3D-seismic patterns associated to faults and natural fractures within complex reservoirs: cases in the Tithonian/Valanginian stratigraphic sequence in Neuquén Basin

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Abstract

In recent years the importance of complex reservoirs for the oil industry grew strongly and pointed to new trends of its world economy. A great deal of complex reservoirs have similar types and configurations of structural heterogeneities: fractures with high-angle to bedding, faults, bed-parallel fractures, early compacted fractures, and fractures associated with concretions.

The understanding from seismic data of structural heterogeneities in these reservoirs, basically faults and fractures, can be a powerful source of optimized geoscientific information. Many fractures within complex reservoirs are in sub-seismic scales and they commonly build very heterogeneous networks. For those networks, conventional 3D seismic data can provide essential information regarding larger faults, but they normally don't provide information about smaller-scale fractures.

Usually, many basic mathematical algorithms are applied to seismic data trying to detect heterogeneities and enhance seismic patterns to be minimally correlated to geological conceptual behaviors expected for deformations into complex lithologies when subjected to tectonic stresses.

The performance of any seismic algorithm used to define structural heterogeneities in complex reservoirs will depend not only on the quality of the seismic data itself (signal/noise ratio, the quality of its imaging and optimal placement of structural events), but fundamentally of the capacity of the seismic data contain and show details (resolution and characteristics of seismic acquisition) of reflection events consistently related with the structural geology. Traditionally, patterns of seismic structural events obtained from conventional data have been described through from the use of some volumetric attributes like curvature and its derivatives.

The objective of this work is to analyze and compare discontinuities extracted by seismic automatic detection methods from conventional amplitudes, and from geometric and instantaneous attributes, to define high-angle to bedding heterogeneities stratabound and non-stratabound within complex reservoirs. To illustrate the results, it was selected an geographic area located in the Neuquén Basin, Argentina, and was used a conventional 3D post-stack seismic data, with adopting an analysis time window correlated to a stratigraphic cross section corresponding to a part of the Mendoza Group, which contains all different kind of complex reservoirs here presented.

Were analyzed seismic heterogeneities characterized by modeled surfaces with dip angles between 60^o and 90^o (high-angle to bedding). Seismic heterogeneities were studied for three different seismic data scenarios: the first involves heterogeneities obtained from primary amplitudes of a pre-stack Kirchhoff time migration; for the second scenario, the heterogeneities were derived using the same seismic data but applying special post-stack processing to optimize the wavelet resolution. In the third scenario, heterogeneities were modeled from geometric instantaneous attributes derived from the same migrated amplitudes.

For each seismic data scenario were defined three different geological cases for description and understanding the geometry of the heterogeneities that traverse complex reservoirs deposited inside a certain heterogeneous sedimentary sequence: a case for major heterogeneities that traverse all the studied strata, focused window inclusive, and two cases to understand smaller heterogeneities that occur limited to the focused window in Mendoza Group stratigraphic sequence which includes the complex reservoirs. The first case was selected to describe a set of high-angle to bedding structural heterogeneities non-bounded by strata, joining the sequence of studied complex reservoirs and all layers below and above them. Those are heterogeneities which have origin at large depths involving the basement (from the thick basal section - thick skin) crossing all the sedimentary sequence, including the strata which contains complex reservoirs. For the other two cases were modeled analytical conditions to detect high-angle structural heterogeneities bounded by the strata which contains the complex reservoirs: one to help analysis of structural heterogeneities bounded by the whole stratigraphic sequence which contains the complex reservoir and, the last one, for smaller scale analysis of heterogeneities bounded by layers that individualize the complex reservoirs.

