SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

SUBSURFACE SEDIMENT REMOBILISATION: fast and large-scale reorganising geology

by
Katrine Juul Andresen, Assistant Professor
Department of Geoscience, Aarhus University

DGF Annual Meeting
March 12, 2016

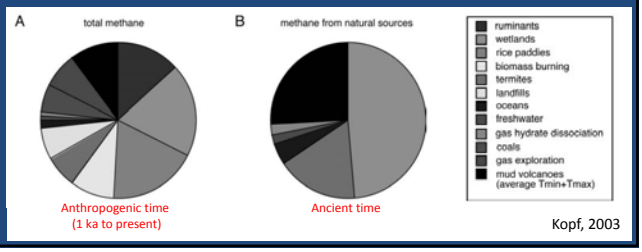
Outline

- What is subsurface sediment remobilisation?
  - Types of structures
  - Processes involved
- Worldwide distribution
  - Key localities
- Multiple scales: from cm- to km-scale
- Fast geology – but how fast?
- Zoom-in on sandstone intrusions in the Danish North Sea

SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

Subsurface sediment remobilisation

- Remobilisation of sediment in the subsurface
- Sand intrusions
  - Typical burial depths of source sand: 10-500 m
- Mud volcano system
  - Typical burial depth of source mud >1 km
- Similar processes, both involving
  - overpressure build-up
  - liquefaction and fluidisation
- Can directly influence human life if reaching the land surface
- Critical for oil and gas exploration
- Contributors to the global emissions of methane from the surface



Kopf, 2003

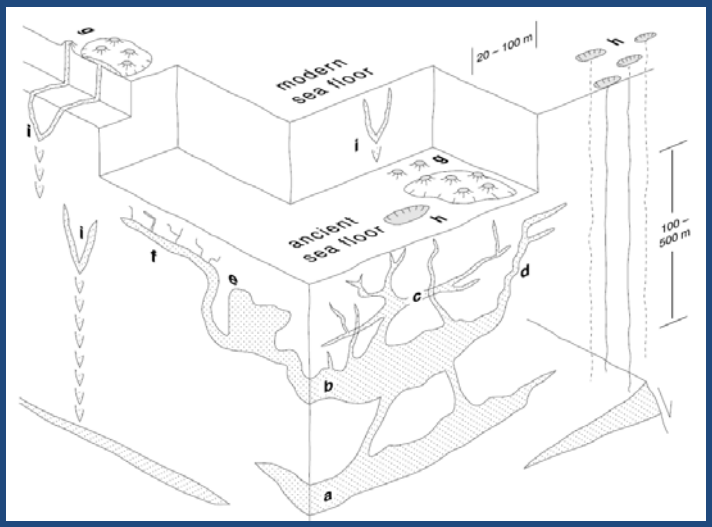
Subsurface sand remobilisation

- Requirements sand remobilisation:
  - Non-lithified source sand (parent bed)
    - Typical burial depth of 10 – 500 m
  - Overpressure development in sealed source sand
    - Disequilibrium compaction
      - Rapid sedimentation
    - Differential loading
      - Channel avulsion, slumps and slides, clinoform progradation, storm waves
      - Lateral transfer of pressure
    - Migration of deep thermogenic fluids (hydrocarbons)
    - Seismicity-induced liquefaction
      - Earthquakes and seismic shocking
  - Seal failure
    - Pressure gradient established
    - Hydrofracturing facilitated by overpressure
    - Polygonal faults
    - Tectonic stress
  - Fluidization, sand remobilisation and injection into host rock to establish pressure equilibrium

Key papers: Jolly & Lonergan, 2002; Hurst et al., 2011

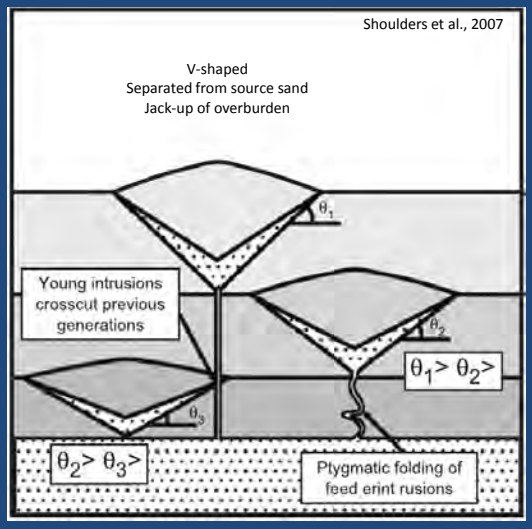
SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

Architecture of sand injectites



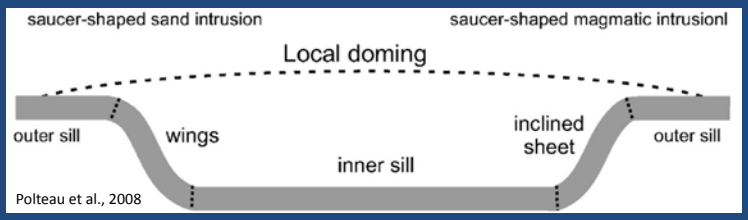
Hurst & Cartwright, 2007

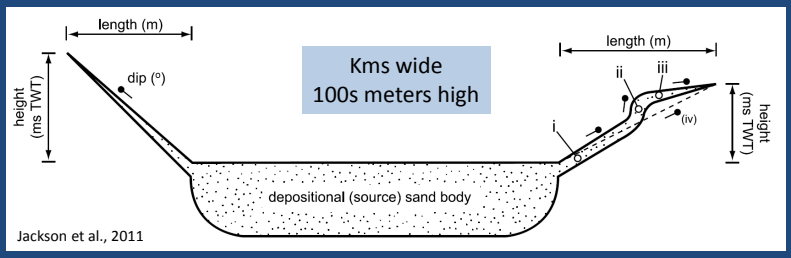
Conical sand intrusions



SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

Saucer-shaped sand intrusions

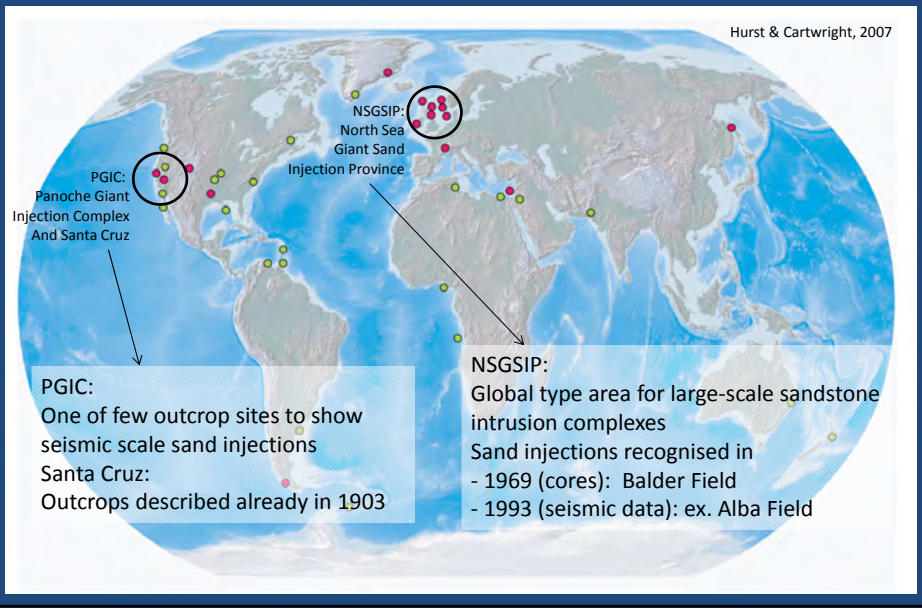




Kms wide
100s meters high

SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

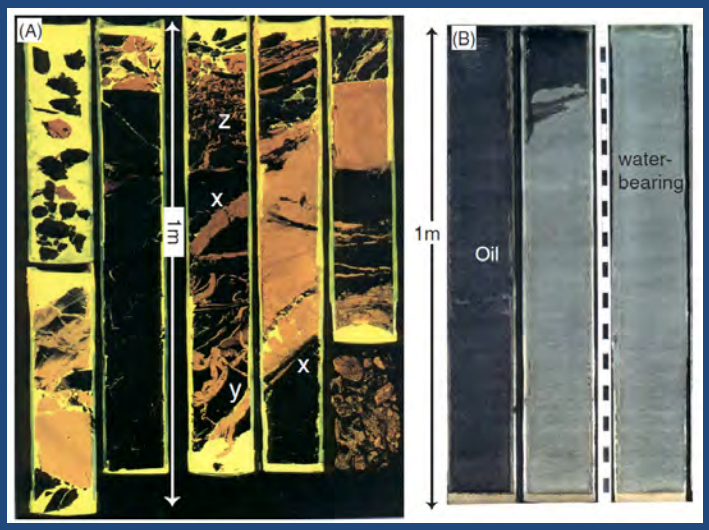
Worldwide distribution of sand intrusions



