Harbour Energy

DEVEX 2022

The Re-Pressurisation of a Mature Paleocene Lista Sandstone Reservoir due to Support from Underlying Silts and Shales

(NSTA source)

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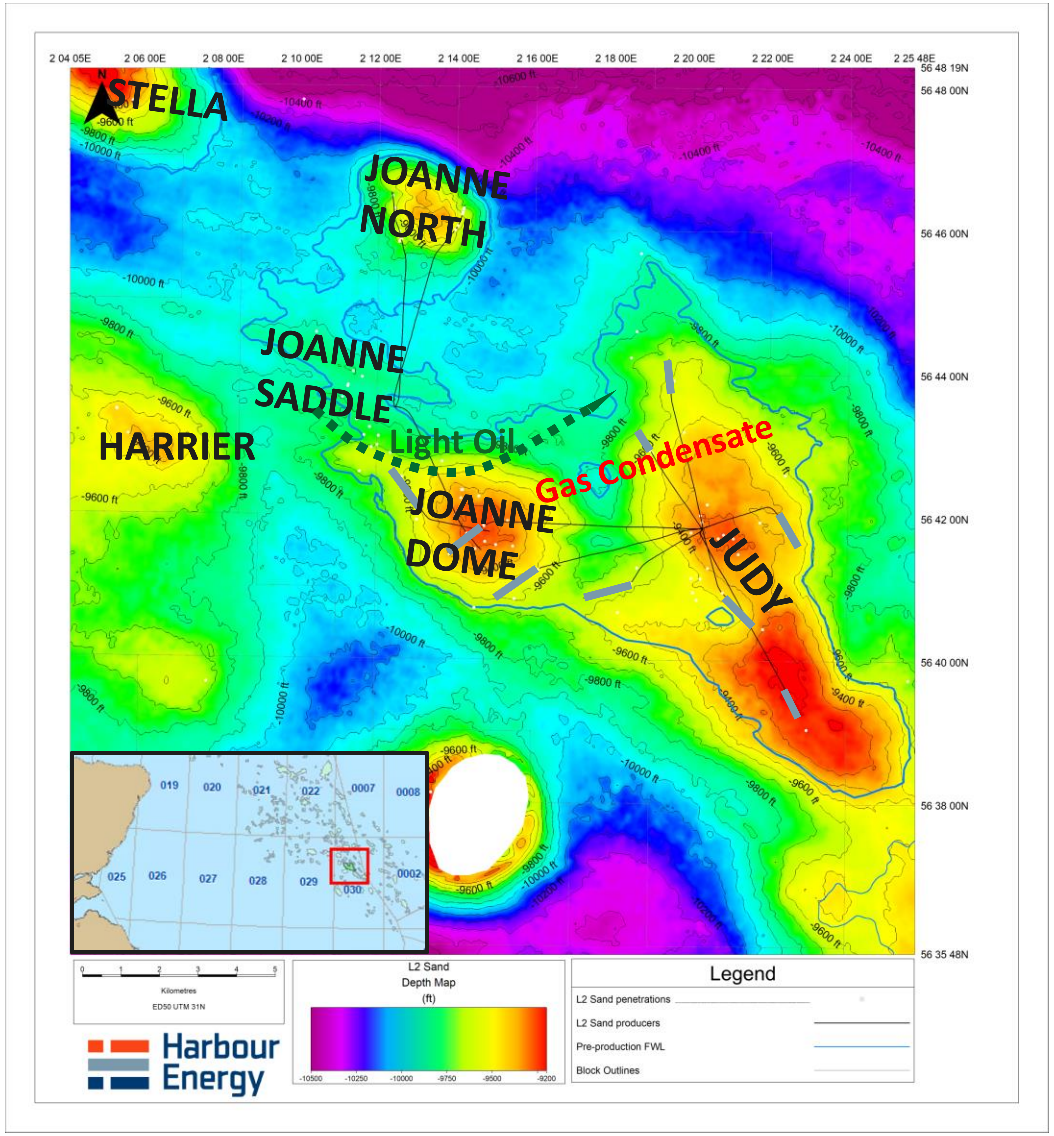
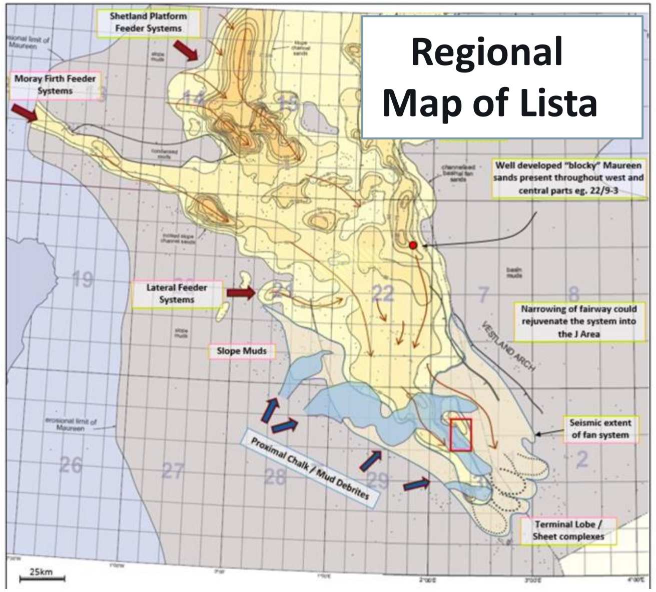
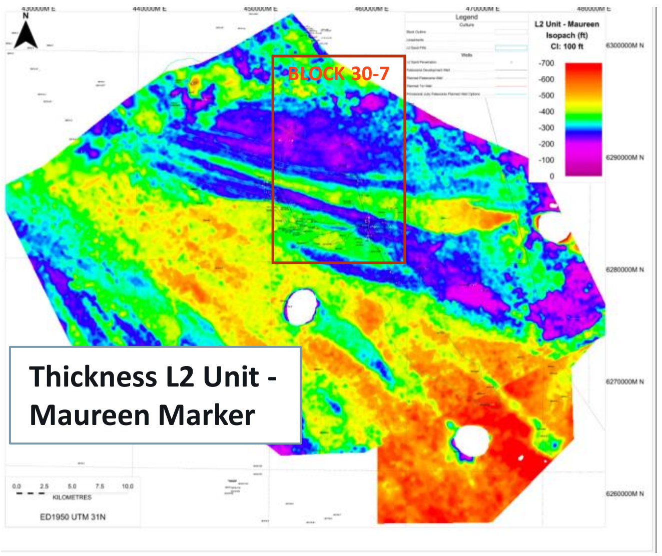
J-Block Lista Reservoir



