Large-Scale Sand Injectites in the North Sea: Seismic and Event Stratigraphy and Implications for Hydrocarbon Exploration*

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Abstract

Large-scale sandstone intrusions are common in deepwater depositional systems, with excellent outcrop examples in California, Patagonia, France, Antarctica, Sakhalin, and Greenland. The largest subsurface examples constitute entire oil fields, particularly common in the Paleogene of the central and northern North Sea. Recent studies have documented their occurrence in the North Sea from the Upper Cretaceous to the Neogene, from the Norwegian-Danish Basin through the northern Central Graben, the Outer Moray Firth, the South Viking Graben, to the North Viking Graben, and in the Faroe-Shetland Basin.

This paper article reviews the tectono-stratigraphy of large-scale sandstone intrusions and their implications for hydrocarbon systems in the North Sea. The origin of the intrusions in the North Sea and in many basins worldwide remains largely unconstrained. In particular, the 1) timing, 2) sand and fluid source, 3) source of overpressure, 4) role of hydrocarbons, and 5) triggering mechanisms remain unresolved. Proposed mechanisms and drivers include liquefaction by earthquakes or meteorite impacts, diagenetic and hydrocarbon fluids, disequilibrium compaction, lateral transfer of pressure. In terms of hydrocarbon exploration, large-scale intrusions are important reservoirs with intricate geometries usually characterised by excellent intra- and inter-reservoir connectivity. Some intrusions may act as long-term fluid conduits and may thus be implicated in hydrocarbon migration and act as long-term fluid conduits (valves), increasing cross-stratal fluid flow over hundreds of metres of section, assisting pressure bleed off and compaction. In other areas, sandstone intrusions may act as fluid sinks when penetrated during drilling. Sandstone intrusions may connect isolated reservoir bodies over tens of kilometres laterally and over several hundreds of metres vertically. The sizes of individual completely injected sandbodies range up to 0.5-1.0 km³ in volume. Only a few such large-scale intrusions have been targeted deliberately, but
several have been drilled before their true origin were realized, causing much confusion in the initial appraisal and production of oil in
these bodies. Intrusions associated with in-situ remobilized sandbodies are extremely common in the North Sea Paleogene and
currently constitute important infill drilling targets on the Gryphon and Alba Fields and several smaller oil fields in the North Sea,
whereas frontier examples include deepwater West Africa.

References

Andresen, K.J., O.R. Clausen, and M. Huuse, 2009, A giant (5.3×10⁷ m³) middle Miocene (c. 15 Ma) sediment mound (M1) above the
doi:10.1016/j.marpetgeo.2009.02.005

Davies, R.J., M. Huuse, P. Hirst, J. Cartwright, and Y. Yang, 2006, Giant clastic intrusions primed by silica diagenesis: Geology
Boulder, v. 34/11, p. 917-920.

Den Hartog, J.D., M.R. Giles, and G.R. Griffiths, 1993, Evolution of Paleogene submarine fans of the North Sea in space and time:


Huuse, M., J. Cartwright, A. Hurst, and N. Steinsland, 2007, Seismic characterization of large-scale sandstone intrusions, in A. Hurst
DOI:10.1306/1209847M873253

EAGE Conference: Faults and Top Seals" - What do we know and where do we go, Montpellier, France, 8-11 September 2003, P-11,
1-10.

intrusions: detection and significance for exploration and production: First Break, v. 21, p. 33-42.

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Large-Scale Sand Injectites in the North Sea:
- Seismic and Event Stratigraphy
- Implications for Hydrocarbon Exploration

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Oil companies:
Chevron, ENI, Kerr-McGee, Maersk, Marathon, Oilexco, Shell,
StatoillHydro, Total

Seismic contractors:
CGGVeritas, ION GXT, PGS, TGS-Nopec, WesternGeco

Software providers (University Grants):
Schlumberger (Petrel/IESX), Landmark (Seisworks/GeoProbe),
SMT (Kingdom Suite)

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Outline

- Large-scale sandstone intrusions in the North Sea and beyond
- History and impact of injectites in the North Sea HC province
- Seismic stratigraphy of injectites (igneous and sand)
- Stratigraphic and geographical occurrence (North Sea)
  - Northern UK Central Graben
    - Early Eocene
  - Outer Moray Firth
    - Mid-Eocene, Late Eocene / early Oligocene, Miocene(?)
  - South Viking Graben
    - Paleocene/Eocene boundary, Early Eocene, Mid Eocene, Miocene
  - North Viking Graben (e.g. Snorre, Gullfaks)
    - Mid Eocene, Late Eocene, mid/late Miocene
  - Northeast Viking Graben
    - Late Oligocene (Måloy slope), Late Paleocene / Early Eocene
  - Norwegian-Danish Basin (Siri Canyon)
    - Late Eocene / early Oligocene, mid Miocene
  - Faroe-Shetland Basin
    - Early Eocene, midlate Miocene
- Summary
  - E&P implications
  - What remains to be discovered? (occurrence, process, significance)

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Worldwide occurrence of large-scale sandstone intrusions

Locations of some large-scale sandstone intrusion complexes:
- Well documented seismic and borehole examples
- Singular or incompletely documented seismic and borehole examples
- Borehole core examples (abundant vs sparse)
- Large-scale outcrop examples
- Seismically defined enigmatic structures of possible sandstone intrusion/extrusion origin, above reservoir level

Huuse 2008: WorldOil

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Analogues for crestal sand injectites in Californian outcrops: Santa Cruz (A, B), San Joaquin Valley (C, D)

Presenter’s Notes: Tar-saturated sandstone dykes and sills in the Santa Margarita diatomaceous mudstones along the coast of central California occur some 50-100 m above massive shelf sandstone, which is oil-saturated in structural culminations.

