Increasing confidence in reef interpretation using dip angle gathers analysis

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Abstract

The uncertainty associated with the seismic interpretation of carbonate reef boundaries primarily relates to the generally limited difference between the velocities characterizing the reef body, and those of the encasing strata. In addition, the carbonate overburden section also generates strong multiple waves, whose physical characteristics are similar to those of the primary reflections, hindering the unequivocal identification of the latter. As a result, through conventional processing, it is often difficult to achieve a high signal-to-noise ratio and to confidently define the reef boundaries. Even employing industry-established, traditional seismic attributes a reef may just appear as a faint shadow or even not be visible. For a more confident interpretation of the reef we propose the adoption of an advanced methodology, based on analysis of dip angle gathers. Such an approach allows for a straightforward and reliable identification of the reef edges, reducing the uncertainties connected with their interpretation and possibly highlighting areas of different reservoir properties.

Introduction

The accurate interpretation of the reef boundaries affects the reliability of the reservoir volume calculations and consequently the confident estimation of the HC reserves, which drive the economic assessment for field development. Reliable reef mapping is also critical for optimal well planning. Moreover, information on karstified and fractured reservoir zones can help to reduce the technological risks related to drilling and to positively impact the well productivity. Finally, knowledge of the distribution of secondary porosity can be implemented into more robust 3D static/dynamic models of the prospect.

Traditionally, conventional pre-stack time or depth processing have provided the seismic volumes utilized in prospect delineation, in the localization of karst zones development and in the discrimination of areas with increased fracturing. One of the main outputs of conventional pre-stack time or depth migration are the migrated gathers in the reflection angle domain. Such migrated angle gathers are then stacked to obtain full or partial angle stacks, which are employed in structural/stratigraphic interpretation and in reservoir characterization. To increase the confidence in the mapping of horizons and faults, and in understanding other features of the subsurface, post-stack seismic attributes (e.g. instantaneous phase, frequency, dip, coherence, etc.) are also often calculated.

The just described approach proves, however, of limited effectiveness in relation to reef-like geological structures like the case history presented in this paper.

Noticeably, the most intense and continuous reflections are produced by horizontal smooth boundaries. Reflections from steeply-dipping interfaces, like the reef flanks, carry less energy and hence can be overlooked – as in the presented specific example.

Moreover, rough subsurface features such as karsts, vugs and fractures are generic sources of diffraction energy, which is significantly lower than those of reflected waves. Owing to this fact, diffraction and reflection events are not distinguishable in the reflection angle gathers domain. Therefore, even if diffractions encode relevant information relating to rough subsurface features, such as those typical of a reef environment, it is almost impossible to identify and separate them on seismic data after conventional migration techniques.

Different from the reflection angle gathers, the dip angle gathers contain seismic information as a function of geological dip. By utilizing these kinds of datasets one can effectively isolate the reflections and diffractions generated by interfaces with high-angle dips and horizons terminations, hence increasing the focus of steep structural geometries – like the reef flanks.

In addition, as shown by Reshef and Landa 2009 and Landa 2012, the responses from smooth continuous reflectors in the migrated dip angle domain are mapped as concave-shaped events, while the responses from diffractors/discontinuities display as quasi-linear ones. This kinematical difference allows for the efficient separation of diffractions from reflections, in dip angle gathers. Once isolated, diffractions can be analysed as a source of

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information related to karsts and to zones of increased cavernousity/fracturing.

For the case study presented here, the processing, post-processing and analysis of the dip angle gathers was performed on seismic data from an oil field located in the Russian Federation. The results achieved show the robustness of the proposed methodology.

Object of study

The target of the study is the Devonian organogenic build-up Livinsky formation of middle-late Frasnian age, located at a depth of ~2600 m. The prospect is defined by a narrow elongated barrier reef which shows up in seismic data as a distinctly pronounced relief, developing in an otherwise relatively flat stratigraphic succession. Figure 1 shows a conceptual geological model for the reef development and its seismic image after conventional seismic processing.