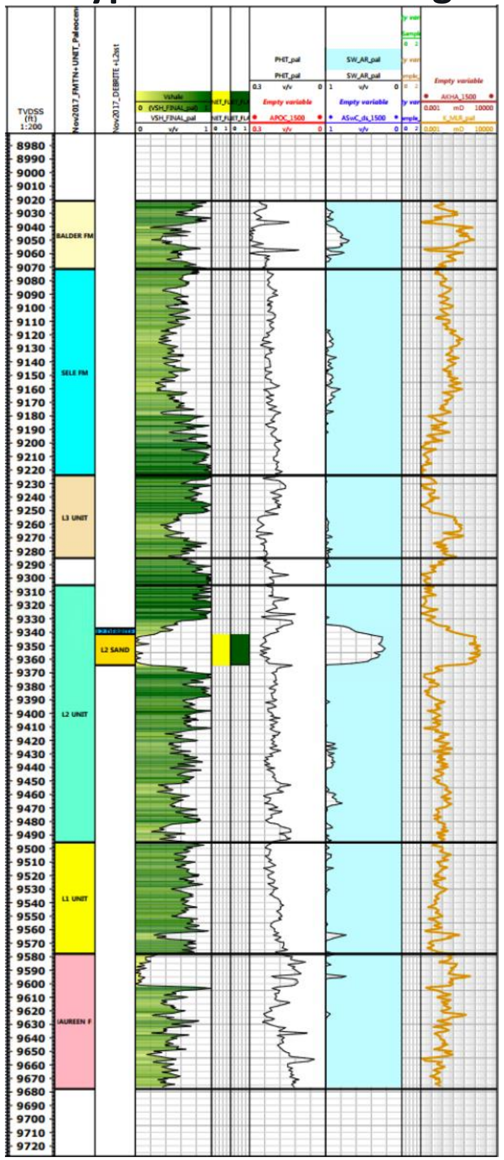
- The J-Block Lista reservoir is located in Quad 30 about 320 km due east of Dundee
- The 2,500 psi over-pressured reservoir mainly contains rich gas condensate/ volatile oil with a GOR in the range 4-5,000 scf/bbl
- To the north west the reservoir contains a light oil with a GOR of about 1,000 scf/bbl
- The hydrocarbon contact is tilted, shallow in the south-east deepening to the north
- Judy and the Joanne Dome were originally developed over 25 years ago using the nine highlighted horizontal wells —

