Characterization and Origin of Anhydrite-Rich 'Lateral Caprock' Adjacent to Halite-Cored Salt Diapirs; Implications for Prospectivity in Salt Basins*

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Abstract

Mapping of salinity levels in groundwater adjacent to salt structures commonly indicates the presence of saline "plumes", which are inferred to form in response to the migration of relatively warm fluids up, and dissolution of halite from, the margins of these structures. To date, the products of this process have not been directly sampled in the deep subsurface. Determining the potential for halite dissolution in the deep subsurface is important because density-driven convection of groundwater, which can drive large-scale fluid, heat and solute transport, is dependent on dissolution of halite from the margins of salt structures. Furthermore, uncertainties related to the geometry and composition of salt structures has implications for hydrocarbon exploration and production; for example, hydrocarbon traps in many basins rely on updip pinch-out of reservoirs against impermeable, halite-dominated "salt" structures. In this study, we use 3-D seismic reflection and borehole data to: (i) document the geometry and lithology of a salt diapir; (ii) assess the feasibility that large volumes of halite can be dissolved from the margins of steep-sided salt structures; and (iii) consider the implications that salt dissolution may have on hydrocarbon prospectivity in salt-influenced basins. Seismic data suggest that a weld is developed along the diapir stem, although borehole data indicate that the stem consists of an inner, c. 1,500 m thick, halite-dominated zone, and an outer, c. 250 m thick, anhydrite-dominated "sheath". We interpret that the anhydrite represents "lateral caprock", which formed late in the basin history in response to the migration of NaCl-poor fluid up the margins of the diapir, and dissolution of halite. The possibility that caprock may form on the flanks of salt structures indicates that lithological variations should therefore be taken into account when risking salt-related pinch-out traps in salt-influenced sedimentary basins. Furthermore, the dissolution of large volumes of halite from the margins of steep-sided salt structures by deep, warm, basinal brines has implications for understanding the patterns and vigour of groundwater flow in sedimentary basins and the location of economically important metals. Our study also shows that the margins of steep-sided salt structures may be misidentified by several hundred metres if time-migrated seismic reflection data are used.

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What is Caprock?

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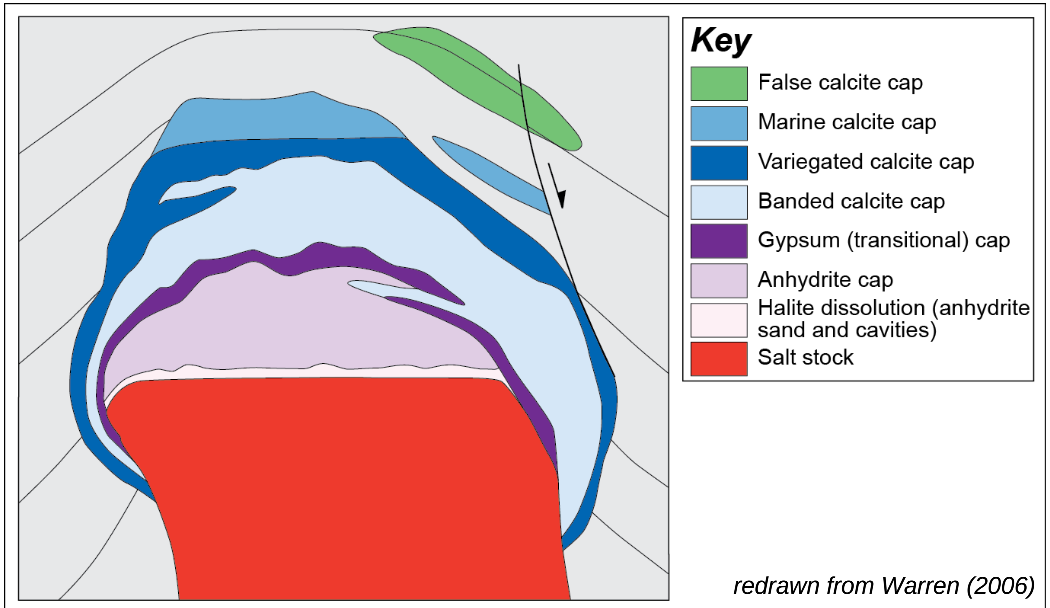
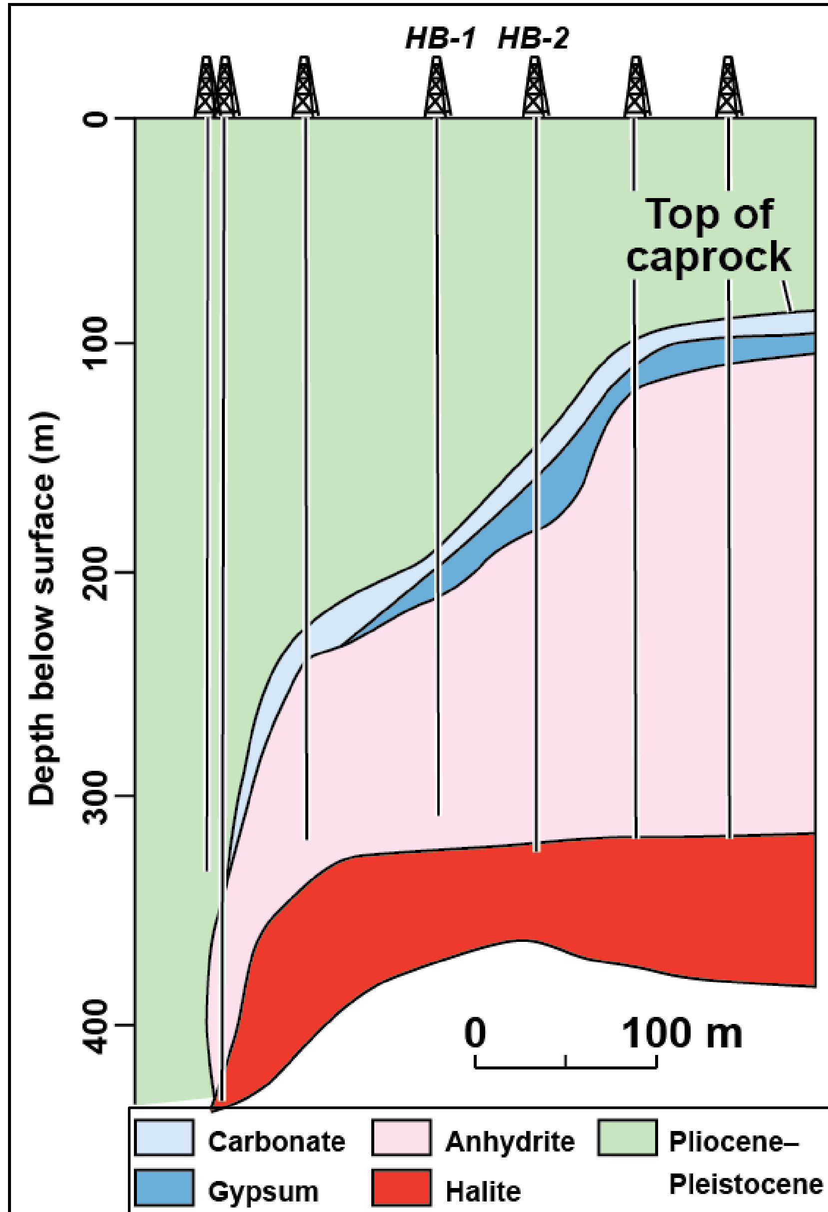


redrawn from Warren (2006)



modified from Hallager et al. (1990)

- A diagenetic product formed at crest of salt structures
- Anhydrite-rich caprock forms due to halite dissolution by cool, NaCl-undersaturated, meteoric water
- Gypsum can form due to rehydration of anhydrite at shallow burial depths
- Gypsum converted to carbonate ($CaCO_3$) by anhydrite dissolution, sulfate reduction by hydrocarbon-hosted bacteria and precipitation of carbonate
- Caprock tapers downwards onto salt structure flanks

