Geostatistical Time-Lapse Seismic Inversion
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Abstract
With the decrease of the oil price and of new discoveries, it is not only important to use new exploration and production methods and technologies but improve and optimize the monitoring of hydrocarbon reservoirs during production. This leads to a more efficient decision making process, while reducing risks and increasing oil recovery factors. Although a relatively new area, nowadays there are already some methodologies that invert time-lapse seismic data, based on a Deterministic or Bayesian inversion framework. This thesis introduces a new iterative geostatistical time-lapse seismic inversion methodology. The objective of this work is the development and implementation of a new methodology able to reproduce the changes of the elastic properties during production time integrating time-lapse seismic reflection data from the different acquisition times. This new approach was tested and implemented in a realistic synthetic dataset Stanford VI-E. The results show a good reproduction of the changes in the elastic properties of interest. It was also concluded, during the comparison of the both methods used in this work, that the horizontal time-slices of elastic differences computed from the conventional global elastic inversion do not reproduce the spatial continuity of the elastic differences values. Otherwise the proposed workflow, reproduces the spatial continuity pattern of these changes with improved accuracy.

Introduction
Time-lapse or 4D, seismic method involves acquisition, processing, and interpretation of repeated seismic surveys over a production hydrocarbon field. The objective is to determine the changes occurring in the reservoir as a result of hydrocarbon production or injection of water or gas into the reservoir by comparing the repeated data-sets along the time (Figure 1). A typical final processing product is a time-lapse different data-set, where we can assess to the amplitude differences between the seismic and therefore the elastic changes of the reservoir. The differences should be close to zero, except where reservoir changes have occurred. Using time-lapse methodologies help us to a better understanding about the fluid production, injection and the geometry of the active reservoirs. The production in these reservoirs causes deformations in the subsurface and changes in the seismic waves velocities. This changes can be monitored and interpreted using 4D seismic. The interpretation of the reservoir pressure, saturation and fluid contacts using these kind of data-sets can contribute for an improvement in production, optimizing the placement of producers and injector wells.

Figure 1- Seismic near-stack amplitude differences between the different times of acquisition during production. From the right to the left: (10, 25 and 30 years of differences after the beginning of production).

Time-lapse studies normally use two or more migrated 3D seismic images obtained months or years apart. These can consist of stacked data volumes or stacks created from partial offset if AVO aspects are considered. To study and interpret the changes in the seismic volumes, some different approaches have been done, however none with the reliability to assess the uncertainty like the geostatistical approach. Geostatistical modeling and inversion techniques contribute increasingly for a better reservoir characterization, there are several modeling techniques that allow the access to different levels of detail in the characterization of the reservoir model, however and regardless of the technique used, there will be always a degree of uncertainty associated with inverse models that is important to evaluate (Azevedo, 2013).

By posing the time-lapse seismic inversion problem within a geostatistical framework it is not possible to propagate the associated uncertainty of the elastic changes during the production phase of the reservoir inverting different times of seismic reflections acquisition separately, once there is no conditioning of the properties changes between each acquisition time. Therefore the main motivation of this work is to have a workable algorithm that with a unique geostatistical approach, integrate the time-lapse seismic reflection data inverting all times simultaneously, ensuring the reproduction of the elastic changes in reservoir during production.
Geostatistical Models for Earth Sciences Applications

Geostatistics was born of the need for modeling the geological resources, enabling to characterize the spatial and space-time of the quantities defining the quantity and quality of a natural phenomenon, in which the attributes have a certain structure in space and/or time (Soares, 2006). The geostatistical methodologies are applied in various fields of Earth and Environmental Sciences. They are a set of statistical tools that quantify the spatial continuity of magnitude study on spatial interpolation models, based on their degree of structural variability and stochastic simulation models that evaluate the degree of uncertainty associated with spatial phenomenon (Soares, 2006).

Spatial Continuity

For the conditional a priori of the data in order to do geostatistical seismic inversions it is necessary to use a set of geostatistical tools in order to describe our data. Spatial continuity analysis is one of those important steps, as it aims to understand the dispersion of the experimental data and the degree of anisotropy between the variables in question (acoustic impedance and elastic impedance). There are some rules combined practices to take into account the study of the analysis of spatial continuity, involving the calculation and modeling variograms. These rules can be compiled and subdivided into the following groups: Quality and Sampling type, Conceptualization of geostatistical model and Data Analysis Statistics (Soares, 2006).