Importantly, this work does not discuss the origins, causes or fit of tectonic strain which have generated the seismic discontinuities detected and interpreted as high-angle structural heterogeneities, intending merely to show the capacity of the seismic data differentiate geometries of coherent and consistent structural events, to better understand the behavior of the structural events that affect the studied complex reservoirs. It is shown that conventional 3D seismic data acquired for studies of complex reservoirs can differentiate types of structural heterogeneities, not only those non-stratabound, but mainly those bound by the strata defined by isolated layers and spatially limited by the intricate distribution of

existent fractures. The results suggest the importance of one working with conventional seismic data, under different scenarios of heterogeneities detection, relating them to geological structures. Results that allow the understanding, the classification and the support to economic analysis of the exploration viability in complex reservoirs. In this sense, 3D conventional seismic data have proven to be a powerful tool for geoscientific analysis of complex reservoirs, being able to suggest how is the result of the action of different tectonic stresses - regional and local, helping future exploration and analysis of possible reservoir stimulation by fracturing

Introduction

The importance of complex reservoirs for the oil and gas industry has grown in function of new trends of world economy. In the literature and industry, there are many and different classifications for complex reservoirs. Complex reservoirs are considered here as a class of reservoirs in which fault arrays and natural fracture networks, have strong control on production behavior, and also is associated to current operational difficulty for such production, due to their very low permeability. This class includes shale gas, shale oil and tight sands, associated to matrix with very low permeability, and which typically need some stimulation, usually hydraulic fracturing, to increase their permeabilities and keep good productivities (Engelder et al, 2009). The understanding of structural heterogeneities in these reservoirs, basically faults and fractures, from seismic data can be a powerful source of geoscientific information.

The study area is located in the Neuquén Basin, Argentina and the studied seismic data window is correlated to a stratigraphic section within the Mendoza Group from Late Jurassic to Early Cretaceous. This section corresponds, in the basin evolution, to SAG phase between two unconformities - Intramalmic and Intravalangian (Sigismondi, 2012) and contains all different kind of complex reservoirs here studied. Plays for these reservoirs are linked to the production by concepts of hydraulic stimulation. Spatial comprehension of the distribution and patterns of natural fractures and faults, besides their roles as permeability networks, is essential to good performance of their production (Gale et al, 2014). Thence, 3D seismic data has increased its importance for complex reservoirs, helping in getting enhancements in their productivities around the world.

For these reservoirs, patterns of seismic structural events are generally obtained by using volumetric attributes like curvature and its derivatives (Chopra & Marfurt, 2015). Here we present a work using amplitude, simple geometric attributes and instantaneous attributes to detect structural patterns which can be associated to different geometries of geological faults and fractures in complex reservoirs.

Such attributes were selected to analyze a set of high-angle structural stratabound and non-stratabound heterogeneities (Casini et al, 2011) for complex reservoirs. There were observed heterogeneities which have origin at large depths involving the basement (from the thick basal section - thick skin) crossing all the sedimentary sequence, including the strata which contain complex reservoirs. There were also verified high-angle structural heterogeneities bounded by the sedimentary strata which contain the complex reservoirs in two more cases: structural heterogeneities bounded by the whole 3rd order stratigraphic sequence which contains the complex reservoir and heterogeneities bounded by layers that uniquely individualize the complex reservoirs, 4th order stratigraphic sequence heterogeneities.

Methods

Whenever we think of methods of seismic automatic detection of structural heterogeneities, we should include the different data inputs associated to traditional and modern techniques for calculation of geometric and volumetric attributes, looking for enhancement of visual perception, through results of structural alignments that would not be easily observed in raw data of conventional migration amplitudes. In this sense, here we introduce three different methods to detect and identify structural heterogeneities in complex reservoirs. The first one, here called Conventional Amplitude Method, is the most simple and is based on amplitude samples from conventional migration data, which are suitable to understand regional discontinuities with large dimensions. The second method here introduced, is based in a natural perception that if one wants to increase the spatial resolution of seismic heterogeneities perceived in 3D data, some processes should be applied (even in the post-stack data), to correct and stabilize the waveforms, using wave shape processes that modify the whole form of final seismic trace. After it, may be possible to observe phase variations which bring optimizations in the spatial resolution of high-angle heterogeneities with consequent differences in the spatial continuities. All of this increases the possibility for detection of structurally coherent events in the space, to identify heterogeneities that could be stratabound, target of the second method for seismic heterogeneities detection here presented. This second method is named here as Sharp Wavelet Method.

