PESGB sand injectite 'master class' Croydon 07 Feb 2017
Hydrocarbon Habitats – Injectites, Oslo & Stavanger 16-17 Feb 2017
Geological Society – Sand Injectites, London, 22-23 March 2017
FORCE Underexplored Plays III, Stavanger, 31/10-01/11 2018
Coming soon: Geological Society Special Publication

Sandstone intrusions and landslides in the North Sea

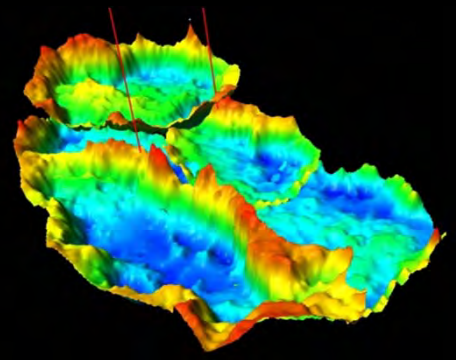
Mads Huuse[1] & Andrew Hurst[2]

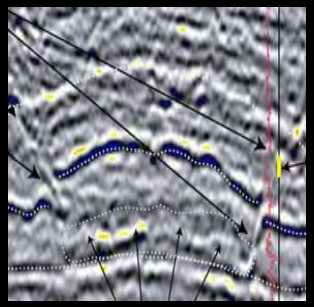
Sand Injection Research Group

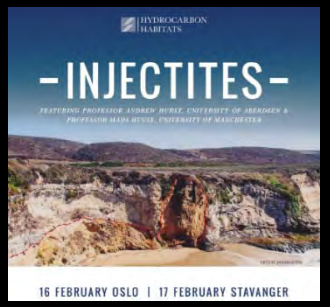
[1]Basin Studies and Petroleum Geoscience Group, University of Manchester

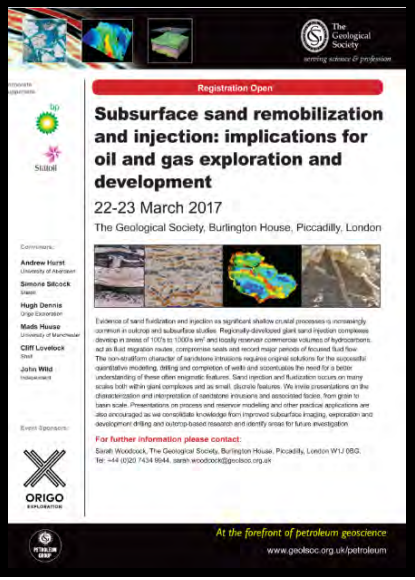
[2]School of Geoscience, University of Aberdeen

With input from numerous colleagues in academia and industry , PhD and MSc students since 2000…









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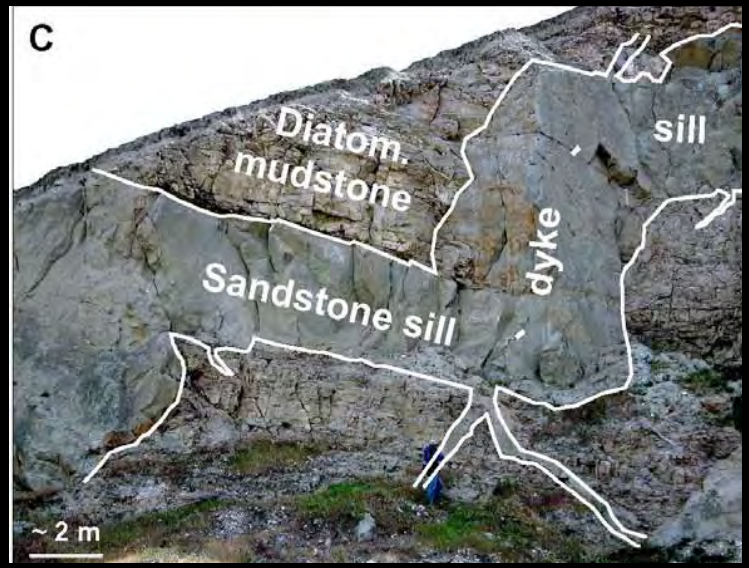
Basin studies

Analogues for crestal sand injectites & extrudites in Californian outcrops:

Santa Cruz Miocene (a, b), San Joaquin Valley Eocene (c) & Cretaceous-Paleocene (d)



Deep-water sand bodies in literature 2016

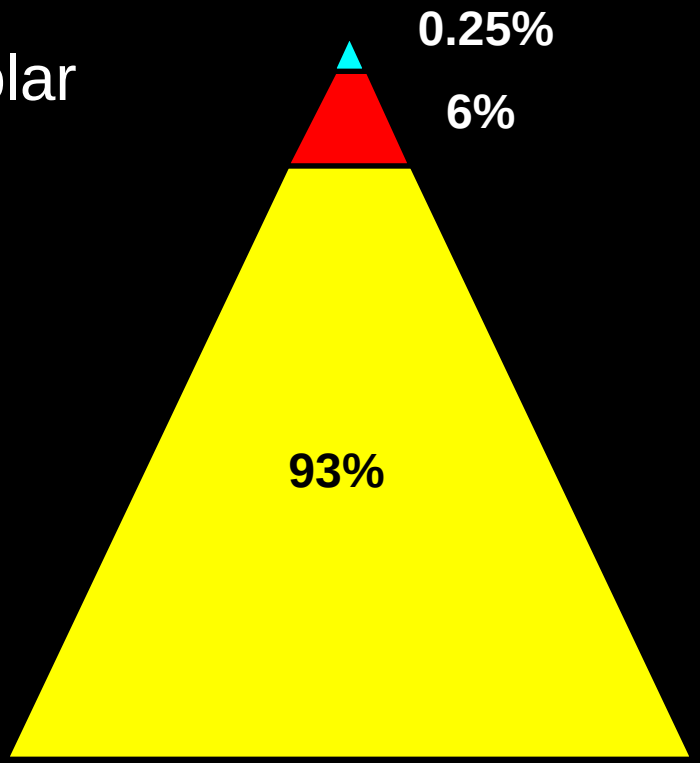
References on Google scholar

Depositional sandstones:

- Turbidites : 57 200
- MTDs : 2 060

Remobilized sandstones:

- Sandstone intrusions : 141



06/2016

Deep-water sand bodies in the literature 2017

References on Google scholar

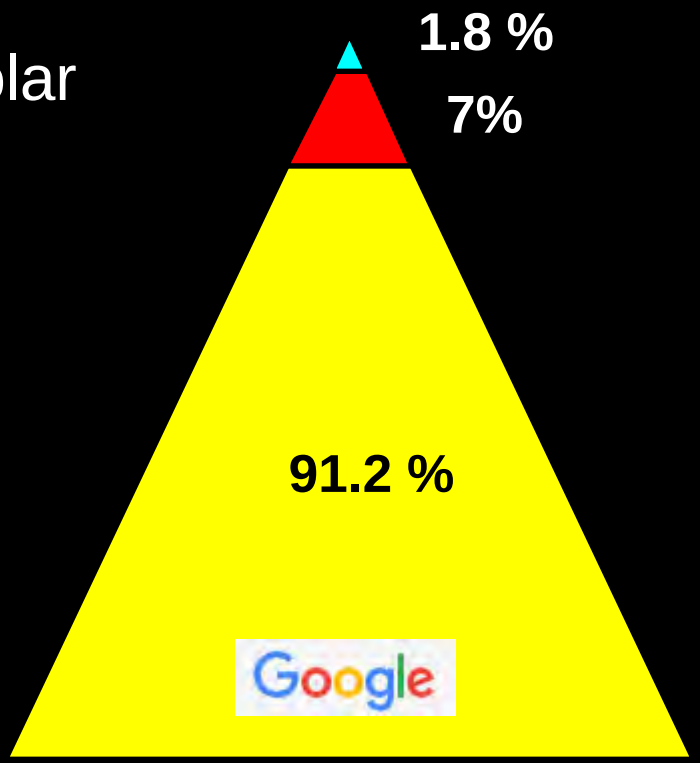
Depositional sandstones:

- Turbidites : 56 700
- Debrites: 2440

- MTDs: 3180
- MTCs: 1340

Injected sandstones:

- Sandstone intrusions: 555
- Sand injectites: 648



27/06/2017

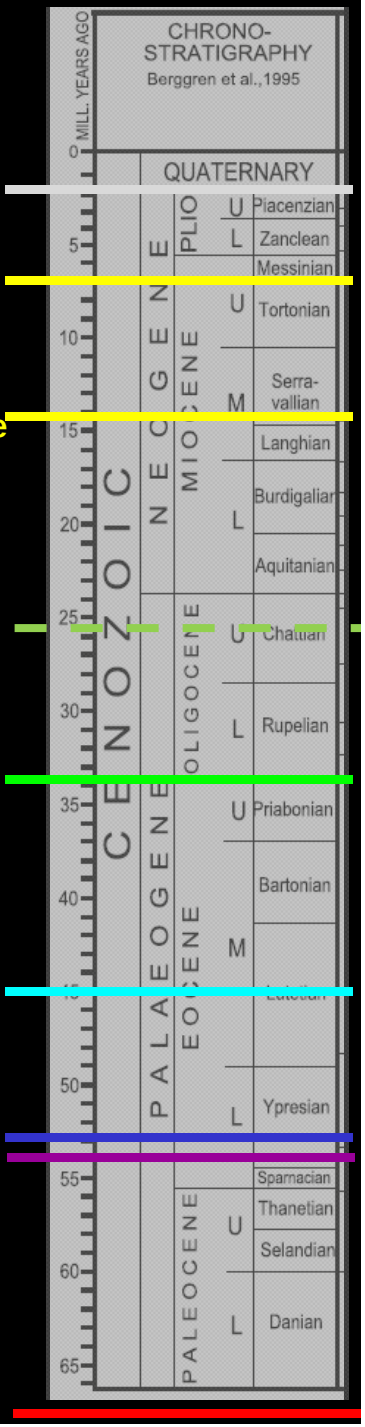
Stratigraphic and geographic occurrence of sand injection complexes in the North Sea

- Northeast Viking Graben
  - Late Cretaceous (Måløy slope), Late Paleocene / Early Eocene
- North Viking Graben
  - Mid Eocene, Late Eocene, mid/late Miocene/Pliocene, Plio-Pleistocene
- South Viking Graben & Utsira High
  - Paleocene/Eocene boundary, Early Eocene, Mid Eocene, Oligo-Miocene
- Outer Moray Firth
  - Mid-Eocene, Late Eocene / early Oligocene, Miocene, ?Plio-Pleistocene
- Northern Central Graben
  - Early Eocene, Miocene?
- Norwegian-Danish Basin (Siri Canyon)
  - Late Eocene / early Oligocene, mid Miocene
- Ringkøbing-Fyn High
  - Late Oligocene
- ?Southern North Sea
  - ?Pliocene

- Faroe-Shetland Basin
  - Early Eocene, mid/late Miocene
- Møre Basin
  - Paleocene?, Miocene
- Barents Sea (Sørvestnaget Basin)
  - Eocene

Acknowledgements:

Numerous colleagues, students and industry sponsors (SIRG Phase I&III)
PGS: MegaSurvey, Geostreamer 3D; TGS: FMB, NSR2D, Geostreamer 3D
CGG: NVG BroadSeis 3D
Schlumberger (Petrel), IHS (Kingdom), Eliis (Paleoscan)



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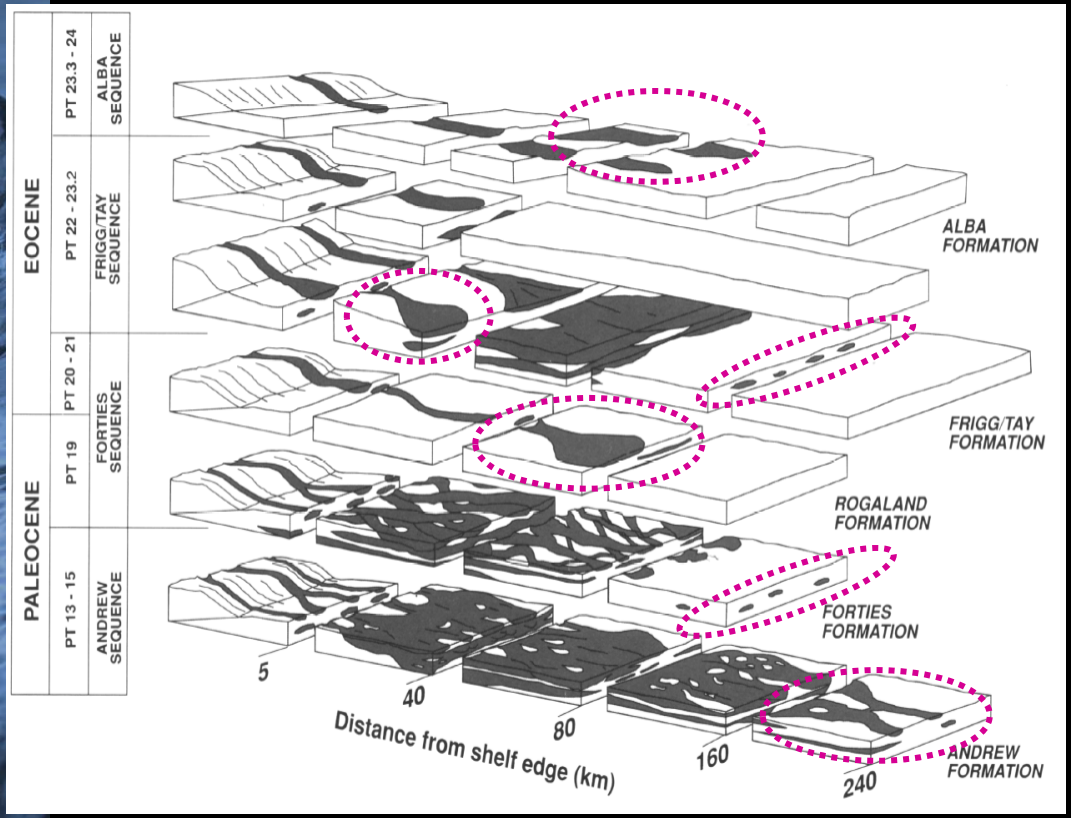
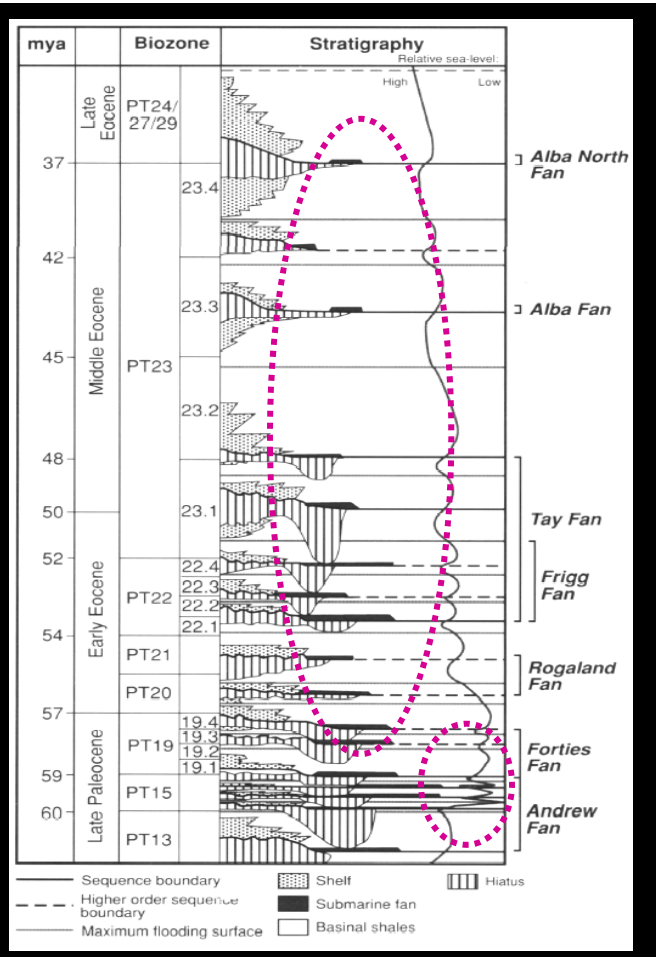
Submarine channels, fans, lobes, in a sequence stratigraphic framework – what about MTDs & injectites?





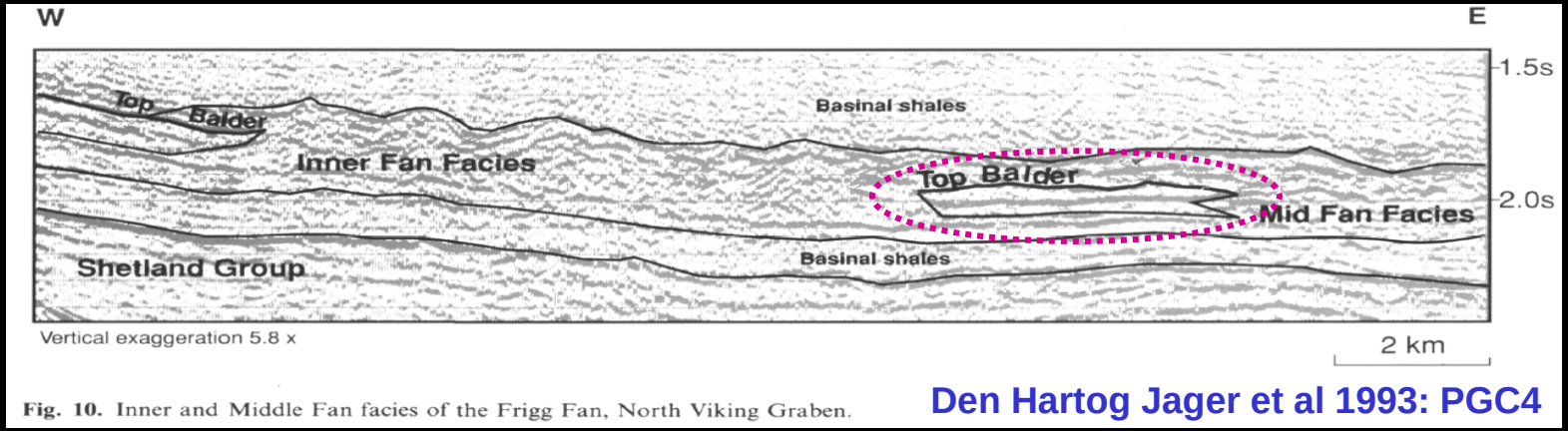


Fig. 10. Inner and Middle Fan facies of the Frigg Fan, North Viking Graben.

