Distibution of overpressure in the Norwegian Continental Shelf

Use of pore pressure data to reveal dynamic trapping of hydrocarbons

OLJEDIREKTORATET

F.Riis, A. Soltvedt, T.A. Knudsen, J.A. Øverland

The problem: Integrate pore pressure data with traditional mapping routines in order to predict contacts and model baffles in complex fields

The concepts: How are over- and underpressures formed. Dynamic trapping of hydrocarbons. Fast gas and slow oil.

Examples of overpressured regimes

Experiencing the significance of Smørbukk hydrodynamics in predicting contacts, barriers – and dry wells

Pore pressures in a North Sea profile and map views

Characterizing the pressure regimes

-The overpressured regime. Fracture pressure and pressure cells

-The hydrodynamic regime. Fluid migration.

-The hydrostatic regime. Capillary seals

-The underpressured regime. Gas leakage.

The time scales

The accumulation as a temporary storage. Glacial cycles and events.

Significance of leakage

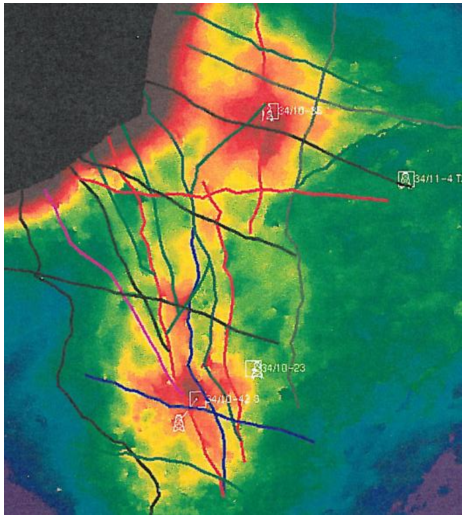
Possible interactions between the accumulation and the leakage

Ormen Lange example

Conclusions

Complex fields

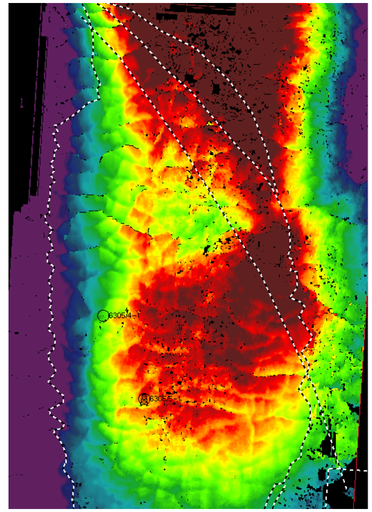
In some fields there is a risk that each segment has a separate pore pressure and hydrocarbon contact. Can the prediction be improved? Implications for modelling of baffles/barriers?



Valemon field, map of the base Cretaceous.

Brent reservoir difficult to map with certainty. Different gas and water pressures in all wells. Stratigraphic and structural baffles/barriers.

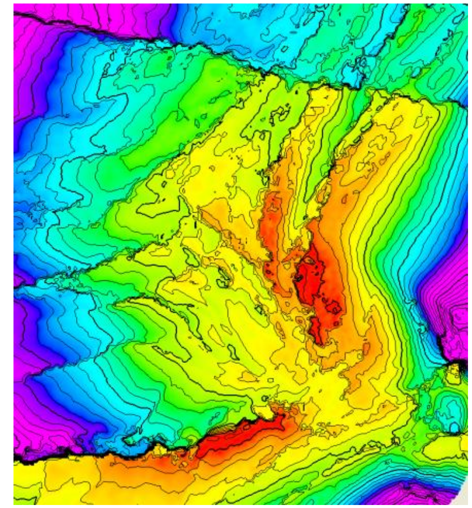
Overpressured regime.



Ormen Lange field, northern part, base Egga reservoir.

The northern part of the field is strongly polygonally faulted, broken up into 100’s of fault blocks. One gas gradient in the field, but all wells have different water pressures.

Hydrodynamic pressure regime



Goliat field, Realgrunnen reservoir.

Strongly faulted. Separate structural segments have different gas and oil contacts. Different contacts and pore pressures in different zones of the reservoir.

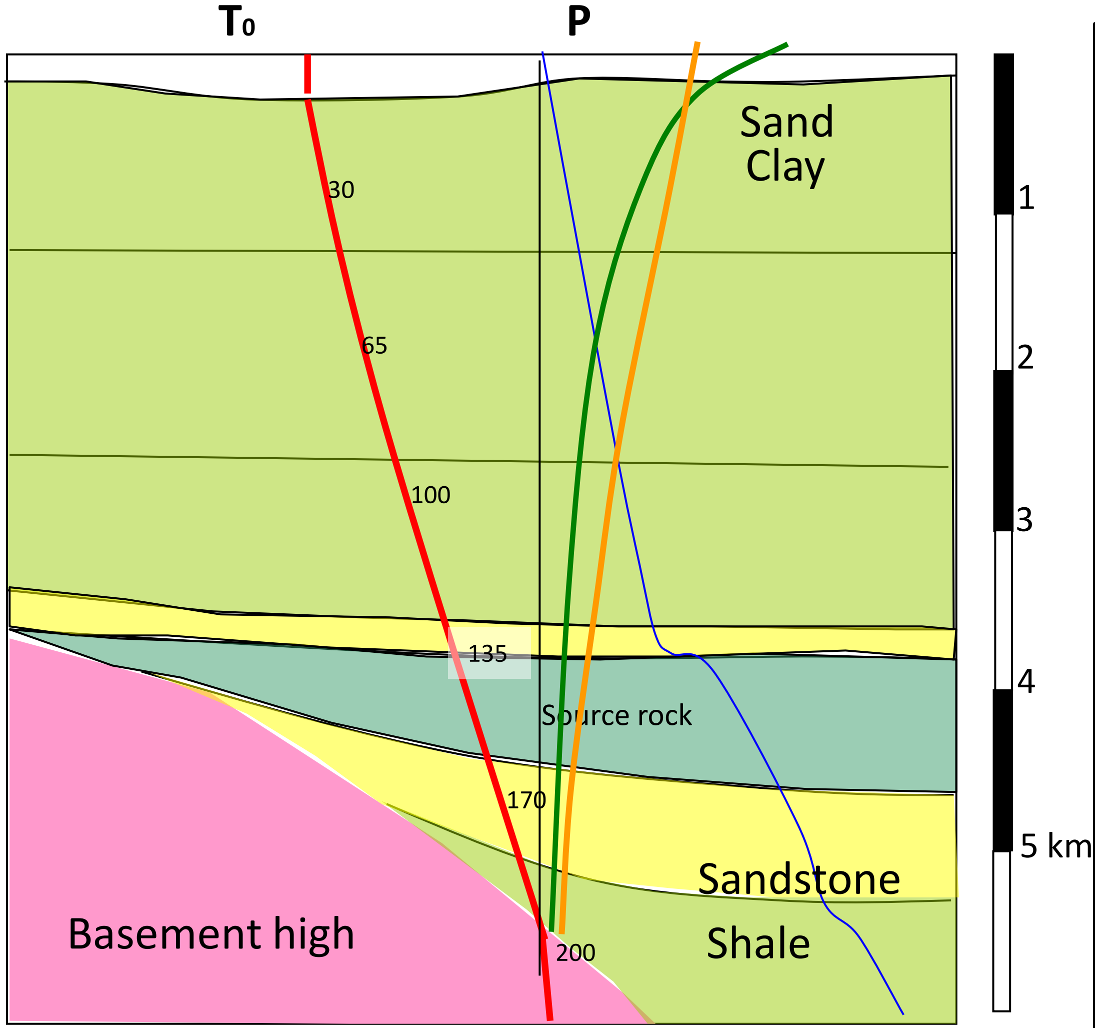
Hydrostatic pressure, tendency to underpressure.

