A seismic reflection image showing geological layers. The image features a prominent, wavy, and somewhat chaotic structure in the center, likely representing a salt body with stringers. The layers are color-coded, with blue and red lines highlighting specific features. The overall appearance is that of a complex subsurface geological structure.

› **STRINGERS IN ZECHSTEIN SALT AS A DRILLING RISK**

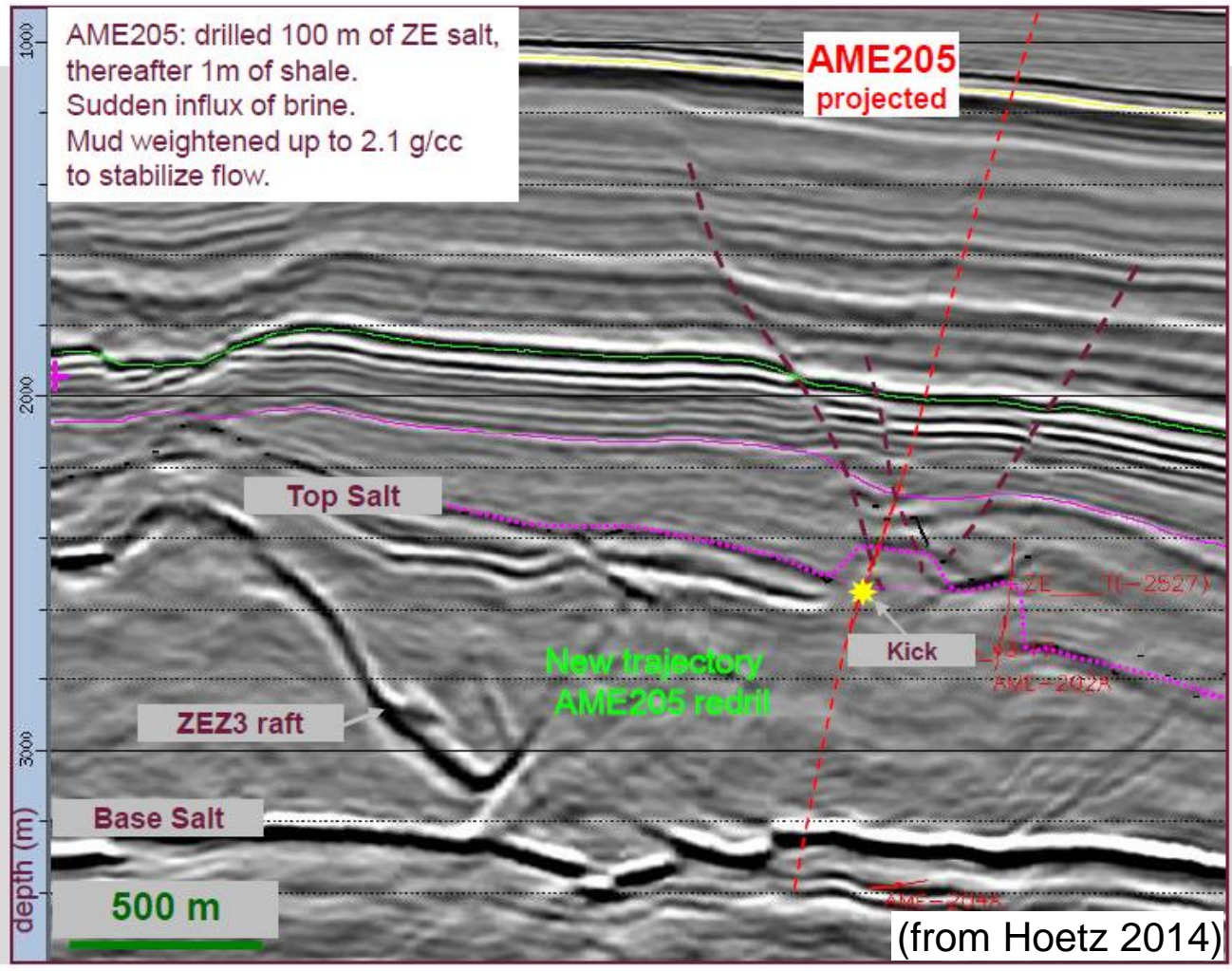
Jan ter Heege, Mart Zijp, Maarten Huijgen, Renaud Bouroullec, Martin Wilpshaar

TNO innovation
for life

Analysis of drilling events in **921** from a total of **2575** wells that have been drilled through the Zechstein formation in the Netherlands shows that:

- › Drilling events (mainly kicks & losses due to overpressures) have been reported in **62** of the **921** wells with pore pressures up to lithostatic pressure encountered
- › Well trajectories should attempt to avoid **anhydrite and carbonate stringers** that are embedded in salt, *in particular* (1) **folded or tilted stringers**, (2) areas where **stringers align with top Zechstein**, (3) stringers in areas where the **base Zechstein is faulted**, and (4) areas below the **flanks of folded top Zechstein**
- › Stringer-related drilling risks can be reduced by applying **improved seismic imaging techniques** to the identification, imaging and mapping of stringers and surrounding salt boundaries (focus on preventive measures)

MOTIVATION & RESEARCH QUESTIONS



- › Elevated drilling risks Zechstein wells due to the presence of stringers with overpressures
- › Interrelated effects on drilling safety & costs
- › Main questions are frequency of occurrence & mitigation measures

Incident led to loss of well & additional costs of 30 mil euro

› Data sources & availability:

- Analysis of 62 wells with drilling events, selected from 921 wells identified in 3 previous projects (Kortekaas 2012; Verweij 2014; Hoetz 2013, 2017)
- Literature review
- Expert meeting organized for this project (February 6th, 2018)

› Geological setting & seismic imaging:

- Brief description of Zechstein lithology, depositional environment, stratigraphy
- Distribution & structures of Zechstein stringers

