Analysis of 4D seismic timeshifts overburden and its relationship with the geomechanical model of reservoirs in a Campos Basin field.

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Abstract

This work seeks to interpret the 4D seismic timeshifts in the overburden of a conventional turbidite sandstone reservoir in the Campos Basin and to calculate an empirical factor of sensitivity between these 4D data and the geomechanical deformations. Gaining information on how the production of the reservoir affects the surrounding rocks is of great interest for the management of oil fields, with impacts ranging from optimization of production to the safety of operations and workers. Anomalies studies of 4D timeshifts are more common in chalk-like fields and unconventional fields of high temperature or pressure, where large deformations are perceived in overburden rocks, different from the characteristics of the field studied in this work. From the geomechanical simulations and 4D seismic data, results are compared and explanations are extracted to support the final interpretations. Two techniques for timeshift calculations are used, cross-correlation and Dynamic Time Warping, as well as structural attributes that are calculated to assist in interpretations where the structural of the area indicates possible influence. Then, a sensitivity factor that relates variations of seismic velocities and geomechanical deformations is calculated by a statistical estimation, allowing the construction of synthetic 4D timeshifts from the deformations simulated by the geomechanical model. Even with discrete timeshift values, in most of the field regions there was agreement between simulated deformations and 4D anomalies, showing that it is possible to extract useful information for reservoir management. The estimate of the sensitivity factor indicates that the overburden studied is sensitive to deformations in the rocks, allowing that small deformations can be detected by the given 4D seismic.

Introduction

The seismic method of reflection is extensively used for the investigation and studies of the terrestrial subsurface, being very used in the research of oil reservoirs. Mechanical waves propagating through the medium are emitted by artificial sources, reflecting in the layers and returning to the surface. The 4D seismic is given by seismic data acquired at different times in the same area processed to highlight aspects that have varied during this time interval. The difference in seismic wave traffic between two 3D seismic data acquired on different dates, ie the 4D seismic timeshift, is an effect caused by the difference in velocities caused by field production effects. From the study of possible causes of these timeshifts, a new field of research was opened linking 4D seismic and reservoir geomechanics.

All producing reservoirs undergoing pressure drop are expected to compact to some degree. The strength of reservoir compaction depends on the degree of reservoir depletion, reservoir strength and surrounding rocks. The rock layer overlying the reservoir is called an overburden. In this region the redistribution of tensions caused by the production of the reservoir causes deformations in the rocks and changes in the seismic velocities, thus allowing the detection of geomechanical effects through the seismic method of reflection. Since the thickness of the overburden usually varies from one to several kilometers, even small changes of velocity, less than one percent, can accumulate at detectable timeshifts near the top of the reservoir (T. Roste et al., 2015). Stress changes in overburden rocks can lead to shifts, fractures and reactivation of faults, ranging from less critical stress changes, inducing small-scale vertical displacements (millimeters to centimeters), to more severe stress changes, inducing fractures and reactivation (Alces et al., 2002; Barkved et al., 2003). Examples in the North Sea, in some chalk-type reservoirs, can compress more than ten meters during field production, inducing significant changes with great impact on well management (Macbeth et al., 2018).

Geomechanical simulations may explain changes in seismic wave transit time in 4D seismic data due to the effects of reservoir production (Stammeijer, 2004, Hatchell et al., 2005, Herwanger, 2013). Other effects that may be related to 4D timeshift, such as subsidence (Fiore et al., 2014) and variation in pore pressure in layers above the reservoir (Garcia and Macbeth, 2013), are related to geomechanical effects. In addition, these effects may show some significant complexities depending on the geometry (Dussault et al., 2007) or overburden lithology (Wong and Macbeth, 2016).

Detailed analysis of the timeshift in the overburden region is highly useful for field management. Considering that the seismic monitoring of the reservoir is normally used to map the remaining reserves, the overburden study can help avoid situations of risk to workers' health, safety and environmental tragedies, as well as drilling problems. Leakage of hydrocarbons, other wastes in seawater, or oil spills in deep waters represent some cases with high potential for environmental and economic impact.

For fields with normal pressure and temperature sandstone reservoirs, overburden timeshifts are less expected as reservoir rocks are less comparing to chalk type reservoirs. For this reason, timeshifts in conventional sandstone reservoirs have little interest in research. Among the examples found in the literature, the interpretation of the Snorre, Heidrun and Statfjord sandstone fields by T. Roste et al. (2017) shows the potential of this analysis in such reservoirs. Although compacting sandstone reservoirs is generally small (centimeters) and often not a problem for well drilling, it is important to obtain and understand all timeshifts in the overburden to separate pressure effects from saturation effects within the reservoir and discriminate the geomechanical effects of other phenomena.