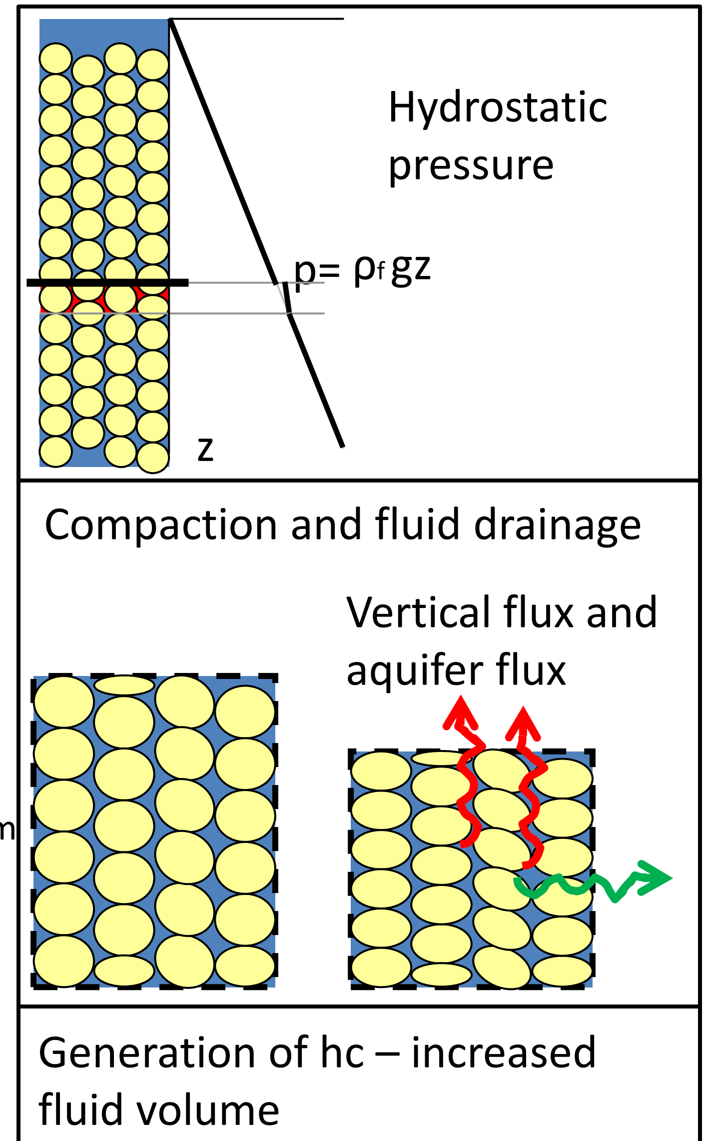
Basin model

Generalised temperature and pressure profiles

Generalised compaction trends for shale and sandstones

The basics



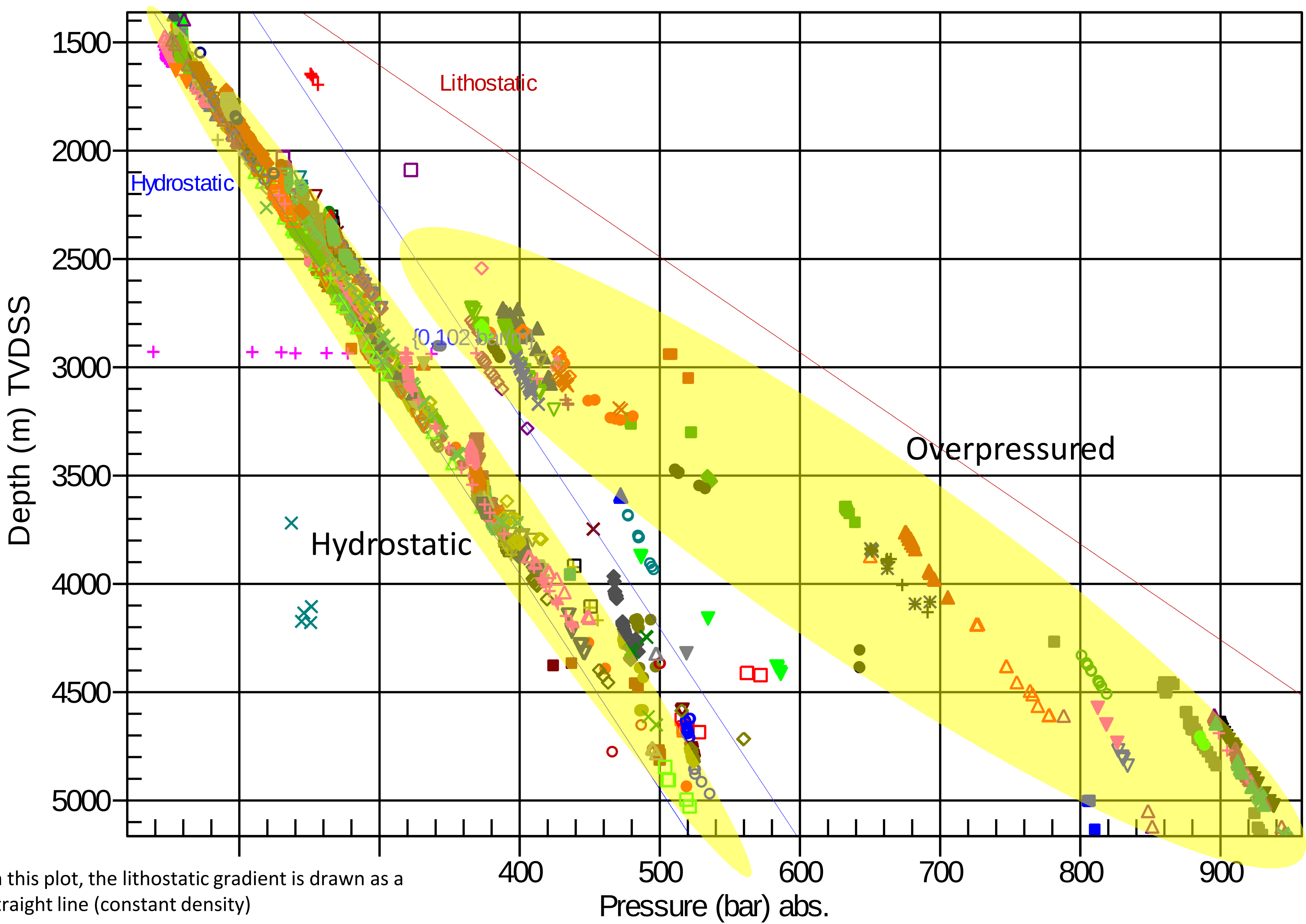


The exponential compaction trends (Sclater and Christie type) were used to calculate lithostatic pressures in the diagrams below