J-Block Lista Reservoir Unit





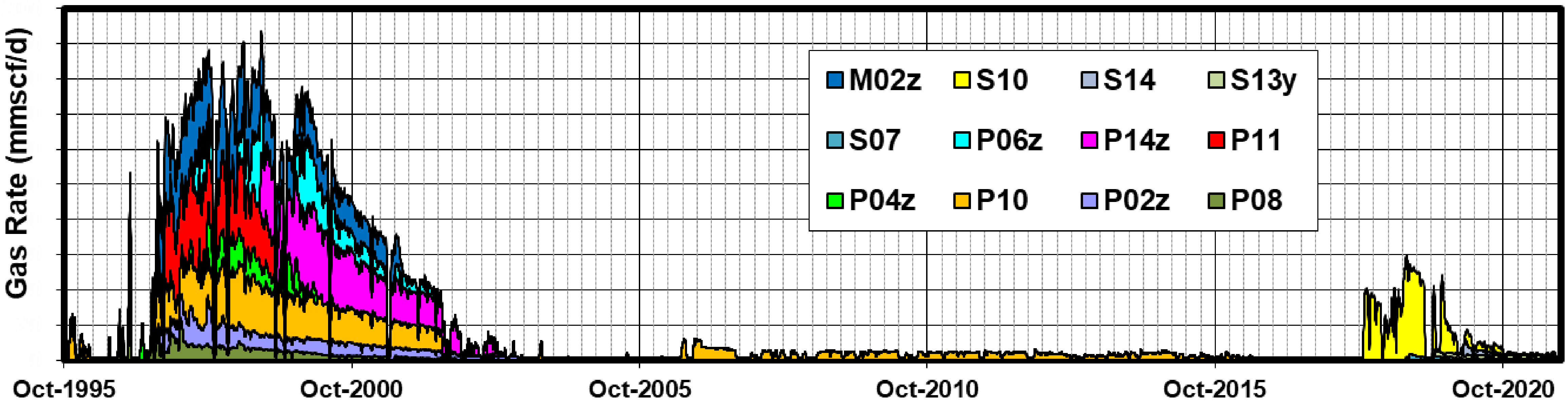
Typical Paleocene Log



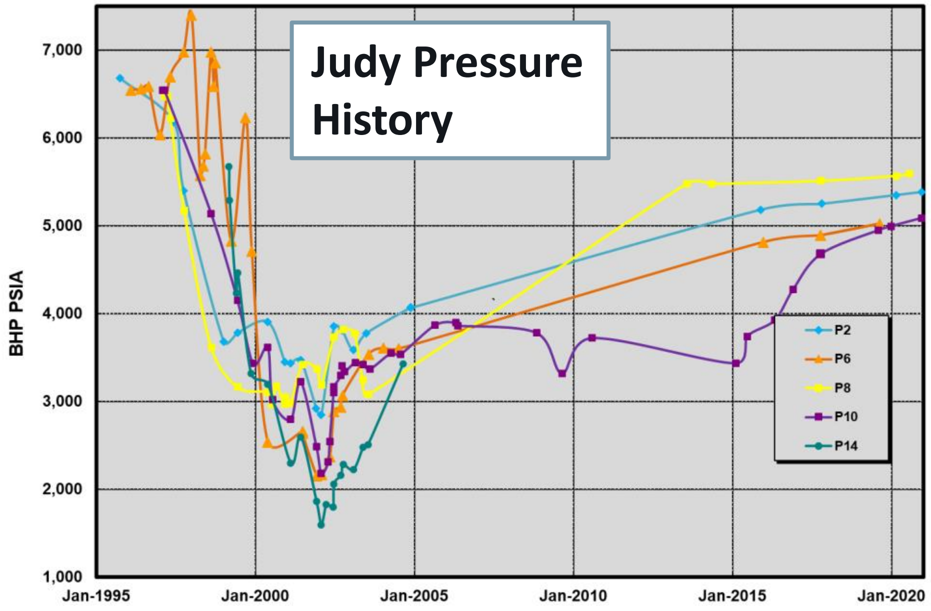
- J-Block is located at the south-eastern distal end of the Lista turbidite system
- The thin ~20ft thick L2 sand with an average porosity of ~22% has a permeability thickness KH of ~500-1,000 mdft
- Above and below the sand, the Lista is predominately shale with some silts, plus occasional thin sands and limestone stringers
- These silts and shales have a typical porosity of just under 20%, which is only slightly lower than the sand
- To the north and east of J-Block the L2 sand is generally either not well developed or absent
- As the sand is only 20ft thick, the geometry and presence of the turbidite sand bodies cannot be imaged seismically
- The L2 to Maureen regional isopach however displays large scale turbiditic features that may be reflected in the L2 sand

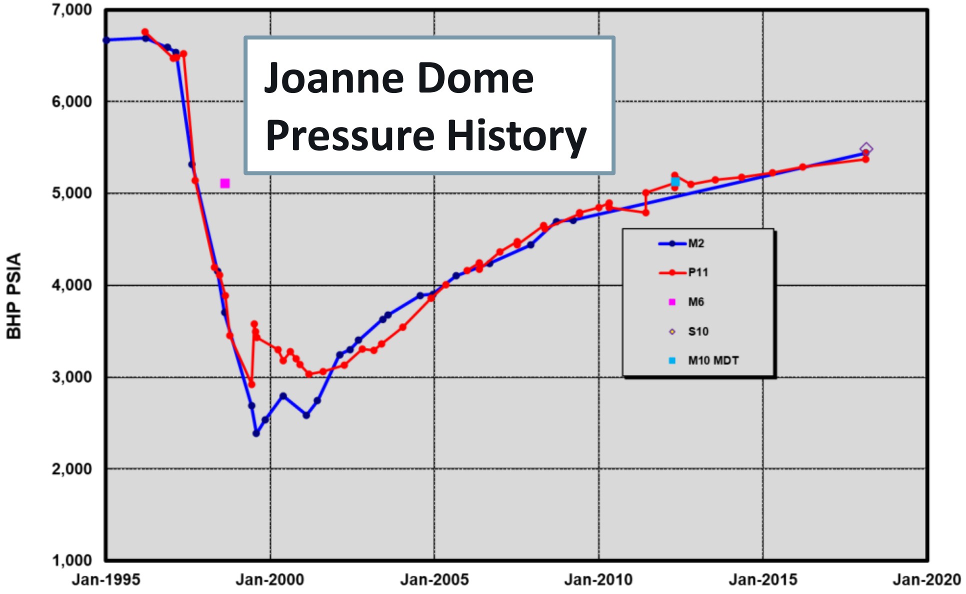
J-Block Lista Reservoir – Production History

- The J-Block L2 reservoir was originally developed using nine horizontal wells
- The majority of the production occurred between 1996 and 2002
- All the wells (except one that was used mainly as a gas injector) had significant water breakthrough, achieving water rates above a 1,000 bbls/d prior before they ceased to produce
- Significant solids production often linked to the water production also contributed to the loss of the wells
- After over 25 years, one of the Phase 1 wells P10 is still producing, with a water rate of several thousand bbls/d