The objective of this work is to describe and understand the relationship between 4D seismic and geomechanics in the overburden and to explain the timeshifts observed in the overburden of a turbidite field in the Campos Basin, performing a flow of steps to estimate a factor R (empirical factor of sensitivity of the rock and relation to deformation) that relates vertical deformations estimated by the geomechanical model and variations in the seismic velocities, thus allowing to model the timeshift from a geomechanical model and confronting it with real timeshifts. Therefore, we seek to evaluate the geomechanical model of the field and facilitate the understanding of the relations of future events resulting from the production observed in 4D seismic. A good correlation between timeshifts modeled and observed in some areas of the field indicates that the signal in the overburden is real and is caused by geomechanical changes, while a weak correspondence indicates that the observed timeshifts are related to non-geomechanical effects. The analysis is restricted to overburden and mainly relating geomechanical and 4D seismic. Non-geomechanical explanations of timeshifts are quoted but are not described in detail.

Method

The main cause of anomalies of timeshifts in the overburden is the variation of the pressure in the reservoir. As previously discussed, the pressure variation causes geomechanical effects that deform the rocks of the reservoir and, consequently, the rocks around it. Based on this information, we will first analyze the pressure variation in the field of study between the periods of the 1997, 2005 and 2010 seismic surveys (see figure 1). The delta pressure data is provided by the flow simulator and aims to adjust the field pressure from measurements pressure during the implementation of wells and the mass balance in the reservoir, honoring the maximum production history. These data are of extreme importance for geomechanical simulation and cover the entire field life from the first oil to the end of its life.

In the pressure variation map between 1997 and 2005, we can divide it into three groups. To the north of the field we have a depletion, to the center an overpressure and to the south we have a drop of pressure again, only that with greater intensity than the anomaly of the north region.

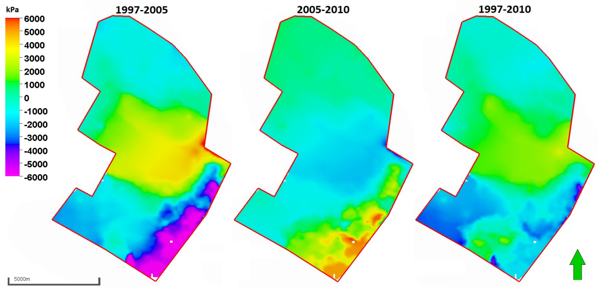

***Figure 1*:** Pressure variation in reservoir on 4D dates.

There is a lithological barrier between the central zone and the zone to the south that does not prevent the hydraulic connection between the zones, but does not behave as a full connection. Between the north and central zones there is no defined lithological barrier, but there was a management of the injection wells and producers that resulted in a very positive balance for the injection in the central zone due to unexpected in producing wells. In the pressure variation map between 2005 and 2010, it can be divided into two groups with small variations. To the north of the field we have an overpressure, to the center and to the south a pressure drop. At that date, due to the small pressure variation, both upwards and downwards, no large geomechanical deformations or significant timeshifts values are expected in much of the reservoir. On the pressure variation map between 1997 and 2010, ie a cumulative two variations noted above. We can also divide it into three groups, similar to those in the 1997-2005 range. To the north of the field we have a depletion, an overpressure in the center, attenuated by the depletion between 2005 and 2010, and to the south we have a drop in pressure. At that date, as in the period between 1997 and 2005, the southern region of the field presents greater chances than the period between 2005 and 2010 to present significant timeshift anomalies in the 4D seismic.

In practice, any pressure variation causes deformations in the rocks of the reservoir, however, so that there is sufficient deformation to cause variations in the speed of propagation of the seismic wave it is necessary that these small deformations, besides displacing the position of the rock, are sufficient to change the voltage field. The rocks in the reservoir under study have good permoporous characteristics and deform relatively easily because they are unconsolidated sands.

The vertical strain tensor, ε_{zz}, is a product of the geomechanical simulation and represented by the volume of deformations in the z-direction. The sum of these deformations layer by layer is the displacement volume, which measures the total displacement of the layer relative to a datum. As the result of the simulation is given in steps, the measurements were calculated only in the periods of the 4D surveys. For a corresponding analysis, the displacement must be correlated to the timeshift, which represents the sum of the variations of seismic velocities. Deformations must be correlated to time-strains.