Quality and Sampling type are important because sometimes there are anomalous values in the sampled data from very strong asymmetric distributions, which, for some steps can generate anomalous values of variogram. Thus, it is necessary to take into account the samples of clusters since these tend to bias the variogram estimators, averages, histograms, among others (Soares, 2006). In very asymmetrical distributions, when there are abnormal values in the variogram, the simpler solution is the removal of the pairs of anomalous points of the average value of the variogram, referring to the respective steps. The spatial variability of a given phenomenon is a very important factor to take into account, because, if different types of data have different structures (special variability), whether on the same resource, it is necessary to treat each variable separately integrating together with the same algorithm (Soares, 2006).

Regarding the conceptualization of a geostatistical model, it is important to set the regionalized variable \( Z(x) \). This regionalized variable is an embodiment is a set of random variables related to spatial features of the phenomenon under study, presenting a spatial correlation between each other (random variable) (Soares, 2006). Conceptualizing the regionalized variable, it is necessary to take into account certain characteristics that shall, in particular the same physical meaning in all samples, ensuring that meaning in the estimated value. Another factor to consider with regard to the support that is measured quantity, since the mixing measured quantities in different formats is not a recommended practice, since they have different variabilities. Finally, it is necessary to define the extent of the field of the regionalized variable, which must be considered homogeneous field on the measures of spatial continuity (means, variances or variograms) to estimate, in situations where the domain is considered heterogeneous, must share the same (as best possible) in homogeneous subdomains and consequently processed and analyzed separately (Soares, 2006).

The Univariate description of a sample consists of making individual analysis of variables to get an idea of the dispersion of the attribute under consideration, understanding the characteristics or tendency of the variables data. Their study is based on frequency tables, histograms and cumulative histograms, obtaining like this the distribution location measures (minimum, maximum, average, median, quartiles, and percentiles), measures of dispersion (range, variance, standard deviation) (Soares, 2006).

The bivariate description consists in the study of the behavior of two variables simultaneously, and the same variable obtained at distinct locations. It allows to establish relations between the two variables, allowing to determine whether the differences between the distributions are significant at the statistical level. For a bivariate analysis using essentially the bi-plots, the bi-histograms and different regression analysis tools (Soares, 2006). In the bivariate analysis of this scientific work was used a type of graphical representations called scatterplots, one most widely used type of chart on the correlation between two variables defined in the same spatial positions.

In the study of space description it is attempted to visualize de variable behavior in relation to their dispersion in space. It is also intended to make the planning of the basic parameters for the calculation of variogram, by viewing the spatial arrangement of the experimental variable data and get a first idea of the
spatial dispersion characteristics of the same variable, like anisotropy and anomalies, among others (Soares, 2006). Within some of the salient features of uni and bivariate analysis which we want to see in this stage, it is noted the location and spatial dispersion of the extreme values of a histogram. There are some situations that need to be taken under account, essentially when they are characterized by higher values of local variances that imply higher spatial inference errors and especially with greater uncertainty, like:

- The higher are the extreme values and agglomerates are in the same area, the greater is the average value and the smaller the value of the local variance;
- The higher are the extreme values and there is no concentration (clumping) in the same area, the greater the average value and the local variance;
- The lower is the extreme values in this area, the lower the average value, unlike the local variance that tends to increase.

**Sequential Simulation Algorithms**

In the proposed methodology of this work it is used the direct sequential simulation (DSS) which is a stochastic algorithm that uses the original variable not requiring any transformation. This new approach (Direct Sequential Simulation) is based on the principle introduced by Journel (1994) for the Gaussian sequential simulation. However, it was with the Soares (2001) optimization that this algorithm allowed to successfully reproduce the variogram and the histogram of a continuous variable (Soares, 2001) using the average and local estimated variances by simple kriging for re-sampling of the distribution law and not defining the local distribution laws (Similar to the GSS method). Nevertheless, the essential advantage of this algorithm is the permission of simulation process and co-simulation, without the need for any transformation of the original variables (Soares, 2001), Thereby more advantageous over other methods, such as the case of indicatrix sequential simulation methods (ISS) and Gaussian sequential simulation (GSS) which require that processing (Soares, 2006). In this work we intend to invert more than one property, therefore it is necessary to use another algorithm entitled direct co-simulation with joint probability distributions, introduced by Horta & Soares (2010). It ensures the reproduction of the experimental joint probability distribution between the primary and secondary variables on the simulated models (Horta and Soares 2010). Therefore this algorithm was created in order to dissipate discrepancies between the joint distributions resultant from the co-simulation and the experimental data.