Heat

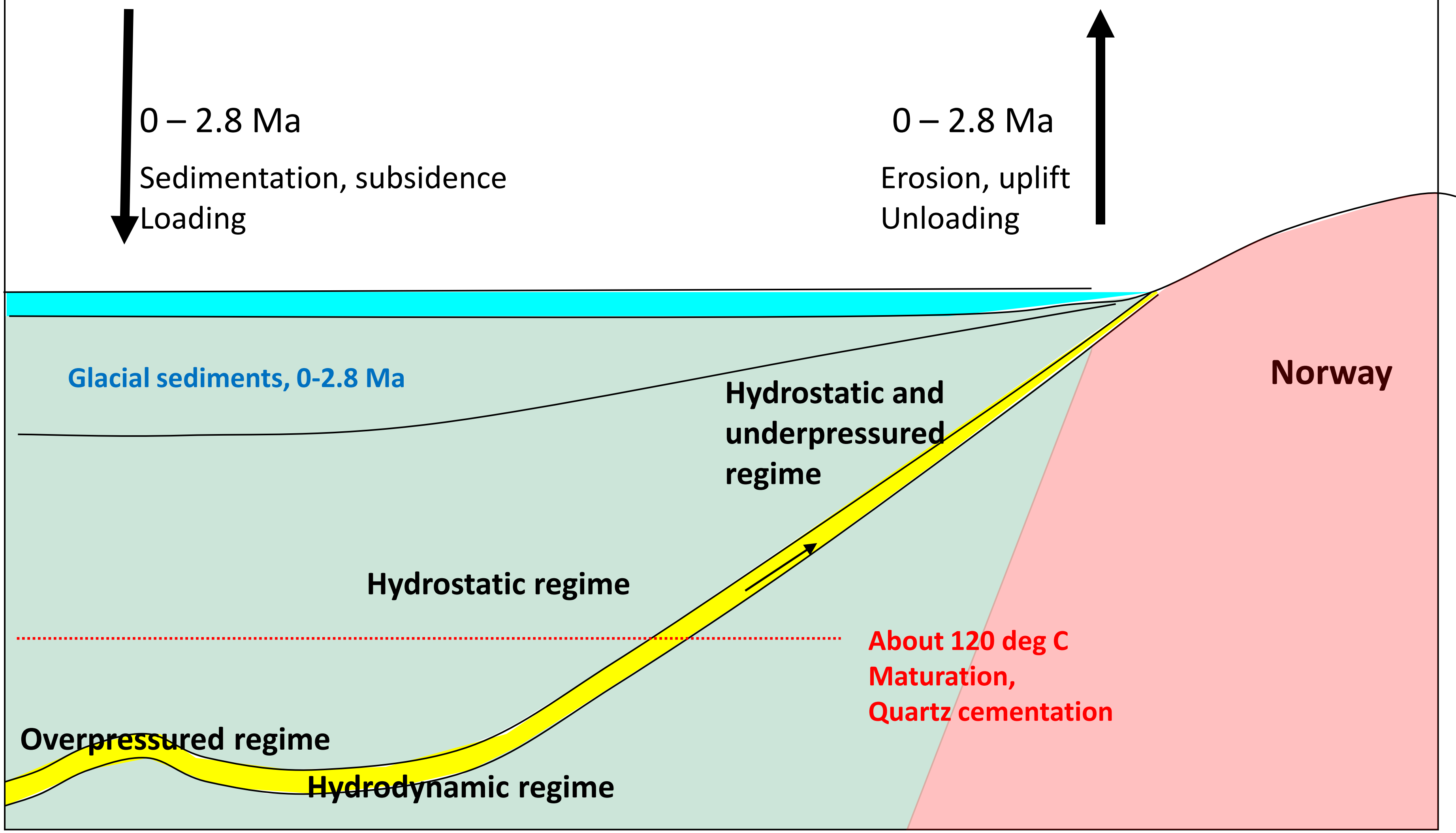
Overpressure – insufficient permeability to drain the fluids completely

Pore pressure plot from a large set of exploration wells, Norwegian Sea, an area of rapid subsidence. High overpressures typically develop from below about 2700 m.



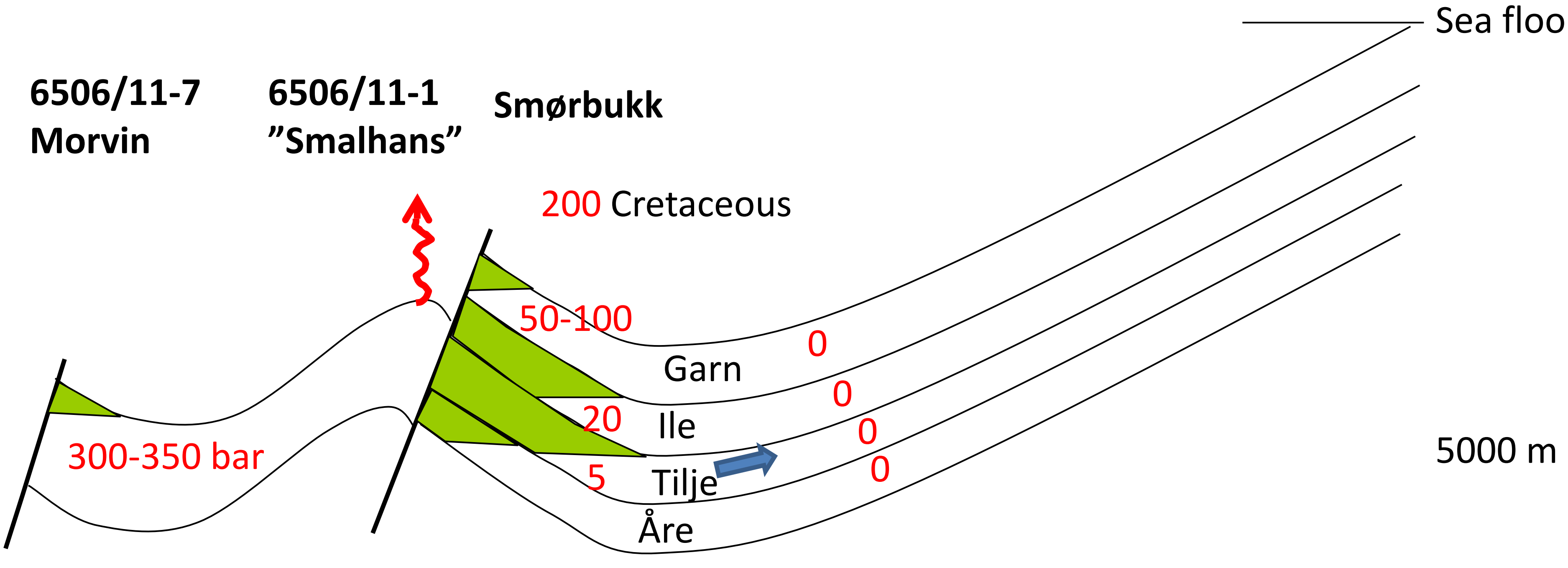
In this plot, the lithostatic gradient is drawn as a straight line (constant density)

Pore pressure regimes in the Norwegian Continental Shelf



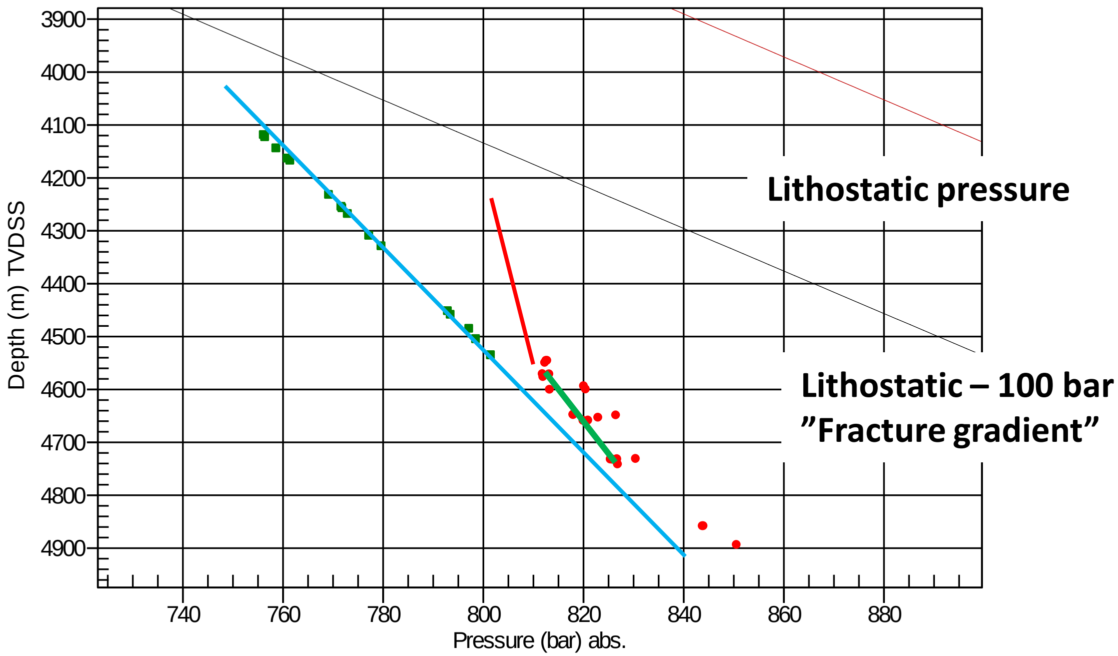
Because of the large amounts of glacial erosion and deposition, the NCS is an area where rapid burial/erosion has taken place. Dynamic trapping of hydrocarbons

Overpressured cell and hydrodynamic trapping Smørbukk structure (Åsgard)