Results

In order to show a significant part of the field of study, representative sections of the area covering most of the regions of interest were chosen, focusing mainly on the lower noise zones and the main zones of deformation. The dip A section is in the southern region of the field where depletion occurs in much of the period between 1997 and 2010, showing a slight overpressure between 2005 and 2010 in part of the area. The southern region presents the highest correlation between timeshift anomalies and simulated geomechanical displacements. Considering approximately that the expected movements are between 1 and 5 cm, it is unlikely that these small movements in kilometers of overburden can change the seismic velocities to the point of being detected, however, in that region the correlation is indicative that the 4D anomalies are for geomechanical effect and not for other reasons. The figure 2 shows the result of the geomechanical simulations of the same section next to the timeshifts calculated by the DTW technique. As previously explained, depletion anomalies are much more detected than overpressure anomalies. This can be seen in the period between 2005 and 2010, when the anomaly in yellow of geomechanical uplift is not detected by the timeshift on its right, in contrast to the slight depletion to its left that is discreetly perceived. Among the major anomalies of overpressure in the period between 2005 and 2010 appears a speed fall anomaly that extends from the sea floor and goes towards the reservoir. This anomaly is not expected and it was not possible to correlate it with anything other than a possible noise, despite its characteristic fingerprint, present in the literature as a characteristic form of signal.

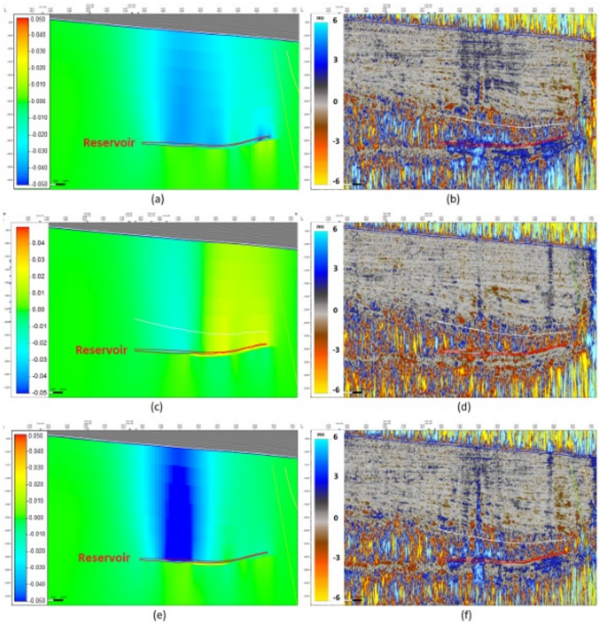

Figure 2 **:** (A) the simulated displacement between 1997 and 2005, (b) the timeshift calculated by the DTW technique between 1997 and 2005, (c) the simulated displacement between 2005 and 2010, (d) the timeshift calculated by the DTW technique between 2005 and 2010, (e) the simulated displacement between 1997 and 2010 and (f) the timeshift calculated by the DTW technique between 1997 and 2010.

The turbidic field studied in this work has a strong influence of the salt tectonics, an assertion already introduced in the description section of the study area. An example of how the 4D timeshift can contribute to the understanding of field structures and their relationship to production effects is now presented. The field is structurally limited by extension border faults to the east and stratigraphically and structurally to the west. These faults seem to continue to occur with fewer tailings and less noticeable in 3D seismic. The structural feature mentioned in section A can be interpreted as one of those faults that are difficult to map 3D data, but are highlighted in some structural attributes, such as the aforementioned attribute of the variance. In order to better visualize these structures and to correlate them more clearly with the extension faults associated to halokinese, a depth-cut of the variance attribute is shown in figure 3 with a red contour of the reservoir projection. These flaws largely follow the north-south trend, as shown by the north-east extension faults. As it approaches the east, the faults are taking the form of the extension structures associated with the southeast stratum. Even though it is more noticeable in the structural attribute, the characteristic of these sub-seismic faults in the 3D data is only a slight change in the reflectors upwards, as a small mound and they are detected by the variance (figure 4). These hills may be associated with a drop in seismic velocity caused by the rise of fluids that take advantage of these ducts, as the velocity model does not represent these velocities the reflectors end up overcorrected and pulled up.

