Gaz de France

Rotliegend
„Tight Gas“
Field Leer (Ostfriesland)
Germany

A Development with a Multiple Hydraulically Fractured Horizontal Well: Project Leer Z4

Michael Koehler

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EBN and TNO Geo-Energy,
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The Presentation is based on a German Paper by M. Koehler and F. Kerekes: DGMK 04/2006, Celle, Germany, ISBN 3-936418-48-9.

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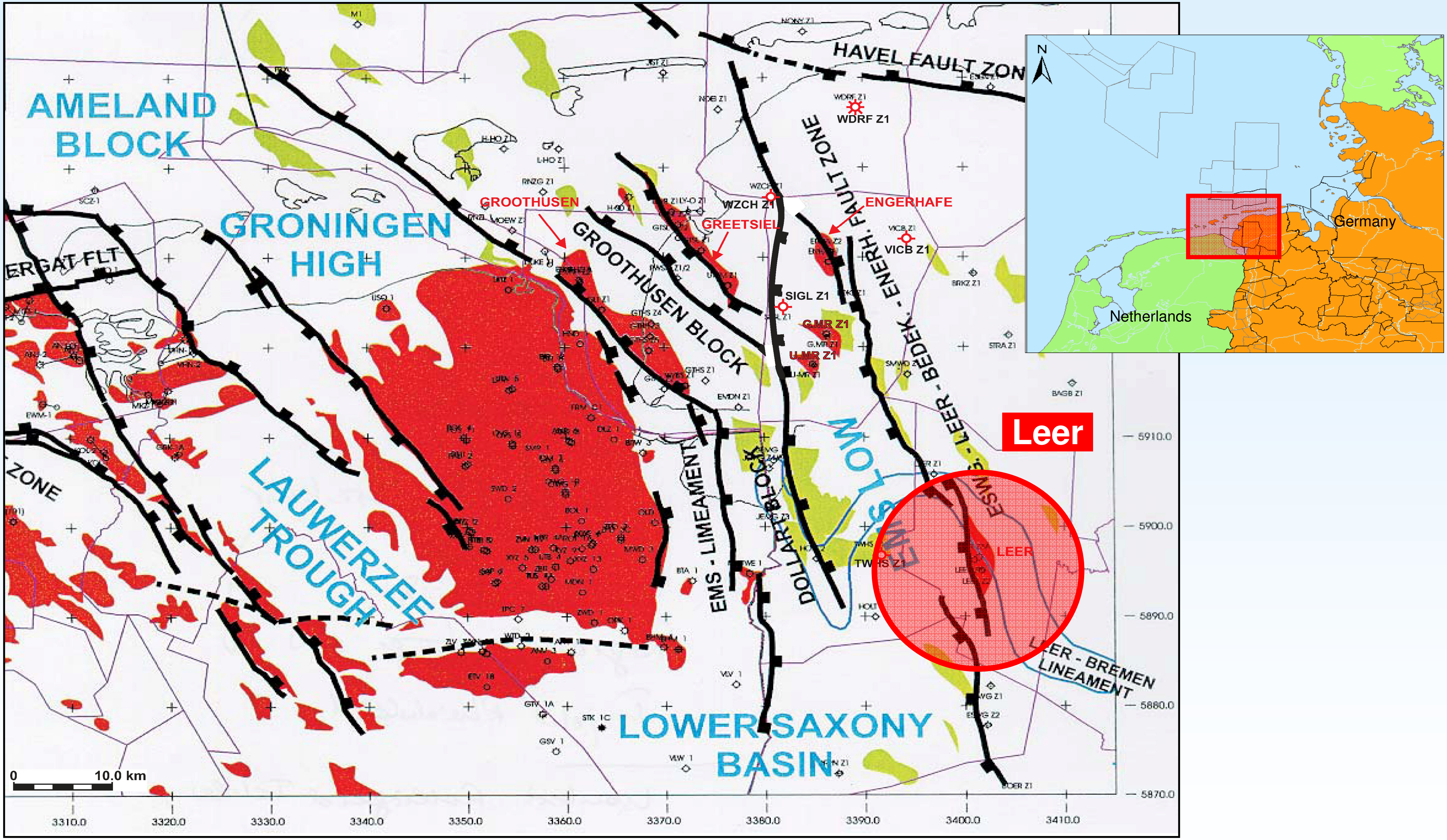
Outlines

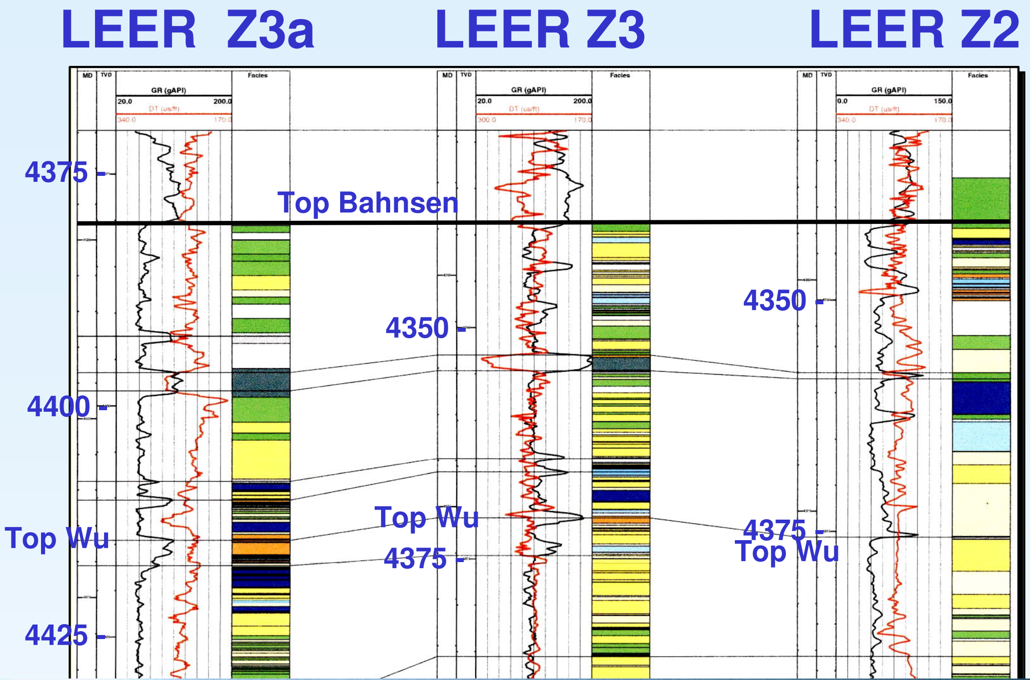
- Gas Field Leer: General Introduction

- Project Leer Z4: Multiple Fractured Horizontal Well
  - Drilling
  - Well Completion
  - Perforation
  - Stimulation
  - Well Cleanup and Tracer Investigation

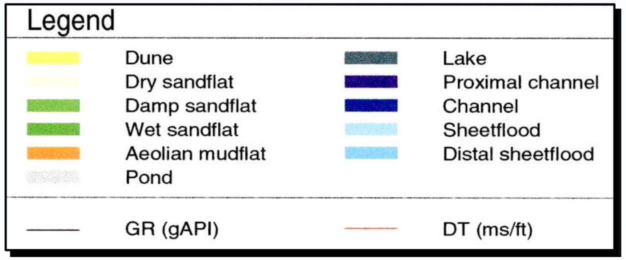
- Conclusions
  - General
  - Positive Experiences
  - Negative Experiences



