Monitoring Reservoir Fluids using Micro Earthquake Technology: Alternative to 4D Seismic

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Summary

Many of the giant oil fields in the Middle East produce from prolific carbonate rock reservoirs. Collectively these carbonate reservoirs hold well over 50% of the world oil reserves. The high rigidity of the limestone-dolomite reservoir rock matrix, a small contrast between the elastic properties of pore fluids, low GOR oil and mixed salinity water are responsible for the weak 4D seismic effect from oil production in the reservoir under study. An alternative reservoir fluid monitoring technique, between wells, was therefore considered. Permanent seismic sensors installed in a borehole and on the ground surface over a producing field will record passive monitoring of micro earthquake activity generated by reservoir pore pressure perturbations (Figure 1). Reservoir production and injection operations create these pressure or stress perturbations that are induced by shear stress release along zones of weakness in these rocks. The injection operation generates reservoir pore pressure increase which creates shear stress increase affecting the stability along the planes of weakness in reservoir rocks like joints, bedding planes, faults and fractures. Similarly reservoir production operation or fluid withdrawal creates a pore pressure sink that affects stability in zones of weakness. The microseisms or minute earthquakes emanating from the reservoir would be recorded simultaneously at a large number of multicomponent seismic sensors that are deployed permanently at various levels in the borehole and over a surface area surrounding the borehole. Special geophones capable of measuring frequency response over 100-1000Hz frequency range would be installed. Reservoir heterogeneities affecting the fluid flow could be mapped by recording the distribution of hypocenter locations of these microseisms or small earthquakes.

Alternative technique

An alternative approach to 4D seismic for reservoir monitoring is proposed. Installation of permanent borehole seismic sensors is proposed for passive monitoring of microseismic activity using 3-component permanent seismic sensors cemented in the borehole at various levels and surface sensors buried and cemented below the ground (Figures 2). Microseismic events or small earthquakes are generated by stress changes as the reservoir stress is perturbed by production and injection activities in the reservoir (Jones & Stewart 1997). The high rock strength, fast wave propagating velocities, high Q (i.e., low seismic attenuation) and perturbation of the reservoir ambient stress state due to fluid injection and production drawdown are favorable for microseismic transmission and monitoring (Shapiro *et al*. 1997). Micro earthquakes emanated from these pore pressure perturbations in the reservoir due to injection and production could map the flood front movement (Jupe *et al*. 1998). Some of the factors that make 4D seismic monitoring less favorable in the reservoir are the same conditions that make microseismicity more conducive for fluid flow-path monitoring in the reservoir.

Monitoring of flood front between wells could provide "an early warning system" to the reservoir engineers.

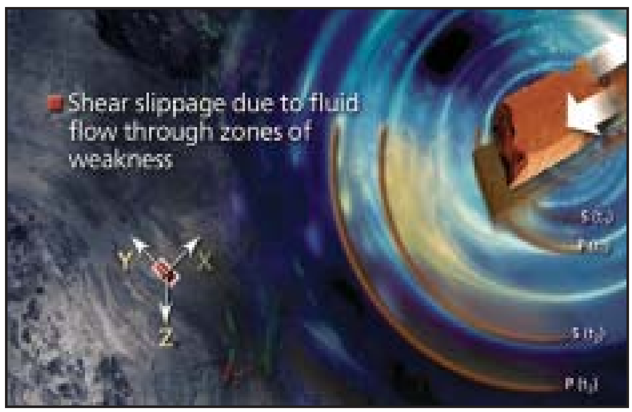

Fig.1. Reservoir production and injection operations create stress perturbations induced by shear stress release and cause shear slippage along zones of weakness in reservoir rocks. Minute earthquakes emanated along the elastic failure surface are recorded in 3-component seismic sensors.

Microseismic events in the reservoir can delineate fluid-flow paths and define conductive fracture geometry at inter-well scale. Timely availability of this information would prevent premature water breakthrough in production wells, identify untapped oil pockets in the reservoir and increase the ultimate recovery of oil (Dasgupta, 2005).

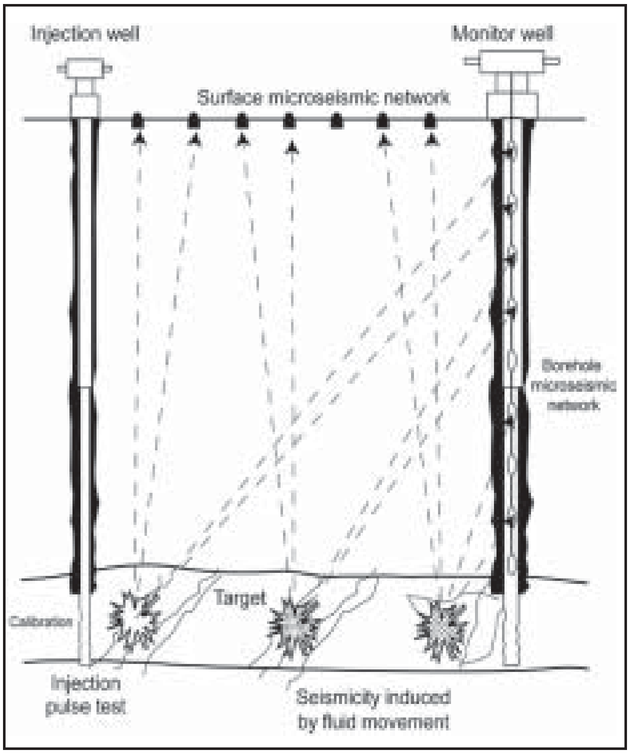

Fig. 2 A network of 3-component sensors permanently cemented in boreholes and on ground surface measure events triggered in the reservoir. Microseisms or minute earthquakes are induced by reservoir rock slippage with reservoir fluid movement.

