of this lithology.

In order to test the methodology, the last step was to apply it in some wells in the Pre-salt, comparing with results obtained in the laboratory, followed by a mathematical formulation that allowed us to use these features as cross-plots.

Igneability feature

- It characterizes the presence of mafic rocks, through a crossing between the density and the photoelectric factor logs, when they are at a certain scale the density log (DEN) 2.0 to 3.0 and the photoelectric factor log (PE) 12 to 2 (figure 2).
- Whenever photoelectric factor log is to the left of density log, it strongly indicates the presence of mafic igneous.
- It helps to distinguish shales, siltstones or carbonates rich in clay because the distance between both logs in shales, siltstones or carbonates rich in clay are greater when compared with carbonate, and it will differentiate these clayey rocks from possible igneous rocks.
- It is necessary to evaluate the caliper log while using this method in order to not generate misunderstandings in the interpretation, distorting the original curve which may form false Igneability features.
- In wells with presence of intrusive mafic igneous rock in limestones, the feature will not recognize an abrupt but transitional contact due to the contact metamorphism.
- The Igneability factor (Ig), as a function of the density and the photoelectric factor, indicates with negative values the hatched situations of the Igneability feature.

$Ig = 3.2 - \rho - 0.1_x Pe$ .... (1)

Fe-Al-Ca feature

- It uses the dry weight results of Fe, Al and Ca of the Litogeochemical tool.
- The scales for each element is Al: 0 to 0.12, Fe: 0.12 to 0 and the Ca: 1 to 0.
- The crossings between the curves give 3 possibilitie of lithologies:

1) hatching in red: igneous rocks.
2) hatching in blue: limestone.
3) without hatching: siliciclastic or clayey levels in the limestone (Figure 2).

- The equation 2- Ϙ (qoppa)- show negative values to indicate the presence of coherent igneous rock (the tests performed were with basalts and dolerites) and positive values indicate sedimentary rocks.
- Values between 0 and 0.8 represent siliciclastic rocks, and values higher than 0.8 represent carbonaceous rocks. Limestones with clay form a transition zone between these two fields.

$Ϙ = Ca - (50/3)xFe - (25/3)xAl + 1.5$ .... (2)

Si-Al feature

- It uses the dry weight results of Al and Si of the Litogeochemical tool.
- The scale for these elements is Al: 0.12 to 0 and the Si : 0 to 0.3.
- The curves of Al and Si plotted in the same track will be hatched in yellow when Al positions to the right of the Si and show two possible meanings (Figure 2):

1) rock composed of aluminosilicates (igneous or siliciclastic).
2) rock with more than 30% Si (very silicified carbonates and sandstones) in the case of only Si increasing to provide hatching.

- The equation 3 - ζ (Zeta)- shows negative values to indicate the presence of siliciclastic or igneous rocks and positive values to indicate carbonate rocks. Limestone with clay content forms a transition zone between these two fields, tending or assuming negative values.

$\zeta = 1 - (10/3)xSi - (25/3)xAl$ .... (3)

Cross-plot Ϙ x Ig

- This cross-plot uses the Ig factor and Ϙ. The Ig factor shows a lithological discrimination that depends not only on the chemical composition of the rock, but which can also be strongly impacted by its structure, whereas the factor Ϙ depends basically on the chemical composition (Figure 3).
- It separates the fields that represent the main lithologies of the Pre-salt, and points to the zone of carbonate approximation to the intrusive igneous, the trend of alteration in basalts (in brown) and the trend of increase of acidity of the igneous rocks (in red) (figure 3).
- The trend indicates the increasing of basaltic alteration.
- Basalts rich in glass and/or altered basalts and dolerites present Ig with positive values.
- Also enables to distinguish limestone, silicified limestone and clayey limestone, in addition to distinguishing limestone from thermal halo that differs from others because it presents negative Ig values.

Cross-plot Ϙ x ζ

- Allows to evaluate the transition from limestone to limestone with clay and silicified limestone.
- Basic igneous is also isolated from the other lithologies and when altered these rocks tend to the field of siliciclastic.
- Once lithology is identified as igneous rock, it is possible to qualitatively estimate its classification in terms of acidity (figure 4).