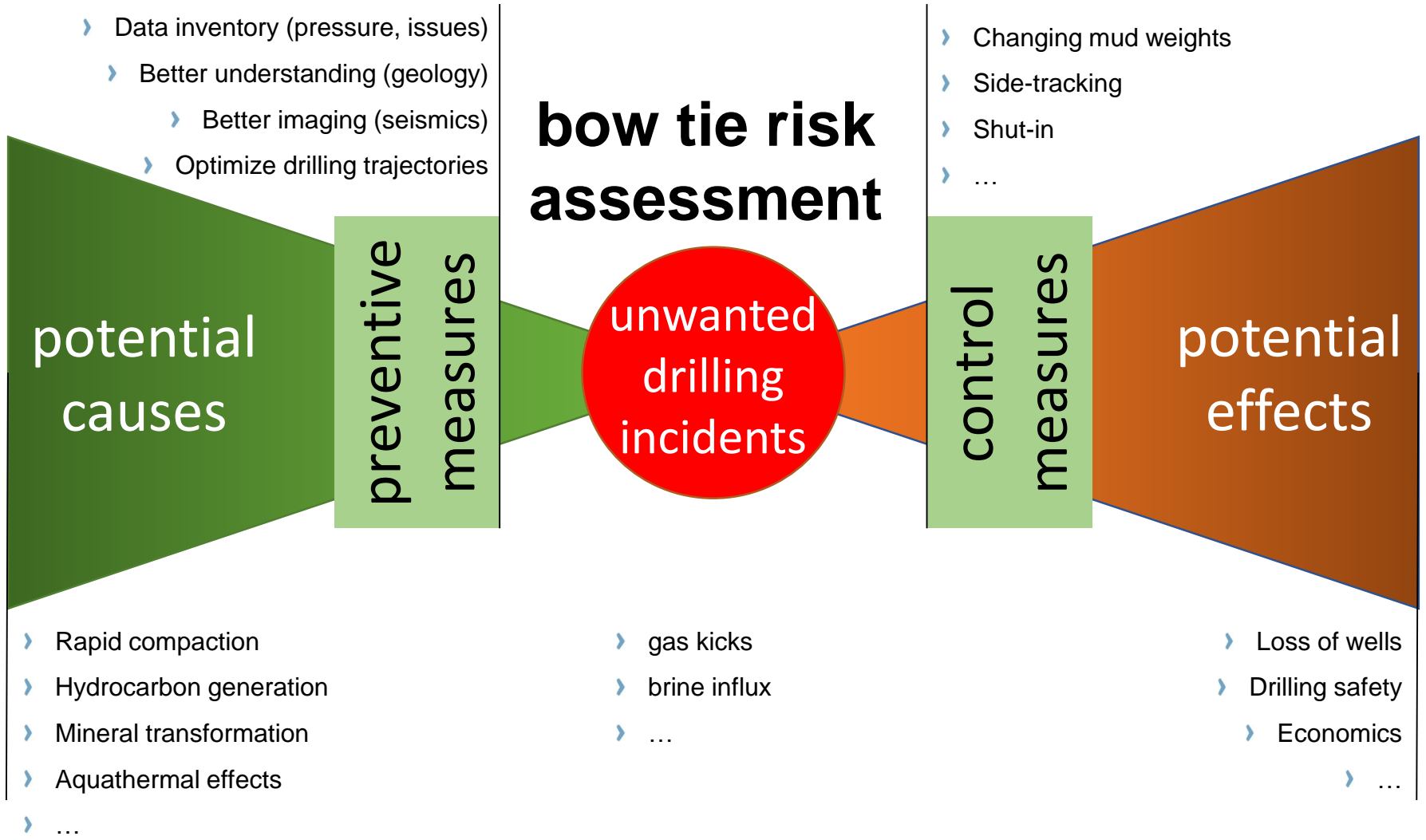
› Theory & controlling mechanisms:

- Mechanisms controlling stringer movement, stress state, overpressures
- Relations stringer deformation, overpressures, pore fluids & drilling risks

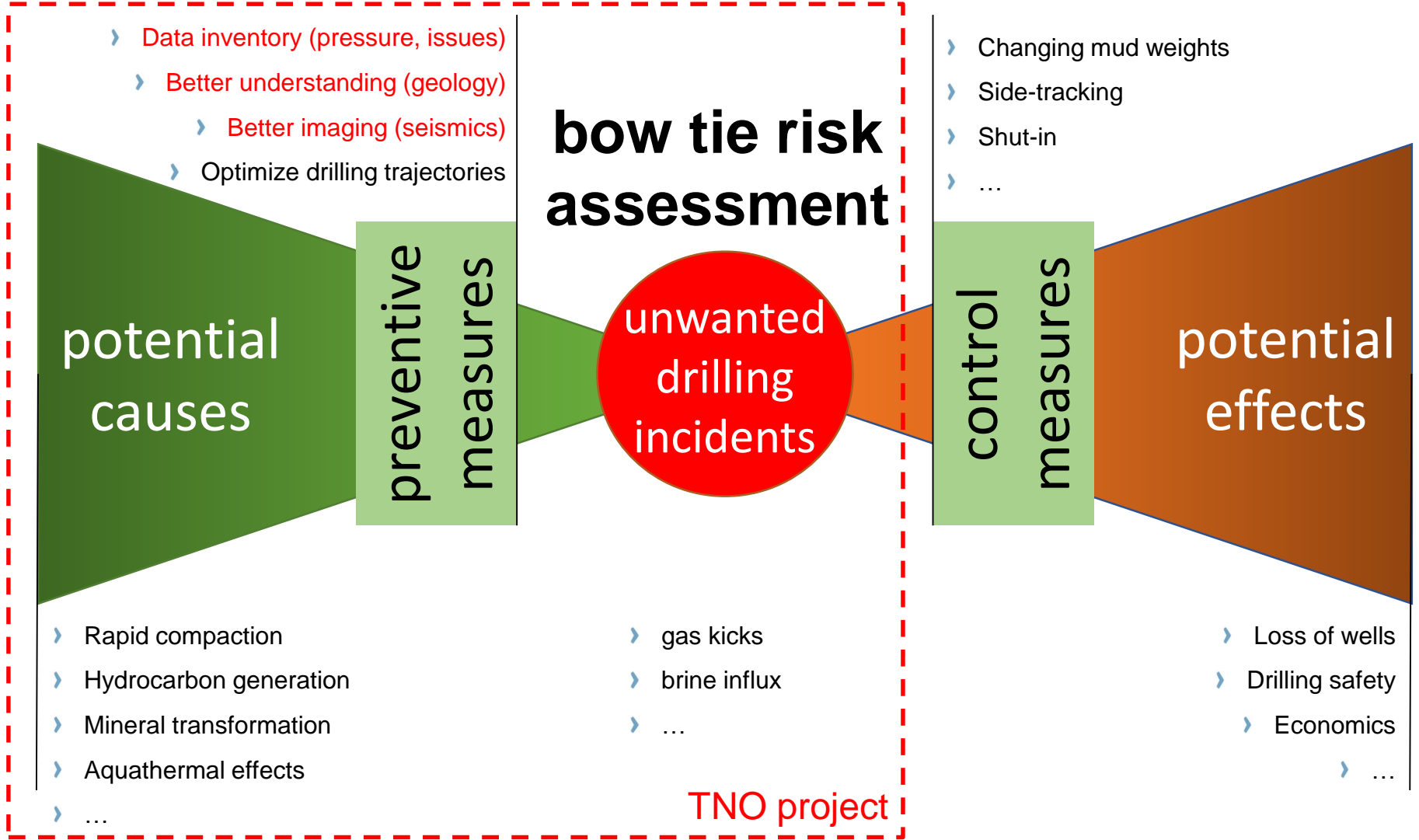
› Constraints & trends for stringer overpressures

