Developing the Arundel Field Maximising Hub Value through Seismic Uplift

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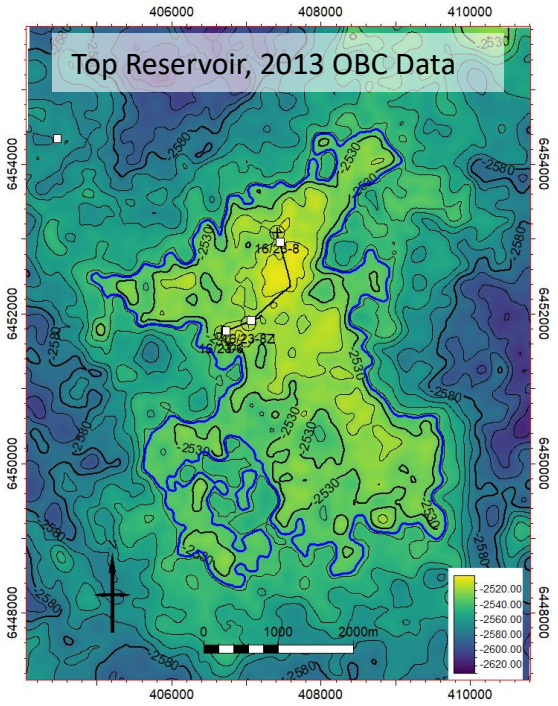
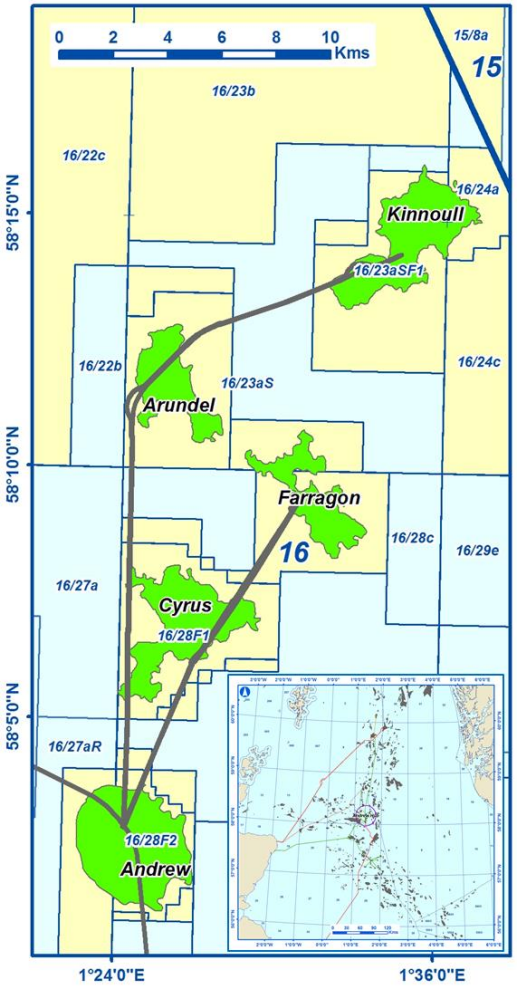
Arundel Area Introduction

- Lista Palaeocene Turbidite reservoirs
- Sands are high productivity with an active aquifer

- Andrew Field and subsea tie-back, Cyrus onstream in 1996
- As Andrew Platform production has declined ullage has been filled by further tie-backs:
  - Farragon in 2005
  - Kinnoull in 2014

- Arundel was brought online in September 2017
- Initial production rates have exceeded 10mbd oil
- Arundel was the first tie-back to be discovered in 2000
  - Why was it the last to be developed?





Arundel History

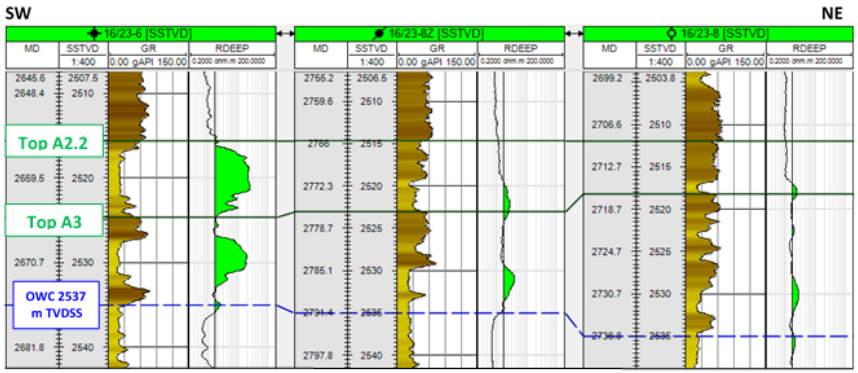
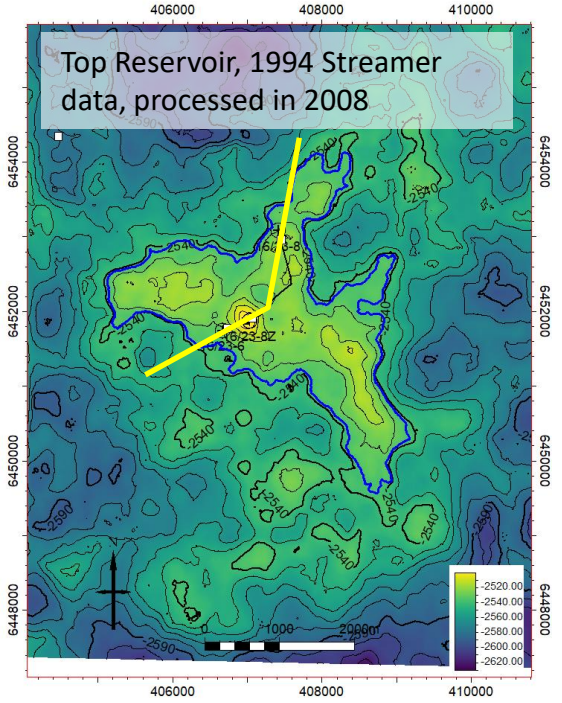
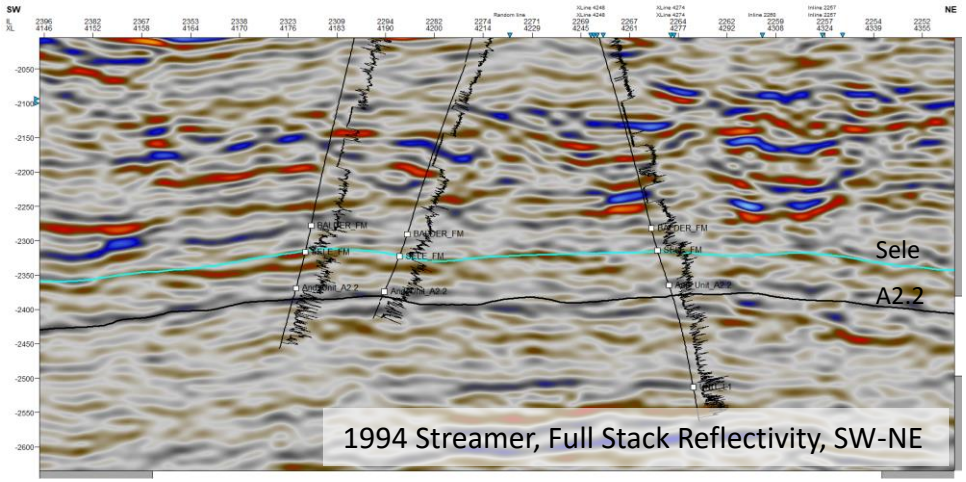