PGIC:
One of few outcrop sites to show seismic scale sand injections
Santa Cruz:
Outcrops described already in 1903

NSGSIP:
Global type area for large-scale sandstone intrusion complexes
Sand injections recognised in
- 1969 (cores): Balder Field
- 1993 (seismic data): ex. Alba Field

Core examples



Lonergan et al., 2000
Alba Field

Szarawarska et al., 2010
Volund Field

Outcrop examples

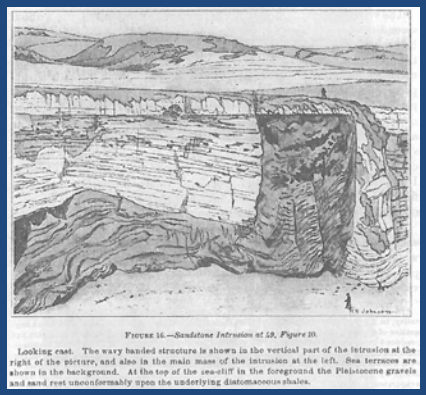


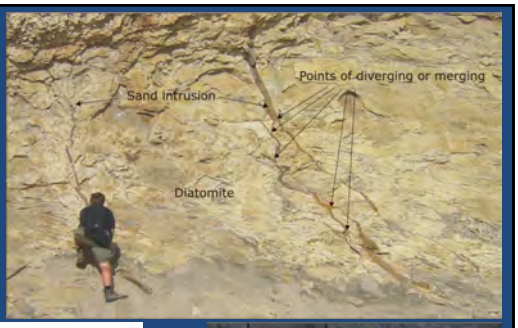
FIGURE 16.—*Sandstone Intrusion at 18, Figure 10.*

Looking east. The wavy banded structure is shown in the vertical part of the intrusion at the right of the picture, and also in the main mass of the intrusion at the left. Sea terraces are shown in the background. At the top of the sea-cliff in the foreground the Pleistocene gravels and sand rest unconformably upon the underlying diatomaceous shales.

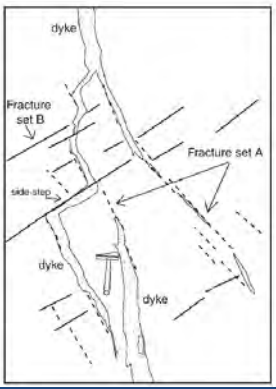
Newsom, 1903

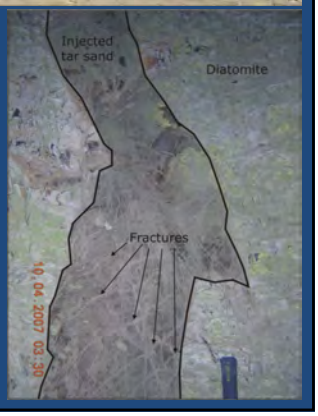
Santa Cruz, California, USA

Santa Cruz, California, USA

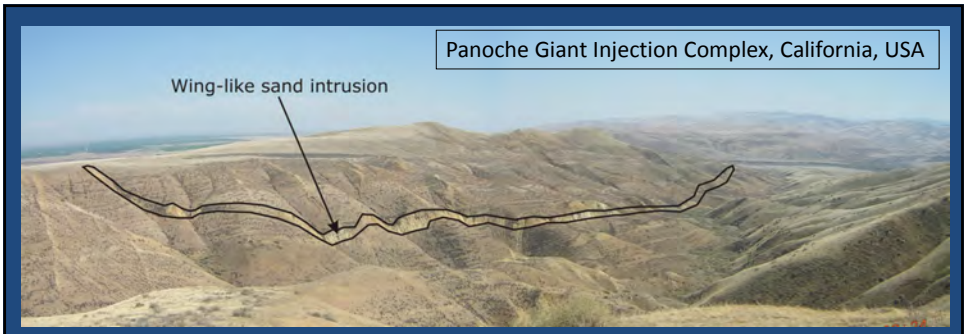


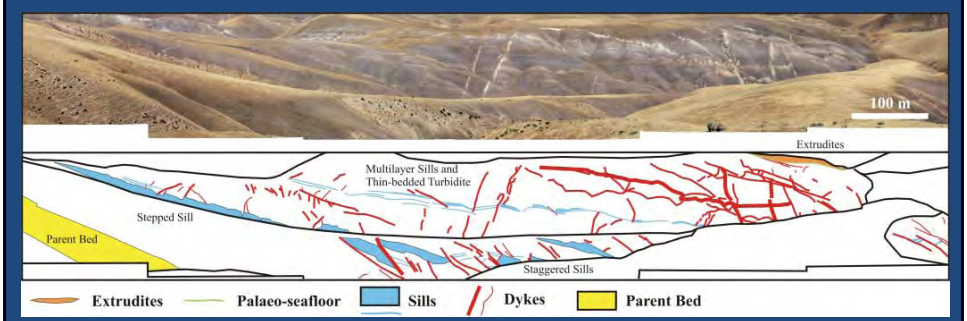
Jolly & Lonergan, 2002





Panoche Giant Injection Complex, California, USA

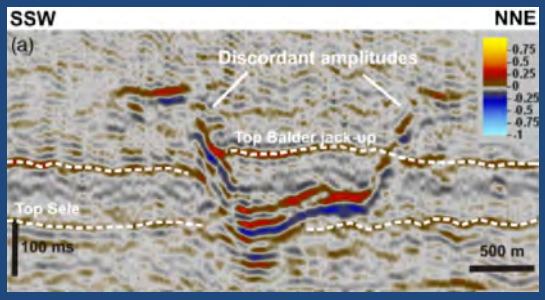




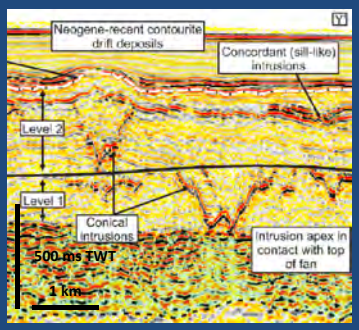
Vigorito et al., 2008 Panoche Hills

SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

Seismic examples



Szarawarska et al., 2010, Volund Field

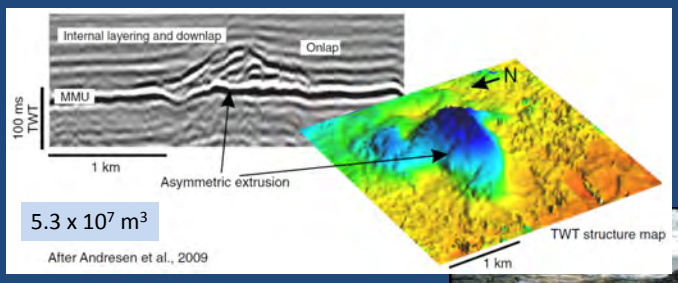


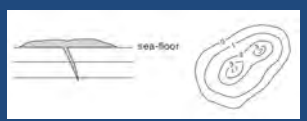
Shoulders et al., 2007, Faroe-Shetland Basin