The oil reservoir succession is characterized by organogenic dolomites, clean from clay impurities, totalling an average gross thickness of about 150 m.

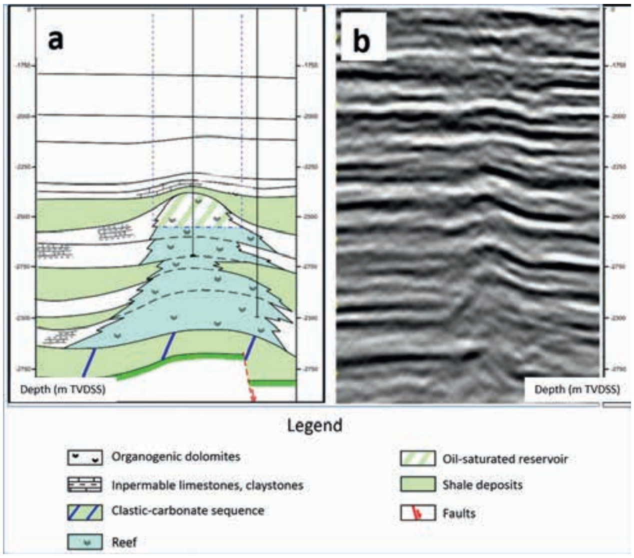

Figure 1 A conceptual development model of the reef (a) and its seismic image (b).

The reservoir is of type porous-fractured-cavernous: the permeable void space is represented by pores and caverns, interconnected by cracks.

Despite the field being already densely drilled, a higher detail in interpreting the ridge topmost part of the reef may add 25-30 m of pay. Especially crucial is the improvement in the interpretation detail and reliability over the reef flanks, which would help to extract residual oil reserves that were not produced by the wells of the ridge zone.

Conventional processing

3D seismic acquisition was carried out to delineate the reef body shape. The seismic processing was initially performed in time domain. To improve the seismic reflections focusing, positioning and continuity, an anisotropic pre-stack depth migration was also executed. For the depth migration purposes, an initial depth interval velocity model was built and subsequently refined through 3D tomography updates.

The quality and speed of velocity model building depend on the a priori available regional information and on the knowledge of the geological features of a particular study area. The velocity model was created in close co-operation with the customer's geological department, which has multi-year experience in the area. The selection and interpretation of the reference horizons employed in the velocity model building was hence carried out by specialists of Wolgodeminoil JV using all the available information, including the historical results from the data processing performed in previous years. The refined depth velocity model and the time-processed gathers were used as the initial data for the conventional pre-stack depth migration and seismic attribute computation.

Figure 2 shows horizontal slices of seismic amplitudes and post-stack attributes, extracted after the full sequence of traditional data processing and pre-stack migration. In the slice on the left, displaying seismic amplitudes, one can distinguish the approximate contour of a reef stretching over almost the entire area from the south-west to the north-east. From the adjacent slices it can be seen that post-stack seismic attributes (dip and coherence) only underline the reef contour.