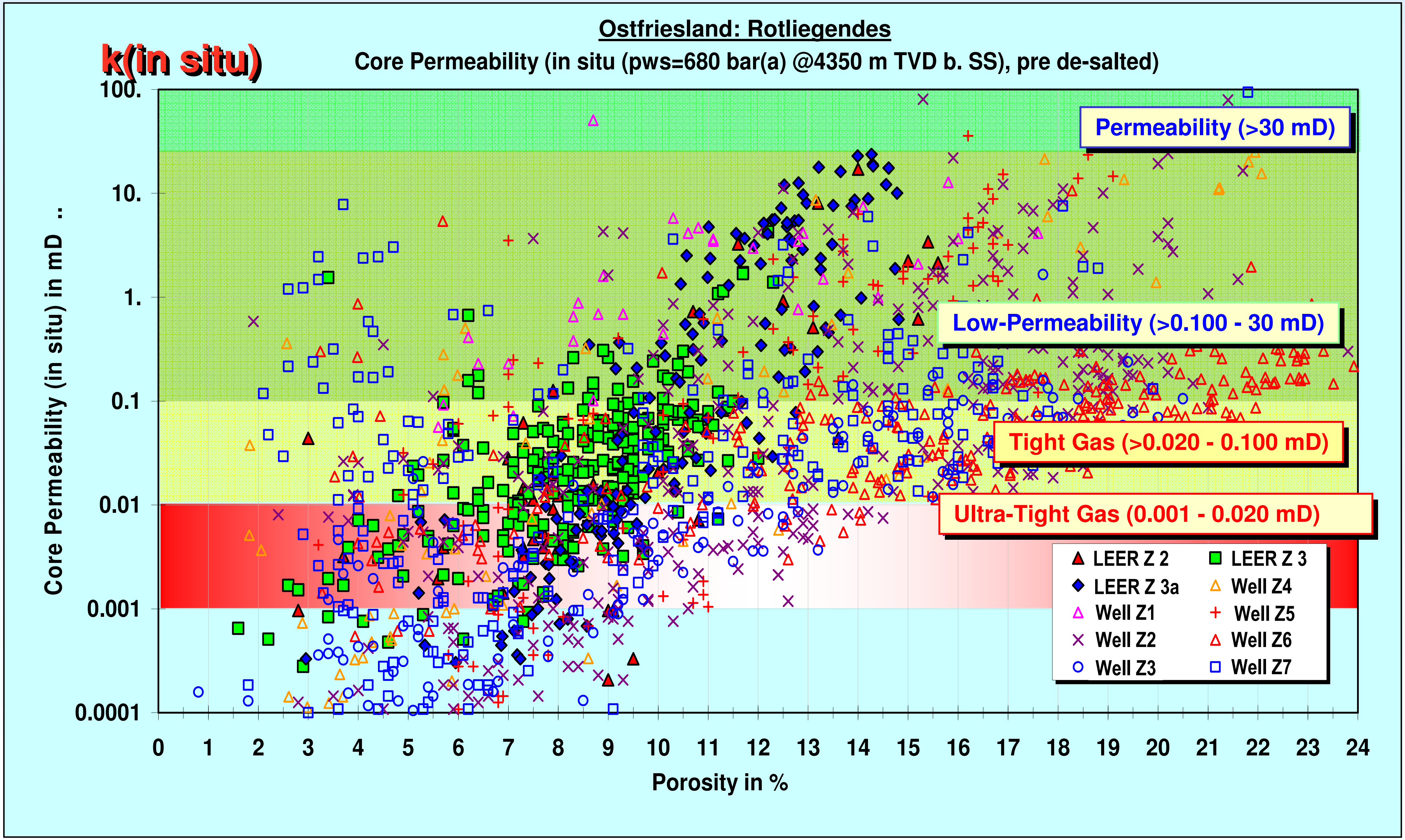
Geological Basemap: NW-German and NE-Dutch Gas Fields



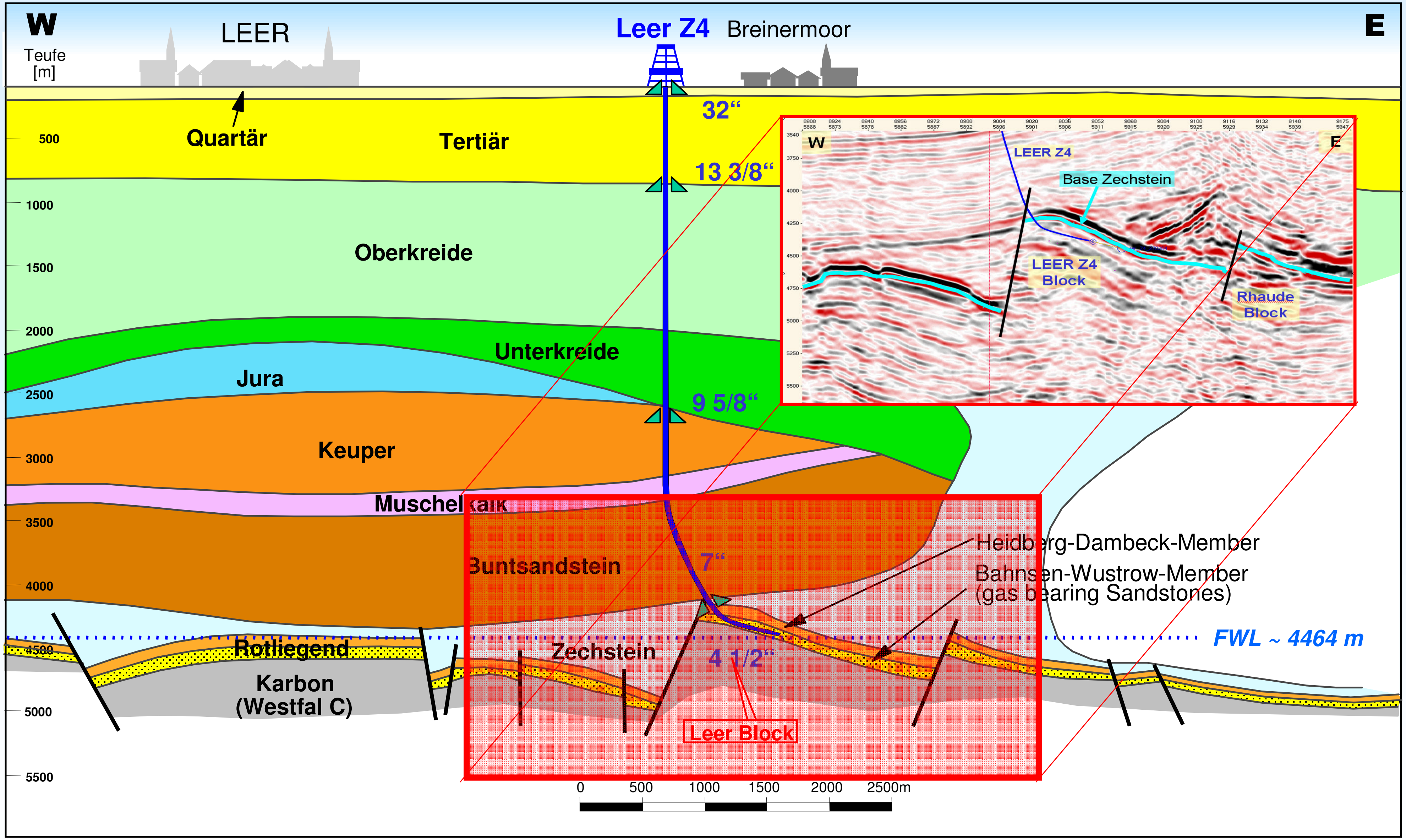
- Leer structure is located on the southern margin of the Permian Basin (Rotliegend, Wustrow- and Bahnsen-Member).
- Depositional Setting: Desert plain: Dominated by aeolian dunes, dry sandflats, and damp sandflats with occasional presence of deposits of wet sandflats and aeolian mudflats.
- Proximal channels with coarse deposits with claystone intraclasts and channels (less mature composition).
  Sheetfloods and lake deposits.
- The reservoir can be sub-divided into five drying upward cycles.
- Sub-units are assumed to be climatically driven by lake base level and ground water table fluctuations.
  Subsequent lateral move of facies belts.
- k_v/k_h= 1/10 vertical barriers and lateral facies boundaries →Risk: Compartmentalization.



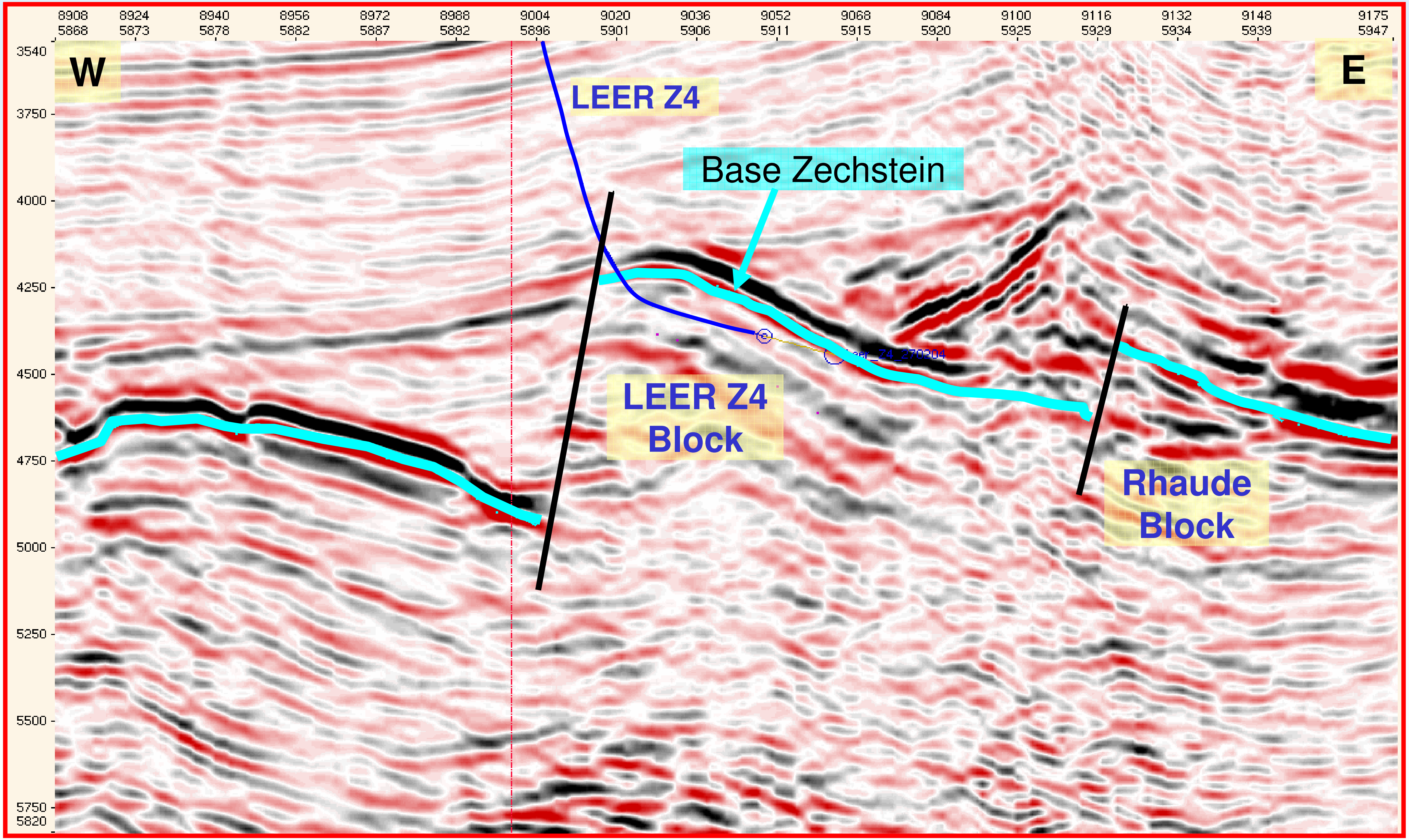
Logging Sequence and Depositional Environment: Leer: Bahnsen- and Wustrow-Member