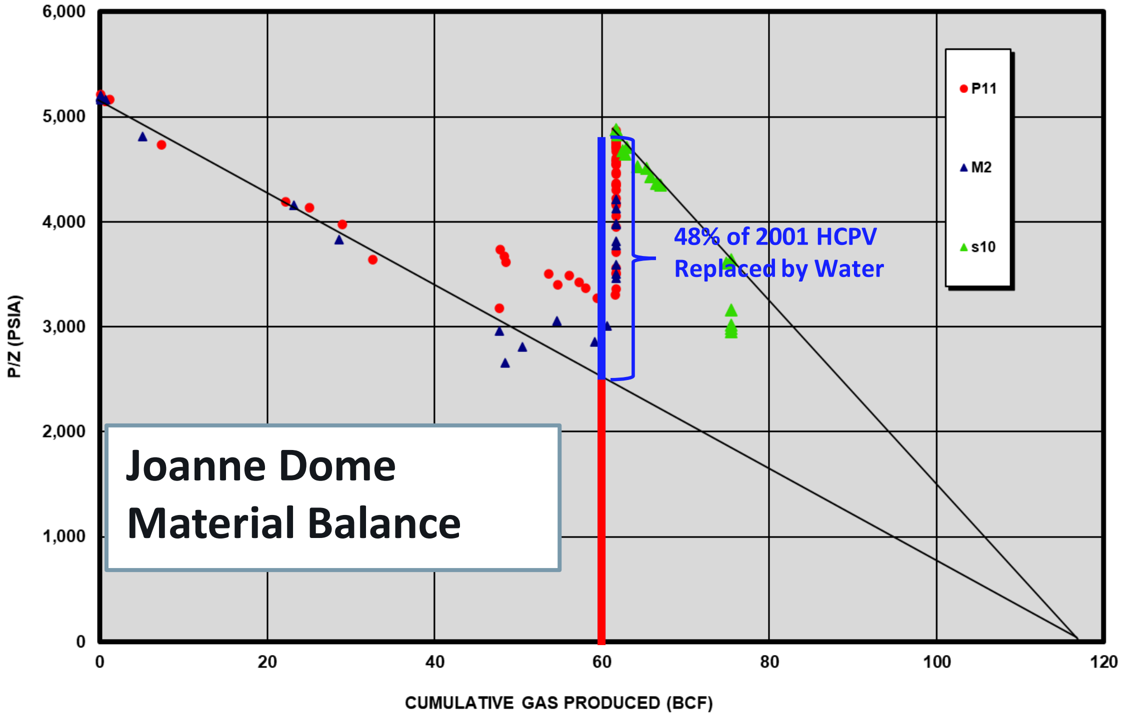


J-Block Lista Reservoir – Pressure History

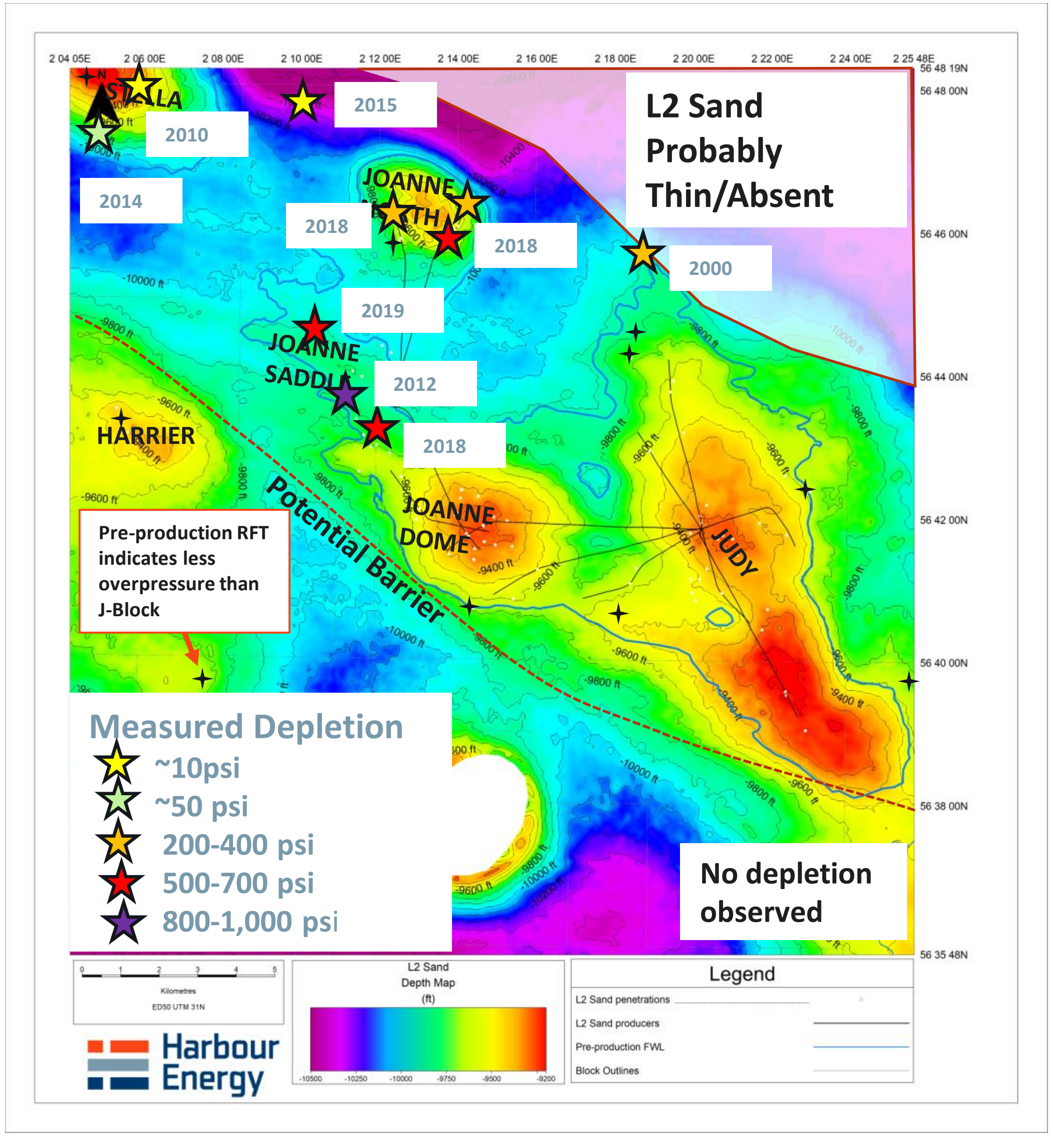




- Both the Judy and Joanne Dome areas were significantly depleted around 2000-2002 with shut-in well pressures close to 2,000 psia
- Since 2002 pressures have recovered to around 5,500 psia, only 1,200 psia below the initial pressure of around 6,700 psia
- The material balance plot for the relatively tank like Joanne Dome area shows that S10 drilled in 2018 confirmed the same initial gas in place as the Phase 1 wells
- This is consistent with pressure recharge from an aquifer influx equivalent to nearly 50% of the original hydrocarbon pore volume (HCPV) (~30% of the total pore volume for average Sw ~ 40%)



