Title: Integrated Reservoir Monitoring of the Ormen Lange field: Time lapse seismic, Time lapse gravity and seafloor deformation monitoring

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Introduction

The Ormen Lange field is located about 100 km off the coast of Norway in the Møre Basin (Fig.1). The reservoir covers an area of approximately 44 by 8 km, at a depth between approximately 2600 and 2913 mMSL. The water depth varies between 700 and 1100 m. The field has been developed by 4 subsea templates; the A-template delivered first gas in 2007, while the fourth C-template delivered first gas at the end of 2012. Primary development drilling is now nearing completion.

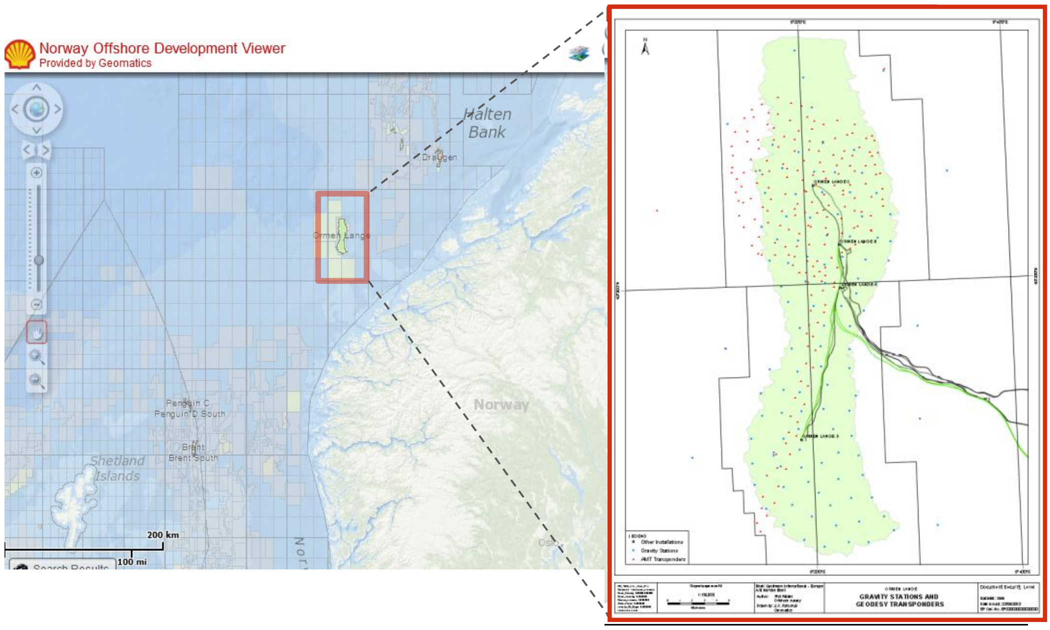

Figure 1: Ormen Lange overview. The field map contains gravity benchmarks in blue, and geodesy stations (AMTs) in red.

The next phase of development at Ormen Lange includes decisions on infill wells, the installation of compression facilities, and enhanced gas recovery. These decisions require a good understanding of the dynamic behavior of the field. Key uncertainties in this respect are fault seal / compartmentalization, and aquifer influx.

Compartmentalization

The Egga reservoir is deformed by a multi-tiered polygonal fault system. These faults have throws of up to 75m at top reservoir and grew during reservoir deposition. The fault patterns vary significantly, with a north to south reduction in throw values being most important.

The main risk for fault seal is through shale (clay) smear. Pressure data from wells drilled after production start up indicates that individual faults can forms baffles of 20 bar. No evidence for compartmentalization has been observed yet. However strong baffling and compartmentalization remains a risk, especially in the northern area, where reservoir quality decreases and fault throw increases (Fig. 2).