› Risk assessment & mitigation measures

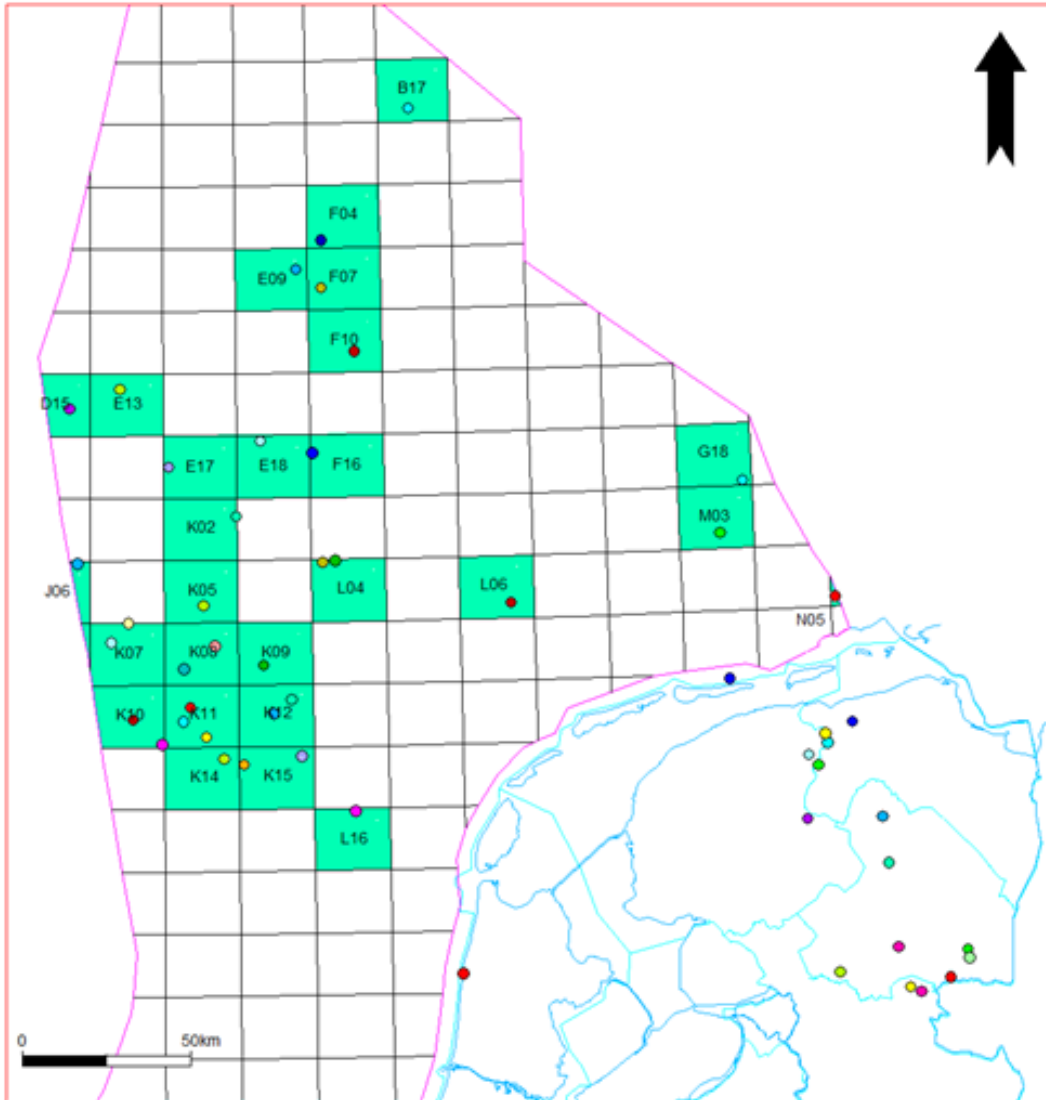
CONCEPTS & FOCUS OF CURRENT ANALYSIS OF STRINGER-RELATED DRILLING HAZARDS



CONCEPTS & FOCUS OF CURRENT ANALYSIS OF STRINGER-RELATED DRILLING HAZARDS



DATA: STATISTICS OF WELLS, DRILLING EVENTS & OVERPRESSURES IN ANALYSIS



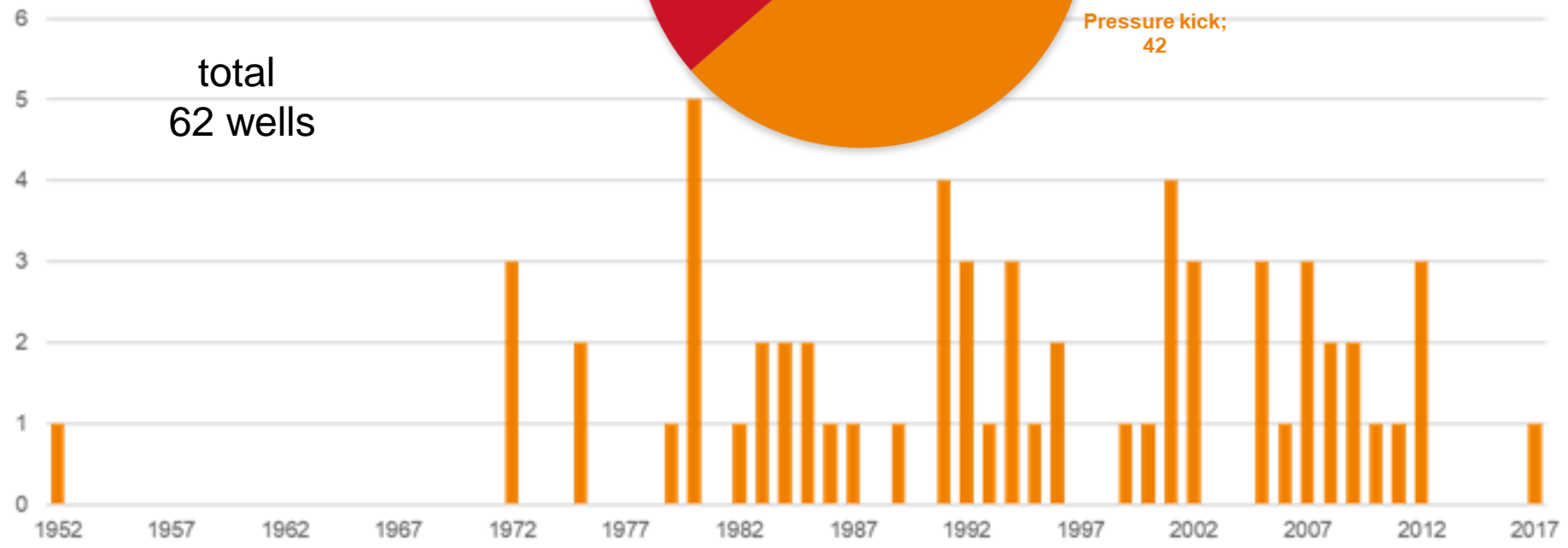
Current analysis:

- › 2575 Zechstein wells
- › 921 wells analysed
- › 84 drilling events (detailed info for 66 events)
- › 81 pressure anomalies
- › 62 wells with drilling events
- › 32 formation pressures analysed
- › 18 pressure kicks from stringers (confirmed using seismics)
- › 1 event encountered H₂S