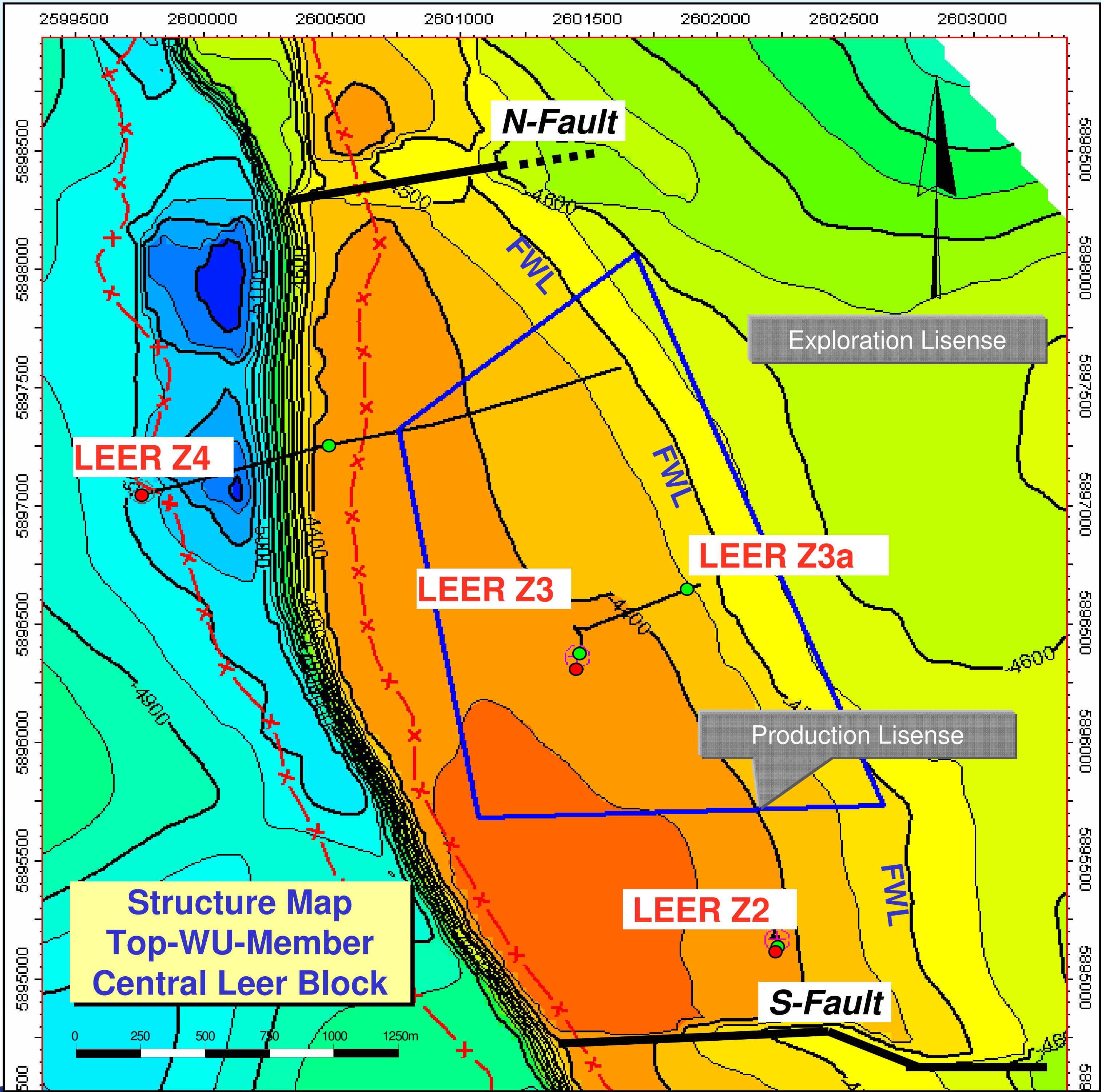
In-situ Permeability Distribution from Core Data: Leer Z2-Z3a and other Ostfriesland Wells



LEER Z4: Drilling Path and Project Target
West-East-Cross-Section: Structure Leer

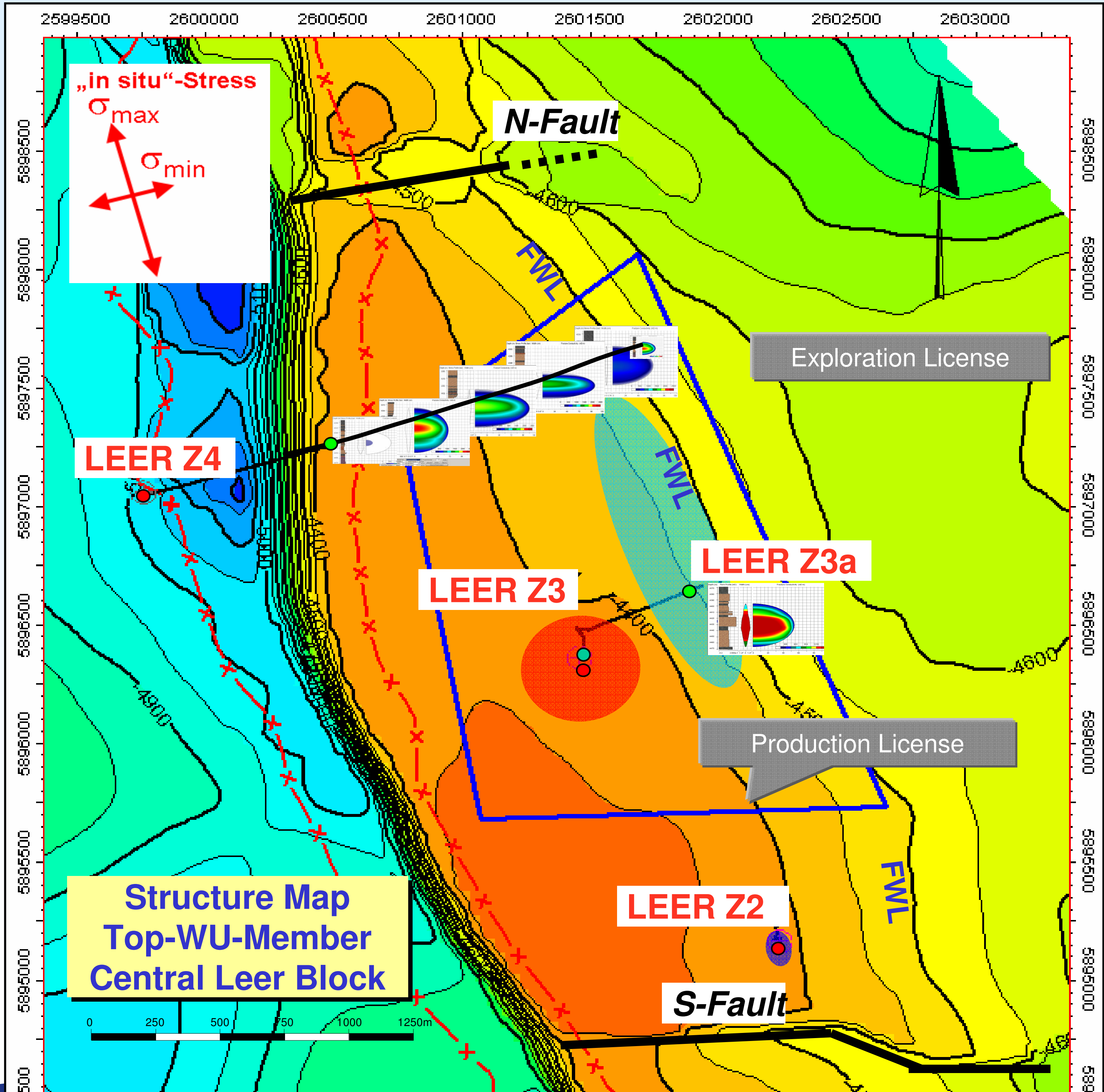


Cross-Section on the Base of PreSDM Seismic (Depths)
LEER Z4 Block: Zechstein/Rotliegend