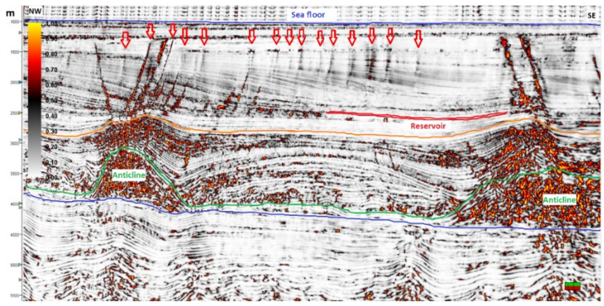

Figure 3 **:** Section of the southern region of the field with structural attribute of the variance. Arrows in red indicate structures associated with the extension movements.

The objective of the more detailed analysis of these structures arises with the observation of some timeshift anomalies that coincide with their lineaments. The figure 5 shows an overburden region south of the field through a dip section and a depth cut of 1615 m. In the section we can see the positive 4D timeshift anomaly indicating a drop in the seismic velocity practically embedded between two structures of the sub-seismic fault type, structures that are highlighted by the variance in the depth cut. In red we have a projection of the reservoir boundary, corroborating with factors related to the production effects that may have caused this anomaly in 4D seismic. This information leads us to see these structures as divisions between partially independent, movable blocks of structure. Consequently, it shows how

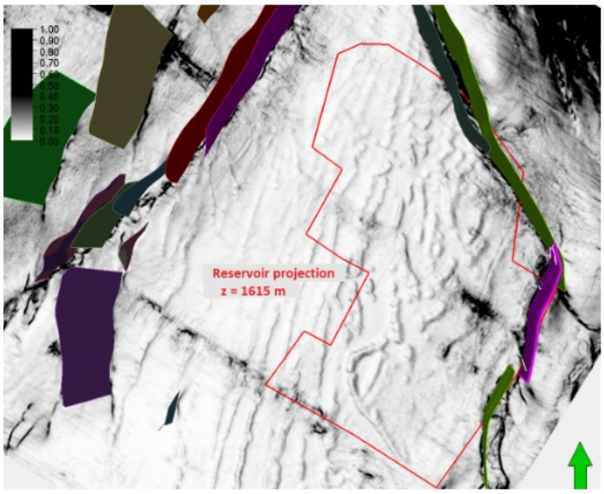

Figure 4: Timeshifts in section F and the variance attribute in the depth cut z = 1615m.

timeshifts can influence the understanding of the field structure and decision making of reservoir management. Better understanding and tracking of these structures is of utmost importance for the safety of operations.

The geomechanical simulation indicates in the same area a dilation of the geomechanical rocks, confirming what is observed in the 4D seismic. However, the simulation shows a distribution of the dilated anomaly well smoothed and laterally continuous.

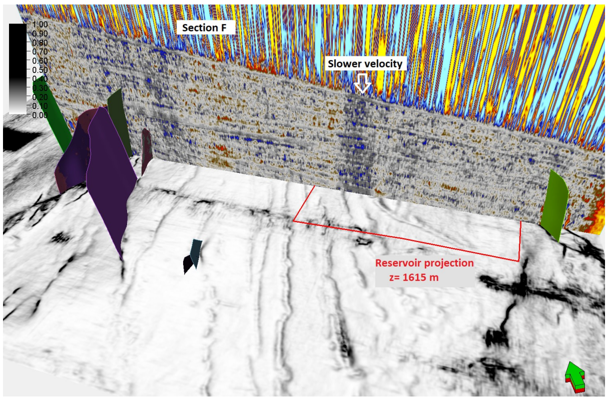

Figure 5: Timeshift in section F and the variance attribute in the depth cut z = 1615m.

A reliable estimate of the R factor depends mainly on a reliable timeshift anomaly consistent with the production, in addition to a predicted forecast of the geomechanical simulation. In the previous chapter a value of R was found through a statistical estimate of 1300. This value shows the high sensitivity of the overburden of the area studied in this work. This indicates that small geomechanical deformations cause variations in seismic velocities sufficient to be detected. As the R-factor is layer-dependent (MacBeth et al., 2018), the closer to the seafloor the R-values tend to be larger (Roste et al., 2015). When compared to other examples seen in the literature, R = 1300 is a high value. This high sensitivity of the overburden in relation to the geomechanical deformation made it possible to perceive timeshift anomalies consistent with the production effects.

