A High Channel-Count, Modular Down-hole System for Permanent Reservoir Monitoring

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Summary (on cover page and not in main body)

We have developed a cost-effective down-hole PRM system. This system, given the name PerForM™, can be installed on production tubing and has a flexible interface, which allows integrating data from other sensors. The system uses electric geophones with electric communication (copper) with full redundancy between the sensor nodes, and high-capacity digital fibre-optic transmission of the measurements to the surface, also with full redundancy. The high-bandwidth digital communication allows the deployment of up to 120 sensor nodes with a total of 480 individual data channels at 2 ms sampling. The digital transmission also allows the possibility of feeding through a wellhead in a sub-sea completion using electrical penetrators and temporary conversion to digital electric signal.

The first pilot system has been delivered to Petrobras and is scheduled to be installed offshore Brazil, Q2, 2013.

Introduction

Seismic surveys are most commonly performed with active sources and arrays of receivers measuring components of the acoustic wave field reflected from inhomogeneities in the rock formation. This can be done either for exploration – mapping structures in unknown formations – or in a repeat mode (or "4D") to map out changes in the formation resulting from the production of a reservoir. In the last few years it has also become more common to map out "passive sources", i.e., using arrays of listening devices to listen to spontaneous acoustic emissions from the rock matrix as a result of either reservoir stimulation or changes in stress and strain in the rock matrix resulting from production of a reservoir.

North America has seen a significant upturn in production from tight-rock reservoir such as shale gas or shale oil, related to a stimulation technique called Hydraulic Fracturing, or "frac'ing". During this process, the segment of a well to be treated is isolated. If the well is cased, the casing will be perforated within the isolated segment, before the pressure inside this segment is increased until the rock starts to fracture. The minute earth ruptures, sometimes one million times less powerful than the smallest earthquake that might be felt by humans, can mostly not be felt on the surface. There can be hundreds or thousands of these very small microseisms and if the origin of each can be mapped, it is possible to create a picture of the fracture network. With the listening devices inserted in a well near the well being treated, smaller tremors can be detected than when the devices are deployed at the surface.

As the reservoir is produced and pressure is reduced, the rock in which the hydrocarbon was contained will compact. This compaction will naturally generate seismic events, mostly of low magnitude. As the reservoir section compacts, the overburden may undergo significant changes in the stress regime. These changes may, in turn, generate micro-seismic tremors the detection and localization of which can be detected and located using arrays of receivers. Knowledge of the frequency and distribution of these is important in the assessment of the "health" of the reservoir, and helps determine where and when mitigating actions should be taken.

For monitoring of reservoir being produced, it may be cost-efficient to install sensor arrays permanently, either on the sea floor (e.g., Barkved *et al.,* 2003) or in a well (Wilson *et al*., 2004). (Permanent Reservoir Monitoring (PRM) receiver arrays reduce the effort when doing repeat seismic reflection surveys (4D). In addition, they make it possible to listen to changes in stress and strain in the reservoir and above, related to the depletion of the reservoir.

Since acoustic emissions from microseismic events have low amplitude, it is natural to assume that these emissions are more easily detected using receivers deployed in a low-noise down-hole environment, than in the much noisier environment on the surface or at the sea floor. In response to this, Petrobras and READ ASA, with funding assistance from DEMO2000 decided to jointly develop a permanent down-hole acquisition system. The system was given the name of PerForM™. The pilot system, consisting of 15 3C Satellites, would be installed in a Petrobras offshore well, Brazil.

Down-hole Receiver Arrays for Active-Source Imaging

The example shown in Figures 1 and 2 (from Smith *et al.,* 2000) shows that placing the receiver array in a well near the features of interest did overcome the gas-cloud problem at Ekofisk where the gas cloud dispersed and absorbed the propagating compressional wave field, making imaging of the top reservoir impossible with surface receivers. A down-hole array also provides a better basis for imaging the steep flanks of a salt body, as well as mapping out changes in such structures induced by production of a reservoir.