Huuse & Mickelson, 2004, Tampen Spur

SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

Sand extrusions (sand volcanoes)

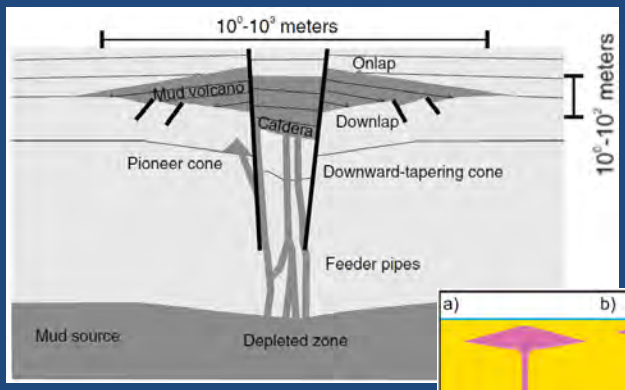




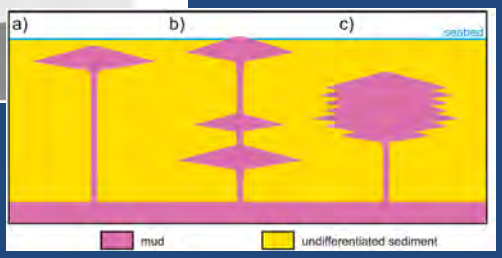
Hurst et al., 2006, Extrudite schematic

Pringle et al., 2007, Western Ireland

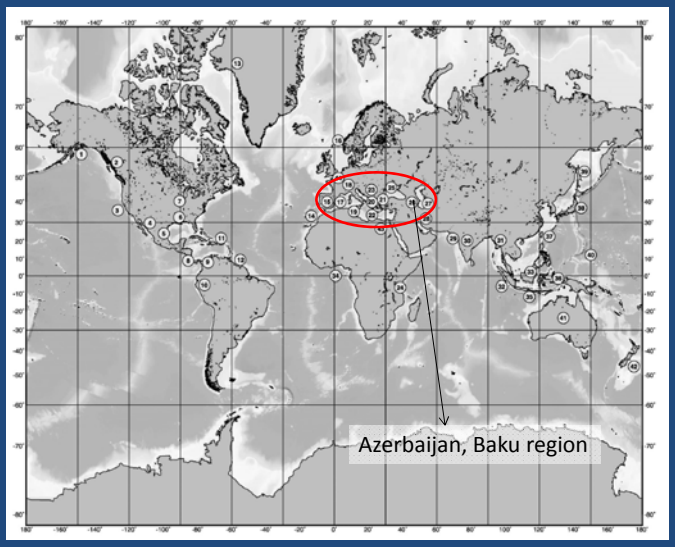
Architecture of mud volcano systems



Stewart & Davies, 2006

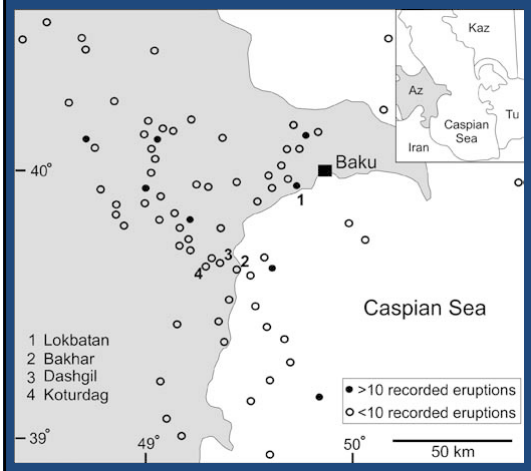


Worldwide distribution– mud volcano systems

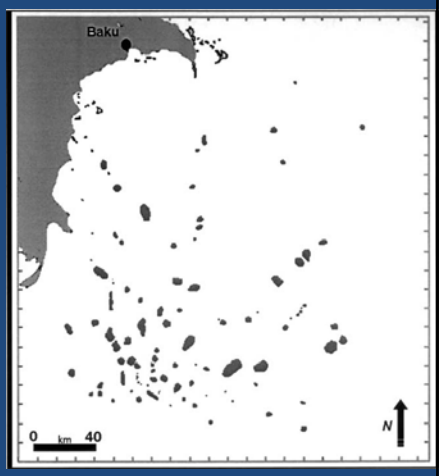


Kopf, 2002

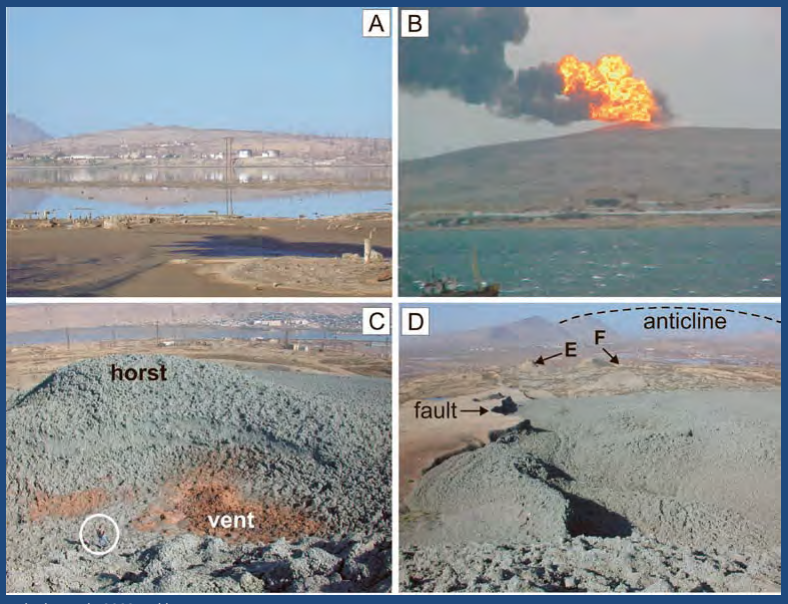
Azerbaijan



Planke et al., 2003



Yuisfov & Rabinowitz, 2004



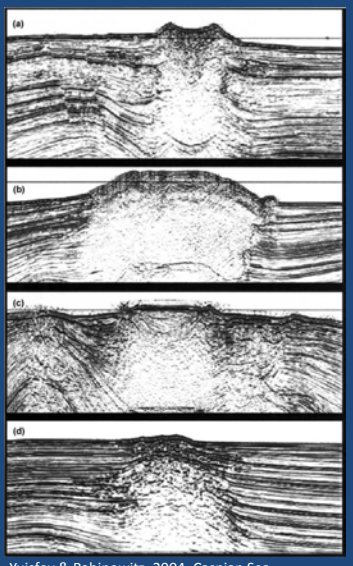
Planke et al., 2003, Lokbatan

https://youtu.be/0xCPXg5lJeg

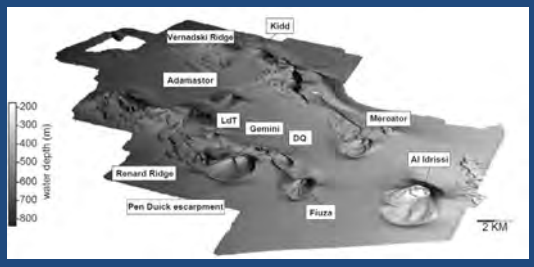
SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