Den Hartog Jager et al 1993: PGC4

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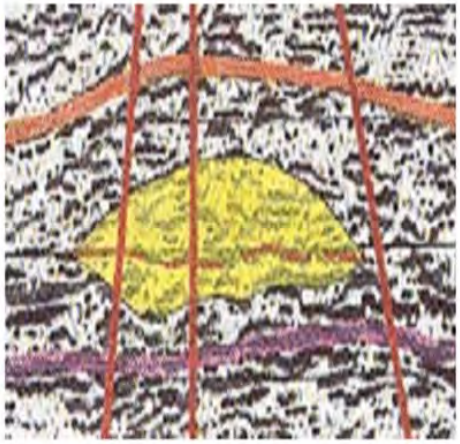
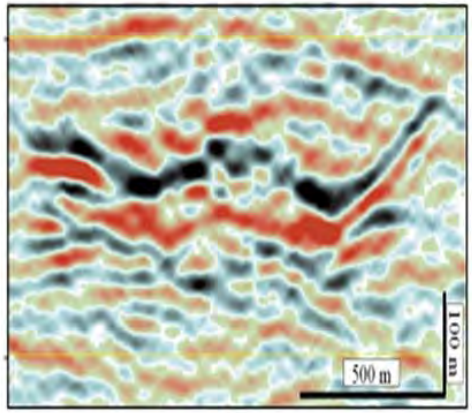
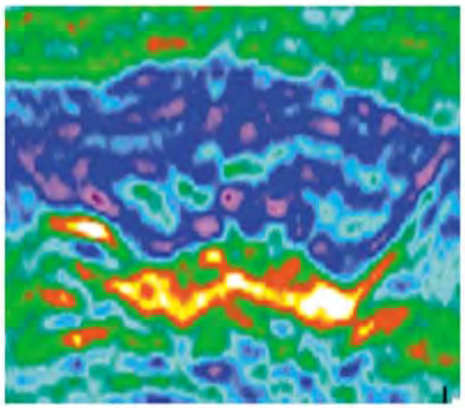
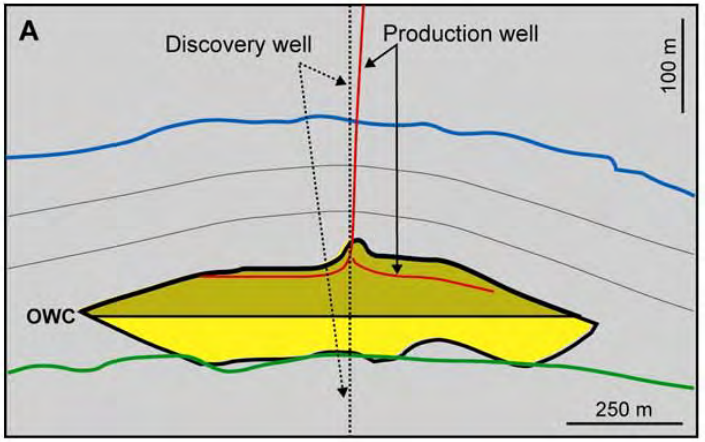
Eocene Alba Field (Grid sst): 1B bbl field discovered by mistake..

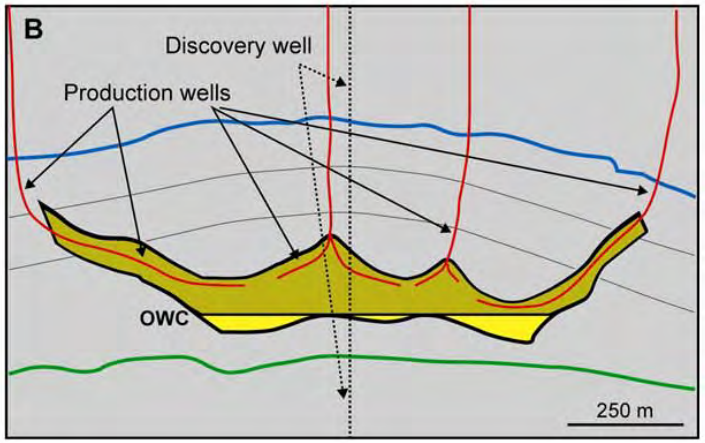
Image quality is clearly important..











Huuse et al. 2003: First Break; Huuse et al. 2007: AAPG Memoir 87

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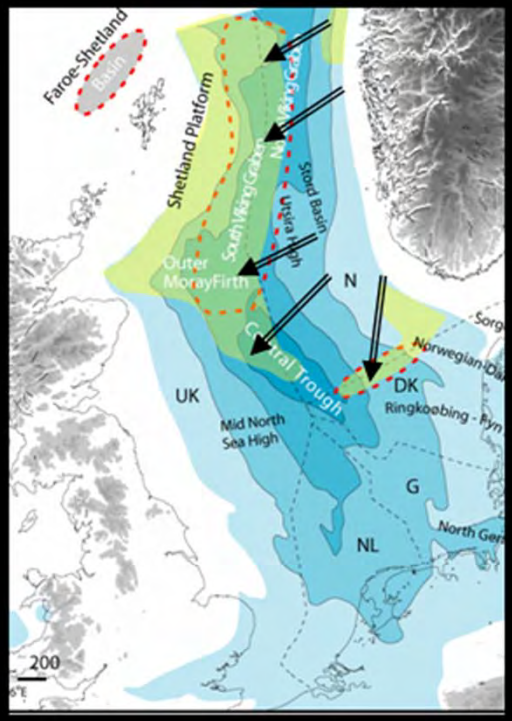
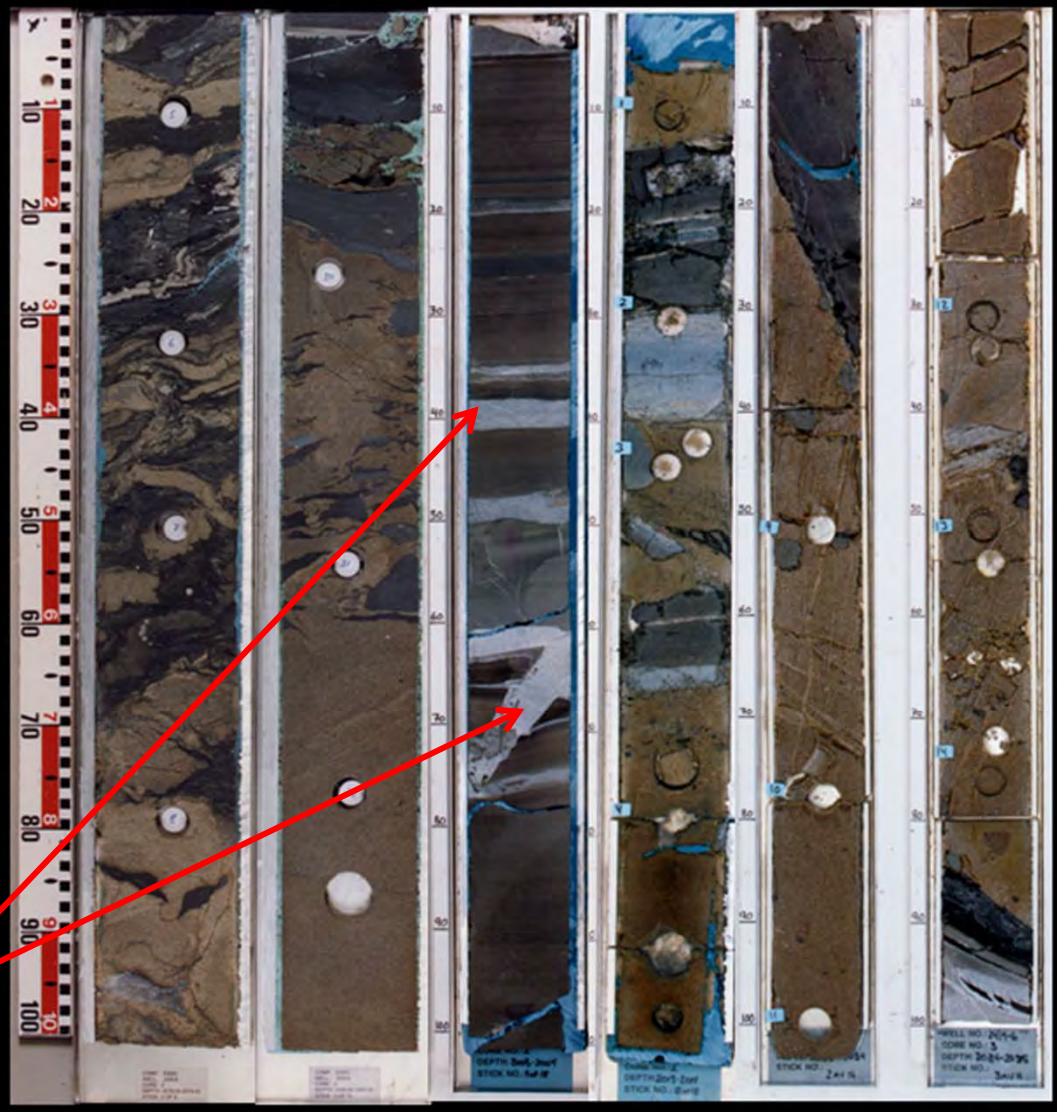
Basin studies

Paleogene sand injectites in cores from North Sea oil fields





Cemented Specimens = rare !

Hurst 2008; WorldOil

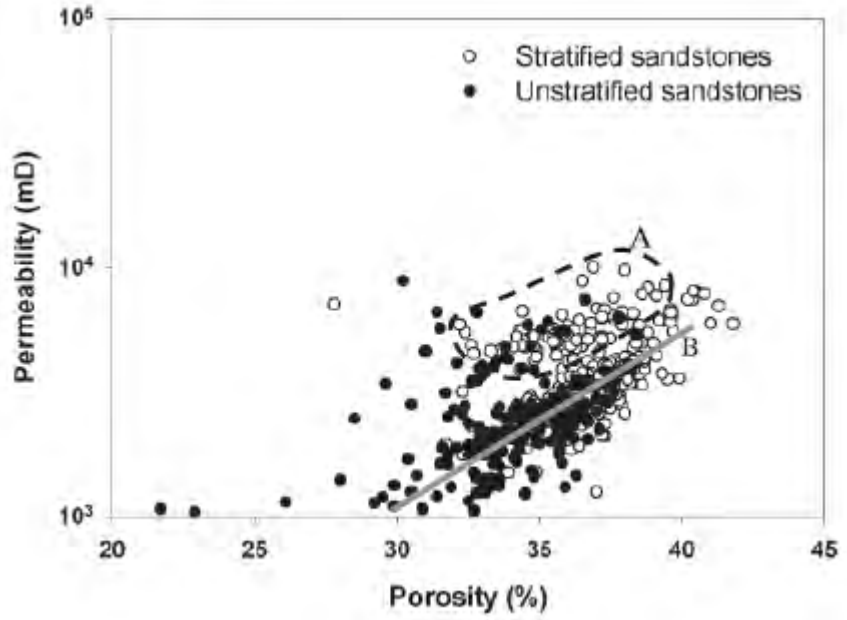
Porosity and permeability generally very high
30-40%, 1-10 D @ 1.6-2.0 km depth

Alba Field (M Eocene Outer Moray Firth)

Table 1. *Statistical parameters for porosity and permeability*

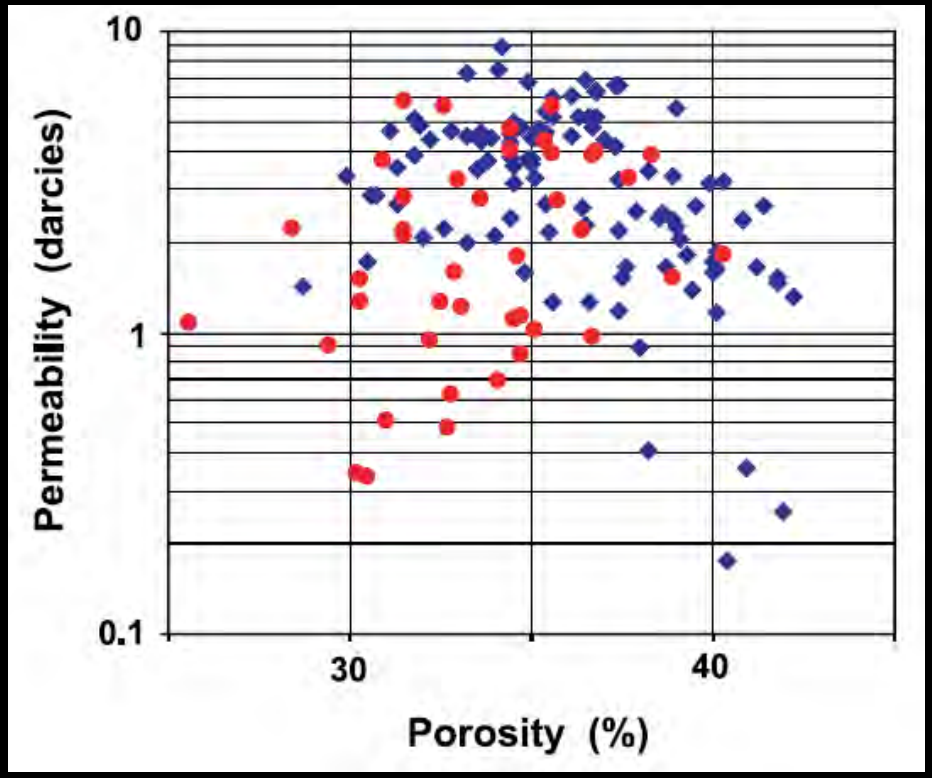
	Porosity (%)			Permeability (mD)		
	n	mean	median	*n*	mean	median
Stratified sandstones	329	36.47	36.4	327	4046	3740
Unstratified sandstones	206	33.85	33.8	205	2548	2360

n, number of samples.



Duranti et al. 2002: Pet Geosci

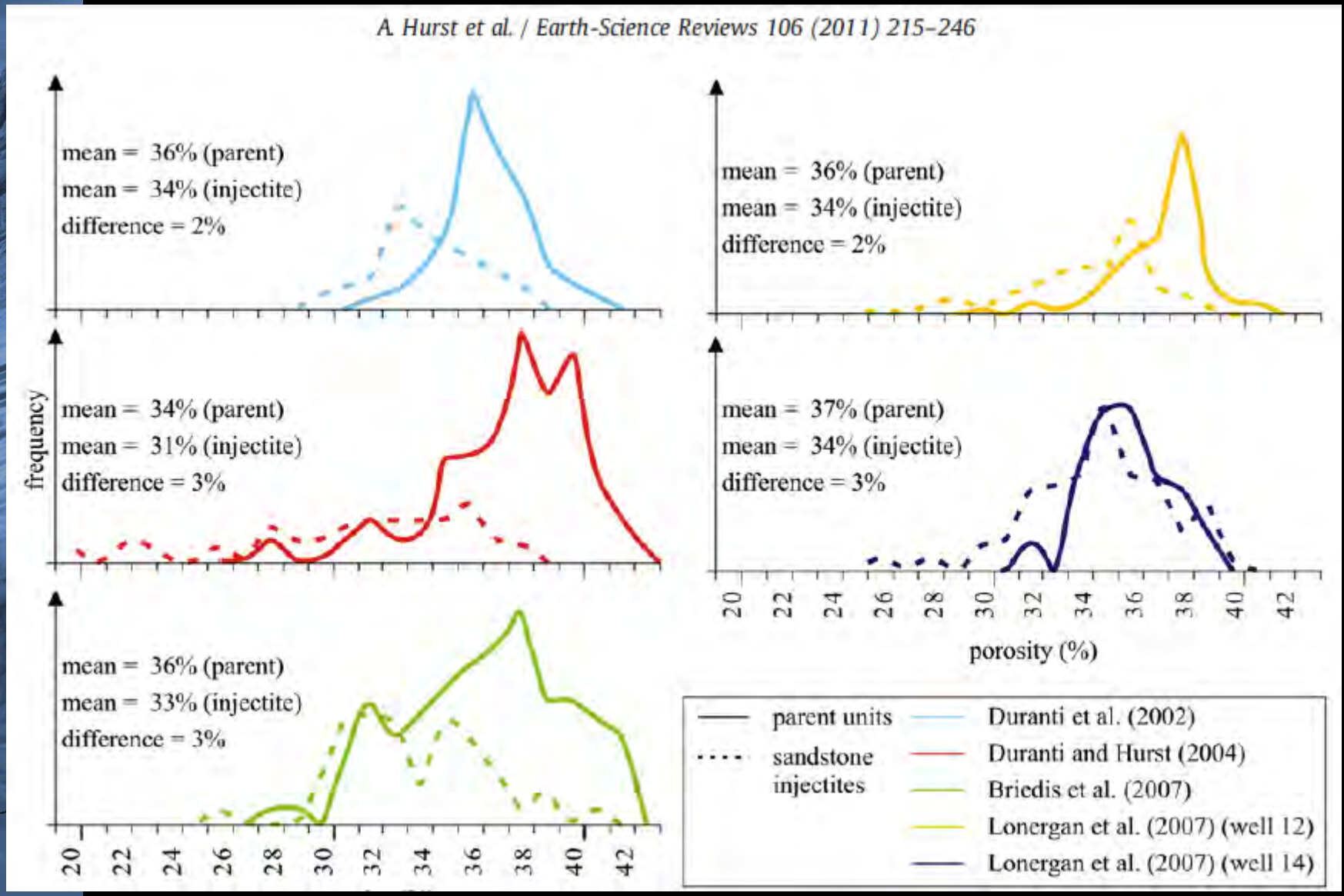
Balder Field (U Paleocene Utsira High)