Scale and Economic Importance

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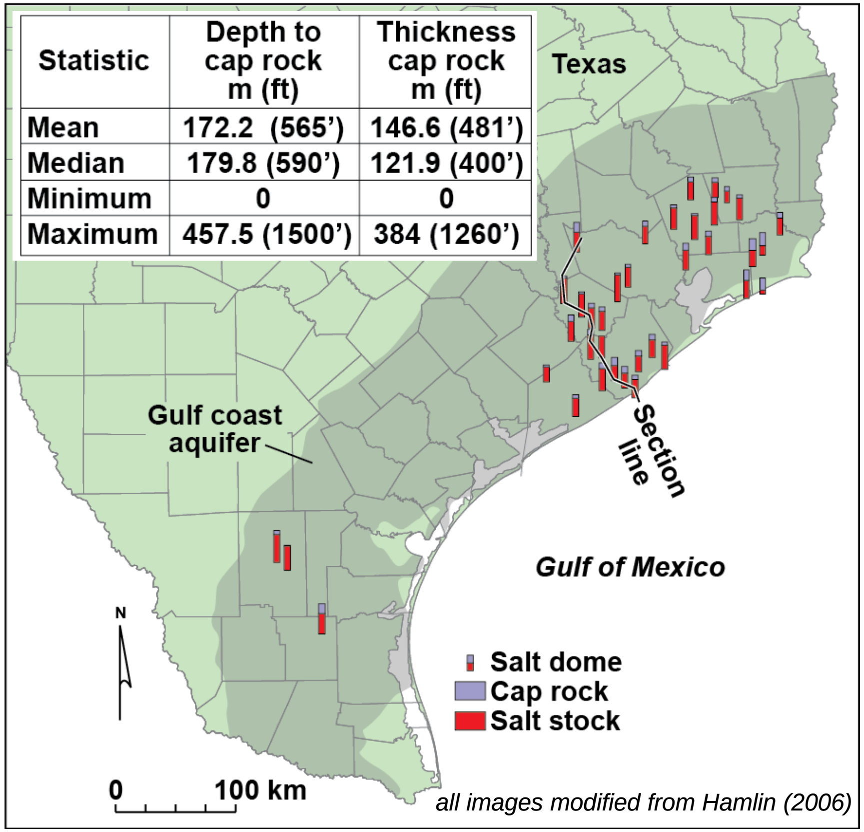
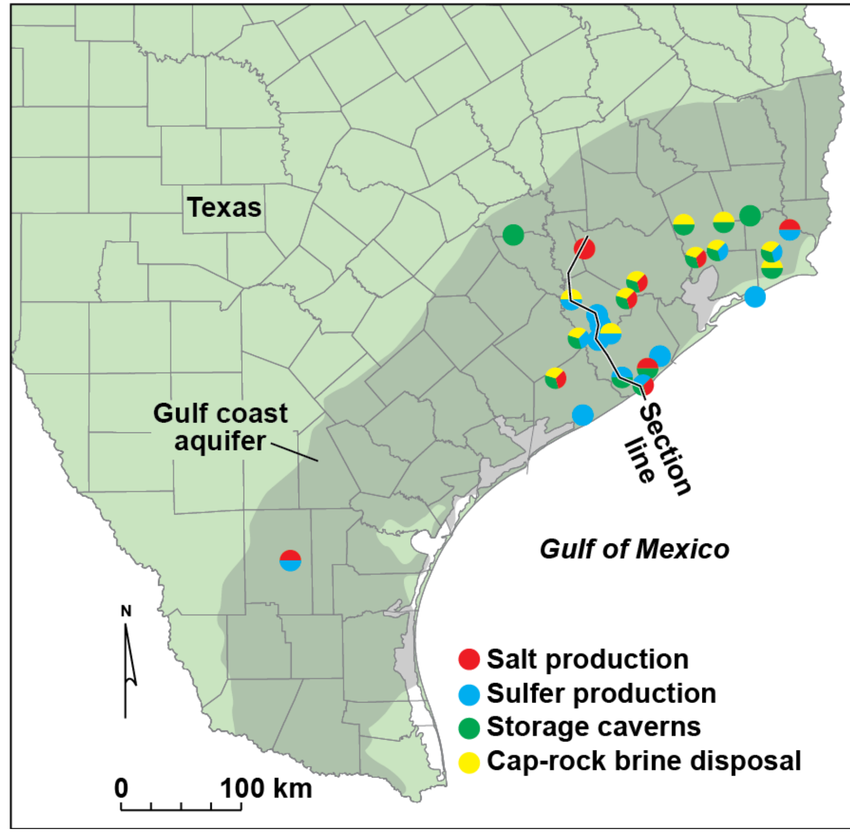
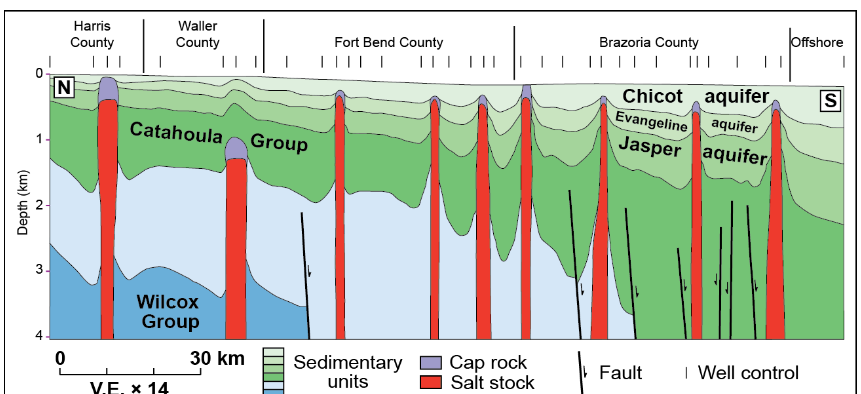
Statistic	Depth to cap rock m (ft)	Thickness cap rock m (ft)
Mean	172.2 (565')	146.6 (481')
Median	179.8 (590')	121.9 (400')
Minimum	0	0
Maximum	457.5 (1500')	384 (1260')