**Geostatistical Seismic Inversion**

The methodology proposed under the scope of this work is based on a family of geostatistical inversion methodologies that use the principle of cross-over genetic algorithm (Azevedo et al., 2013b). This iterative geostatistical methodology is based on two key main ideas: the use, at the end of each iteration, of global optimizer based on a genetic algorithm with the cross-over principle; and the perturbation of the inverted models with stochastic sequential simulation, the Direct Sequential Simulation (Soares, 2001). The affinity criterion, that measures the convergence of the inverse procedure and guide the genetic optimization algorithm, is based on the correlation coefficient between synthetic and real seismic volumes, which is achieved by the maximization or minimization of an objective function that measures the mismatch between inverted and real seismic. Seismic inversion as explain in the precious section is an inverse, nonlinear and with multiple solutions problem that can be summarized by the Equation 14 (Tarantola, 2005), and in geostatistical seismic inversion case, one wish to calculate the parameters (elastic impedances) which give rise to the known solution, real seismic. The objective is to estimate a subsurface Earth model that after being forward modeled, produces synthetic seismic data that shows good correlation with the recorded data. Depending on the limitations associated with the chosen inversion methodology resultant inverse models, can be acoustic and/or elastic impedance, for post-stack seismic data, or density, P-wave and S-wave models if a more elaborated inversion algorithm is being used to invert pre-stack seismic reflection data (Francis, 2006).

Geostatistical seismic inversion methodologies may be divided in Trace-by-trace geostatistical seismic inversion or global geostatistical seismic inversion methodology depending how the model parameter space is perturbed. The first class of methods perturb the inversion grid sequentially in a trace-by-trace basis, while global approaches generate at once realizations for the entire inversion grid. Contrary to trace-by-trace approaches, global approaches can to keep low signal-to-noise areas with a poor match during the entire inversion procedure.
**Applied Methodology**

The general workflow of the proposed methodology is represented in the Figure 2 and it can be briefly described by the following sequence of steps:

1) Calculate from the existing hard-data differences between well-log measurements related to each year of acquisition time and for each property to invert. These data will be used as conditioning in the simulation procedure;

2) Stochastic sequential simulation of a set of N acoustic and elastic impedance models using DSS and co-DSS with joint probability distributions respectively. Both properties are conditioned to the available well log data and, in the case of elastic impedance, will also be conditioned to the previous acoustic impedance model. To note that, the residues of each time are simulated in a masked grid, conditioned by the differences between the seismic of each year: the zones which don’t occur amplitude changes in the seismic data, are not simulated and are filled with the data from the acoustic and elastic impedance models from the first year, in order to have the full grid to calculate the synthetic seismic data;

3) Calculate synthetic seismic data volumes for each year from each pair of realizations generated in the previous step. The synthetic seismic data is obtained by the convolution between the angle-dependent wavelets and the reflectivity coefficients computed by Fatti’s approximation for each angle gather;

4) Compare the synthetic seismic volumes, in a trace-by-trace basis, with the corresponding recorded seismic data in terms of correlation coefficient where the final result will be a best local correlation cube that store the traces that produced the highest correlation coefficient. This process of seismic comparison is applied to all times simultaneously obtaining, at the end of each iteration, eight local correlation cubes: four volumes to each properties, each pair associated to each acquisition time. From the best traces selected simultaneously and stored in the best correlation coefficient volumes it will be computed the correspondent best elastic volumes for acoustic and elastic impedances. The best elastic volumes along with the local correlation coefficient volumes, are then used, as secondary variables in the co-simulation process for generating a new set of impedance models in the next iteration. The new ensemble of impedance models, for the next iterations, will be conditioned by the available well-log data (and each impedance model at each realization, in the elastic case) but also by the best volumes (best elastic and local correlation cubes) computed in the previous iteration. The iterative geostatistical inversion procedure finishes when global correlation coefficient between the synthetic average and the recorded partial angle stacks, for all the available n angle stacks, is above a certain threshold;
Figure 2: Graphic representation of the geostatistical time-lapse inversion.

