IGNEOUS BODIES CHARACTERIZATION BY MEANS OF SEISMIC REFLECTION ATTRIBUTES AND WAVELET TRANSFORM

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Introduction. The aim of this work is the detection and characterization of several igneous bodies observed in a series of 2D reflection seismic sections. The seismic survey has been acquired offshore Senegal and western African margin, SW of Dakar.

The identification, description and characterization of the igneous bodies is carried out by means of the complex seismic attributes. The considered attributes are the Reflection Strength and its first and second derivative, the Instantaneous Frequency, the Instantaneous Phase, the Cosine of the Instantaneous Phase and the Sweetness. Moreover, in order to improve the visualization of the entire seismic dataset, the Continuous Wavelet Transform (CWT) is applied to the data. The CWT helps to better discriminate the geometrical features and the morphologies of the igneous bodies.

The seismic attributes analysis and the CWT allow the identification of the amplitude anomalies related to the igneous bodies, the description of the different seismic facies and the understanding of mutual relationship and behavior. Furthermore, this process consents the evaluation of the geometrical properties of the intrusive bodies such as thickness, lateral extent, emplacement depth. It also allows the delineation of the structural deformations that affected the overburden due to the igneous intrusion.

Finally, the variation in the attribute response let us to recognize in each seismic profile three seismofacies and to classify the intrusive bodies based on their age, shape and level of emplacement.

Seismic reflection data. This study is carried out interpreting eighteen seismic lines extracted from a 3D data volume. In particular, the entire dataset is composed by eleven in-lines and seven cross-lines. In Fig.1 the map of the survey with the position of the seismic lines here analyzed; in Tab.1 the most important acquisition and recording parameters are reported. All the sections are time migrated with zero phase conversion applied.

A *line by line* description of each amplitude anomaly is carried out. The seismic lines are characterized on the basis of their amplitude, phase and frequency by means of the complex seismic attributes (Taner *et al.*, 1979; White, 1991; Satyavani *et al.*, 2008; Barnes, 2001; Yushun, 2011; Subrahmanyam and Rao, 2008) Reflection Strength and derivatives, Instantaneous Phase, Instantaneous Frequency and Sweetness.

Tab. 1 - Acquisition and recording parameters.

Type of energy source	Air Guns
Number of source	2 groups
Source depth	5.5 m (+/- 1m)
Shot point interval	25 m
Number of streamers	10
Streamer length	6000 m
Number of traces	480 / streamer
Trace interval	12.5 m
Nearest seismic offset	360 m
Streamer depth	7 m +/- 1 m
Number of channels	10x480 + 37 auxiliary channels used
Record length	8100 ms
Sample interval	2 ms

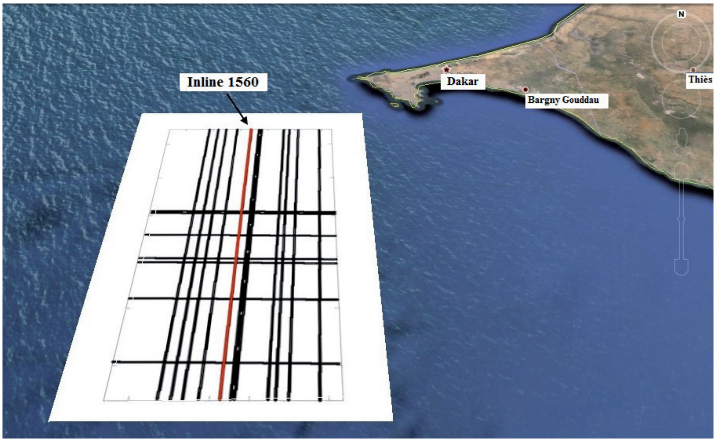

Fig. 1 – Map of the survey. In black are the positions of the analysed seismic sections. The inline 1560 is highlighted in red. The width of the map is 30 km along the E-W direction and 60 km in the N-S direction.

The Reflection Strength attribute permits to visualize the data taking into account the seismic reflectivity and, in particular, it highlights the strong impedance contrasts related to lithological changes and thus allows to discriminate the limits between sequences and to localize the amplitude anomalies from the igneous bodies.