Reservoir Stimulation and Monitoring

A whole industry has developed around monitoring micro tremors induced by pressure treatment of production wells (e.g., Drew *et al.*, 2005). When both P and S waves, generated from the microtremor, is detected in a nearby observation well, the azimuth to the event hypocenter can be determined from the polarization of the P wave, and the distance to the hypocenter from the time delay between the P and the S arrivals. This technique has been formalized for an array of receivers using migration focusing and deconvolution (e.g., Haldorsen *et al*., 2012). In Figure 3, we show data in a time window of data around the P and S arrivals, and in Figure 4, the azimuth to the event hypocenter and the "image" of the event location, giving the distance from the array and the depth of the event hypocenter.

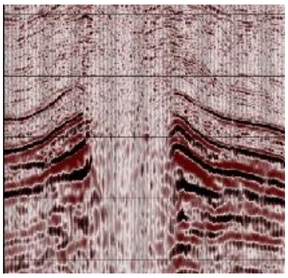

Figure 1. *Problem: Surface seismic data does not image the crestal reservoir section at Ekofisk (Smith et al., 2000).*

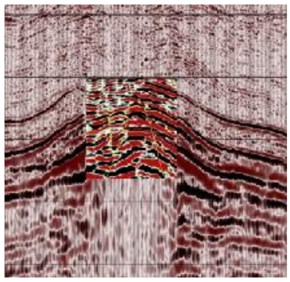

Figure 2. *Inserting the down-hole VSP results shows the missing information and better resolution where surface seismic does not.*

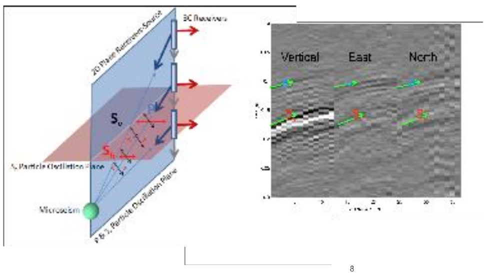

Figure 3. *On the right, schematics of P, Sv and Sh waves generated from a microseismic event. On the right, the 3 wave fields as recorded by an array of 12 3C geophones.*

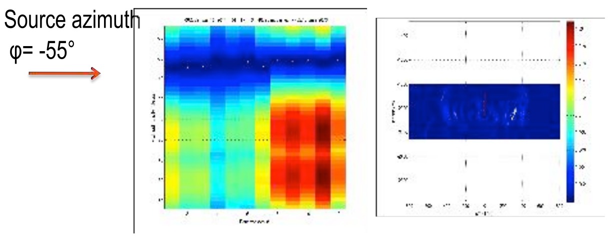

Figure 4. *On the left, the azimuth to an event is determined; on the right, a migrated and deconvolved, fixed azimuth image of an event, shows the distance and the depth of event.*

These same methods can readily be used with permanently installed receiver arrays for monitoring acoustic emission from fractures generated in and around the producing reservoir, and help the assessment of the "health" of the reservoir, and help determining where and when mitigating actions should be taken.

Benefits of Electric Down-hole PRM Systems

- Better microseismic detection
- With an active source and imaging in a VSP geometry
  - Higher resolution,
  - Improved image below salt (Rønholt and Chenin, 2006)
  - Improved image below gas (Smith *et al*., 2000)
- VSP data can be combined with OBC data to greatly improve the quality of the OBC image (Rønholt and Chmela, 2003)
- Cost effective when compared to repeat streamer surveys or OBC systems
- Electrical modules can be combined with Pressure, Temperature, E/M or other production or reservoir monitoring sensors
- Additional cost benefits when combined with the acquisition of ancillary data
- Possible to install in an existing well

Mitigations of Perceived Drawbacks of Electric Down-hole PRM Systems

- Coverage can be increased significantly through using multiple migration of the data (Jiang and Hornby, 2006; Farmani *et al.,* 2012)
- Expected lifetime of down-hole electronics: Modern electronic chips have high temperature rating and long lifetime

The Objectives for the PerForM™ project

- A cost-effective system that can be installed in a production or injection well.
- Can be used for VSP surveys whenever needed.
- Can be used to monitor acoustic emissions induced by stimulation or depletion of a reservoir.
- A flexible interface to enable integrating data from other sensors (pressure, temperature, etc.)