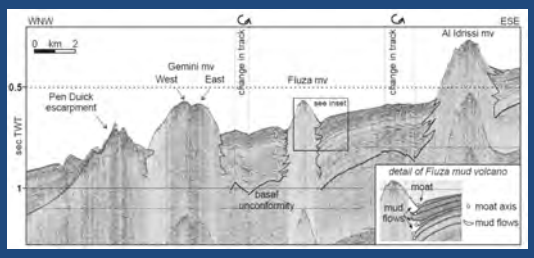
Hovland et al., 1997, Dashgil

Seismic examples

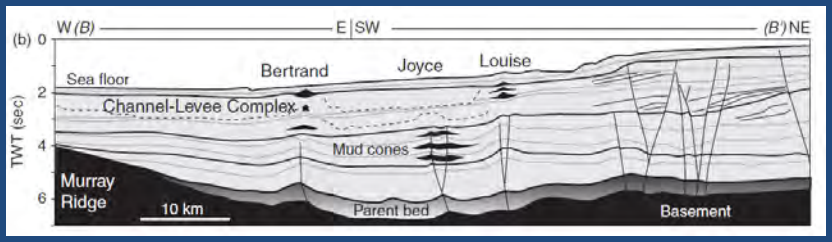


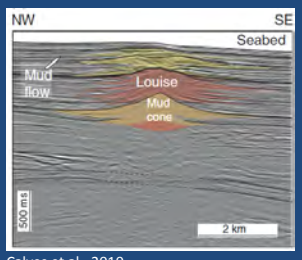
Yuisfov & Rabinowitz, 2004, Caspian Sea



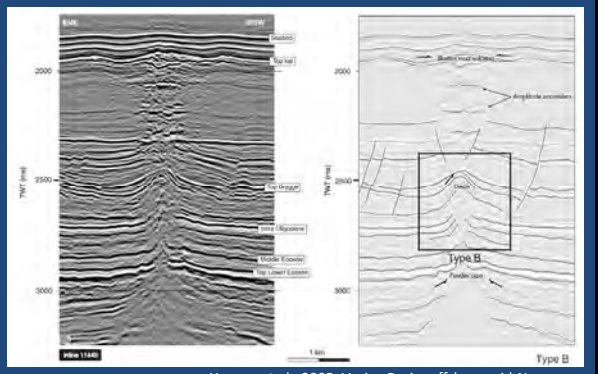


Van Rensbergen et al., 2005, Gulf of Cadiz



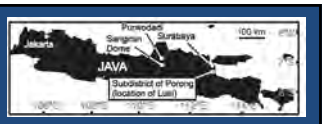


Calves et al., 2010,
Indus Fan, offshore Pakistan

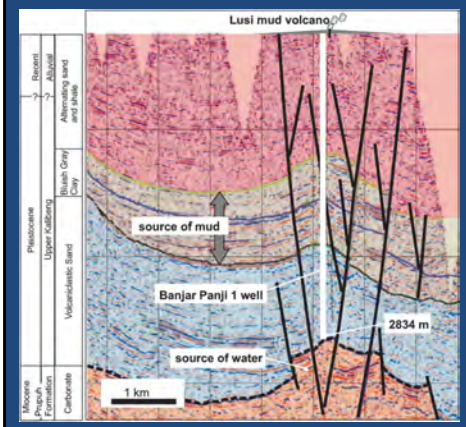


Hansen et al., 2005, Vøring Basin, offshore mid-Norway

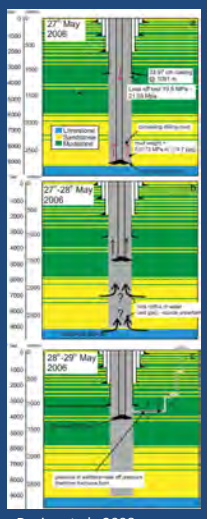
Lusi mud volcano



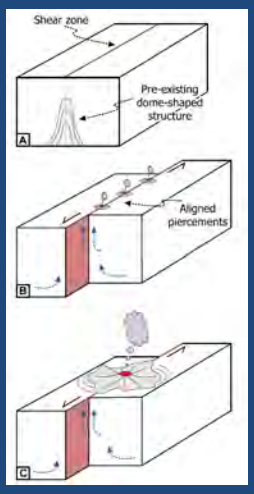
- Largest active mud volcano on the surface of the Earth
- Eruption began May 29 2006
- Covers 7 km^2
- Longevity estimated to 25-30 years (Davies et al., 2011)
- Max eruption rates 180.000 m^3 per day
- 13000 families have lost their home
- Dispute on trigger:
  - Man-made: hazardous drilling 150 m from main vent
  - Natural: Earthquake on May 27 2006