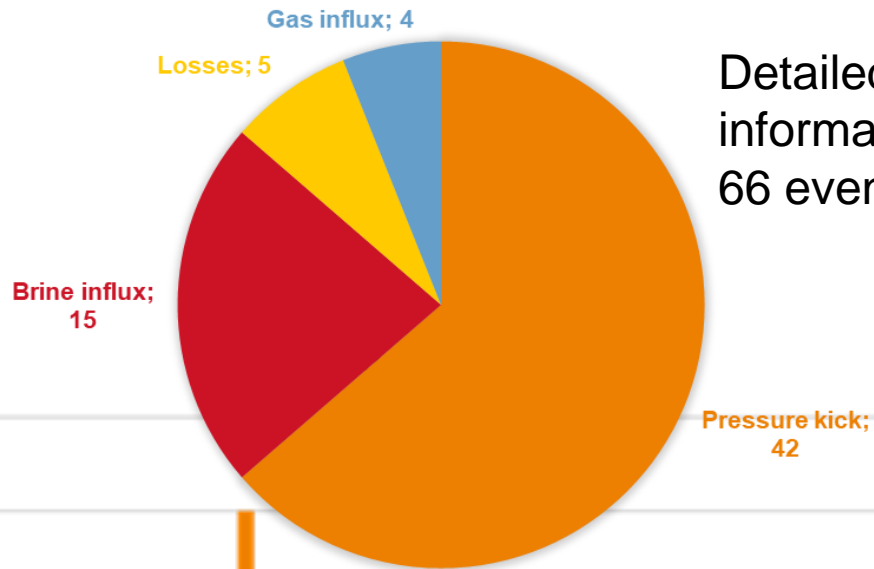
DATA: TIMING OF ZECHSTEIN WELLS WITH DRILLING EVENTS & TYPE OF EVENTS

Zechstein wells with drilling events

total
62 wells

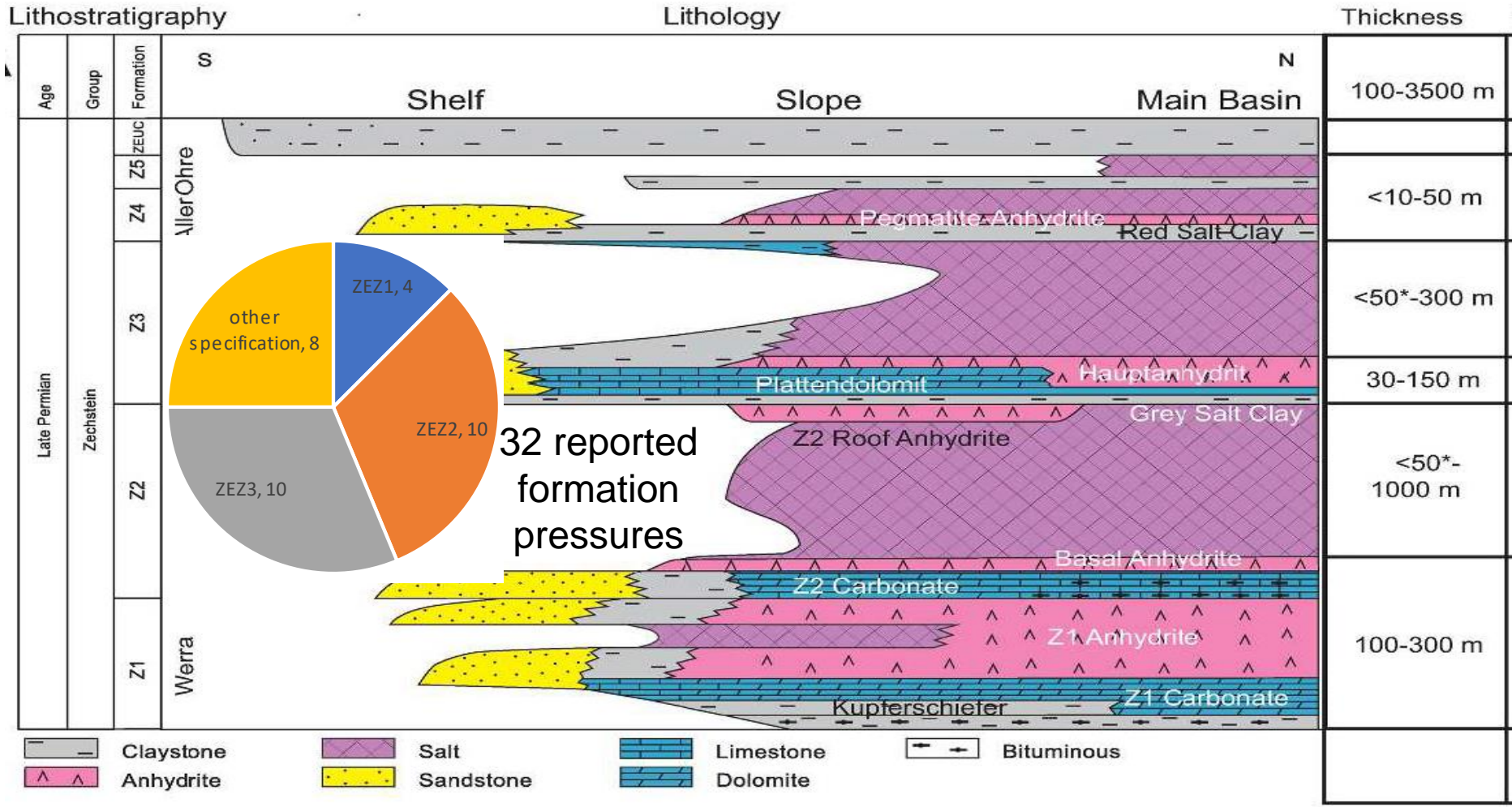


Drilling event type



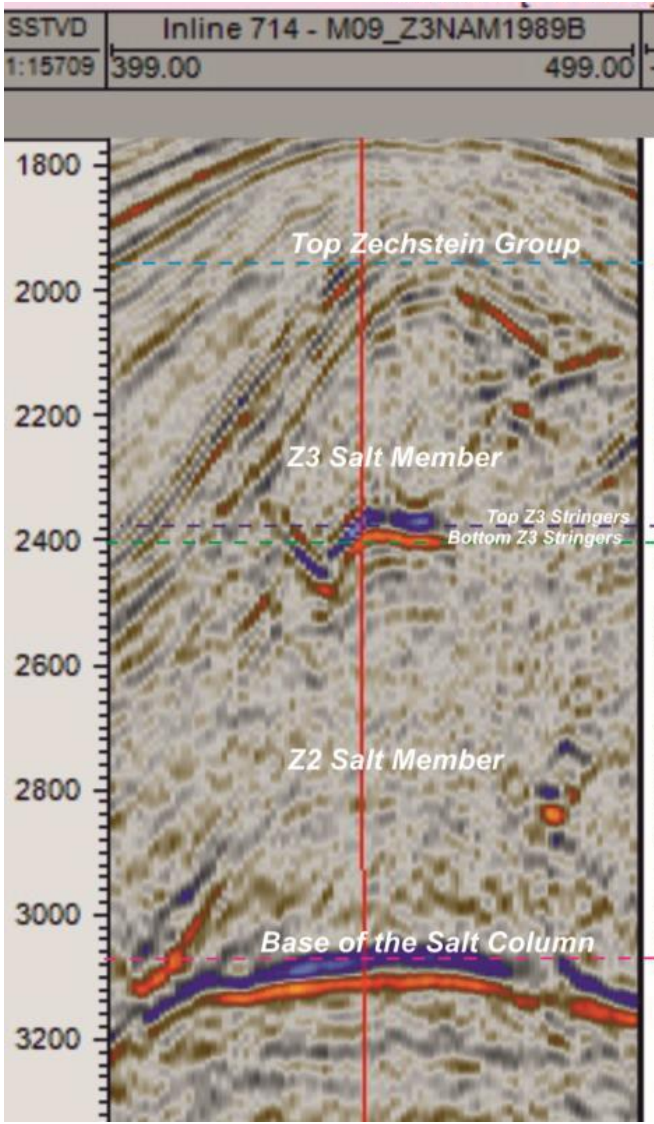
Detailed information on 66 events

GEOLOGY: RELATION OVERPRESSURES TO (ZEZ1-ZEZ3) ZECHSTEIN LITHOLOGIES

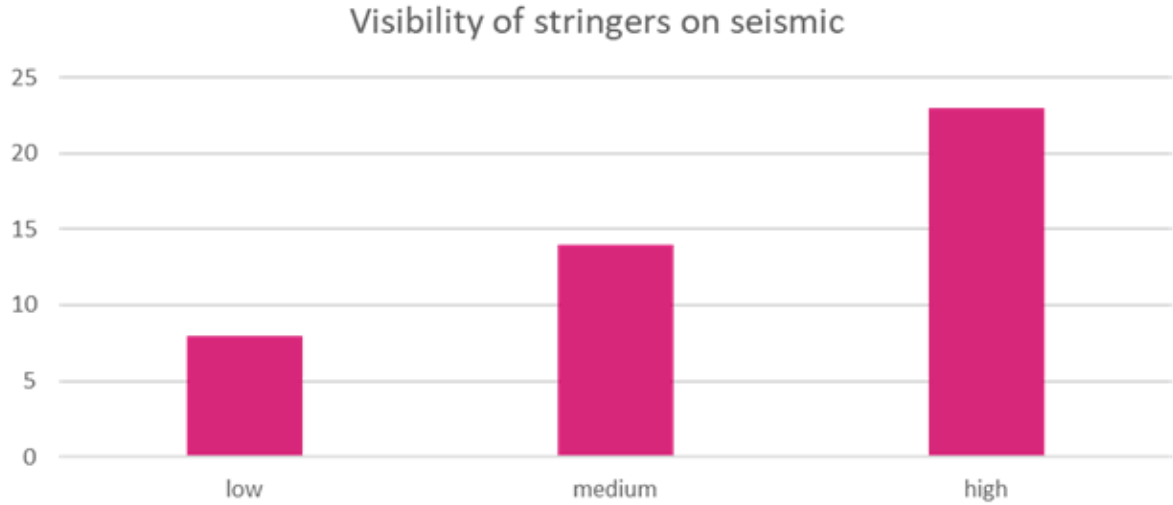


(from Geluk, 2007)

SEISMICS: VISIBILITY STRINGERS ON SEISMIC SECTIONS

