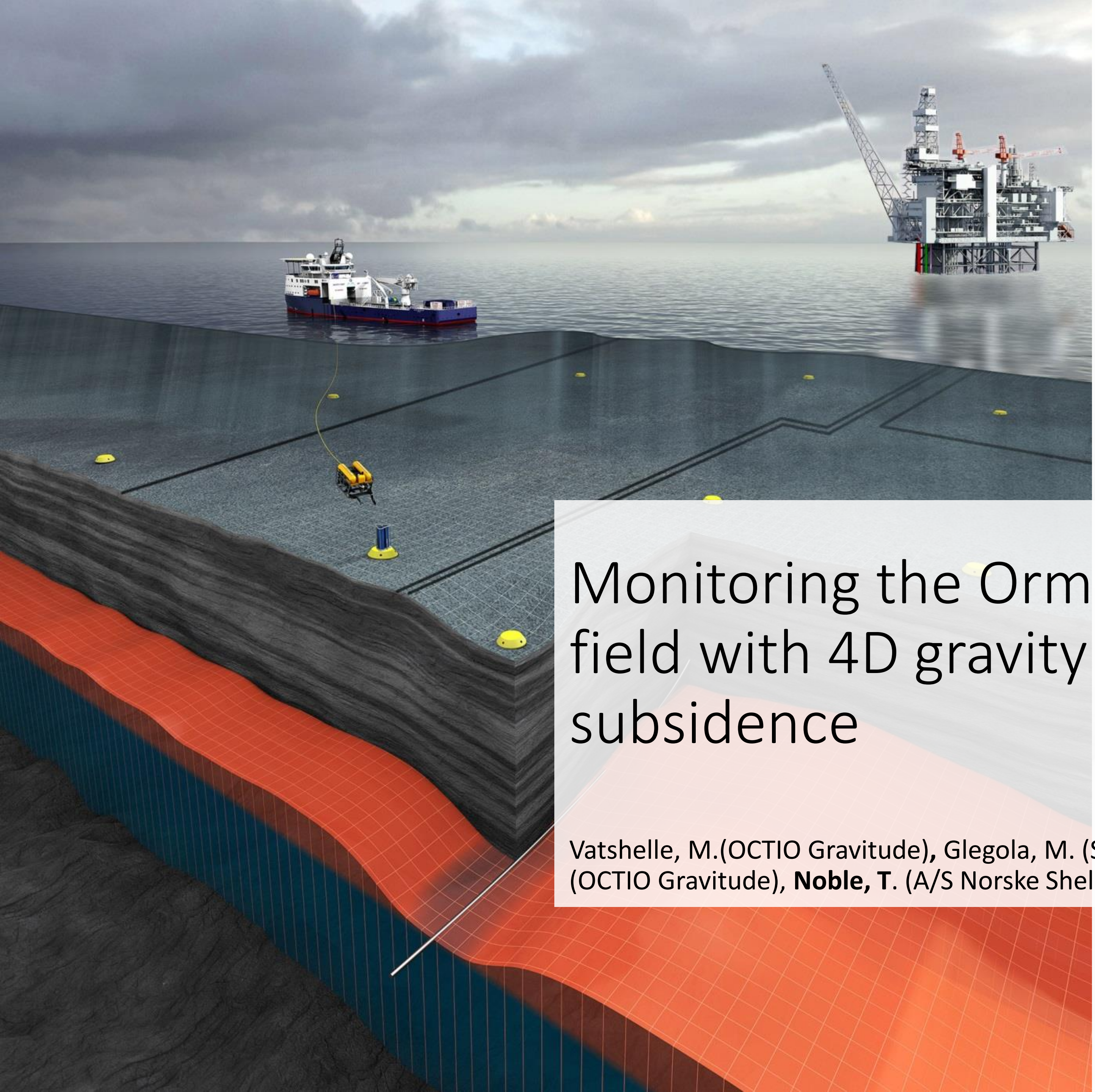

Monitoring the Ormen Lange field with 4D gravity and seafloor subsidence

Vatshelle, M.(OCTIO Gravitude), Glegola, M. (Shell Global Solutions), Lien, M. (OCTIO Gravitude), **Noble, T**. (A/S Norske Shell), Ruiz, H. (OCTIO Gravitude)

PARIS 2017
79th EAGE Conference & Exhibition

Outline

- The principles behind 4D gravity and subsidence monitoring
- The Ormen Lange field case:
  - Subsidence results
  - 4D gravity results
- Summary and concluding remarks

Two Independent Monitoring Tools

- **4D gravity at the seafloor**
  - Direct measure of **density changes** within the reservoir

- **Subsidence (4D pressure) at the seafloor**
  - Field-wide measure of reservoir **compaction**

- Both:
  - Are **cost-effective**: surveys cost down to 10% of seismic survey
  - **Fast turnaround:** processing and interpretation can be finalized within months after a survey
  - Environmental friendly: passive measurements