- sandy debrites and high-concentration turbidites
- sand injections

Briedis et al. 2007: AAPG Mem 87

Reservoir properties of sand injectites



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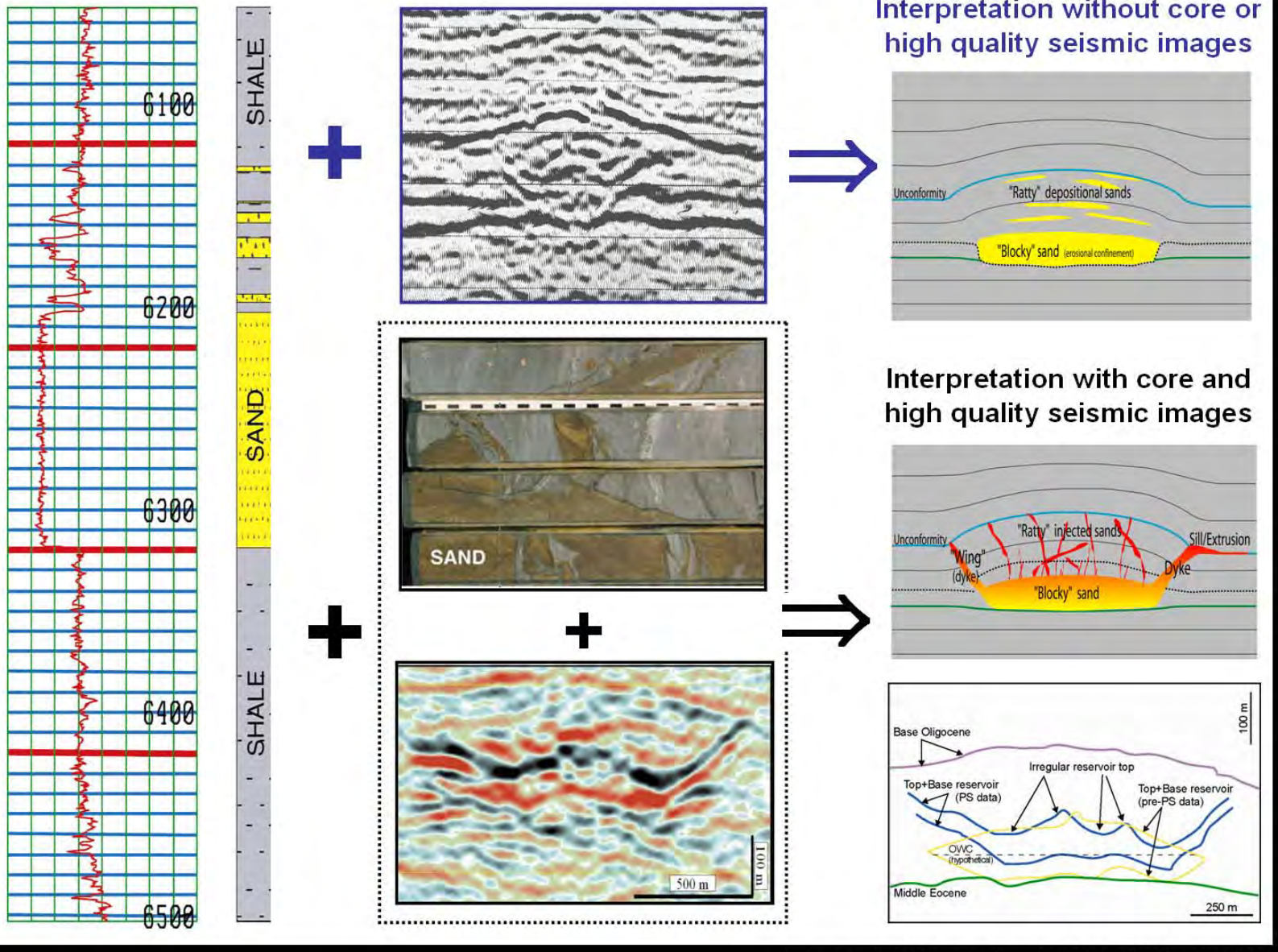
Interpretation depends on data type, data quality, and mindset..



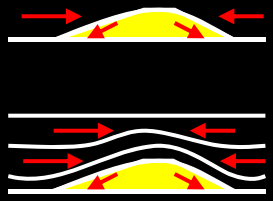
Huuse et al. 2003: First Break; Huuse 2008: WorldOil

Basin studies

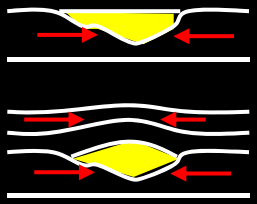
Seismic stratigraphic recognition of depositional, remobilised and fully injected sandstones

Depositional sandstone (no remobilisation)

Mound (turbidite or extrudite)

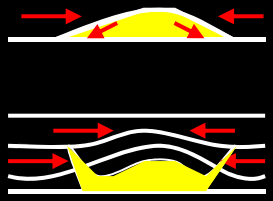


Channel fill (truncation, onlap fill)

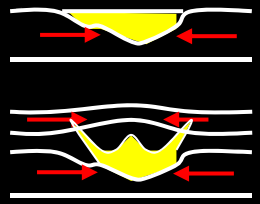


Remobilised sand (in situ)

Remobilised mound

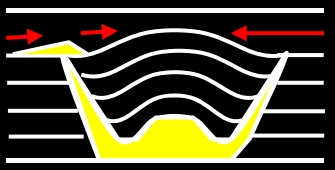


Remobilised channel fill

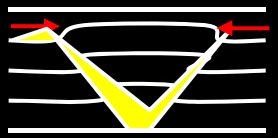


100% **injected** sand (saucer-shaped injectites)

Laccolith and marginal dykes (+ extrudite)

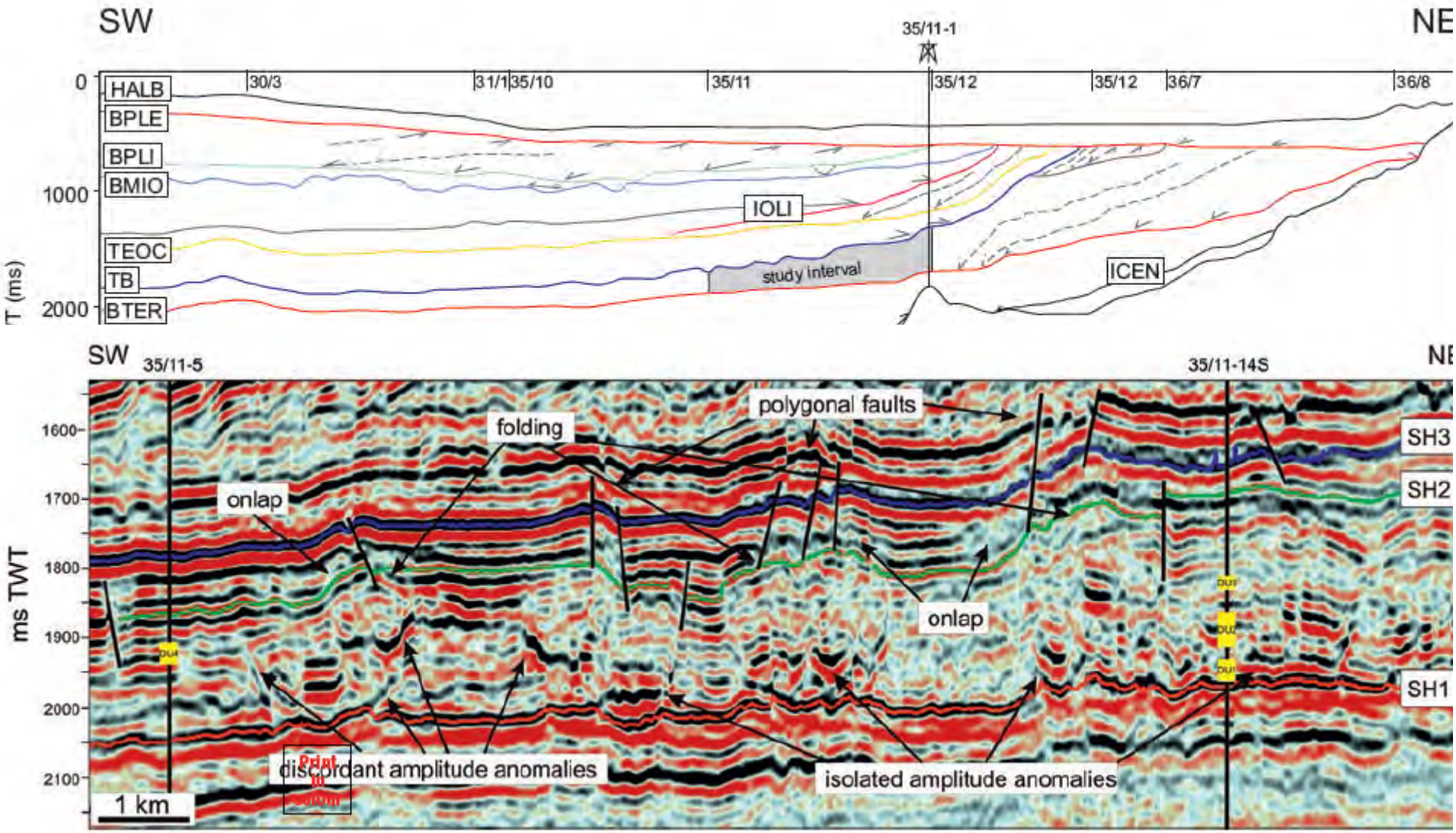


Conical injectite



Huuse et al. 2012: EAGE

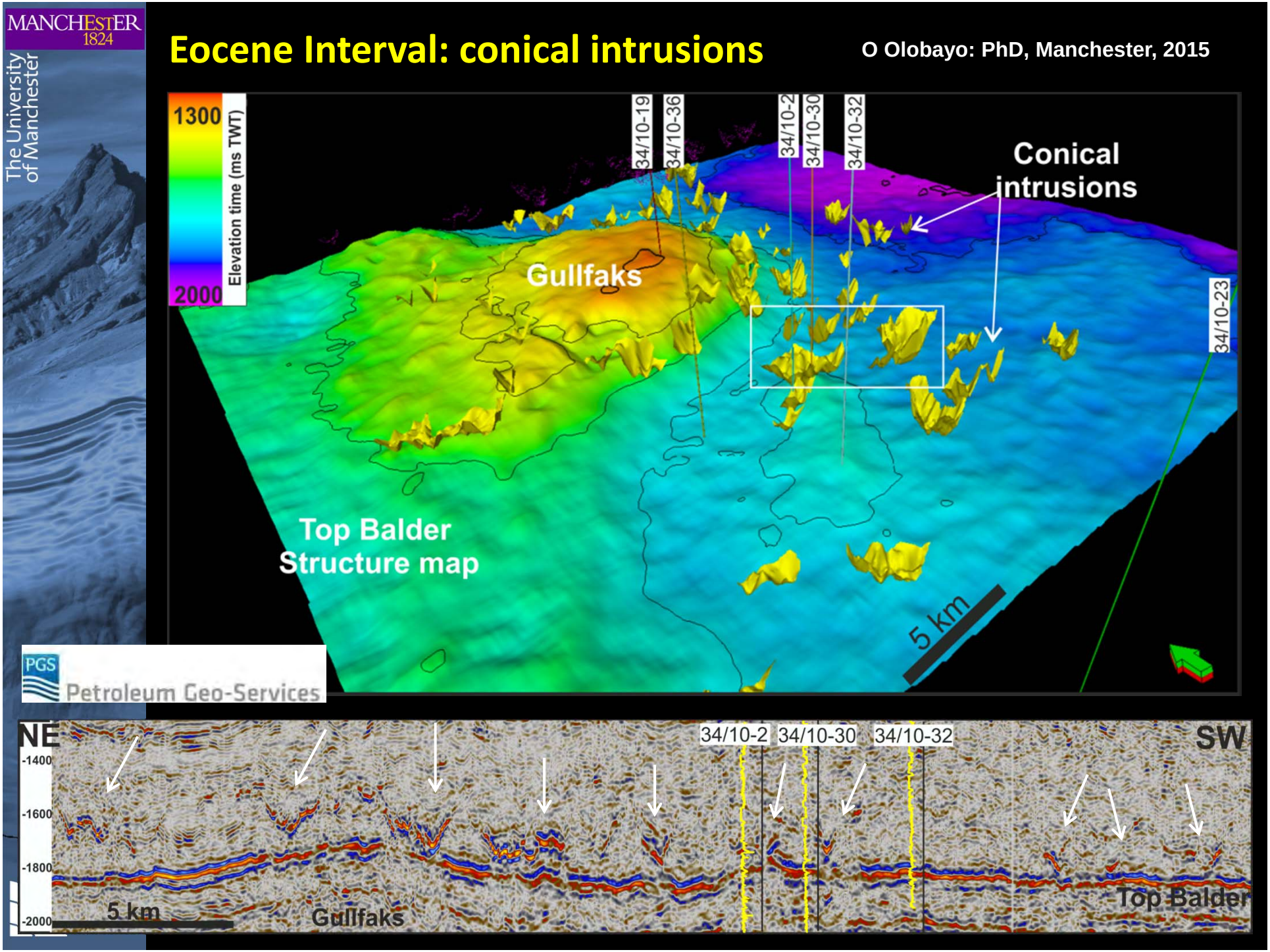
Paleocene sand remobilization at base of palaeo-depositional slope: 35/11 (NE North Sea)



Dmitrieva et al. 2012: Petroleum Geoscience

Eocene Interval: conical intrusions

O Olobayo: PhD, Manchester, 2015



Depositional vs Remobilized and Injected Sandstones: NNS

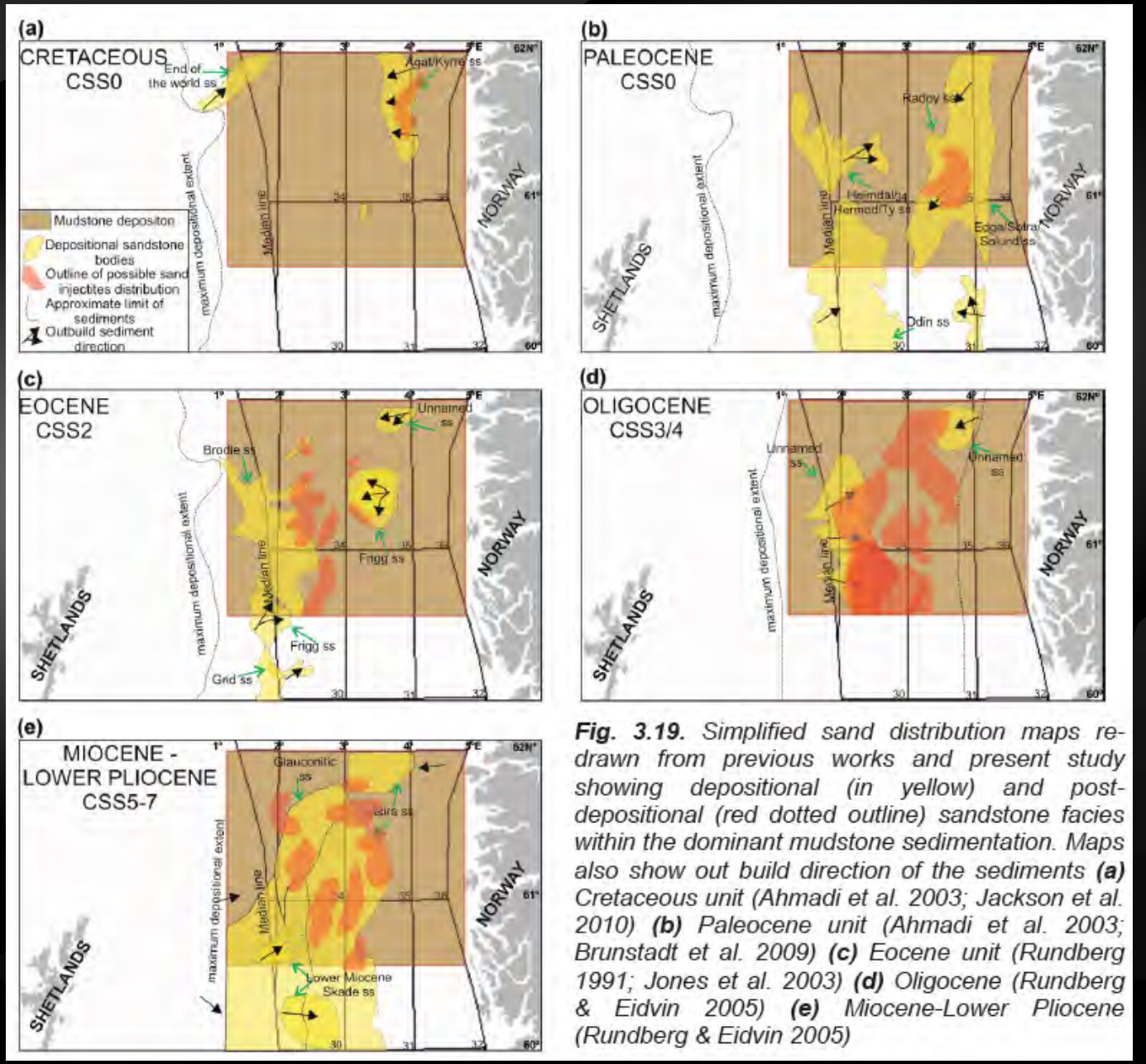


Fig. 3.19. *Simplified sand distribution maps re-drawn from previous works and present study showing depositional (in yellow) and post-depositional (red dotted outline) sandstone facies within the dominant mudstone sedimentation. Maps also show out build direction of the sediments* ***(a)*** *Cretaceous unit (Ahmadi et al. 2003; Jackson et al. 2010)* ***(b)*** *Paleocene unit (Ahmadi et al. 2003; Brunstadt et al. 2009)* ***(c)*** *Eocene unit (Rundberg 1991; Jones et al. 2003)* ***(d)*** *Oligocene (Rundberg & Eidvin 2005)* ***(e)*** *Miocene-Lower Pliocene (Rundberg & Eidvin 2005)*

