Can we identify leaking wells in the North Sea through inexpensive modelling?

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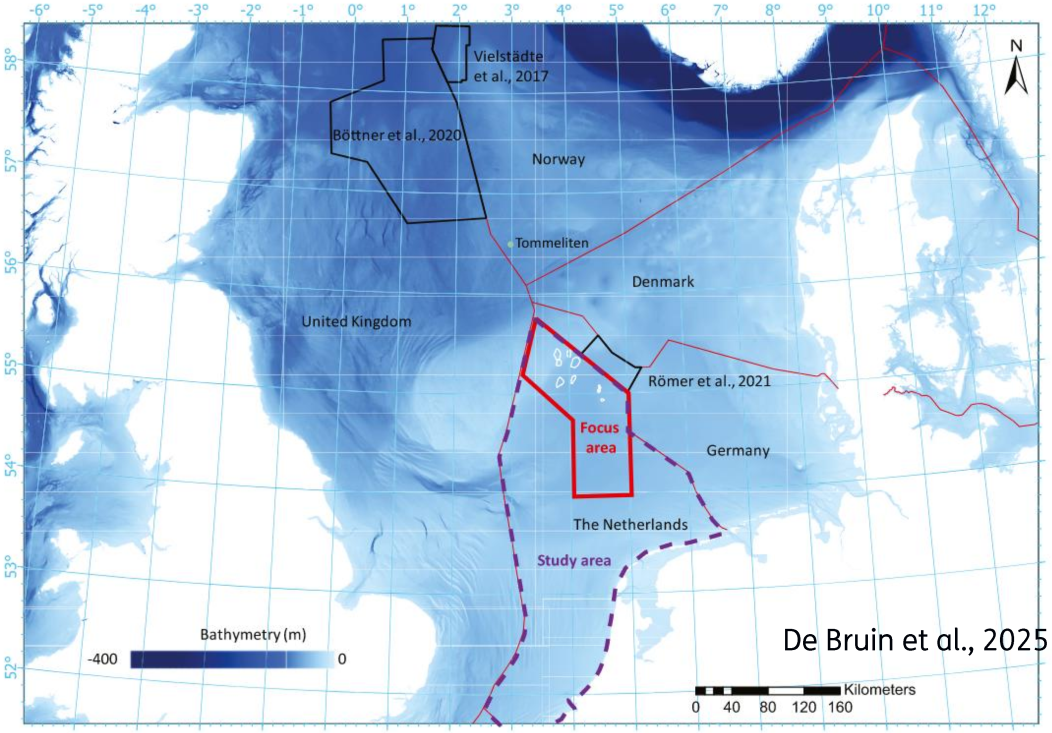
TNO innovation for life

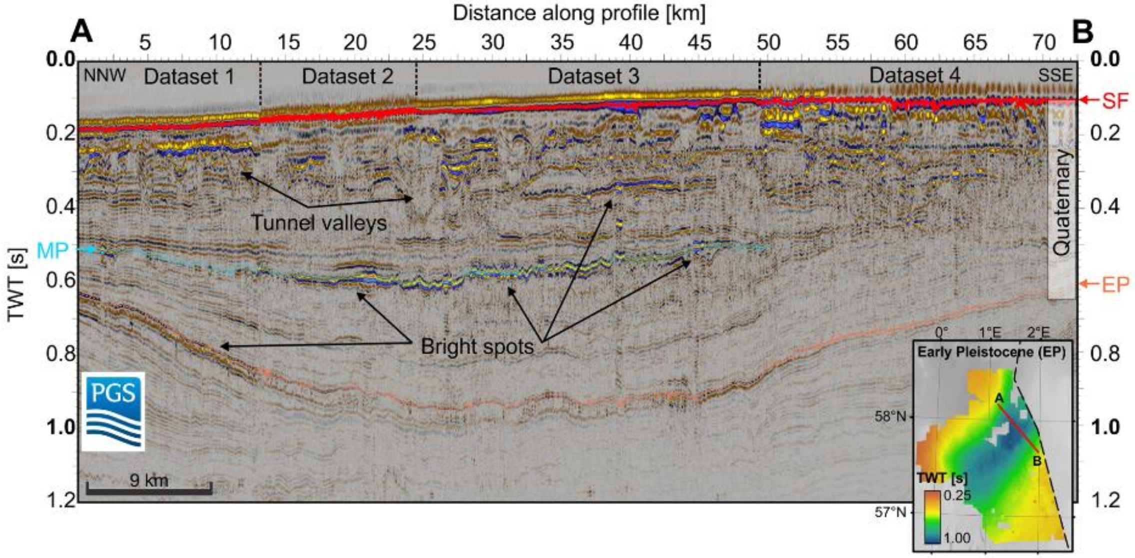
Setting the Scene

- Several studies have shown gas leakage at the seabed from some abandoned wells in the North Sea
- The gas is of biogenic origin from accumulations scattered scattered around the North Sea
- These shallow gas zones were usually not the main target
- However, there are many wells that intersect them that could lead to higher risk of leakage
- The mechanism for leakage in these wells have not been studied previously
- Understanding the leakage mechanism and pathway may result in a screening method for high-risk wells