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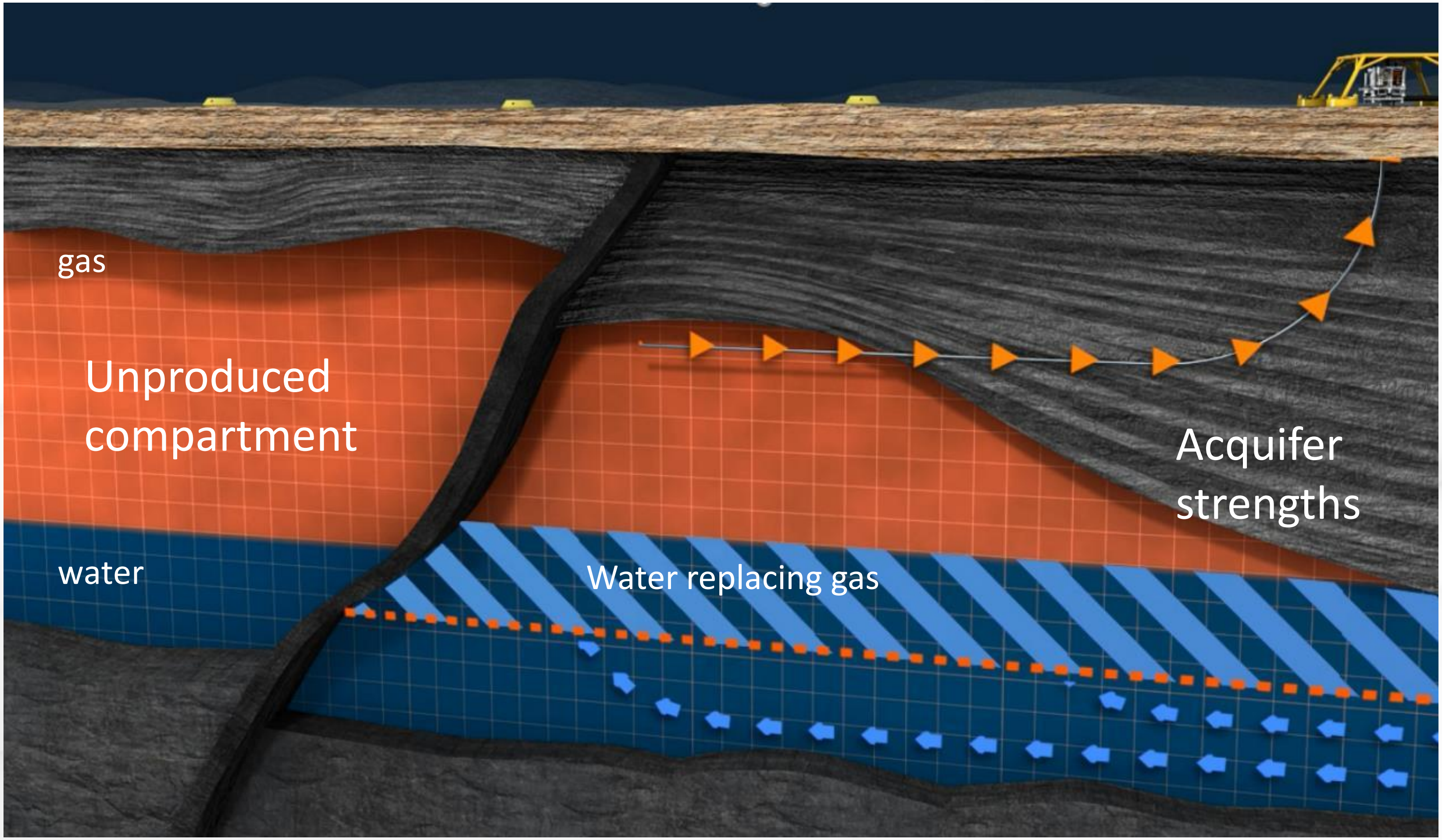
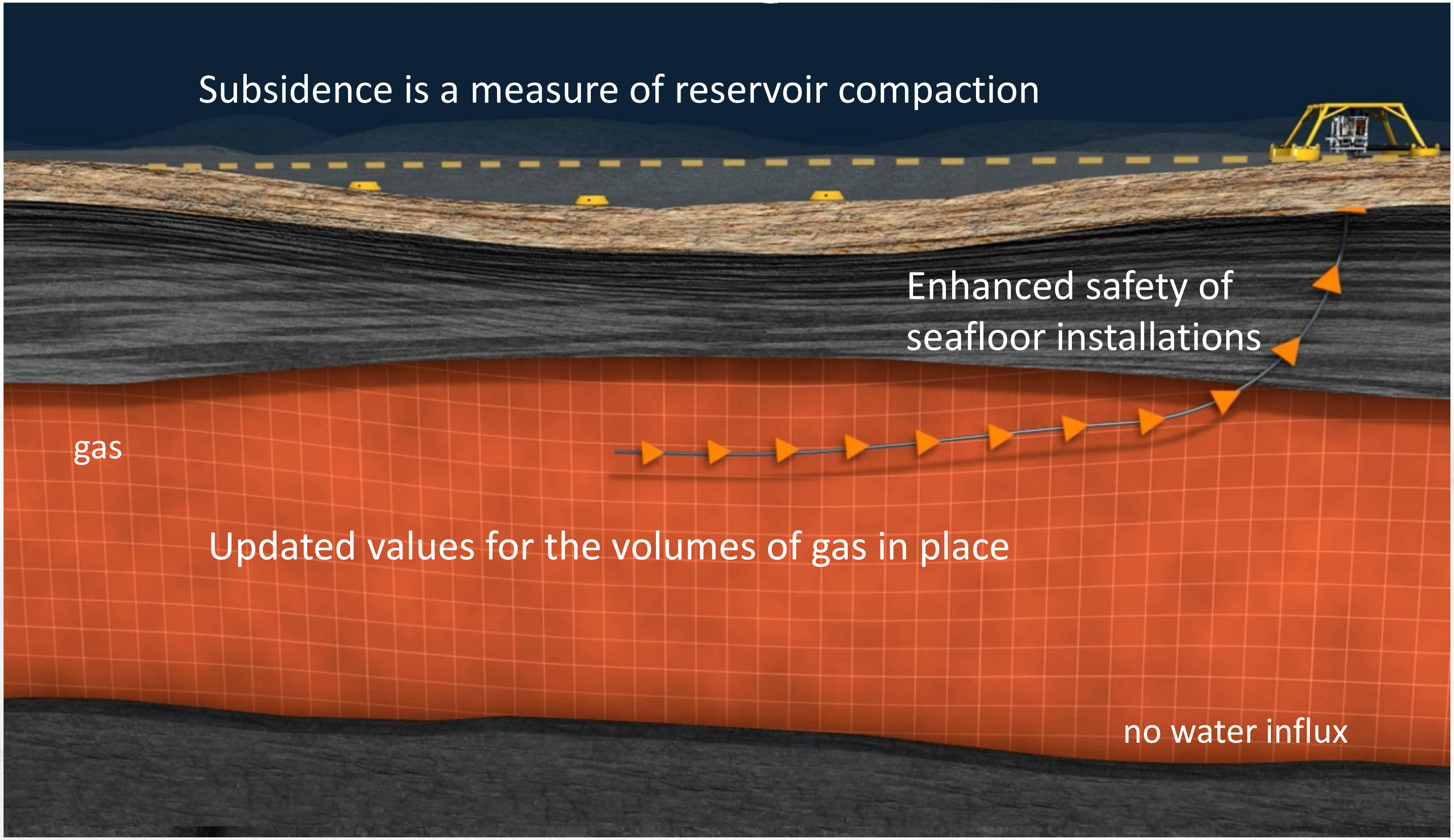
Information from 4D Gravity and Subsidence