Figure 4. Gamma ray and resistivity well log correlation panel for Arundel E&A wells with top A2.2 and A3 units and OWC. Note reduction in thickness and sand presence in A2.2 unit moving SW to NE across the field.



- Discovery well 16/23-6 drilled in 2000 by Chevron. Oil column encountered, ~20m column height
- Shallow relief - very uncertain STOIIP
- 2007/8 – 1994 Streamer data reprocessed in regional PSDM
- 2008 – two appraisal wells drilled
  - 16/23-8 – deep to prognosis, poor NtG in crucial A2.2 reservoir unit
  - 16/23-8Z – deep to prognosis, also poor NtG despite being only 350m east of 23-6 discovery well
- **Considered too small & risky to develop**



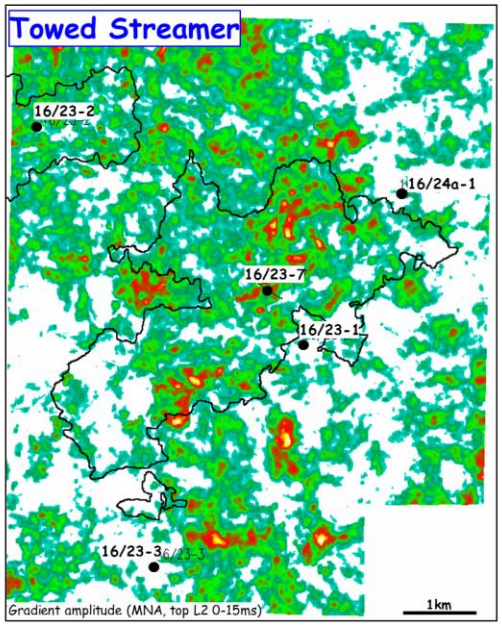
How did our understanding change?

1. In 2010 BP acquired an OBC survey over Kinnoull
   - Massive uplift in imaging, especially in the AVO quality, which is crucial to mapping sand distribution
2. Kinnoull flowline laid on seabed, but deviated to pass over Arundel with tie-in point.
3. 2013 – OBC survey acquired over Arundel Field, merging in with coverage of Kinnoull to the east

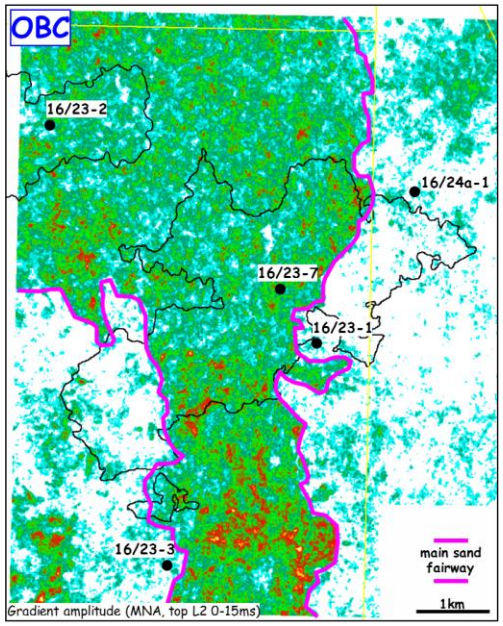
Why such a big uplift?

- Eocene Sandstones – fast, chaotic multiple generators
- Multi-azimuth illumination combined with better demultiple