De Bruin et al., 2025

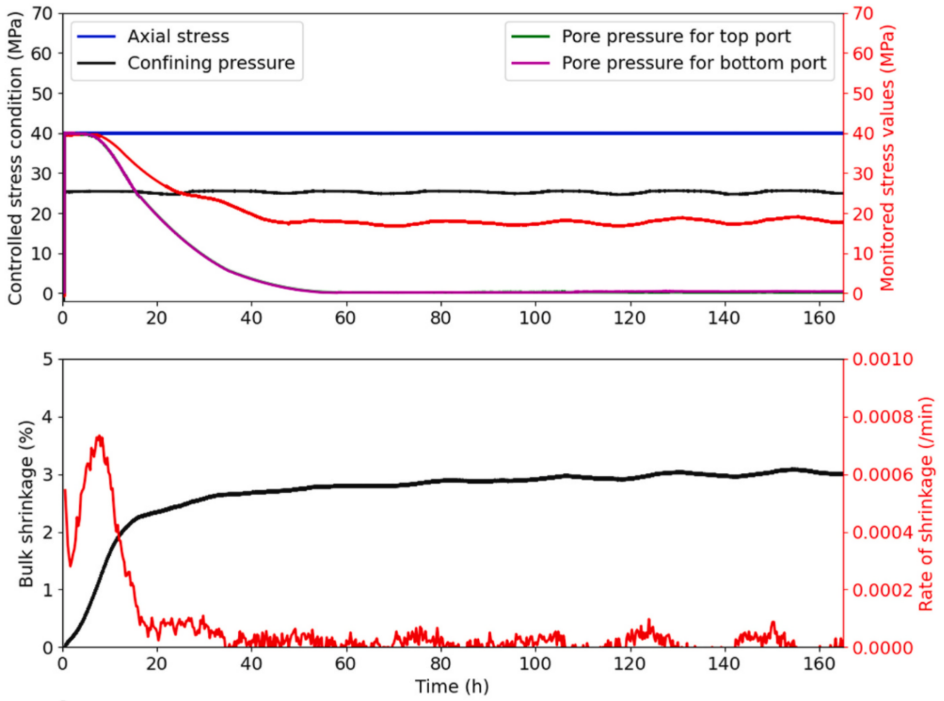
Bottner et al., 2020

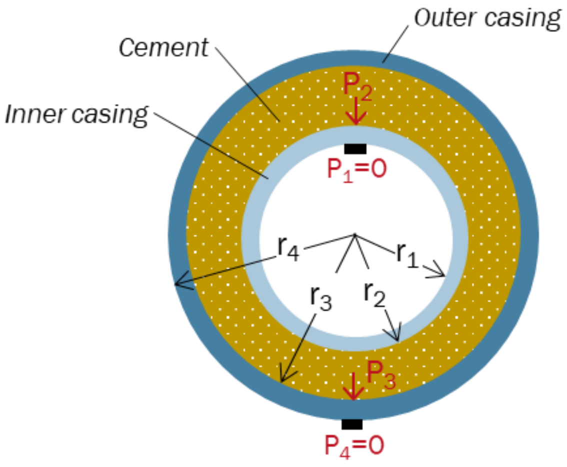


Meng et al., 2021

Cement's Initial Stress

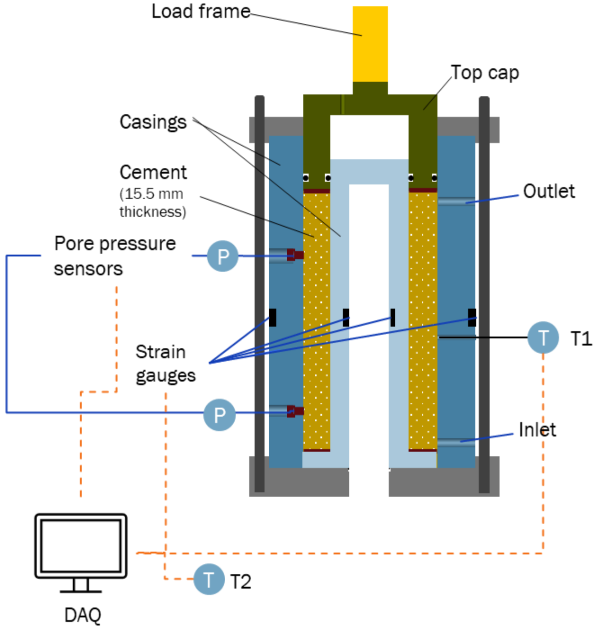
- Cement slurry placed in well annuli undergoes hydration reactions as it sets
- These reactions cause the formation of a solid poro-elastic skeleton
- However, they also cause an internal shrinkage
- This leads to a pore pressure drop in the cement which results in a stress drop
- This was first measured by Los Alamos National Lab for a cement plug
- We have recently conducted this measurement for a cement sheath (Corina and Moghadam, 2025)
- The stress drop in cement increases the likelihood of debonding

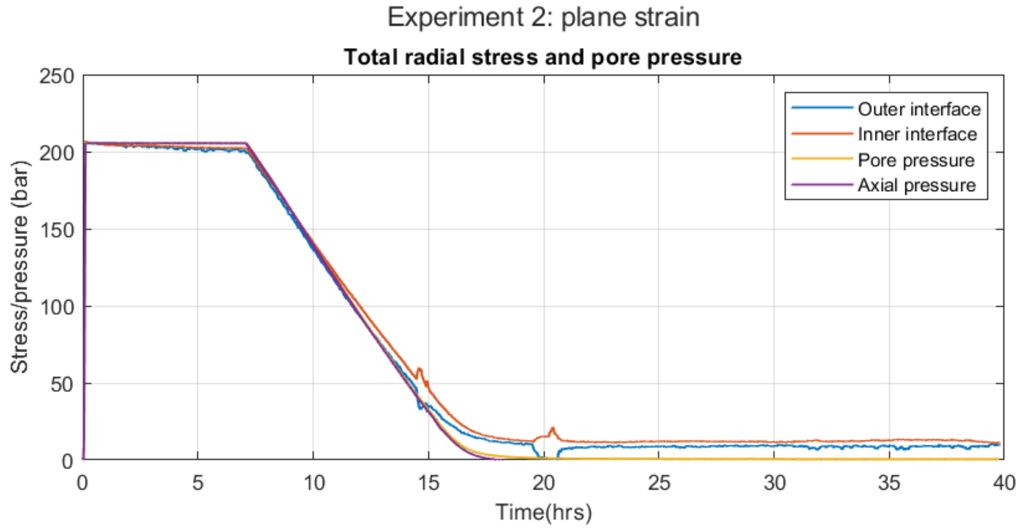


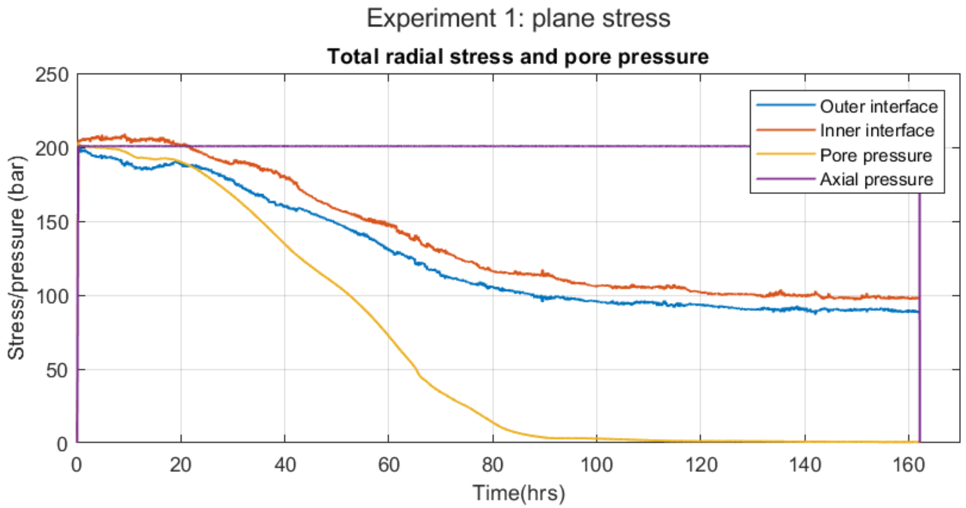


TNO's Experiments

- We have developed a setup to measure cement pore pressure, temperature, and stress at both interfaces of cement
- The results show a significant decline in cement stress as it cures
- The outer interface declines more than the inner interface