Davies et al., 2011

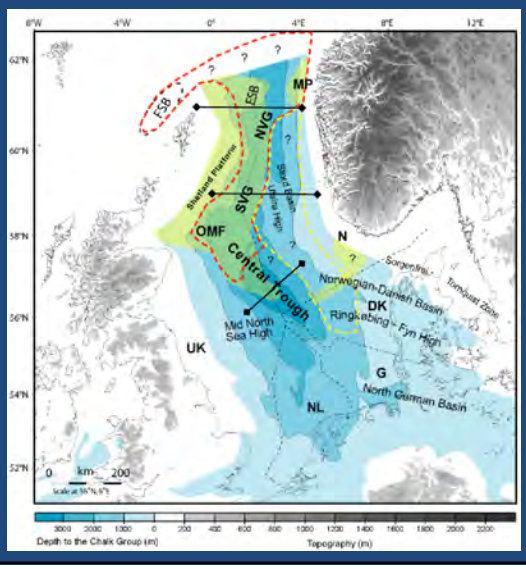


Davies et al., 2008



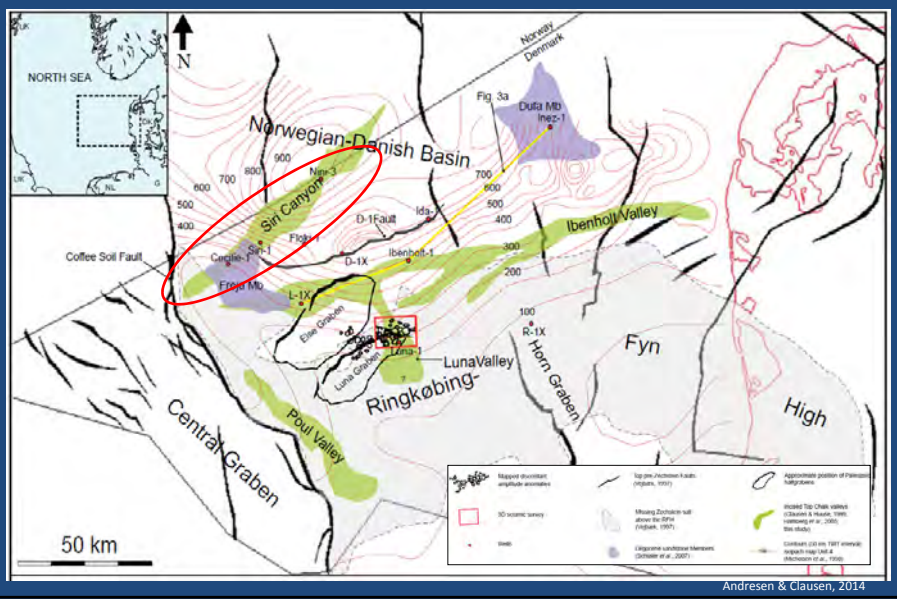
Mazzini et al., 2009

Zoom-in on sandstone intrusions in the Danish North Sea



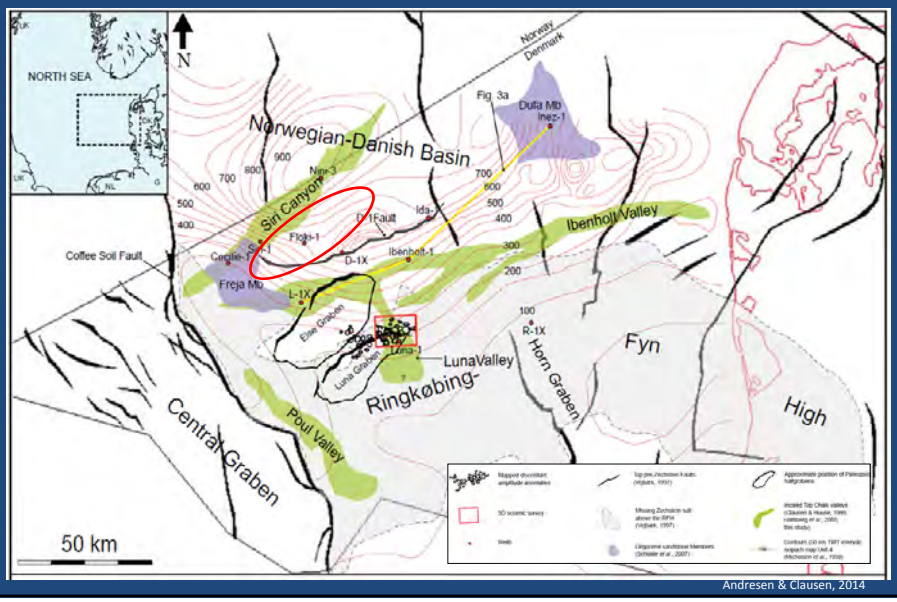
Huuse et al., 2012

Sand intrusions in the Danish North Sea



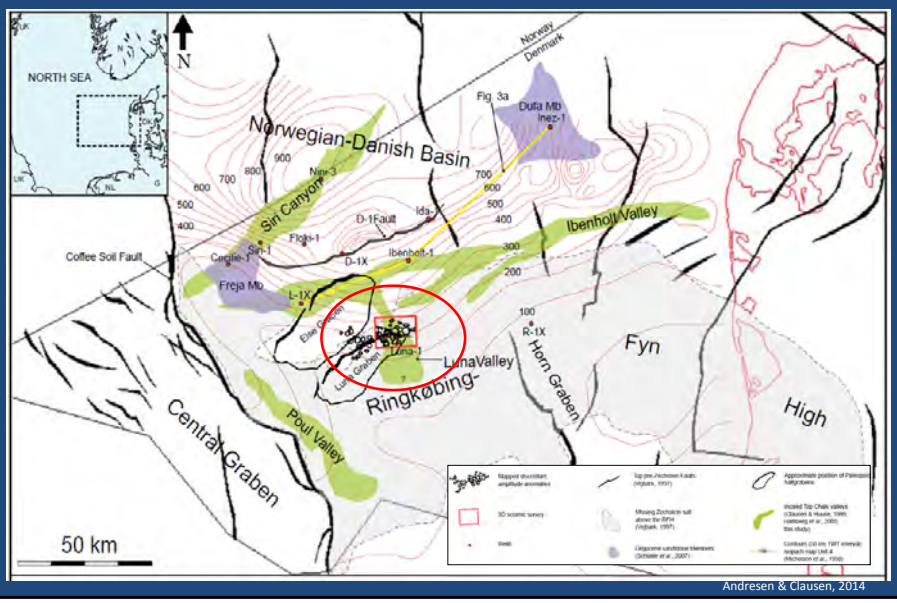
Andresen & Clausen, 2014

Sand intrusions in the Danish North Sea

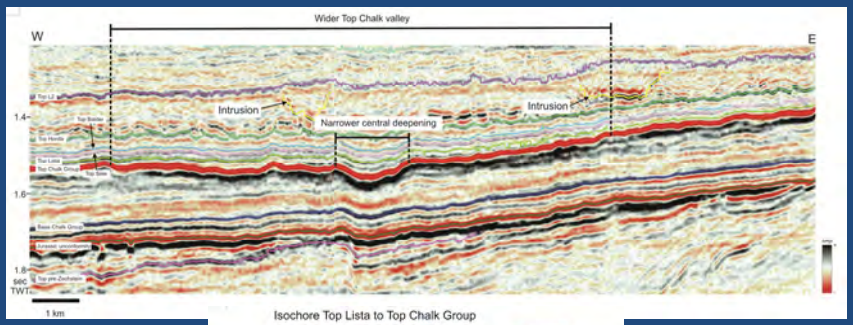


Andresen & Clausen, 2014

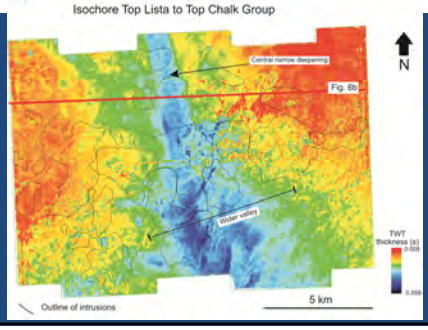
Sand intrusions in the Danish North Sea



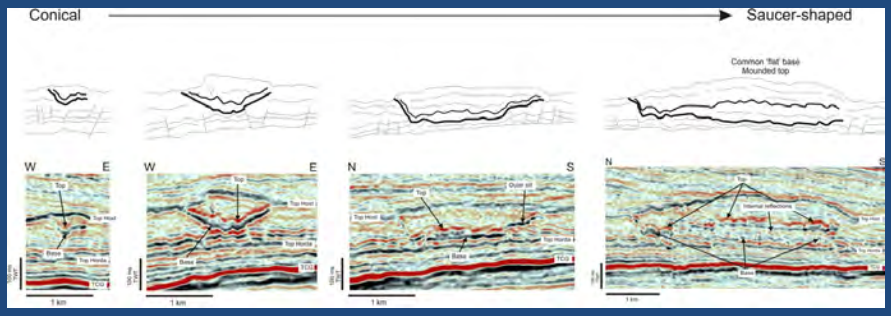
Andresen & Clausen, 2014