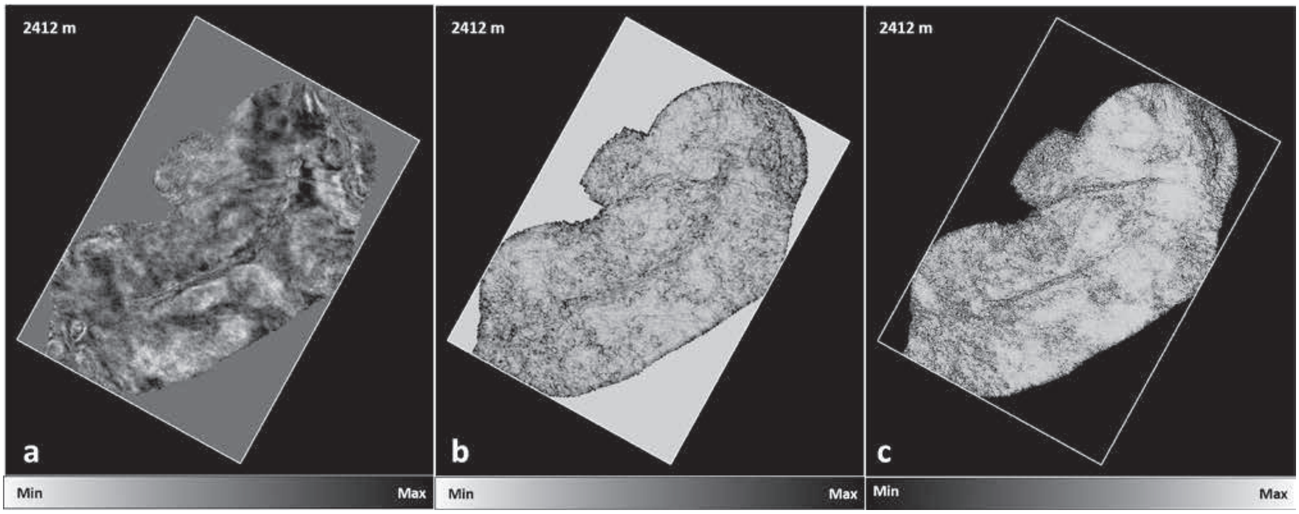

Figure 2 Amplitude (a), dip (b) and coherence (c) depth slices.

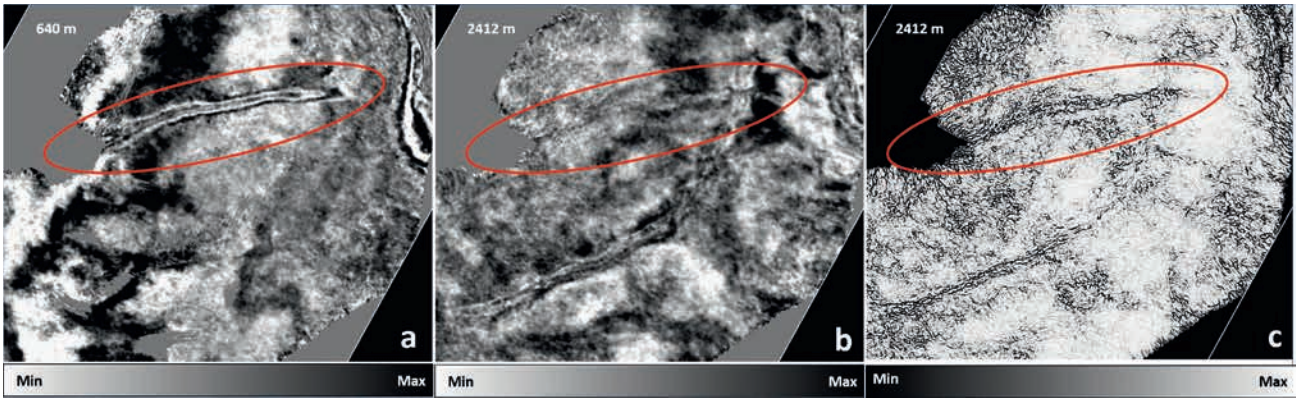

Figure 3 Amplitude depth slice in the shallow part (a); amplitude depth slice (b) and coherence depth slice (c) in the target interval.