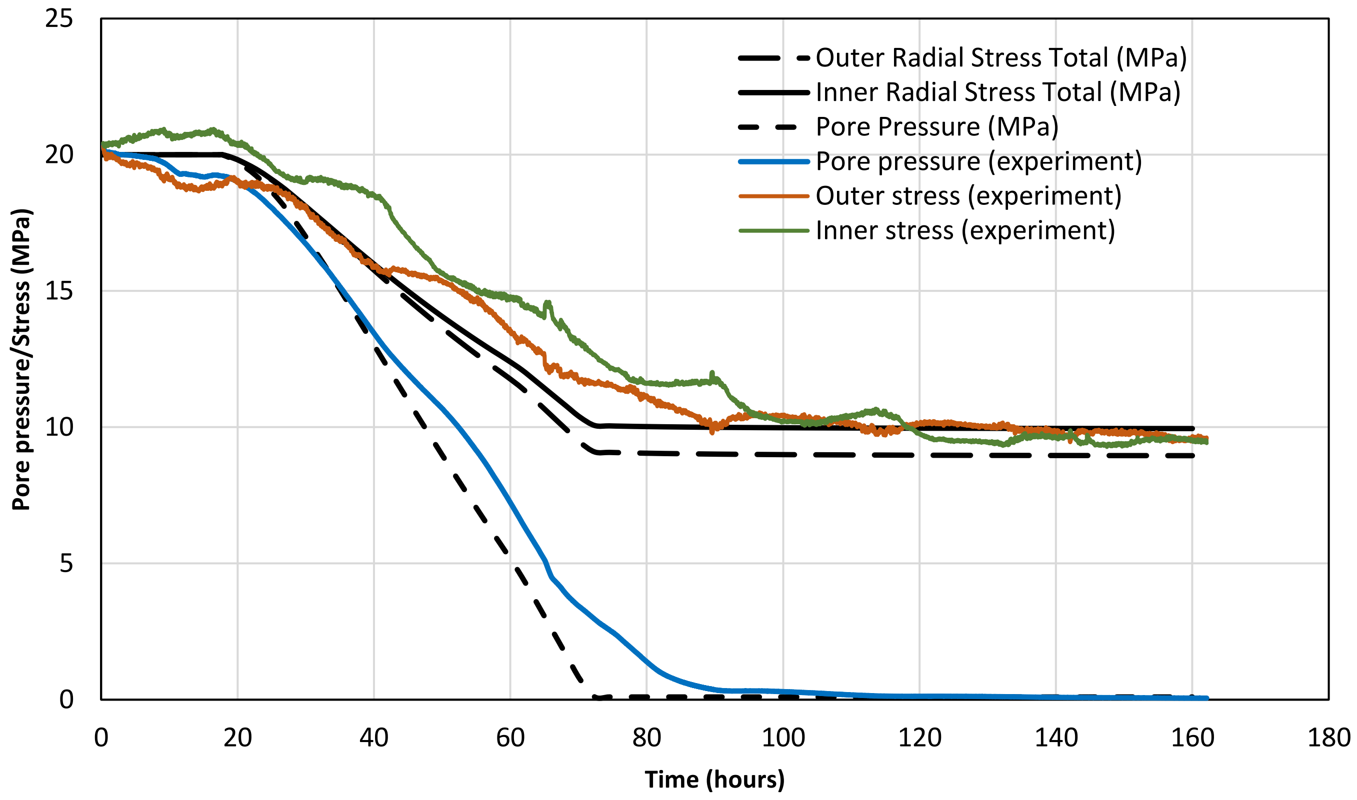






Modelling

- Finite element modelling of the Constant pressure tests confirms the experimental observations
- This has been published (Moghadam and Loizzo, 2024)
- The model shows lower stress on the outer interface
- This increases the confidence in out understanding of cement behavior



Analytical Method

- We have developed an analytical method to predict the stress drop in a cement sheath during curing
- This is verified using lab experiments (Corina and Moghadam, 2025)
- Using analytical methods increases the efficiency of analyzing a larger dataset compared to FEA models

$$A_r^m = \frac{(1-2\nu^m)r_o^2 r^2 + r_o^2 r_i^2}{2G^m(r_o^2 - r_i^2)r}$$

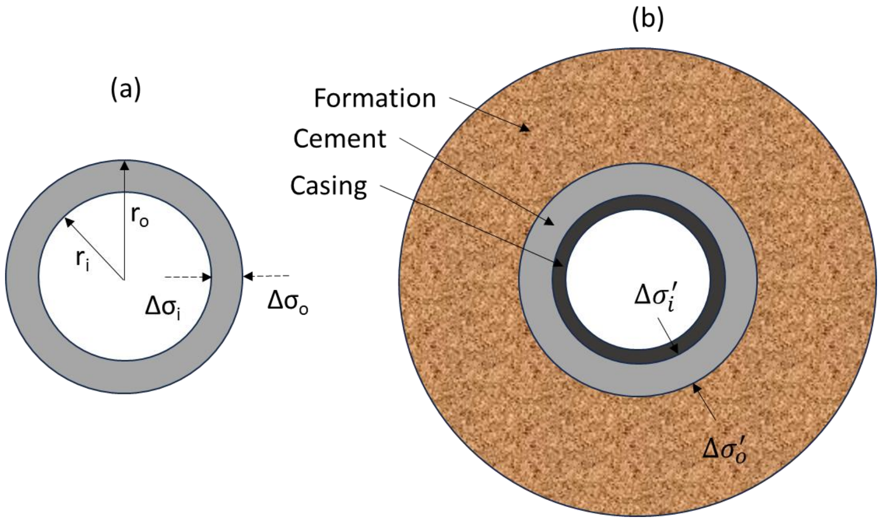
$$B_r^m = \frac{-(1-2\nu^m)r_i^2 r^2 + r_o^2 r_i^2}{2G^m(r_o^2 - r_i^2)r}$$

$$\Delta\sigma_o{}' = \Delta P^{cem}(\alpha_o - 1)$$

$$\Delta\sigma_i{}' = \Delta P^{cem}(\alpha_i - 1)$$

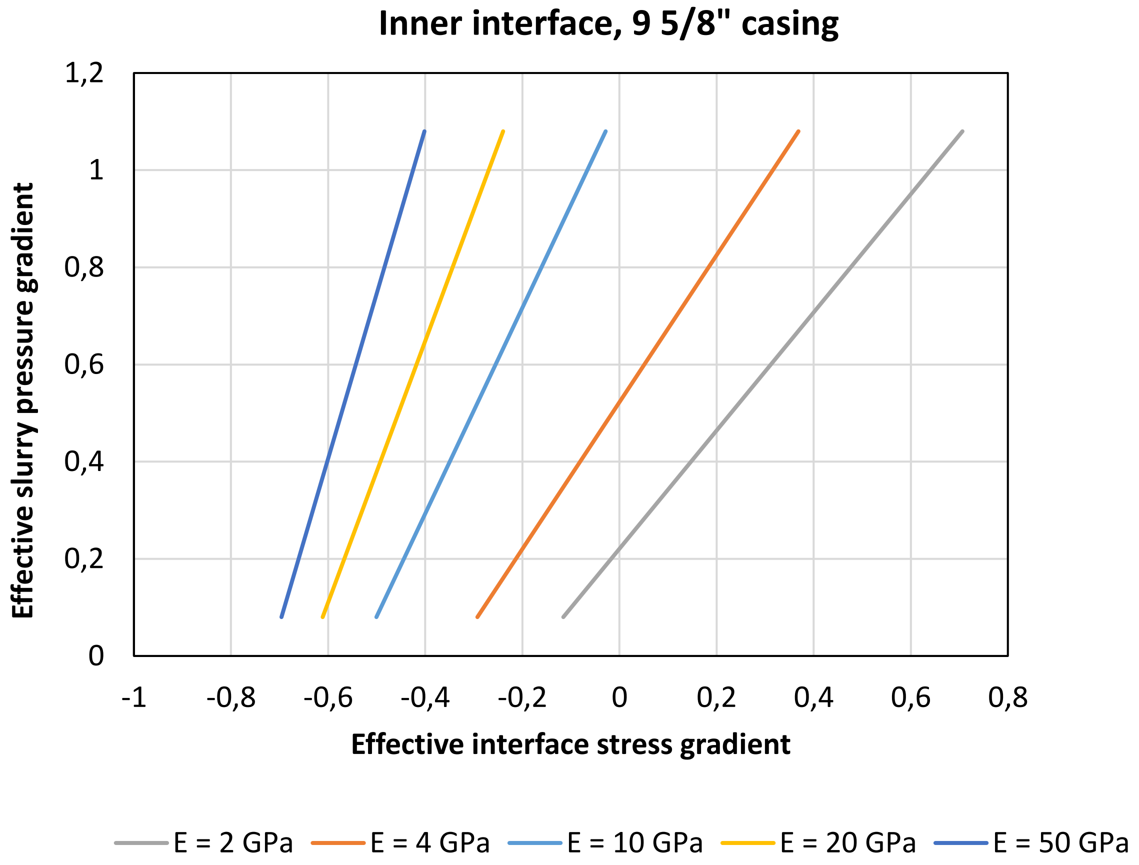
$$\left(A_{r_o}^{cem} - B_{r_i}^{f}\right)\alpha_o^t + B_{r_o}^{cem}\alpha_i^t = A_{r_o}^{cem} + B_{r_o}^{cem}$$