O Olobayo, PhD Manchester, 2015

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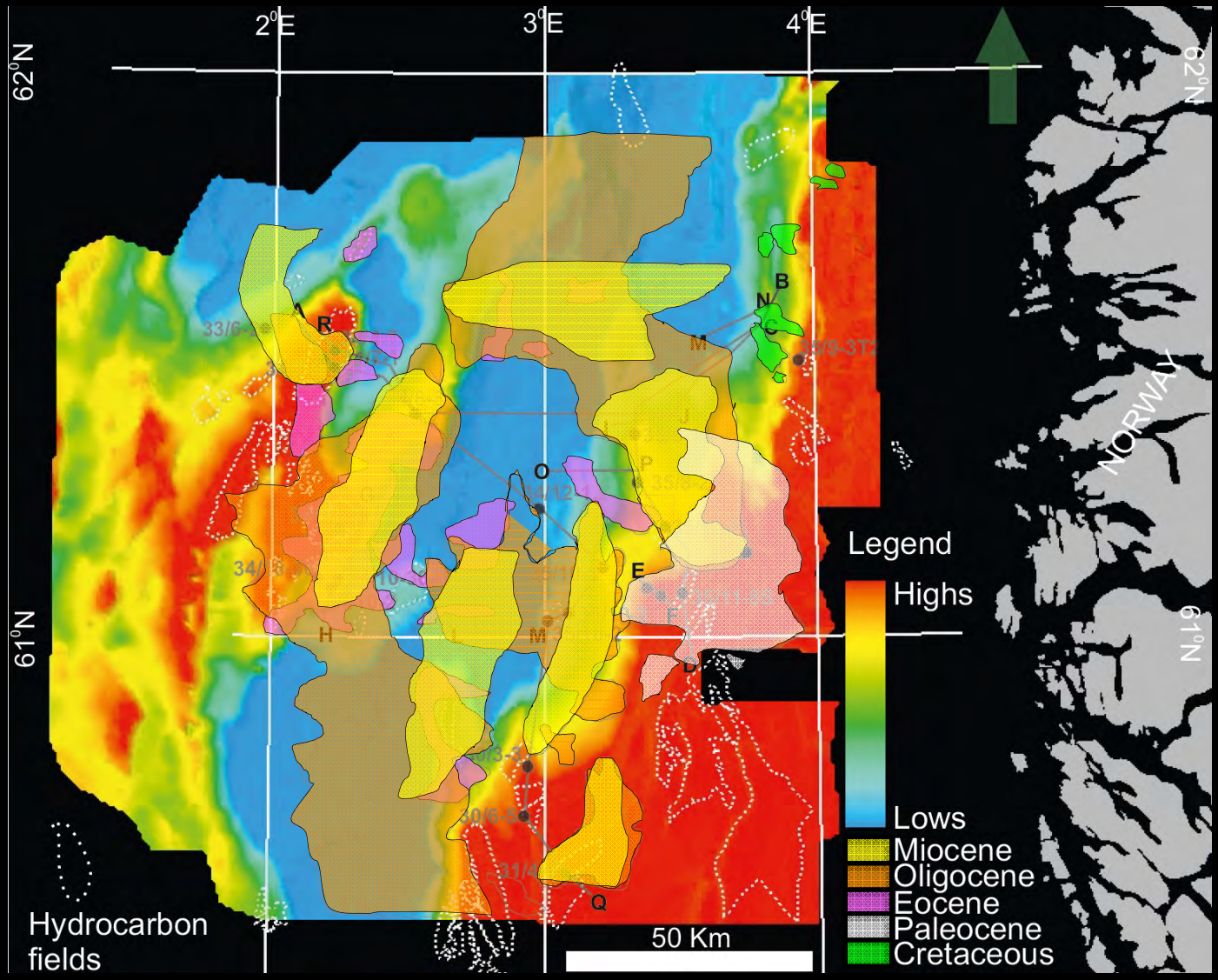
Spatio-temporal distribution of sand injectites



O Olobayo: PhD, Manchester, 2015

Basin studies

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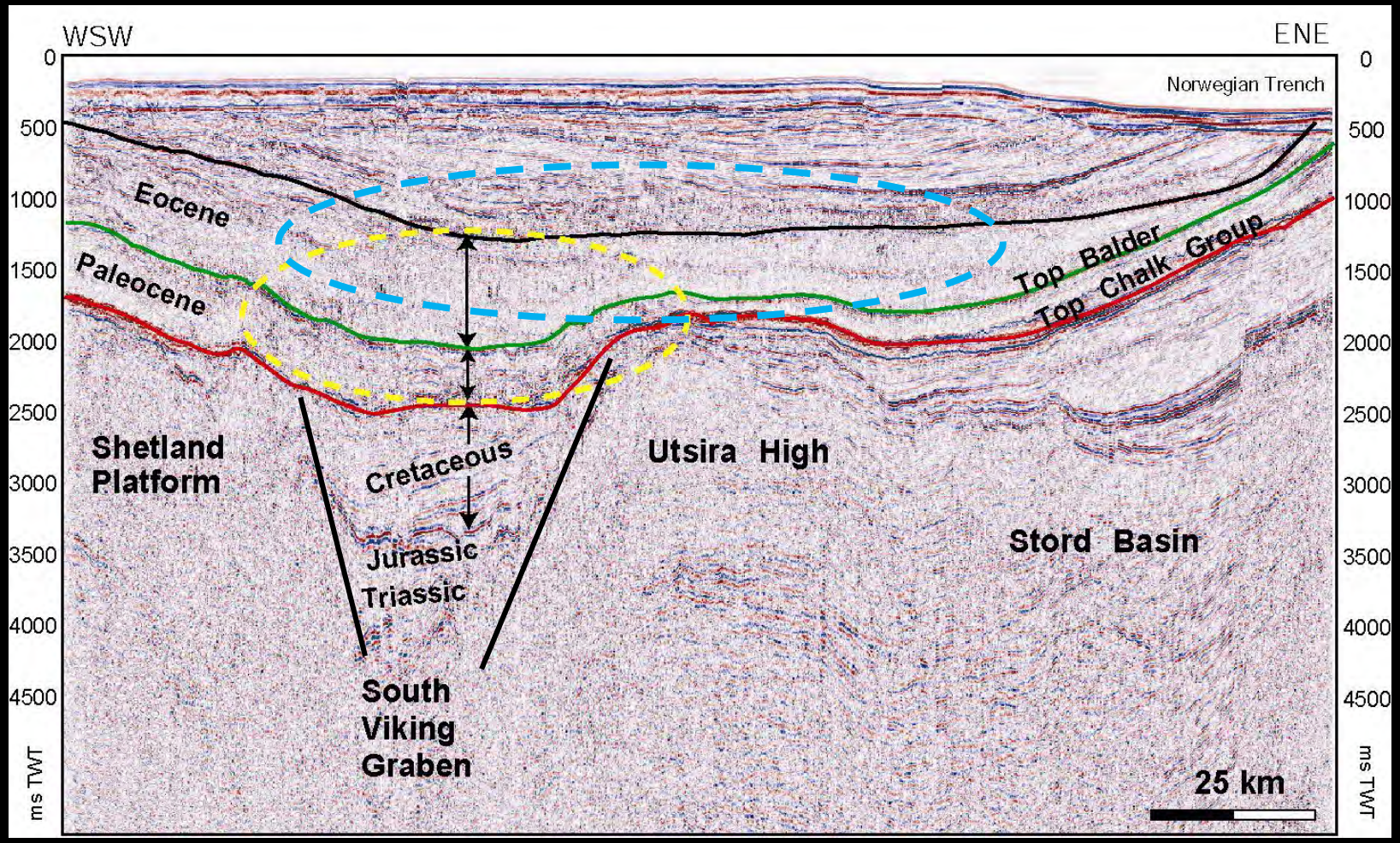
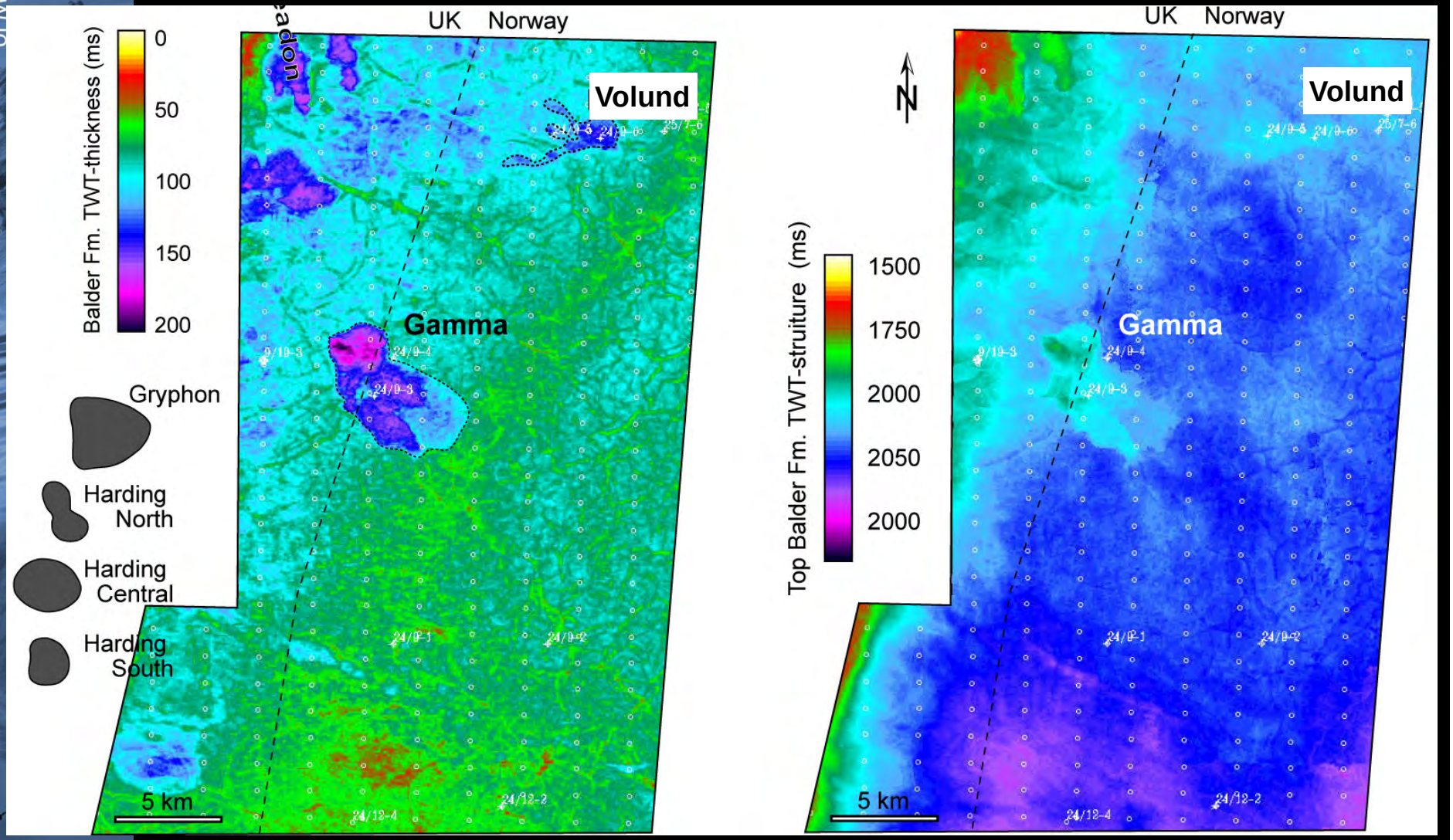
Structural-stratigraphic setting of large-scale sand injectites in the South Viking Graben & Utsira High



Basin studies

Isolated massive sandstone mounds in the South Viking Graben: Balder (earliest Eocene) thickness and TWT structure

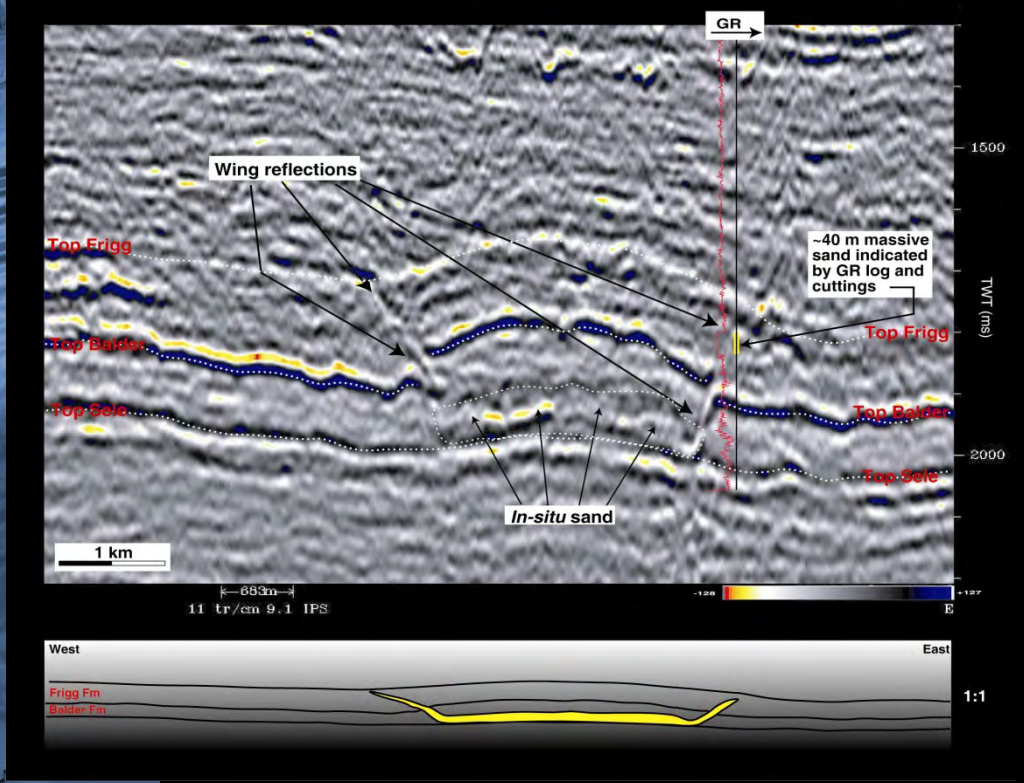


Basin studies

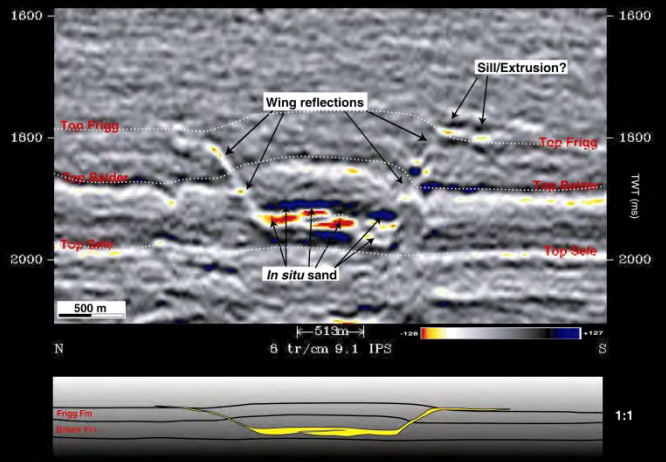
Steep-sided Balder sandbodies with “wings”, Norwegian Block 24/9

Different reflection characteristics due to variations in pore fluid and cementation, and seismic acquisition/processing

24/9-3 Gamma (24/9-4) & 24/9-12 Frosk

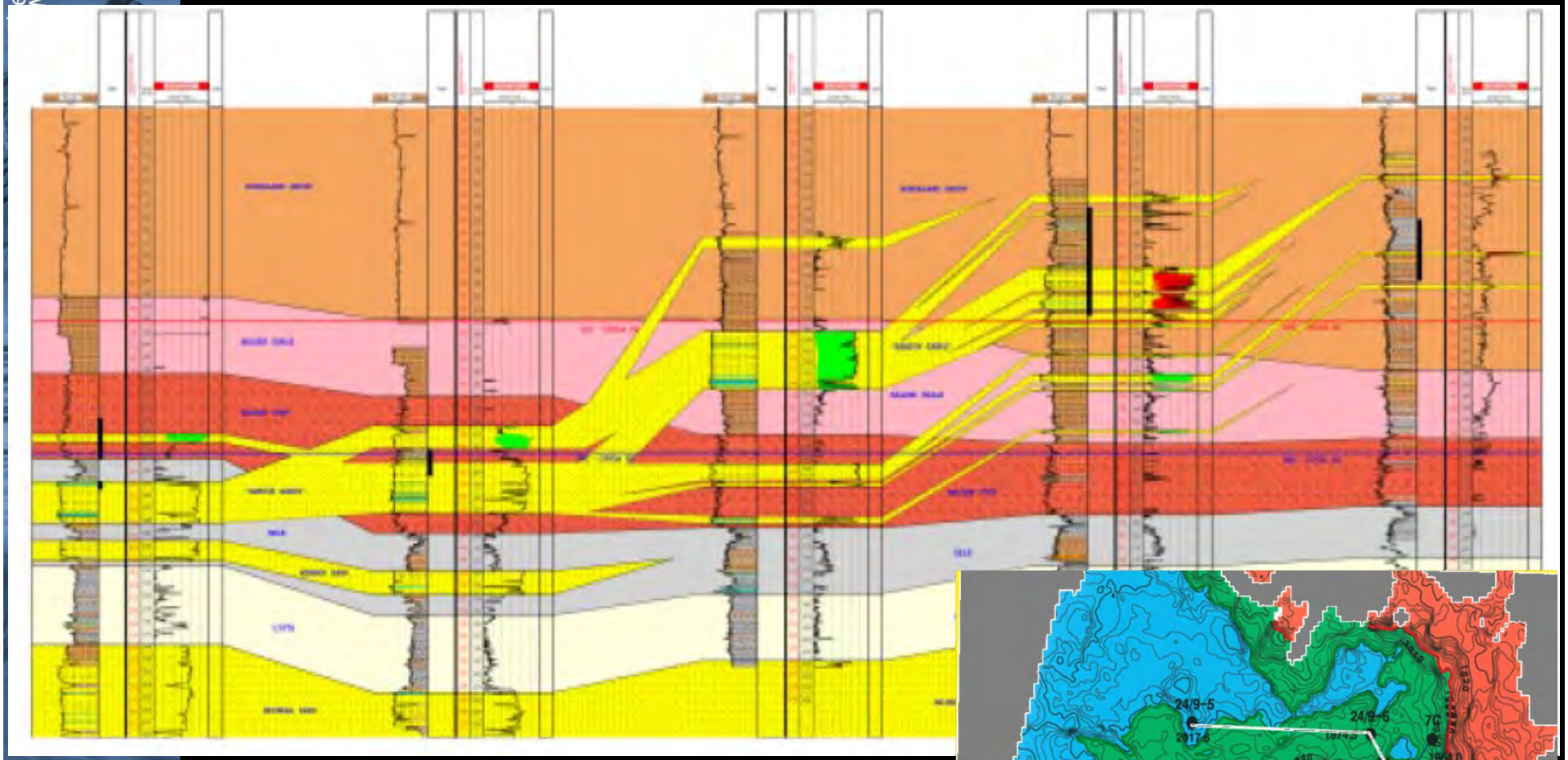


24/9-5 Grieg 24/9-7 Volund



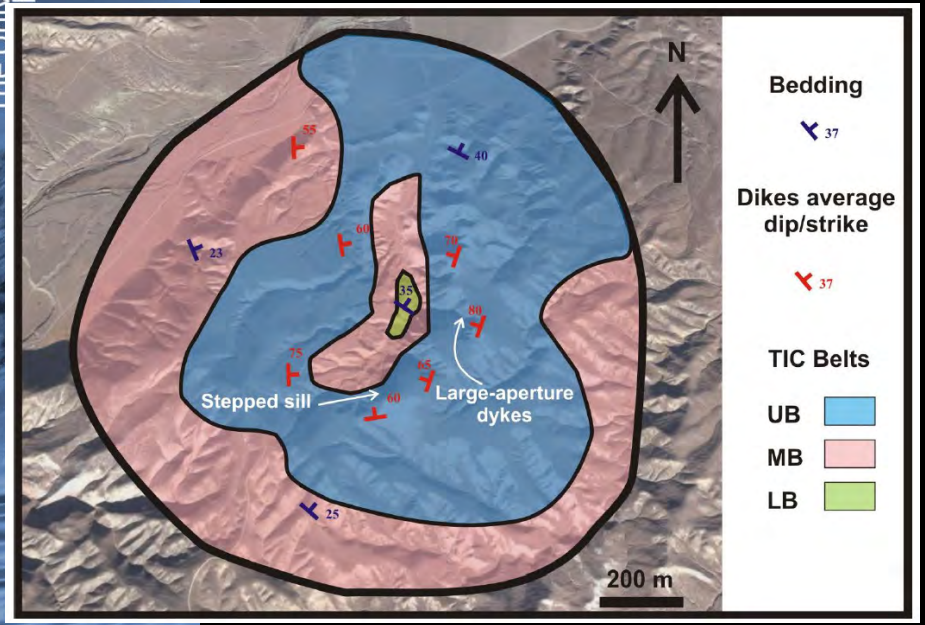
SIRG Phase I (2000-2002)