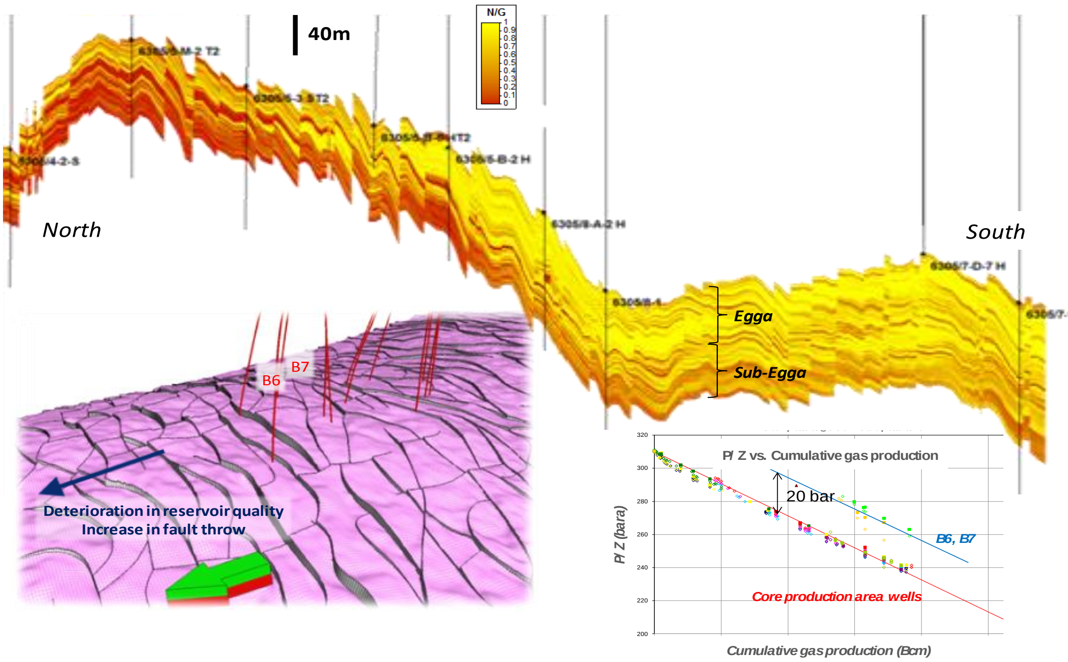

Figure 2: Polygonal faulting of the Egga reservoir. Deterioration in reservoir quality and increase in fault throw towards the north increases fault baffling potential and risk of compartmentalization

Aquifer influx

An aquifer has been interpreted to be connected to the southern half of the field. The aquifer strength is a significant uncertainty, of particular importance to several infill opportunities that have been identified in the south. Narrowing this uncertainty also has value for overall field management decisions. The limited production history in this area does not yet reveal any information on the strength of the aquifer.

Areal monitoring: feasibility studies and field trials

A range of geophysical monitoring methods has been considered to reduce these key uncertainties, identify and de-risk future infill well targets, and support long term development decisions.

The following list of technologies has been assessed by a combination of feasibility studies and pilot programs:

- Time-lapse seismic
- Seafloor geodesy
- Time-lapse gravity
- Time-lapse EM

Time-lapse seismic is the most mature technology in this set. It has been shown to deliver important information on contact movements, depletion patterns, and injection patterns. It also has a higher lateral resolution than any of the other areal monitoring techniques. However, a feasibility study for Ormen Lange indicated that the water influx signal will likely be very small and nearly impossible to detect. Furthermore, the strength of the depletion signal is such that it would take a very high quality survey, and 5+ years of production, to detect this signal. Three complementary non-seismic technologies were therefore assessed.

The continuous measurement of surface deformation, with the aim to derive information on production induced compaction, is a well known method for onshore fields. The application of this technology offshore in the form of seafloor geodesy is new. The advantage of this technology is that data is collected continuously, and can thereby provide a detailed view of the compaction behavior of the reservoir. Data collection is also significantly cheaper than time-lapse seismic. To test and develop the technology, a 10 sensor trial was installed in 2007 at Ormen Lange. The sensor network collected data continuously until 2009. The resulting data had an accuracy of 6mm per km in measuring lateral displacements.

Offshore time-lapse gravity is a relatively new technology. It has been matured and successfully applied by joint venture partner Statoil to monitor seafloor subsidence and aquifer influx in a number of Norwegian gas fields. The size of Ormen Lange combined with its relatively shallow depth below mud line makes it a good candidate for time-lapse gravity. This was confirmed in a detailed feasibility study. However, water depth and seafloor temperature at Ormen Lange are more extreme than at any other surveyed field, which results in data acquisition and processing challenges. Time-lapse data results from a pilot program conducted in 2007 and 2009 proved this technology feasible at Ormen Lange.

Time-lapse EM is an immature technology, but would have the advantage of being directly sensitive to saturation changes, without the need for a complex rock physics model, such as in the case of time-lapse seismic. A feasibility study was done. The result indicated that while the aquifer influx at Ormen Lange would be visible on time-lapse EM data, it would take 7+ years for the signal to be measurable. As time-lapse gravity has both a successful track record as well as a higher sensitivity to water influx at Ormen Lange, time-lapse EM was not selected.

Thus based on two pilot projects and several feasibility studies, three techniques were selected to provide spatial monitoring data: time-lapse seismic to provide information on depletion patterns and potentially baffled or isolated fault blocks, at a high resolution; seafloor geodesy to provide information on the same, but on a continuous basis and relatively cheaply; and time-lapse gravity to monitor aquifer influx.

Time-lapse seismic

A baseline for 4D seismic was acquired in 2008. The first monitor survey is planned for 2014. The time-lapse seismic signal is primarily expected to be a time shift over the reservoir interval, related to reservoir depletion and compaction. This response is difficult to predict (Ref Johnston, and papers referenced therein). The depletion induced velocity increase has been measured on core plugs, and the results are calibrated against time-lapse seismic measurements over other Shell operated North Sea fields. This portfolio of depleting gas fields is relatively small and diverse however, so the signal strength remains a key uncertainty. A 2D test to calibrate the signal strength was considered. However the nature of the overburden at Ormen Lange makes it likely that time-lapse 2D, without the benefits of 3D processing, would be much noisier than time-lapse 3D. A 2D test may therefore be inconclusive. The decision on timing of the first full field monitor survey is therefore driven by a careful assessment of the feasibility study results, and uncertainties therein; and the value of early monitoring data.