$$A_{r_i}^{cem}\alpha_o^t + \left(B_{r_i}^{cem} - A_{r_o}^{cas}\right)\alpha_i^t = A_{r_i}^{cem} + B_{r_i}^{cem}$$



Analytical Method

- The analytical model estimates the drop in cement stress due to curing
- The results can be used to generate plots such as the one presented here
- The effective pressure of the slurry (slurry pressure minus formation pressure) at the depth of interest should be calculated and converted into a gradient
- Using the plot, and considering the formation Young's Modulus, this can be converted to cement stress after curing



Hypothesis

- We can estimate the initial effective slurry pressure gradient in a cement sheath using typical well data available
- This depends on formation pressure, slurry sg, spacer/mud sg, and the length of the cement sheath
- The analysis should be conducted at a depth slightly above the shallow gas zones
- Using the analytical model we can then estimate the cement's interface stress
- **We hypothesize that wells with a lower cement interface stress are more prone to debonding and leakage if shallow gas is present**

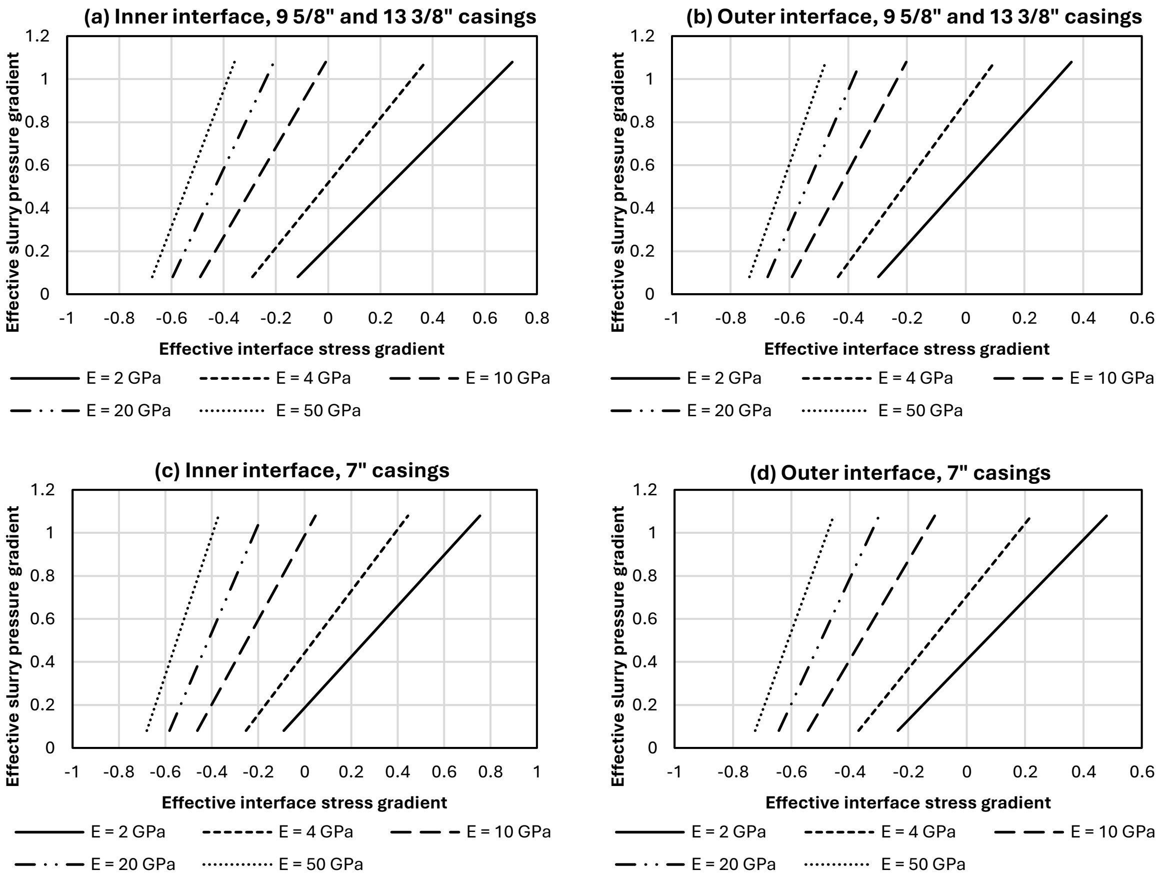
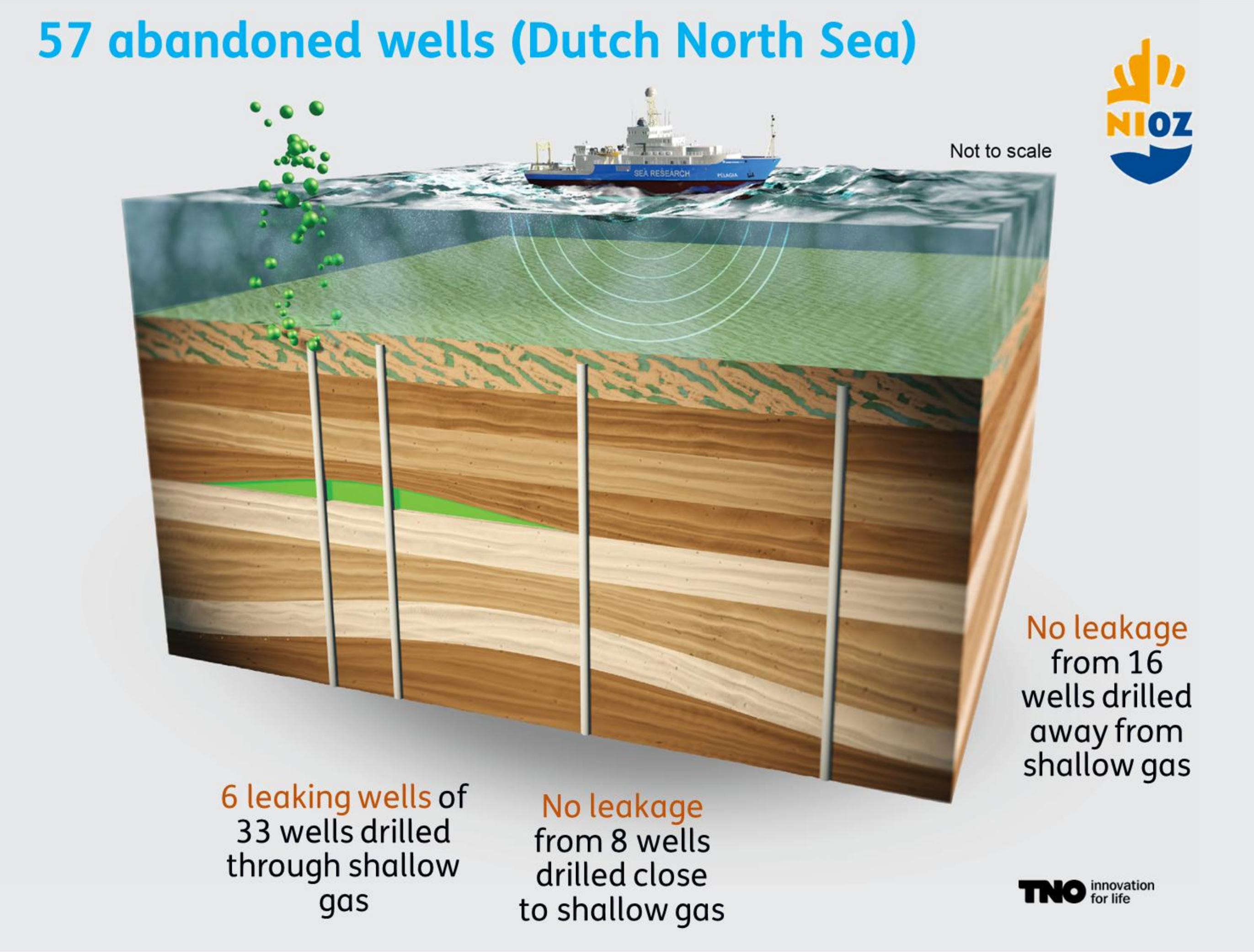