The third method here introduced for study of high-angle discontinuities has its fundaments in the Fourier analysis, to define spectrum of real signals with a complex symmetry. For such signals, the negative part of the spectrum contains redundant information with respect to the positive part, and is defined as a complex signal (or analytical) one that is formed after removing the negative part of the real continuous signal spectrum. The definition of a complex signal which maintains the characteristics of the actual signal is very advantageous for the derivation of useful concepts for seismic heterogeneity detection, like the application of instantaneous phase for three adjacent traces. Taner et al (1979) were the first to formulate seismic attributes using parabolic curve to laterally fit the phase values, adjusted according to the analyzed seismic trace window. For 3D data sets, phase dips (arrays of in-line and cross-lines) are computed and the value at the central trace is computed and applied in the interpretation of seismic heterogeneities. This third method is here treated as Intra-Layer Method and should be applied strictly to cases of stratabound heterogeneities

Below, are some processing steps applied for seismic data conditioning, applied to the three methods mentioned before.

▪ Normalization of post-stack amplitudes and phases, for detection and identification of multi-volume discontinuities.

▪ Noise attenuation
▪ Definition of seismic attributes favoring the interpretation of layer deposition processes to define stratabound and non-stratabound high-angle heterogeneities.
▪ Correlation of attributes observed from the different seismic methods described above, defining structural textures correlated with high-angle heterogeneities.

With these steps, appropriate seismic textures have been enhanced for the investigation of high-angle heterogeneities patterns in complex reservoirs which were here done by a technique for automatic extraction of seismic discontinuity surfaces described by Randen et al (2001), which is able to transform structure of heterogeneities into continuous surfaces.

Results

Results obtained from discontinuity automatic detection applied to seismic heterogeneities to high-angle to bedding in complex reservoirs, such as tight sands, shale gas and shale oil, show that such heterogeneities can be well defined from conventional seismic data. As illustrations, some figures show a comparison between the methods described here in a shale gas region. Figure 1 shows a main TWT window of migrated amplitude data (PSTM Kirchhoff) with length of 5s. On such amplitudes was applied Conventional Amplitude Method that was able to clearly define three of major structural segments groups with high-angle to bedding: a first group, non-stratabound and with higher concentration of events, has dominant azimuth NNW and dipping 70^o NE (red arrows). This group of segments traverses the entire main window of studied seismic data, from the most basal layers going to the superior stratigraphic sections, maintaining the same structural behavior, including the equivalent region of Mendoza Group. Similarly, a second group with a lower concentration of events, also non-stratabound, cuts across the main data window with dominant direction NNE dipping 75^o NW (blue arrows) and are interconnected with the previous group of NNW heterogeneities in the bottom leftmost region (traced closed-line). Note that there are very few occurrences in the bottom rightmost portion of the window (dotted closed line), indicating more isolated heterogeneities. Finally, a third group of heterogeneities is marked, with the least concentration of events, with azimuth WE and dipping around 80/85^o alternating to N and to S (green arrows), with uneven spatial distribution. In Figure 1, a secondary window is superimposed, with TWT between 700ms and 2000ms, showing migrated amplitudes which include the complex reservoirs here analyzed between two unconformities: Intramalmic and Intravalangian. This secondary window is also used to compare differences between the detection methods here introduced.
For the application of Sharp Wavelet Method we adopted the seismic time-processing concept of seismic elementary-layer, or rock layer (Bulhões & Amorim, 2005), which defines the smallest thickness that a seismic data can be time-resolved. This thickness is defined as the critical point to calculate and obtain the seismic data with the technique of Volume Amplitudes (TecVa®) and is intrinsically related to the concept of Fresnel zone. In Figure 2, the main window with the result of Conventional Amplitude Method is the same shown in the Figure 1, but now, it is superimposed by a secondary window with the result of the Sharp Wavelet Method, standing out heterogeneities towards NNW with dip around 60^o NE (black arrows), that can be classified as isolated stratabound heterogeneities. In the left part of the secondary window, is lightly suggested a vertical corridor of heterogeneities. Finally in Figure 3, perhaps the most significant result showing a differentiation of dominant detected events (brown window), from those previously illustrated in Figures 1 and 2. Noteworthy is the Intra-Layer Method, which distinguishes high-angle heterogeneities events, dipping about 90^o (white arrows), and which highlight the presence of stratabound heterogeneities limited by the thinnest layers that the conventional seismic here used can resolve. Note also the discrepant dips of the dominant events related to the others shown in the main window. Emphasis is done for a corridor of vertical heterogeneities on the left region of the brown window.