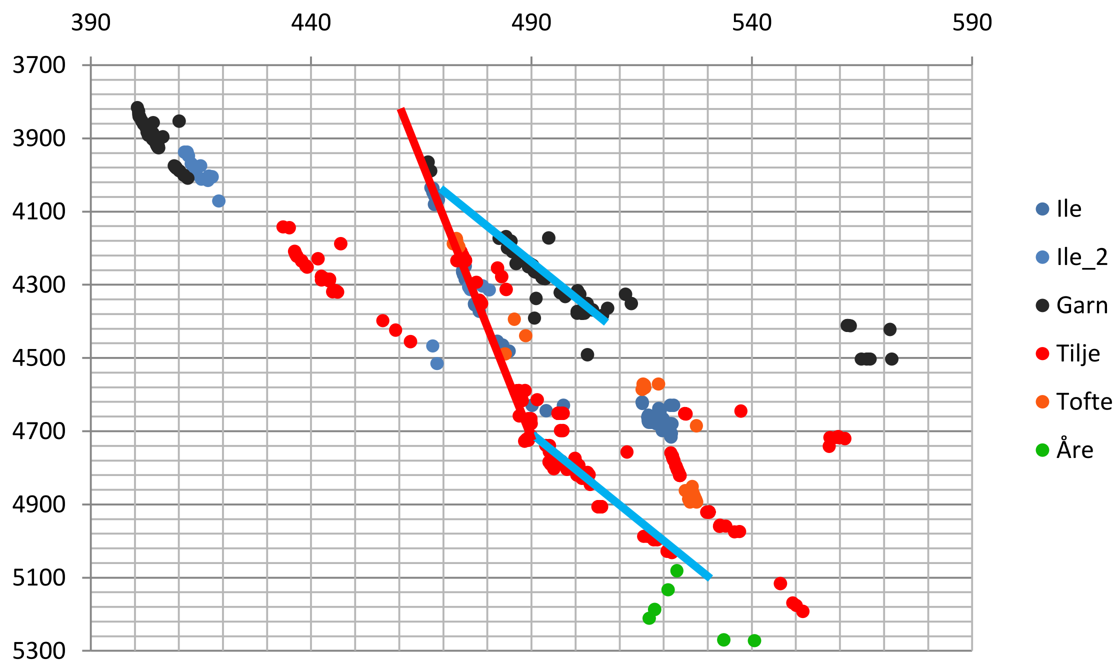
The highly overpressured cell to the left is sealed by the fault towards the Smørbukk structure. Overpressure in this cell is controlled by vertical seep/leakage, hence the shallowest closure is dry (a small updip hc column is possible). The Smørbukk structure is capable of bleeding off overpressures by Darcy flow in the permeable formations towards the east. Presumably there is no significant bleed-off at the top, since the caprock of the Smørbukk structure is overpressured. Consequently, contacts and pressures in the aquifer formations depend on their permeabilities and the properties of the barriers/baffles in the system. Red numbers show approximate overpressure relative to hydrostatic, and the corresponding hydrocarbon columns are shown in green. Very high gas columns due to the good sealing capacity (high pressure in the cap rock).

The area is covered by about 1000 m of glacial sediments, and the present pore pressure setting and main hydrocarbon generation is believed to take place in the last 2.5 million years.



Pore pressures from the overpressured regime (western part) 800 bar

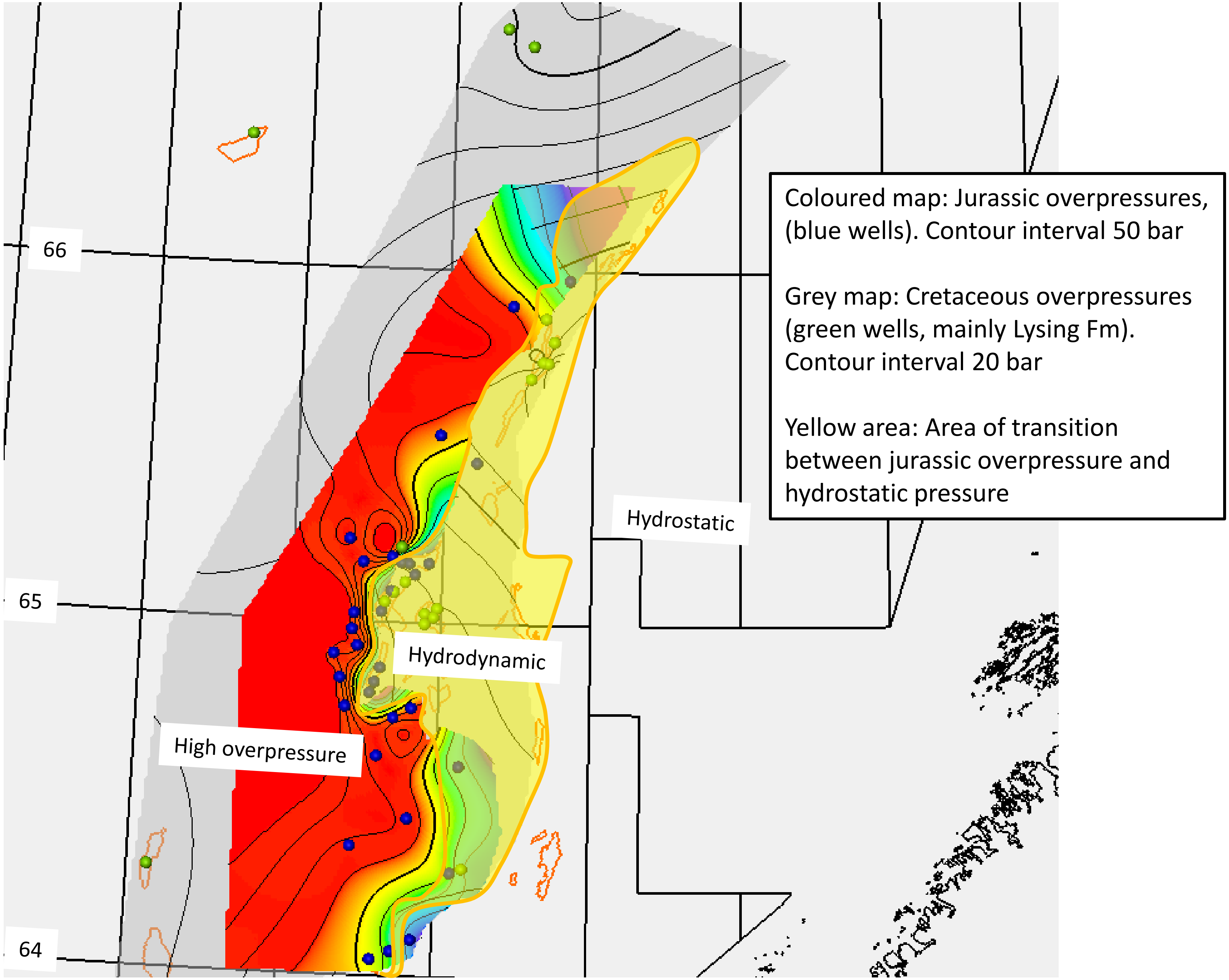
Red: deep well
Green: Shallow well
Oil gradient drawn through the highest quality data points.
Deep structure has potential for a thick oil/gas column