Figure 1: Summary of the cement interface stress results at various initial slurry pressures and formation Young's Moduli (E). The results for 9 5/8" and 13 3/8" are similar and therefore presented in the same subfigures. (a) and (b) subfigures show the inner and outer interface stresses after curing, respectively, for the 9 5/8" and 13 3/8" casing sizes. (c) and (d) subfigures show the inner and outer interface stresses, respectively, for the 7" casing size.

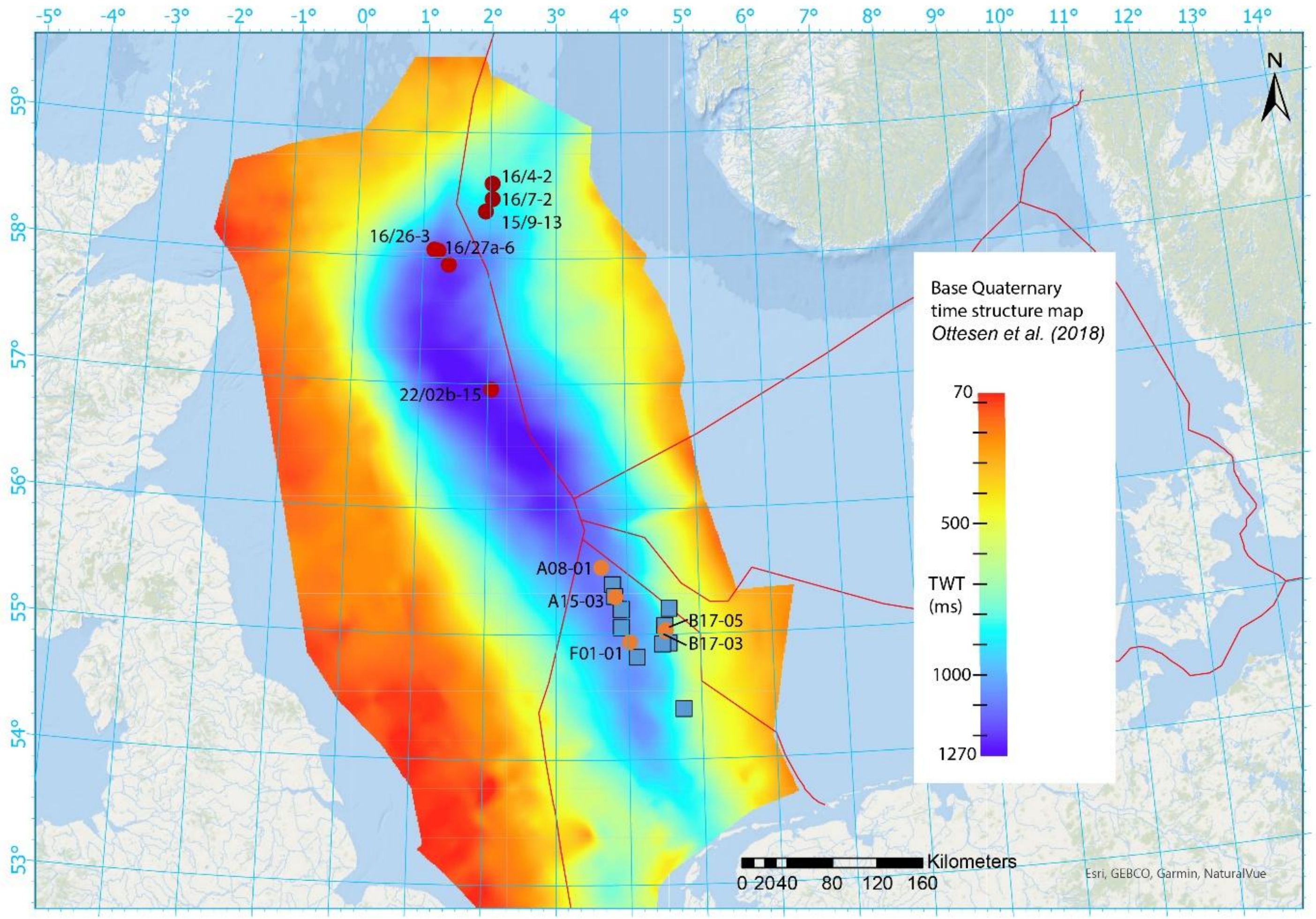
Field Evidence

- AGE/NIOZ has been conducting a project on several wells in the North Sea that penetrate shallow gas (De Bruin et al., 2025)
- Some of these wells show methane plumes at the seabed
- We reviewed some of these wells and extracted relevant information from public sources
- In addition, we investigated several wells from the Norway and UK sectors that were recently investigated (Vielstädte et al., 2015, 2017; Böttner et al., 2020)
- It is important to look at wells that are leaking and non-leaking in the same region to test our hypothesis
- The goal is to understand whether we can predict the state of the cement sheath and potential leaks using modelling