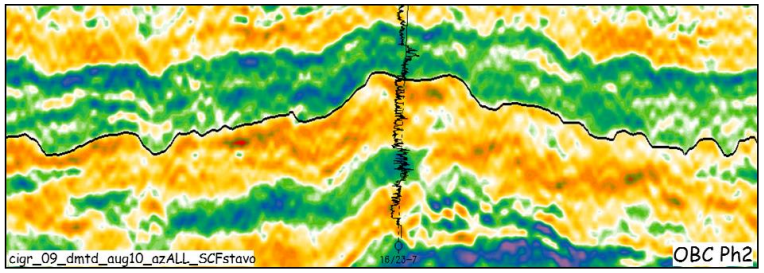
1994 Acquisition, 2008 PSDM



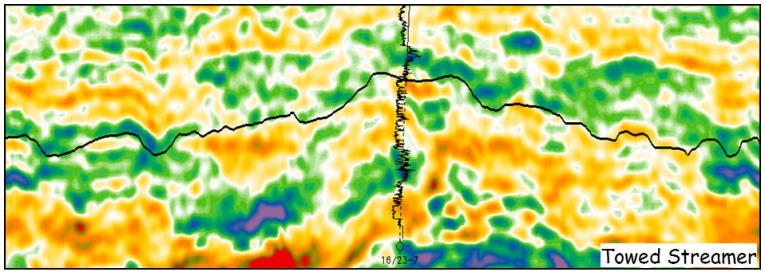
2010 OBC



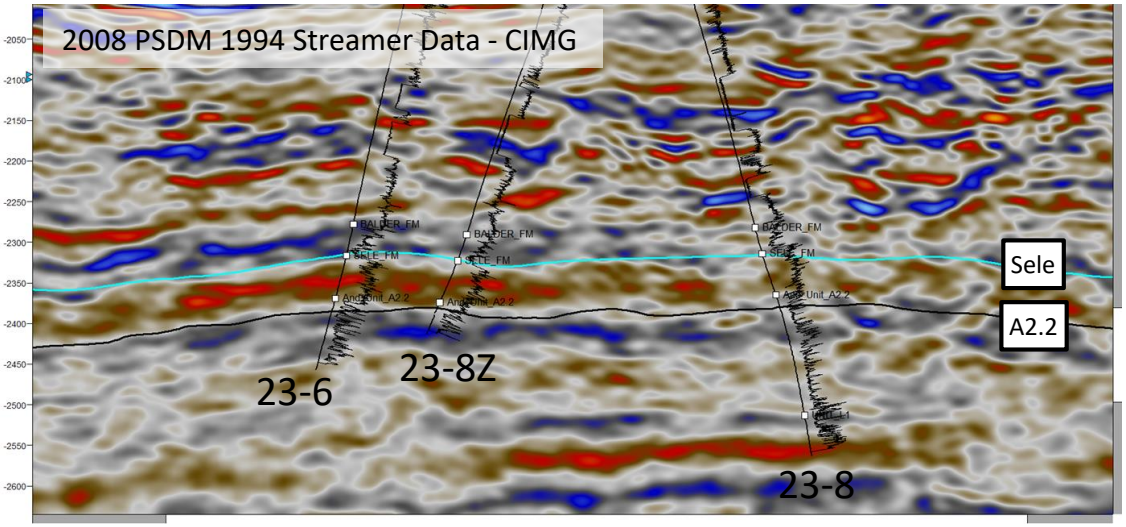
2010 OBC, Gradient Coloured Inversion

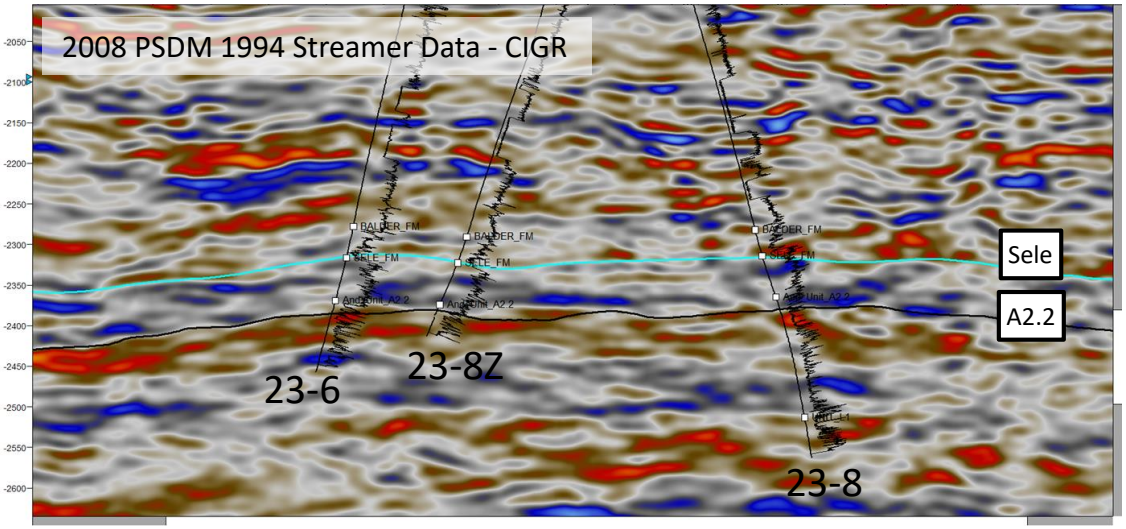


Towed Streamer, Gradient Coloured Inversion



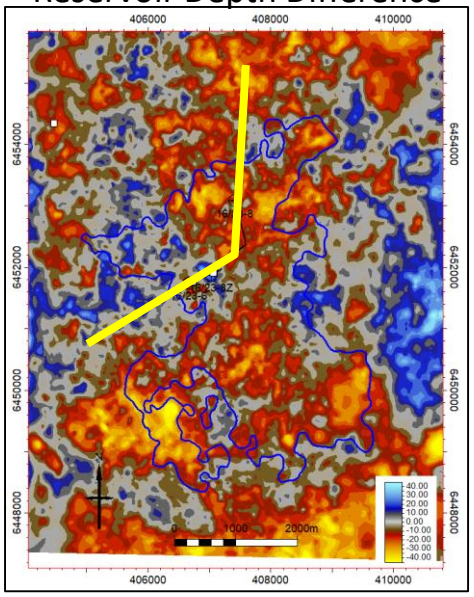
Arundel PSDM 1994 Streamer Data





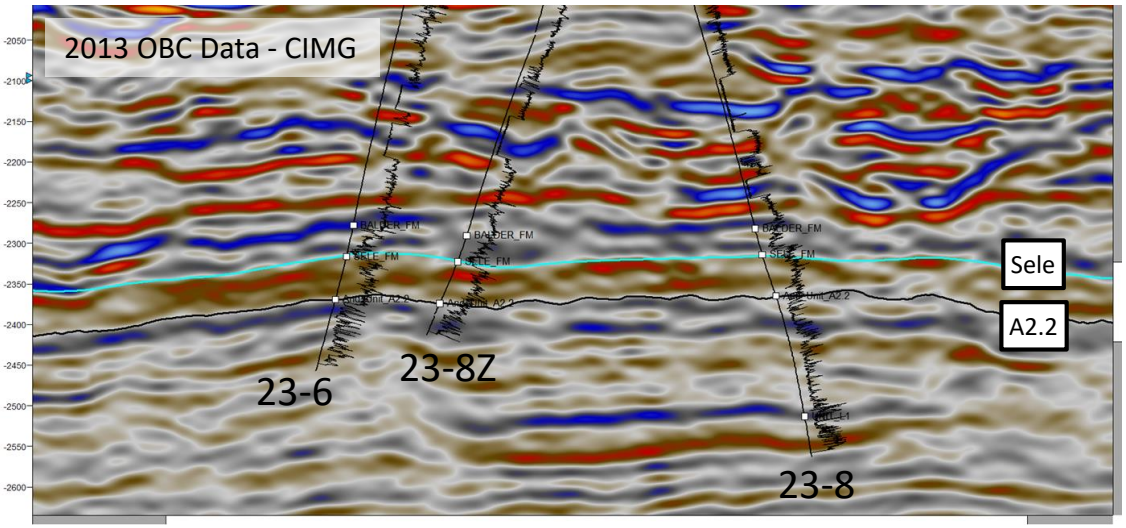
- CIMG usually used to map top reservoir - zero crossing highly ambiguous and nibbled by multiple energy
- Even Top Sele is not a clear pick
- L1 Sand at base of 23-8 well has some expression but no clear terminations