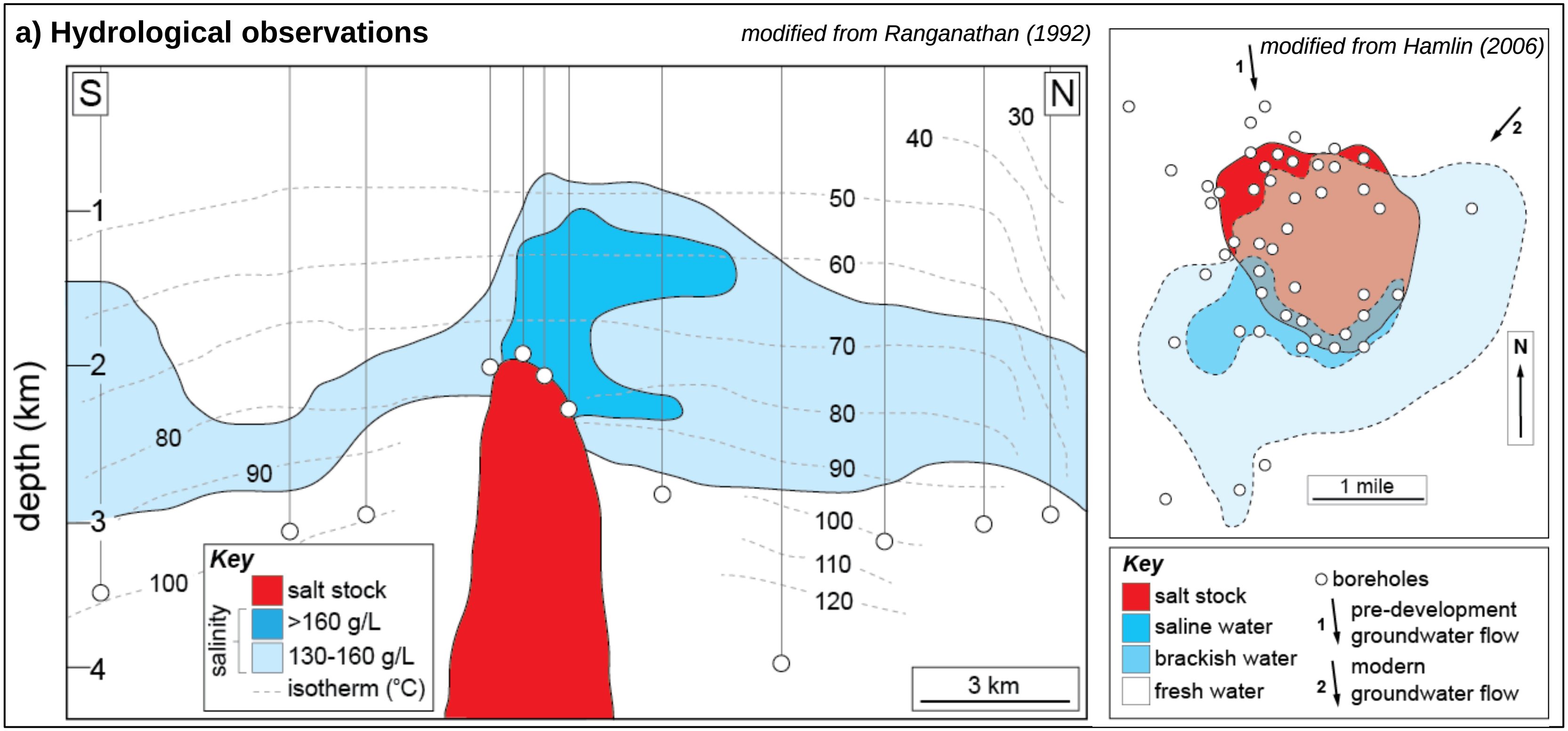


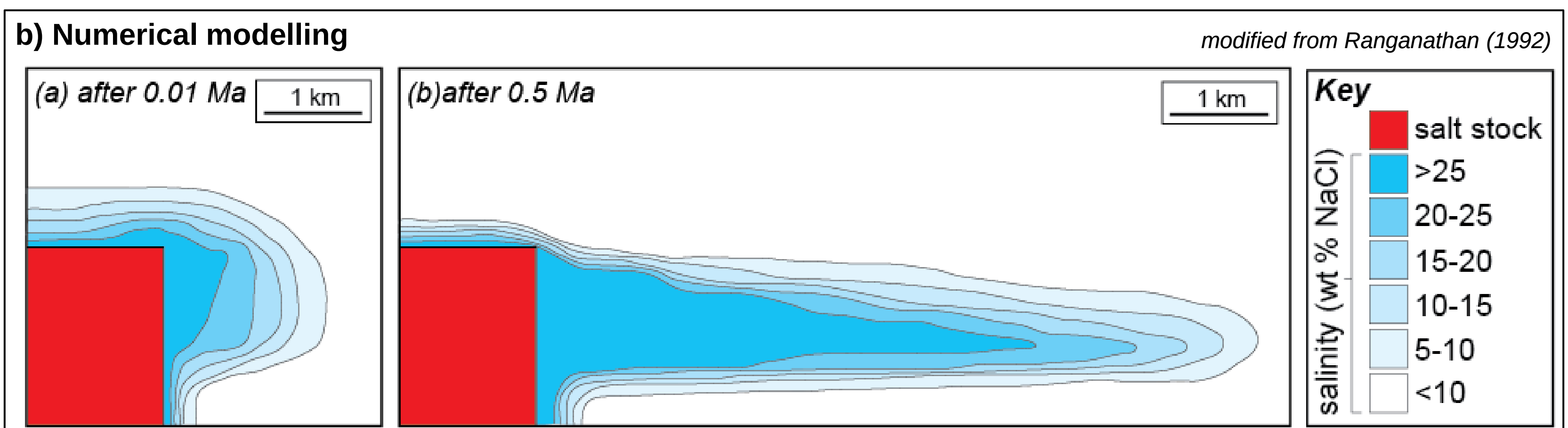




- Caprock common above many Gulf Coast diapirs
- Borehole data provide data on composition and thickness of caprock; lack of evidence for caprock at diapir margins
- Economically important

Dissolution at Salt Diapir Flanks?





Plausibility of Lateral Caprock

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- Salt-sediment interface at diapirs margins typically highly-deformed and highly-permeable
- Abundant geochemical evidence for deep-seated flow of warm, non-meteoric waters at margins of salt structures
- Numerical models suggests dissolution occurs at margins of salt diapirs for a range of salinity and permeability scenarios
- **Are there natural examples of deep-seated (>1 km) lateral caprock adjacent to natural diapirs?**

Study Area

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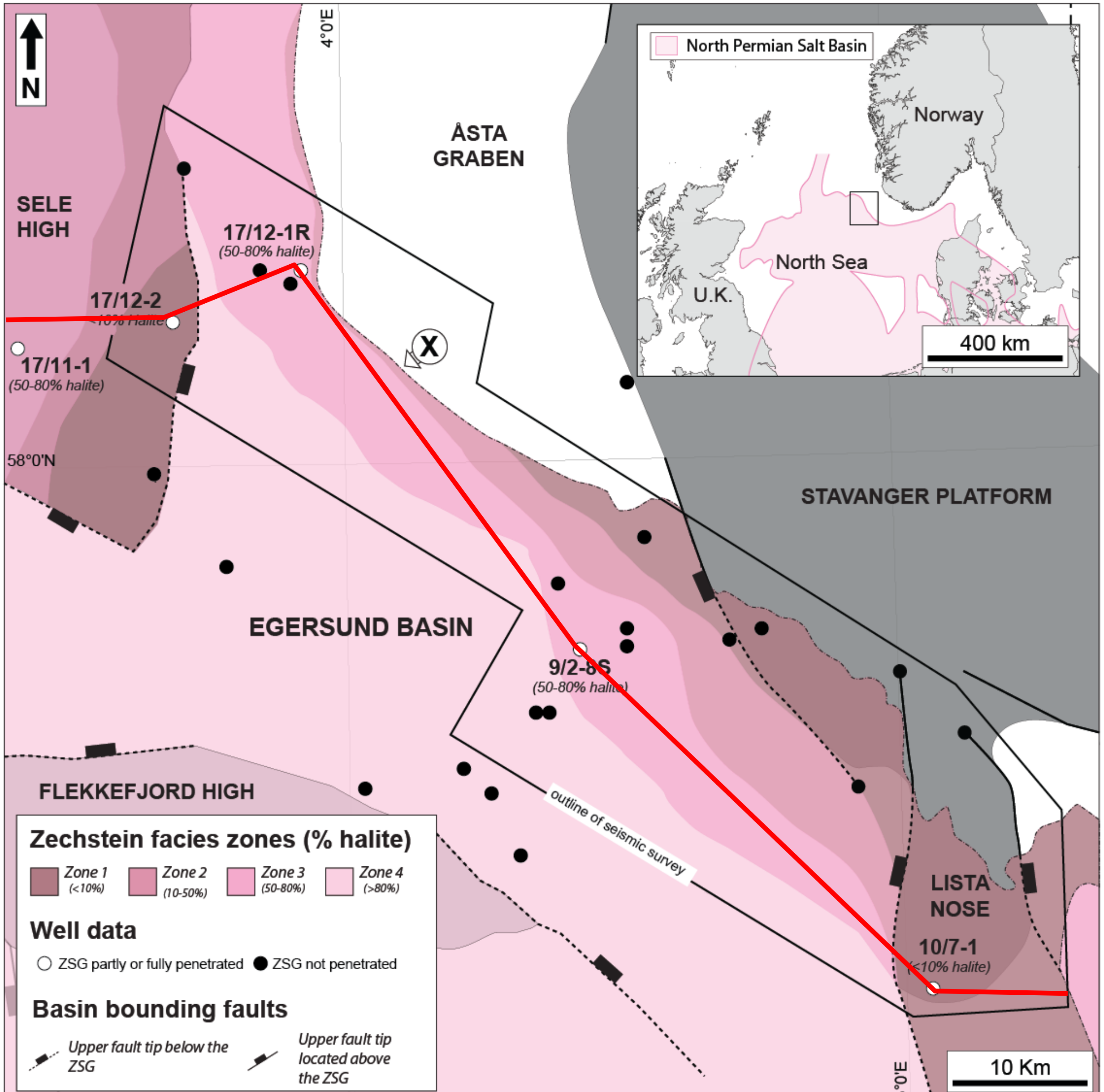