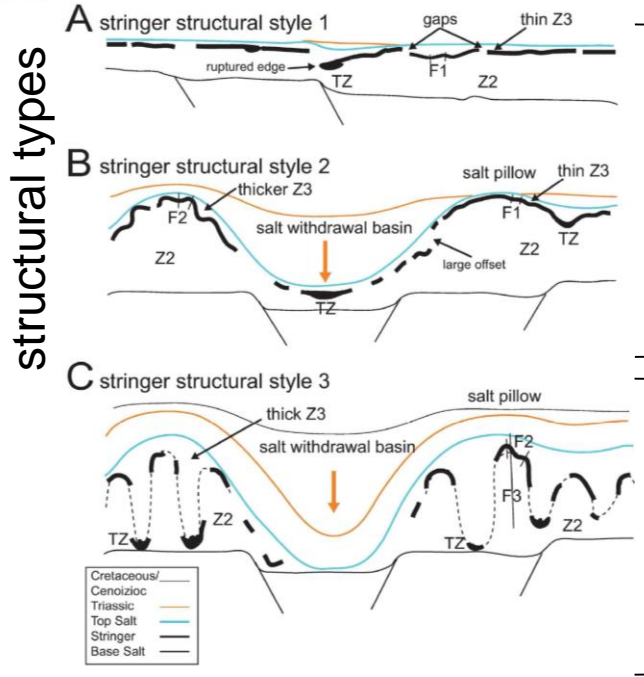
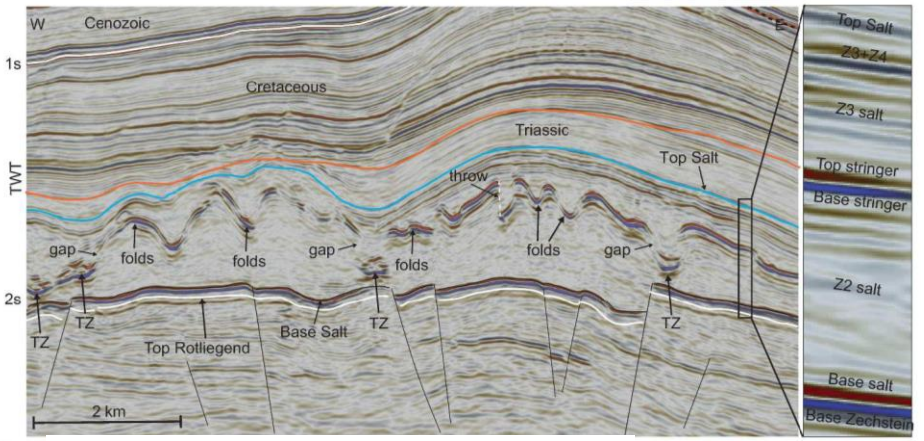
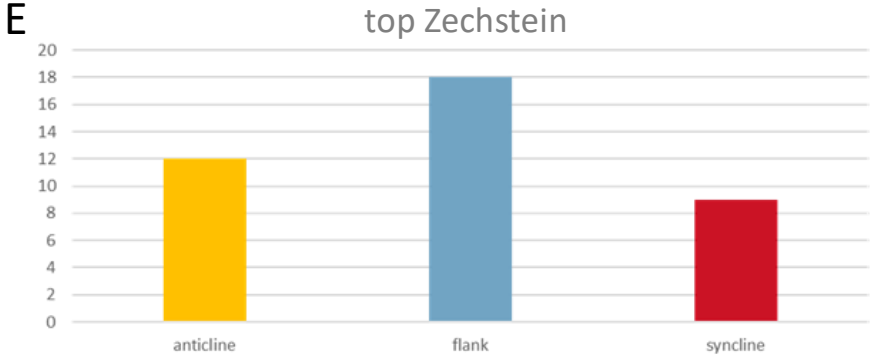
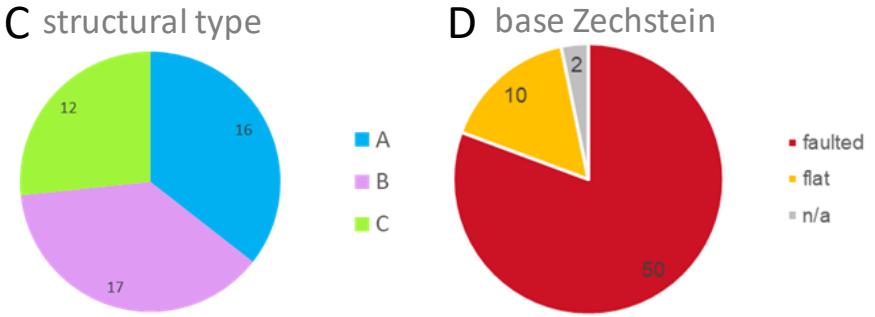
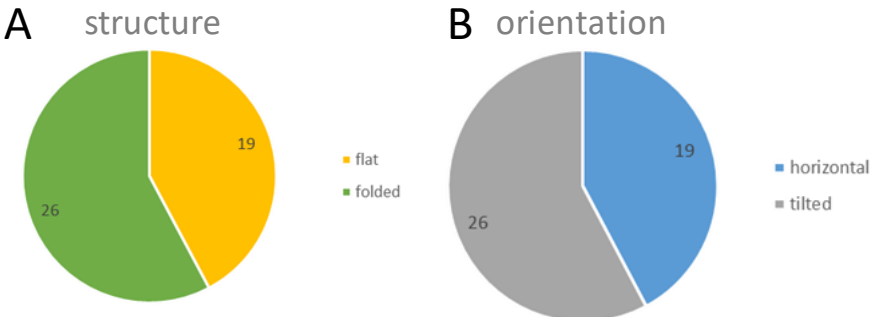


- › Stringer visible in 54 out of 62 wells with drilling events
- › Depth of drilling event correlates with depth stringer in 45 out of 62 wells
- › Stringers associated with drilling events are usually visible on seismics (3 visibility classes low-high)