Information from 4D Gravity and Subsidence

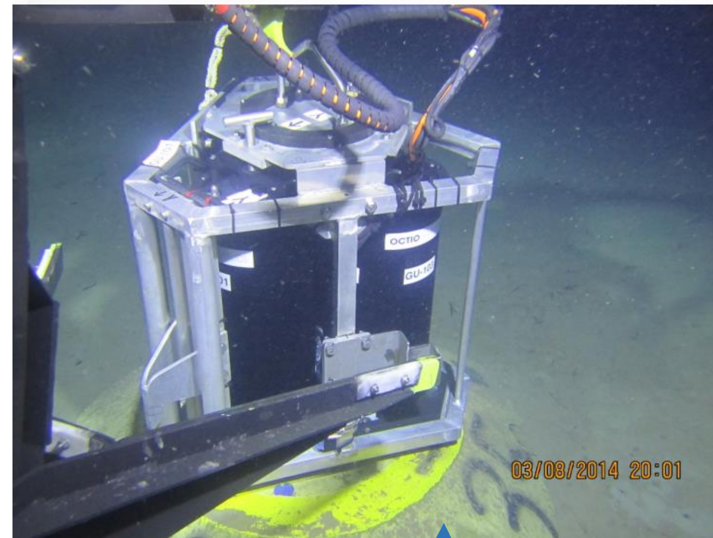


The Surveys in a Nutshell

Sensor frame with three **relative gravimeters** and three **pressure sensors**

Primary measurements: gravity and **pressure** at the seafloor

ROV



Concrete platform
20’ per measurement
Repeated visits

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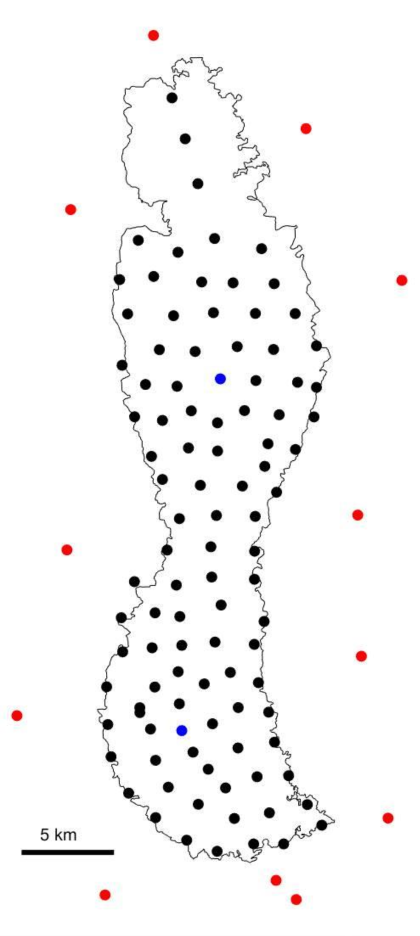
The Principles of the Technology

- Pressure and gravity are measured at a set of concrete platforms at the seafloor through repeat surveys
  - **Normal stations:** visited at least twice per survey
  - **Base stations:** visited > 10 times; Allow correcting for instrumental drift (mainly of the gravimeters)
  - **Zero-level stations:** outside of the field, no subsidence or change of gravity expected
- Tide sensors deployed during the whole survey at a subset of stations
  - Allow to refer all measurements to normal sea and atmospheric conditions



Ormen Lange

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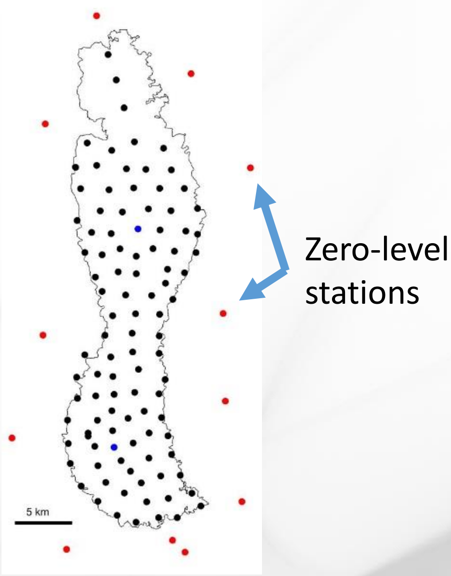
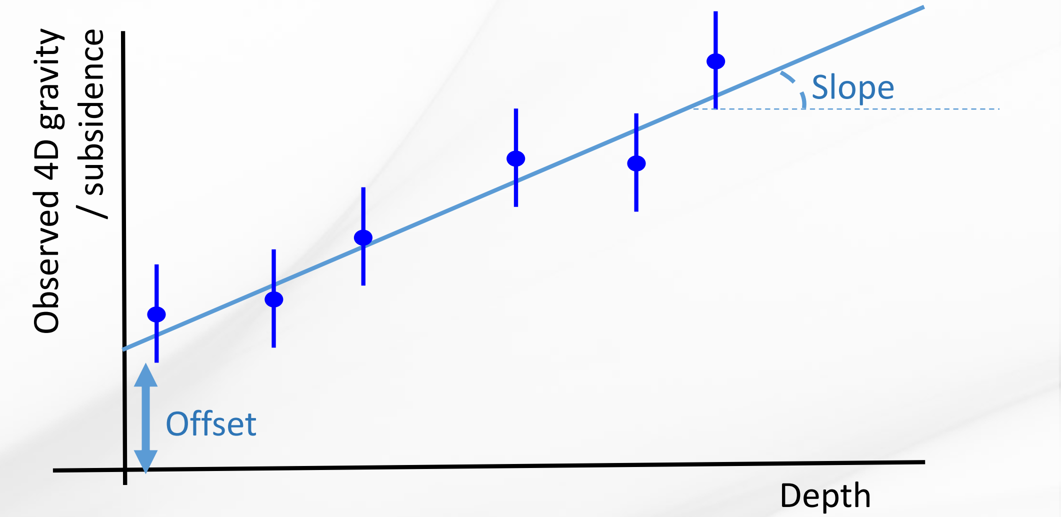
The Role of Zero-Level Stations