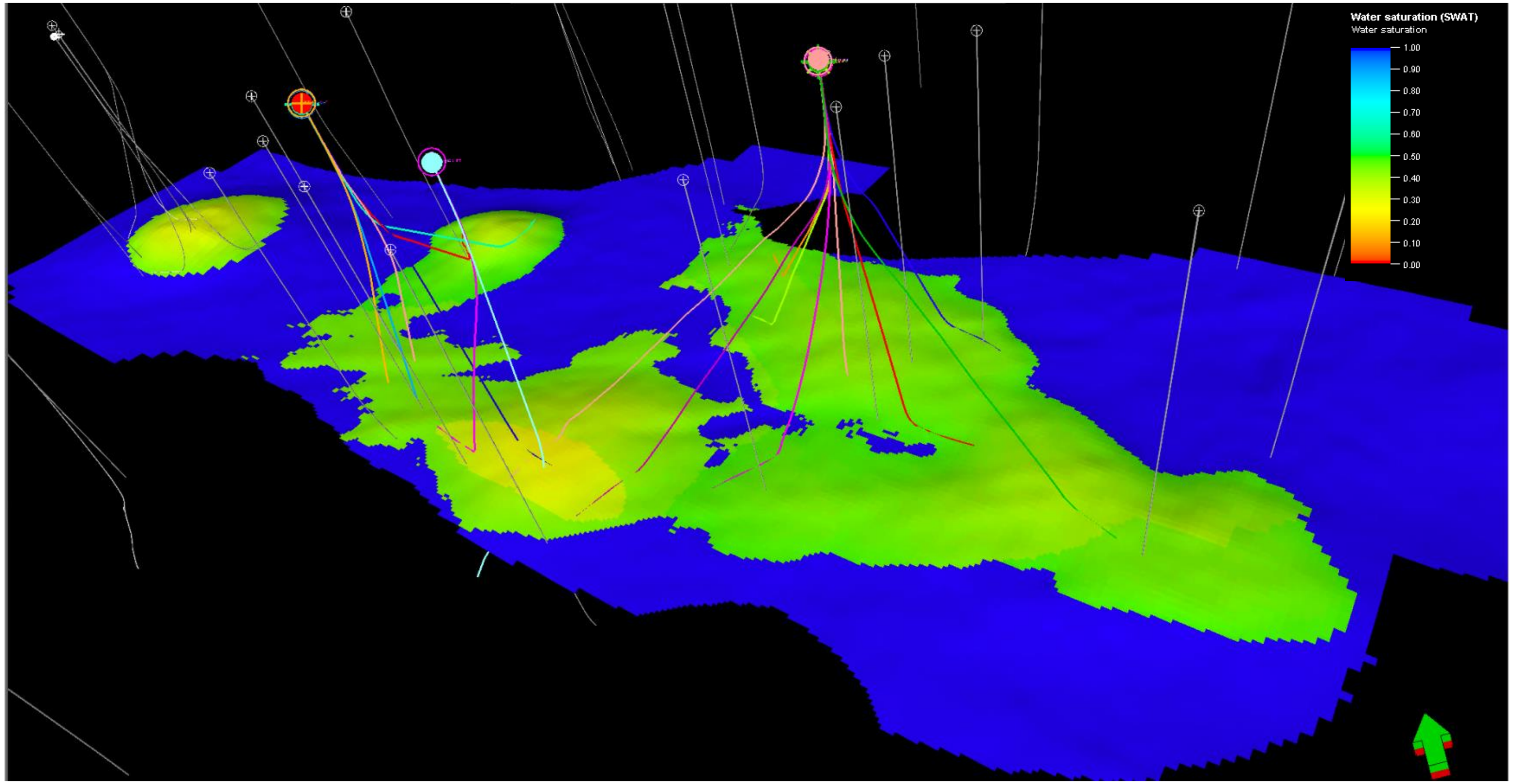
J-Block Lista Reservoir – Aquifer



- Production data supports significant aquifer support
- The significant pressure re-charge observed since 2002 indicates that up to about 30% of the total pore volume has been replaced by water
- After re-charge the average reservoir depletion was only 1,500 psi
- If the aquifer was confined to the L2 sand, depleted by 1,500 psi with a typical total compressibility of $< 1 \times 10^{-5}$, the total area of the aquifer would need to be over twenty times the area of the reservoir
- The area of the L2 sand lobe connected to the reservoir is however only about two or three times the area of the reservoir
- Additionally formation pressure data shows that this relatively small area has only been depleted by at most a few hundred psi
- Significant aquifer support is therefore required from the formations above/below the L2 sand, thick shales / silts