Therefore, according to the observed amplitude response, each seismic section is divided into three different seismofacies (Fig. 2). The seismofacies A is located in the upper part of the sections and is characterized by alternating reflectors with medium to high Reflection Strength response. The seismofacies B (below A) is constituted by a package of reflectors that have the maximum amplitude values, alternated by thin reflectors with medium amplitude values. The seismofacies C, located in the lower part of the sections, presents discontinuous reflectors

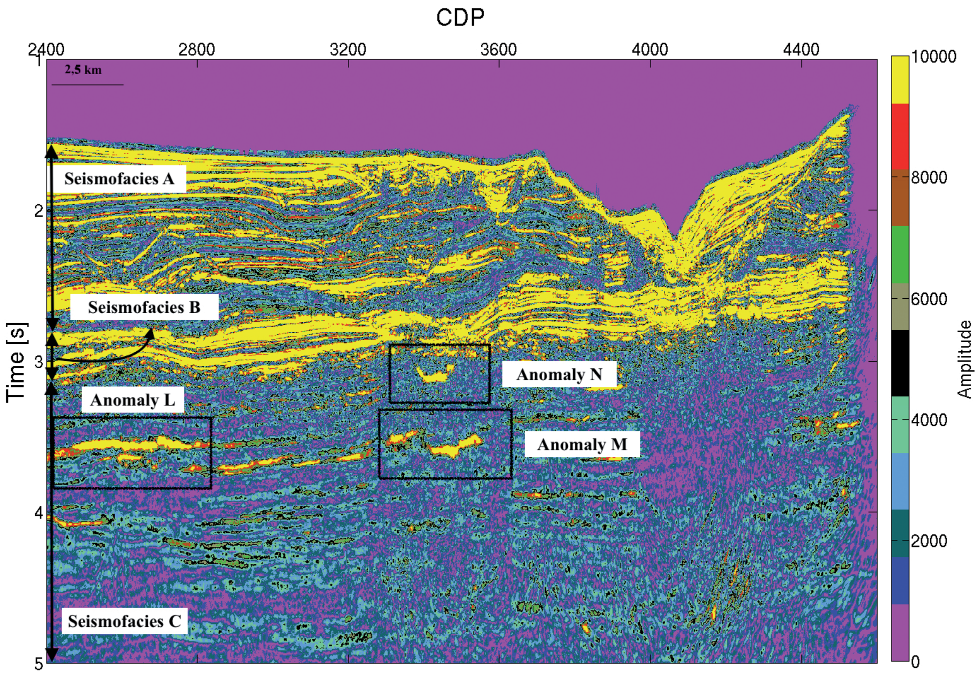

Fig. 2 – Reflection Strength of the inline1560. The limits between the seismofacies A, B, C and the localized amplitude anomalies L, M and N, related to the igneous bodies, are highlighted. The strong impedance contrasts between the anomalies and the host-seismofacies C are evident.

with amplitude values much smaller than those of seismofacies A and B. In Fig. 2 is shown an example of the result obtained through the application of the Reflection Strength attribute for the inline1560 and the limits between the seismofacies A, B and C and the amplitude anomalies L, M and N are highlighted.

The Instantaneous Phase attribute is applied in order to emphasize the lateral continuity of strong as well as weak events, to estimate the geometrical properties of the amplitude anomalies and to highlight the discontinuities, such as discontinuities.

The Instantaneous Frequency attribute is useful to discriminate the different range of frequency that characterized the data. In particular, the three seismofacies exhibit distinct Instantaneous Frequencies trends: the seismofacies A and B are characterized by medium to high frequency reflectors, while the seismofacies C shows a low frequency content. Furthermore, the amplitude anomalies highlighted by the Reflection Strength attribute correspond to low Instantaneous Frequency anomalies.

The Sweetness attribute is calculated by the combination of Instantaneous Frequency and Reflection Strength (Hart, 2008; Riedel, 2010; Yushun, 2011) and it is useful to better distinguish the events characterized by high values of acoustic impedance. This attribute clearly highlights the limits of the three seismofacies as well as the anomalies. The seismofacies A presents dominant Sweetness values around zero and, within it, few reflectors with higher Sweetness values are observed. The seismofacies B is made up of packages of laterally continuous reflectors with medium-high Sweetness values. Below, the seismofacies C is characterized by the presence of less continuous reflections, compared with the seismofacies A and B. They exhibit quite high Sweetness values and are enclose in a background that presents Sweetness values comprised between 0 and 1000.

