4D Seismic & Petroleum Geomechanics for Hydrocarbon Reservoirs

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Abstract

Time-lapse seismic reservoir (Sweet spot) monitoring is the process of acquiring and analyzing multiple seismic surveys, repeated at the same site over calendar time, in order to image fluid-flow effects in a producing reservoir. If each survey is 3-D seismic, then the resulting set of time-lapse data is often termed 4-D seismic, where the extra fourth dimension is calendar time. In addition to 4-D seismic, there are other viable methods of time-lapse seismic monitoring including repeated 2-D surface seismic, surface-to-borehole VSP, Microseismic (music of oil), Multicomponent seismic (S-wave) and borehole-to-borehole crosswell seismic geometries. There are interesting new developments in monitoring techniques, including time-lapse electromagnetic surveys, gravity data, and satellite, Fibre-optic OBC (Ocean Bottom Cable) system (4Cstations), electroseismic , Real-Time Casing Imager (RTCI)., Real-Time Completion Monitoring (RTCM) and ground-penetrating radar data. The goal of seismic reservoir monitoring is to image fluid flow in a reservoir during production. This is possible because, as fluid saturations and pressures in the reservoir change, the seismic reflection properties change accordingly. Whereas the geology is assumed to be constant, fluid-flow variables such as saturation, pressure, and temperature are highly time variant during production. A single 3-D seismic data set images reflectors that contain combined information about both the static geology and the dynamic fluid-flow properties, but the coupled rock and fluid contributions are difficult to separate. In two or more time-lapse 4-D seismic data sets, difference images can be constructed in which, to first order, the geology part subtracts out since it is time invariant, to produce images of the time-variant fluid-flow changes. Seismic Reservoir Monitoring (SRM) : Use of seismic data to monitor behaviour within a reservoir ,Component of a comprehensive monitoring campaign.

This is the basic concept of time-lapse seismic reservoir monitoring. Time-Lapse Seismic (TLS) : Use of repeated seismic surveys ,Subset of seismic reservoir monitoring 4-D Seismic (4-D): Use of repeated 3-D Seismic surveys,Subset of time-lapse seismic.

Introduction : 4th Generation Seismic Oil & Gas Industry

1st, 2nd, 3rd Generation Seismic are 2D,3D,4D respectively. Continuous seismic surveillance extends 4D methodology. Offshore, permanent sensors (with up to 4 components: X, Y, Z and pressure) are installed, usually in a cable, in the sea-bed above any oil or gas field in a one-time installation before production starts. Time-lapse" or "4D" are names used to describe geophysical data sets that are acquired over the same area at different epochs in time (3D + the dimension of time = 4D). The general purpose is to analyse differences between data sets from different epochs, the underlying assumption being that such differences are due only to production or injection from subsurface reservoirs. Differences between data sets due to other sources such as variations in acquisition/processing parameters, tides, and background noise, must be removed or equalised prior to differencing. Just as 4-D seismic revolutionized the ability to manage reservoir production, real-time completion monitoring has the potential to revolutionize the ability to manage deepwater wells by understanding evolution of flow, drawdown, and impairment in real time.

Fig. 1: Seismic Exploration: Leading (Cutting) Edge Technology

Survey index	seismic record arguments	data dimensionality
1D	T	1D
2D	Lx, t	2D
3D	Lx, Ly, t	3D
4D	Lx, Ly, t, τ	4D
3D/3C	Lx, Ly, t, α_r, φ_r	5D
4D/3C	Lx, Ly, t, τ, α_r, φ_r	6D
3D/9C	Lx, Ly, t,α_s, φ_s, α_r, φ_r	7D
4D/9C	Lx, Ly, t, τ, α_s, φ_s, α_r, α_r	8D

Where: t = time, Lx = offset on x,
Ly = offset on y, τ = date of seismic survey,
α_r = azimuth of a component recorded at a receiver point, φ_r = bearing of a component recorded at a receiver point, α_s = direction azimuth at a shot point , φ_s = direction bearing at a shot point.