Design Requirements

In order for the system to be permanently installed downhole in a HPHT environment, operate long term, have modularity and flexibility, the system had to fulfil the following design requirements:

- Life-time of a minimum 6 years at 125ºC.
- Sustain temperatures up to 150ºC.
- Sustain pressures up to 10,000psi (690bar).
- Redundancies, e.g., in the electric telemetry between nodes, and in the digital optical telemetry to the surface, to enable the bypassing of failed components.
- Optical digital telemetry to the surface rated at 8Mb/s.
- Pass through sub-sea wellhead using one electrical penetrator (or 2 for 100% redundancy).
- 4C sensor modules with 24 bit digitization
- Sampling from 2 ms to 0.25 ms.
- High-capacity telemetry system allows up to 120 4C sensor nodes at 2 ms sampling

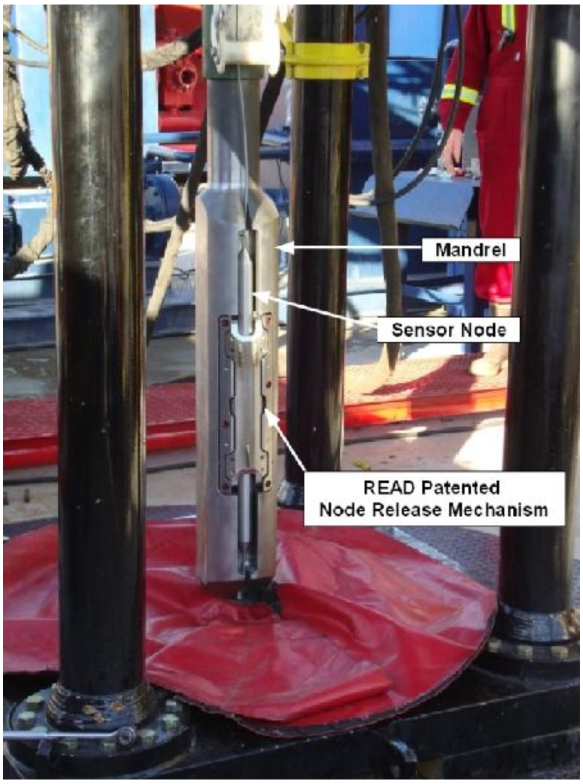

Figure 5. *Installing a* PerForM™ *sensor node on production tubing.*

Installation in a Well

One of the requirements for the design was that the sensor nodes could be installed attached to production tubing. For appropriate acoustic coupling to the formation, the sensor nodes will have to be pushed against the casing. Unlike the motorized arm of traditional VSP tools that extends and presses the tool against borehole wall, PerForM™ uses a simple burst-disk to release each sensor node from its carrier, and a dampened metal spring to push the released sensor node against the casing. The release system is completely independent of the sensor node, and does not require any electronics or motors. Figure 5 shows a PerForM™ sensor node, mandrel and release mechanism mounted on production tubing.

Where a PRM system would be installed would depend on a total assessment, considering the purpose of the installation, the availability of existing wells where the sensor nodes can be installed, and the noise environment expected in either of the available wells.

The pilot system, consisting of a data acquisition system and 15 3C sensor nodes, has been delivered to Petrobras and is scheduled for installation in an offshore well in Q2 2013.

Conclusions

An acoustic array installed permanently in a well near the reservoir, can detect smaller seismic activity in the reservoir. The new PRM system, PerForM™, encompassing a data-acquisition system, a high-capacity digital optical telemetry system and down-hole multi-component acoustic sensor nodes, allows for permanently installing up to 120-level 4C acoustic sensors with 480 individual sensors. The system can be used on its own or be combined with receivers on the surface.

The industry has been slow to accept PRM systems. However, the modular design of PerForM™ makes it possible to combine the acoustics with other sensors or equipment, measuring, e.g., pressure, temperature or flow-rate. When a PRM system is combined with measurements that are already accepted, and sometimes required, by well managers, it may improve the cost-efficiency of the combined system and may make acceptance easier.

Acknowledgments

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