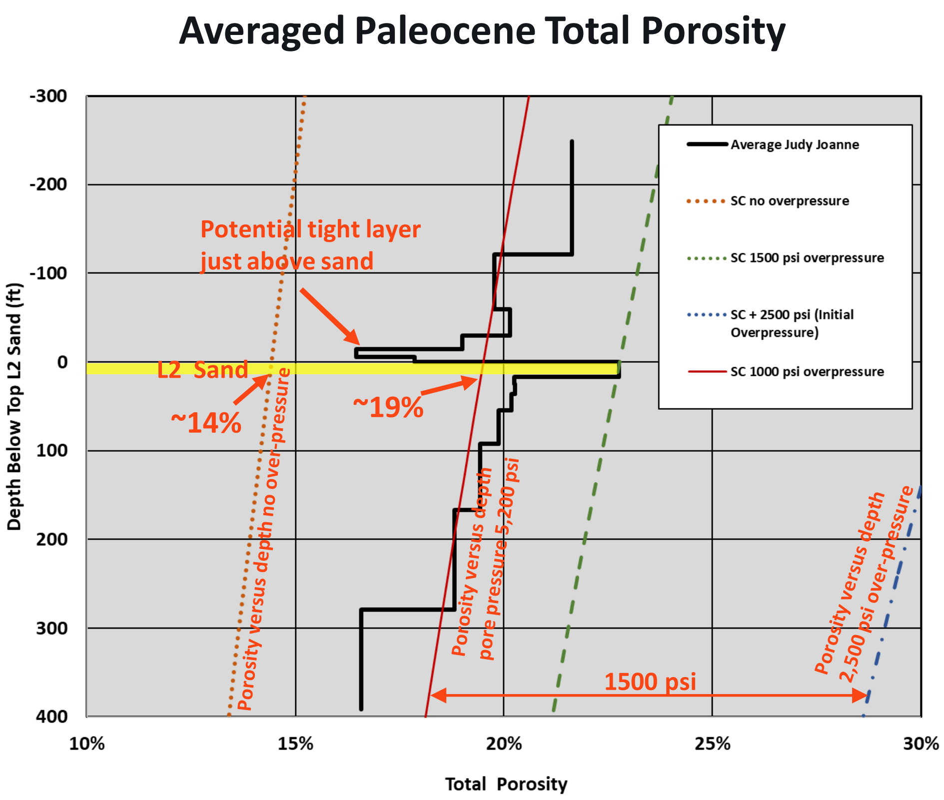
J-Block Lista Reservoir Model

Model Initial Water Saturation



- A 3D regional reservoir model has been built
- The aim has been to achieve a good history match with the aquifer fully included within the 3D model
- This ensures that the modelled aquifer is consistent with realistic parameters for the under and over lying silts and shales
- Due to the very low permeability of the silts and shales most of the aquifer support is expected to come from rock very close to the L2 sand
- This required the model to use thin layers next to the reservoir

Porosity of Formation Above and Below the L2 Sand



Layer Porosity averages based on ~50 Judy & Joanne dome area wells

Proportional layering is used from the Balder to the top L2 sand and from the base L2 sand to Ekofisk

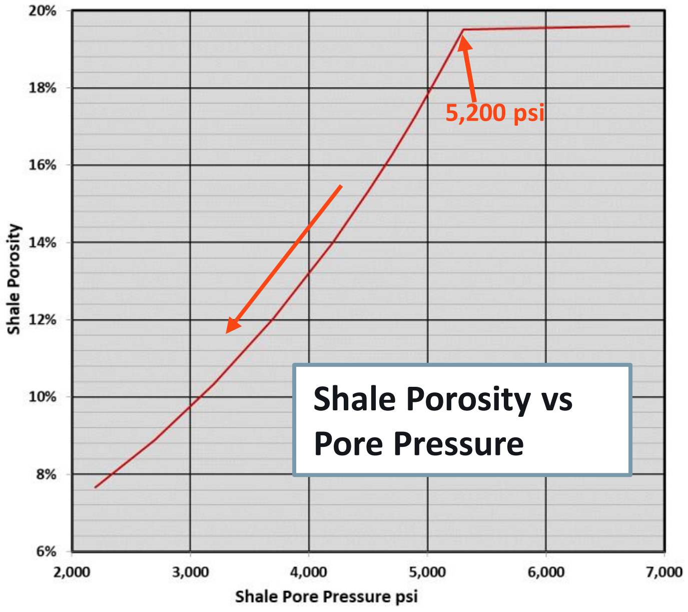
Depth is based on average layer thickness