Study Area

- Map of all the wells considered in this study in the Netherlands (de Bruin et al., 2025), the UK (Böttner at al., 2020) and Norway (Vielstädte et al., 2015), plotted on the base Quaternary map (Ottesen et al., 2018)
- All wells are found in the same North Sea Basin
- Blue squares are non-leaking wells in the Netherlands, and the circles indicate leaking wells



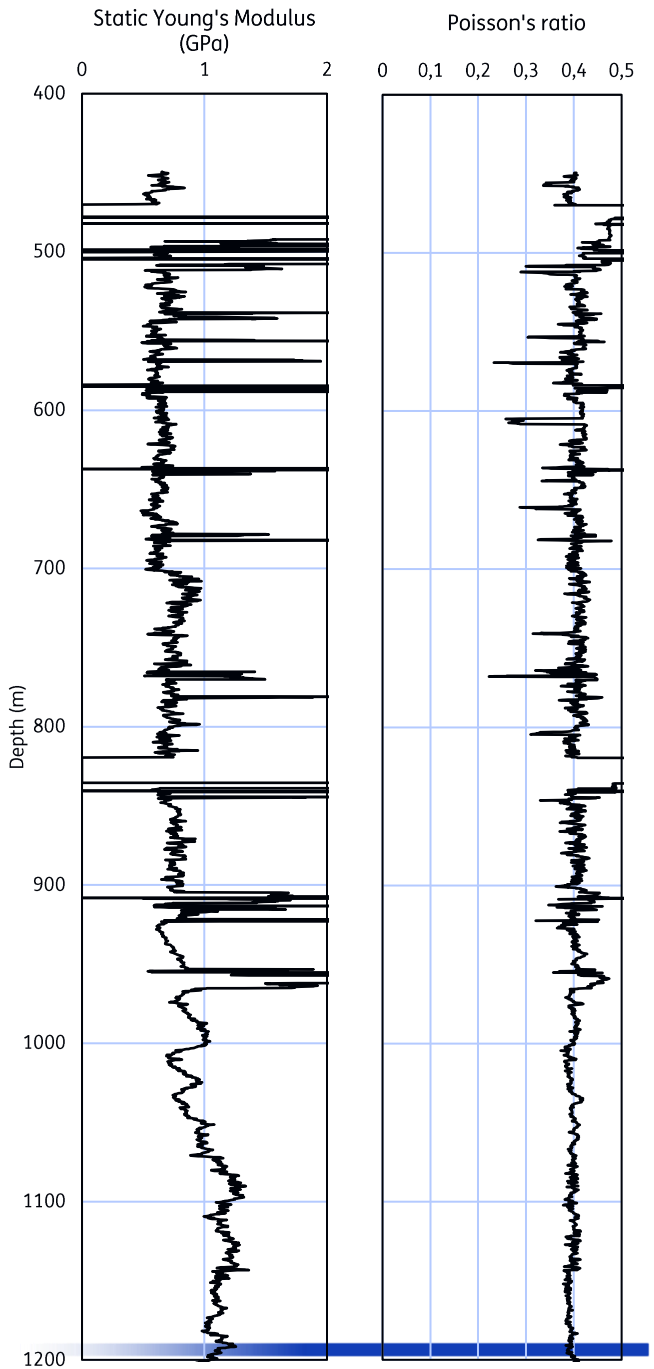
Input Data

- In total, we evaluated 20 wells
- 14 wells from the Dutch sector, 3 from Norway, and 4 from the UK
- Generally casing sizes intersecting the shallow gas are 7”, 9 5/8”, or 13 3/8”
- Cement slurry SG ranges between 1.3 and 1.9
- The length of the cement sheath varies considerably
- The depth of interest is generally selected to be above the highest shallow gas zone

Well	Jurisdiction	Plume at seabed?	Casing size (inch)	Slurry s.g.	Spacer/mud s.g.	TOC (m)	Average annulus s.g.	Depth of interest (m)
A12-03	Netherlands	NO	7	1.70	1.25	250	1.48	500
A15-04	Netherlands	NO	7	1.52	1.15	100	1.45	500
A18-01	Netherlands	NO	13.375	1.60	1.27	100	1.53	500
A15-02	Netherlands	NO	9.625	1.86	1.03	100	1.68	450
B14-01	Netherlands	NO	13.375	1.60	1.28	660	1.34	800
F12-05	Netherlands	NO	9.625	1.3	1.28	222	1.29	550
B17-06	Netherlands	NO	9.625	1.52	1.26	140	1.46	600
F02-03	Netherlands	NO	13.375	1.6	1.20	0	1.60	700
F02-04	Netherlands	NO	13.375	1.75	1.20	0	1.75	900
F04-01	Netherlands	NO	13.375	1.6	1.30	136	1.53	600
A08-01	Netherlands	YES	13.375	1.60	1.29	186	1.48	500
A15-03	Netherlands	YES	7	1.50	1.15	230	1.34	500
B17-05	Netherlands	YES	9.625	1.60	1.03	125	1.46	500
B17-03	Netherlands	YES	9.625	1.50	1.3	196	1.42	500
F01-01	Netherlands	YES	9.625	1.60	1.44	230	1.53	500
16/7-2	Norway	YES	13.375	1.58	1.11	700	1.14	750
15/9-13	Norway	YES	13.375	1.56	1.1	520	1.16	600
16/4-2	Norway	YES	13.375	1.90	1.22	400	1.36	500
16/26-3	UK	YES	13.375	1.54	1.26	240	1.43	600
16/27a-6	UK	YES	13.375	1.50	1.21	100	1.44	500
30/1f-8	UK	YES	13.375	1.56	1.25	600	1.33	800
22/2b-15	UK	YES	13.375	1.50	1.04	0	1.50	500

Input Data

- Elastic properties of formations are needed to use the analytical model
- We used the sonic and density log data from the A15-03 well to evaluate the dynamic Young's Modulus and Poisson's ratio
- We used a correlation by Horsrud (2001) that is based on soft shales in the North Sea to convert the values to static
- Overall, the formations in the North Sea Group are soft
- We use a Young's Modulus of 0.7 GPa and Poisson's ratio of 0.4 for the entire study, assuming that it is representative for all the wells