GEOLOGY: RELATION OVERPRESSURES TO ZECHSTEIN & STRINGER STRUCTURE

number of stringer-related drilling events



A & B:
stringers align with top salt

C: stringer structures **do not** align with top salt

GEOLOGY: RELATION OVERPRESSURES TO ZECHSTEIN & STRINGER STRUCTURE

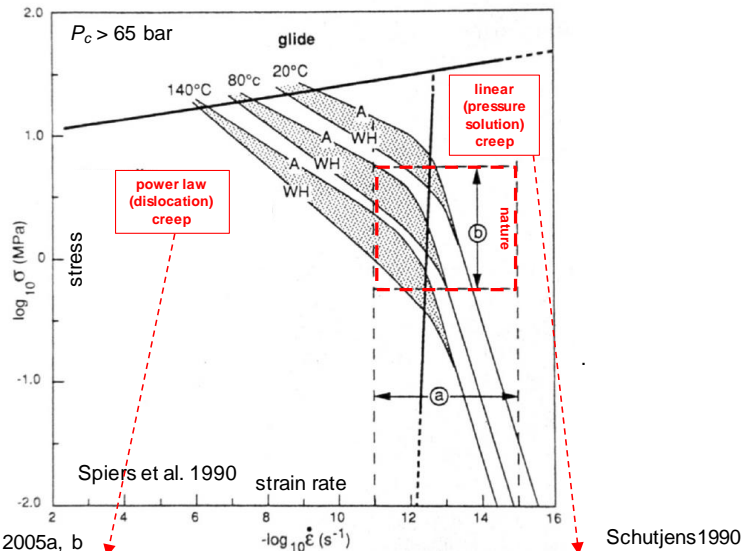
number of stringer-related drilling events



Key points:

- › A relation between number of events and structures *alone* is not a good indicator for likelihood of events (e.g., more wells may be drilled in areas with faulted base Zechstein)
- › A screening of (all) wells for stringer occurrence is required for statistics on relations between structures and events
- › Most events associated with (1) folded and tilted stringers, (2) areas where stringers align with top Zechstein, (3) areas a with faulted base Zechstein, (4) areas below the flanks of folded top Zechstein

MECHANISMS CONTROLLING STRINGER MOVEMENT, DEFORMATION & STRESS STATE



Deformation mechanisms in rocksalt:

- › Control the movement of salt and stringers within salt bodies
- › Control the deformation and stress state of stringers by a complex interplay between time-dependent creep mechanisms and microstructural processes (dynamic recrystallization)
- › Can be used to model the stress state in salt and stringers (e.g., finite element models), and thereby the pore pressure evolution (compaction, fracturing, folding)

starting material

2 mm

intragranular substructure (subgrains)

100 μm

fluid-assisted grain boundary migration

grains

glide planes

subgrain walls

$$\dot{\epsilon} = A \sigma^n \exp\left(\frac{-Q_r}{RT}\right)$$

$\dot{\epsilon}$ - strain rate
 A - constant
 n - stress exponent
 Q_r - activation energy
 R - gas constant
 T - temperature
 n = 5.6 ± 0.5
 $Q_r = 80 \pm 6$ kJ/mol
 log A = -1.56 ± 0.54

grains

dissolution

precipitation

D

dissolution

$$\dot{\epsilon} = A \frac{DCS}{RT} \frac{\sigma}{d^3}$$

$\dot{\epsilon}$ - strain rate
 A - constant
 D - diffusivity
 C - solubility
 S - boundary thickness
 R - gas constant
 T - temperature
 σ - stress
 d - grain size

