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4D Seismics - principles and application

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ABSTRACT

The aspect of monitoring reservoirs clearly comprises all aspects of data acquisition, processing and interpretation. Certain rules apply in order to keep the monitoring process stable, where the most important ones are:
- to maintain the same 3D-acquisition geometry: the same geometry then guarantees that the same S/N-ratio in terms of noise-suppression is achieved, one example being here e.g. the aspect of multiple-suppression for the entire data-volume.
- to maintain the same processing flow: nevertheless of course e.g. residual statics have to be computed based on the individual volumes of data. Another example here is the process of deconvolution.
- to use the first 3D-volume (usually called the base-line survey) to establish the basic processing flow as well as to establish the underlying macromodel (velocities V(x,y,z) and velocity interfaces) and (if needed), by sequence stratigraphic interpretation the 3D-litho model of the reservoir unit.
- to decide upon the monitoring quantity, i.e. which quantity to use for 4D-evaluation. The default here is to use Acoustic Impedance (AI) (which means that after proper imaging the data is subject to a suitable inversion algorithm, usually at post-migration stage).
Clearly the type of reservoir to be monitored has impact on the acquisition effort, since we have to distinguish between two basic types of reservoirs:
- High-impedance reservoirs, i.e. carbonates. As a „rule of thumb“ the maximum changes here are up to 5% (in acoustic impedance) and
- Low-impedance reservoirs, i.e. sandstones. The „rule of thumb“-Figure here is up to 10% of AI-change.
In any case for the actual reservoir under consideration its sensitivity to fluid substitution has to be evaluated, usually based on the Biot-Gassmann-formalism for the Zero-Offset case. This part of a 4D-evaluation is called the calibration part. If done properly, the outcome is a reliable estimate of the dynamic range of the changes in acoustic impedance due to ongoing production. In addition one needs to estimate the lateral „area of change“ to be expected by producing the re-
servoir during the timespan in between the two seismic surveys.
This is achieved in two ways as summarized below:
- the reservoir simulator is used for a homogeneous reservoir model (i.e. constant porosity,constant permeability, pressure data and a given set of relative permeabilities along with the initial saturation values as well as the non-reducible saturation values).
- use of fractional flow curves by applying Welge’s tangent construction for the break through (bt)-point.
Up to now we have tacitly assumed that the reservoir is an oil reservoir above bubble point.However, as soon as the reservoir is produced below bubble point, or if there is a free gascap,then P-wave data alone do not allow anymore to quantify for saturations! In order to be able to quantify for gas saturation, the use of shearwaves is mandatory.Shearwaves of the type P down/S-up resulting from mode conversion at the reflector unfortunately show a similar AVO-effect just like P-waves and therefore cannot be used to quantify for gas saturation.
Having acquired the two surveys, i.e. the base line survey as well as the monitoring survey,the last step in processing (after inversion) is the differencing of the two acoustic-impedance cubes. The resulting difference-volume now has to be studied, interpreted and evaluated.
This procedure as a whole is called the σ-(sigma)-approach, and, as the name already indicates,is a statistical method to be applied in two steps:
- step 1: this step represents the analysis-step. Here we apply the analysis-tool to the overburden of the reservoir (= subset of the entire volume, where there is no change due to ongoing production). The outcome of this exercise is the estimate for what is called the amount of Non Repeatable Noise (NRN). The actual procedure is based in prin ciple on the Law of Large Numbers (Bernoulli, 1713 and Borel, 1909) and the Central Limit Theorem. Of course the quantity NRN is time- and space variant and also is calculated for the target volume and below. Here in principle the method of Averaging Over Time (AOT) as well as Averaging Over Time and Space Coordinates (AOTXY) is applied for selected sub-volumes. In this context a subvolume is defined in two possible ways:
- either by a timeslice (Tstart = const.)
- or by e.g. an interpreted interface (e.g. top of reservoir).
The dimension of the subvolume (to be used for AOT) in time-direction is called a tN-comb, where N stands for the number of „teeth“ (=samples) to be included in the averaging process. The outcome of each AOT-application is an areal grid of values.
It is evident that the actual amount of NRN being present primarily depends on the actual 3D-acquisition parameters and increases with decreasing coverage. In passing therefore it should be noted that if the actual

coverage goes below a threshhold value then these acquisition parameters are only acceptable for that what is called a structu ral 3D-survey, because the amount of NRN would exceed by far the changes in acoustic impedance to be monitored, and as a direct consequence then quantified monitoring in a reliable manner is not possible anymore.

- step 2: this is the evaluation part, which is applied to the subvolume containing the actual reservoir . The crucial step here is to define the area of no change, and as a direct consequence the „area of confidence“ for mapping changes in acoustic impedance, which are due to ongoing production in the reservoir. Again the quantity NRN forms the basis for this part: the „area of minimum background noise energy represents“ the „area of no change“, which has to be excluded for the mapping part, i.e. for the quantified interpretation.

As can be seen, above procedure is quite similar to geostatistics, where one analyses the data first (variograms etc.) and evaluates the data thereafter (kriging, co-kriging etc.)

In terms of 4D in general, two areas of application have to be distinguished:

- detection of drained/undrained compartments. Here one is interested only in actual fluid movements within the reservoir in order to be able to identify undrained compartments.

- quantification of actual changes in saturations. This second application of course contains the first one (i.e. drained vs undrained) by definition.

It is evident that the next immediate step after having established the result of a 4D-evaluation study with the result of a quantified saturation map has to be to use the reservoir simulator again, but this time with the actual reservoir model, and rerun the simulation. The outcome of this exercise then (after having adjusted the actual reservoir model according to the 4D-results) is an optimum reservoir model, which in its fluid flow properties matches the result of the actual measurement (= 4D-seismic results).

4D-seismics (if applied properly) is one of the most important tools to improve and optimize production in the long term, i.e. it is a strategic tool as well. We mention just one particular application: if one plans to initiate a waterflood-program, by using the concept of „fluid flow gradient maps“ the positions of the injectors to be drilled can be optimized, thus eliminating the otherwise applied technique of „geometric pattern“-drilling. Based on above methodology one example will be discussed, which addresses the monitoring of an actual waterflood-pilot for a carbonate reservoir in Middle East.

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