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Reservoir Analogues Characterization by Means of GPR

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SUMMARY

The study of hydrocarbon reservoir analogues is increasing important because often there is a gap between ultra high-resolution data obtained by well logs and the information extracted from reflection seismic data. Ground Penetrating Radar (GPR) can be applied to extend the knowledge attainable from outcrops and boreholes obtaining an improved stratigraphic, tectonic, structural, geomechanical and petrophysical characterization of rock masses that can be considered analogue to hydrocarbon reservoirs.
The primary objective of this work is to provide examples of GPR imaging and rock characterization helpful during exploration, exploitation and modelling of hydrocarbon reservoirs. We assess the GPR capability to identify rock layers related to sedimentary processes and features and to karstic/dissolution phenomena or tectonic processes, which can be often associated with higher porosity and permeability zones. Integrated velocity, attenuation and attribute analyses are discussed and validated with outcrops and rock samples data.

Introduction

The study of hydrocarbon reservoir analogues is increasing important because often there is a gap between ultra high-resolution data obtained by well logs only within available boreholes and the lower resolution information extracted from reflection seismic data. Ground Penetrating Radar (GPR) can be considered one of the most common geophysical methods for near surface investigation and can be applied to extend the knowledge attainable from outcrops and boreholes performing a stratigraphic, tectonic, structural, geomechanical and petrophysical characterization of rock masses that can be considered analogue to hydrocarbon reservoirs.
The primary objective of this work is to provide examples of GPR imaging and rock characterization helpful during exploration, exploitation and modelling of hydrocarbon reservoirs. We assess the GPR capability to identify rock layers related to sedimentary processes and to karstic/dissolution phenomena or tectonic processes, which can be often associated with higher porosity and permeability zones. Moreover, we provide examples of discontinuity network reconstruction and rock characterization using combined electromagnetic (EM) velocity and attenuation analyses and attributes calculations.

GPR velocity analysis

Usually, GPR surveys encompass only 2D single fold profiles, processed with basic and semiautomatic algorithms. An accurate subsurface imaging can be achieved only with multi-fold 2D and 3D dataset and dedicated processing flows.
Correct estimation of radar wave velocities is a crucial task to convert two-way traveltimes into real reflector depths and to properly migrate the radar wavefield. Moreover, the velocity of radar waves depends on the EM properties of materials and accurate estimates from GPR data can provide additional subsurface knowledge.
Single-fold GPR data allow only a very row velocity estimation using diffraction hyperbola (via direct fitting or migration velocity scans), while on multi-fold data much more accurate velocity analyses can be performed using several integrated techniques such as: reflection hyperbola fitting, semblance analysis, Constant Velocity Stack, Constant Velocity Gather, or Common Image Gather analysis, like in reflection seismic.
Figure-1 provides an example of results obtained with 250MHz antennas in an abandoned limestone quarry, where the carbonates are analogue to offshore reservoirs. The stack section (B), obtained from CMP having 1200% folding, shows higher signal-to-noise ratio and improved reflector continuity as compared with the near offset one (A). In figure-1C we plotted the stack section with the interval smoothed velocity field superimposed. It’s interesting to note that the velocity reconstruction is accurate enough to highlight the sub-horizontal high velocity levels related to karstic dissolution and a low velocity zone due to a fractured area.

Figure 1 *Single offset 250MHz GPR section (A); Stack section (1200% folding), (B); Stack section with the smoothed interval velocity field superimposed (C).*

GPR attenuation analysis

In order to integrate the velocity macro-model, we analyse GPR amplitudes to estimate the attenuation characteristics of the rock mass and therefore extract further information from the data.
For low-loss media the EM attenuation can be approximated as: $\alpha \cong \sigma_e / 2\sqrt{\mu_0 / \varepsilon_e}$ i.e. a frequency independent behaviour. This equation can be considered a good approximation even at the dispersive limit (Bradford, 2007) and is therefore reasonable over the GPR range.
The variation of intrinsic attenuation values with space and depth can be used to characterize the rock mass and to identify zones with similar materials and fluid content.
We measure the local maximum absolute value in a time window spanning the extension of the radar wavelet and centred at the reflector's location. We consider the absolute maximum of each trace as reference amplitude to calculate the mean attenuation (in dB/ns or dB/m) from surface to each reflector (further details about the procedure can be found in Forte and Pipan, 2008).
Figure-2 provides an example of attenuation analysis performed on selected traces of a 2D GPR section acquired on a reservoir analogue with abrupt lateral changes between limestone and dolomite. The obtained results (fig. 2B) show that dolomite has always attenuation higher than 0.8-1dB/ns decreasing with depth, while limestone has intrinsic attenuation almost constant with values close to 0.5dB/ns. The results are consistent with the dolomite content determined on selected samples taken at the same positions of the GPR amplitude analyses (Fig. 2C).