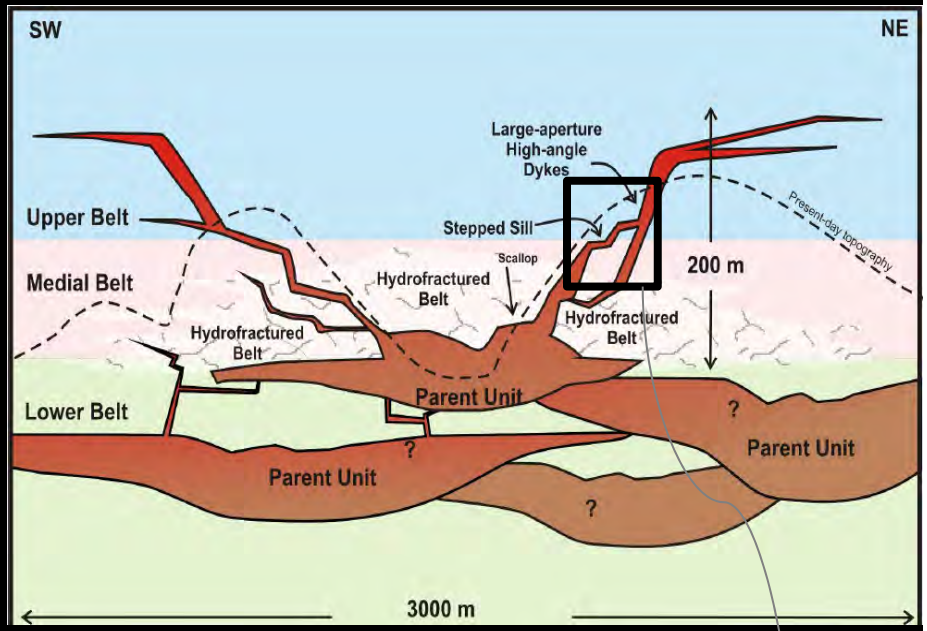
100+ Mb oil field in completely injected sandstones: Volund crosscutting 200 m stratigraphy



Szarawarska et al. 2010, Basin Research

Eocene Intrusions in outcrop





UB: Sill dominated (up to 30m thick)+ dykes
MB: Medial Belt (Sill + dykes)
LB: Parent unit (Domengine sands)+ intrusions

Looks like wings departing from parent units. Circular in 3D

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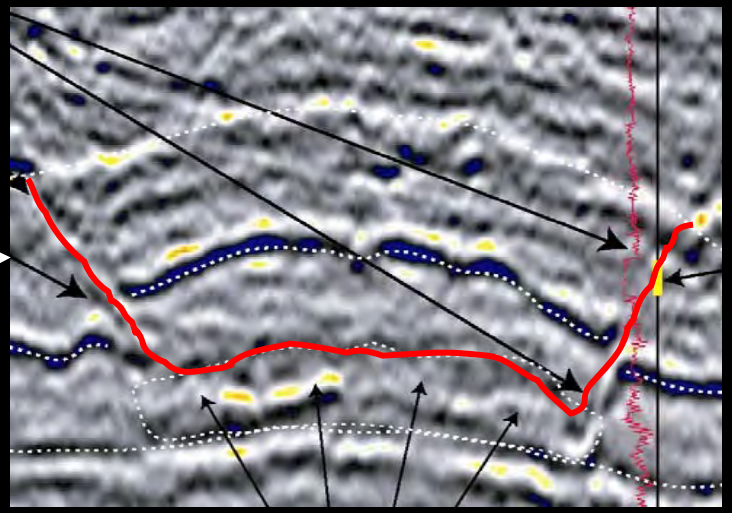
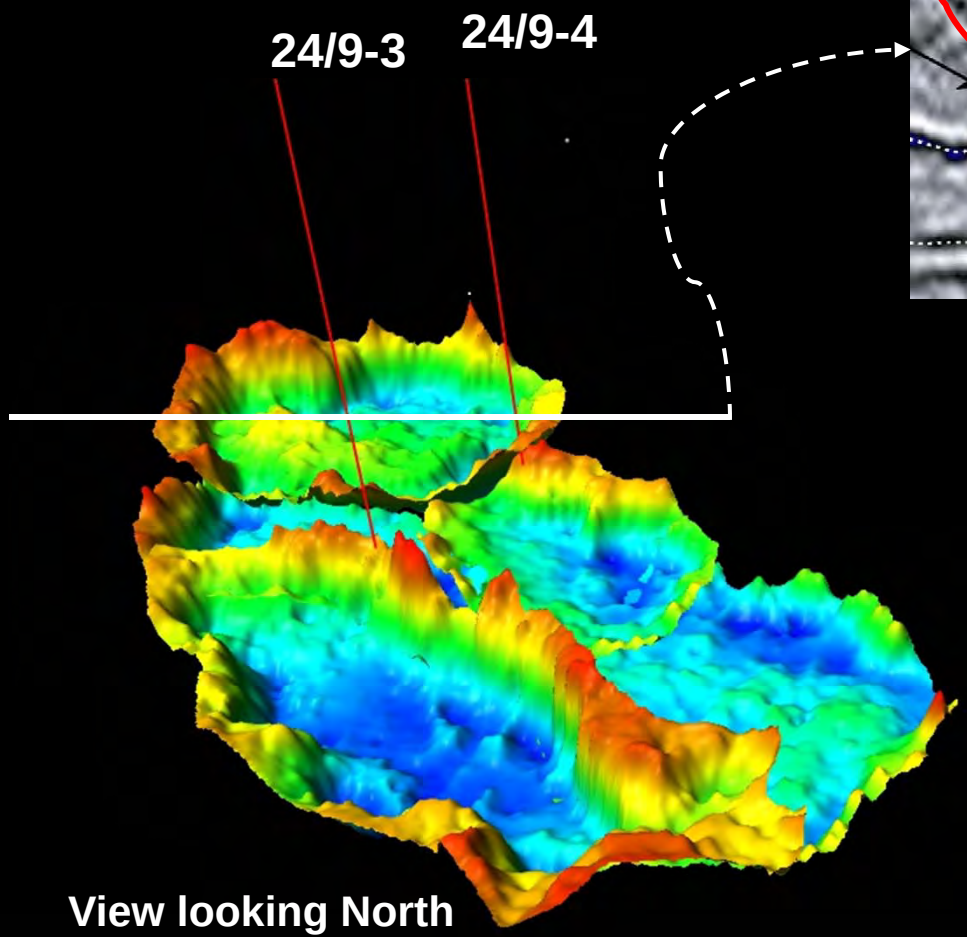
Gamma: Heavy oil in sand injectite reservoir ‘stranded’ on the border

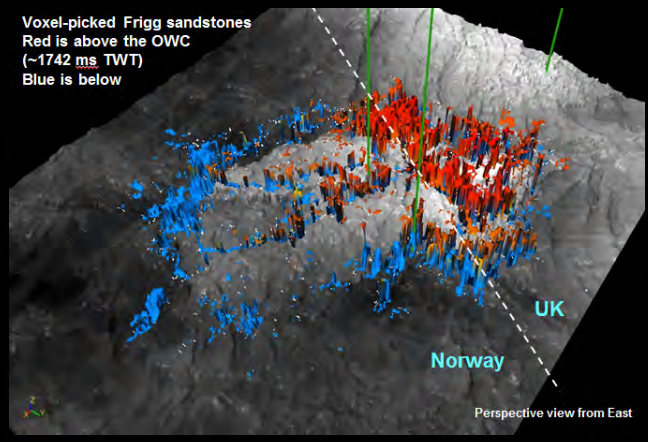
Wing-like reflections emanate from massive Balder-age sandstone on a scale similar to Alba and other SI fields (>200 m vertical)

Oil hosted in crestal intrusions. **Total sandstone volume ~ 2.5 km^3**

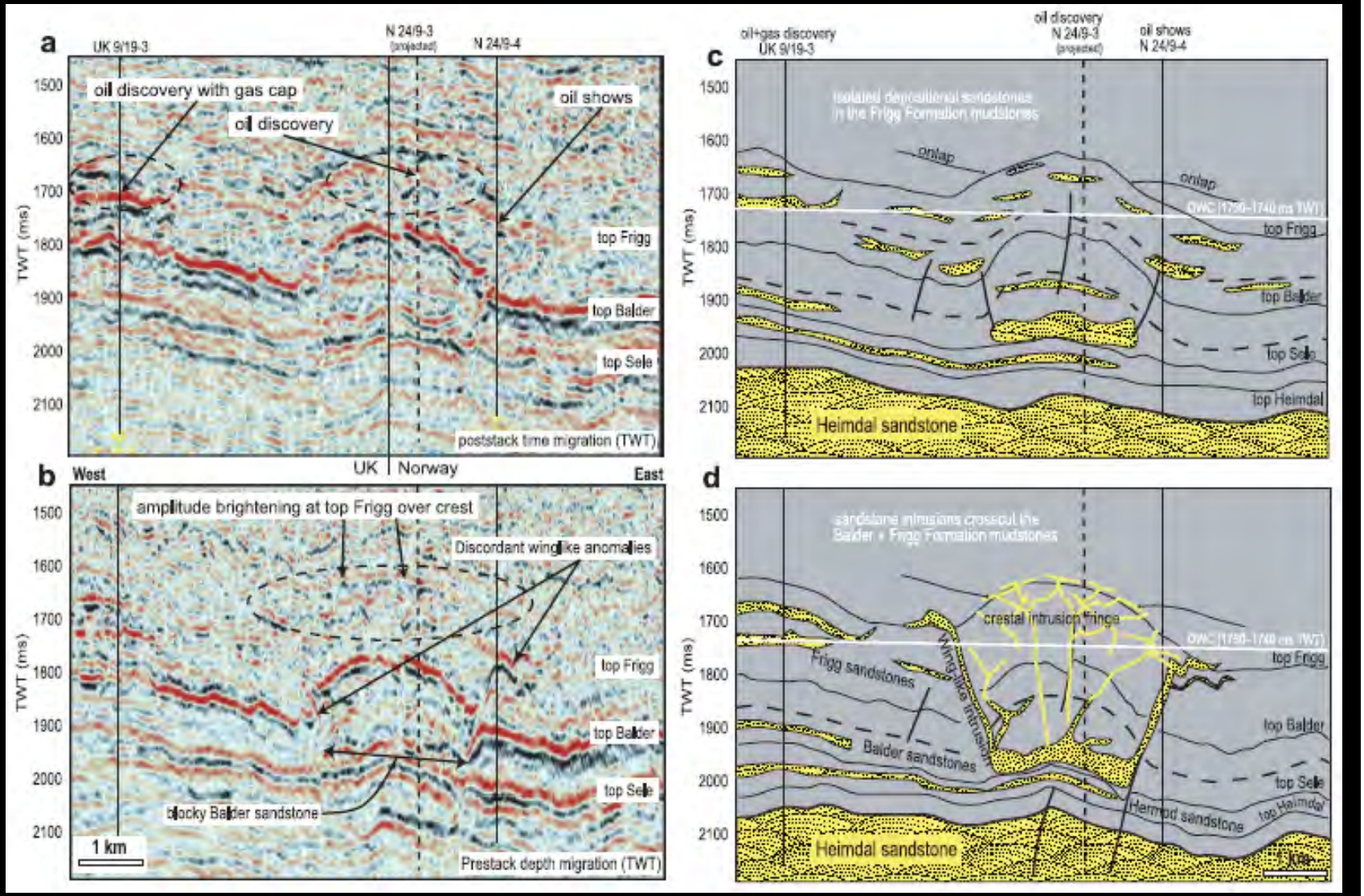




View looking North



A sizeable pool on the median line: Gamma (N24/9-3, -4):
Legacy data and model vs re-processed data and re-mobilized model



More than one model can explain observations..

Huuse et al. 2007: AAPG Mem 87

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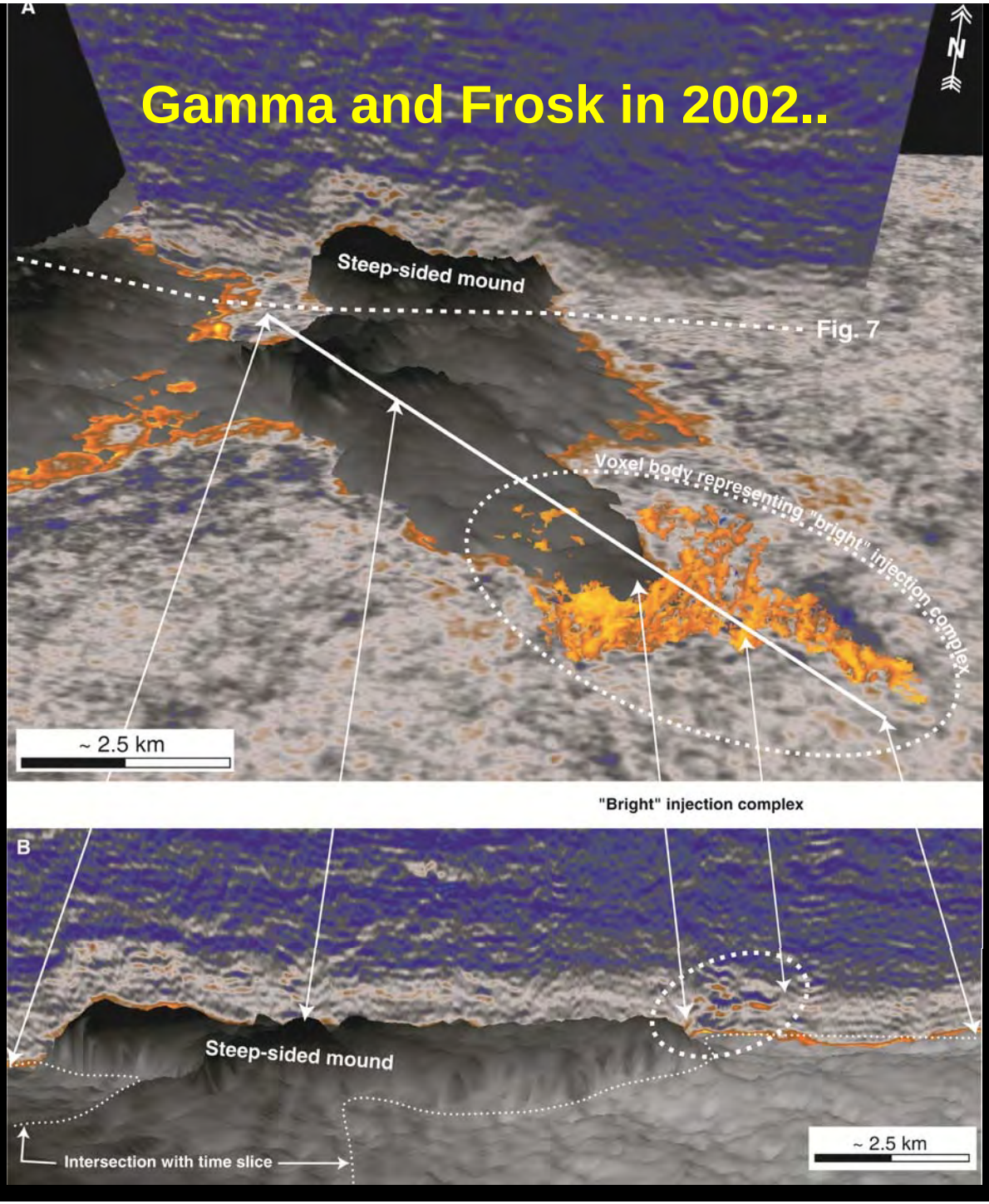
Gamma and Frosk in 2002..