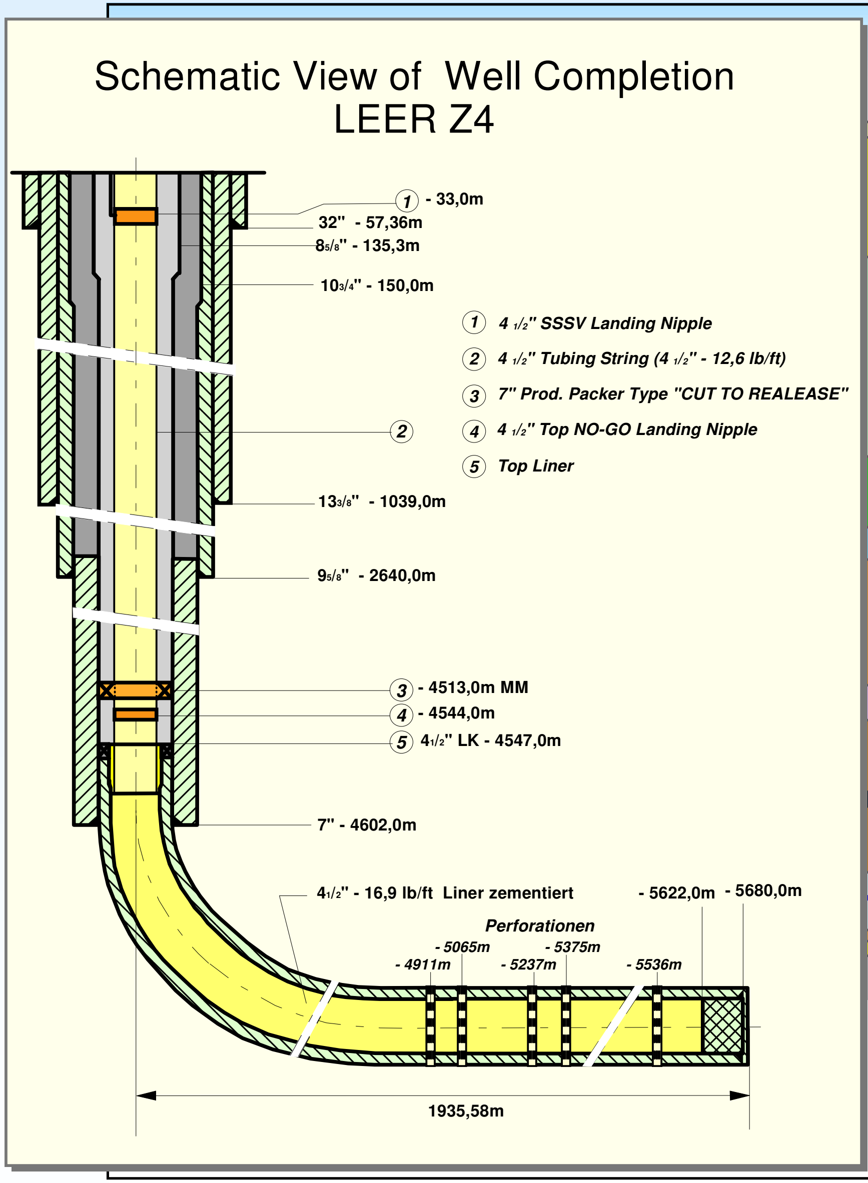
- Length and Width:
  N/S: 3.9 km x E/W: 1.2 km
  Area: 4.7 km²
- Structural Dip: 4.5° ENE
- Ref. Depth: 4420 m TVDss
- Reservoir Pressure: 680 bar
- Temperature: 150 ℃
- Gross Thickness: 78 m
- Net Thickness: 45 m
- Porosity: 9.7%
- Water Saturation: 34%
- Permeability: 0.020-0.150 mD
- FWL : 4464 m TVDss
  GWC: 4450 m TVDss
- OGIP (P90, P50, P10):
  3050, 4300, 5600 Mio. m³(Vn)

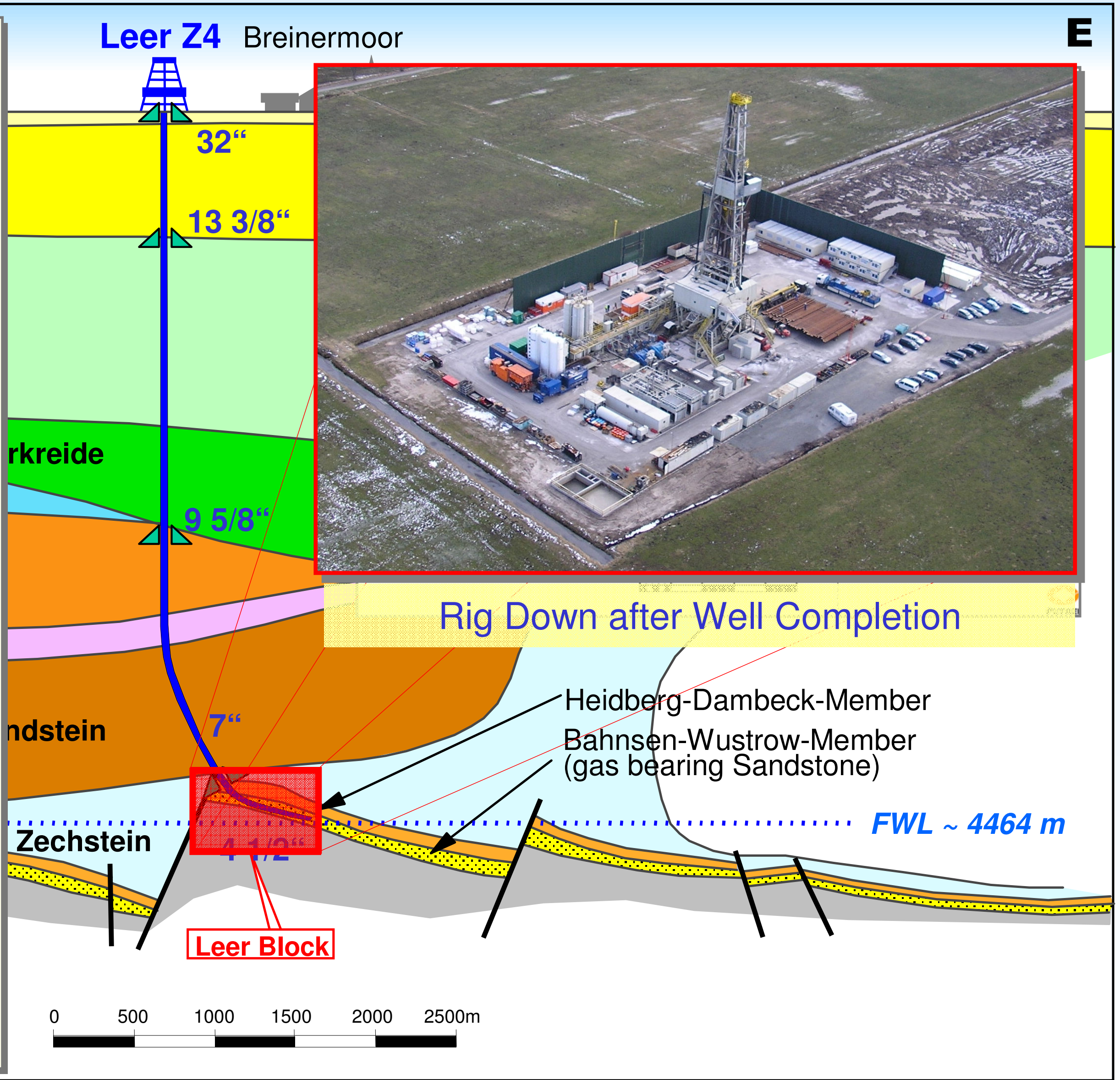
Reservoir Parameter: WU- & BA-Member Central Leer Block