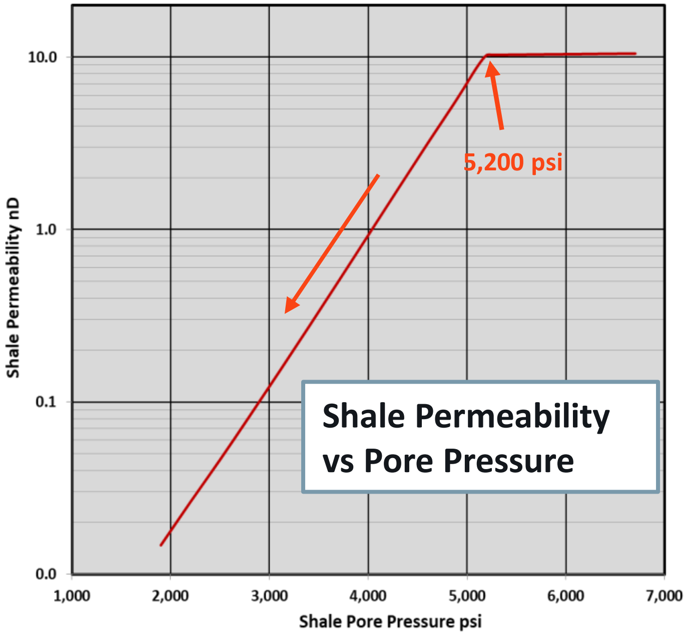
- The plot of porosity of the formation above and below the L2 sand shows a depth trend
- This trend is consistent with theoretical Sclater Christie shale porosity versus depth trends
- These trends are functions of the maximum historical geological net overburden stress

  Net overburden stress = Lithostatic stress – Pore Pressure

- At the current depth of the L2 sand, at normal pressure in the absence of any over-pressure, the porosity of shales would be expected to be about 14%
- Alternatively at the initial reservoir fluid over-pressure of ~2500 psi the porosity would be expected to be over 30%
- The trend through the averaged layer data fits a trend with an over-pressure of ~1000psi
- This trend gives a shale porosity just below the L2 sand of ~19%
- If pore pressure in the shale declines below ~5,200 psi (1,000 psi over-pressure) the net overburden stress in the shale would exceed the maximum stress experienced during geological history
- The porosity of the shale would then decline as the shale irreversibly de-waters
- The pressure of the reservoir after a long period of re-charge is observed to be close to this critical pressure

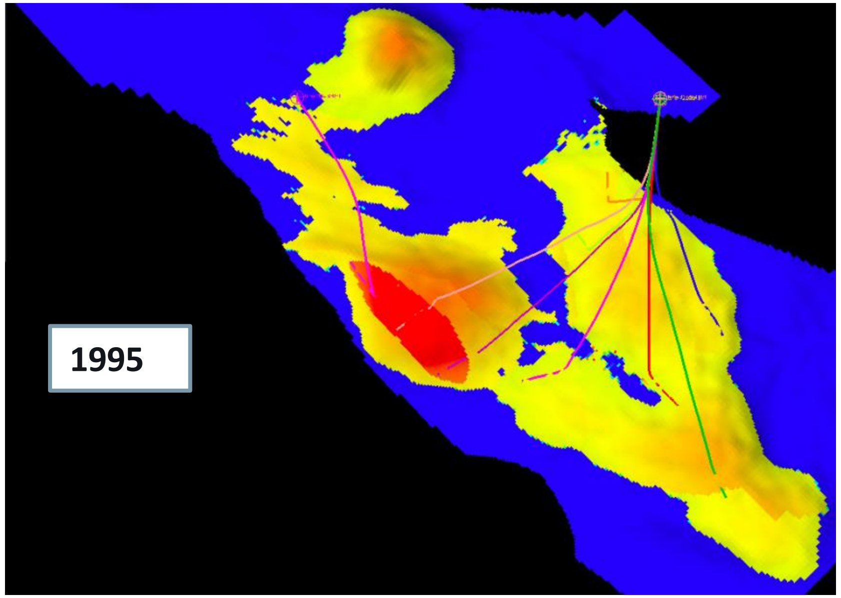
Properties of the Formation Above and Below the L2 Sand