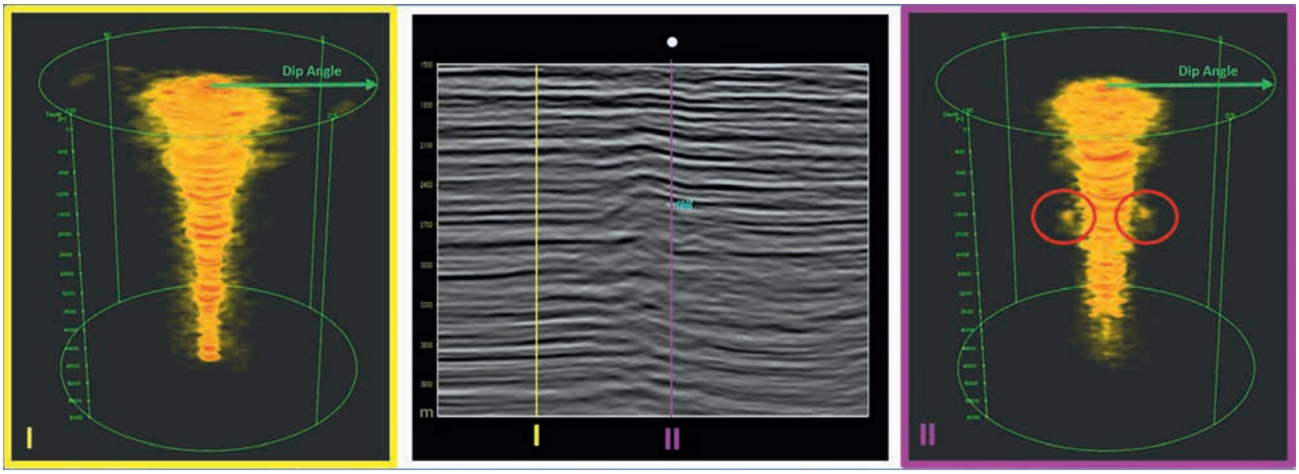

Figure 4 Two dip angle gathers and their locations on a conventional seismic section. The amplitude anomalies are distinguished at large dip angles on the right gather at a well location.

Traditional post-stack attributes should not be expected to add any new significant information to the amplitude seismic volume as they are derivatives of the latter. Furthermore, any distortion of the seismic waveform, present on the stacked amplitude data (not related to the geology), will generate anomalies in the traditional seismic attributes, complicating their interpretation.

In Figure 3c, highlighted by the red ellipse, one can see a coherence anomaly displayed at the target interval. It can be interpreted as a reef or for a fault area, but the results of drilling do not confirm either the one or the other. The investigation of shallower depths (slice in Figure 3a) shows the presence of a wide channel in the upper part of the section, confirmed by well data. Such a channel casts a seismic shadow and causes a change of the recorded waveform in the underlying reflections (Figure 3b). The purpose of post-stack attributes, such as coherence, is precisely the localization of this type of change; yet, like in the presented case, they may generate a non-geological anomaly that can be mistaken for a structural or stratigraphic element of the subsurface.

Dip angle gather calculation

To increase the quality of the seismic image at the target interval, the pre-stack depth migration and decomposition in the local angle domain was performed. This procedure obtains dip angle migrated gathers. Each trace in these gathers carries information about the energy of seismic waves associated with the normal to a local reflection surface or, in other words, about geological dips (Koren et al., 2007). Figure 4 depicts a conventional seismic section and two azimuthal dip angle gathers.

The gather to the left is located in a zone with a relatively flat bedding. The gather to the right is instead positioned at a well location which penetrated the reef slope. On the gather to the right, one can observe an increase in the intensity of the amplitudes at large dip angles. This increase in intensity can be caused both by reflection from the steep reef flank or by diffraction. The dip angle gathers can be used to meet two challenges: obtaining a clearer image of the reef flanks and localizing the inhomogeneities causing diffractions.

Refinement of the reef flanks

As described earlier, the reef flanks are characterized by higher dip angles compared to the enclosing stratigraphic succession. Therefore, in order to improve the image quality of such steep reef boundaries, it is necessary to enhance the reflection energy from large dips. In the dip angle domain this can be done in various ways. Tests have shown that, in this particular case, the optimal approach is through the internal muting of small dip angles. Stacking such dip-filtered dip angle gathers leads to a seismic image with a higher component of energy from large angles, thereby with an increased focus on the reef flanks. So, the dip angle processed volume creation consists of the two major steps. Firstly, the internal muting parameters are evaluated to efficiently suppress the reflection energy from small dips.

Secondly, the muted dip angle gathers are stacked to produce the filtered dip angle volume. Let us consider the following examples. Figure 4 presents a conventionally processed seismic section: the reef flanks are poorly imaged, yet still interpretable. Considering, however, another reef section, as in Figure 5a, the image quality is further reduced and the reef boundaries cannot be unequivocally defined. Figure 5b depicts the same section after processing of the dip angle gathers: the new image significantly helps to increase the confidence in the reef interpretation.