Calculation of the differences between well-log data of each year

Stochastic Simulation of AI and ∆AI

Stochastic Co-Simulation of EI and ∆EI

Fatti’s approximation

Forward modelling

Seismic comparison per angle

Selection of best AI and EI cubes

Selection of best local correlation cubes for both properties

Simulate until the number of realizations is reached.
Comparison between geostatistical elastic inversion and geostatistical time-lapse inversion methodologies

In this work, made comparisons between seismic reflections and elastic models from the two geostatistical workflow used, to prove the efficiency of the proposed methodology taking into account the main goal of this study: the assessment of elastic properties changes from the simultaneous procedure of seismic reflection data integration associated to the acquisition times.

In this section, were presented the comparison between seismic, and as explained before, the 5 partial angle stacks used, did not show significant differences between then, therefore, after computing synthetic seismic of the best-fit models in the geostatistic elastic inversion procedure and the synthetic seismic from the mean of the best-fit models using the geostatistic time-lapse inversion, it was only used the near stack to do the comparisons. As previously stated, using the synthetic seismic of the mean of the best models helped us to grant a higher spatial continuity. The figure 3 is illustrating the differences between real seismic data and the synthetic seismic data from both methodologies.

It was also presented the main goal of this work, to evaluate if the real changes in elastic properties are being assessed and propagated during the dynamic changes in the reservoir. Therefore in the Figure 4 are shown the real differences between the properties of interest (AI and EI), the mean of the best models using geostatistic time-lapse inversion method and the differences between the best models using the geostatistical elastic method. This differences are done subtracting the previous models by the models of the next year of acquisition, so it is expected to see lower values in production zones. The main objective by comparing this differences, is to see, which applied method can reproduce better the spatial location of the maximum and the minimum values.

The figure 5 represents the differences between elastic impedance models of each acquisition year. Like in the previous figure, is used the mean of the best models inverted by the method of geostatistic time-lapse seismic inversion against the best geostatistical elastic inversion models, and the real differences from the real data that is supposed to address. This differences are much difficult to see when compared with the acoustic impedance showed previously, even so, the main goal of this comparisons can be achieved, the reproduction of the real changes on the inverted models.

Conclusions and future work

Moreover and in order to evaluate the performance of the proposed methodology, were also run a global elastic inversion for each year separately conditioned by the same data set. The results obtained from both methodologies were compared between them regarding the seismic reflection data and the properties differences between each acquisition year. Although the synthetic seismic is similar for both methods, the horizontal time-slices of elastic differences computed from the global elastic inversion present no spatial continuity once the elastic difference values are not in the right locations in the simulation grid. Otherwise the proposed method, even also do not show a good spatial continuity, we can verify that elastic different values appear in the right location and within the property boundaries. This better reproduction of elastic changes (Figures 4 and 5) during all the years of production, can be explained by the fact that the proposed methodology is able to simultaneously integrate the different seismic reflection data allowing the link between the differences from the previous and the next year of the acquisition time. Another great advantage when compared to other seismic inversion algorithms (deterministic and bayesian), is the possibility in presenting scenarios as solutions, allowing a better assessment and quantification of the spatial uncertainty related with the geology subsurface. All this advantages come with some limitations especially the computation costs and time consuming once we are doing several seismic inversions simultaneously. Another fact that can great limit the proposed methodology is associated to be a recent and in developing area and the need to have more seismic acquisitions during the reservoir production stage. The fact that this methodology strongly depends on the available 4D seismic data acquisition drives to a higher exploration costs and consequently the need of a better improvement and knowledge regarding a study area. For these reasons, the development of this proposed methodology would need more research and time investment to improve the optimization of the workflow and the constraints in this approach.

As future work, we can go through this problem, integrating the petro-physical properties to build reliable rock physic models, when we have more available wells-log data, in order to accurately estimate the elastic properties and their dynamic behavior along the oil field life.
Figure 3 Comparison the near angle stacks between the real seismic (left column), the Synthetic seismic computed from the mean of the models from the last iteration using geostatistic time-lapse inversion (center column) and the synthetic seismic from the best-fit models using Gei (right column). The seismic results are related to the different times of acquisition divided by lines, being the first related to the year 0 and the last to the year 30.
Figure 4 Acoustic impedance differences from: the real (left), geostatistical time lapse inversion (middle) and global elastic inversion (right) for the T0-T10, T10-T25, and T25-T30 years respectively.
Figure 5 Elastic impedance differences from: the real (left), geostatistical time lapse inversion (middle) and global elastic inversion (right) for the T0-T10, T10-T25, and T25-T30 years respectively.
References


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