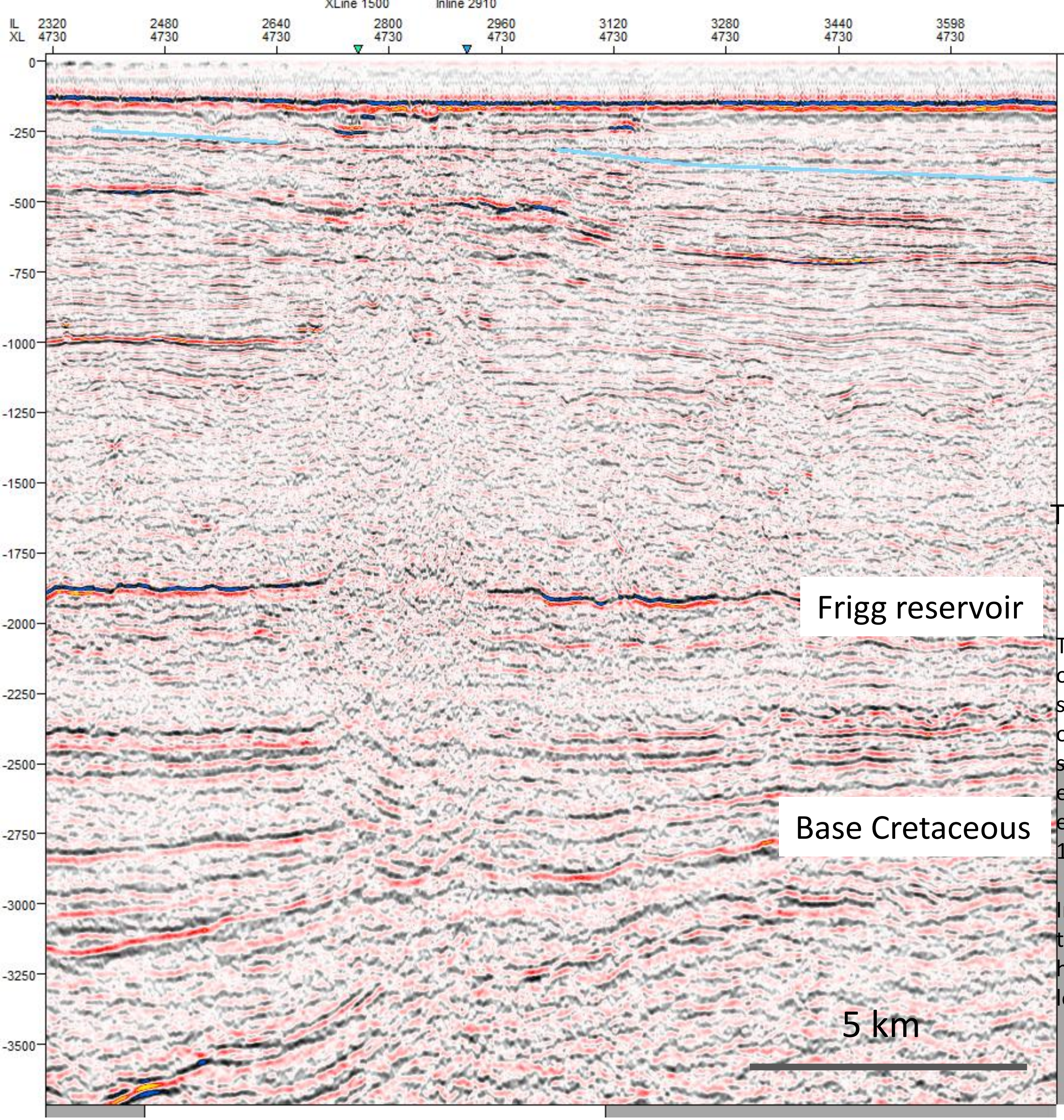
Pore pressures from the hydrodynamic regime (eastern part) 450 bar

Data from several wells on the structure east of the boundary fault. Pore pressures drop from overpressured to hydrostatic conditions. Each reservoir formation is coloured

Map showing pressures in excess of hydrostatic in the Norwegian Sea



Frigg area gas flux



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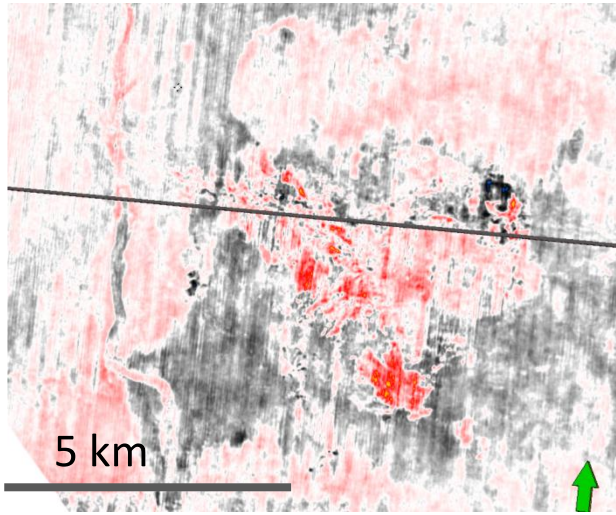
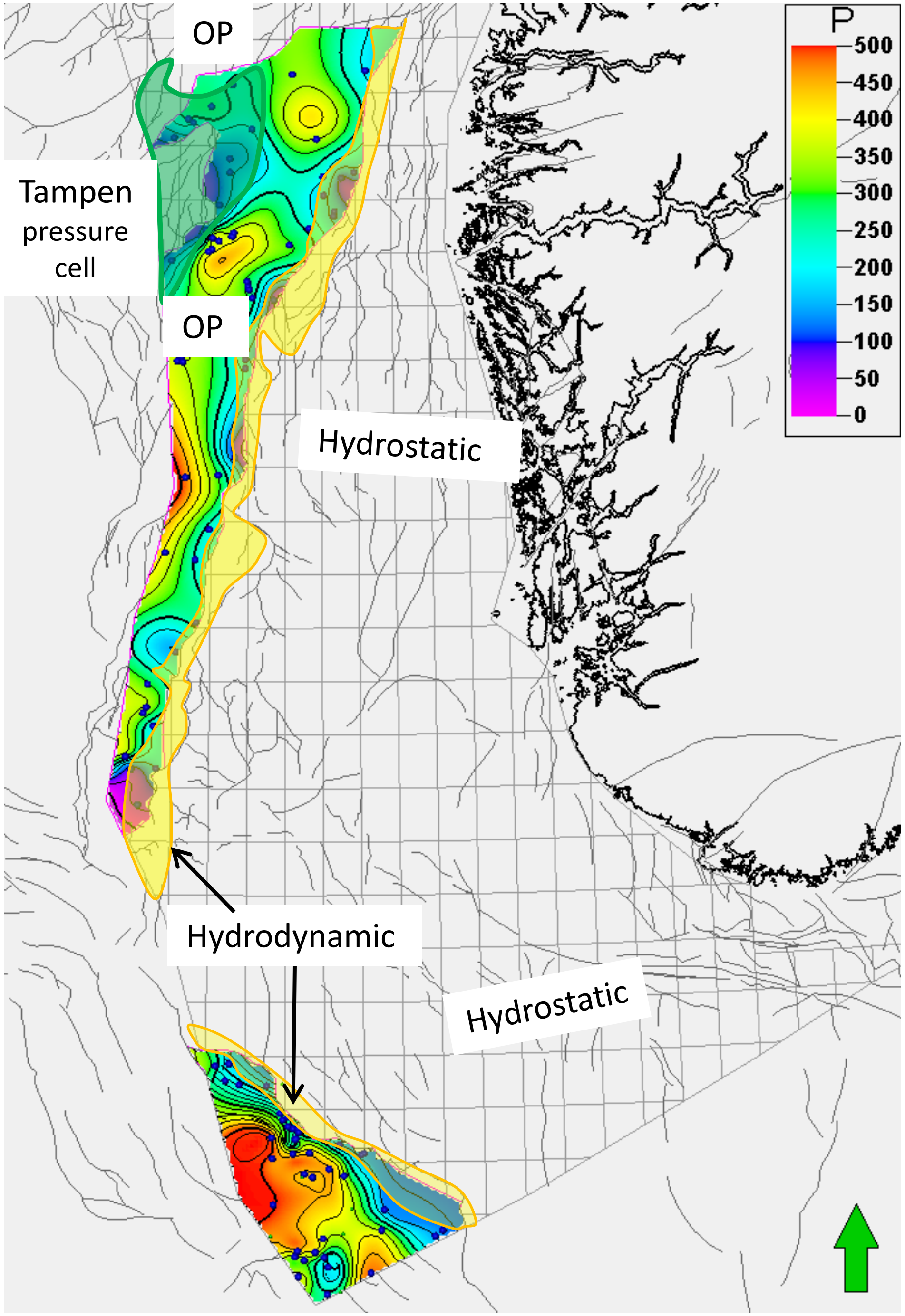


Time slice 228 ms across shallow anomaly

The Frigg area gas fields constitute a good example of dynamically trapped gas. Gas migrates into the structures from the deeply buried and overpressured Jurassic source rocks below, and seeps upwards through the caprock. A gas seep is easily visible in seismic data, and gas and oil was encountered in the Miocene/Oligocene in well 25/2-10 close to this pipe.