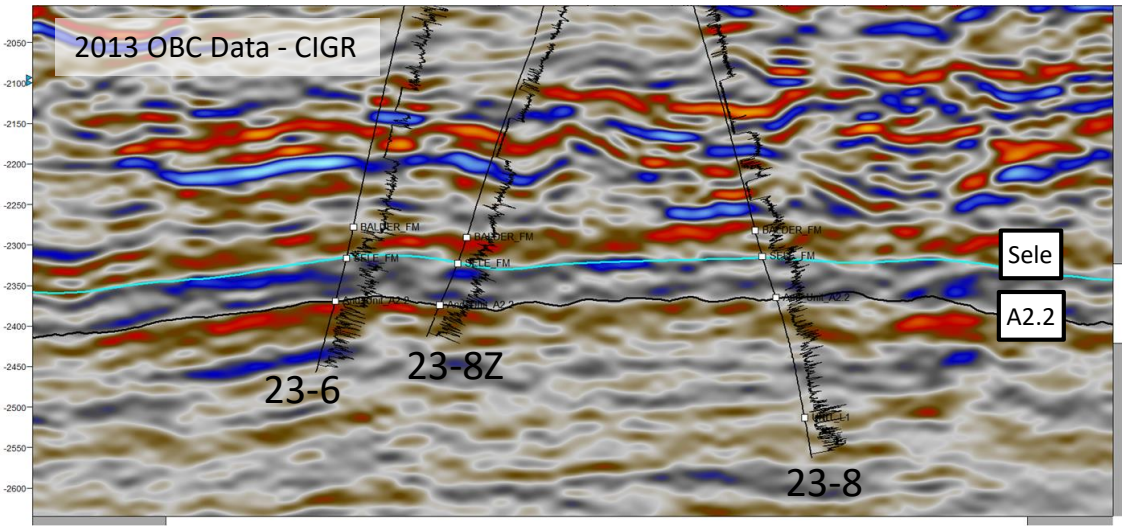
Streamer – OBC Top Reservoir Depth Difference



Orange = OBC is shallower

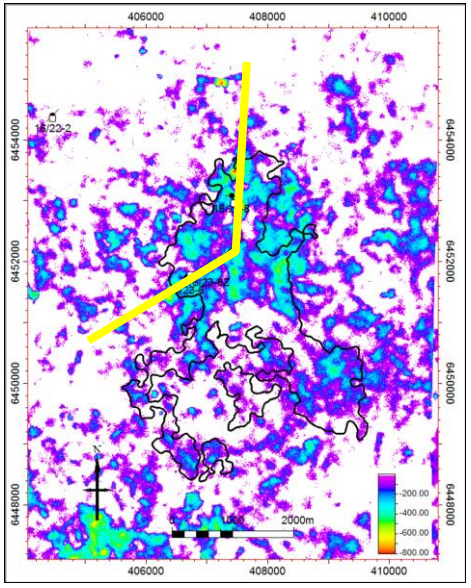
Arundel 2013 OBC Data





- OBC has better tie to Eocene sands
- More coherent mapping of Sele and Top A2.2
- The first potentially reliable attributes for use in well planning and geological description
- OBC affected by Eocene multiple generators

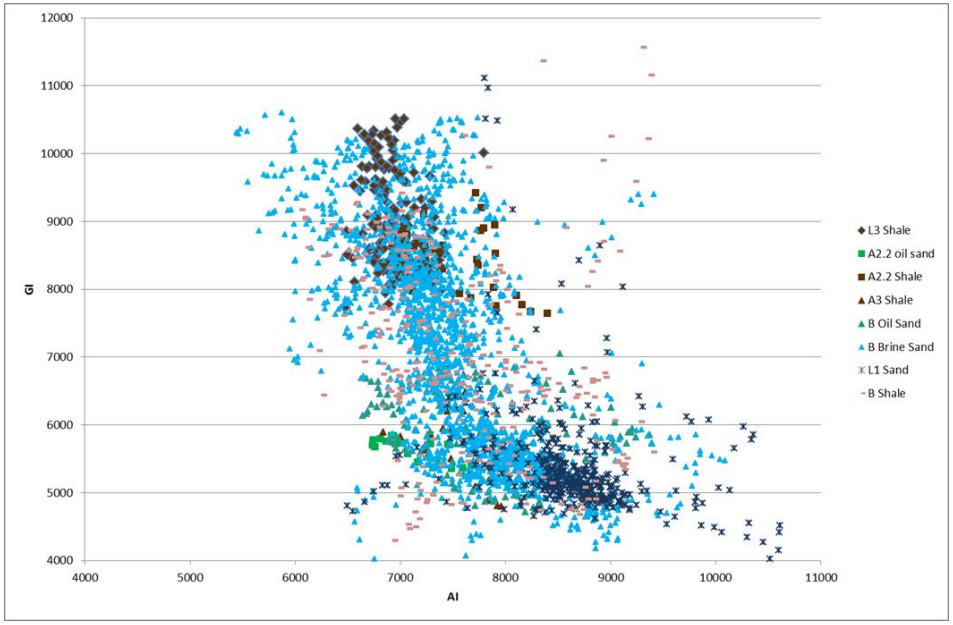
OBC Fluid Attribute – Conformance?



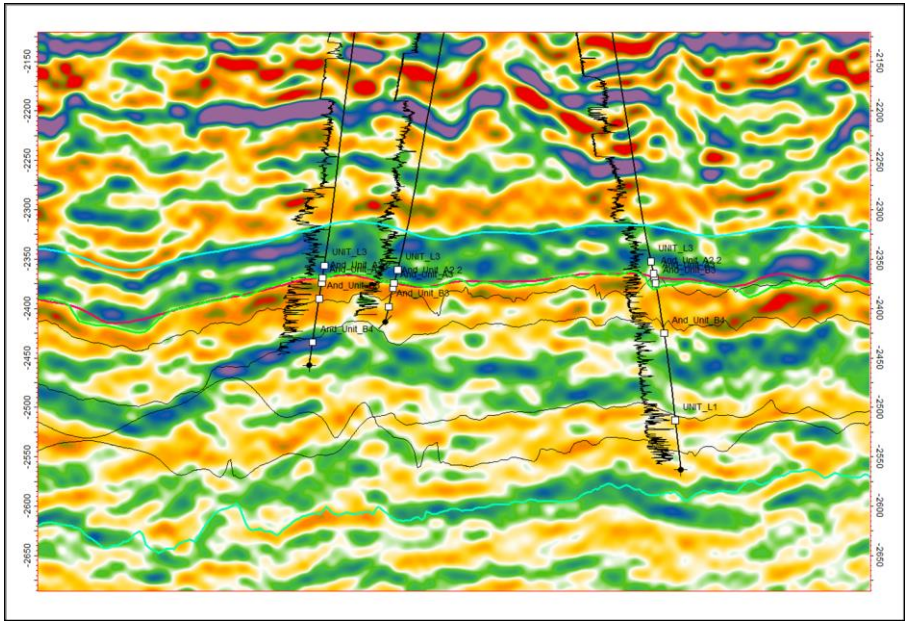
Did OBC solve everything on Arundel?