Sandstone dykes and sills crosscut 500+ m of Cretaceous and Paleogene shales in the San Joaquin Valley of central California.
Analogues for North Sea sand injectite 'wings': Jurassic Hare Elv Fm, East Greenland

Presenter’s Notes: Tar-saturated sandstone dykes and sills in the Santa Margarita diatomaceous mudstones along the coast of central California occur some 50-100 m above massive shelf sandstone, which is oil-saturated in structural culminations.

Sandstone dykes and sills crosscut 500+ m of Cretaceous and Paleogene shales in the San Joaquin Valley of central California.
Outcrop analogue and seismic modelling of large-scale (wing-like?) sand injectite in the Eocene of the San Joaquin Valley (CA)

Huuse et al. 2007. AAPG Memoir 87

Presenter’s Notes: Seismic modelling of outcrop analogue for a wing-like intrusion: Tumey Hills Eocene (San Joaquin Valley, CA).

The modelling uses outcrop geometry populated with subsurface physical properties; in this case we used shear-wave velocities to simulate the Alba/Chestnut wings and compare with PS data. Note that complex intrusion geometry is poorly resolved on the seismic section with realistic frequency content (D-left). Increasing frequency content to 4 times the realistic value enables the resolution of some complexity (D-right).
Deformed or 100% injected reservoirs in the North Sea Paleogene

Large scale sand injectites in the North Sea

Szarawarska et al. 2008: PESGB/PETEX
Submarine fans in a sequence stratigraphic framework - are they all primary depositional sandstones?

Den Hartog Jager et al 1993: PGC4
Paleogene sand injectites in cores from North Sea oil fields
Interpretation depends on data type, data quality, and mindset.

Interpretation without core or high quality seismic images

Interpretation with core and high quality seismic images
Data quality affects geological model and development plans

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

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Wing-producers ⇨ doubled production on Gryphon (UK 9/19)

Sand-injection impact on production. Oil from the seven horizontal wells in Gryphon field's sand wings has revitalized production. Injection-wing wells now account for about 13% of cumulative production from the field.
Jack-up or differential compaction associated with igneous intrusion

Figure 10. Example of magmatic traps and mode of occurrence. Top: seismic image: trap generated by sill jack-up. Silh are high-amplitude events crosscutting stratigraphy; image courtesy of PCS. Bottom: seismic image: trap generated by differential compaction; image courtesy of Sintec. (A) Cross section model of trap generated by sill jack-up. (B) Cross section model of trap generated by differential compaction. Figure is modified from Hansen (2004).
Structural-stratigraphic setting of large-scale sand injectites in the South Viking Graben (within yellow-dash outline)

Presenter's Notes: Most intrusions located in basin central region overlying Mesozoic grabens, but marginal examples are also known. Seismic-scale intrusions mainly confined to the Paleogene (imaging bias?), but core-scale intrusions occur from Jurassic onwards.
3D visualizations of injected sands reservoirs: South Viking Graben
Isolated massive sandstone mounds in the South Viking Graben: Balder (earliest Eocene) thickness and TWT structure
Volund Field: Balder sand with marginal ‘wings’

Discordant ‘wings’

Jack-up

Regional Top Balder

OWC

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Volund Field seismic expression:
~ saucer-shaped igneous intrusions

Total sandstone volume
estimated ~ 0.5 km$^3$

Huuse et al. 2007, AAPG Memoir 87
Volund: 3D morphology

- Sill (wing)
- Dyke (wing)
- Inner sill

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North Viking Graben injectites, extrudites and mudstone diagenesis

Utsira sandstone (part extruded from Oligocene?)

Remobilized sandstone (Oligocene)

Cortical sandstone infusions

Snorre Field (Jurassic - Triassic)

2 km

Opal A
Opal CT

Polygamonally faulted claystones

Base Tertiary

Top Balder

Base Mioocene

Base Cretaceous

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Huuse 2008: WorldOil
Faroe-Shetland Basin (NE Atlantic): Conical intrusions below and 1km above Eocene fan, independent of polygonal fault dips
Mid-Miocene (15 Ma) sand volcano ~ 0.05 km³ above the Paleocene Siri channel trend, Norwegian-Danish Basin: a link with gas migration and lateral transfer of fluids?

Andresen et al. 2009: MPG
Silica diagenesis and sand injectites

Davies et al. 2006: Geology

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Seismic stratigraphy of depositional and injected sandstones: summary

- **Depositional (no remobilisation)**
  - Mound (turbidite or extrudite)
  - Channel fill (truncation, onlap fill)

- **Remobilised depositional sand**
  - Remobilised mound
  - Remobilised channel fill

- **100% injected sand (saucer-shaped injectites)**
  - Laccolith and marginal dykes (+ extrudite)
  - Conical injectite

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Sandstone intrusions in the North Sea: summary

Stratigraphic and geographical occurrence (North Sea)
- Northern UK Central Graben
- Outer Moray Firth
  - Mid Eocene, Late Eocene (early Oligocene, Miocene(?))
- South Viking Graben
  - Pliocene/Eocene boundary, Late Eocene, Mid Eocene, Miocene
  - North Viking Graben (e.g., Snares, Oufit"
  - Mid Eocene, Late Eocene, middle Miocene
- Northeast Viking Graben
  - Late Eocene, Late Oligocene, Late Paleocene / Early Eocene
- Norwegian-Danish Basin (Siri Canyon)
  - Late Eocene (early Oligocene, mid Miocene
  - Fanoe-Shetland Basin
  - Early Eocene, middle Miocene

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E&P implications of sand injectites

- Enigmatic sandstone distribution
- Excellent reservoir properties
  - Fluid reservoirs and sinks
- Long-term conduits for fluid flow
- Pore-pressure prediction
- History of fluid expulsion
- Drilling hazards