Huuse et al. 2004, Geol Soc Memoir 29

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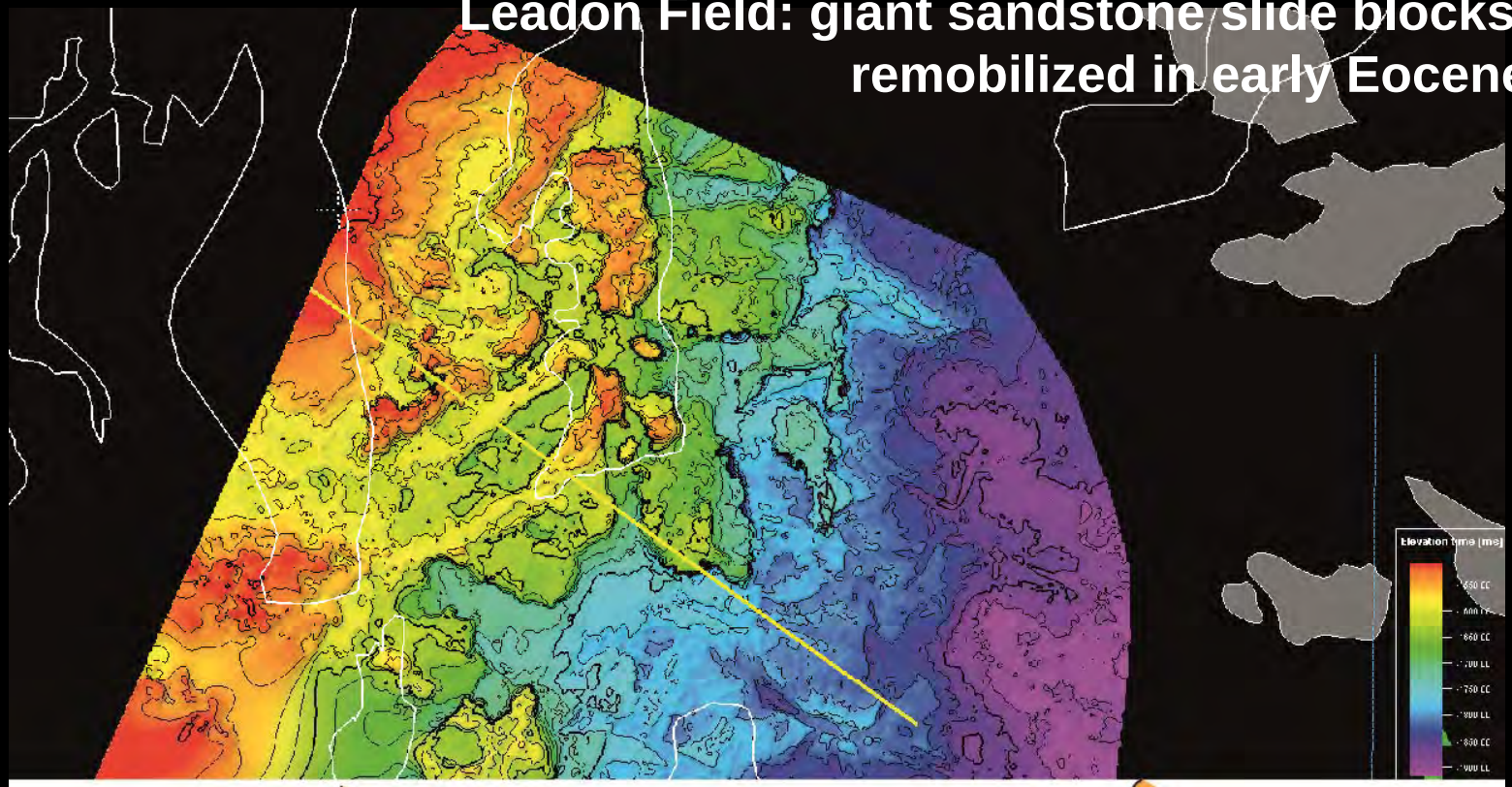
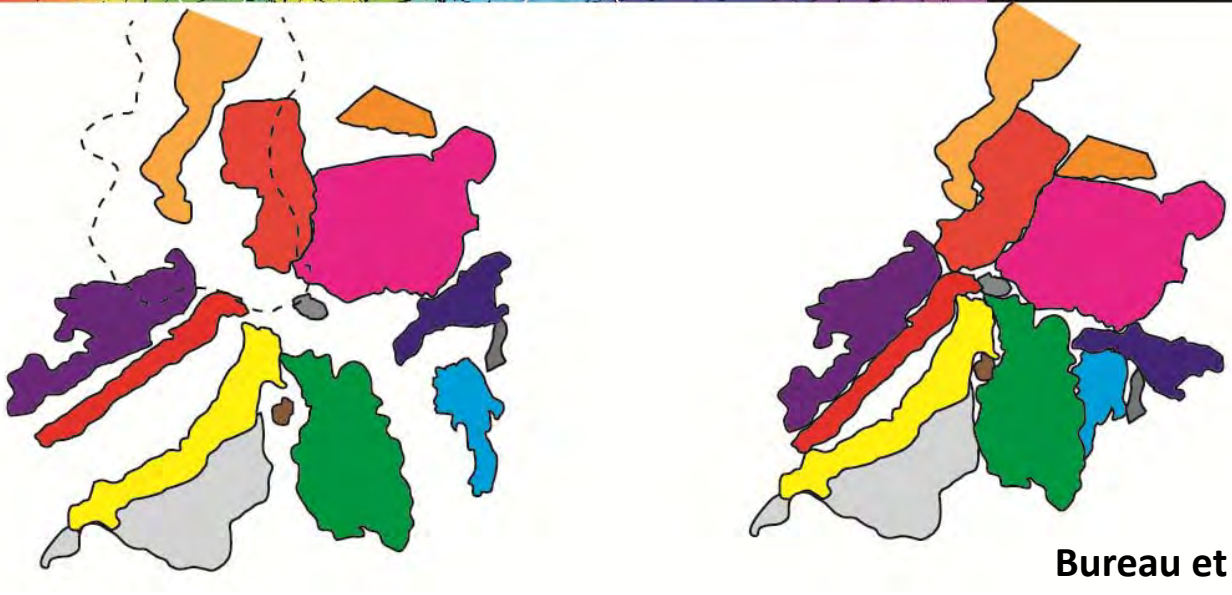
Leadon Field: giant sandstone slide blocks, remobilized in early Eocene





Bureau et al 2017

Landslides as sources of isolated and remobilised sandy bodies?

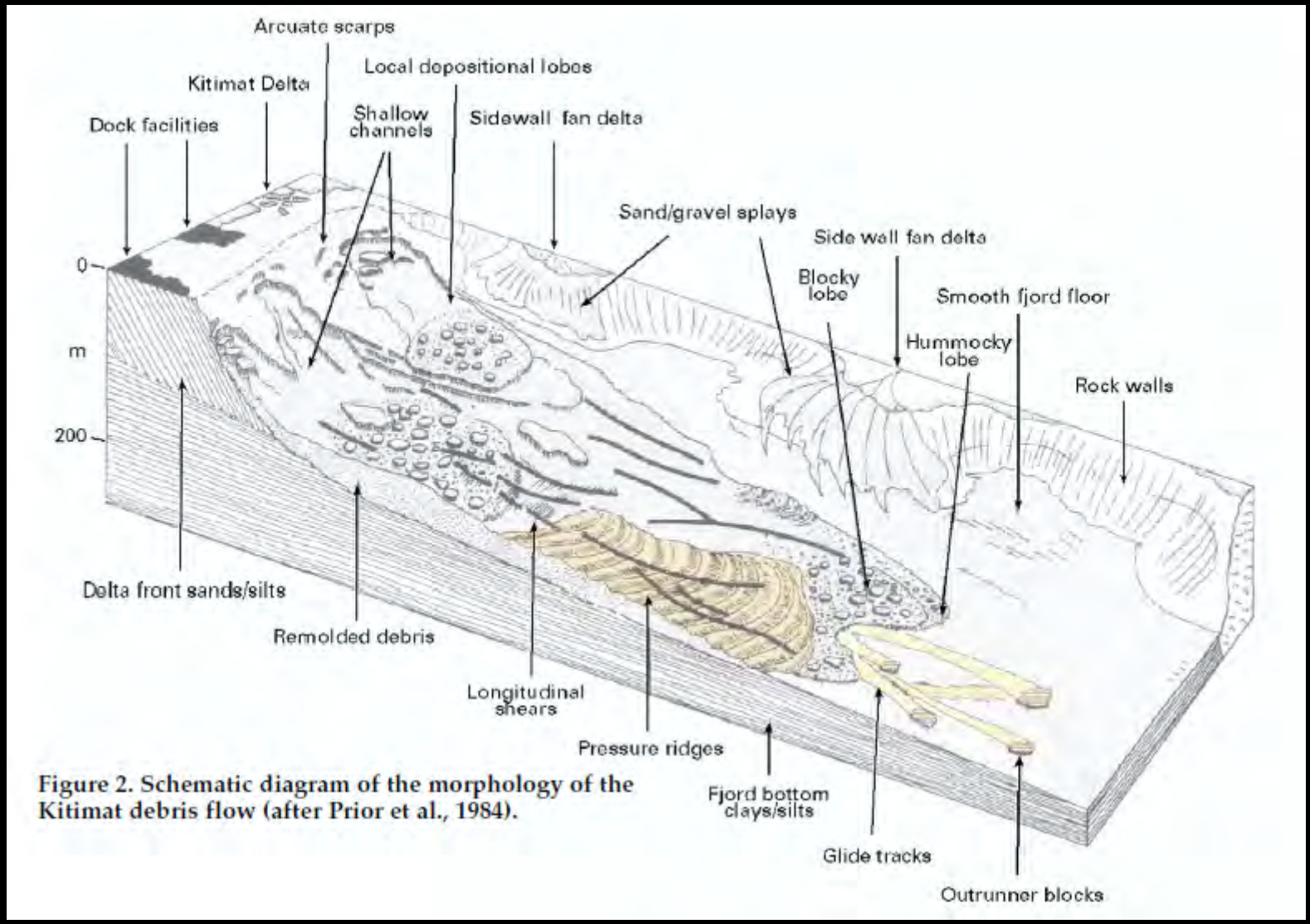


Figure 2. Schematic diagram of the morphology of the Kitimat debris flow (after Prior et al., 1984).

Nissen et al. 1999: TLE

Models..

3 possible origins:

- Fully intruded
- Sculpted by bottom currents/erosion
- MTDs / slide blocks

Fully Intruded sandstone	Balder (Odin) depositional sandstones sculped by bottom currents	Mass transport deposits
1/ Deposition of Dornoch delta Dornoch delta	1/ Deposition of Dornoch delta Dornoch delta	1/ Deposition of Dornoch delta Dornoch delta
2/ Deposition of Balder and Frigg Fm Top Frigg Top Balder	2/ Deposition of Odin Sst (Early Balder)	2/ Deposition of Odin Sst (Early Balder)
3/ Remobilisation and injection of Dornoch (+Heimdal ?) sandstone near top Frigg age.	3/ Erosion by bottom currents	3/ Slide blocks = MTDs
	4/Deposition of Balder and Frigg Fm 5/ Sandstone remobilisation and injection near top Frigg age. Top Balder Top Frigg	4/Deposition of Balder and Frigg Fm 5/ Sandstone remobilisation and injection near top Frigg age. Top Balder Top Frigg

Bureau et al 2017

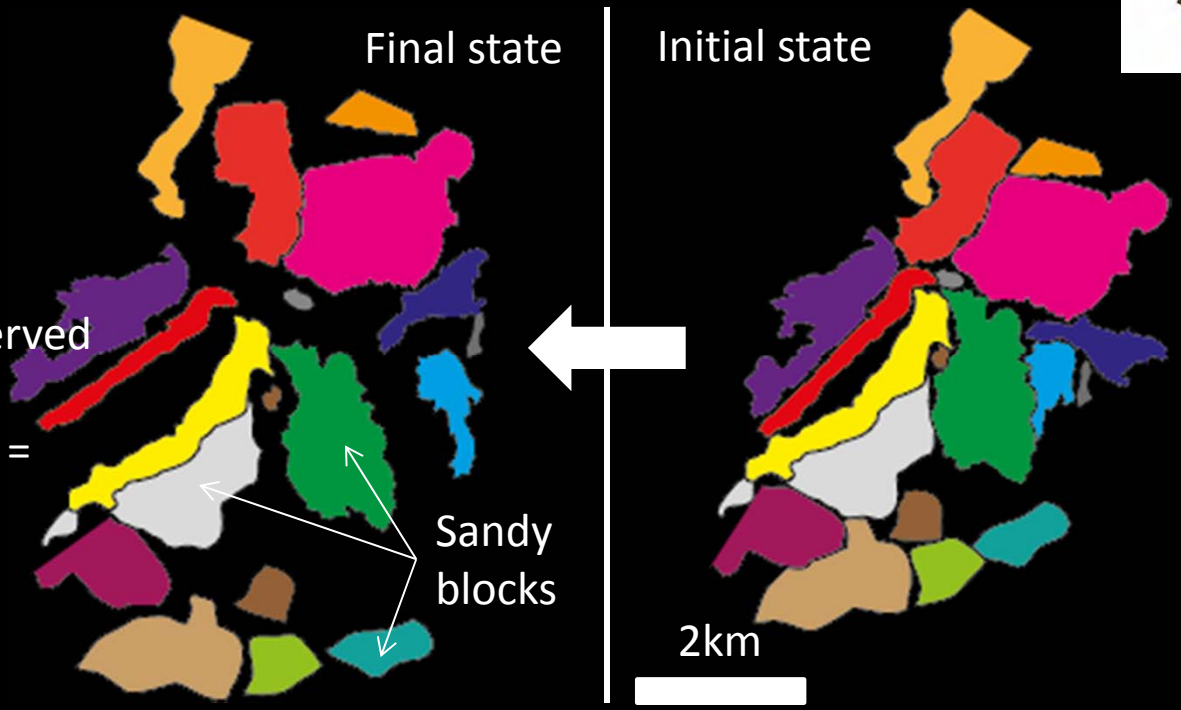
Killer evidence !??

Jig saw geometry v jack-up v Balder drape v wings/crestal injectites

- Jigsaw organisation

- Balder thickness preserved above sandy blocks

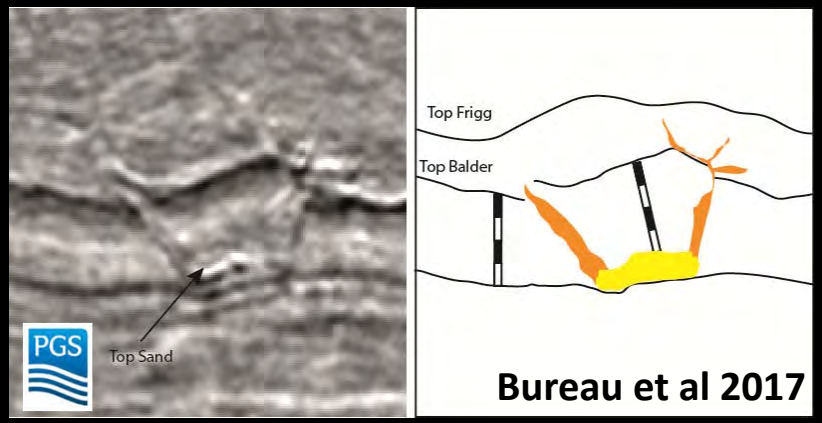
➔ Pelagic sedimentation = drape



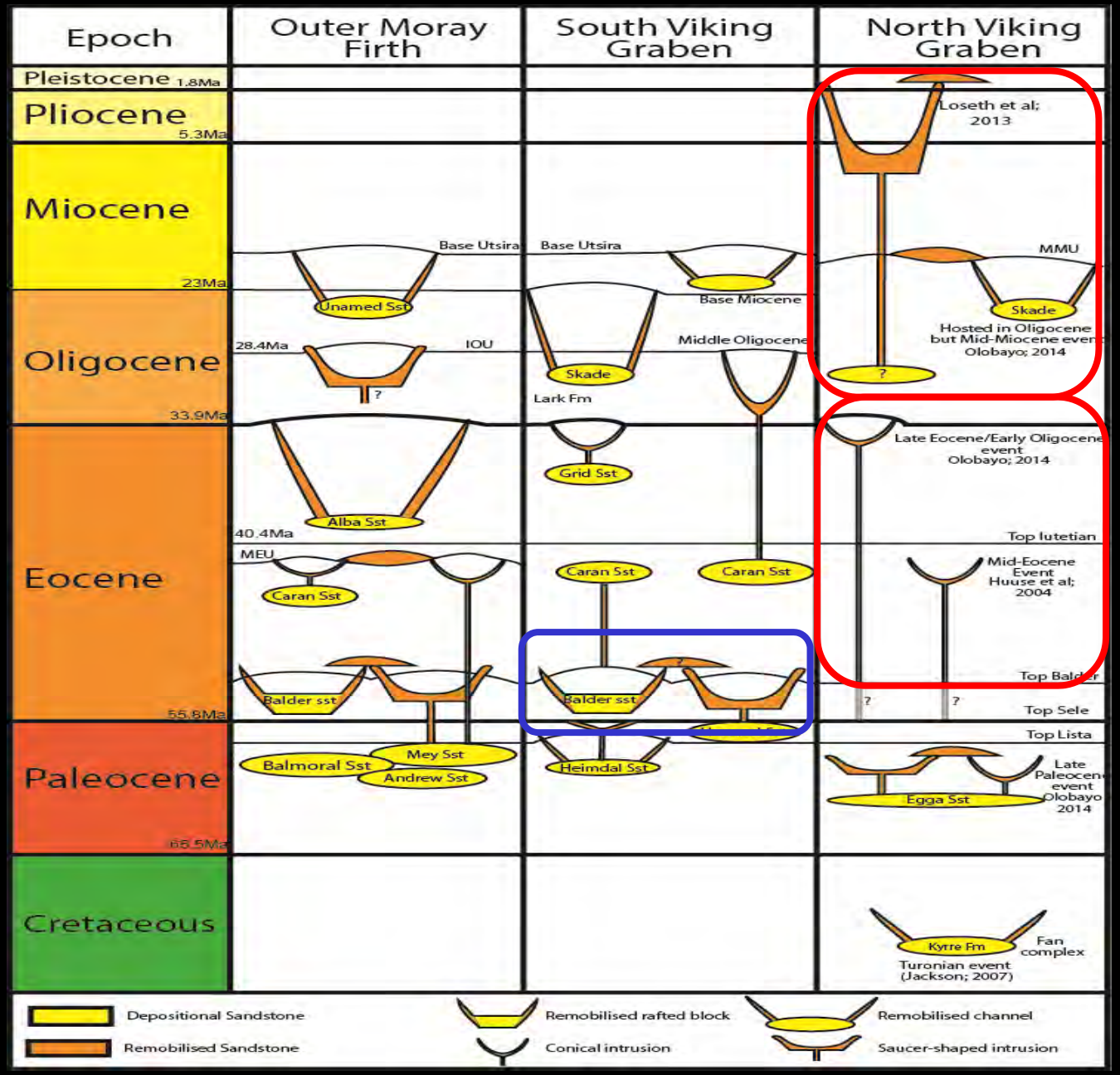
Problems:

- **How to move sandy blocks without destroying them?**
- **How to form perfect drape?**
- **Trigger mechanisms?**

Solution to conflicting observations: more than one way to form injectites and sometimes they have been superimposed..



North Sea Injectite Stratigraphy (in progress since 2000..)