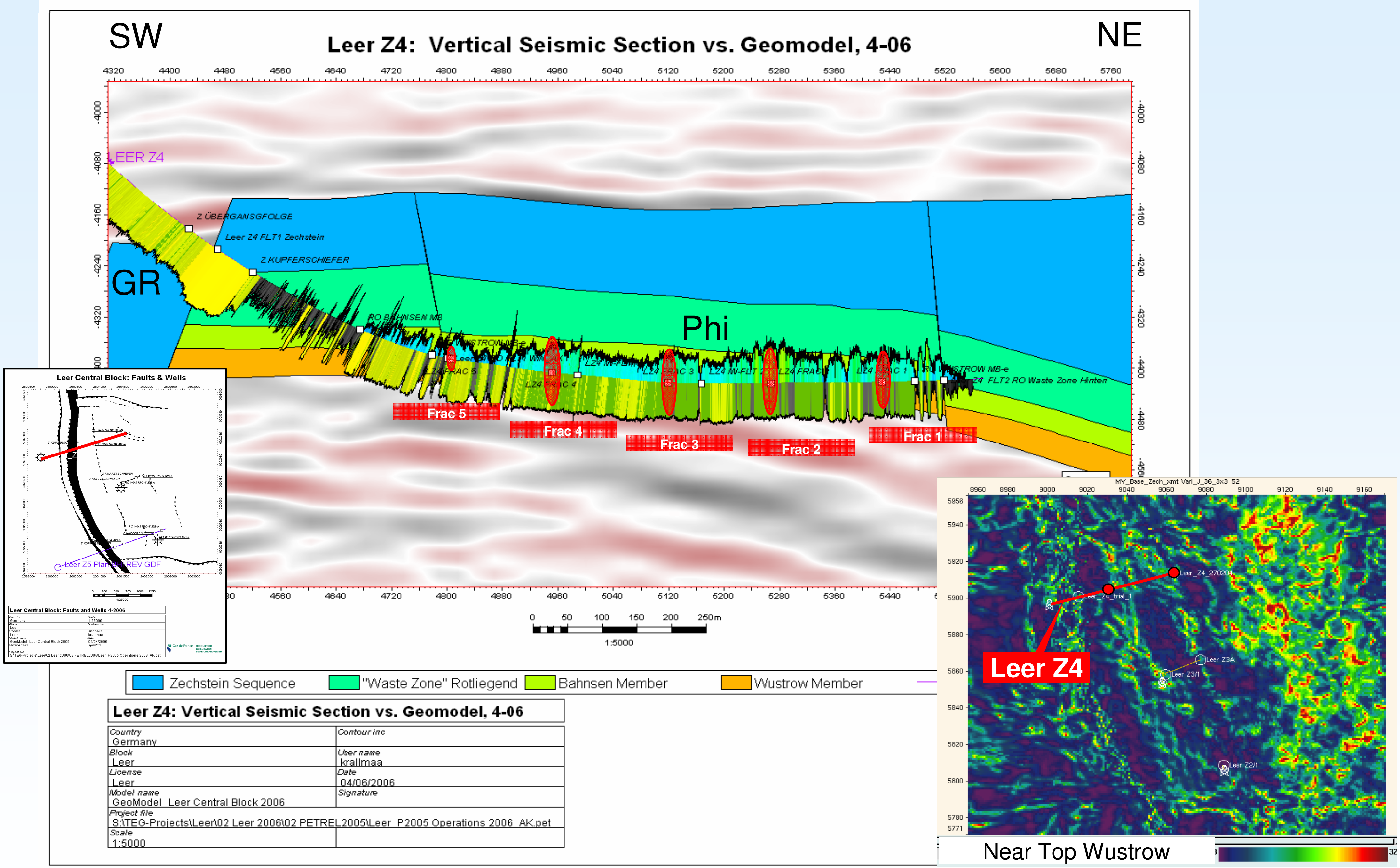
- **LEER Z2: 1971**
  - Gas Rate = 1500 - 1000 m³(Vn)/h
  - @WHFP = 8 - 5 bar
  - Permeability = 0.020 mD
  - OGIP = 5 Mio. m³(Vn)
- **LEER Z3: 1978**
  - Gas Rate = 1000 - 1500 m³(Vn)/h
  - @WHFP = 266 - 224 bar
  - Permeability = 0.050 mD
  - OGIP = 150 - 200 Mio. m³(Vn)
- **LEER Z3a (post frac): 1998**
  - Gas Rate = 9 500 m³(Vn)/h
  - @WHFP = 440 bar
  - Permeability = 0.150 mD
  - OGIP = 530 - 600 Mio. m³(Vn)
- **LEER Z4: 2005**

Field History: Well History & Test Results

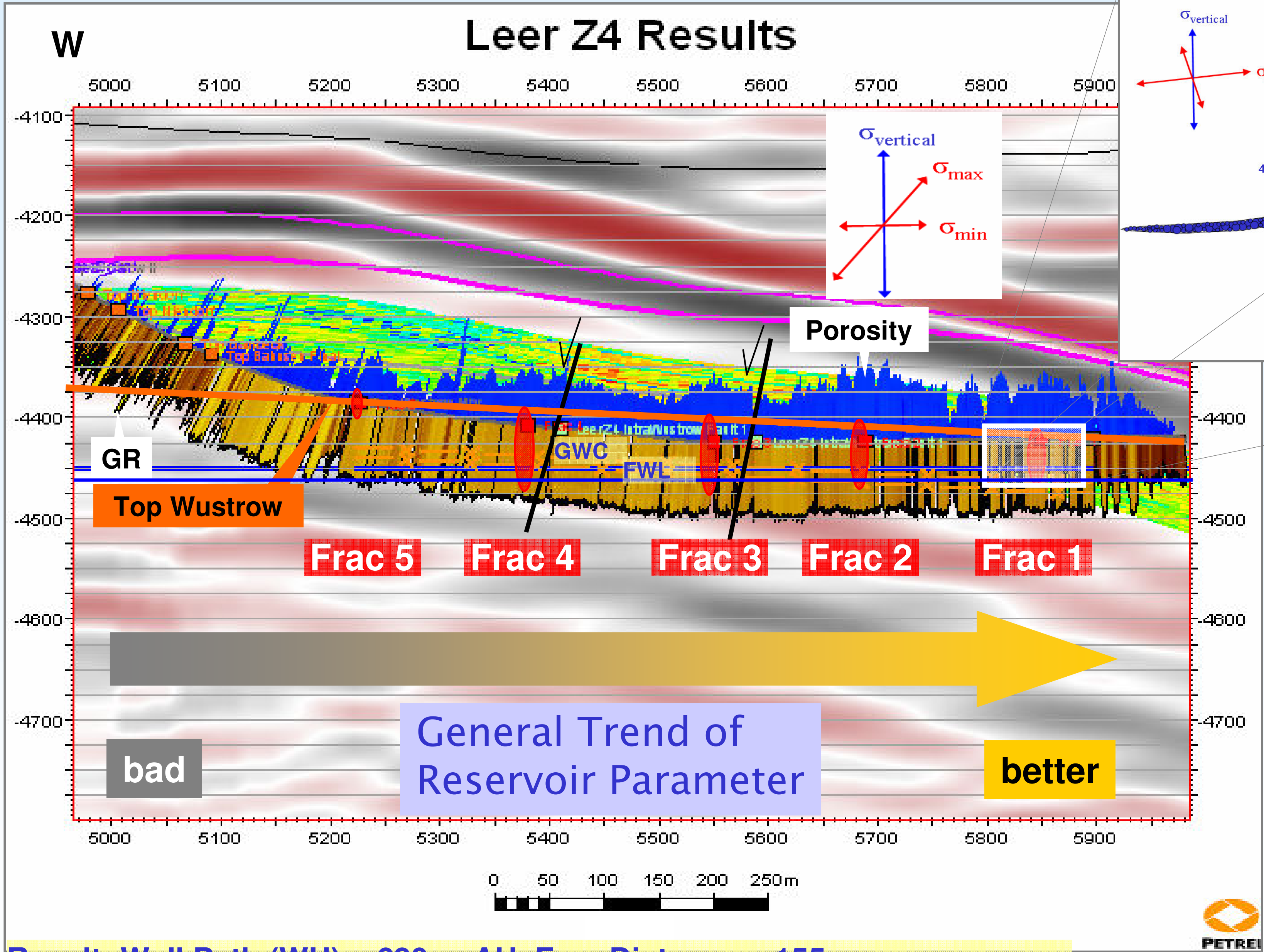


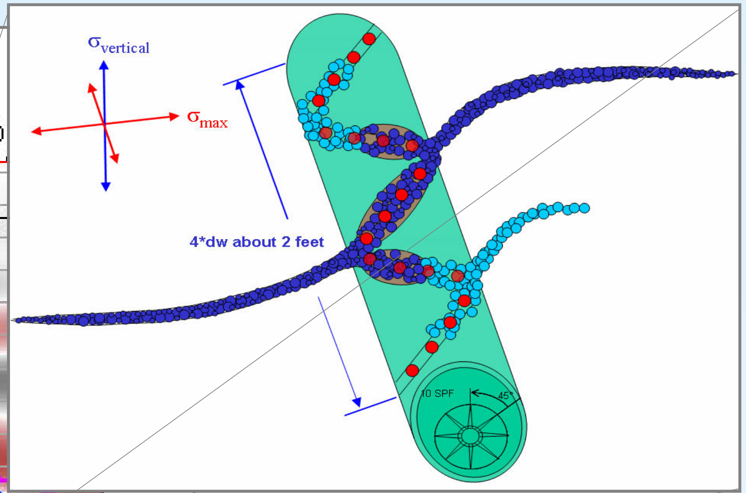


LEER Z4: Well Path:
W-E-Cross Section of Leer the Structure



Leer Z4: Seismic Section vs. Geomodel Reservoir Section

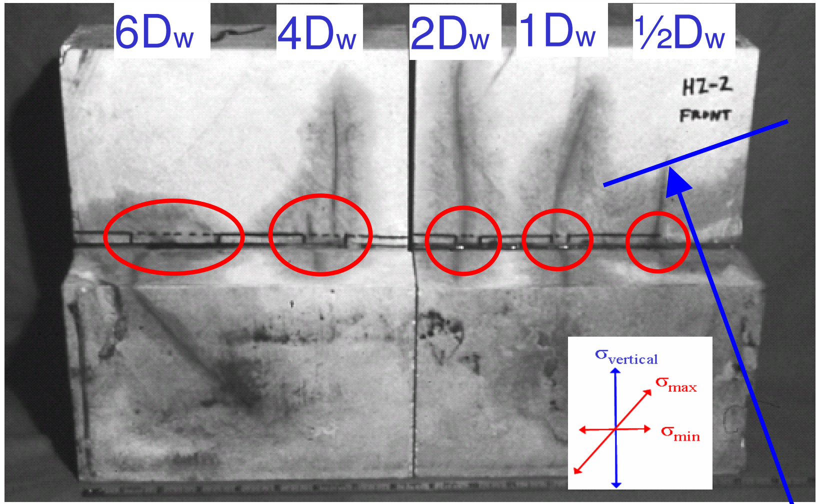




- Successful application of LWD-tools
- Estimation of fracture positions based on logging results → Influenced by: Sub seismic faults and compartments.
- Optimum number of fracture stimulations: Local conditions, numerical simulation and literature.
- Limited access: short perforation length