The right-hand column in Figure 6 shows horizontal slices of the volume obtained after the dip angle gather processing. It can be seen that a more distinct image of the reef boundaries has been achieved in comparison with the standard post-stack attributes.

It should also be noted that the new data, generated from the dip-filtered dip angle gathers, is much less sensitive to the distortions caused by irregularities in the overlaying section. Noticeably, the amplitude anomaly in the northern part of the survey, visible on conventionally processed seismic amplitudes and emphasized by coherence, is almost entirely removed after the proposed dip angle processing. Well evidence validates such a result, showing no elements within the target interval, which could generate the amplitude anomaly. Thus the adoption, within the established interpretation workflows, of the new seismic data obtained from dip angle processing, not only increases the confidence in identifying steep interfaces of even limited velocity contrast, such as the reef flanks, but it also reduces the risks of mapping seismic artifacts as subsurface elements. Figure 7 shows the detailed reef surface resulting from the interpretation of the new attribute.

Inhomogeneity detection

Low-amplitude faults, karsts, fracture zones and other small-scale geological features are often not detected or resolved on

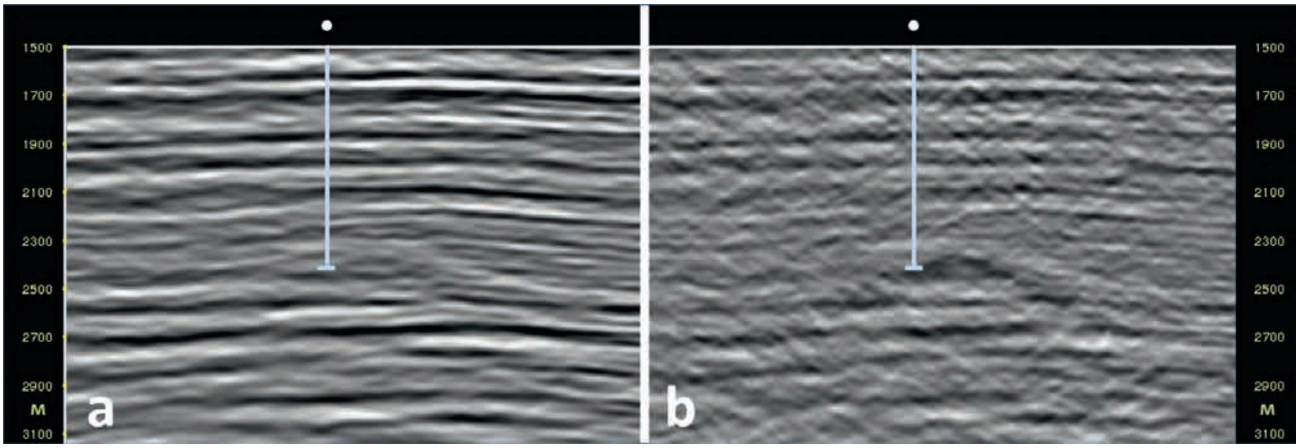

Figure 5 Conventional section (a) and the same section after processing of the dip angle gathers (b).

