

INTRODUCTION

INTEGRATION BETWEEN 4D AND RESERVOIR FLUID FLOW PROPERTIES

Some history

When we follow the history of the development of the seismic technique to reveal the unknown subsurface then we note different developments that determined at large the progress of this particular geophysical method. In most cases this progress found its origin in a technological improvement that triggered the application. In that category, for example, the computer played an important role in acquiring and processing the seismic data. Hand in hand with this progress went the description of the seismic measurement in terms of the underlying principles of acoustic wave propagation. The computer made it possible to mimic the seismic technique and in doing so to understand the sensitivity of the measurement to the heterogeneity of the complex geological subsurface. More importantly the computer facilitated the processing of actual recorded seismic data by recognising that in order to make an image of the subsurface the journey of the acoustic wave into the Earth has to be replayed in some way or the other with the measurement as input. It was with no doubt Jon Clearbout who, as the first scientist, brought this concept to our attention. He stated that what we have to do is to follow the acoustic wave from its source into the subsurface to its reflection point and back to the recording transducer, the geophone. In order to achieve this goal, Jon claimed, you need wave theory to downward continue the seismic data from the source and the geophone to the interior reflection point and then look at time zero. For it is at just this time instant when the downgoing wave from the source and the upgoing wave at the receiver meet. The reflection point has been moved, migrated so to speak, to its true position in the Earth and hence the name of the game: migration. Thus it is the causality of the acoustic arrival that makes it possible to convert the 2D-space and 1D-time measurement at the Earth's surface into a 3D image of the subsurface in a process that nowadays is denoted as depth imaging. It is clear that one must have a background model to move the data to that particular depth location.

Time-lapse seismic

In the nineteen-nineties experiments were carried out where, after some elapse of time, the seismic measurement was repeated at the same location with the intention to find out whether the seismic contrast had changed. The latter being triggered for example by the change of reservoir conditions due to the exploitation programme. This type of geophysics was coined as 4D seismic to honour the repetition of the process in time, which is however substantially larger than the actual seismic measurement time. Since the sampling rate in the two time directions is not comparable, it is a bit presumptuous to call the process 4D; the term 'time-lapse seismic' describes the process in a better way. The sampling rates of the common 3D measurement are chosen such that the 3D heterogeneity is sufficiently captured. The repetition interval has to be chosen such that the localised change of the 3D heterogeneity is sufficiently captured.

In the realm of time-lapse seismic we distinguish three problem areas:

1. Repeatability.
2. Effects of saturation, pressure and flow.
3. Reservoir management.

Repeatability

Time-lapse seismic puts severe constraints on the repeatability of the experiment in the 3D configuration. If these conditions are not met the differences in acquisition are mixed with the differences in the reservoir.

- Verhelst et al. discuss how a close cooperation between processing and reservoir geophysicists can lead to an increased repeatability. This is illustrated at the hand of the Snorre time-lapse project. The repeatability analysis appears also to be of assistance for the subsequent use of the time-lapse data for optimizing field development.
- Druzhinin and MacBeth use a novel form of cross-equalization of 3-D time-lapse data, which allows an accurate computation of differences in the seismic response. The method is tested on 4C-4D data from the Teal South field, Gulf of Mexico. It appears that the scheme works well, even when there are large non-repeatable differences between surveys.
- Dillen et al. propose to tackle the non-repeatability issue by recursively eliminating the temporal contrasts between time-lapse wave fields. The

method removes the time-shifts and restores the amplitudes of difference reflections. This effect is shown numerically with several examples, modeled with the finite difference method.

Effects of saturation, pressure and flow

With the time-lapse seismic method, one aims to monitor changes in the reservoir through time. In order to be successful it is important to understand the relation between on the one hand the reservoir properties (rock type, porosity, hydrocarbon properties, saturation, pore pressure, matrix stress, fracture orientation and distribution, permeability, temperature, etc.) and on the other hand the seismic parameters of the reservoir (bulk and shear modulus (isotropic or anisotropic) and mass density) and their effect on the seismic response measured at the surface.

- MacBeth introduces two general laws to describe the sensitivity to hydrostatic stress observed in the laboratory on a selection of unsaturated reservoir core and outcrop sandstones. The relations are based on using the concept of excess compliance as a pseudo-function to describe all internal weaknesses, regardless of whether their origin is cracks, contacts or other mechanisms. The relations explain the pressure dependence of compressional and shear wave properties of sandstones.
- Schoenberg proposes a model for time-dependent anisotropy and permeability induced by pore pressure variation. Whereas the solid phase in Biot theory is described as a homogeneous elastic medium, the solid phase of real reservoir rocks is far from this ideal. Schoenberg models the dynamic elastic properties of the rock by adding to the almost isotropic compliance tensor of the background, an excess, necessarily quite anisotropic, fracture compliance tensor associated with the fractures. The key assumption, that still needs experimental verification, is that fracture compliance is more sensitive to effective static stress, anisotropic external stress less pore pressure, than is the background. According to the author, the development and refinement of such models will become critical as multicomponent data and advanced inversion methods yield improved estimates of seismic anisotropy. In addition, it should be possible to extend the method to permeable rock by use of Biot theory.
- Marschall introduces the concept of the pore pressure build-up coefficient, which allows to account for changes in differential pressure in the standard fluid substitution procedure. Moreover, he discusses the effect of different saturation profiles on elastic moduli. These theories cover the kinematic aspects in an acceptable manner, but the effects of attenuation remain not very well explained.

- Mercerat et al. discuss a specific scaling behaviour of the transmission response of reservoir rock under varying ambient stress. They propose a model that explains this type of scaling behaviour. Estimating the scaling parameters that appear in this model gives valuable information about the stress-dependent behaviour of the reservoir rock.
- Fanchi et al. propose to link integrated flow modeling to high-resolution time-lapse seismic images. Input to the integrated flow model can include seismically derived velocities, densities, Poisson's ratios, etc. The integrated flow model can predict the flow paths of injected fluids; the injected fluid distribution may be imaged using time-lapse seismic.

Reservoir management

- Stammeijer et al. state that, given the maturity of the North Sea as an oil and gas province, it is not surprising that 4D seismic methods are more and more used for reservoir monitoring and management. Nevertheless, a number of unresolved 4D technical issues remain. According to the authors the technology must be developed quickly while reaping the benefits of 4D now. A risk-reward balance has resulted in a two-pronged approach aimed at increasing both the breadth and depth of the implementation efforts in the shortest possible time: a further roll-out of the 4D technology in proven areas of application, complemented by testing in uncharted territory.
- Sonneland et al. present a set of new timelapse seismic analysis tools for mapping dynamic reservoir features such as subsidence and the flow properties of the fracture network, which often make up migration paths for hydrocarbons or injector fluids. Knowing these dynamic components of the reservoir behaviour helps the asset team to improve the management of the produced water and detect by-passed pay.
- Oldenziel recalls that the interpretation of time-lapse seismic is dependent on well-data and a rock physics model that is calibrated at the well locations. For most fields the time-lapse well control is limited, leaving only one alternative: to use the reservoir model to provide the necessary information for interpretation of the time-lapse seismic. According to the author this leads to a classical Catch-22 problem: the time-lapse seismic is acquired to improve the quality of the reservoir model, while the reservoir model is used to calibrate the time-lapse seismic.

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