4D Seismic – Status and Future Challenges

Future challenges: Not all reservoirs are ideal candidates for 4D seismic technology. The industry has gained substantial experience through a large number of 4D seismic surveys across a large variety of reservoir situations, including clastic, carbonate and fractured reservoirs under various recovery schemes. The oil and gas industry now regards 4D as a proven technology for monitoring fluid movements

and identifying undrained compartments in thick offshore clastic reservoirs. The challenge for the geophysicists is to extend the 4D technique to thin-bedded clastic reservoirs, carbonates, onshore sedimentary basins and extra heavy oil and tar sands . Although it has been a success story so far, there are important challenges that need to be met to ensure that the technology will be a frequently used tool world wide. In our view the most crucial challenges are: Improved vertical 4D resolution (ideally, 1-10m); Improved repeatability, enabling application to carbonate reservoirs; and Innovative ways to combine 4D seismic with other measurements and simulation methods. Time-lapse seismic is now a proven technology for monitoring fluid movements and identifying undrained compartments in thick offshore clastic reservoirs. Several challenges still exist, however, in particular the use of the technology for carbonate and thin-bedded clastic reservoirs.

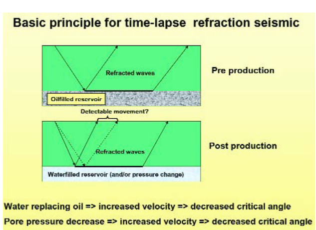

Fig. 2: Basic principle for time-lapse refraction seismic. A minor velocity change in the reservoir layer might cause a significant shift in critical offset at the surface, since the distance from the top reservoir interface to the surface is typically several kilometers, and a change of 1 degree in critical angle will then lead to several tenths of meters change in critical offset.

The Physical Basis: 4-D Gives Reservoir Surveillance

Reservoir surveillance during production is a key to meeting goals of reduced operating costs and maximized recovery. Differences between actual and predicted performance are typically used to update the reservoir's geological model and to revise the depletion strategy. The changes in reservoir fluid saturation, pressure and temperature that occur during production also induce changes in the reservoir acoustic properties of rocks that under favorable conditions may be detected by seismic methods. The key to seismic reservoir surveillance is the concept of differential imaging using time-lapse, or 4-D measurements.

Time-lapse seismic methods are usually based on differences in seismic images that minimize lithologic variations and emphasize production effects. Seismic velocity and density changes in a producing reservoir depend on rock type, fluid properties, and the depletion mechanism. Time-lapse seismic responses may be caused by: Changes in reservoir saturation. Displacement of oil by gas cap expansion, gas injection or gas exsolution resulting from pressure decline below bubble point; these decrease velocity and density. Water sweep of oil increases velocity and density.

Pore fluid pressure changes during fluid injection or depletion. Injection will increase fluid pressure, decreasing the effective stress acting on the rock frame and lowering seismic velocities. Compaction during depletion reduces porosity and increases velocity and density. Temperature changes. An increase in temperature increases fluid compressibility, and as a result decreases reservoir seismic velocities and density. Reservoir factors that affect the seismic detectability of production changes can be evaluated in order to determine which geological settings and production processes are most suited for reservoir monitoring. Each field is unique, and modeling of the seismic response to production, based on reservoir flow simulation, is used to evaluate the interpretability of seismic differences and to determine how early in field life a time-lapse survey can be used to monitor reservoir changes. The optimal times for repeat seismic surveys depend on detectability and the field's development and depletion plan. Planning for repeat surveys in the context of field surveillance will maximize the value of the data. Seismic Repeatability: The difference between two seismic surveys is not only sensitive to changes in reservoir rock properties, but also to differences in acquisition and processing.

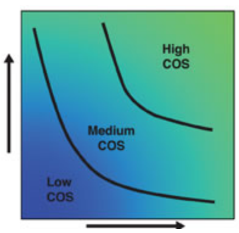

Fig.3: Dependence of 4-D chance of success (COS) on detectability and repeatability.
Detectability-rock properties, fluid properties, depletion process
Repeatability-acquition geometry, overburden complexity, processing similarity, signal to noise

Petroleum Geomechanics

Geologists, petrogeophysicists/petrosadists, drilling engineers, reservoir engineers concerned with: wellbore stability; fracture stimulation; Reservoir drainage patterns; naturally fractured reservoirs; overpressures; fault seal integrity, or; image log interpretation.