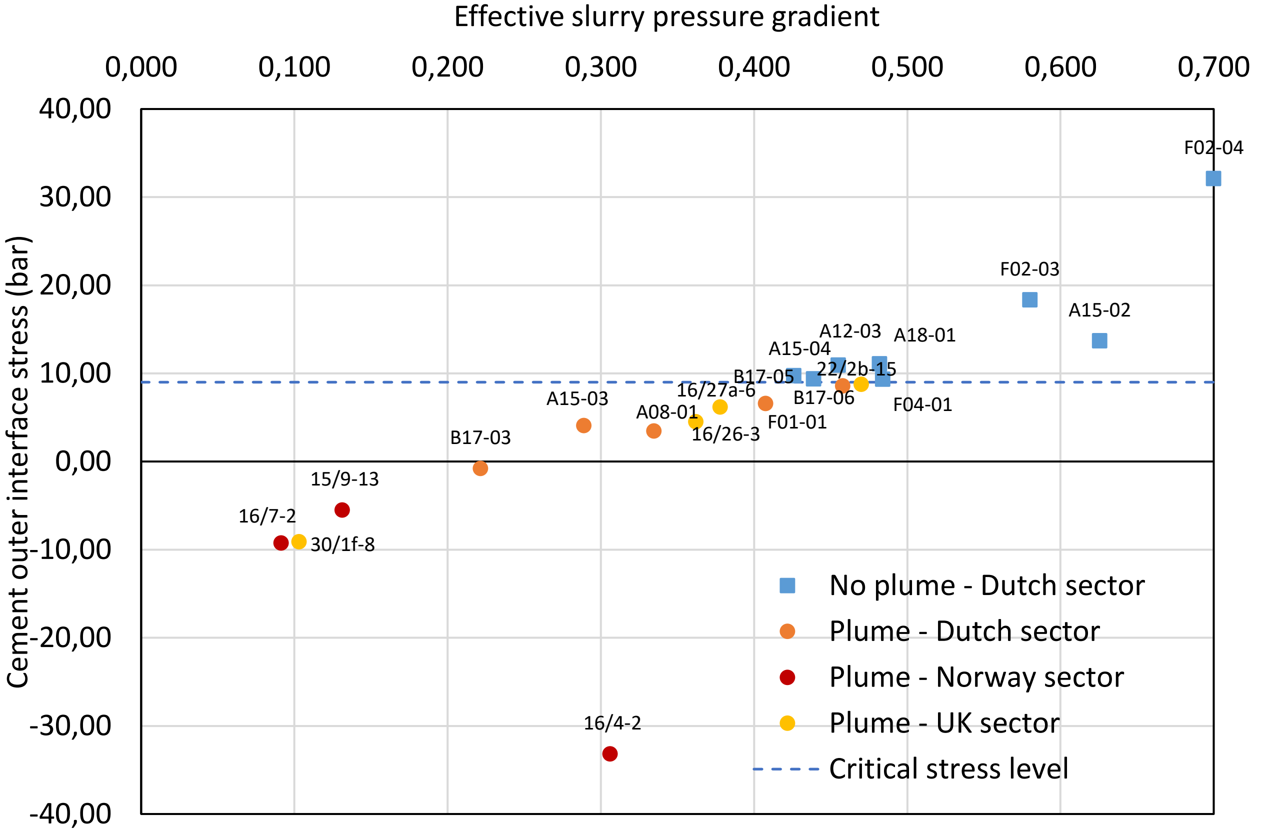
Results

- Both inner and outer interface stresses were estimated
- Outer interface stresses are generally lower
- The impact of well operations such as pressure tests, production tests, and abandonment operations was not considered
- The assumption is that a lower initial cement stress reduces the factor of safety for the remaining operations

Well	Effective slurry pressure gradient	Effective (inner) interface stress gradient	Inner interface stress (bar)	Effective (outer) interface stress gradient	Outer interface stress (bar)
A12-03	0.455	0.4560	22.34	0.2234	10.95
A15-04	0.426	0.4270	20.92	0.1990	9.75
A18-01	0.484	0.4992	24.46	0.1904	9.33
A15-02	0.626	0.6418	28.31	0.3108	13.71
B14-01	0.316	0.3295	25.83	0.0552	4.33
F12-05	0.262	0.2743	14.79	0.0165	0.89
B17-06	0.439	0.4530	26.64	0.1596	9.39
F02-03	0.580	0.5962	40.90	0.2677	18.36
F02-04	0.700	0.7174	63.27	0.3643	32.13
F04-01	0.482	0.4972	29.24	0.1888	11.10
A08-01	0.335	0.3487	17.09	0.0705	3.46
A15-03	0.289	0.2899	14.21	0.0835	4.09
B17-05	0.408	0.4217	20.67	0.1345	6.59
B17-03	0.222	0.2340	11.46	-0.0158	-0.78
F01-01	0.458	0.4722	23.14	0.1750	8.57
16/7-2	0.091	0.1022	7.51	-0.1259	-9.25
15/9-13	0.131	0.1426	8.39	-0.0937	-5.51
16/4-2	0.306	-0.6026	-29.53	-0.6773	-33.19
16/26-3	0.378	0.3921	23.06	0.1051	6.18
16/27a-6	0.362	0.3760	18.42	0.0922	4.52
30/1f-8	0.103	0.1144	8.97	-0.1162	-9.11
22/2b-15	0.470	0.4851	23.77	0.1792	8.78