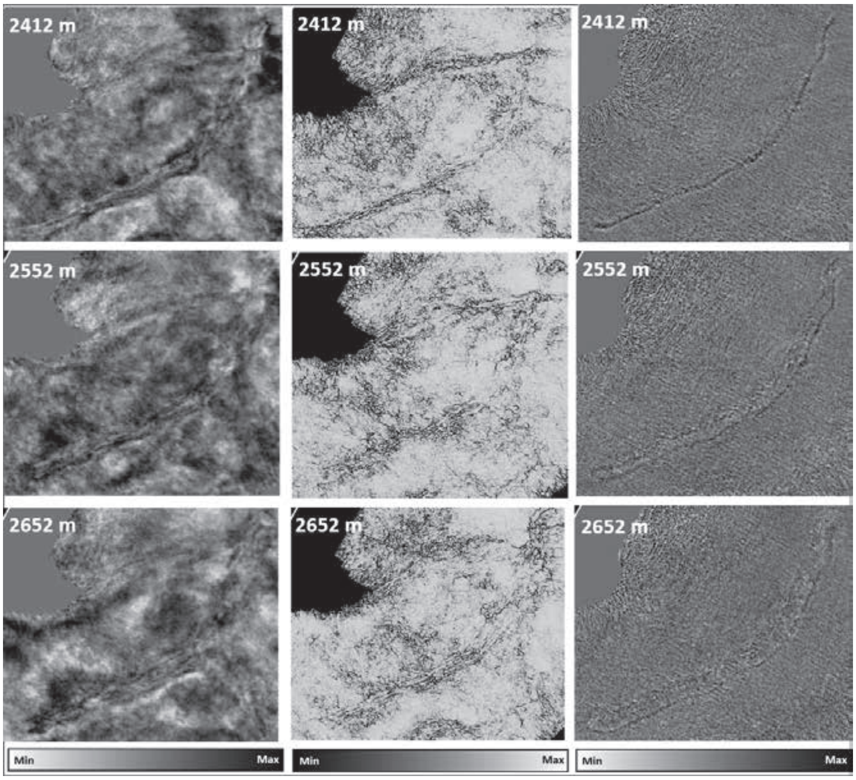

Figure 6 Horizontal slices at different depths. Left column: conventional amplitudes, middle column: conventional coherence, right column: amplitudes after processing of the dip angle gathers.

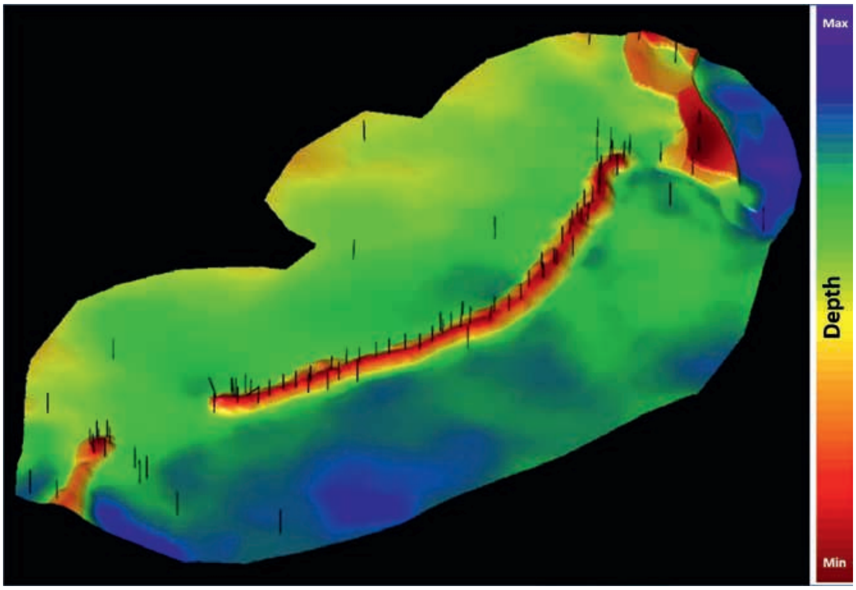

Figure 7 The reef surface resulting from the interpretation of the new seismic data obtained from dip angle processing.

conventional post-stack seismic attributes. These elements, and other objects causing sharp changes in physical properties, are generic sources of a diffraction energy and cause scattering of seismic waves in multiple directions. In a dip angle gather located at zero offset from a point diffractor, a diffraction event migrated with the correct velocity displays as flat (Reshef and Landa, 2009). After the dip muting applied to the dip angle gathers, the post-stack focusing of the diffraction wave (which has comparable amplitude for all dips) increases, returning higher amplitude intensity in the resulting dip angle processed trace. Under this perspective, high intensity areas within a dip angle processed volume can serve as diffraction indicators, i.e. they highlight abrupt changes in the subsurface physical properties. Figure 8a shows the distribution of the amplitude intensity along the reef, after the dip angle processing: warm colours mark zones of high amplitude intensity, i.e. diffractor indicators.