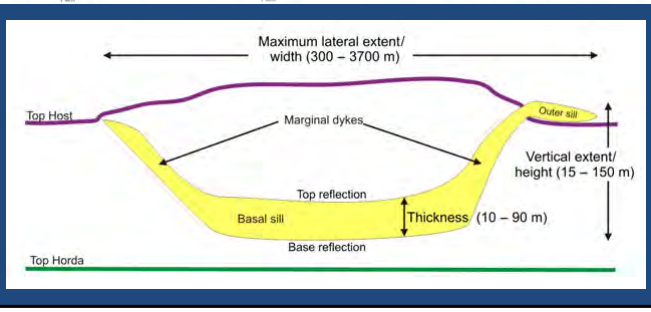


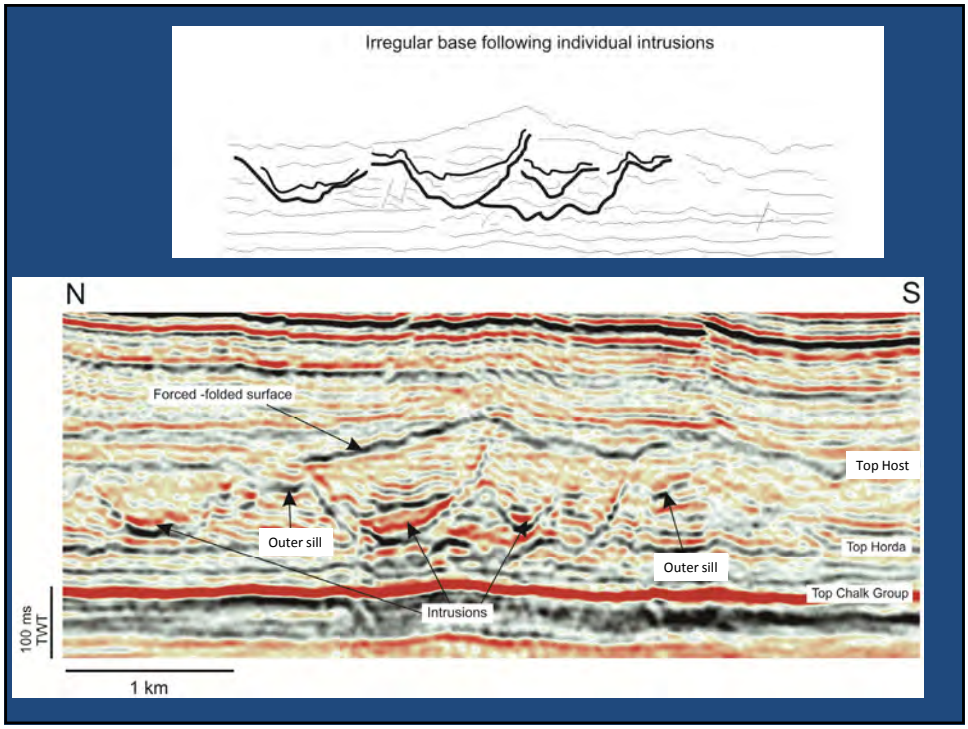
Isochore Top Lista to Top Chalk Group

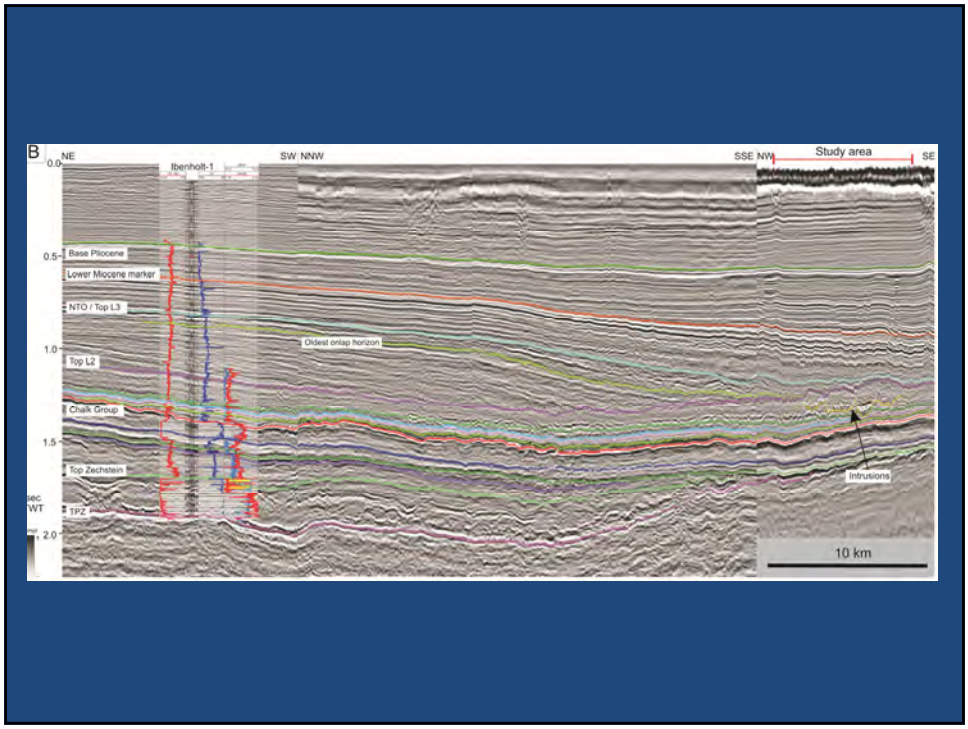


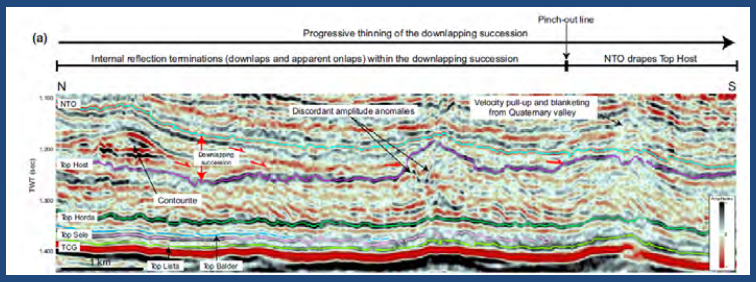
Andresen & Clausen, 2014

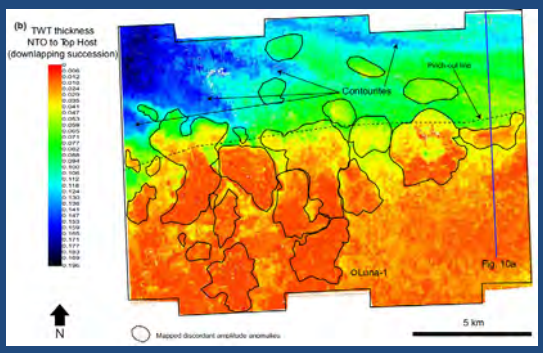




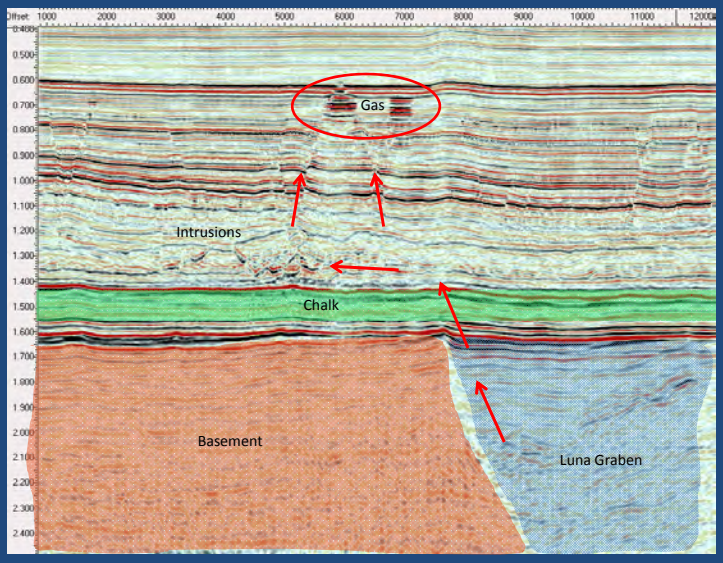

Irregular base following individual intrusions
N
S
Forced -folded surface
Top Host
Outer sill
Top Horda
Outer sill
Top Chalk Group
Intrusions
100 ms
TWT
1 km


B
NE
Ibenholt-1
SW NNW
SSE NW
Study area
SE
Base Pliocene
Lower Miocene marker
NTO / Top L3
Oldest onlap horizon
Top L2
Chalk Group
Top Zechstein
TPZ
Intrusions
10 km