starting material

500 μm

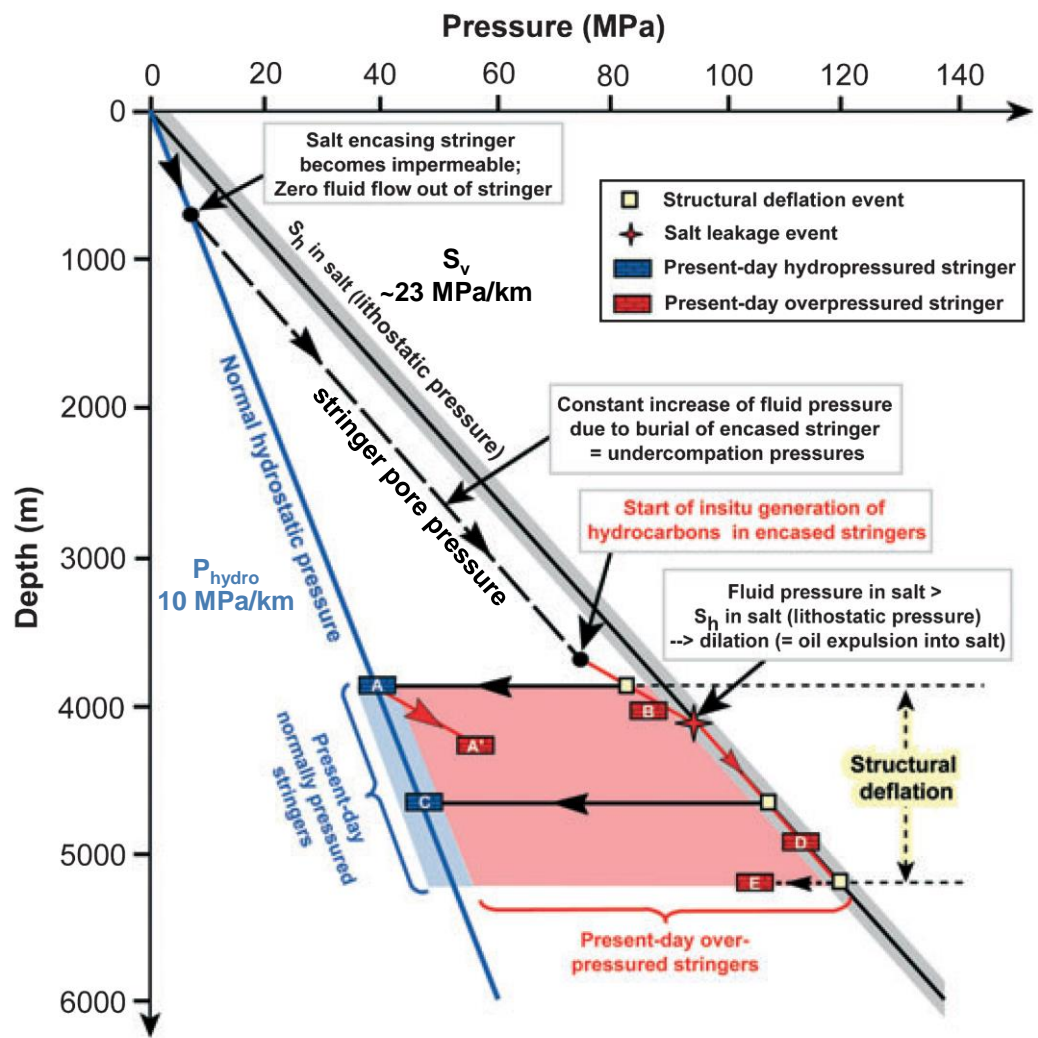
50 μm

indentation

overgrowth

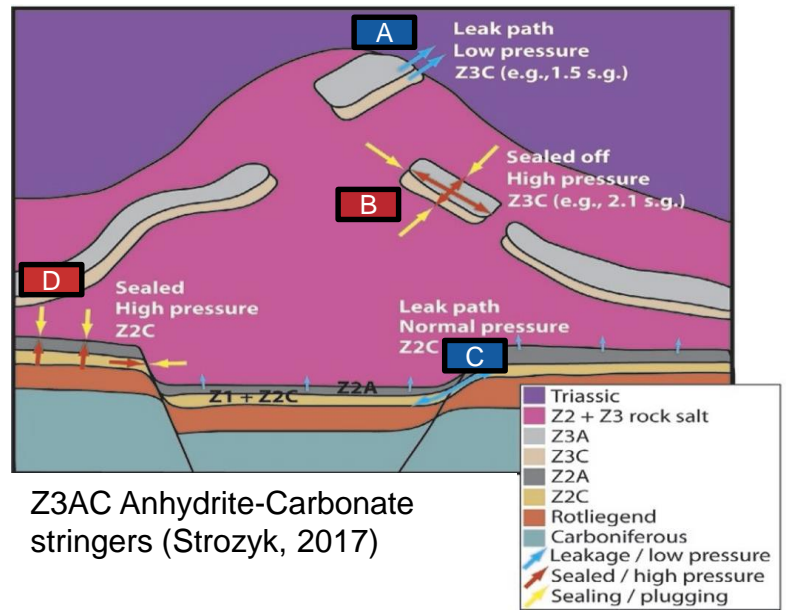
100 μm

OVERPRESSURES: CONSTRAINTS ON MAXIMUM EXPECTED PORE PRESSURE



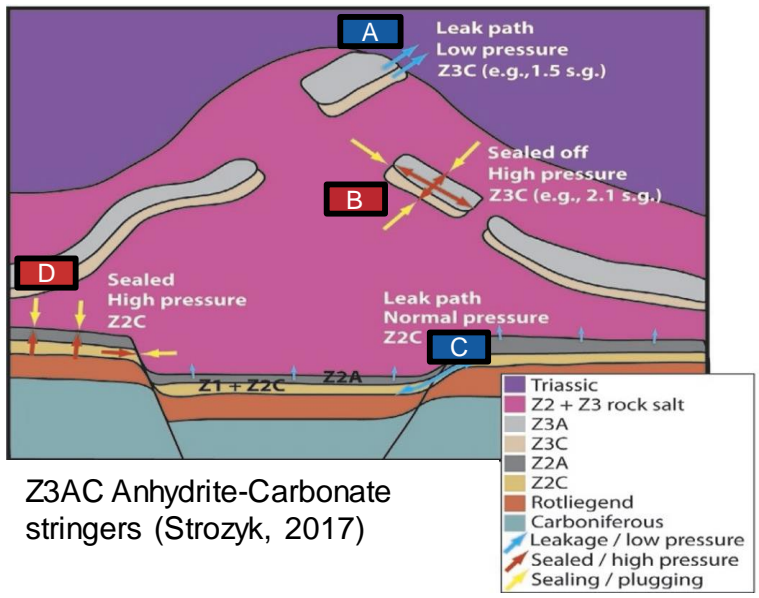
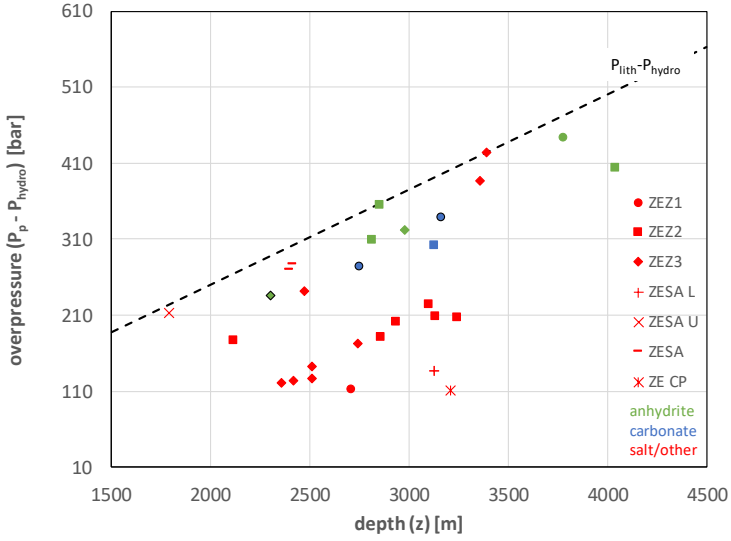
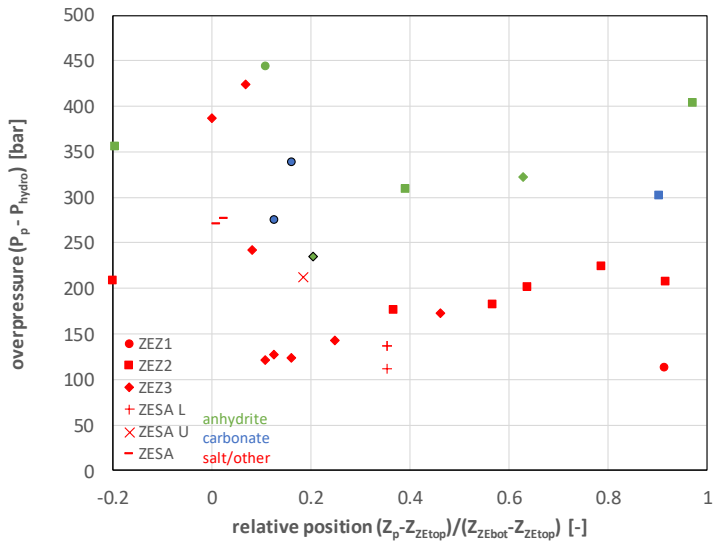
Analogue example for South Oman Salt Basin (Kukla et al. 2011)

- Average trends for S_v , P_{hydro}
- Location-specific stresses from density and sonic logs
- Pore pressure constraints in salt: $S_v \approx S_h$; $P_p < S_h$
- Stringer settings determine pore pressures



Z3AC Anhydrite-Carbonate stringers (Strozyk, 2017)

OVERPRESSURES: TRENDS WITH LOCATION WITHIN ZECHSTEIN AND DEPTH



- › No trend of overpressure data with relative position within the Zechstein
- › Increasing overpressures with depth due to different (diverging) hydrostatic and lithostatic pressure gradients

RISKS: COMPARISON OF STRINGER-RELATED DRILLING RISKS

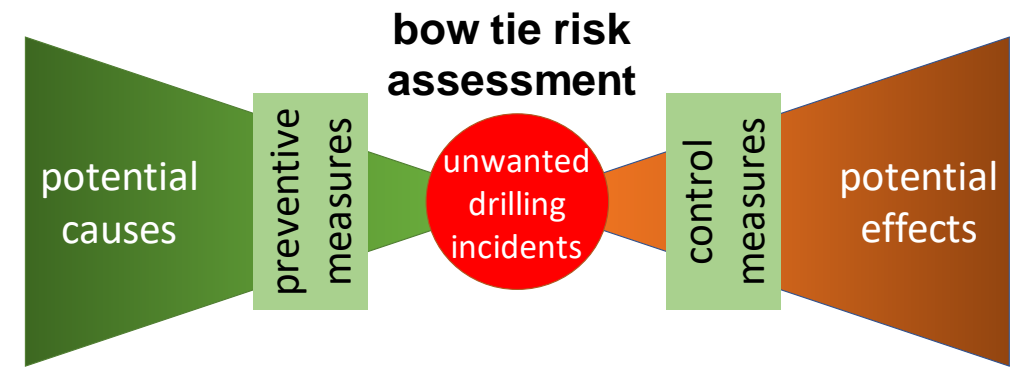
		consequences	increasing probability or likelihood				
			A	B	C	D	E
		Operations	No occurrences % of wells < 0.01%	Few isolated occurrences > 0.1%	Occurs more than once per decade on average > 1%	Occurs more than once per year on average > 10%	Frequent occurrences
increasing effect or severity	1	no effect (only affects efficiency)					
	2	minor effect (remediation by standard procedures)				kicks due to drilling stringers with over-pressures	
	3	moderate effect (additional remediation required)					
	4	major effect (major remediation required)			delayed operations due to stringers		
	5	failed operations			failed operations due to stringers		