In order to increase the confidence in localizing these areas the dip angle processed volume was spectrally decomposed. Figure 8b illustrates the result of the spectral decomposition in RGB blending mode. In this new dip angle seismic attribute, diffractor indicators characterized by high intensity display a marked RGB glow.

Well data validation

Detailed well data analysis was carried out in order to better comprehend the geological factors giving rise to high intensity values in the new dip angle seismic attribute and to understand how to increase the field development efficiency, knowing the areal distribution of such factors.

According to core samples and well log data, the reef is characterized by fractured, cavernous and porous rock types. Analysis showed a distinct relationship between such lithotypes and the amplitude intensity in the spectrally decomposed, dip angle processed volume. In particular, there is a robust correspondence between higher percentages of cavernous-void rock type and the stronger amplitude intensity values of high frequency attribute obtained after spectral decomposition of dip angle processed volume. The cavernous-void lithotype is characterized by overall high porosity and by the presence of relevant cavities; as evidenced from the cores, the dimensional variance of the cavities is broad: from 0.1 cm to 0.1 m. (Figure 9a). In the case study area, high porous rocks (porosity > 10%) record the highest percentages of the cavernous-void tock type.

The percentage of porous-cavernous sediments was identified and the relationship with the seismic attributes was studied. In

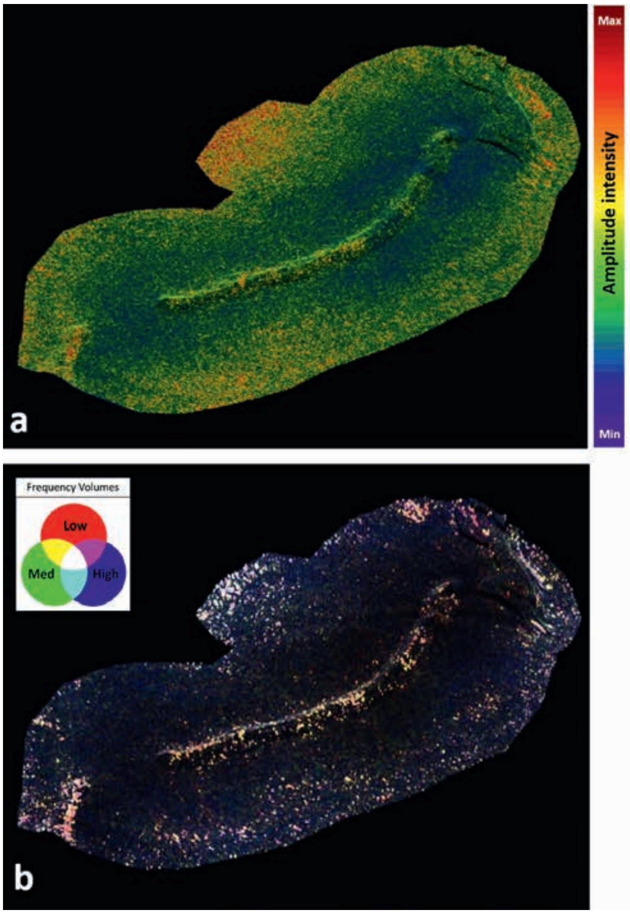

Figure 8 The dip angle processed volume intensity (a) and the spectral decomposition result (b).

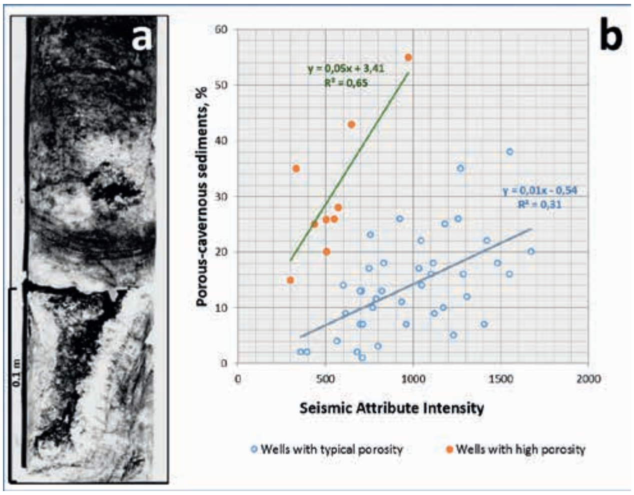

Figure 9 A core sample with a cavity (a) and the seismic vs. well data relationship (b).