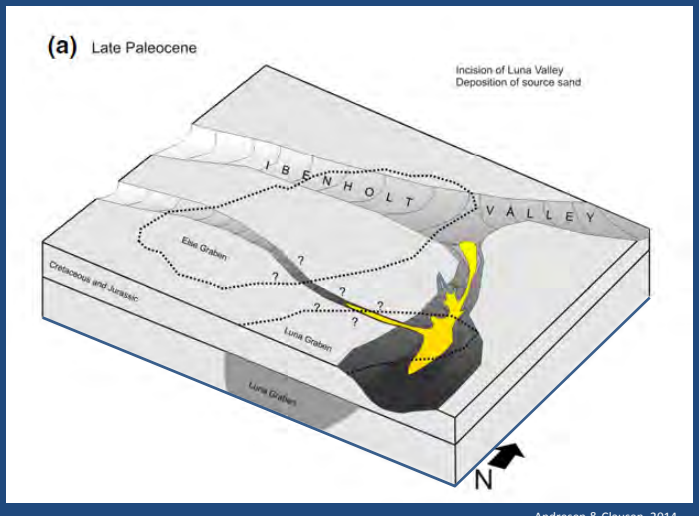




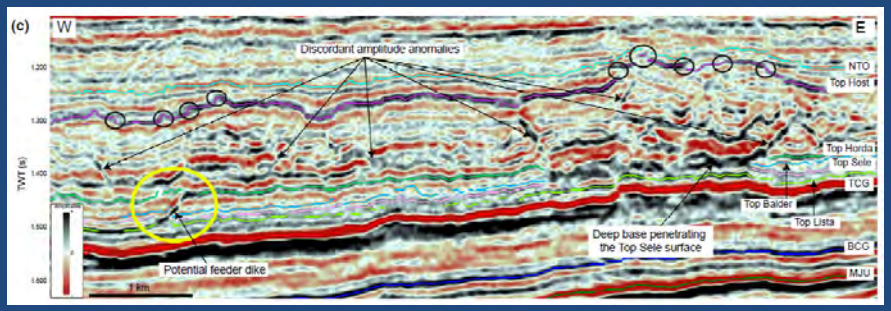
Andresen & Clausen, 2014

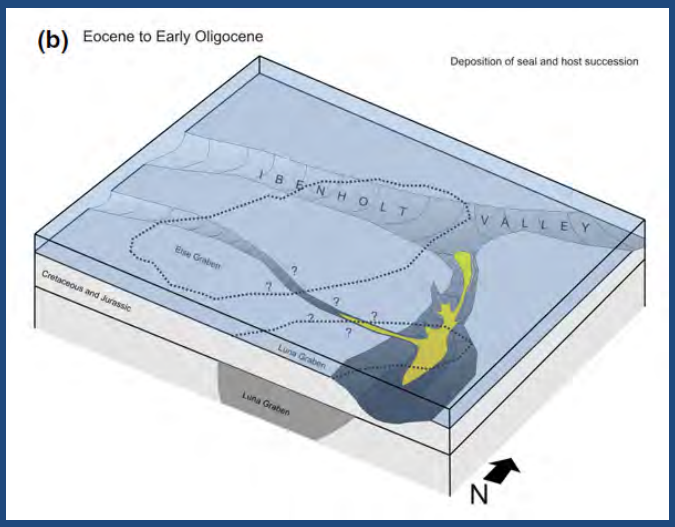


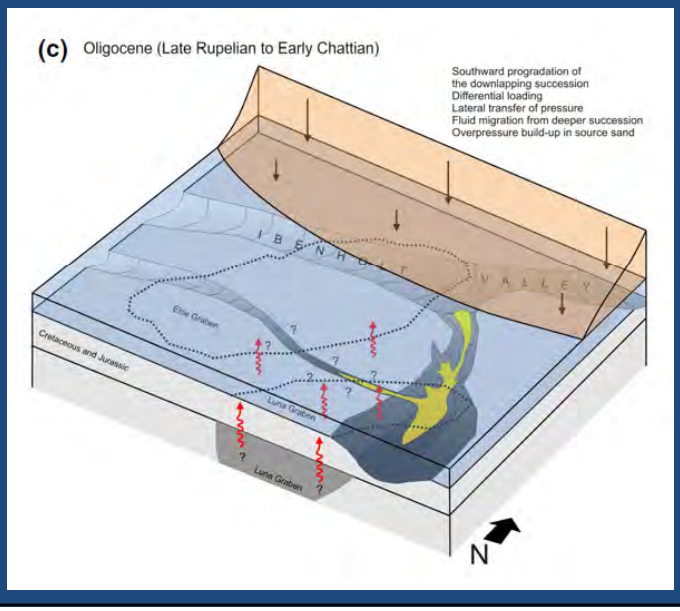
Model of formation

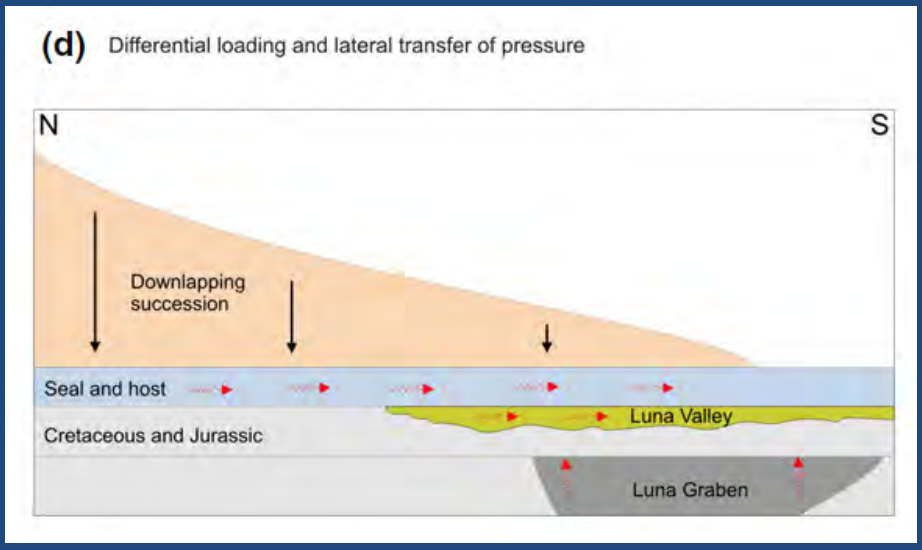


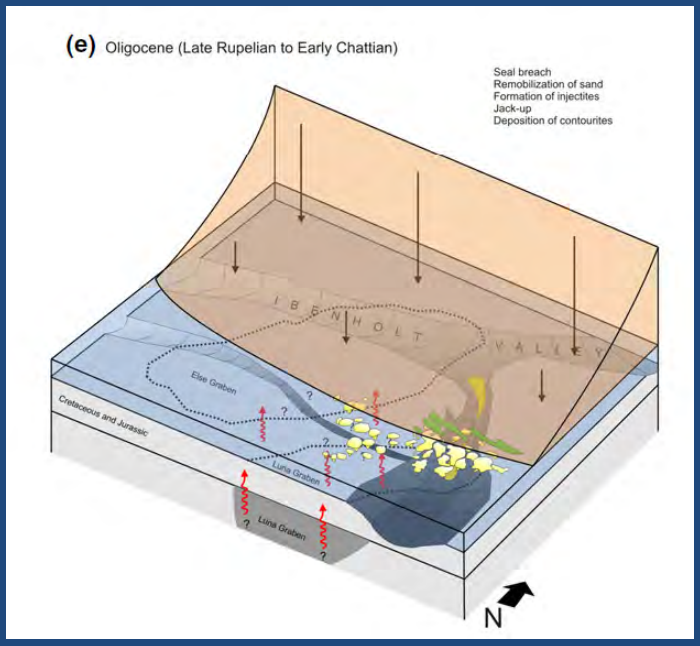
Andresen & Clausen, 2014

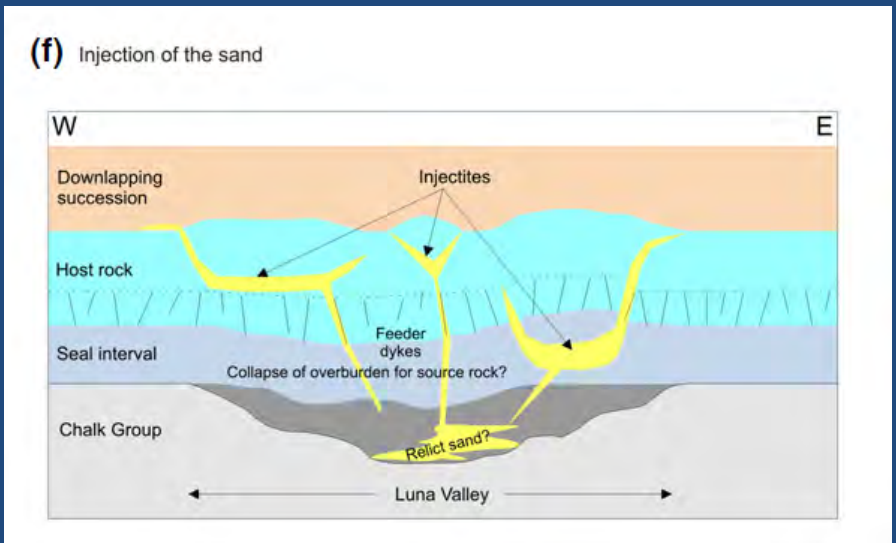

(c)
W
E
Discordant amplitude anomalies
NTO
Top Hod
Top Hordaland
Top Sele
TCG
Top Balder
Top Lista
BCG
MJU
Deep base penetrating the Top Sele surface
Potential feeder dike
TVT (s)
1 km