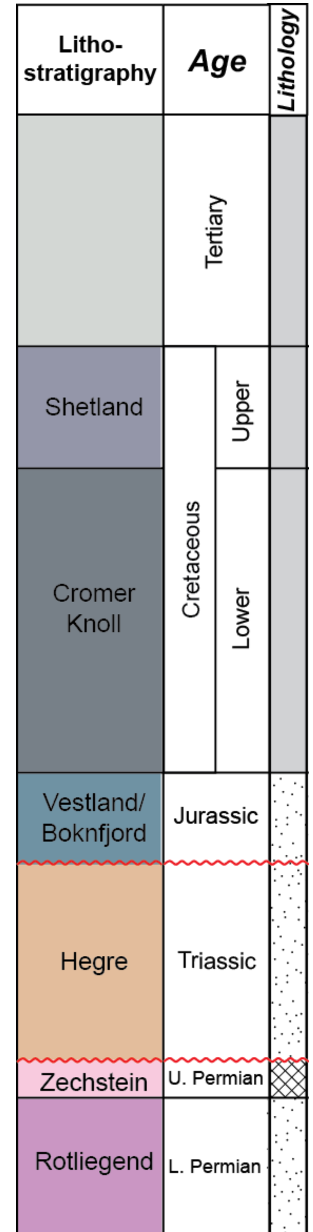

Study Area

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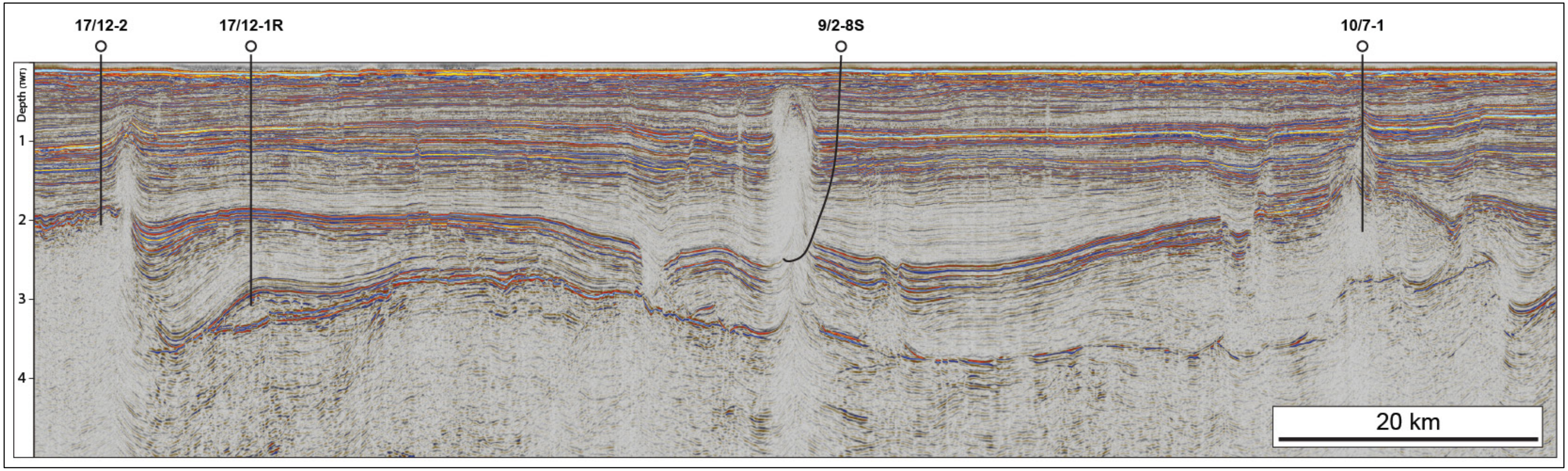
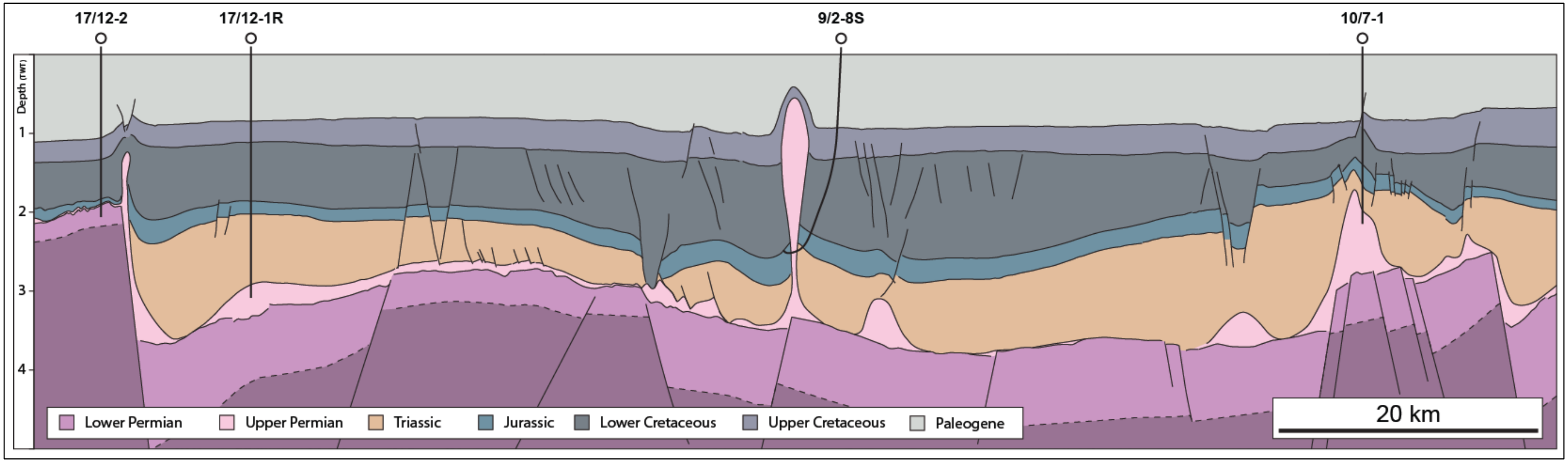
a) Seismic section



b) Geoseismic section



Basin Margin - 17/2-2 and 10/7-1

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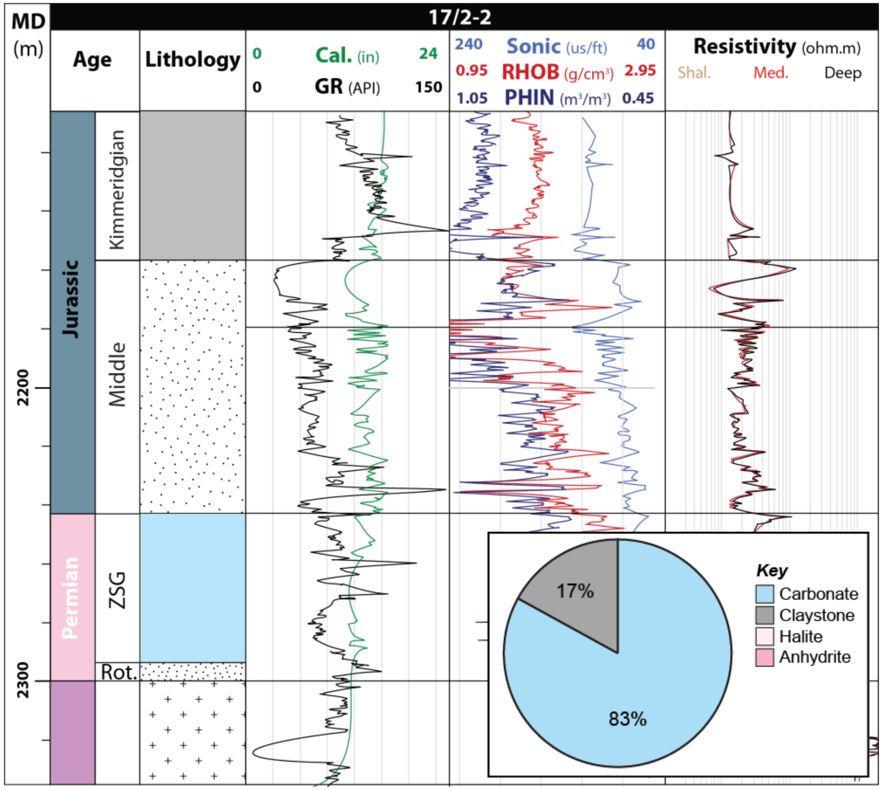

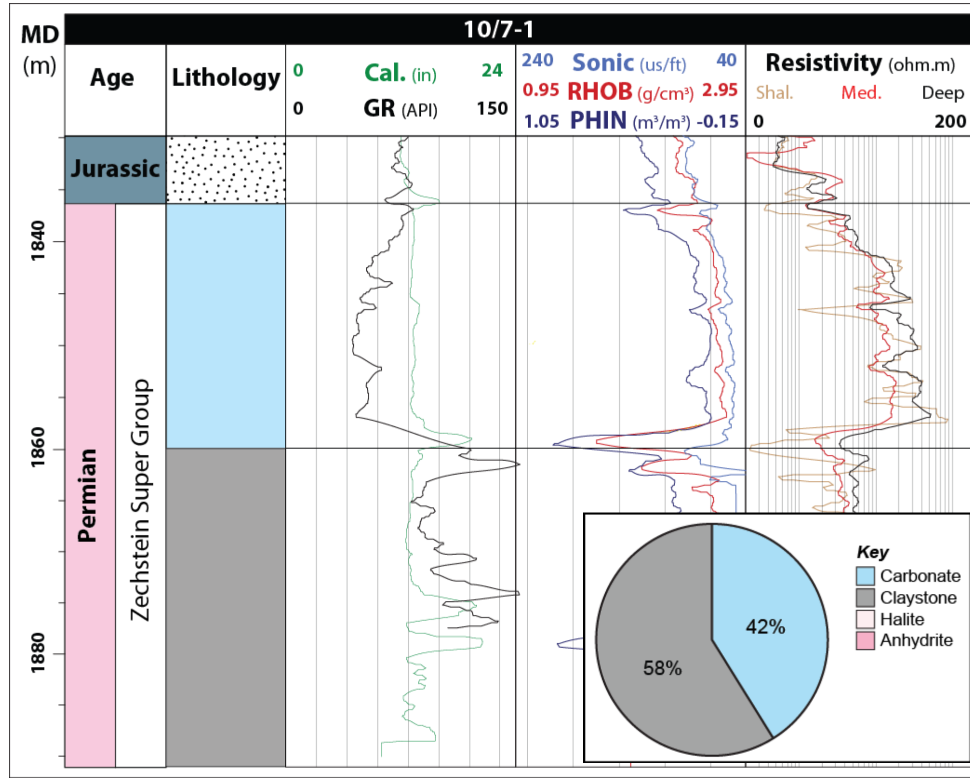

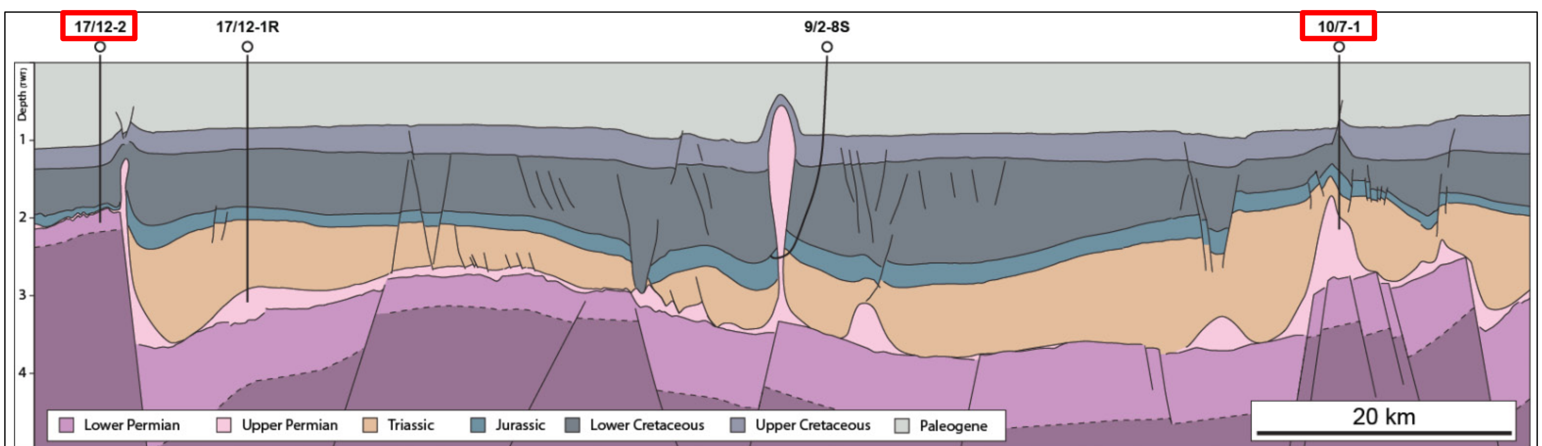

- **17/2-2**- ZSG penetrated; thin and carbonate-dominated
- **10/7-1**-top of salt diapir drilled; ZSG caprock(?) sequence