- The accuracy of both 4D gravity and subsidence is improved by constraining the change in these stations to be zero





- They allow correcting for a bias and a calibration factor (slope) between surveys

  $\Rightarrow$ **the method is self-calibrated**
- Once the correction is applied, the spread of zero-level stations is a **direct measurement of time-lapse accuracy**
- Obtained accuracy in 4D gravity is down to **2 µGal**, in subsidence it is **2 mm**

Gravity and Subsidence Monitoring at the NCS

Field	1st survey	# of surveys	Seafloor depth (m)	Reservoir depth (m)	Area (km^2)	N. stations	Application
Troll	1998	6	320	1400	30 x 50	113	Reservoir compaction, aquifer influx
Sleipner	2002	4	80	800 / 2350	4 x 10	50	Temperature and density of CO_2
Statfjord	2012	2	140-200	2750	5 x 25	53	Subsidence; aquifer strength
Mikkel	2006	4	230	2500	3 x 12	21	Aquifer strength; volumes of gas in place
Midgard	2006	4	240-310	2500	10 x 20	60	Compartmentalization; infill well planning
Snøhvit	2007	2	250-340	2500	20 x 20	86	Volumes of gas in place
Ormen Lange	2007	5	295-1130	2000	15 x 50	120	Next slides

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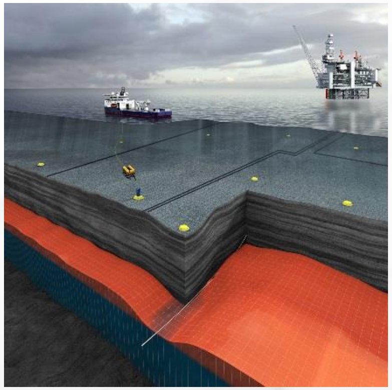
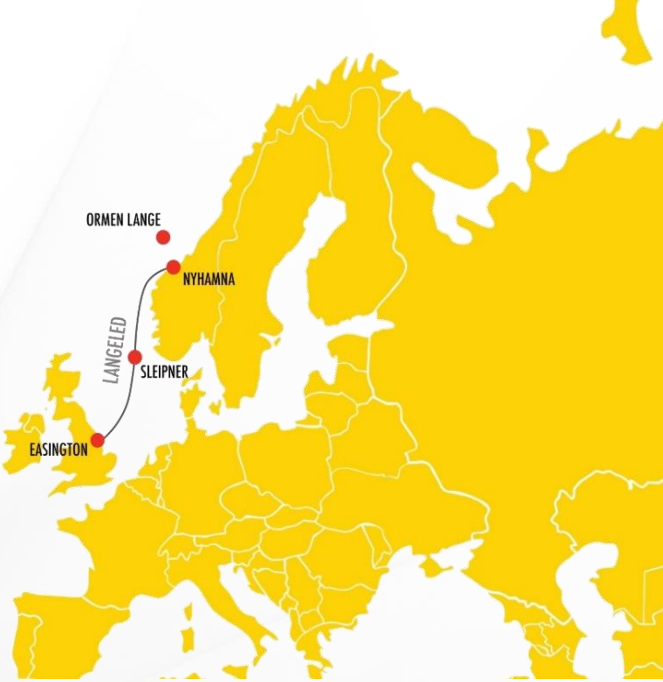
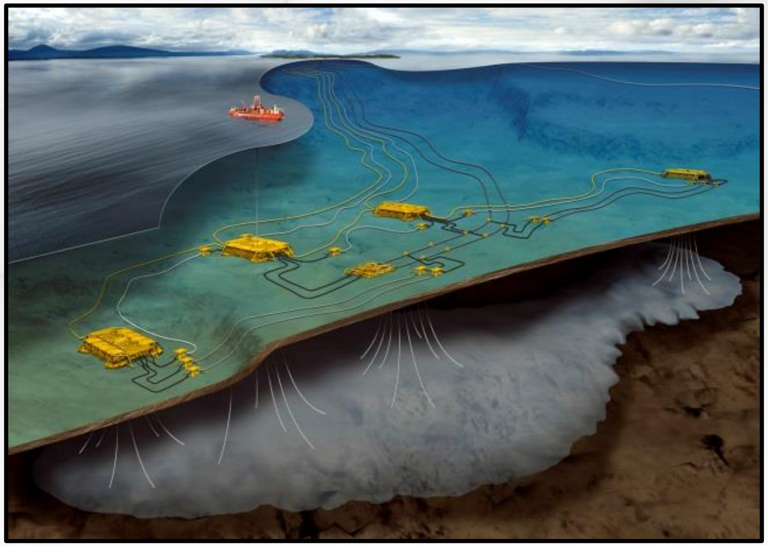


Gravity and Subsidence Monitoring at Ormen Lange

Ormen Lange in Context



- Located in the Møre basin on the NCS
- Reservoir depth: $2600 - 2900$ m below sea level
- Areal extent: 44×8 km^2
- Operated by Shell with four licence partners
- Currently producing through four subsea well templates