Conclusions

Heterogeneities in complex reservoirs are sometimes very difficult to be differentiated. The distinction of discontinuities associated with faults and fractures when suggested by conventional 3D seismic, adds great value to the information in building models of spatial heterogeneities. Distinguish between stratabound or non-stratabound heterogeneities, and differentiate the distribution of isolated and interconnected structural events, are key tasks for production of hydrocarbons from complex reservoirs, mainly those using fracturing stimulation to generate artificial permeabilities. Examples using conventional 3D seismic data from Neuquén Basin have shown that the analysis of such data is important to add descriptive information about the spatial distribution and characteristics of structural heterogeneities which may be strongly possible, mainly related to natural fractures. Three methods for seismic detection of high-angle to bedding heterogeneities are presented here, that enhance the use of conventional seismic data for understanding and generation of more consistent models of natural fractures.

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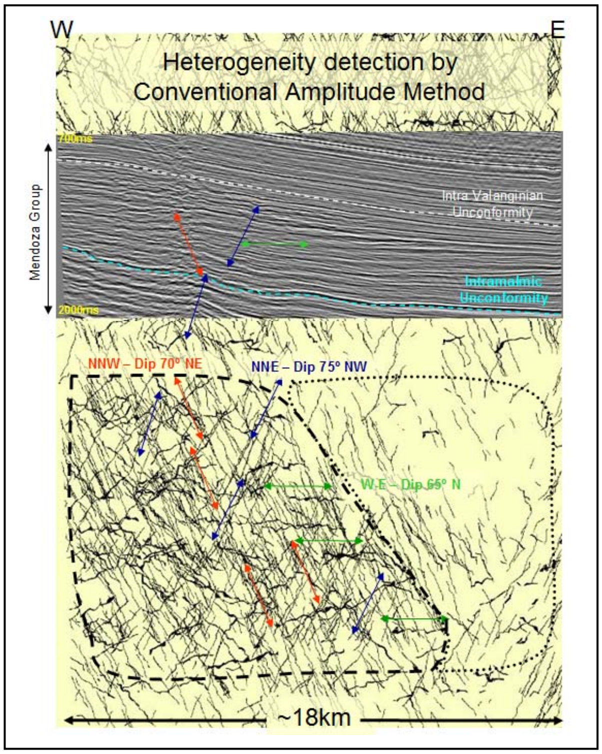

Figure 1. Main TWT window (5s lenght) of migrated amplitude data. On such amplitudes was applied Conventional Amplitude Method to detect major structural heterogeneities. It was possible to define three major structural segments groups with high-angle to bedding. A first group, non-stratabound and with higher concentration of events, have dominant azimuth NNW (red arrows) and dipping 70º NE. This group traverses the entire main window of studied seismic data maintaining the same structural behavior. Similarly, a second group with a lower concentration of events and also non-stratabound, traverses the main data window and has dominant NNE direction dipping 75º NW (blue arrows). It is interconnected with the previous group of NNW heterogeneities. A third group of heterogeneities is identified, with the least concentration of events in the window and azimuth WE dipping around 80/85º alternating to N and S (green arrows), with uneven spatial distribution. A secondary window is superimposed with TWT between 700ms and 2000ms, showing migrated amplitudes which include the complex reservoirs, here analyzed between the Intramalmic and Intravalangian unconformities. This secondary window is also used to compare differences between the detection methods here introduced.