Calibration of velocity effective-stress relationships for 4D seismic : Injection and depletion of reservoirs results in a change in both saturation and pore pressure conditions. Saturation is affected in terms of changing fluid density in the reservoir pore space whereas changes in pore pressure alter effective stress conditions which are generally thought to control seismic velocity response. Time-lapse (4D) seismic data is used to visualize changes in a reservoir due to injection or depletion, such as movement of hydrocarbon contacts due to production, as well as to locate bypassed pay or isolated compartments. Discrete 3D seismic surveys are shot a few years apart in order to extract difference profiles which show changes in velocities and amplitudes due to production. However, 4D seismic surveys are expensive, so experimental feasibility studies need to be carried out in order to verify whether, for example, increases in effective stress due to depletion will show detectable velocity change in a 4D survey. Such feasibility studies are often carried out on core plugs in the laboratory where velocity-effective stress relationships can be assessed under controlled stress and pore pressure conditions and the results can then be inserted into models of 4D seismic response that incorporate both stress and saturation changes.

Geophysical applications include dry and saturated measurements of reservoir dynamic elastic properties and the impact of stress and pore pressure change for application to 4D seismic monitoring.

4D Time-lapse Seismic Data Analyses

The general objective of time lapse 4D seismic monitoring is to track production related changes in the reservoir and determine areas of bypassed production, or inefficiencies in the production process. This is accomplished through the comparison of 3D seismic surveys that have been recorded at various points in time over the life of the field. The analysis of time-lapse seismic data generally includes the following steps: 1) Estimate the types of velocity and density changes that will occur in the reservoir during production. 2) Create synthetic seismic traces that represent the reservoir conditions for a range of production scenarios. 3) Analyze the synthetic traces to determine the types of changes that may occur in the seismic data. 4) Compare the seismic surveys that were recorded at various times in the field's production history. 5) Calibrate the 3D seismic volumes to remove spurious differences related to seismic acquisition and processing as well as changes in the near surface. 6) Subtract the calibrated seismic surveys and map the differences. 7) Interpret the calibrated 3D surveys and the difference surveys to determine the areas of the field that have been changed during production. 8) Compare the seismic differences to the synthetic traces to analyze the types of changes that have occurred in the reservoir (pressure, temperature, saturation, etc.). 9) Estimate the area and volume of these produced areas and compare to the known production of the field.

The most important feature of time-lapse seismic monitoring data is the opportunity to compare seismic images as a function of elapsed time. Careful attention to data processing issues is needed to ensure that images obtained at one time are validly comparable to subsequent images. This is especially true for seismic difference sections, in which one seismic image is subtracted from a second seismic image acquired at a different time.

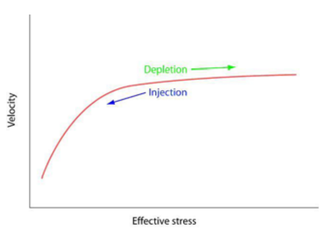

Fig. 4: Schematic velocity-effective stress relationship for reservoir sandstones. Velocity is more sensitive to stress change at low levels of effective stress. Hence, velocity is likely to be more sensitive to injection, where effective stress is lowered as compared to depletion, where effective stress increases.

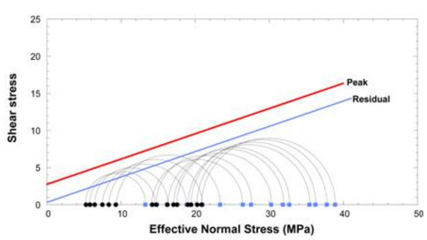

Fig. 5: Mohr circles for in situ stress conditions compared to laboratory-derived rock (peak) and fault (residual) strength.

Conclusions

High frequency imaging: The optimization of the vertical resolution is achieved through high frequency imaging (HFI), a process that sustainability extends the usable bandwidth of conventional seismic data. In addition to achieving high repeatability ,another challenge in 4D seismic is to obtain higher frequencies in order to image and quantify subtler time- lapse effects. This is particularly important in the context of continuous monitoring where repeat surveys are acquired every year/ monthly of complex reservoir. 4-D and its merits : 4-D uses a series of repeated 3-D seismic surveys over a field ,the fourth dimension is calendar time- the interval between surveys. Differences between successive seismic surveys indicate change in producing reservoirs , such as fluid movement ,or pressure and /or temperature changes. Analysis of these differences allows fluid-front surfaces to be tracked within reservoirs as a function of time. Tracking reservoir fluid position during production provides advanced warning of production behaviour change that may be used to prolong well life and/ or change production schedules to enhance ultimate recovery. Conventionally , wells provide most data available during production. 4-D can provide similar data and provide it throughout the interwell space. Manifold benefits can be expected by identifying unswept pools using 4-D.

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