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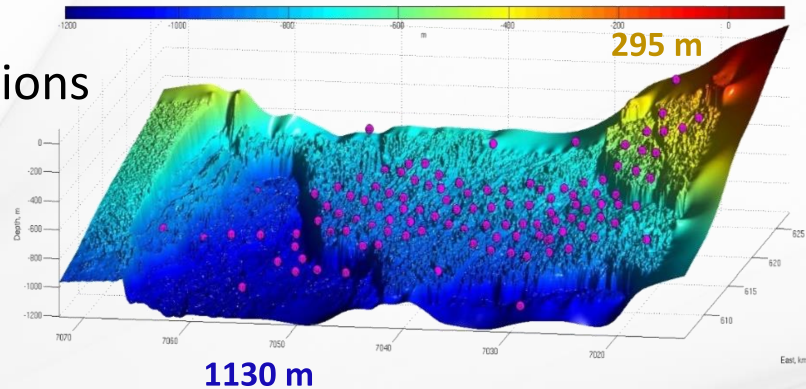
Ormen Lange in Context

- An integrated reservoir monitoring program is employed to assist with late field-life development decisions (e.g., compression facilities)
- Two aspects are key input for such decisions:
  I. aquifer strength and influx
  II. potential compartmentalization
- 4D gravity, subsidence and seafloor geodesy are used in addition to 4D seismic

4D Gravity and Subsidence Monitoring

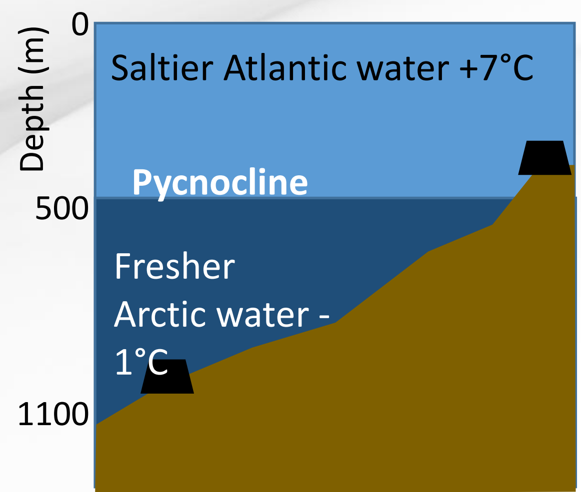
Acquisition history:

- Pilot surveys in 2007 and 2009 at eight stations
- First fieldwide base-line survey in 2012
- Repeat surveys in 2014 and 2016



Ormen Lange specific challenges:

- Large seawater depth range: 300-1150m imply:
  - Spatial variations in the measurement conditions across the field
  - Fast time variations: pycnocline depth varies by 150 m in hours (impact of 9 cm in pressure-to-depth and 3.75 µGal in gravity corrections)
- Because of oceanographic variations, seafloor subsidence cannot be measured with the required accuracy using 4D seismic time-shifts



4D Gravity and Subsidence Results

- At each survey, stations are visited at an average of three times
- This allows to compute single-measurement repeatability as an estimator of acquisition and processing uncertainties
- From the spread of the zero-level stations a direct measure of the accuracy in the time lapse results is obtained
- For the 2012 and 1014 measurements, the average station uncertainties and the time-lapse accuracy are:

	2012 (stat)	2014 (stat)	Time-lapse (stat + syst)
Depth	4 mm	3 mm	6 mm
Gravity	1.9 µGal	1.2 µGal	3 µGal

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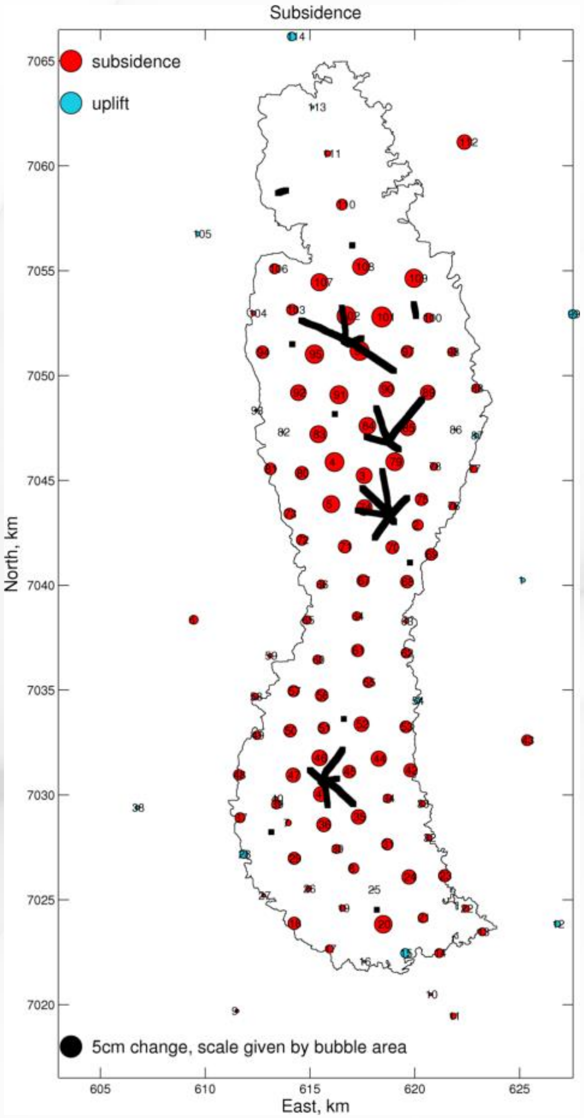
12-14 Subsidence Measurements

Measured subsidence at each concrete platform:

- The results are compatible with zero within measurement noise for the zero-level stations
- A significant, smooth subsidence signal is observed with a maximum of approximately four cm in the north
- The values measured in the south are smaller than anticipated from models
- The results are consistent with and applied to calibrate the seafloor geodesy system



De Vries et al. [2017], A Long term Seafloor Deformation Campaign at Ormen Lange Gas Field. *First EAGE workshop on Practical Reservoir Monitoring.* DOI:10.3997