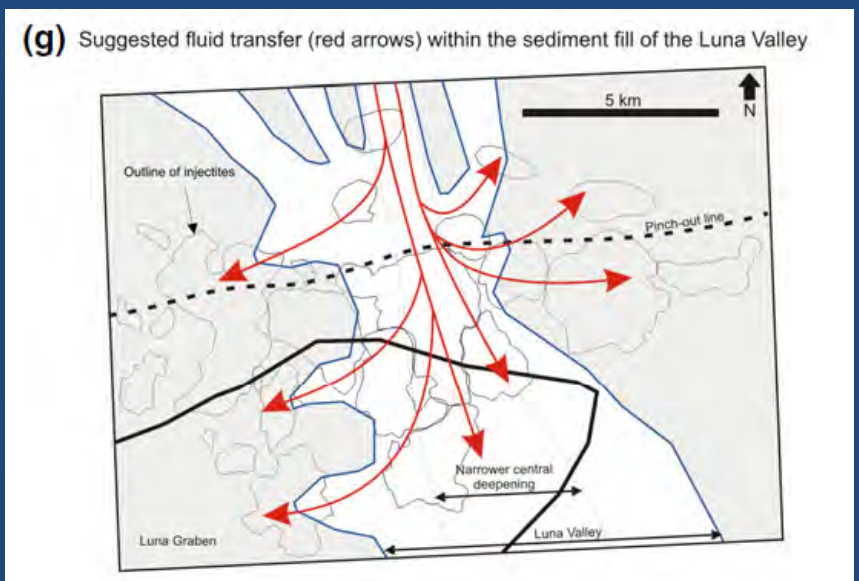

(b) Eocene to Early Oligocene
Deposition of seal and host succession
IBENHOLT
VALLEY
Elke Graben
Cretaceous and Jurassic
Luna Graben
Luna Graben
N

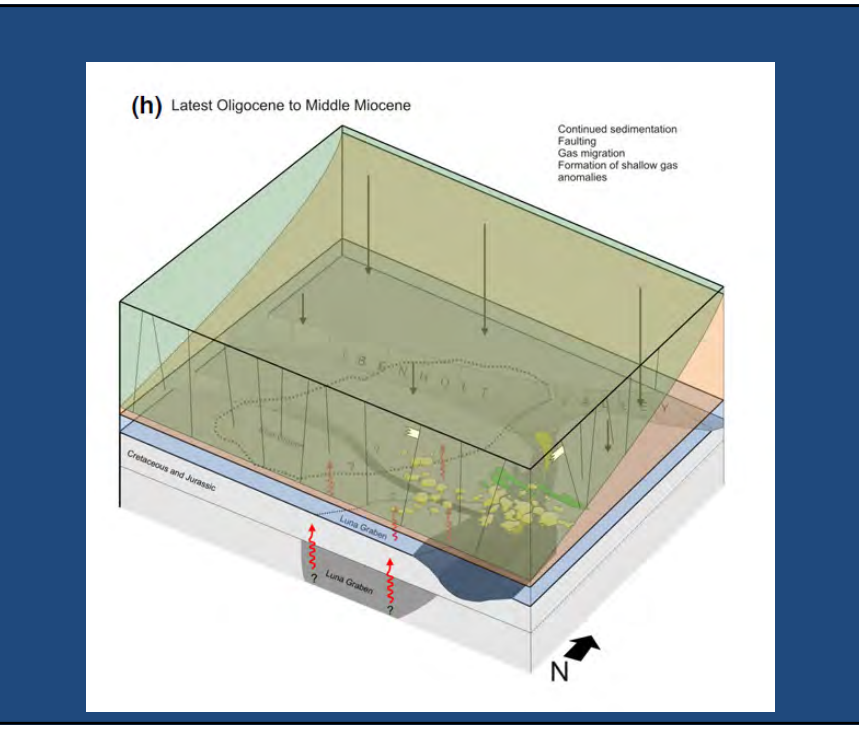

(c) Oligocene (Late Rupelian to Early Chattian)
Southward progradation of the downlapping succession
Differential loading
Lateral transfer of pressure
Fluid migration from deeper succession
Overpressure build-up in source sand
Cretaceous and Jurassic
Luna Graben
N


(d) Differential loading and lateral transfer of pressure
N
S
Downlapping succession
Seal and host
Cretaceous and Jurassic
Luna Valley
Luna Graben

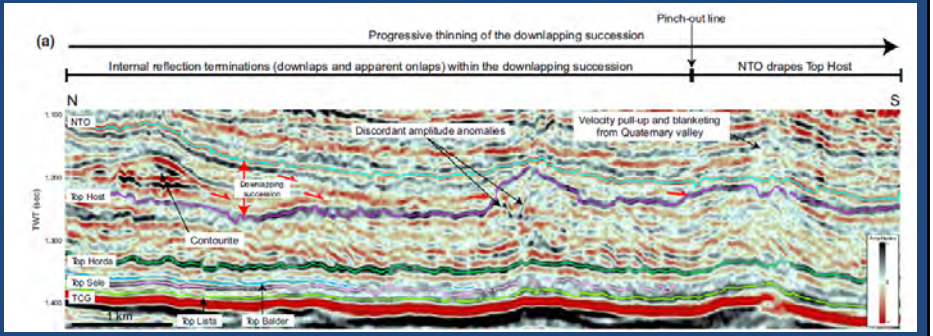

(e) Oligocene (Late Rupelian to Early Chattian)
Seal breach
Remobilization of sand
Formation of injectites
Jack-up
Deposition of contourites
IBENHOLT VALLEY
Elst Graben
Cretaceous and Jurassic
Luna Graben
Luna Graben
N


(f) Injection of the sand
W
E
Downlapping succession
Injectites
Host rock
Seal interval
Feeder dykes
Collapse of overburden for source rock?
Chalk Group
Relict sand?
Luna Valley


(g) Suggested fluid transfer (red arrows) within the sediment fill of the Luna Valley
5 km
N
Outline of injectites
Pinch-out line
Narrower central deepening
Luna Graben
Luna Valley


(h) Latest Oligocene to Middle Miocene
Continued sedimentation
Faulting
Gas migration
Formation of shallow gas anomalies
Cretaceous and Jurassic
Luna Graben
Luna Graben
N

How fast?

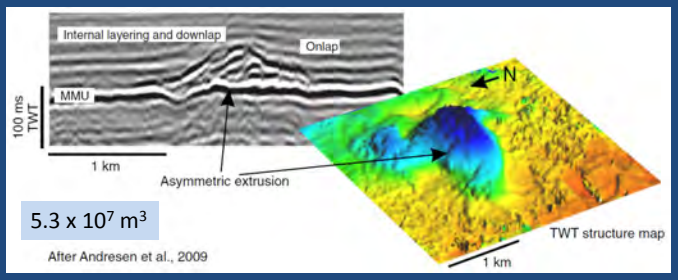


Top Host ca. 28 Ma
NTO ca. 25 Ma
Max duration 3 Myr
Min duration: could be significantly shorter!

Max 1.8 km^3 of sediment in total

SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY

How fast?



Andresen et al., 2009:
Mid Miocene sediment mound above the Siri Canyon

Duration
Max 2 Myr (interfingering scenario): 40 m /Myr
Max 200 kyr (onlapping scenario): 4 m/ 1000 yr


SCIENCE AND TECHNOLOGY
AARHUS UNIVERSITY
Thank you for your attention