- Arundel still presented many challenges even in the light of better seismic data
  - The interval of interest is very thin, < 10m
  - Rock properties are more complex than Kinnoull with shales and sands potentially having similar AI/GI properties
  - Overburden more complex Eocene Sand distribution than Kinnoull
  - Attributes were useful, but no standout single attribute as worked so well at Kinnoull

AVO Rock Properties: AI-GI Cross Plot

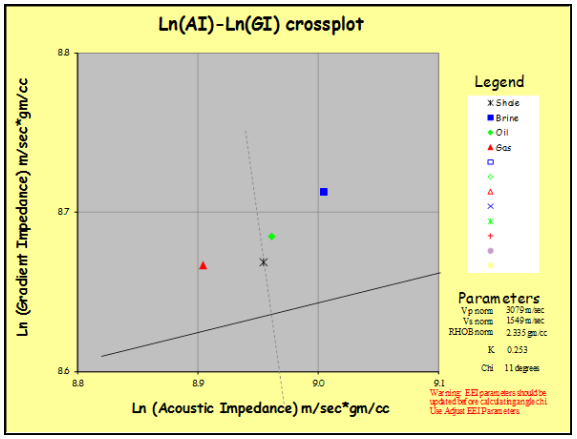


SW-NE Section – CIGR Data

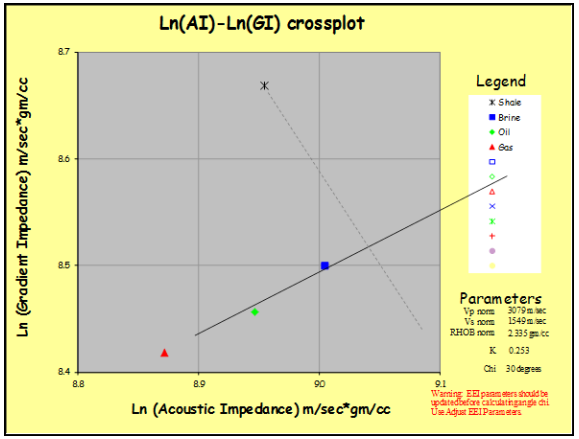


Rock Properties and Attributes

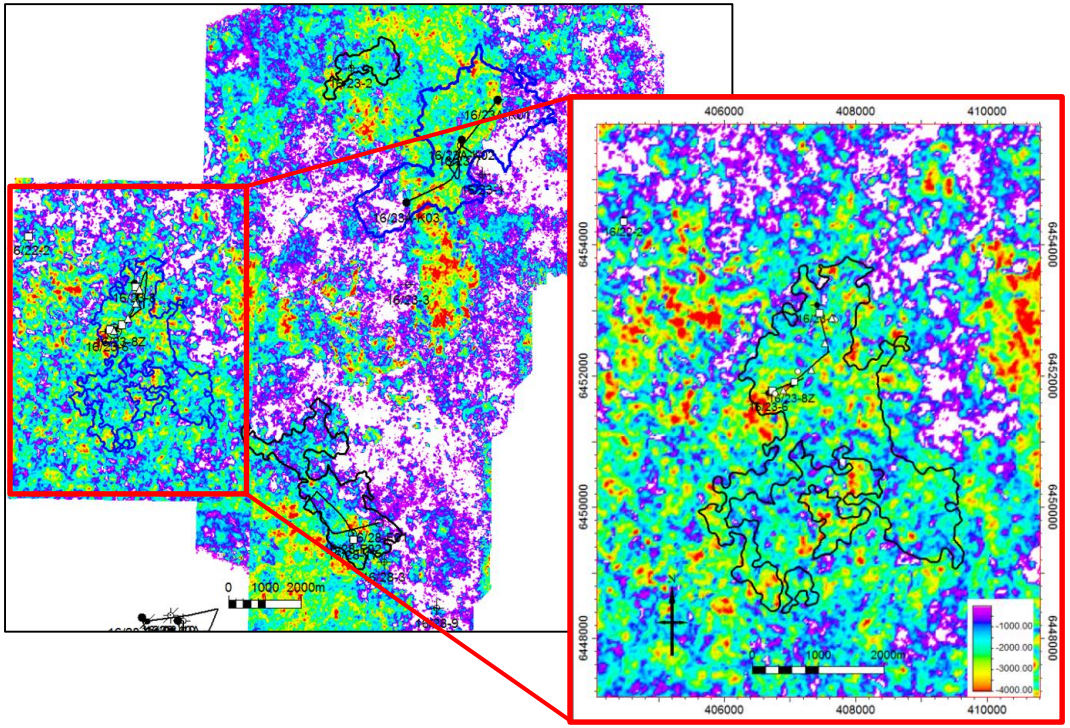
A2.2 Sand (Target) to A3 Shale



A3 Shale to B1 Sand



CIGR – Top Pick Amplitude



- CIGR attribute very strong at Kinnoull and delimits the sand fairway
- Arundel also gets a strong response, but does not calibrate with the well observations at A2.2 level (younger than Kinnoull)
- Amplitude mainly shows B sand fairway, A2.2 and A3 have too similar rock properties and are very thin (<10m)

- **Key Message – subtle variations in stratigraphy and rock properties matter!**

2015-2017

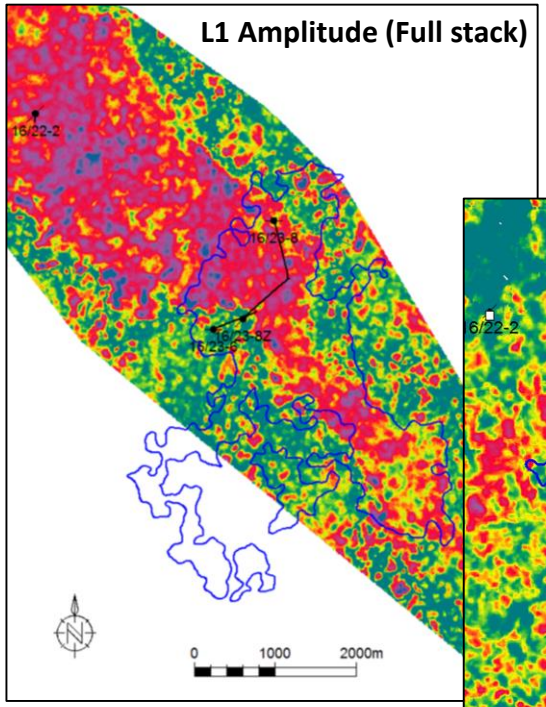
- Andrew Platform CoP early 2020s
- Rig slot available – is this finally the time for Arundel?