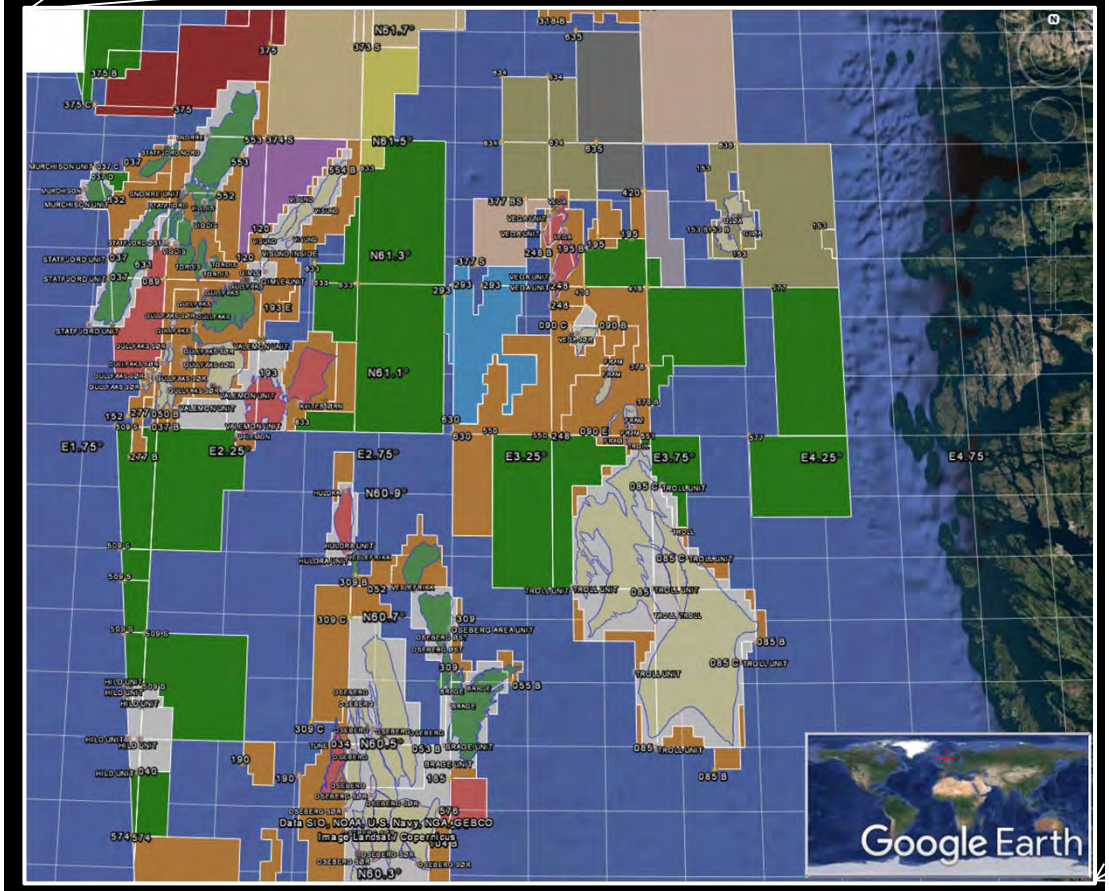
Bureau et al 2017

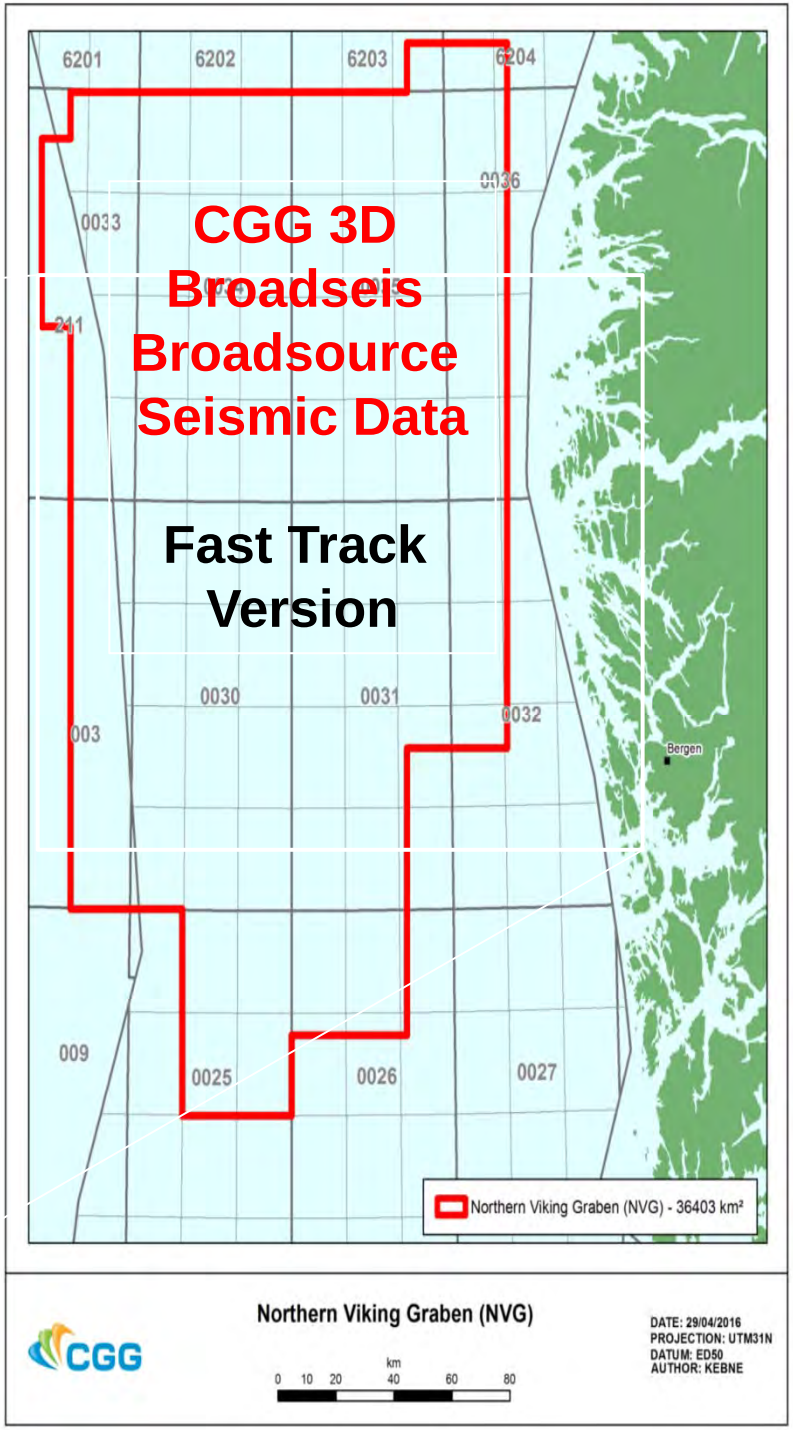
MANCHESTER 1824
The University of Manchester
SIRG Sand Injection Research Group
Basin studies

New images of a ‘mature’ basin:

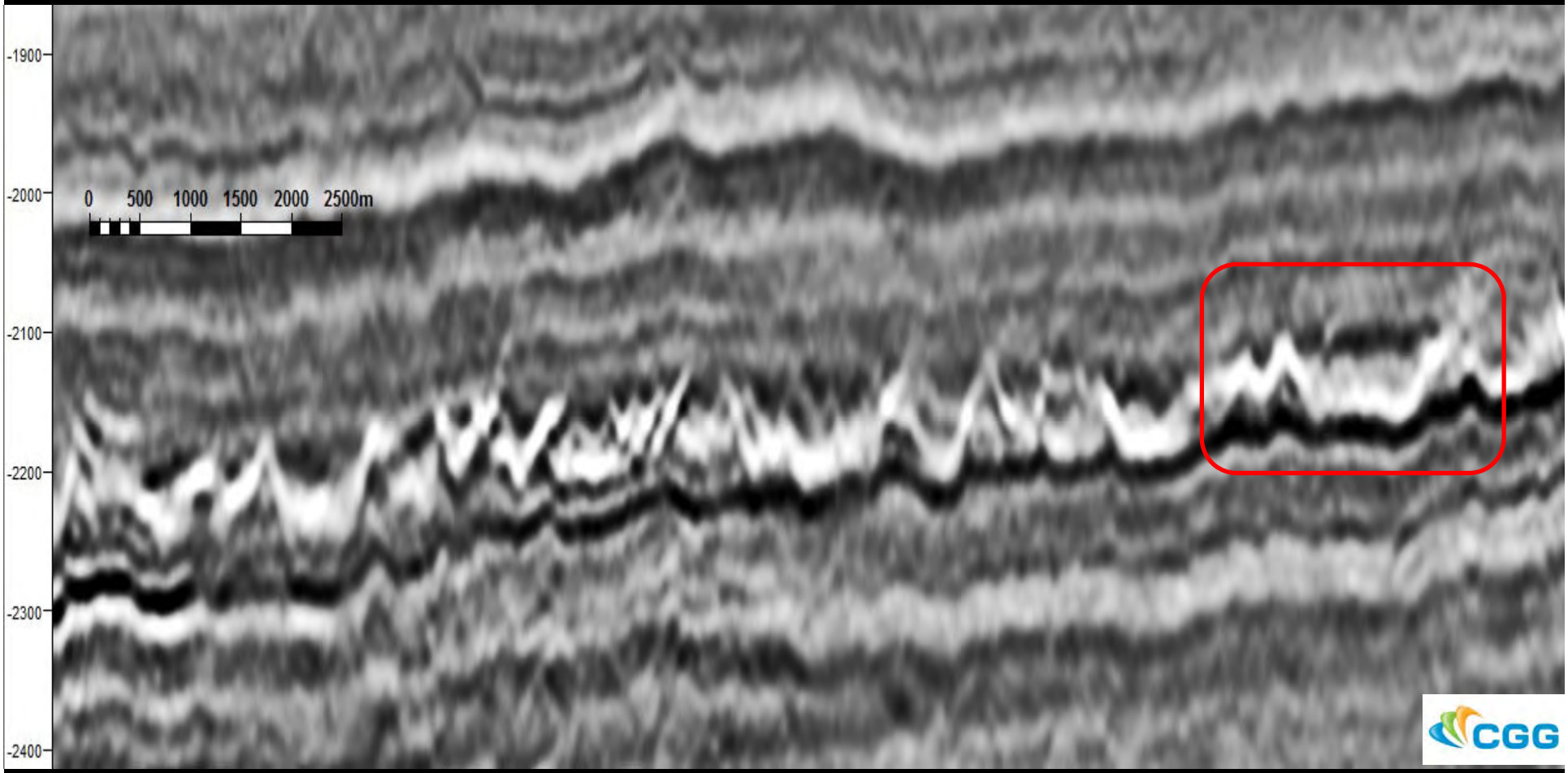
- Lots of well data
- Lots of old models
- Lots of new details and insights

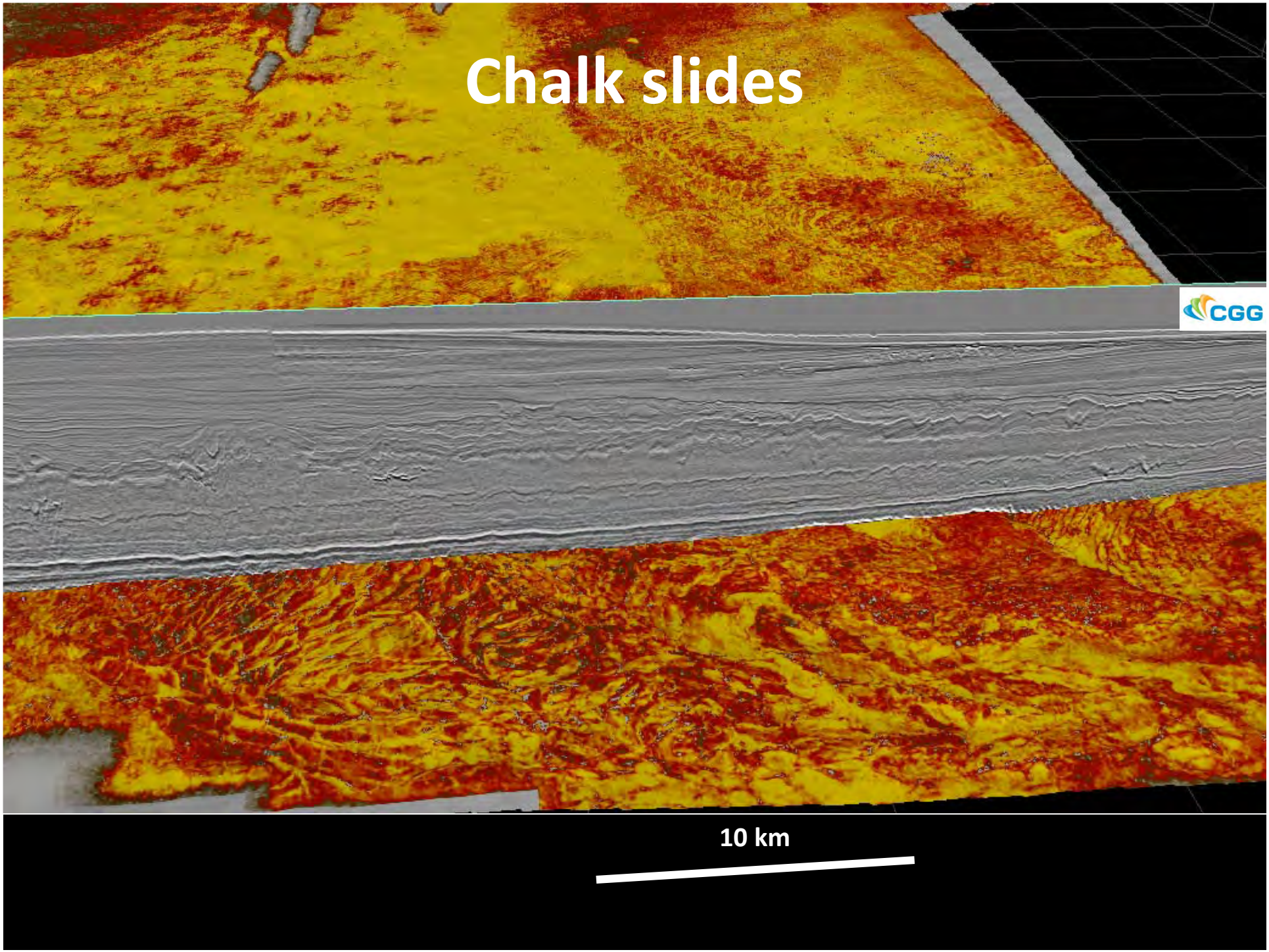
→ Wipe the storyboard clean



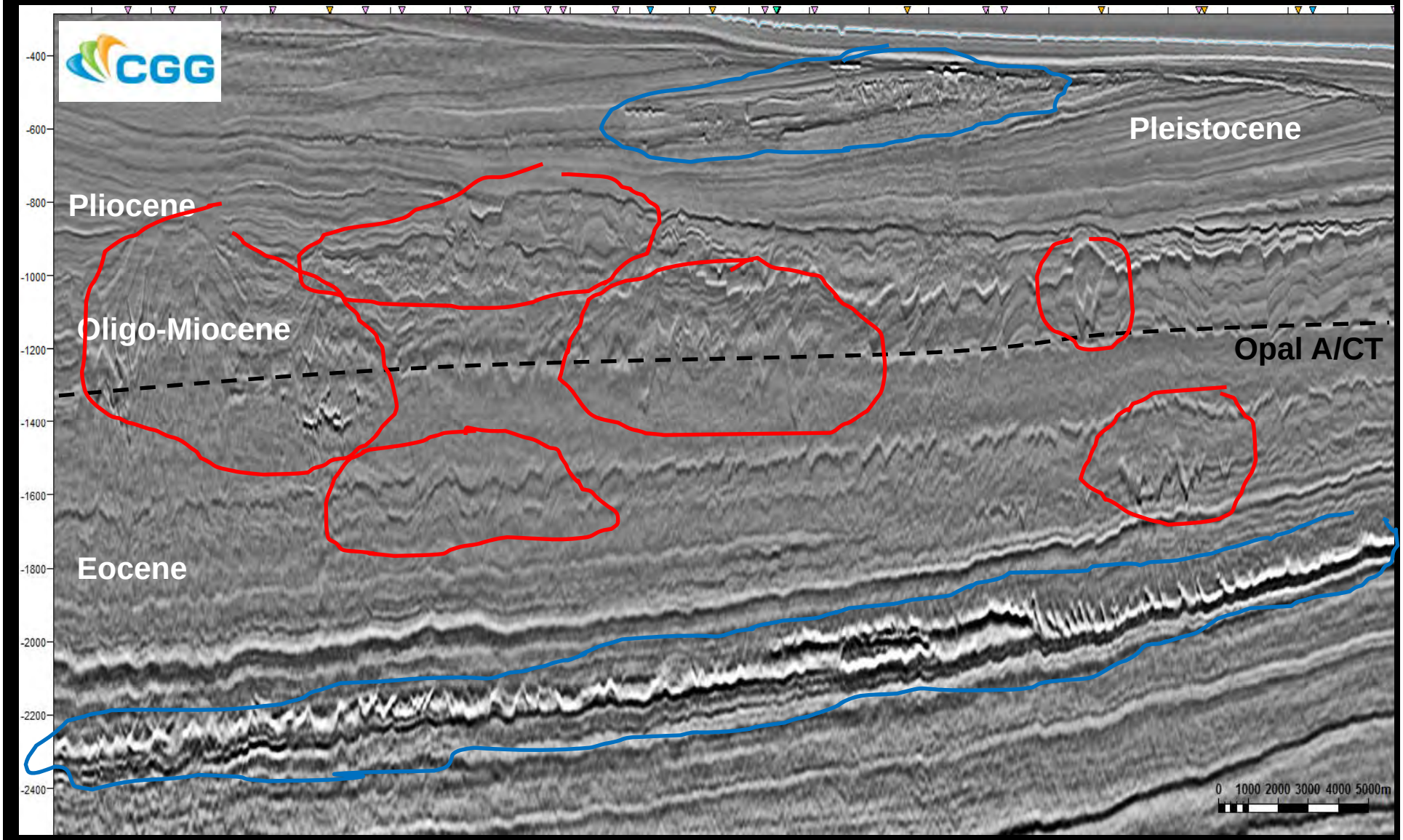


Applying diagnostic criteria: often not that easy



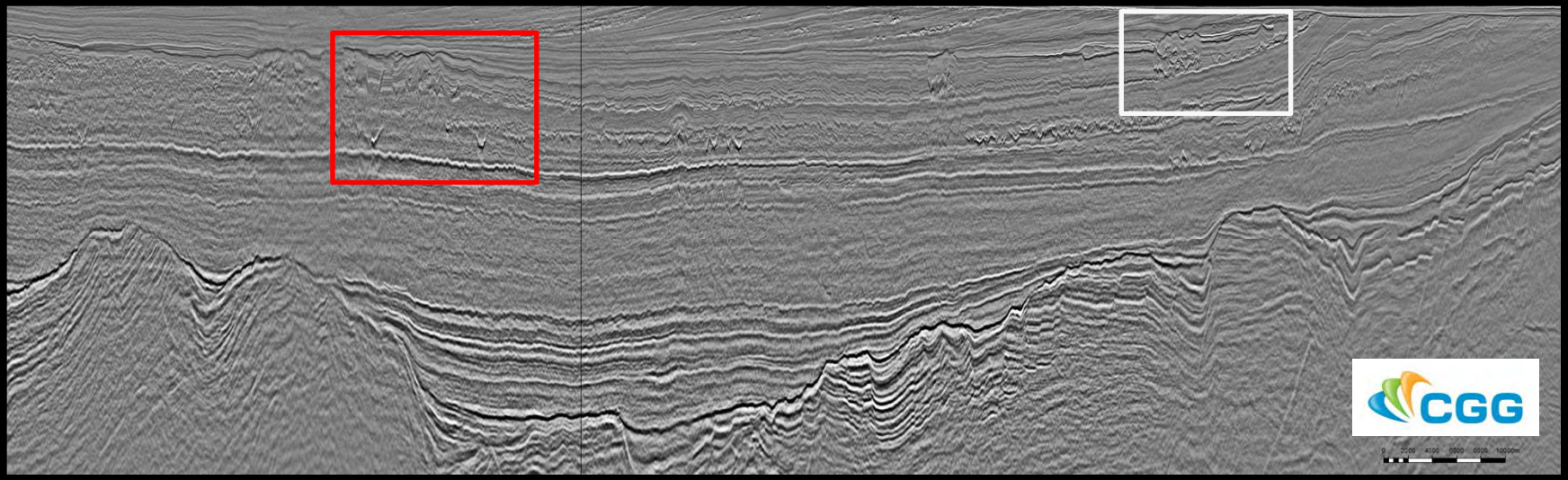

Chalk slides
CGG
10 km

Chalk slides below Eocene, Oligocene, Miocene, Pliocene (and Pleistocene?) 'injectites'
- Landslides easy to recognise when not polygonally faulted..