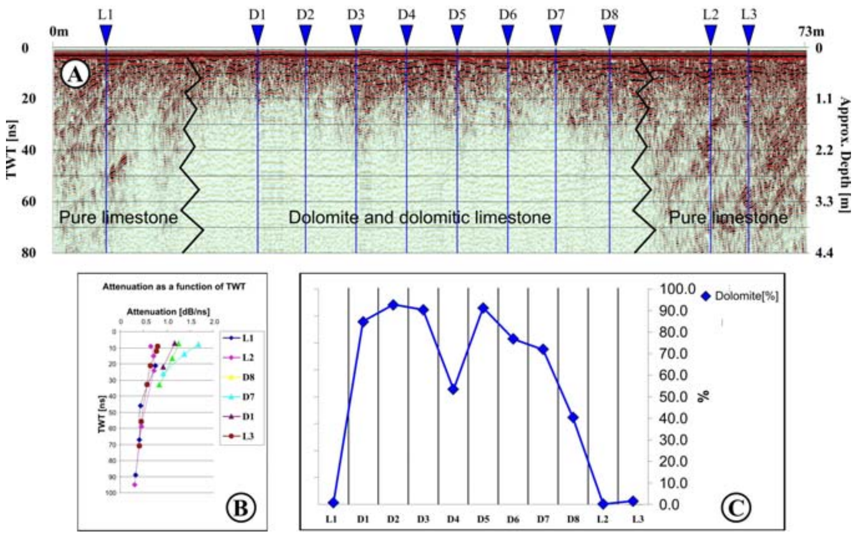

***Figure 2** GPR Attenuation analysis on selected traces (A and B). In (C) the dolomite content of samples taken at the same positions of amplitude analyses.*

GPR attributes

A promising technique, applicable without restrictions to GPR data, is the attribute analysis. The interpretation of GPR datasets is mostly based on subjective assessments of reflection-pattern characteristics (amplitude, phase continuity, shape), which are heavily dependent on the interpreter's expertise. Over the past few decades, similar issues in reflection seismic have been addressed by the introduction of the seismic attributes.
Several attributes analyses can be performed on 2D and 3D GPR dataset including instantaneous attributes, coherency measurements, spectral decomposition or other spectral related attributes and texture attributes, among the others. These techniques, well known on reflection seismic analysis, in recent years have been tested also on GPR data with the necessary adjustments (Corbeanu et al., 2002; McClymont et al., 2008; Forte et al., 2010). Figure-3 shows an interpreted 800MHz amplitude profile (A), and two calculated attributes (Dominant Frequency, B and cosine of instantaneous phase, C). It' s apparent that a detailed information extraction can be achieved only comparing and combining different attributes.

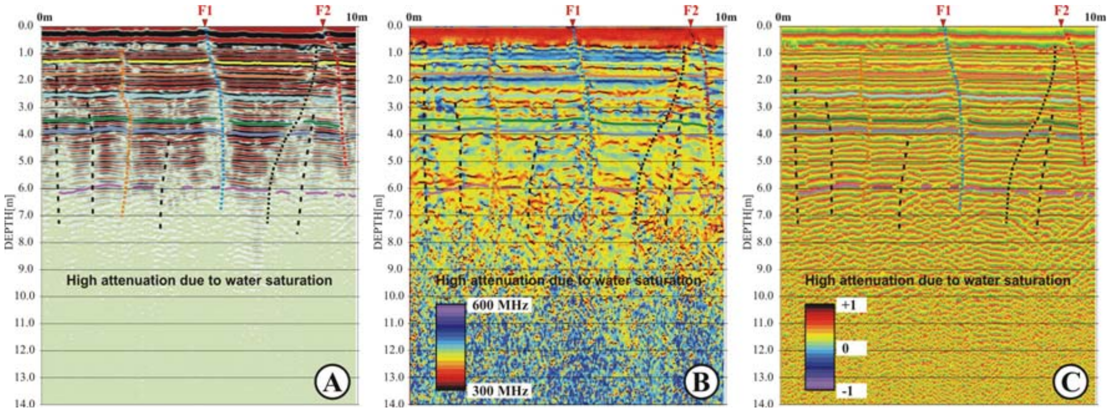

***Figure 3** 2D attributes examples: reflection amplitude (conventional data plot), (A); Dominant Frequency (B); Cosine of instantaneous phase (C).*

In Figure-4 there is an example of attributes based on 3D data volume: normalized energy gradient was calculated on selected inlines and crosslines (A). High values correspond to karstic horizons, which are clear on the outcropping face (B).