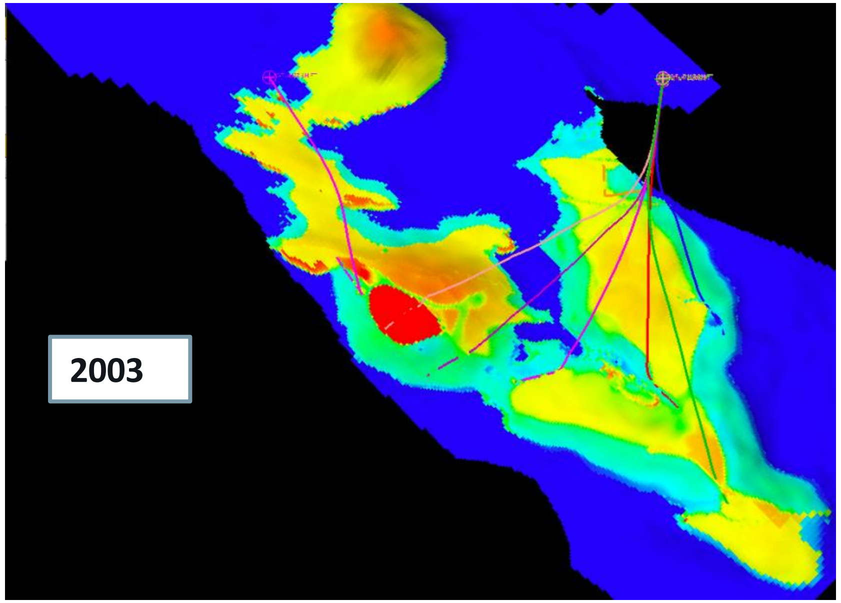


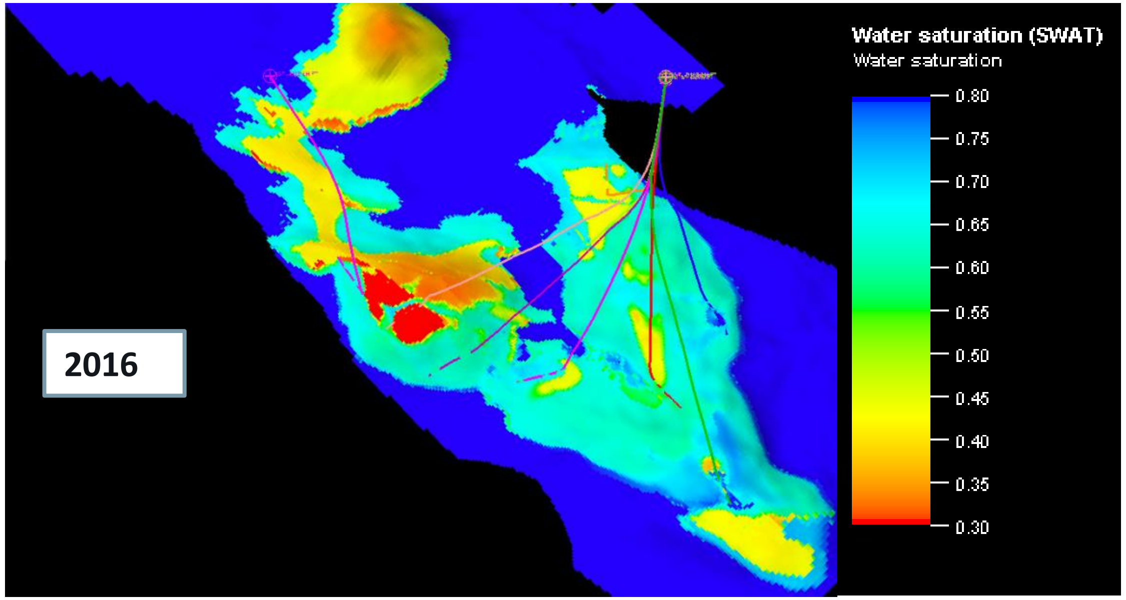
- To build a model for the silts and shales adjacent to the L2 sand, parameters such as compressibility and permeability need to be estimated
- It has therefore been assumed that the shale porosity follows Sclater Christie compaction curves when there is sufficient depletion for net overburden stress to exceed the previous maximum stress
- It is estimated that this happens once the pore pressure falls below 5,200 psi
- At this pressure there is a very large increase in the compressibility of shale due to compaction with the porosity decreasing irreversibly
- The decline of the shale pore pressure is constrained by the rate fluid can escape from the nano Darcy rock
- In the absence of data, the shale permeability has been estimated by the method of Yang & Aplin (2010)
- When the pressure declines and the shale compacts the permeability rapidly declines
- During the model history matching, the permeability needed to be increased by factor of ten to obtain a good match
- This probably reflects the impact of higher permeability silts and occasional thin sands

Evolution of Aquifer Water Encroachment



- The model clearly shows that the silts and shales above and below can predominately generate an edge water influx
- In 2003 at around the time of maximum depletion, significant areas away from the edge of the reservoir are un-swept
- By 2016 the influx of aquifer that has caused the pressure re-charge has significantly increased the area that has been swept





Summary & take-away

- The significant pressure re-charge seen in the J-Block L2 sand reservoir is mainly due to aquifer influx
- Due to both limited extent and depletion, the L2 sand surrounding the reservoir is not the main source of aquifer
- The thick silts and shales surrounding the L2 sand must therefore contribute to the aquifer influx
- Modelling has shown that a nanoDarcy permeability in the range of ~100 nD is sufficient to generate the required influx
- Using this model a good history match can be obtained that matches
  - Well pressure history
  - Water breakthrough and production
  - Encroachment of water from the edge of the reservoir that eventually reaches the centre of the reservoir
- The aquifer support from the silts and shales has been particularly obvious in this reservoir because
  - The reservoir is thin only ~20ft
  - The over-pressure has allowed shale permeability and porosity to be preserved
  - The depletion of the surrounding aquifer has been measured
  - The long 25+ year history
  - Significant pressure re-charge during a long period of minimal production
  - Continued data acquisition from wells that ceased production up to twenty years ago as a means for identifying remaining potential

Special mention and thanks to those involved:

DEVEX 2022

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