- Progress
  - Robust core-area STOIIP
  - Ability to map top reservoir
  - Promising attributes

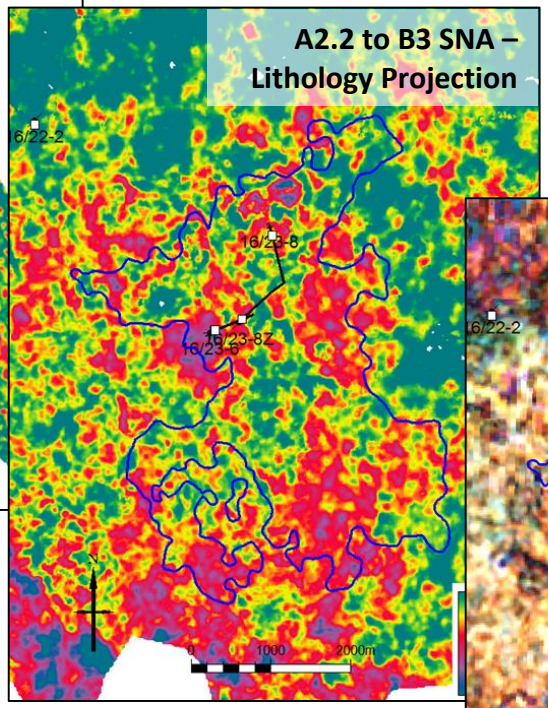
- Remaining uncertainties
  - Net to Gross distribution
  - Depth Conversion – Not STOIIP, but stand-off to OWC

- Mitigation
  - Drill a long horizontal geo-steered well designed to exploit upside case but robust enough for downside (low net) outcome
  - Case and perf allowing water-shut off and selective isolation of intervals likely to cut water

Seismic Attributes – how did we use them?

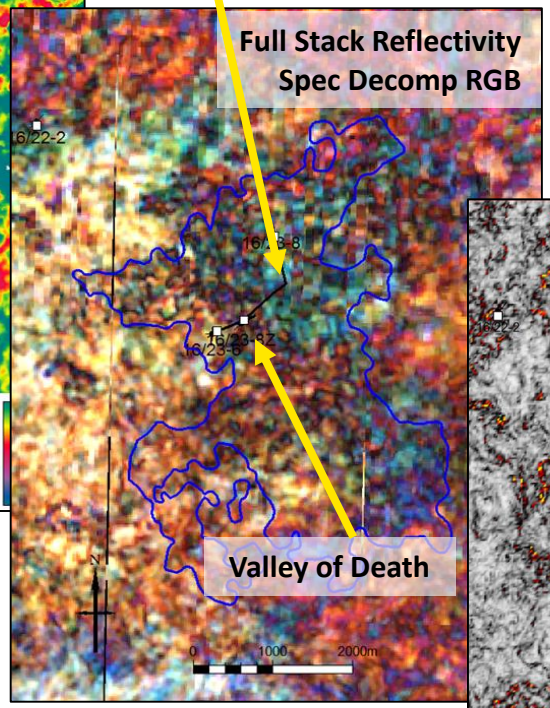


- The L1 Sand is a deeper Lista Sand – Rock Properties analysis indicated this sand is harder than shales in AI space
- Confidence in data ✔

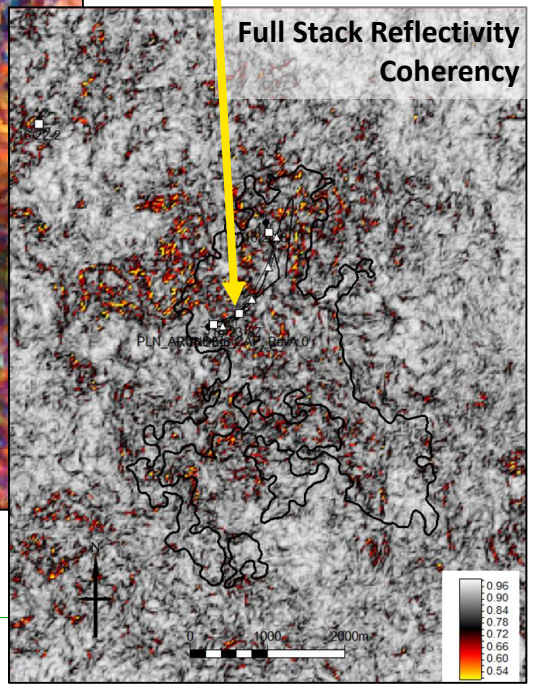


- Noisy data, because of weak rock property response, but some indication of NNW channel direction

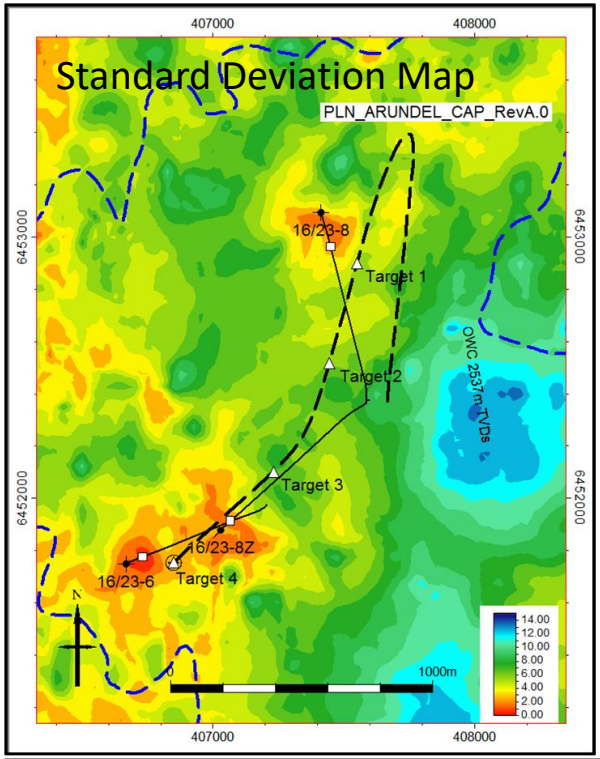
- Spec Decomp highlights area of better sand at 23-6, but seems restricted in extent - **Downside Case**
- Hints of weaker, but discernible spec decomp response in East – **Upside Case**