- › Moderate risks for pressure kicks (that can be controlled by well operations) & delayed operations
- › High risks for permanent well shut-in (high impact)

LEGEND

- minor risks (standard risk mitigation protocols)
- moderate risks (additional risk mitigation measures)
- high risks (modify or shut-in operations)

RISKS: SOME KEY MITIGATION MEASURES



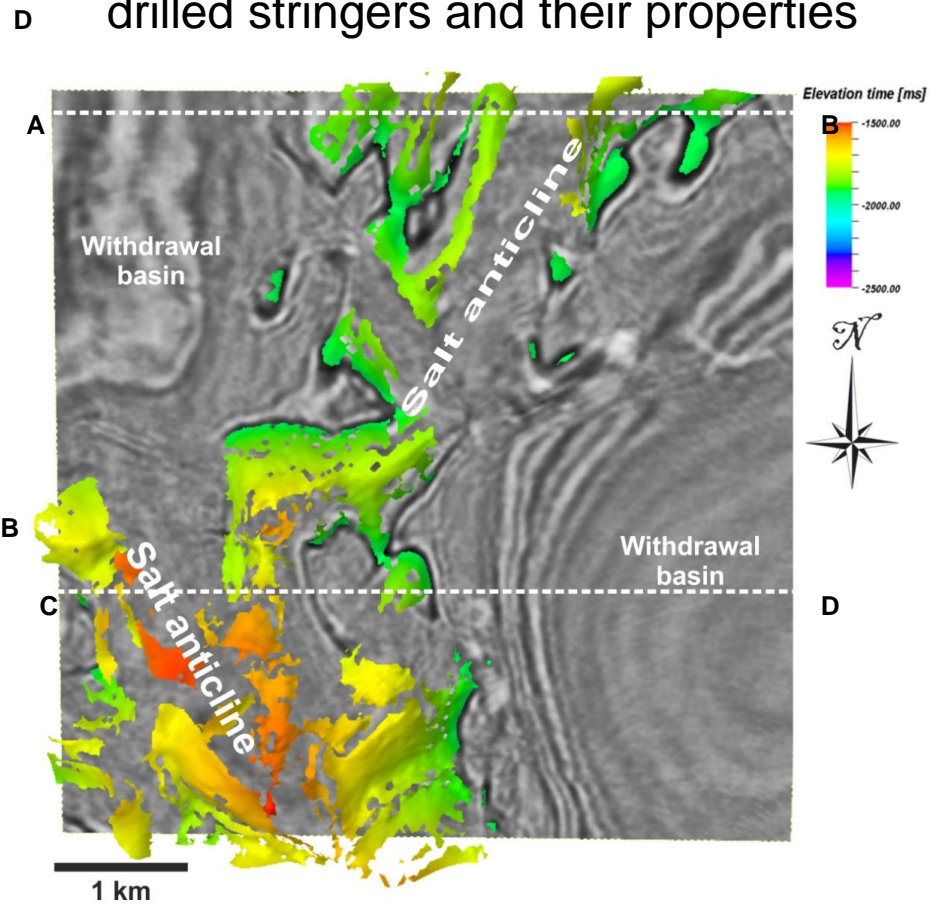
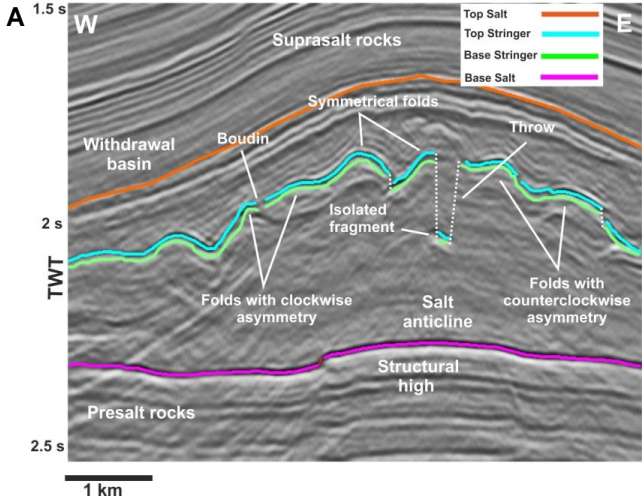
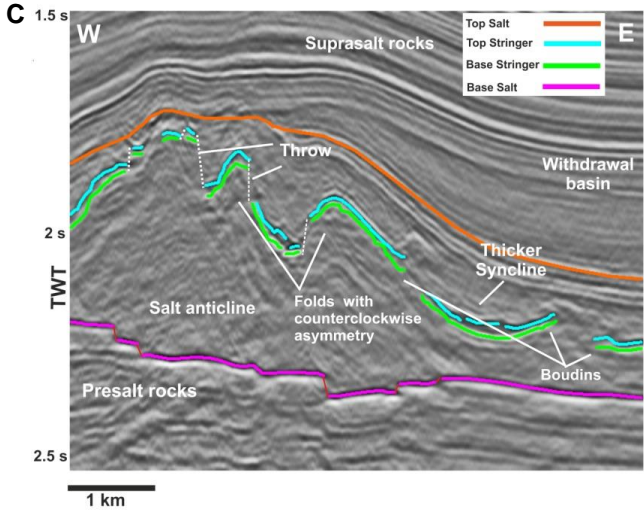
Mitigation Measures	Typical examples
<i>Preventive Measures</i>	
1 Regulations, contingency plans & internal procedures	Well planning, monitoring & mitigation protocols, regulations & best practices for drilling stringers
2 Geological characterization	Prediction of rock types, overpressures & pore fluid content of stringers
3 Seismic imaging	Analysis of location, geometry, spatial extent and distribution of stringers
<i>Control Measures</i>	
1 Modification of drilling fluids (mud weights)	Increase mud weight to handle brine or gas kicks
2 Flowback	Flowback of drilling fluids to reduce fluid exchange between formation and well
3 Well shut-in & sidetracking	Shut-in & cementation of (parts of) well, potentially side-track around stringer

CONCLUSIONS

- › Stringers in the Zechstein mainly originate from Z2 and Z3 lithologies with most of the stringers consisting of Z3 anhydrite-carbonate (Z3AC) stringers
- › The current study analysed relations between the number of events and properties of stringers or the Zechstein salt. A screening of (all) wells for stringer occurrence is required for statistics on relations between structures and events to provide a good indicator for likelihood (risks) of events
- › Most drilling events are associated with (1) folded and tilted stringers, (2) areas where stringers align with top Zechstein, (3) areas with faulted base Zechstein, (4) areas below the flanks of folded top Zechstein
- › Overpressures can be up to the maximum overpressure constrained by the lithostatic pressure (in particular for carbonate and anhydrite formations). Maximum possible overpressure is increasing with depth without a clear trend of overpressure with the relative position within the local Zechstein formation
- › ~80% of stringers associated with drilling events are visible on seismics but the quality of seismics is an important factor for identifying stringers and predict potential drilling issues prior to drilling. Better seismics and improved seismic processing techniques will help reducing stringer-related drilling risks

RECOMMENDATIONS FOR FURTHER RESEARCH

- › Screening of wells with no drilling events for drilled stringers and their properties



- › Improved 3D seismic imaging of stringers