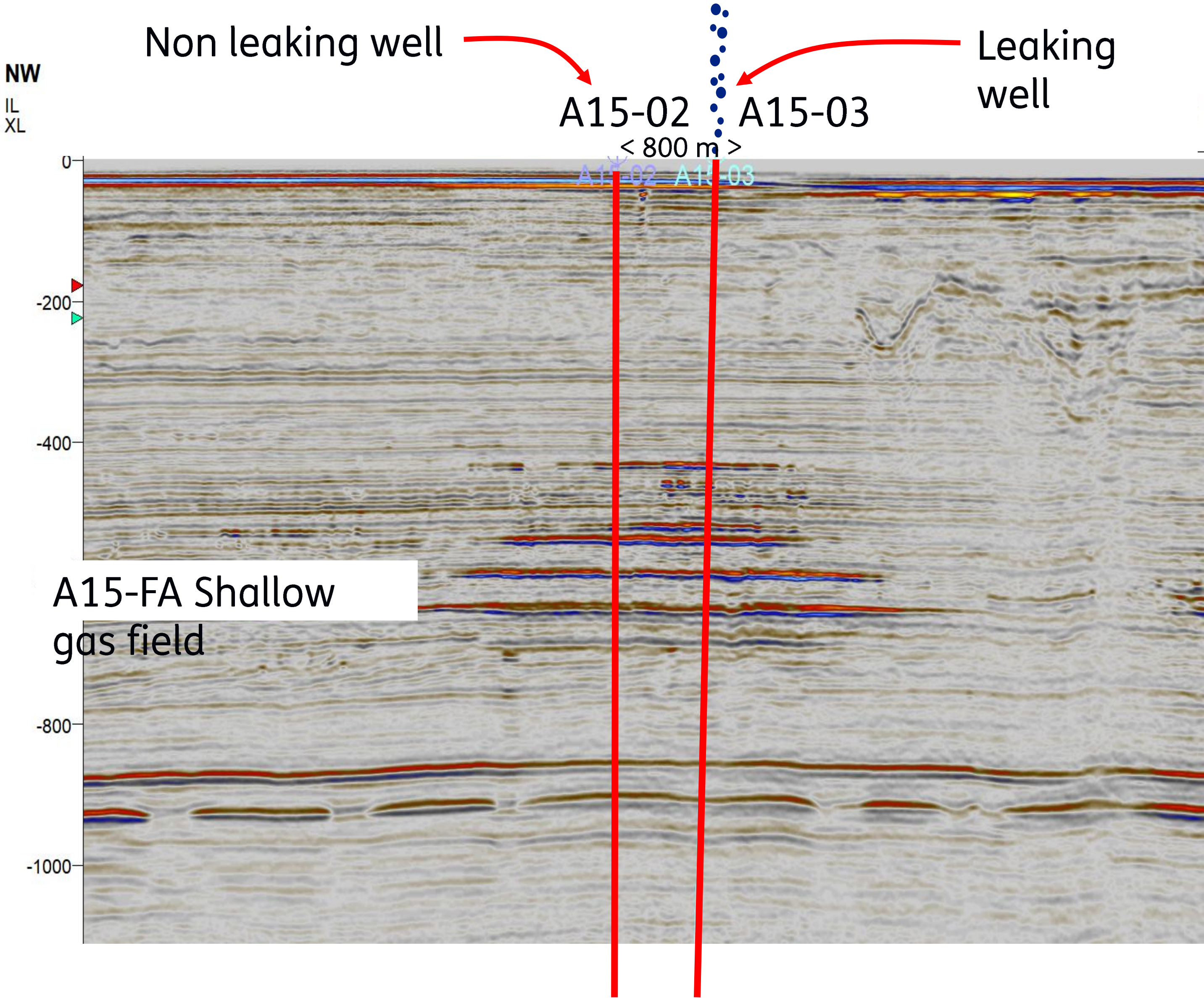
Analytical Assessment

- This figure presents the plot of cement interface stresses versus the initial effective slurry pressure gradient
- The non-leaking wells are generally in the top right corner
- This indicates that as expected, wells with higher cement stress may have a lower chance of leaking (above 9 bar stess)



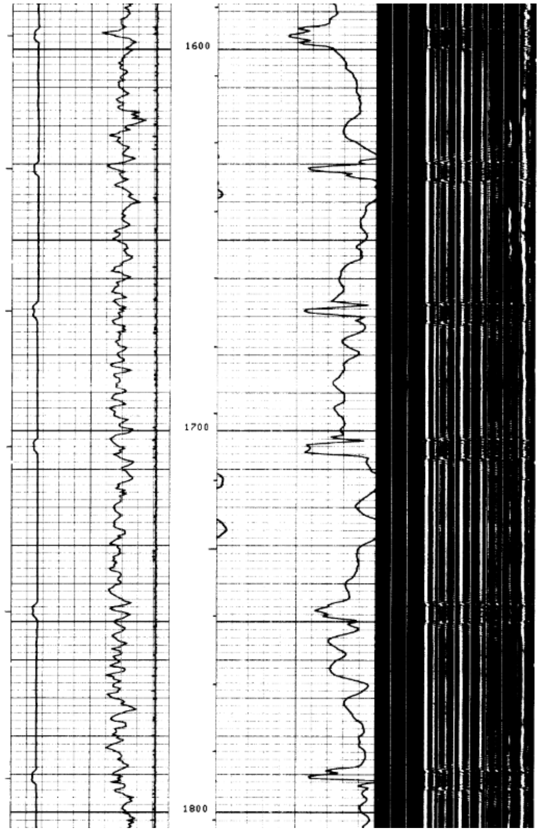
A15-03 versus A15-02

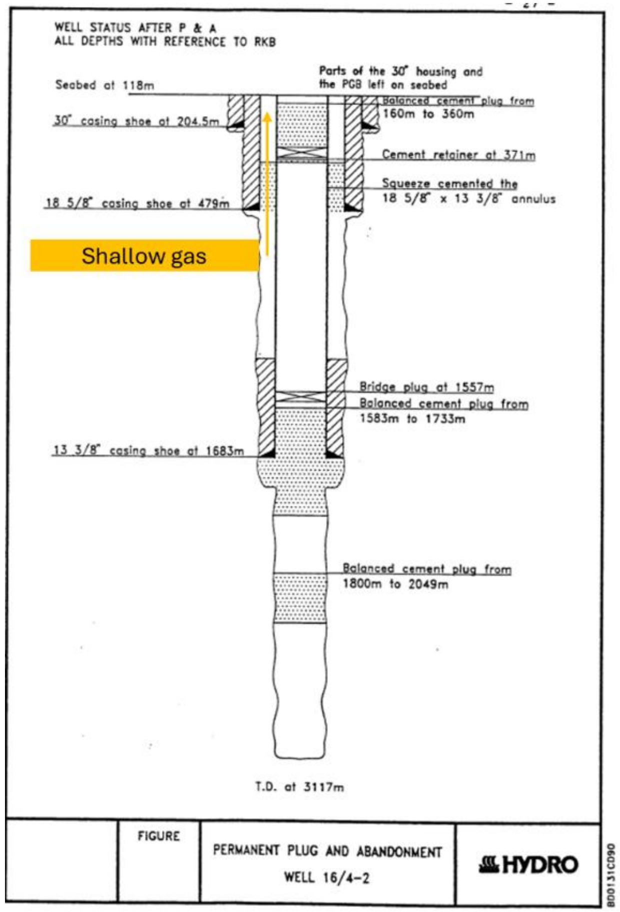
- Wells A15-03 and A15-02 are only 800 m apart
- They both intersect the same shallow gas zone
- However, only A15-03 well shows leakage at the seabed
- Well A15-02 has annular cement with a specific gravity of 1.86 above the shallow gas, with a TOC at 100 m, using a two-stage cementing technique
- However, A15-03 was cemented with a 1.5 SG slurry, with TOC at 230 m
- The initial cement stress available for the A15-03 well cement is significantly lower



General observations

- The wells in the Norwegian sector have a considerably lower slurry sg and shorter cement column above shallow gas making them more prone to leaks
- A well in Norway was not cemented against the shallow gas zone
- Another well indicates gas bubbles around the wellhead that does not seem to have been remediated (failed squeeze attempt)
- Another well has reported major cementing issues (ran out of cement) that lead to a poor cement sheath confirmed by CBL/VDL
- Generally, we find that well leakage can be largely attributed to poor well design against the shallow gas zones





Problems were encountered while cementing the 18⅝" casing and a proper seal could not be obtained. Gas bubbles were seen seeping around the wellhead. A high viscosity plug consisting of 6 ppb Hicell was pumped, and a 20ppg barite plug squeezed against it in an attempt to control the gas. Nevertheless the gas seepage occurred intermittently throughout the well.

Limitations

- This work only considers 20 wells in the North Sea that intersect shallow gas.
- It is not clear whether this assessment can be applied to deeper gas sources. Leaking gas from deeper sections may enter permeable intermediate formations. Thus, leaks may not be identifiable at the surface or seabed.
- The assessment in this work only considers the stress change in cement due to hydration shrinkage, ignoring the operational parameters.
- The presented methodology can only predict whether a leakage pathway may be present, however, leakage only occurs when a gas source is also available.

Lessons learned

- Modelling has been shown to predict the likelihood of well leakage on a small subset of wells
- Generally, we see a better performance for higher effective slurry pressure (this is typically limited by formation fracture pressure)
- Lower formation stiffness, higher cement density, and a longer cement sheath improve the cement bond quality
- This study can be used to assess a large number of wells to identify the high leakage risk locations
- This saves considerable costs for monitoring and remediation activities
- This methodology can be used to assess legacy wells in the CCS context
- In addition, it can be used to enhance the design of new wells to avoid leakage issues in the future

THANK YOU FOR YOUR TIME

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