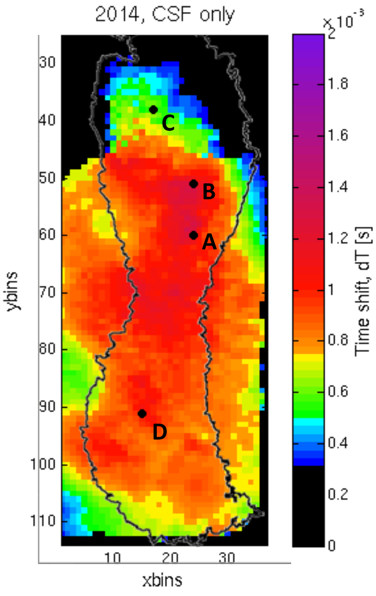

Figure 3: modelled time shift over the reservoir for the 2014 seismic monitor survey

Time-lapse gravity

Time-lapse gravity measures subsurface mass changes and can therefore be used to detect water influx and to monitor gas production. A full field baseline survey, the first in a non-Statoil operated field, was acquired in 2012 with excellent data quality. A first full field monitor survey is planned for 2014. During the 2012 survey further measurements were taken at the pilot stations that were previously surveyed in 2007 and 2009. This has provided us with time-lapse data from two monitor surveys over a limited area of the field. The results indicate a significant change in the gravity field over the main production area due to gas offtake, which is in line with the predicted change from reservoir models. The pressure data indicate that the central part of the field has been subsiding by an average of approximately 2 cm/year since production start up.

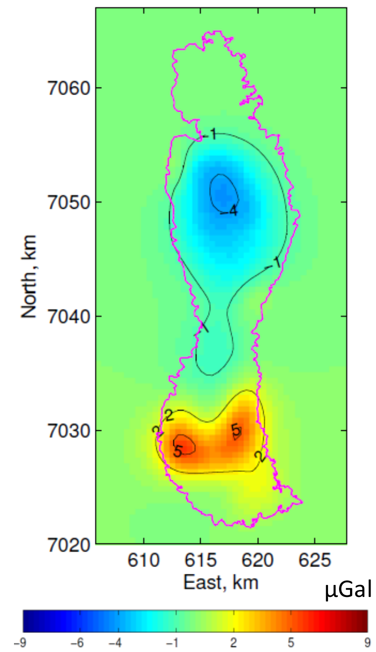

Figure 4: Modelled gravity change 2014-2012: the signal is positive where significant water influx results in an overall mass increase; the signal is negative where gas offtake results in an overall mass decrease.

Time-lapse seafloor geodesy

Time-lapse seafloor geodesy monitors lateral surface deformation by means of acoustic distance measurements between 175 network nodes. Seafloor subsidence is measured by a subset of the network which is equipped with pressure sensors. A successful two year trial was followed in 2010 by a world first commercial system consisting of 175 sensors covering a 15x12 km area. The network has been operating with partial success for three years, with nine data downloads collecting over 30 million data points. Although initial data results since 2010 have been found to be inconclusive, after data analysis from the latest 2013 download we now expect usable data from the full network in 2014. Subsidence data, collected by a subset of the network, has provided an upper bound to reservoir compaction.

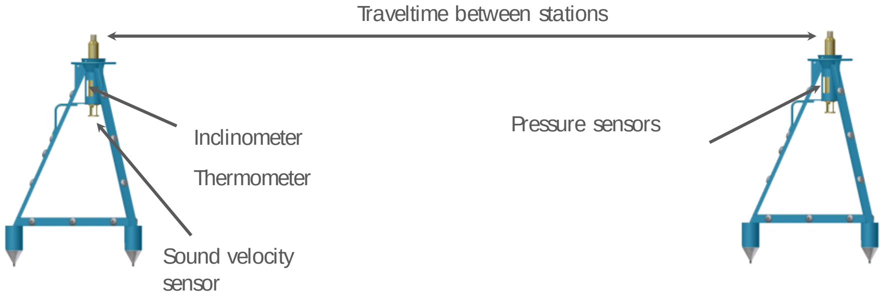

Figure 5: Seafloor geodesy measurement setup

Results and look forward

A comprehensive assessment of monitoring solutions has led to the deployment of a set of complementary monitoring technologies. Workflows for joint inversion of the data and integration into reservoir models are being developed.

The integrated results are expected to significantly enhance our understanding of the dynamic behaviour of the field, and to lead to optimized development decisions. For two of the three technologies the first monitor data will be collected in 2014, making this a key year for monitoring at Ormen Lange.

Aknowledgements

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