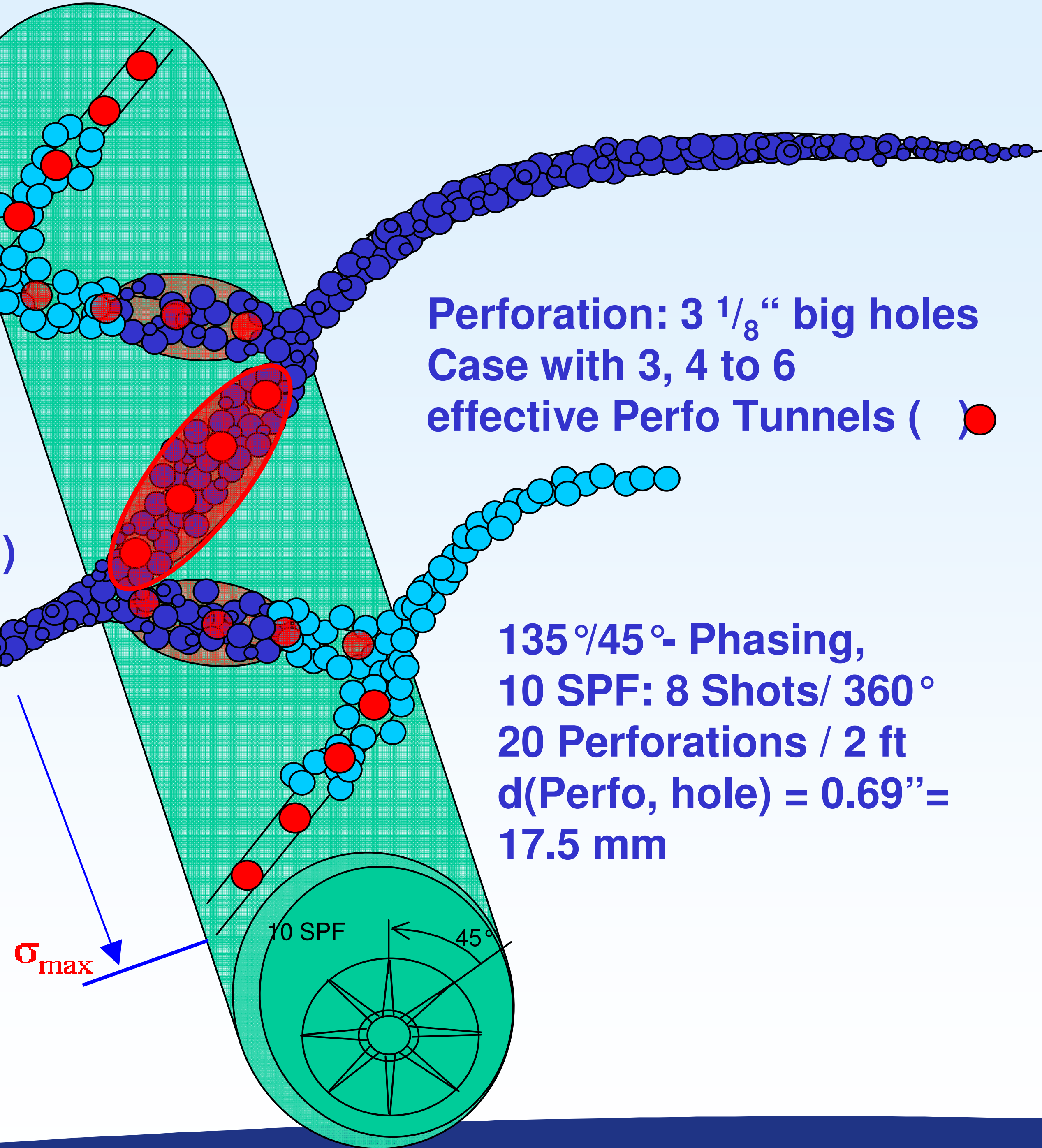
Result: Well Path (WU) = 680 m AH, Frac Distance = 155 m, Net-Thickness = 328 m AH, Porosity = 11.1%, Water Sat. = 31.9%, 3 Compartments (cutoffs: Phi>= 9%, Sw< 50%)

LEER Z4: Cross Section : W-E - Well Path with GR- and Porosity-Log together with Frac-Positions



Influence of Perforation Sections on Frac-Initiation (Dw= Well Bore Diameter)
Reference:
El-Rabaa (1989): SPE 19 720
(from Soliman (2004): SPE 86 992)

L(Perfo)

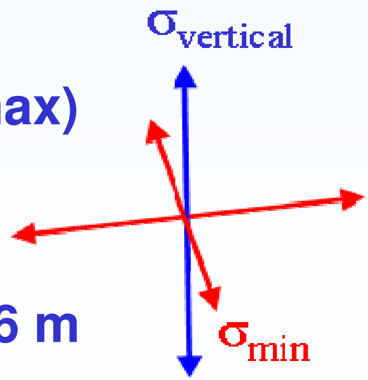


Perforation: 3 $^{1}/_{8}$" big holes
Case with 3, 4 to 6
effective Perfo Tunnels ( )

135°/45°- Phasing,
10 SPF: 8 Shots/ 360°
20 Perforations / 2 ft
d(Perfo, hole) = 0.69"= 17.5 mm

El-Rabaa:
L(Perfo) <= 4*Dw(max)

Soliman:
L(Perfo) ca.2 ft = 0.6 m



Expected Fracture Initiation and Propagation based on a 3 $^{1}/_{8}$" Perforation Gun

$$\Delta p_{Perfo} = C_1 \cdot q_{Injection}^2 \cdot \rho_{fluid} \Big/ \left(n_{Perfo}^2 \cdot C_d^2 \cdot d_{Perfo}^4 \right)$$

Δp_{Perfo} = Perforation Friction

$q_{Injection}$ = Injection Rate

ρ_{fluid} = Fluid Density

n_{Perfo} = Number of active Perforations

C_d = Form Factor f(Erosion)

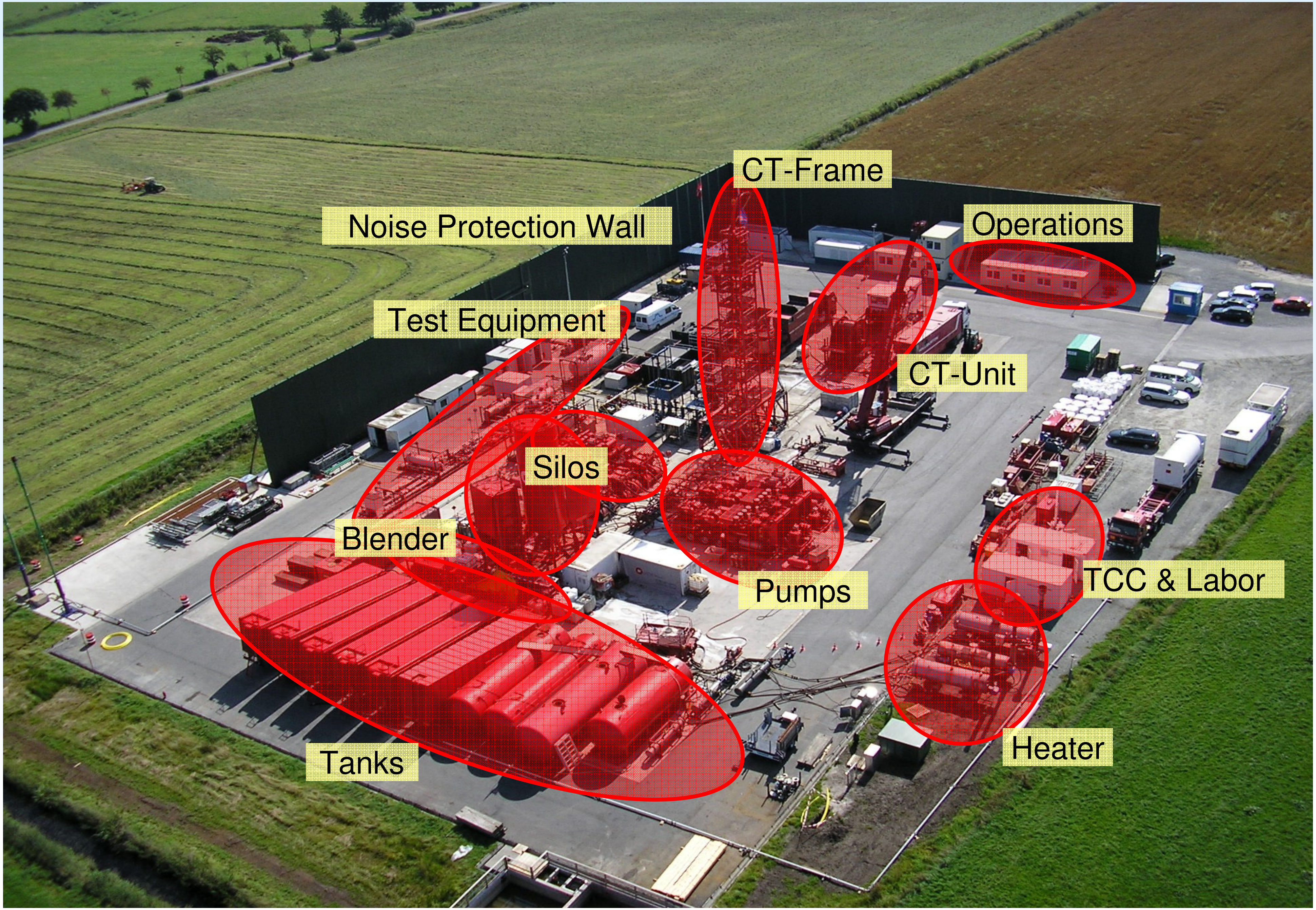
d_{Perfo} = Perforation Diameter @Casing