Feasibility study

A feasibility study consisting of rock physics, petro-acoustic data analysis and seismic modeling was recently conducted over a mature producing area in a Saudi Arabian oilfield. The impact of fluid saturation changes on seismic response was computed by forward modeling. The study included analyses of different seismic monitoring methods, both active seismic and passive microseismicity measurements. A history matched fluid simulation numerical model was initialized from the beginning of production in 1953 and was run in prediction mode to reservoir depletion in 2032 at a one-year time steps (Dasgupta, 2005). The model was tested for consistency at 24 wells. The objective was to study seismic monitoring methods using permanent downhole sensors. Modeling quantified the seismic response of reservoir saturation changes as brine replaces oil. Seismic forward modeling was performed using Gassmann's fluid substitution equations. Fluid substitution modeling concluded that because of low impedance contrast between the oil and injected brine and the stiff carbonate reservoir frame, time lapse surface 3D seismic or conventional 4D seismic is unlikely to detect the flood front within the repeatability of surface seismic measurement (Figure 3). Results of the feasibility study provided the most practical options for seismic monitoring and design specifications for a field trial.

Field pilot design

This feasibility modeling demonstrated that the sensitivity of the 4D seismic measurements is low in this carbonate reservoir with low GOR (gas oil ratio). The weak 4D response can be mitigated to some extent with improved repeatability (Landrø 1999). Repeatability, however, needs to be measured as it cannot be simulated. In order to measure the repeatability under optimum conditions proper field pilot design needs to be performed. Permanent sensors cemented in the borehole have optimum coupling and the best repeatability. The field design in this study assumed permanent borehole sensors installed during the well completion of a newly drilled vertical well.

For active seismic experiment the following acquisition techniques were investigated:

- Cross-well seismic survey— permanent receivers in a well and a borehole seismic source deployed periodically in a neighboring well.

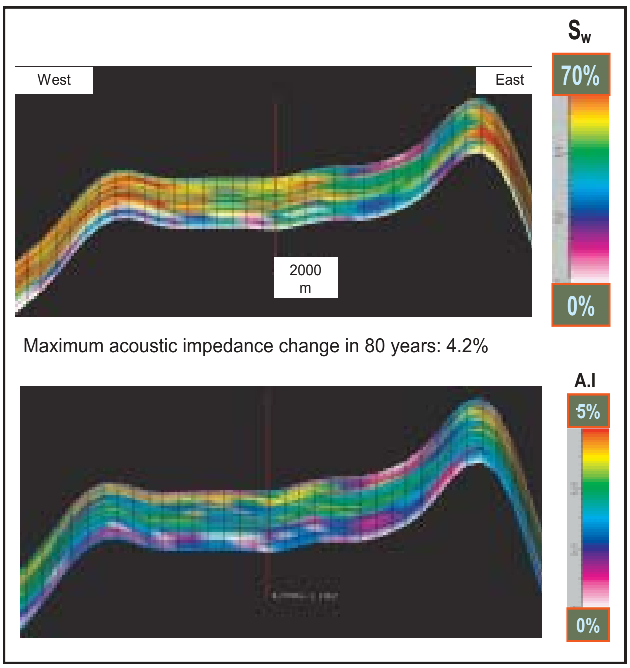

Fig. 3. Water saturation (S_w) changes from the fluid simulation model for year 1953 to 2032 and the resultant acoustic impedance (AI) change over the same time period

- Offset VSP surveys – permanent receivers in a well and surface source at fixed locations at different azimuths.
- Offset VSP with buried source – permanent receivers in a borehole and seismic electro-mechanical source installed permanently in a shallow hole. This would provide ideal coupling of both source and receivers.

From a practical implementation stand point in only the offset VSP survey was recommended as economically feasible. The others are either too costly or too cumbersome to attempt a field implementation. The considerations in the recommendation included available technology, cost-benefit, reliability and proven technique.

For passive recording, the main focus in modeling process is the spatial distribution and number of sensors for recording the microseismic events. These factors have a significant effect on the system performance.

The borehole sensors to be used for microseismic monitoring are the same as those required for offset VSP. The specifications of the instruments, however, in terms of sensitivity, recording bandwidth and vector fidelity are more stringent in order to recording these weak seismic events. The coupling of these sensors to the formation at the borehole wall is also important. Permanently cemented sensors behind the casing or sensors mounted on the production tubing with a permanent clamping mechanism ensure the requisite coupling (Figure 3).

Conclusions

The feasibility study demonstrated that a combination of repeated VSP surveys and passive microseismic recording would be best suited for reservoir pore fluid monitoring. Permanent sensors would improve the seismic repeatability and enhance the resolution and signal to noise. Repeatability is the key issue due to near surface seasonal variations.

Permanent borehole installations should include along with seismic, sensors for measuring pressure, temperature, saturation and flow rates, continuously, as the fluids are produced. Permanent seismic sensor would be part of the instrumented oil field of the future (Lumley 2001). With increasing completions in horizontal multilateral wells, continuous seismic imaging and microseismic recording would open up new possibilities for real-time reservoir monitoring and well interventions. Permanent seismic sensors will become part of instrumented or "smart" wells of the future

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