Basin Centre – 17/12-1R

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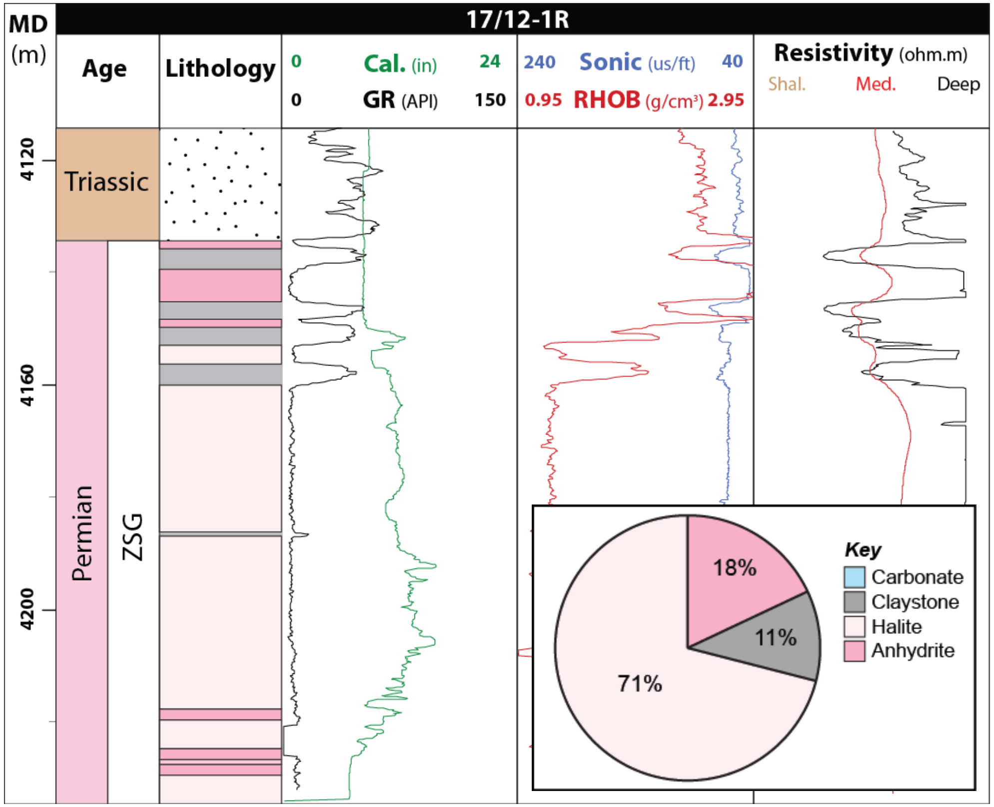
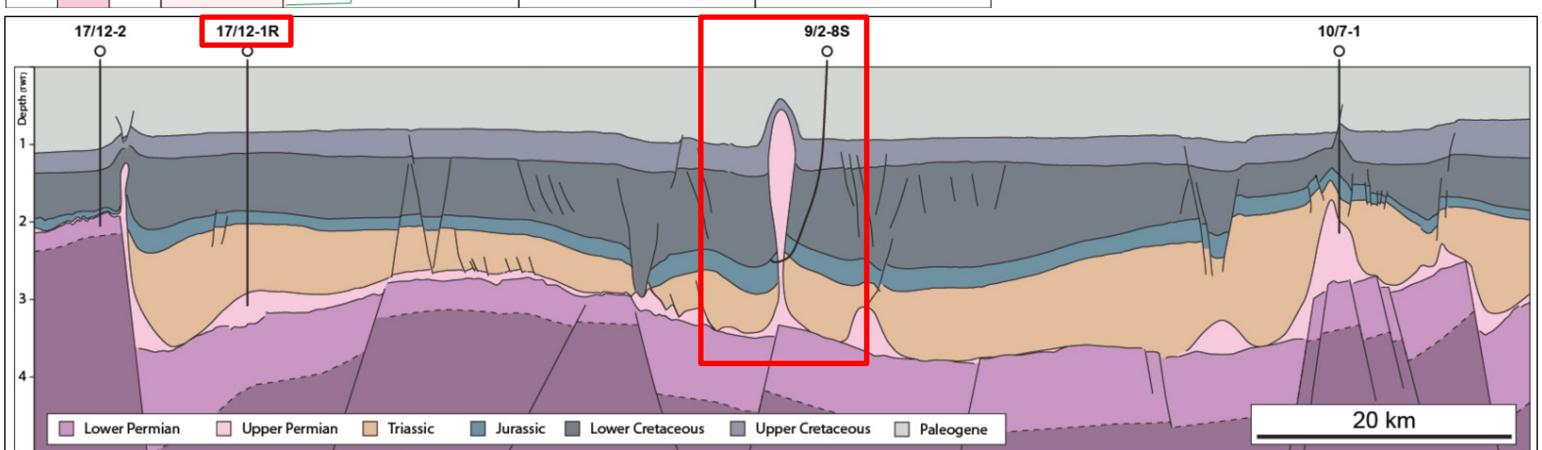


- Upper 40% (83 m) of ZSG penetrated
- Lower 58 m halite-dominated with thin (<5 m) anhydrite and claystone
- Low-relief structure suggests preservation of stratigraphic layering
- Anhydrite and claystone could be primary (depositional) or secondary (diagenetic)



Basin Centre – 9/2-8ST4

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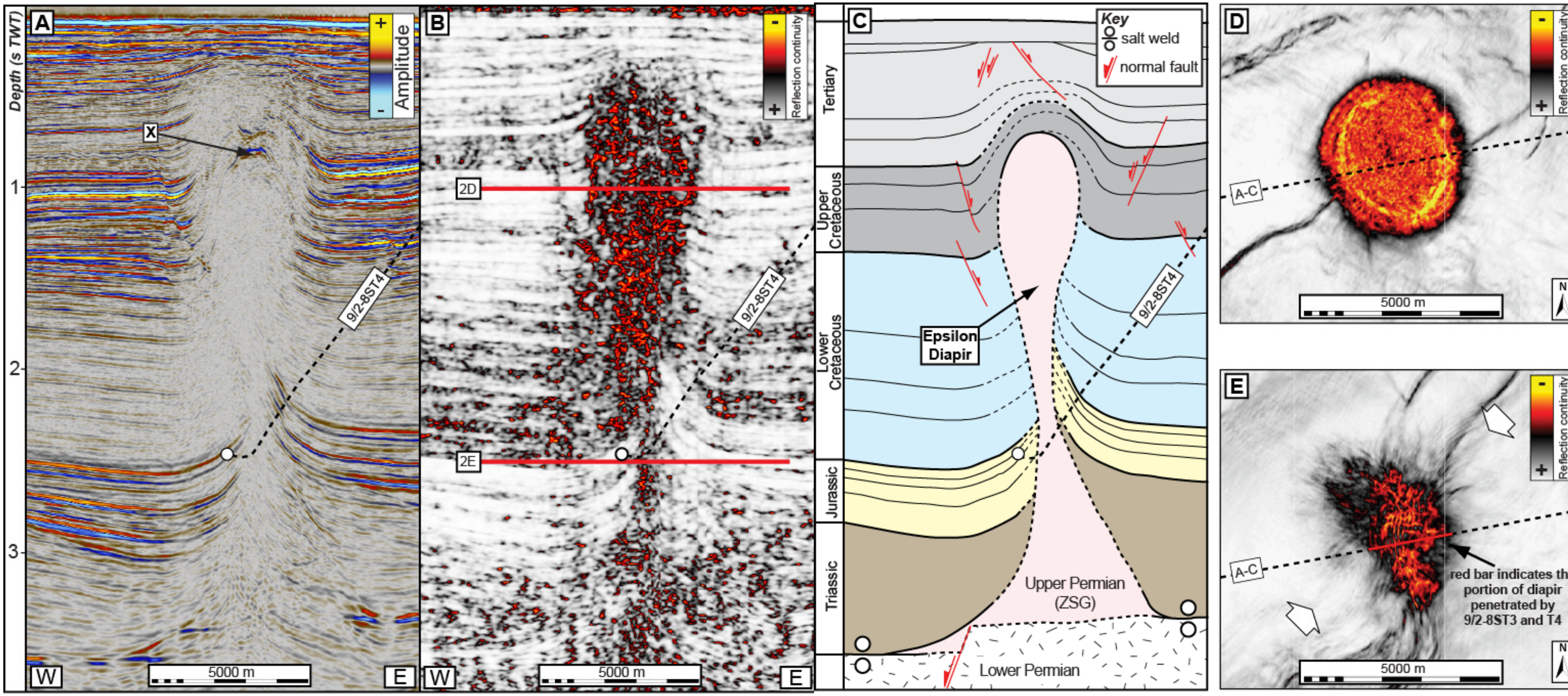