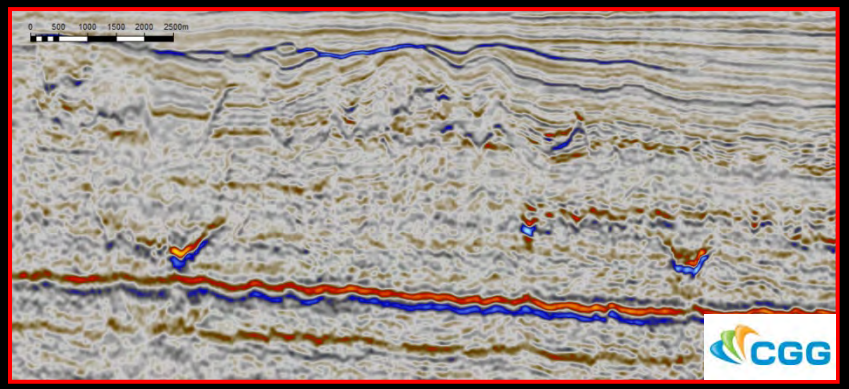


Fast Track NVGMERGE broadband 3D seismic data courtesy of CGG

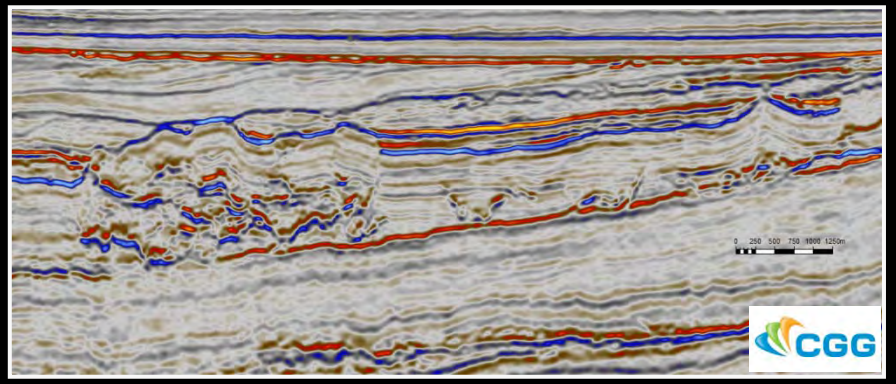
Broadband 3D seismic section (W-E) from Gullfaks to Måløy Platform: multiple disturbed intervals: Paleocene, Eocene, Oligo-Miocene, Pliocene, and areas of no disturbance



V-brights and Hordaland mounds

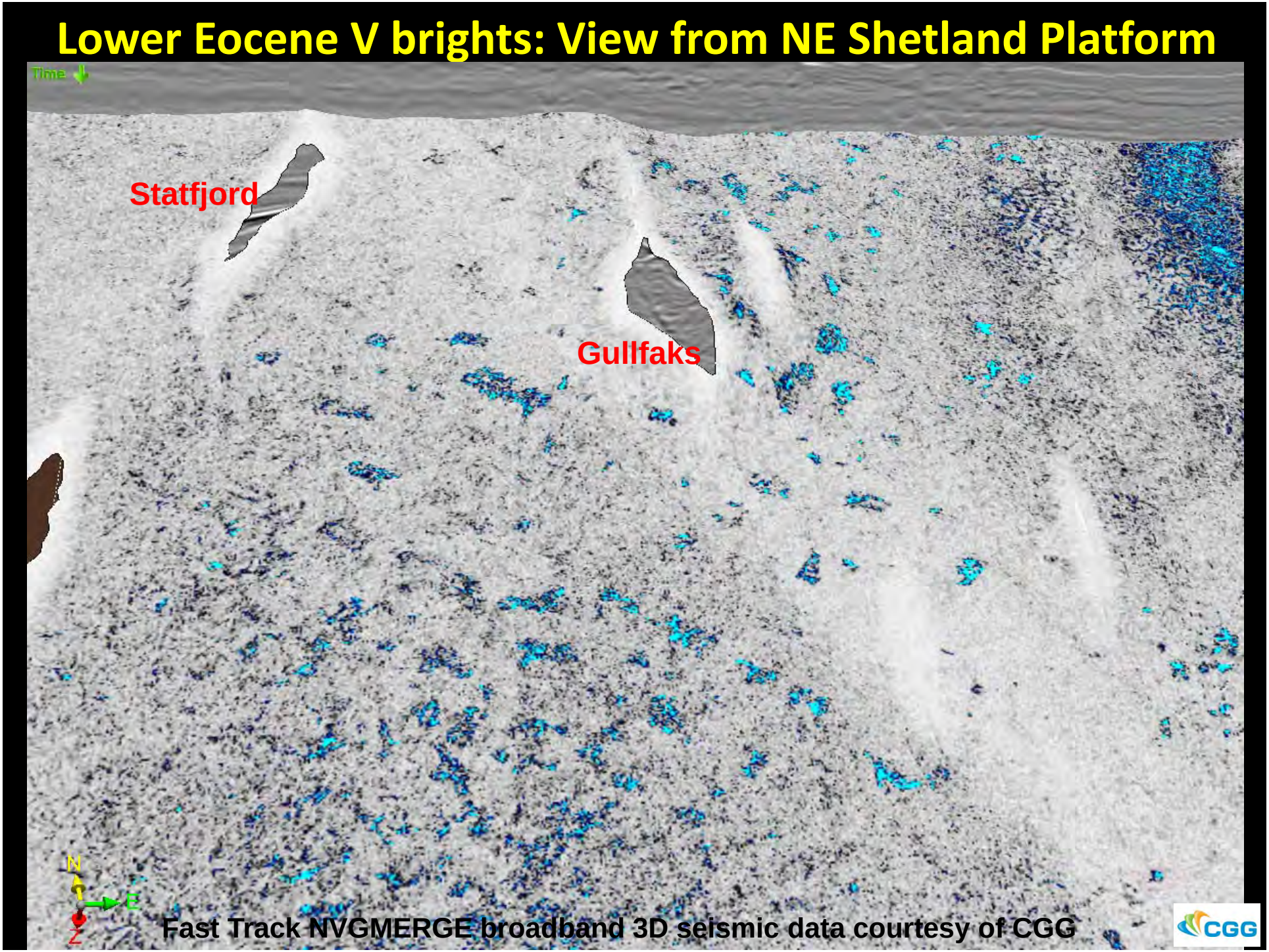


Paleocene+Eocene depo sst, Hordaland mounds



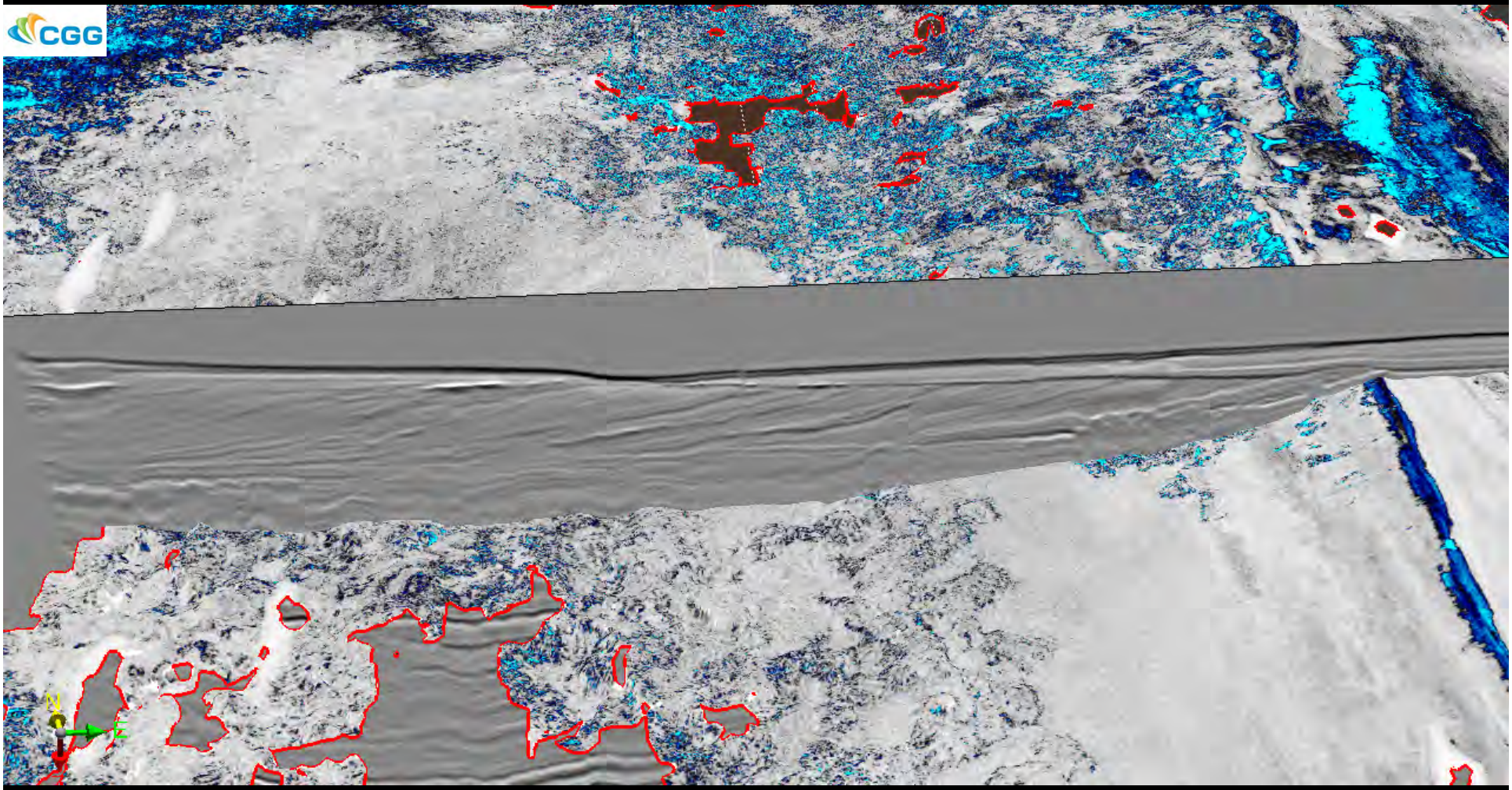
Fast Track NVGMERGE broadband 3D seismic data courtesy of CGG

Lower Eocene V brights: View from NE Shetland Platform

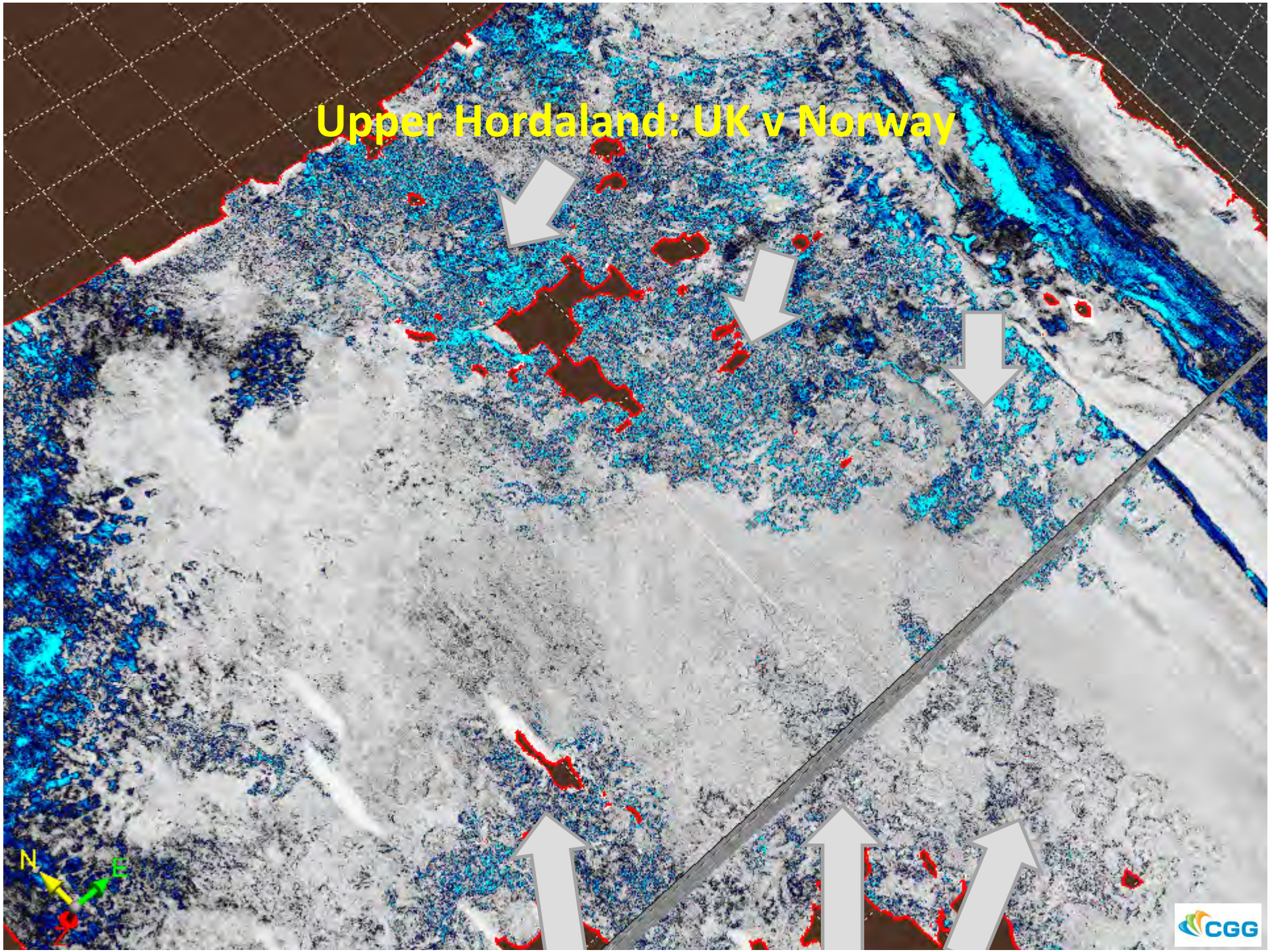


Fast Track NVGMERGE broadband 3D seismic data courtesy of CGG

Upper Hordaland sands supplied NW from UK, West from Norway

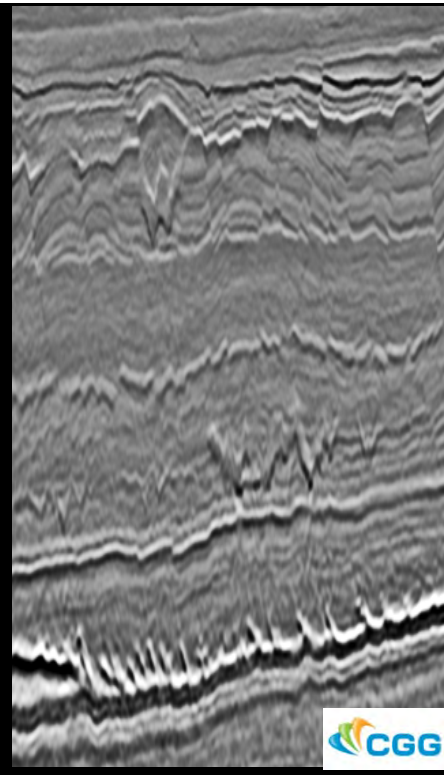


Fast Track NVGMERGE broadband 3D seismic data courtesy of CGG


Upper Hordaland: UK v Norway
N
E
CGG

SUMMARY..

- At least 7 sand injection events in the North Sea
  - 8-10 Myr interval
  - some 3-500 m of sedimentation between each episode
- Exploration targets, risks and hazards
- Excellent reservoir properties (30-40%, 1-10D)
- New images facilitate large-scale understanding
  - Importance of landslides in isolating sandy blocks and wholesale translation down-slope
  - Importance of palaeogeography, slope processes and diagenesis as important as 'the usual suspects' (tectonics, petroleum migration..)
- Complex geometries, patchy cementation and variable fluid contents complicate prediction, but seismic images and daring oil companies are catching up!



Thanks to:
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