In this area, the cover of glacial sediments is not as thick as in the Norwegian Sea example, and the hydrocarbon system may have been active since at least since the mid Miocene

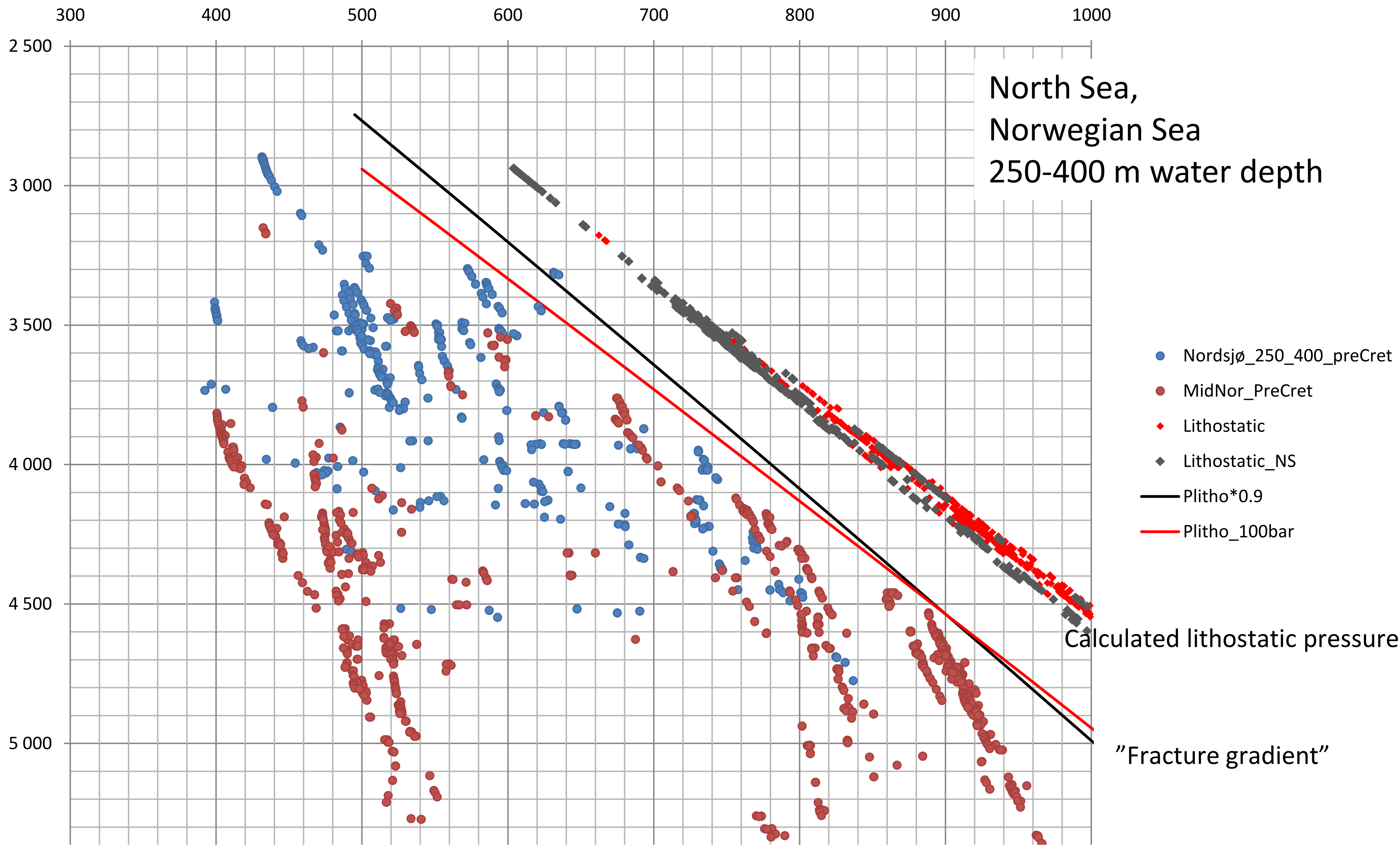
Map showing pressures in excess of hydrostatic in the North Sea



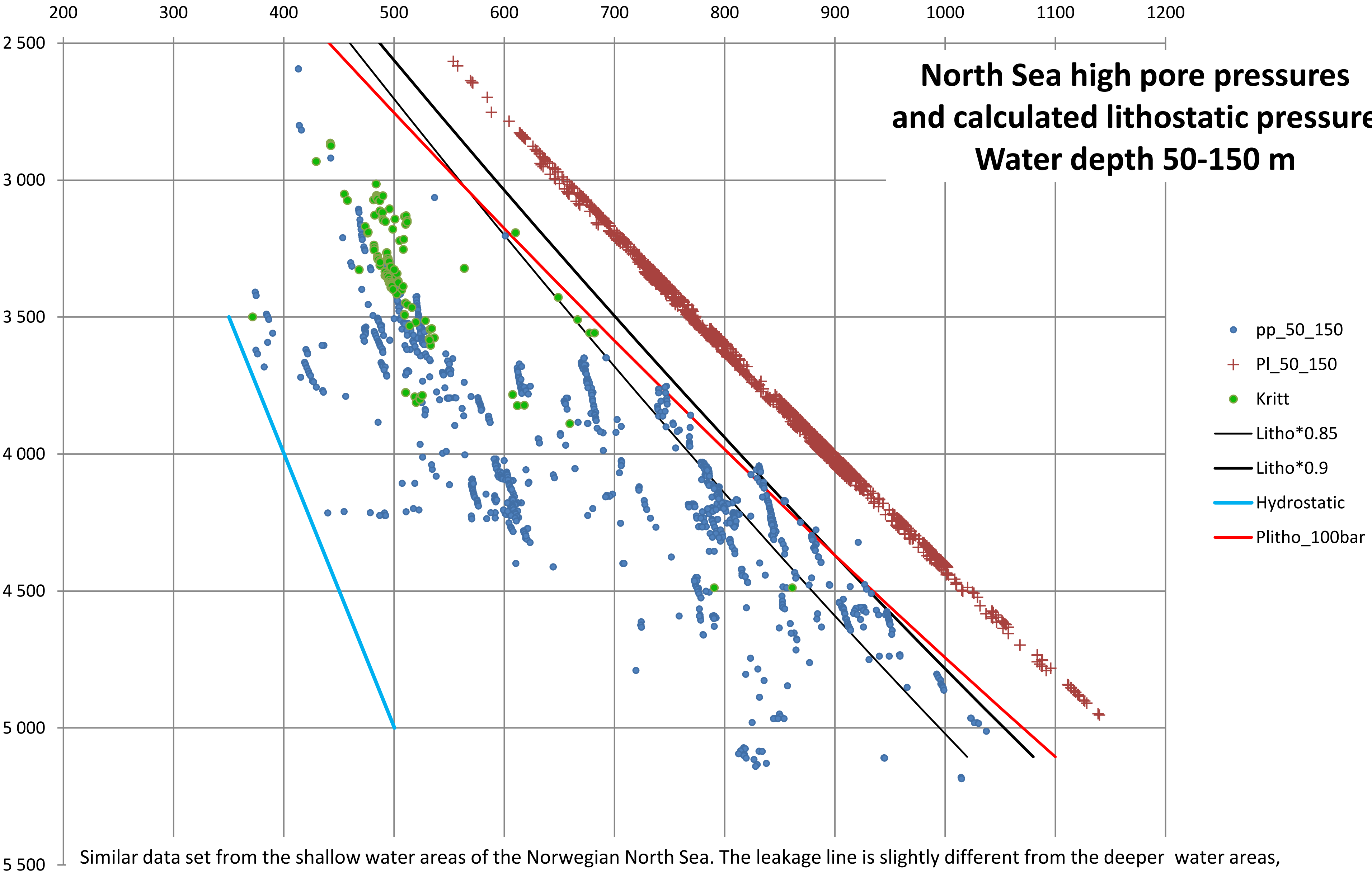
Pressures in Jurassic reservoir rocks, based on exploration wells marked by blue dots

Note: the contouring is only based on well data, and does not take into account the structural maps.