- Exploration well drilled in 1997-1998 to test structural closures either side of a steep-sided diapir
- Shallow marine reservoir (Middle Jurassic) onlapping diapir
- Well stuck (5936 m); sidetracked to 9/2-8ST2 (5680 m); T2 sidetrack stuck (6011 m); T3 sidetrack (5628.5 m) reached TD (7203 m), failed to penetrate reservoir and passed directly from salt (via "faulted zone") into Upper Jurassic shales; T4 sidetrack (6144 m) reached TD (7584 m)
- **Reservoir was dry and tight…**

Basin Centre – 9/2-8ST4

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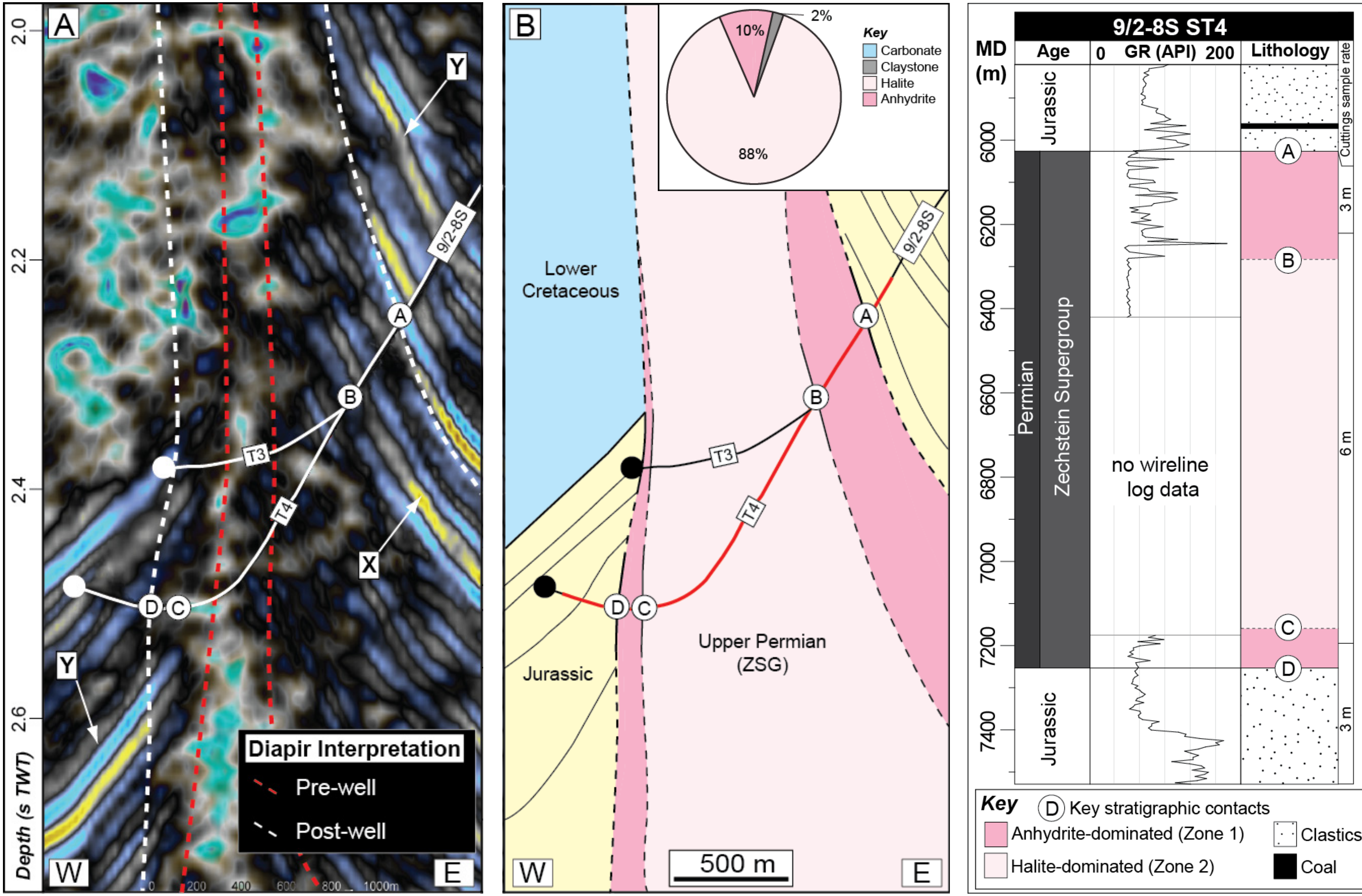