Therefore, the detection of the anomalies related to the igneous bodies is performed through the application of the seismic attributes. In particular, the Reflection Strength and the Sweetness attributes permit to isolate the high amplitude value anomalies from the low reflective seismofacies C. The Instantaneous Phase allows the identification of some sills within the seismofacies B masked by chaotic reflections. These igneous bodies present antiformal junctions, T- and F-shaped morphologies and saucer-shaped geometries. The Instantaneous Frequency permits to characterize the sills as bodies with a frequency range of 25-30 Hz. The amplitude anomalies within the seismofacies C show values between 10 and 25 Hz, while the anomalies in the seismofacies A show values up to 40 Hz. Regarding to those within the seismofacies B, they are not resolved due to the chaotic facies with too high frequencies.

The Continuous Wavelet Transform (CWT). In order to improve the geometry interpretation, the Continuous Wavelet Transform (CWT) is applied (Debauchies, 1988; Mallat, 1989; Zhang *et al.*, 2006). The CWT provides a method for displaying and analysing signals as a function of time and scale. The scale and the frequency are related to an inverse relationship of proportionality, which means that the higher the scale the lower the frequency. Therefore, the wavelet transform allows to decompose the seismic data into a time versus scale (frequency band) domain and subsequently, if needed, to reconstruct them in the scales of interest. The analysis of the reconstructed common scale volumes permits to obtain a representation of the frequency information, which is contained in a seismic section.

In particular, the CWT is defined as follows (Debauchies, 1988; Zhang *et al.*, 2006):

It can be considered the cross-correlation between the seismic trace and the dilated and scaled versions of an user defined wavelet. The mother wavelet is the analysis wavelet function, a is the location parameter of the wavelet, so that (t-a) defines the shift of the wavelet along the trace, and b is the scaling (dilation) parameter.

By shifting and scaling the mother wavelet, the Wavelet Transform is able to capture information of short duration (high frequency) or information of long duration (low frequency), at the same time.

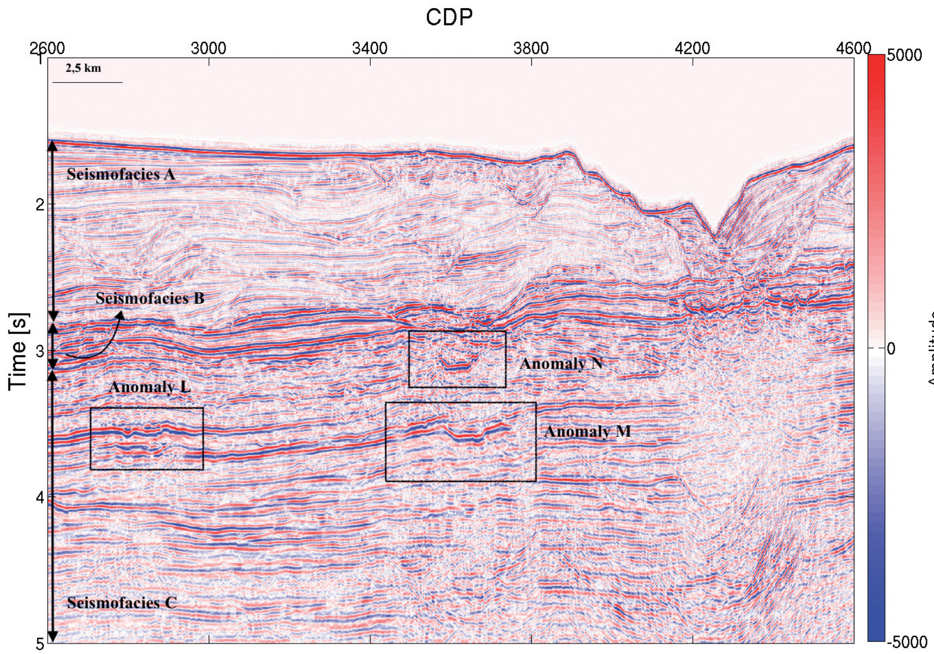

Fig. 3 – Reconstruction of the inline1560 through the sum of the coefficients of the chosen db2 scales. The limits between the seismofacies A, B, C and the localized amplitude anomalies L, M and N, related to the igneous bodies, are highlighted.