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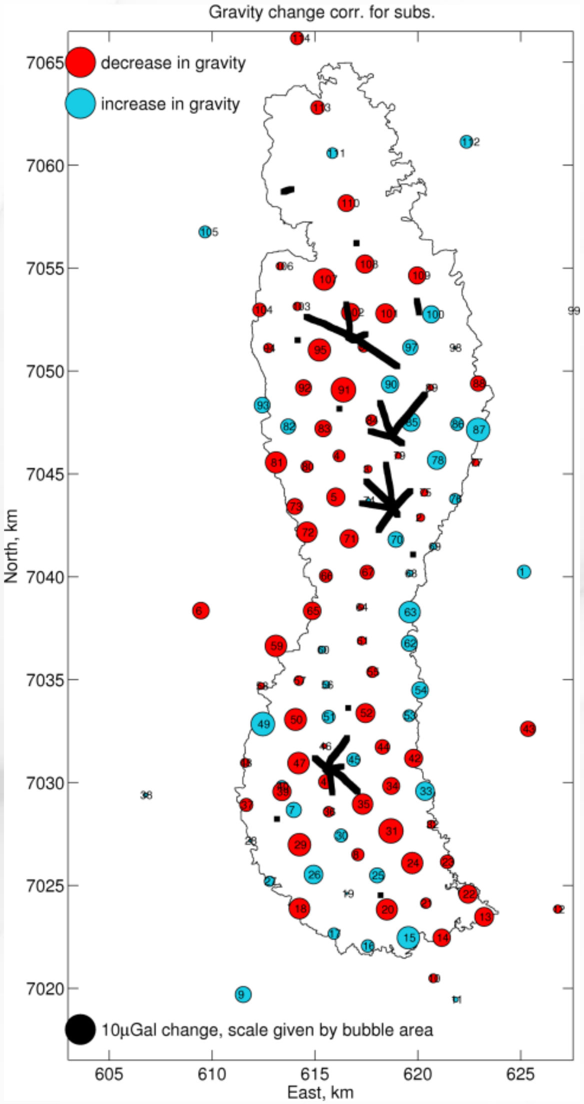
12-14 Gravity Measurements

Measured gravity changes at each concrete platform:

- The changes are caused by three effects:
  I. The advance of the water front from neighbouring, extensive aquifers is seen as positive changes, as water is denser than gas.
  II. Gas depletion causes a decrease in mass, hence in the gravitational attraction from the reservoir itself
  III. Seafloor subsidence due to reservoir compaction causes the concrete platform to move closer to the centre of the Earth
- Gas take-out signal dominates in the north and around the production template in the south



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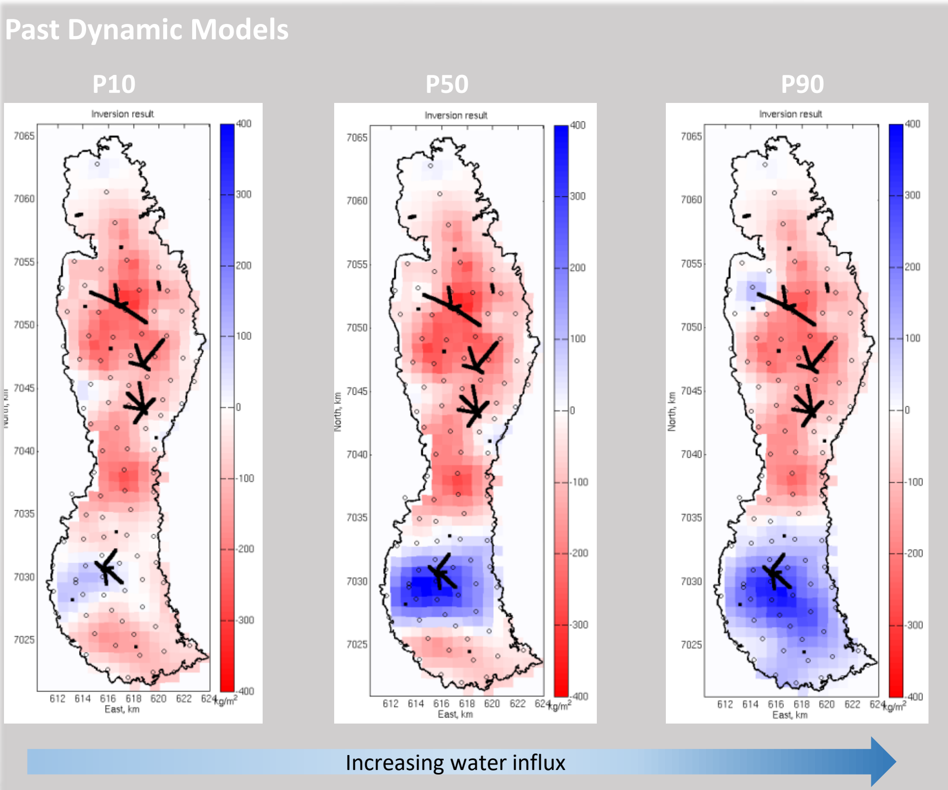
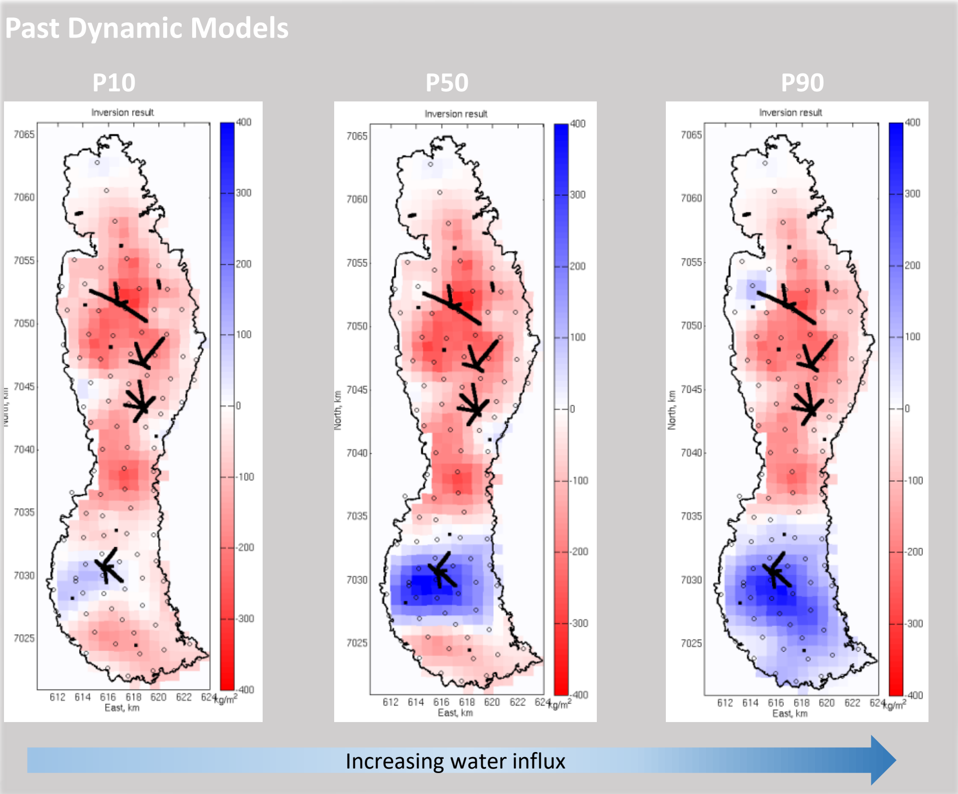
Gravity Inversion Results, Modelled vs. Measured Gravity Signal