Use of the techniques together

- The use of all these methods together can give us more information, especially when it comes to igneous rock.
- The Igneability feature will indicate the position of bodies of mafic igneous, as well as the Fe-Al-Ca feature that will accurately indicate the top and base of igneous bodies with 3m or more thickness. If the mafic igneous is extrusive, both features will agree on the top and bottom of the same.
- If the mafic igneous is intrusive, the Igneability feature and the Fe-Al-Ca feature will not agree with the top and bottom position (Figure 5).
- In all of the situations described above, the Si-Al feature will indicate hatching, however, it will also hatch in the case of shales, sandstones or limestones with higher clay-minerals content. Therefore, comparing to the other two features, we have a diagnosis to know of the existence of siliciclastic contributions or greater argilosity in the limestone. Comparing these zones to the Fe-Al-Ca feature, we will always have cross-hatches when this indicates igneous rock, but we will also have a hatch, often intermittent when the Fe-Al-Ca feature indicates siliciclastic. Carbonates will never have a hatch in the Si-Al feature, unless they contain a large amount of clay-minerals in their composition (Figure 5).

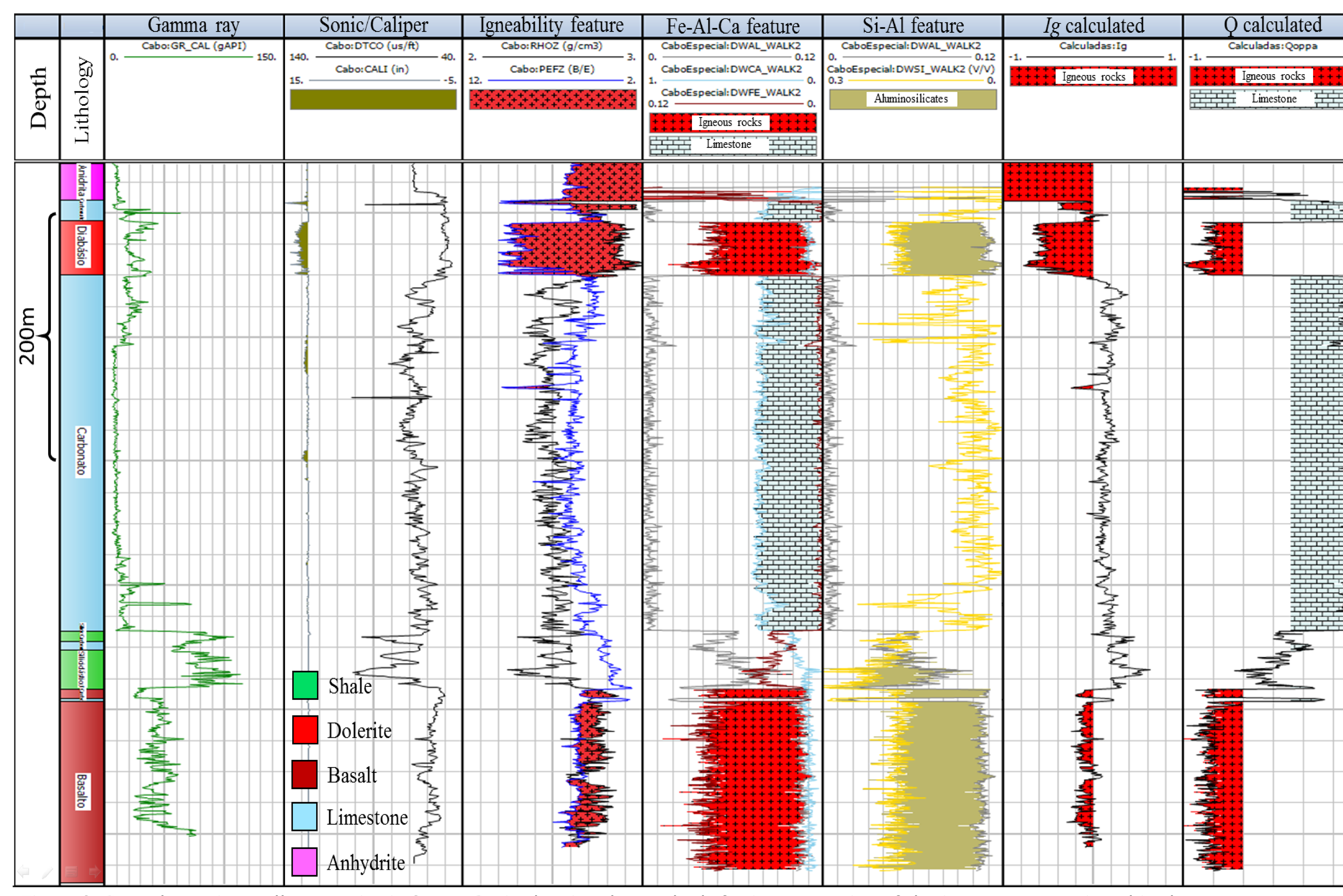

Figure 2. Pre-salt section well composite in Santos Basin showing the methods for interpretation of the igneous as mentioned in the text.