Compilation of pressure data from the overpressured regime

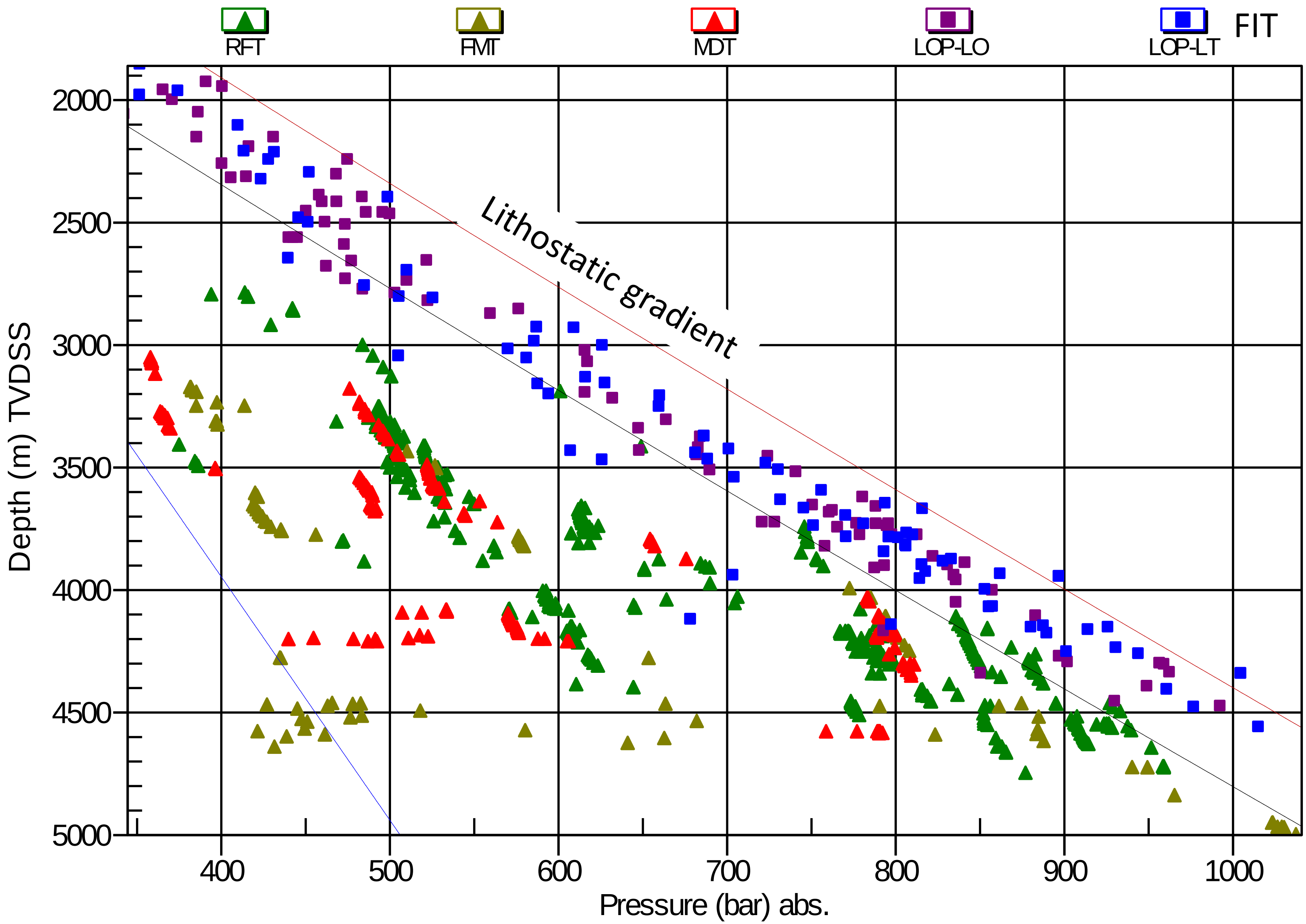


Plot showing pore pressures from released exploration wells in the North Sea and Norwegian Sea where water depths are in the range 250 – 400 m. Pore pressures tend to build up to a certain pressure gradient which is approximately 100 bar below the lithostatic (red line in the diagram). Note that the Norwegian Sea and North Sea data have quite similar leaking pressures. This ”leakage gradient ” is related to the fracture gradient obtained from leak-off tests, but it is suggested that late glacial events could be of importance to determine the exact position of the ”leakage line”.

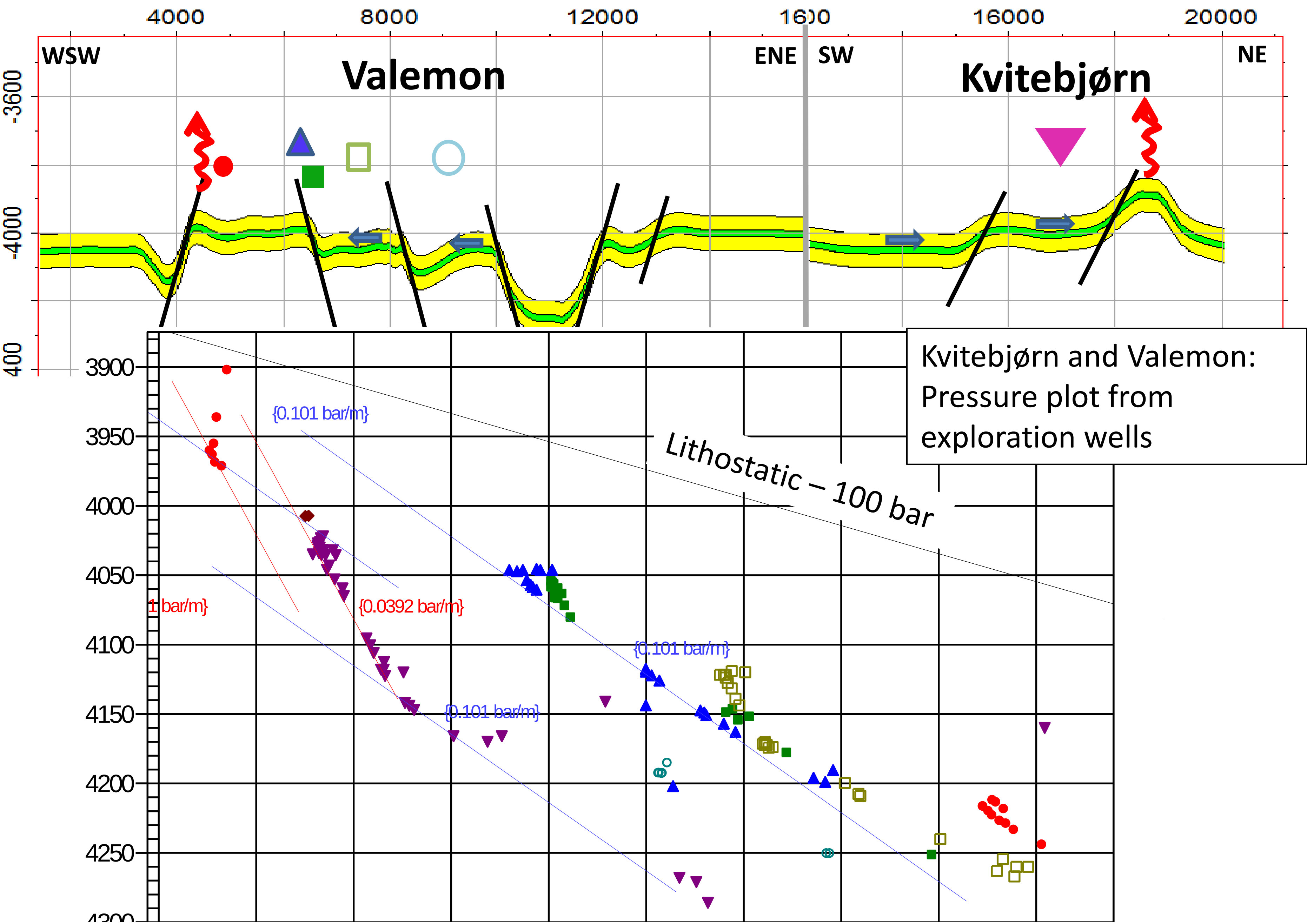


Similar data set from the shallow water areas of the Norwegian North Sea. The leakage line is slightly different from the deeper water areas, partly due to the difference in water load, but there is an indication that the leakage line is also slghtly closer to the lithostatic pressure gradient. In both diagrams, most of the high pressures below 3500 m depth were measured in Jurassic rocks.