C_1 = Unit Factor

Perforation Pressure Loss for limited Entry Fracture Treatment
Based on sharp-edged orifice equation (Romero SPE 63009 and Shah, GRI-Paper)

Parameter	Symbol	Unit	Big Hole with 3 1/8"-Gun 10 SPF Perforation 20 holes/2 ft Low Case	Most Likely	High Case
Hole Diameter	d(hole)	inch	**0.56**	**0.56**	**0.56**
		mm	14.2	14.2	14.2
Phasing		Deg.	60	60	60
Holes/360°		1	6	6	6
Perforation Length	L(Perfo)	inch	**1.87**	**1.87**	**1.87**
		mm	47	47	47
Effective Number of Holes	N(holes)	1	**3**	**4**	**6**
Fluid Density	Rho(fluid)	kg/m³	**1 040**	**1 040**	**1 040**
		lb/gal	8.68	8.68	8.68
Injection Rate	q(injection)	m³/min	**4.00**	**4.00**	**4.00**
		bpm	25.16	25.16	25.16
Injection Rate per Hole		bpm/hole	8.39	6.29	4.19
Proppant Quantity	m(Prop.)	tons	**120**	**120**	**120**
		lbm	264 555	264 555	264 555
Discharge Coefficient	Cd		**0.89**	**0.89**	**0.89**
Perforation Pressure Drop	D(p,perfo)	psi	1 856	1 044	464
		bar	**128**	**72**	**32**

LEER Z4: Expected Perforation Friction



LEER Z4:
Layout: Frac- and Test-Equipment

Principle Treatment Schedule:
Data Frac 1 (Breakdown & SRDT 1) → Mini Frac → Data Frac 2 (SRDT 2) → Main Frac

Remarks

- All fracture fluids will be marked with fracture individual tracers

1. Breakdown

- Initiation of a fracture
- Stable fracture propagation

2. Step Rate Down Test 1

- Estimation of near well bore friction (perforation and tortuosity)
- Estimation of effective numbers of perforations (min. 3 - 4 „big holes“)

3. Shut-in

- ISIP, fracture closure and reservoir pressure

4. Mini Frac

- Creation of a x-linked fracture
- Modelling of fracture propagation
- Leak-off behavior, erosions with x-linked gel and low conc. proppant stage (1 - 3 ppg)

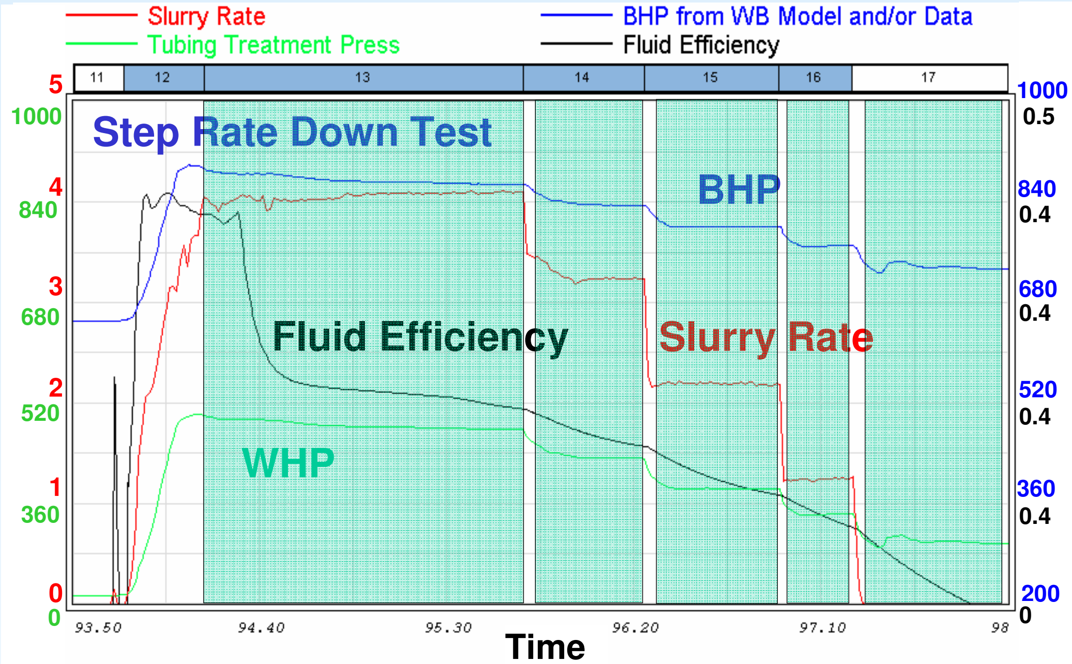
5. Step Rate Down Test 2

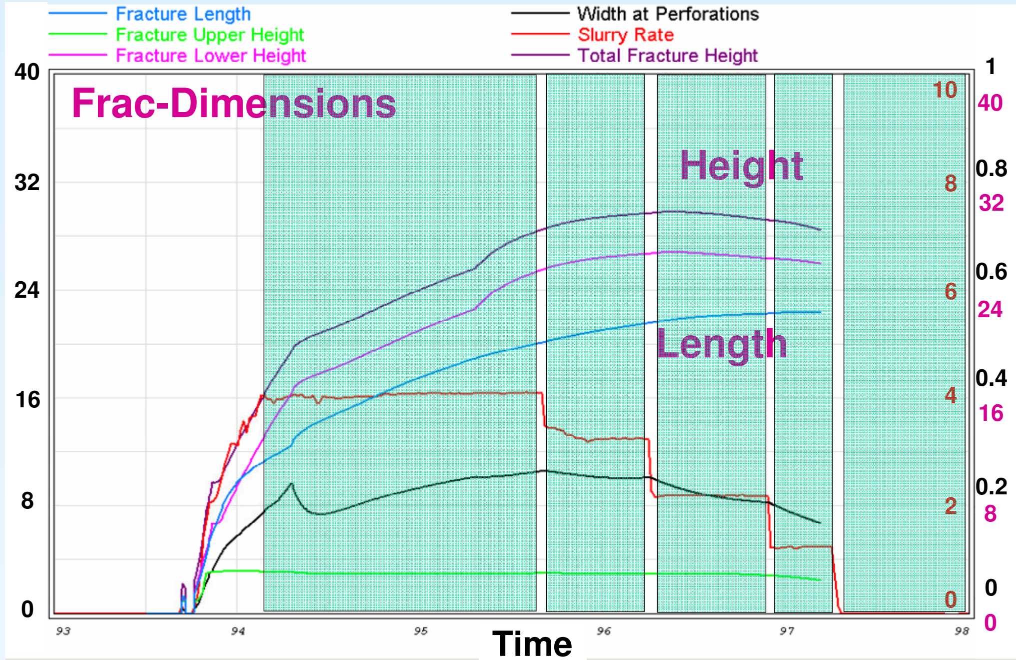
- Analog Step Rate Down Test 1 Recognition of differences