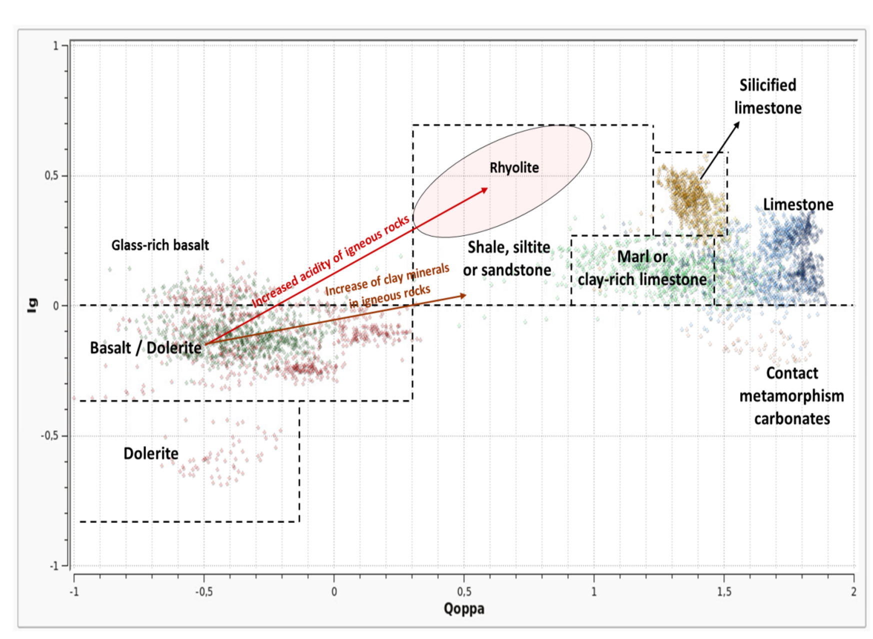

Figure 3. Cross-plot using Ϙ (qoppa) calculated against Ig calculated for the separation of lithologies from the Santos Basin Pre-salt.

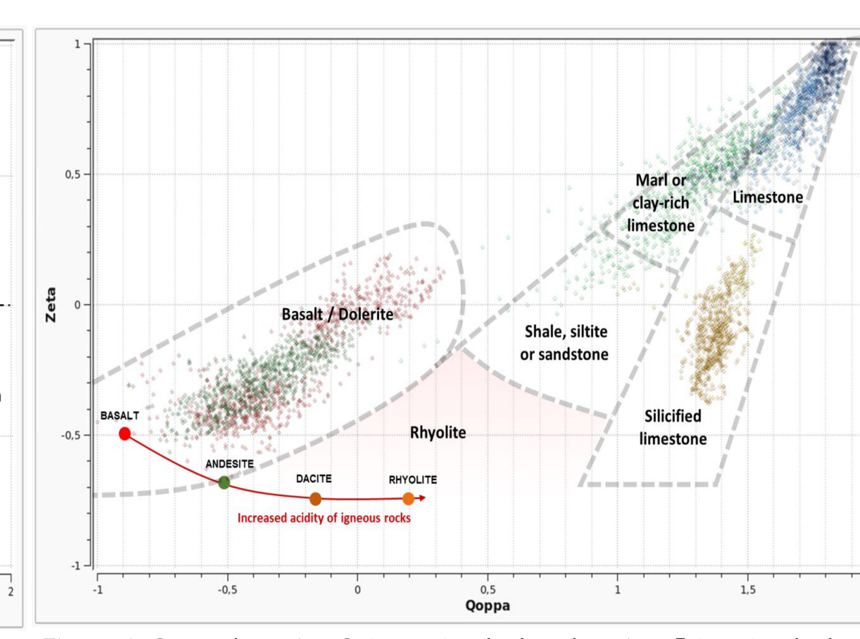

Figure 4. Cross-plot using Ϙ (qoppa) calculated against ζ (zeta) calculated for the separation of the Pre-salt lithologies of the Santos basin, with points representing igneous rocks patterns (basalt, andesite, dacite and rhyolite) of Le Maitre (1976).