Overpressured North Sea wells, shallow water depth



Pore pressures red and green, Leak off pressures purple and blue, North Sea shallow water

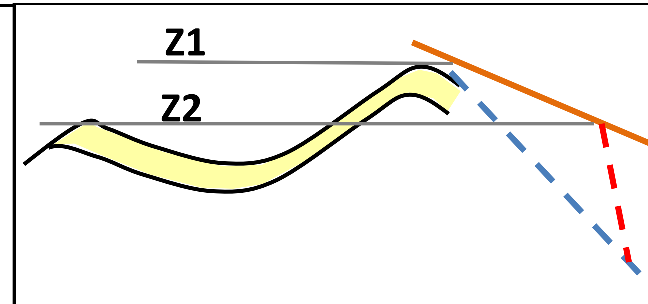


Real life, complex field: Difference in contacts and pressures can be caused by a combination of vertical leakage, fluid migration within "pressure cell " and different leakage lines. Better predictions of contacts and pressures can be obtained if the dynamic system is understood

Overpressured regime: 3 simple cases

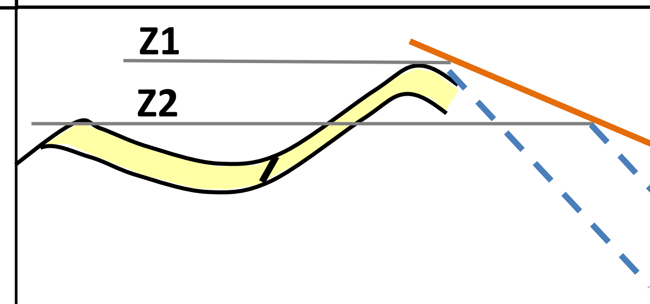
One segment (”pressure cell”). The maximum theoretical hc column is determined by the top point of the cell and of the accumulation:

$$h = (Z2-Z1)*(\rho_{bf}-\rho_w)/(\rho_w-\rho_g)$$ $h \sim 1.8*\Delta Z$



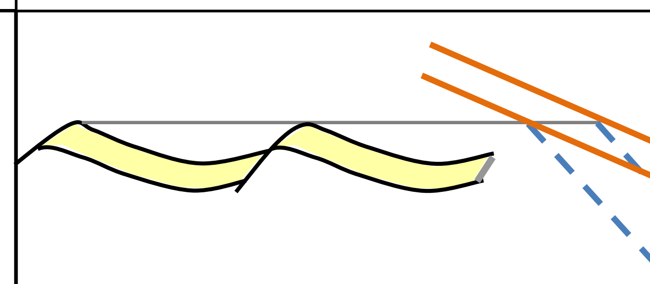
Two segments (”pressure cells”), equal leakage pressure. The difference in water pressure is determined by the top points of the cells:

$$\Delta P = (Z2-Z1)*(\rho_{bf}-\rho_w)*g$$ $\Delta P \sim 0.13*\Delta Z$



Two segments (”pressure cells”), different leakage pressures, but equal depth to top. The difference in water pressure is simply:

$\Delta P = \Delta FP$ FP = leakage pressure



Case 1: Predict contacts before drilling new segments/prospects. Iterate to determine top depth of segment.
Case 2: Predict locations of barriers/baffles, compare with hypotheses of fluid migration in aquifer.
Case 3: Lithostatic pressure and fracture pressure will change with increased water depth. Example, the Kvitebjørn-Valemon water pressures

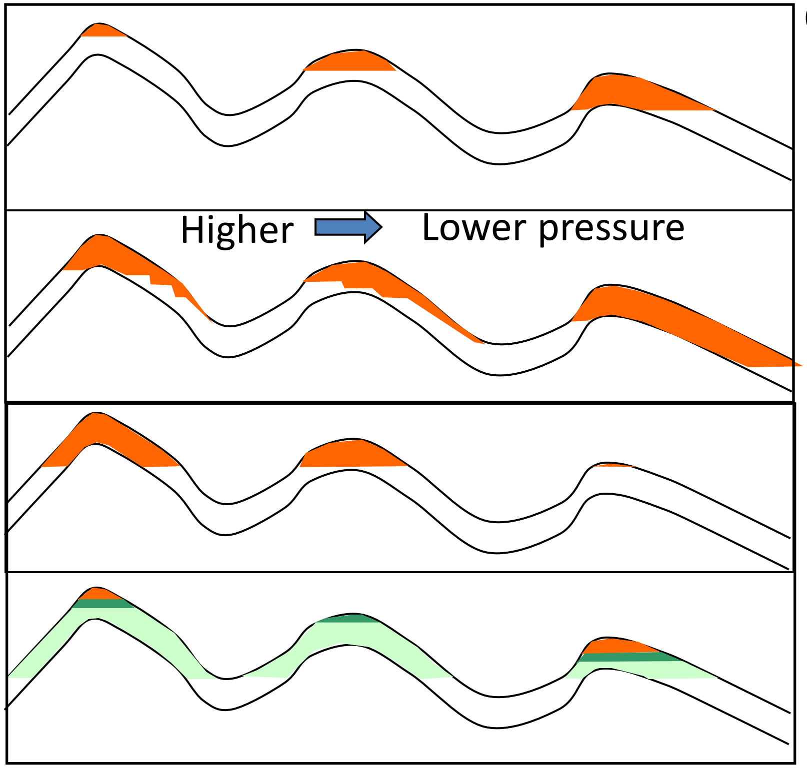
Time scales: Gas formation and seepage

- 35/2-1 Gas discovery ”Peon”: cap rock about 0.5 Ma. Shallow gas in general
- Sites of continuous gas seapage, e.g. Gullfaks (Hovland 2007)
  - 10 m^3 gas/day at 100 m below sea level - 116 cm^3/second - 3.65 BSm^3 in 10^5 years.
- Accumulated leakage from Snøhvit area, Hammerfest Basin through glacial times
  - estimated to be in the order of 500 BSm^3 in 2.5 Ma
- Tilting of Troll and migration of gas into Troll East
  - estimated to exceed 500 BSm^3 in 1- 4 Ma.
- Generation of oil and gas in the Åsgard - Heidrun area
  - estimated to postdate the onset of glacial sedimentation, - 2.8 Ma

Time scales: Glacial cycles

- Full cycle: 10^5 a, since 1Ma. Between 1 and 2.8 Ma typically 40.000 a.
- One big glaciation: 10-20.000 a. Ice load/unload, sea level changes
- Significant erosional/depositional events: 10-20.000 a.
- Huge landslides: ”Instantaneous”, but recurrence time 10^5 a.
- Pressures and contacts seem to be reequilibrated after the last glaciation(?)

Conclusions



Contact distributions in four pressure regimes

Overpressured regime, single pressure cell:
Pressure controlled by leakage from top

Hydrodynamic regime, aquifer fluid flow.
Deeper contacts towards lower pressure

Hydrostatic regime. Horizontal contacts.
Small variations can be due to capillary seals

Underpressured regime. Contacts controlled by net leakage. Horizontal paleo-contact (base of residual hc).

Migration and leakage of fluids is rapid compared to many other geological processes. Trapping of hydrocarbons and adjustment of pressures in the NCS are suggested to be dynamic processes which are influenced by glacial cycles and could be modelled in time scales of 10^3 to 10^5 years.

Accumulations with complex segmentation tend to occur where fluids are drained both by vertical seeping into the cap rock and lateral migration in the aquifer

Possible further studies:

Quantification of vertical leakage of hydrocarbons

Interaction with glacial and biological processes

Integrate results into geomodelling and reservoir simulation