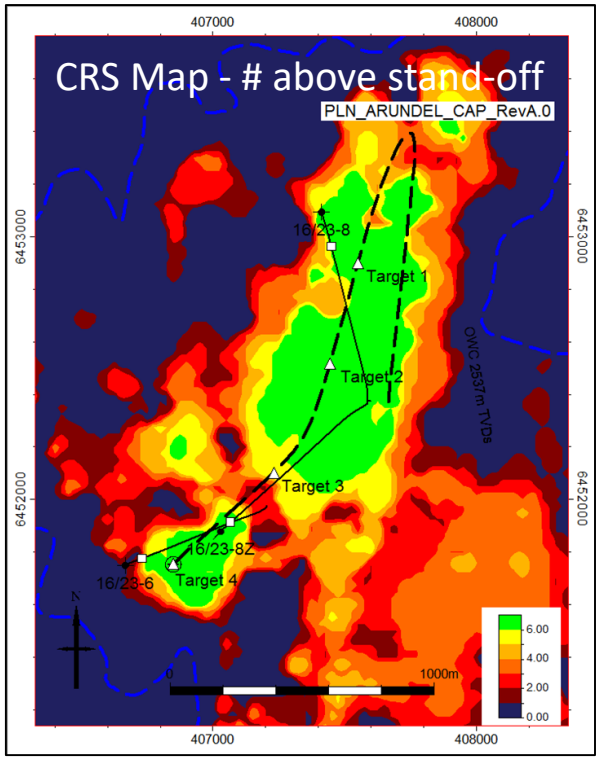


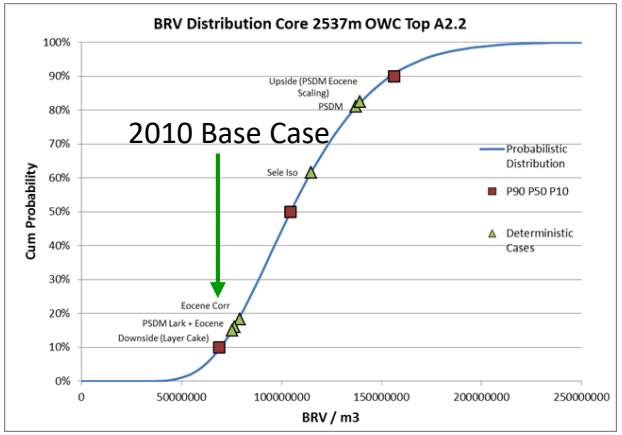
- Coherency used as a QC – aim to drill well in areas of coherency reflectivity
- Chaotic zone around 23-8Z highlighted which is a consistent feature on all attributes – zone of lithological and structural risk



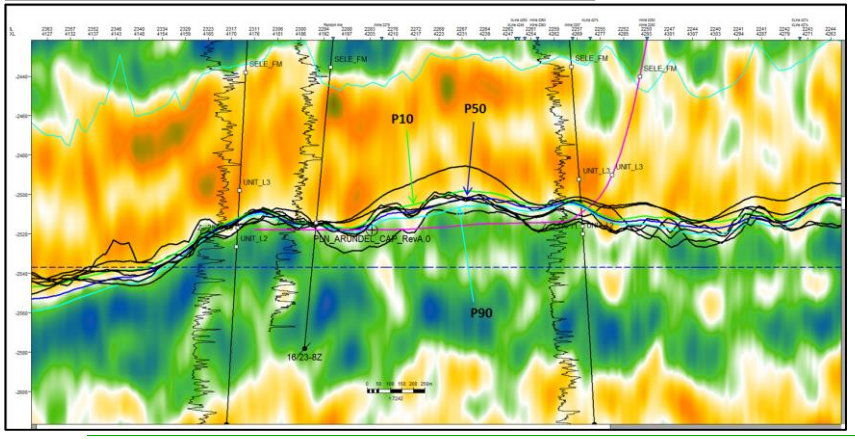
Depth Conversion Uncertainty







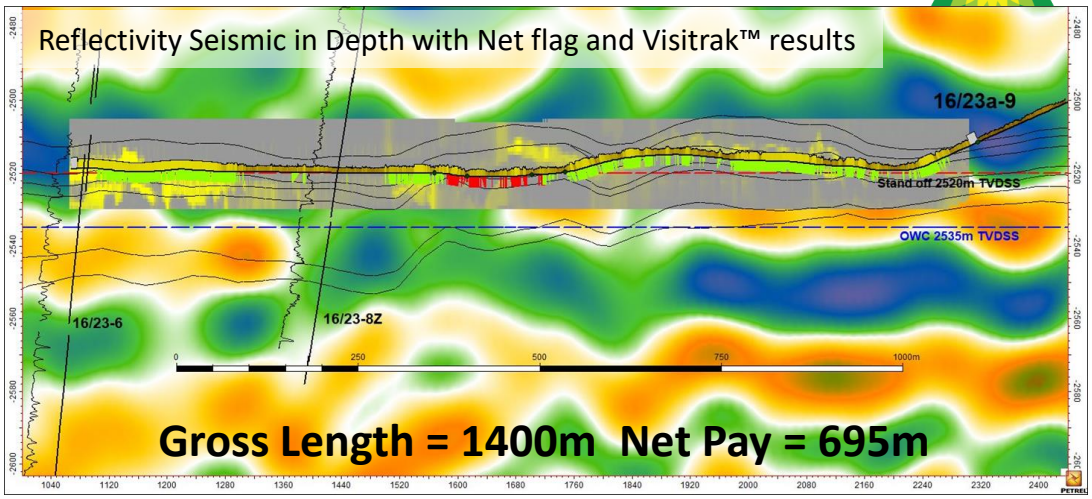
Deterministic BRV cases against Probabilistic



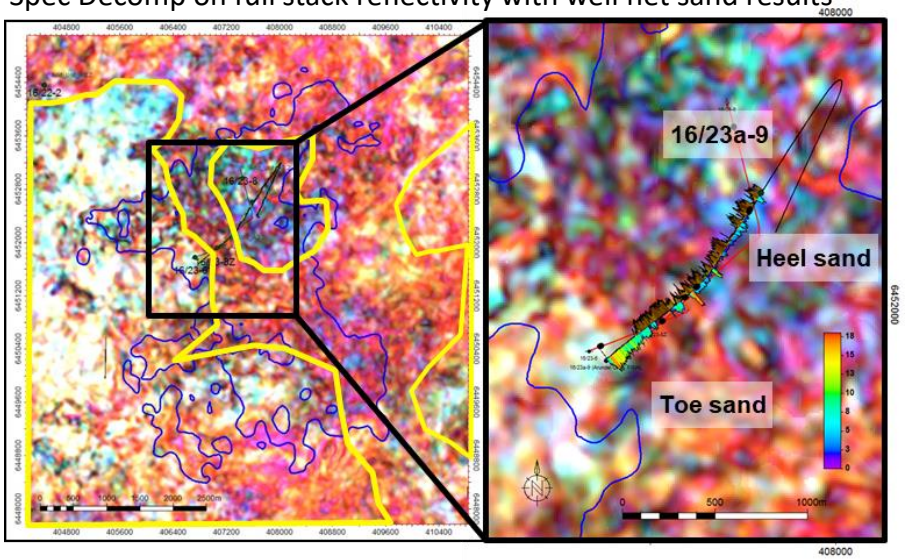
- Key Risks – not maintaining stand-off to OWC and drilling into unstable over-burden shales
- Completed a number of deterministic depth conversion scenarios
- Well trajectory considered the standard deviation and the "CRS" map – how many depth conversion scenarios maintain a 15m + standoff to the OWC
- Gave confidence to well plan, and highlighted areas of key risk – especially the "valley" close to 23-8Z