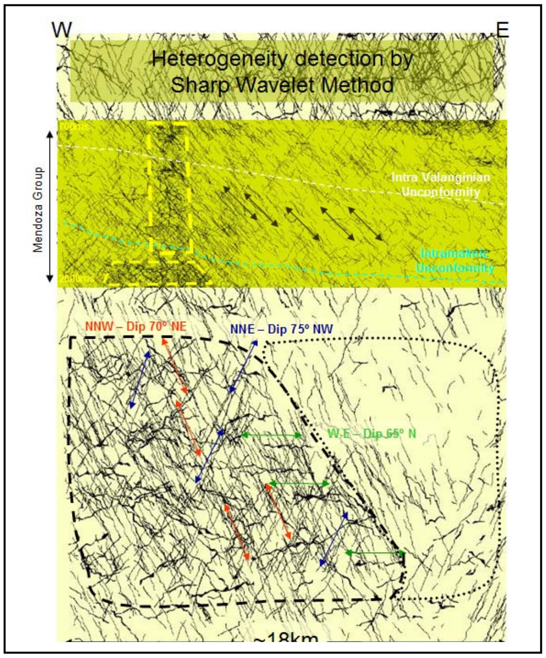

Figure 2. The lower main window is repeated with the result of Conventional Amplitude Method already shown in Figure 1, but now it is superimposed by a secondary window (mustard) with the result of the Sharp Wavelet Method, standing out heterogeneities towards NNW with dipping about 60^{o} NE (black arrows), here classified as isolated stratabound heterogeneities. On the left part of the secondary window, lightly appear vertical and horizontal corridors of heterogeneities (yellow traced line).

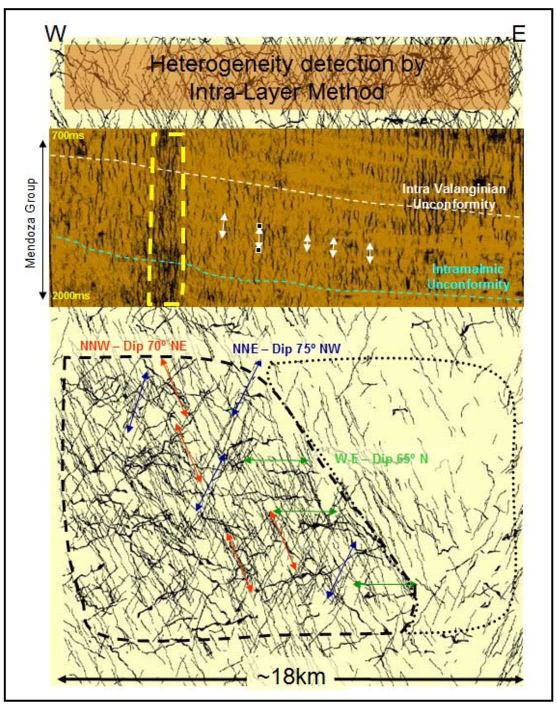

Figure 3. The most significant result, shows a differentiation of the dominant detected events (brown window), from those previously illustrated in Figures 1 and 2. Here, the Intra-Layer Method distinguishes high-angle heterogeneities events, dipping about 90^{o}, and which highlights the presence of stratabound heterogeneities limited by the thinnest layers that studied conventional seismic can resolve. Dominant events have discrepant dips (white arrows) related to the others shown in the main window. Emphasis is done for a strong corridor of vertical heterogeneities on the left region of the brown window.