Stratigraphic Architecture

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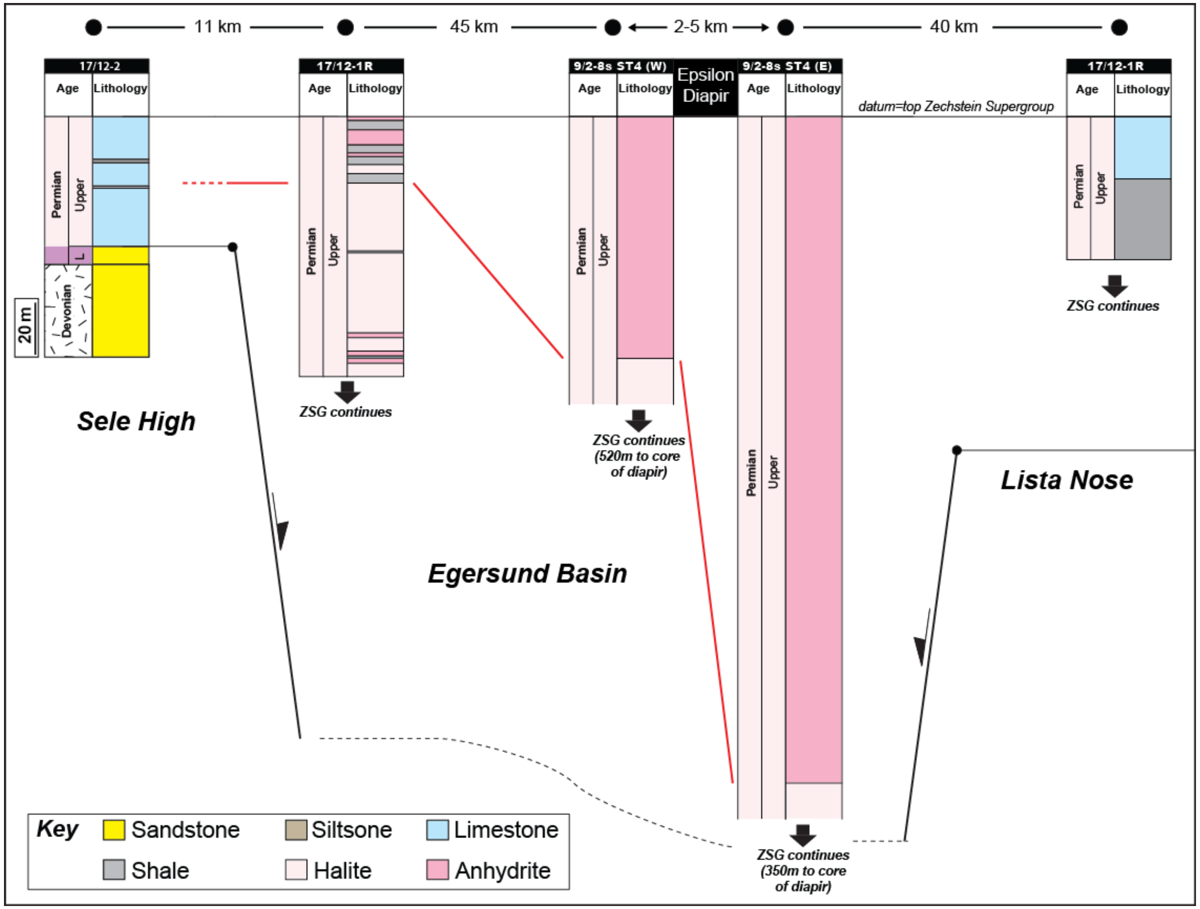
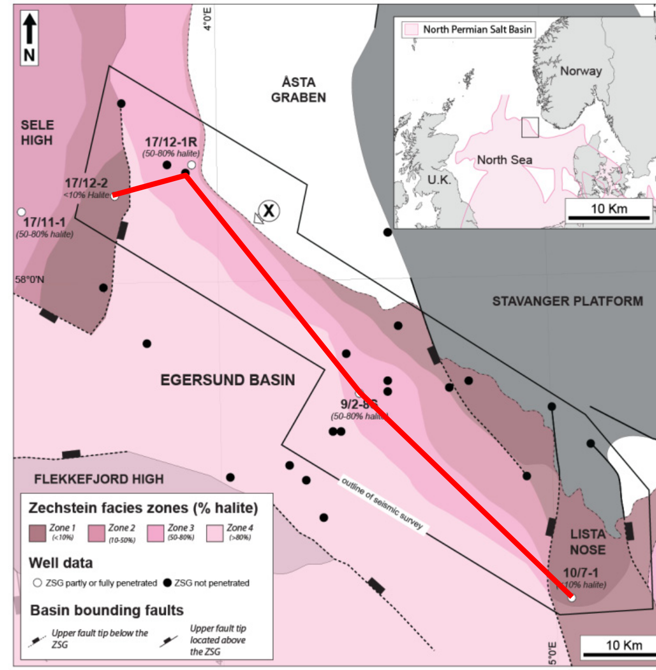
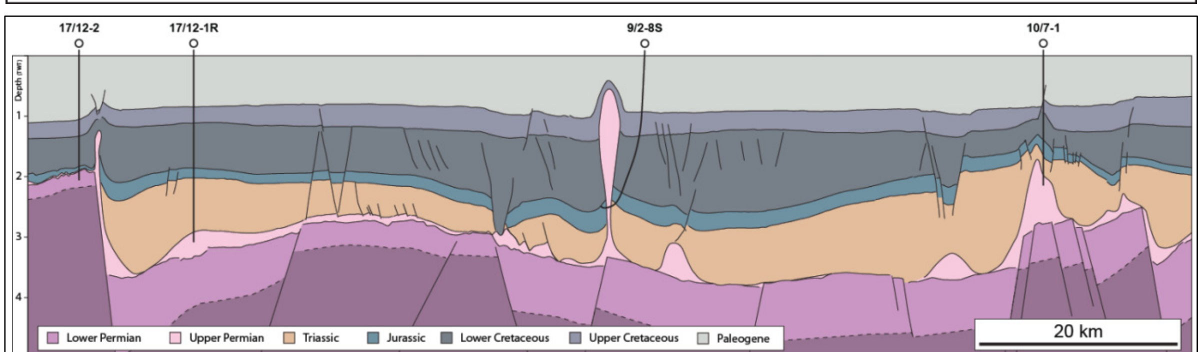
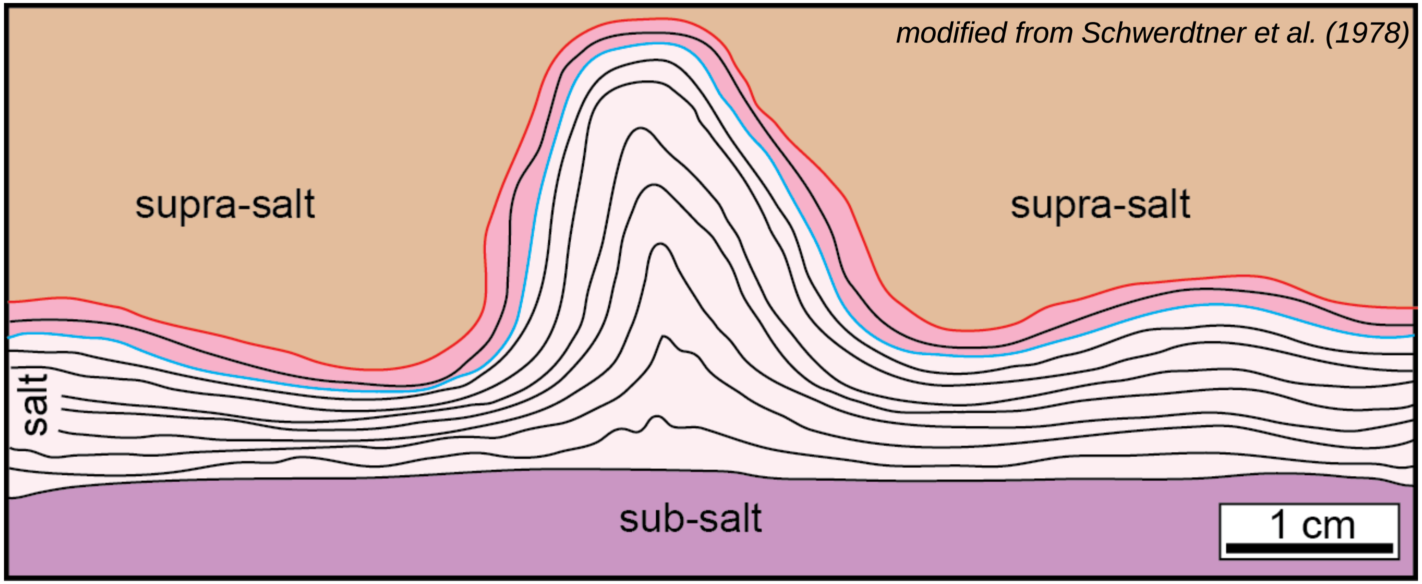


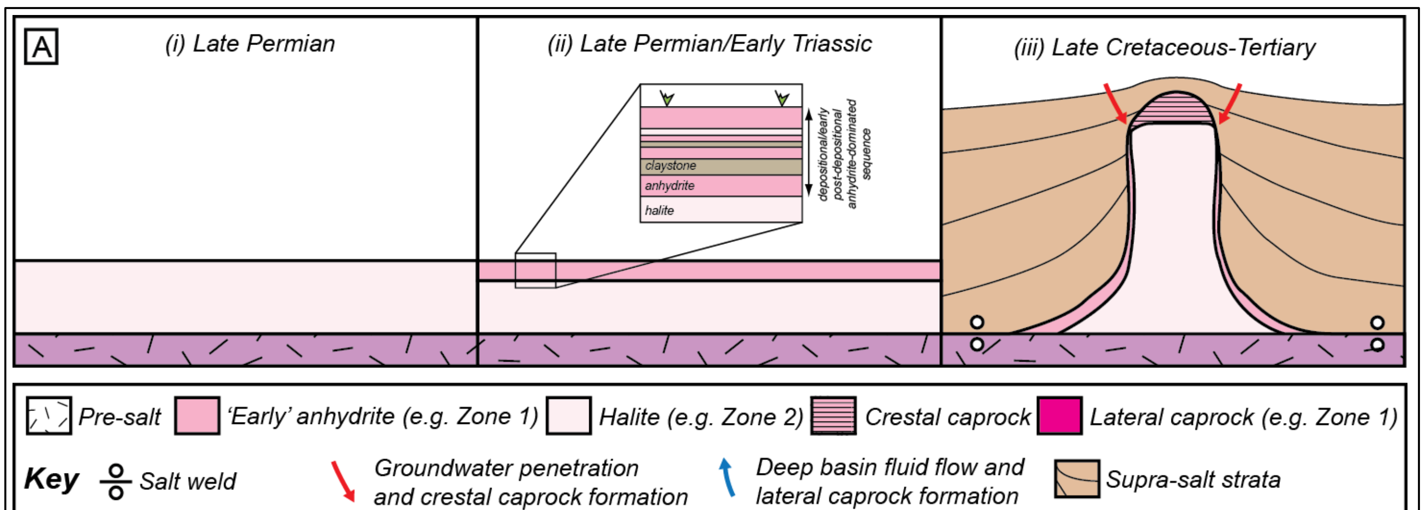




- ZSG changes in thickness and lithology from basin margin (<100 m and carbonate-dominated) to centre (>100 m and halite dominated)
- ZSG locally anhydrite-dominated in basin centre; i.e. upper part of 17/12-1R and outer parts of 9/2-8S
- Upper anhydrite 3-5 times thicker (236 m) in 9/2-8S than in other locations
- **What is the origin of the anhydrite adjacent to the Epsilon diaipir…?**

1) Rotated Stratigraphic Layering





modified from Jackson & Lewis (2012)

- Stratigraphic layering can be preserved in high-relief salt stocks
- Model suggests succession in 9/2-8S represents repeated stratigraphy either side of an upright, antiformal anticline
- Anhydrite thickness changes related to pre-growth variations in syn-salt subsidence or spatial variations in depth of caprock formation during Early Triassic exposure