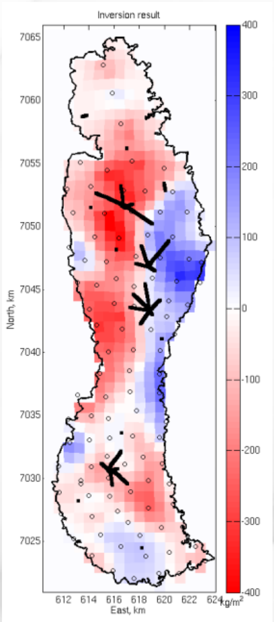


Past reservoir models carried a wide range of aquifer influx scenarios, from weak to strong

Gravity Inversion Results, Modelled vs. Measured Gravity Signal

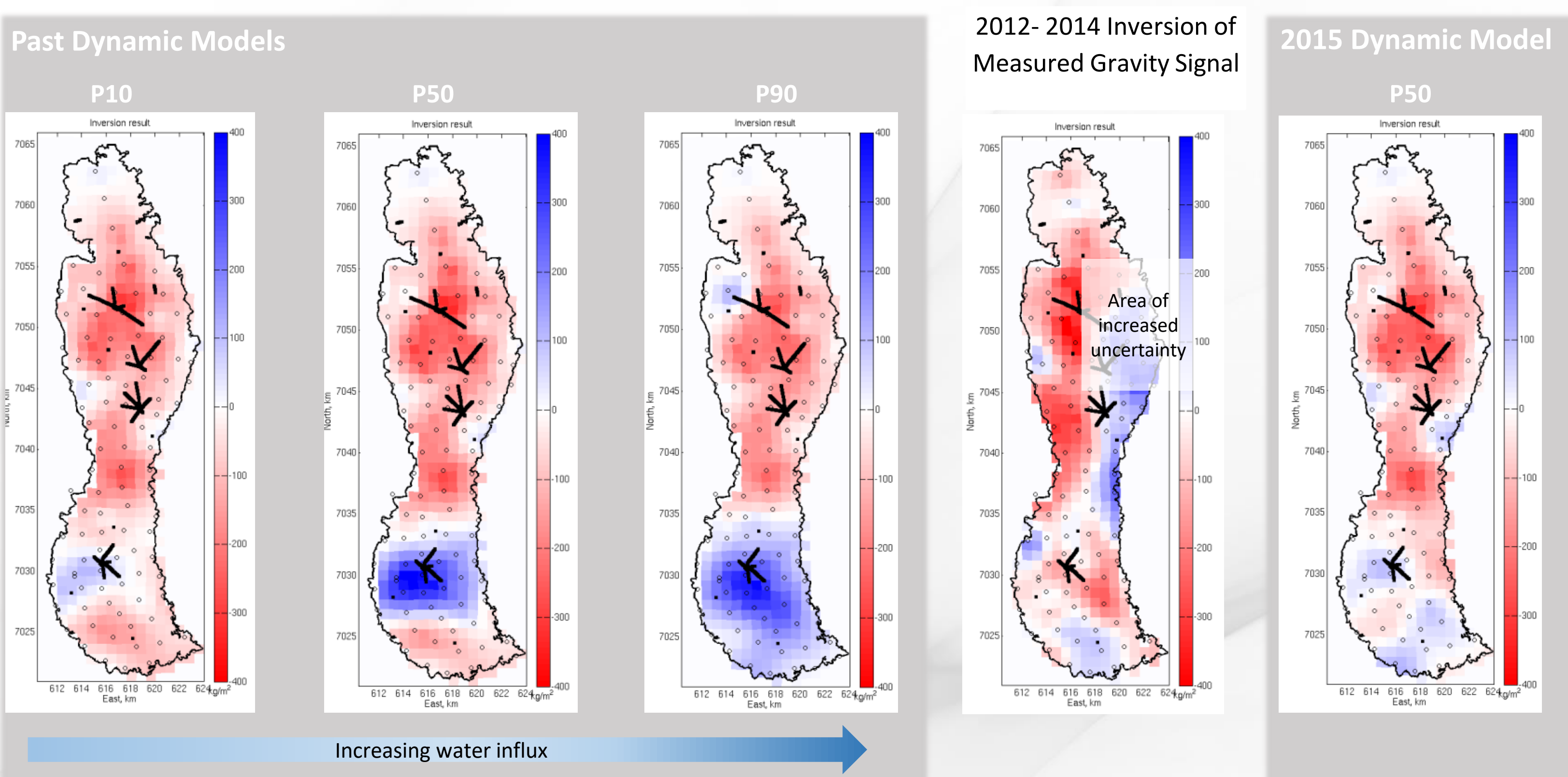


2012- 2014 Inversion of Measured Gravity Signal



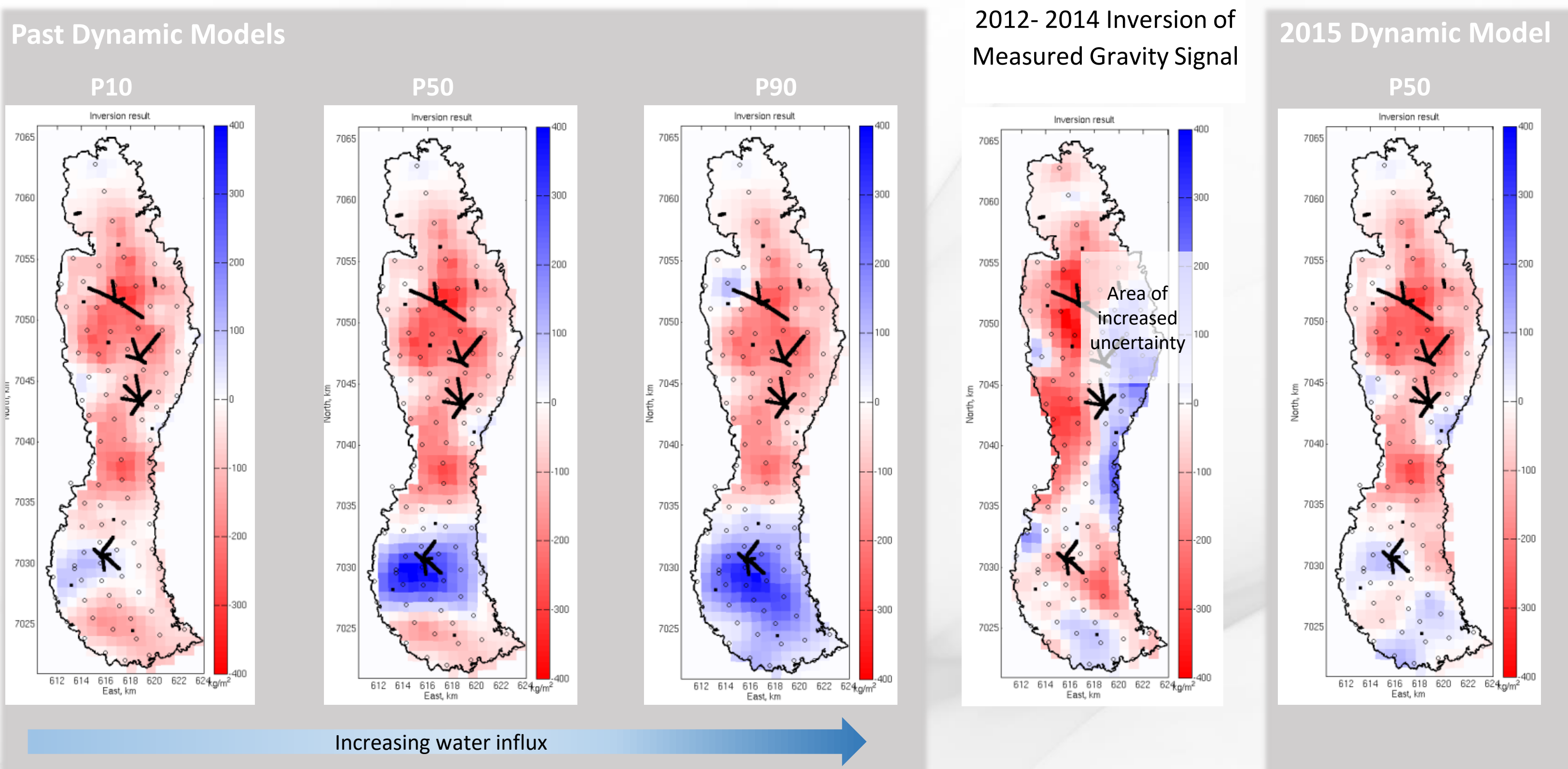
2012-2014 gravity results indicate an aquifer behaviour that is consistent with the weaker aquifer scenarios

Gravity Inversion Results, Modelled vs. Measured Gravity Signal

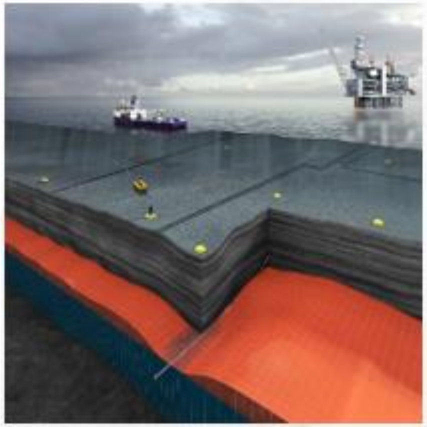


With appraisal well information, as well as historical production and pressure data, the refined predictive models are in general agreement with the gravity signal

Gravity Inversion Results, Modelled vs. Measured Gravity Signal



A similar workflow will be carried out this year with 2016 measurements. Additional information will improve the signal to noise ratio and help improve areas with elevated uncertainties.



Summary and Conclusions

- A monitoring program including time-lapse seismic, seafloor geodesy and field-wide 4D gravity and subsidence surveys is put in place at Ormen Lange
- Interpretations based on independent observables, 4D gravity and seismic, provides enhanced confidence in the interpretation of a weak aquifer scenario
- 4D gravity and subsidence monitoring are provided at lower cost compared to 4D seismic, and with a significantly faster turnaround
- Subsidence results provide a clear picture of seafloor deformation, that is key for understanding and monitoring reservoir compaction
- 4D gravity assists in narrowing uncertainty ranges, especially wrt aquifer strength and influx

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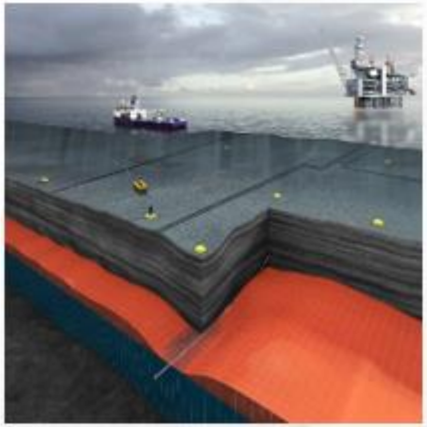

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