Starting from the result of the more reliable R value, it was possible to construct synthetic 4D timeshifts closer to the real ones. Figure 6 shows the synthetic 4D timeshift calculated from the factors R = 1300 and the strain matrix, ε_{zz}. Other values of R can be calculated. The factor R is dependent on the lithology and the initial state of stresses, so in several overburden intervals different values can be extracted that will represent the estimated region better than the others . An approximate R-value for the field is of great importance for the predictability of geomechanical deformations in a future interpretation of 4D timeshift data, either reprocessed data or a new 4D seismic acquisition.

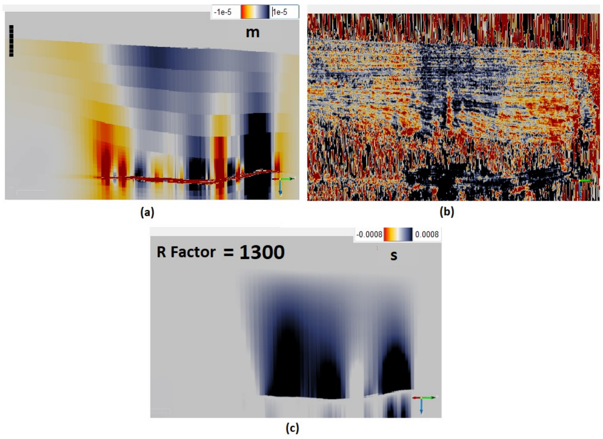

Figure 6: Section A: (a) deformation; (b) real timesdift 4D; (c) time shift 4D synthetic with R = 1300.

Other physical processes not reported in detail in this work may cause 4D timeshifts. Among them are reasons that can cause real anomalies, such as reactivation of faults, injection outside the reservoir zone and hydrocarbon leaks. A distinct possibility is that of noise produced during the acquisition and processing of seismic data, processes that may cause artificial anomalies. The timeshifts analyzed in this work are in regions of good quality and low noise levels, even in regions of faults levels have remained low. The anomalies agree with the field pressure data, being consistent with the production and can hardly be related to other effects.

Conclusions

It was possible to extract important information for field management from 4D timeshifts in the overburden region of the Campos Basin turbiditic reservoir. Even without large pressure variations between the studied periods and maximum variations in the seafloor close to 5 cm, it was possible to detect the effect of geomechanical changes through the variations of seismic velocities in regions of the field where there was mainly depletion. For the analyzes to be done with better security, an adjusted model of field pressure is required, a geomechanical model with as much information as possible and, not least, well processed 4D seismic.

When comparing geomechanical shifts and timeshifts, it was possible to evaluate how close the simulation forecasts are to those of the 4D data. Among the depletion regions, the southern region of the field presents a correlation between the methodologies, but in the northern region there was no similar agreement, attributed mainly to the region heavily structured by extension faults associated with the tectonics. From this interaction it was possible to generate information capable of being used in an update of both the field pressure adjustment and the geomechanical simulation model, showing the importance of using geological faults in the simulations to increase the predictability of the deformations. In most regions where there were strong overpressure effects, timeshifts were not able to detect significant variations in seismic velocities, confirming what has been found in other published works on the subject and associating this phenomenon with the effects of hysteresis. The only exception came from the data between 2005 and 2010 when an anomaly was found, responding with a slight increase in velocities due to overpressure.

A direct relationship between seismic velocity variations and the vertical strain tensor proved to be inefficient in selecting an R factor that could be used in the construction of synthetic timeshift timeshifts. However, a statistical form of estimation was proposed and presented a satisfactory result, indicating the value of R equal to 1300 for a region where the 4D anomalies fit well with the geomechanical simulations. This value is much greater than values found in fields in the North Sea of the Chalk type, confirms the expected and shows that in the region studied in this work the overburden is much more sensitive in relation to variations of seismic velocities caused by geomechanical deformations than in other places with large deformations in the rocks above the reservoir. For this reason, anomalies can be detected and interpreted, bringing useful information to the understanding of the field. With the result of the more reliable R-value it was possible to construct synthetic 4D timeshifts closer to the real ones, increasing the predictability of finding geomechanical deformations in a future timeshift interpretation in a new 4D seismic acquisition.

Thus, this work evidences the possibility of adding valuable information to reservoir management through 4D seismic timeshifts. The relationship between the 4D data and the geomechanical and structural aspects of the field, contributing to the estimation of geomechanical variations directly from 4D seismic and indicating areas of the reservoir that are more compact with the effects of production.

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