Arundel Static Well Results

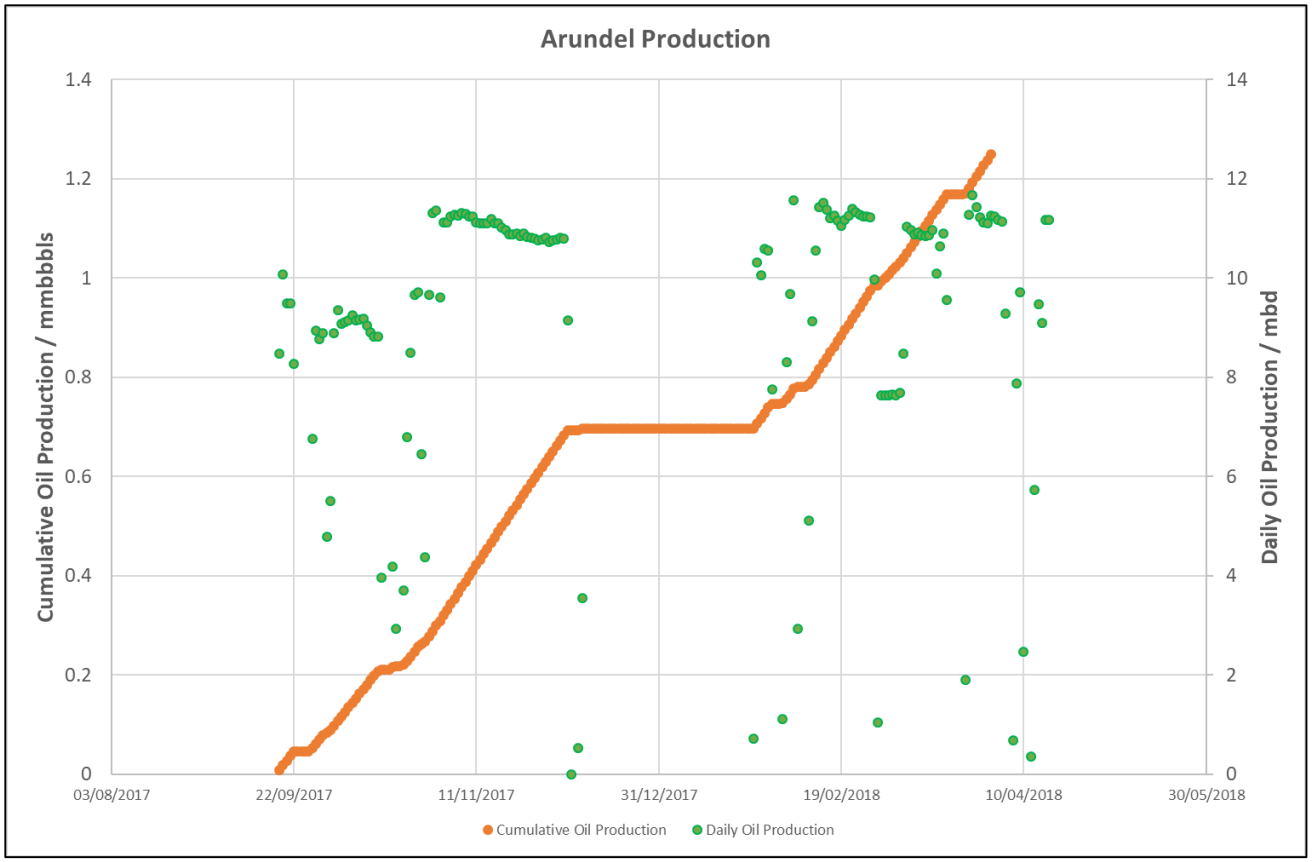
- Visitrak™ data invaluable in geosteering well
- Individual sand dips steeper than seismic dips
- Real structure more benign than seismic image – impact of multiples?
- Reasonable correlation of Spec Decomp image with well result, including materialisation of the "Valley of Death"
- Penetration of Visitrak™ tool is limited, but indications are multiple thin sands 1-3m thick.



Spec Decomp on full stack reflectivity with well net sand results



Arundel Well Performance



- Well has been producing a steady 10-11 mbd with no water cut so far. The Arundel well has its own dedicated MPFM so well surveillance is good
- Water cut is expected due to low stand-off (15m) to OWC and lateral distance to the contact being small

Future Outlook for Arundel and Seismic

- 2nd production well?
- Water shut-off, assuming water ingress is localised
- Given the well is sub-sea even interventions are very costly and would require a vessel or rig
- 2017 – we acquired an OBN on OBC 4D survey over the Kinnoull Field in September 2017. Early results are yielding very good data quality and strong 4D signal – could we replicate this at Arundel?
- 3D reprocessing may de-risk a 2nd well in the south by enhancing the AVO for fluid and lithology indicators and reducing depth conversion uncertainty

Conclusions

- Arundel development is delivering value for BP through incremental oil and CoP extension for the other Andrew Hub fields

- High quality seismic data can reduce uncertainty unlocking developments like Arundel, but helping to address irreducible uncertainties, which were then mitigated by well design and real-time data acquisition

- We skewered the pancake!

Acknowledgments

- I would like to thank BP for their permission to give this talk

- Planning, drilling and bringing the Arundel well online was a co-ordinated multi-disciplinary effort between Reservoir, Drilling and Subsea functions. This presentation has attempted to show the impact of Geophysics on the Arundel Development, but other functions and subsurface disciplines had a huge impact and will have their own story to tell on delivering this project

- I would like to particularly acknowledge colleagues in the Reservoir Team: Rory Leslie, Zoe Sayer, Lex Love, Rosemary Anthony, Sara Newns, Mairi Nelson, Simon Whiteman