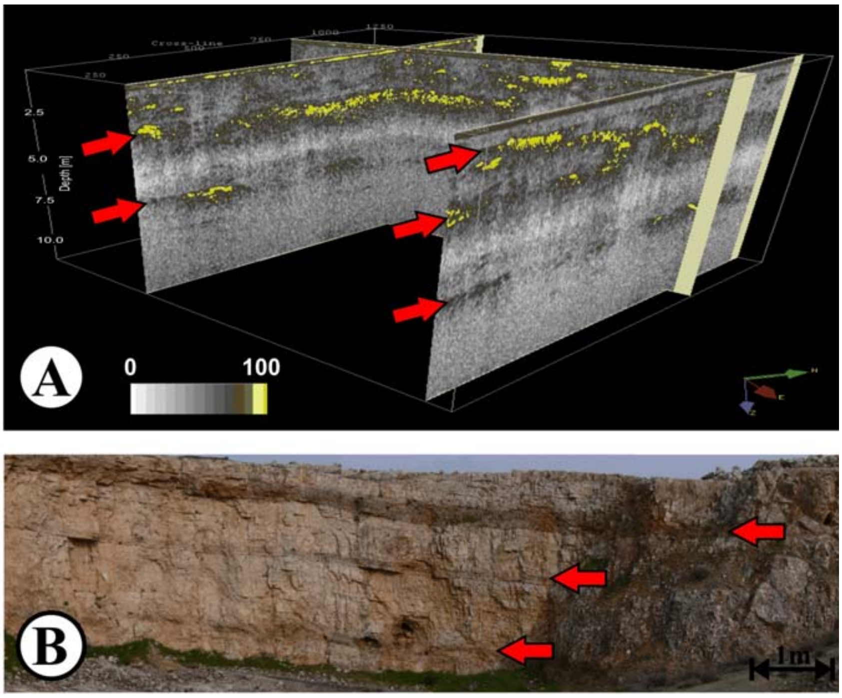

***Figure 4** Normalised energy gradient calculated on a 3D GPR volume (A) compared with the related outcrop photograph. Red arrows mark karstic levels.*

Using integrated attributes analyses it is possible not only better image subsurface features but also to highlight both stratigraphic and tectonic structures at cm-dm level, i.e. with a detail comparable to the one attainable from borehole data. Figure-5 gives an accurate subsurface reconstruction (B) extending the information extracted by the rock outcrop (A); small letters refer to zones having similar characteristics on quarry face and on interpreted GPR section.

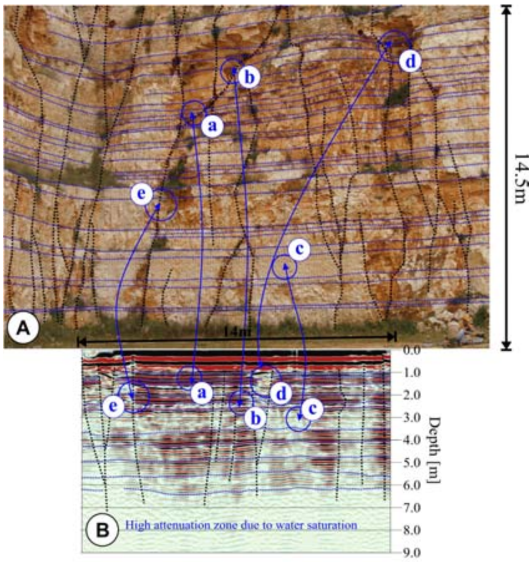

Figure 5 *Comparison and validation of GPR data interpretation (B) with quarry face mapping (A).*

Conclusions

This study tested the applicability of GPR techniques in the analysis of rock volumes, analogue to hydrocarbon onshore and offshore reservoirs. The information provided by integrated velocity and attenuation analyses on 2D sections allows a good correlation with stratigraphic, geomechanical and geochemical data. Instantaneous, trace and volumetric attributes can be successfully applied both on 2-D and 3-D GPR dataset to enhance the identification and characterization of lithological variations and to reconstruct the 3D discontinuity network.
GPR offers a unique high-resolution tool to extend the knowledge of rock masses obtained from exposed rock faces, outcrops and boreholes to 3-D volumes with a high level of accuracy. Such opportunity is of primary interest in the study of reservoir analogues and, in general, in the field of reservoir modelling and conceptual model implementation.

Acknowledgements

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