2) Rotated Crestal Caprock

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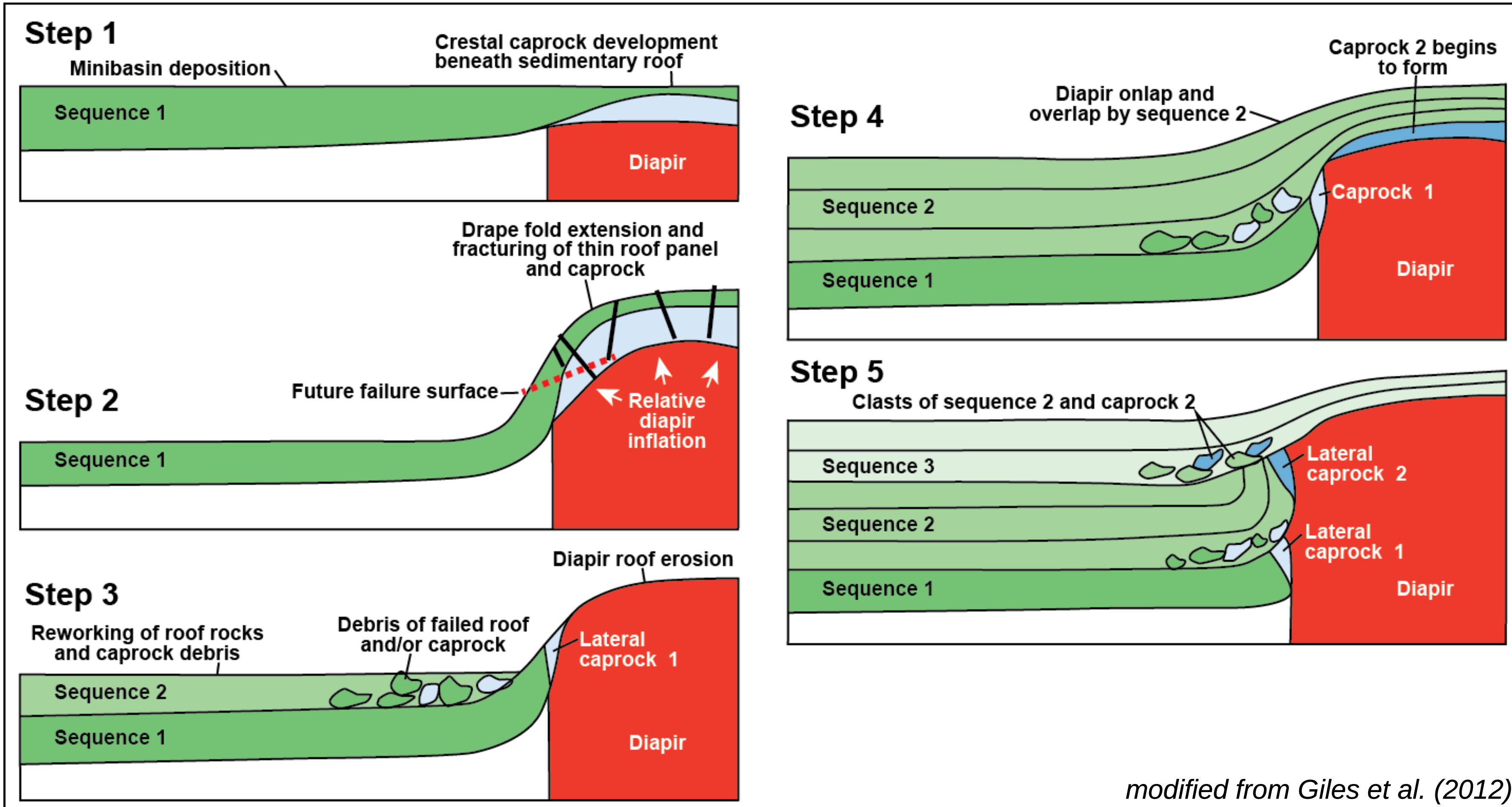

modified from Giles et al. (2012)

- Anhydrite forms as 'crestal' caprock at diapir crest
- Rotation of crestal caprock fringe onto diapir flanks to form lateral caprock
- What is the vertical continuity and thickness of lateral caprock formed in this manner?

3) Diagenetic Lateral Caprock

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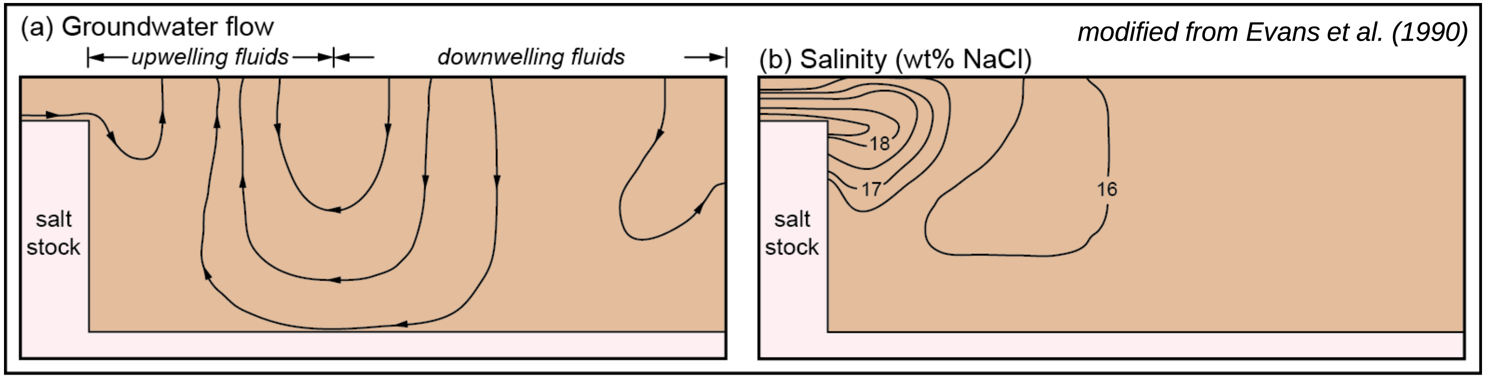

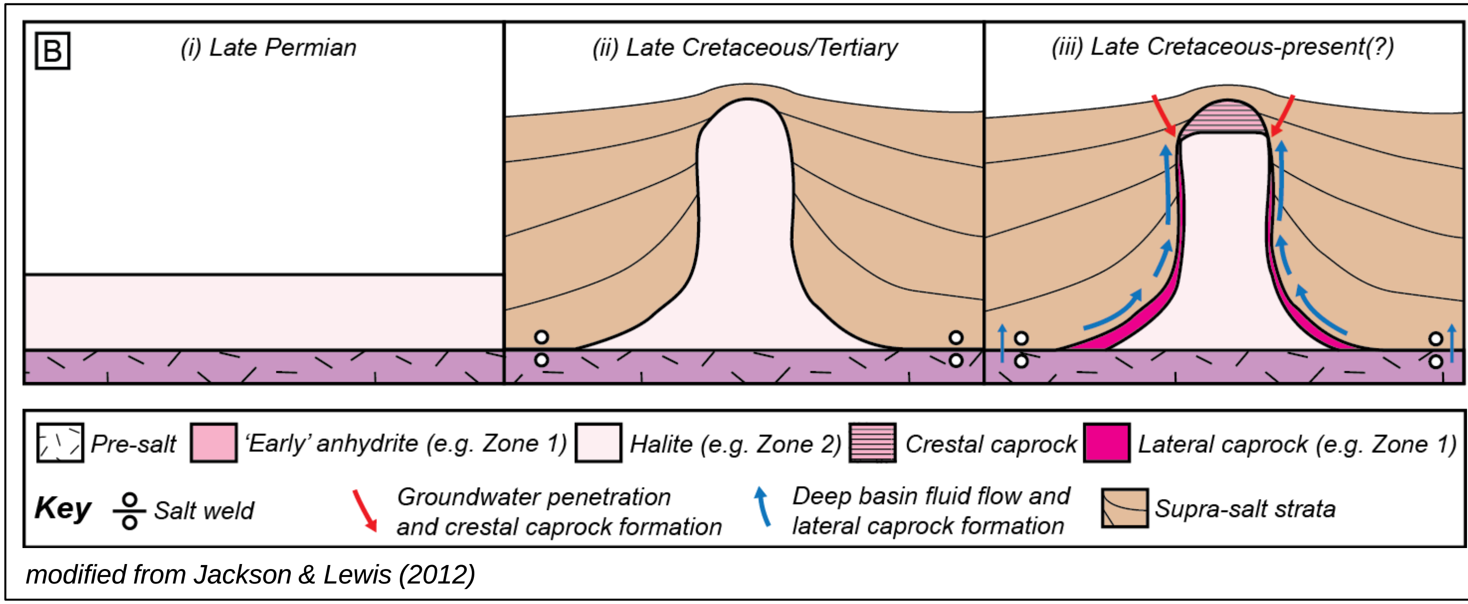

- Lateral caprock forms due to flow of NaCl-undersaturated fluid up diapir flank
- Sheath tapers upwards due to progressive salination of ascending fluids
- Dissolution-related volume loss at diapir flank accommodated by outward (buoyancy) pressure exerted by diapir
- Model consistent with hydrological and geochemical data, and can account for thick and vertically variable lateral caprock

Conclusions

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- Anomalously thick anhydrite deposits are developed adjacent to a km-scale, steep-sided salt stock

- Three potential models for anhydrite formation; (i) rotated stratigraphic layering; (ii) rotated crestal caprock (lateral caprock; *sensu* Giles et al., 2012); and (iii) diagenetic anhydrite (lateral caprock; *sensu* Jackson & Lewis, 2012)

- Available geological data suggest diagenetic anhydrite may be the most plausible model

- Additional data required to construct testable criteria for recognising and determining origin of deeply-buried lateral caprock