Finally, the CWT can be interpreted as a bank of band pass filters process, but it is more flexible than other time-frequency transform such as the Short Time Fourier Transform (STFT). Unlike the STFT, that uses a window with fixed width, the mother wavelet is dilated and translated in such a way to be designed to balance the resolution between time domain and frequency domain. Furthermore, the CWT is particularly useful to locate and identify signals with exotic spectral characteristics (Sadowsky, 1996).

As well as for the seismic attributes, a *line by line* CWT analysis is carried out.

The CWT is tested using three different mother wavelets: the Haar wavelet, the order 2 Daubechies wavelet (db2) and the Morlet wavelet (morl).

Although the best result was expected by the application of the Morlet wavelet, that is the commonly used wavelet, if the transform is aimed at improving the quality of the seismic section (Sadowsky, 1996), the db2 is adopted. As an example, the reconstruction of the inline 1560 through the sum of the coefficients of the chosen db2 scales is shown in Fig. 3.

The analysis shows that the anomalies related to the igneous bodies can be approximated in a frequency range from 20 up to 30 Hz. This is in agreement with the Instantaneous Frequency response. Furthermore, the application of the CWT is useful to discriminate the igneous bodies within the seismofacies B that are masked due to the presence of a chaotic facies.

Conclusions. The Senegal Basin is characterized by the presence of discordant low frequency high amplitude reflection anomalies that are interpreted as Miocene intrusive bodies (Rocchi *et al.*, 2007). This interpretation is supported by the data obtained from the on-shore survey of the Senegal area. The main result of this survey is the identification of magmatic activity ranges from Oligocene to Quaternary.

From the *line by line* analysis of the eighteen seismic lines results that the detected nineteen sills can be classified on the basis of their age, levels of emplacement and geometries. In particular, most of the sills develop within the seismofacies C at the first level of emplacement

(TWT >3.5 s). These anomalies show a flat inner saucer geometry, often bounded by an inclined sheet that crosscuts upwards the seismofacies C, and deform the overburden reflectors in a gently symmetrical antiformal fold.

The amplitude anomalies, which develop in the second level of emplacement (3.5 s < TWT < 2.7 s), show a concave-upwards saucer-shaped morphology and are characterized by the formation of two inclined sheets, often one steeper than the other. Moreover, some of these bodies show T- and F-shaped or antiformal morphology. At the third level (TWT <2.7 s), only two sills, developed within the seismofacies A, crosscut the seismo-stratigraphic reflectors, obliterate the underlying seismofacies B and deform the overlying reflectors as a structural dome.

Furthermore, by applying the seismic attributes, it is possible to better distinguish the sills based on the strong Reflection Strength and Sweetness response, which allow to isolate the seismic anomalies from the low amplitude background. Likewise, the Instantaneous Phase consents to distinguish, particularly within the seismofacies B, the seismic bodies characterized by a composite shape and masked in a chaotic facies. The Instantaneous Frequency is useful to differentiate the igneous bodies on the basis of the frequency values, always lower than the host-rock.

According to the seismic attributes, the results obtained by the application of the CWT permit to classify the anomalies as bodies with a frequency range of 25-30 Hz. Moreover, this tool permits to characterize the bodies based on their geometrical features and it is fundamental to compute thickness, lateral extent, emplacement depth, diameter-to-depth ratio and related-fold amplitude of the sills. Furthermore, from the obtained measurements it is possible to understand the relations between thickness and emplacement depth, to compare thickness and the related-fold amplitude and to compute the relationship between these parameters.

This work can supply new inputs improving the knowledge of the stratigraphy, of the geological setting and of the evolution of the investigated area. The achieved characterization of the igneous bodies can be of crucial importance for the hydrocarbon exploration. The presence of igneous intrusions in a petroleum system could cause important effects on the maturation of the source rocks, on the creation of structural and stratigraphic traps and, finally, could affect the oil migration pathway (Holford *et al.*, 2012; Thomson, 2007; Thomson *et al.*, 2008; Svensen *et al.*, 2006).

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