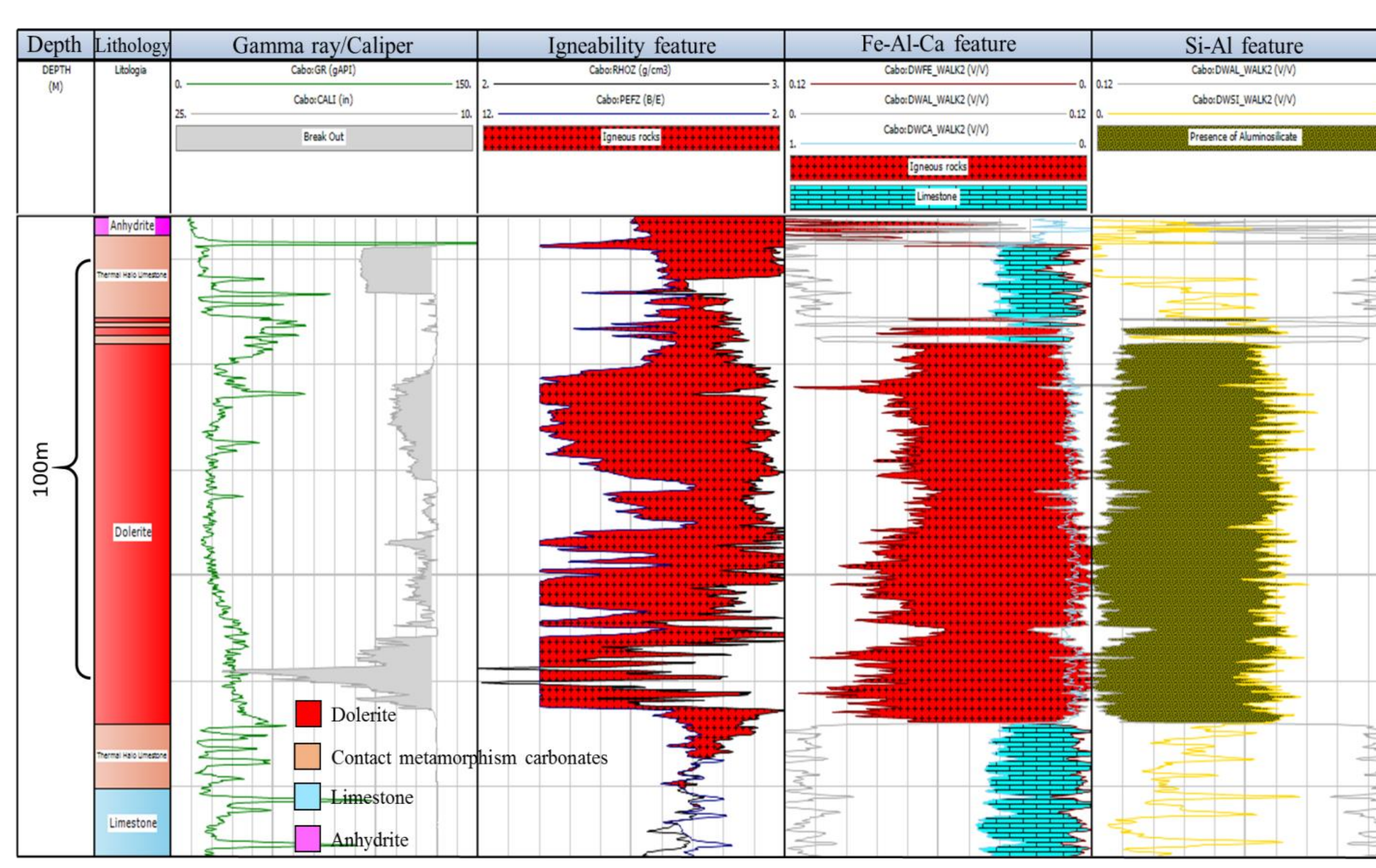

Figure 5. Pre-salt section well composite in Santos basin showing the use of the methods together for the identification of intrusive igneous rocks.

Conclusion

By using these tools, it is possible to accurately identify the top and bottom of igneous rocks, indicate whether they are mafic, and whether they are intrusive or extrusive when they are in contact with limestones. For the other lithologies it is possible to indicate siliciclastic contributions and increase of clay in the carbonates of the Pre-salt.

The mathematical translation of the features allows us to compare them with other petrophysical parameters, or even to generate algorithms that suggest the interpreted lithology of the Pre-salt automatically, associating them with other logs.

The development of these features has provided us with more security for the identification and characterization of igneous rocks, and is now widely used in fields such as Mero and Buzios. But it is only applied after the well logging, since it is not usual to use the density and litogeochemical tools in LWD, although we have fluorescence and x-ray diffraction to help us indicate the presence of igneous rocks in real time.

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