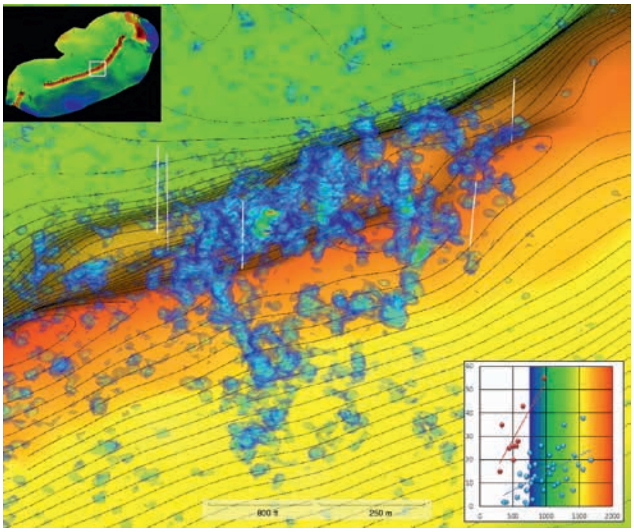

Figure 10 The distribution of high amplitude intensity of the spectrally decomposed dip angle processed volume.

the analysis, the wells were divided into two groups: the main group reported a typical average porosity from the target reservoir (7.7%), while a separate smaller group recorded higher average porosity values (9.5%). The relationship between the intensity of the high frequency part of the decomposed dip angle processed volume and the percentage of cavernous-void sediments for both groups is shown in Figure 9b.

Based on the joint analysis of seismic and well data, it can be concluded that the high intensity areas in the dip angle seismic attribute are related to zones of rock deconsolidation. This deconsolidation is associated with an increased percentage of high-porosity intervals, determined by cavities and karst development. The presence of karsts is also confirmed by the increased borehole diameter (up to 50 cm) and by porosity values reaching 24% or more. Drilling activities through the deconsolidating intervals incurred in technical difficulties, e.g. mud loss and tool failure. As a result, the complex drilling conditions negatively impacted the logging quality, the accuracy and precision of log interpretation and the robustness of the seismic well data relationship.

Figure 10 shows a fragment of intensity distribution within the reef body, extracted from the dip angle seismic attribute. The low intensity values are rendered transparent.

The warm, bright anomalies in Figure 10 represent high values of the dip angle attribute intensity and, according to the crossplot, they reference high values of well data of the main group. Consequently, it can be inferred that they can be caused by an increased matrix porosity. Cool blue colours code high values of the attribute intensity for wells in the high-porosity smaller group (and the average values for wells in the main group). Therefore, they likely correspond to rock deconsolidation areas owing to caverns and cracks and represent ideal targets for placement of new wells. However, one must be prepared for possible drilling complications as a result of the increased chance of karst development.

The relationship shown in Figure 9b, also provides the prerequisites for differentiating the geological model for the various types of void space. This will enable a more accurate prediction of the reservoir properties in the inter-well space, which is important for correct assessment of reserves, optimal field development and effective reservoir stimulation.

Conclusion

New independent seismic attributes based on the dip angle gather processing allow increased confidence in reef mapping and identification of zones of different rock type. Furthermore, the new attributes are less sensitive to the physical anomalies in the upper part of the section. It is important to note that the new attributes were obtained by the decomposition of conventional seismic data, which are available to all oil and gas companies, i.e. no ‘special’ field data is required. The authors believe that the described technology, in conjunction with traditional techniques, can significantly improve the speed and accuracy of reef interpretation.

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