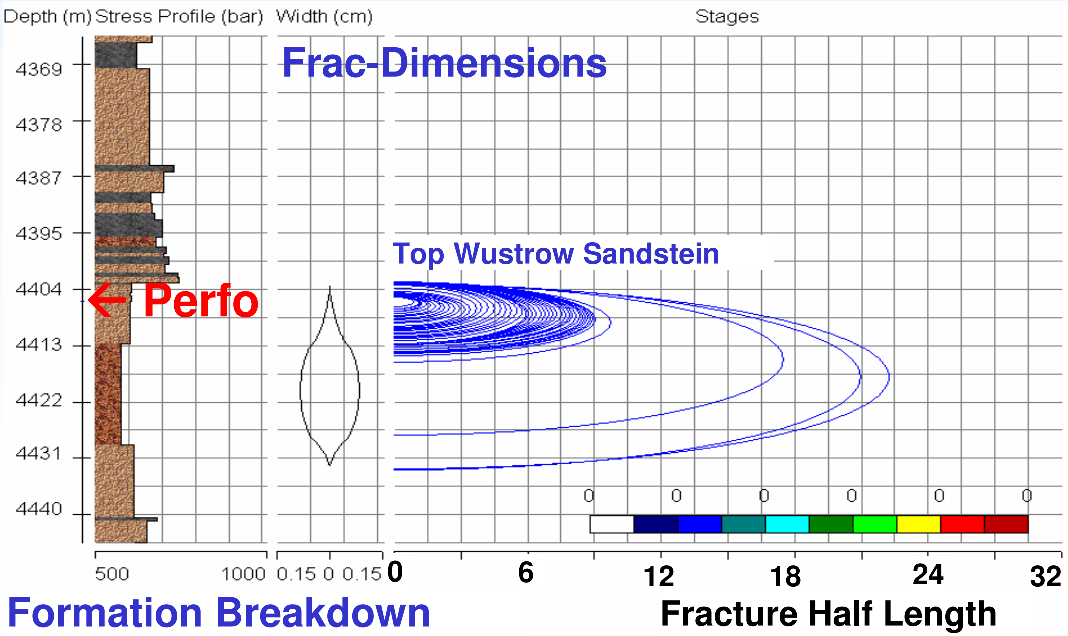
6. Main Frac

- Based on the previous examinations

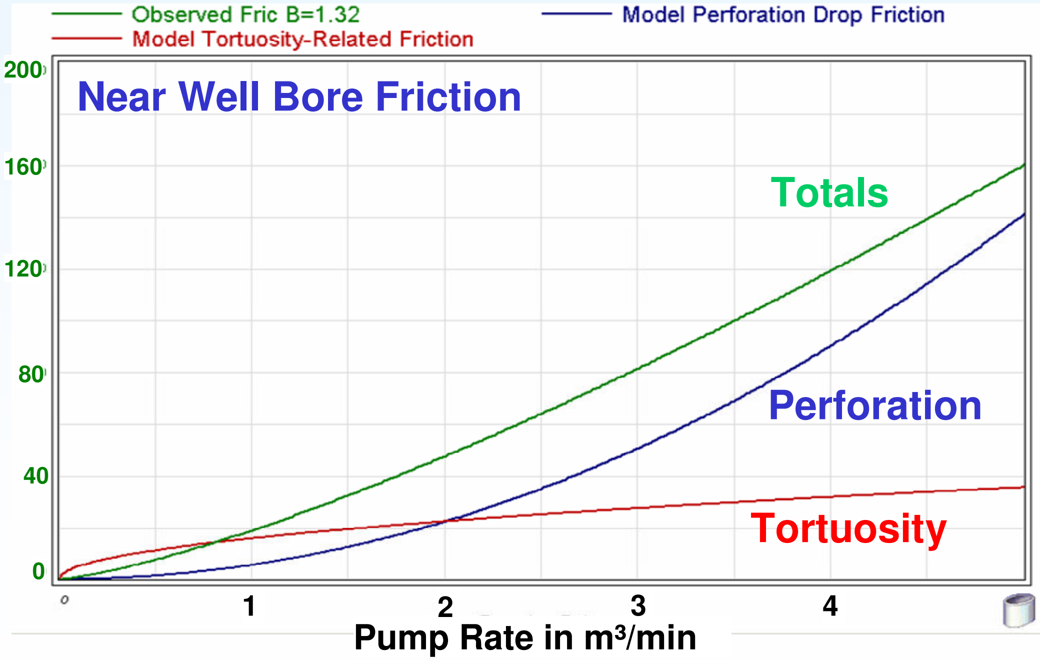
LEER Z5: Treatment Schedule



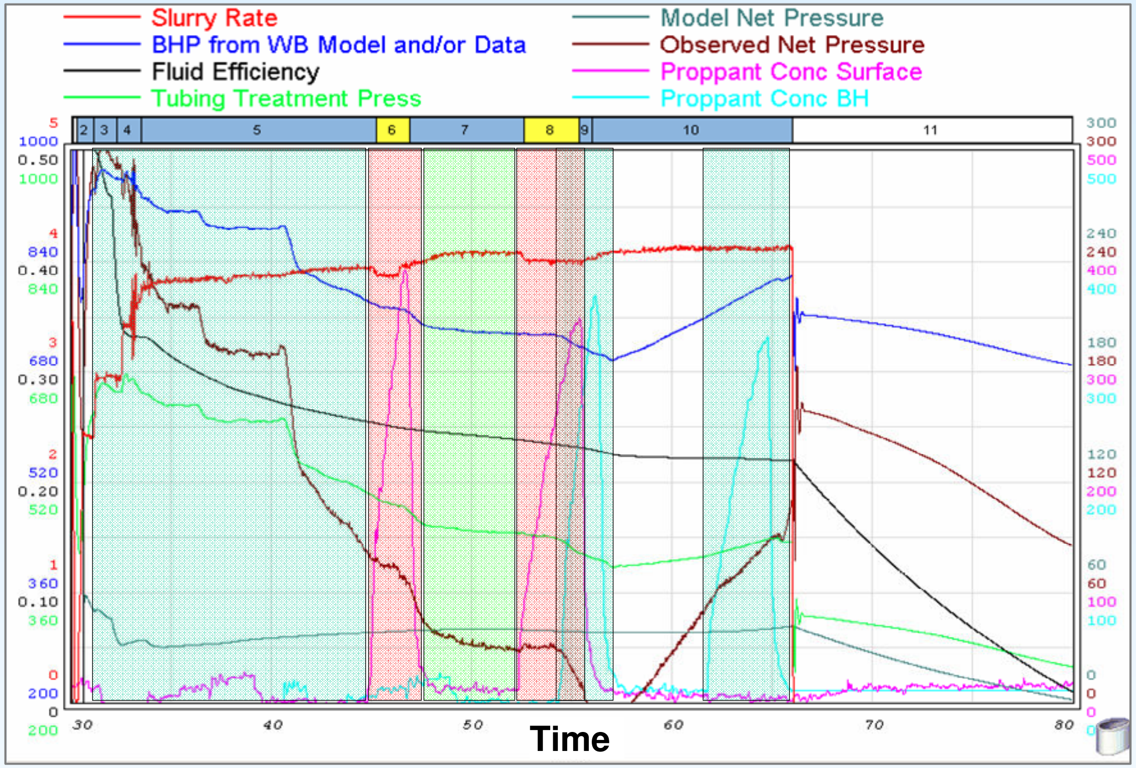


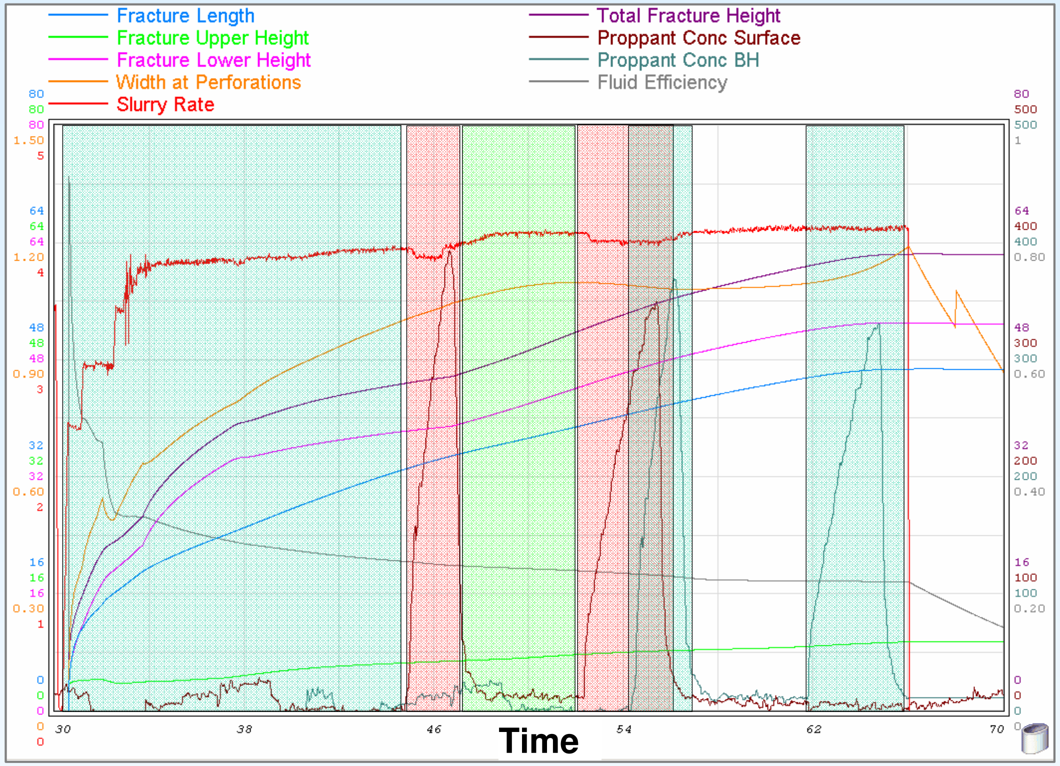


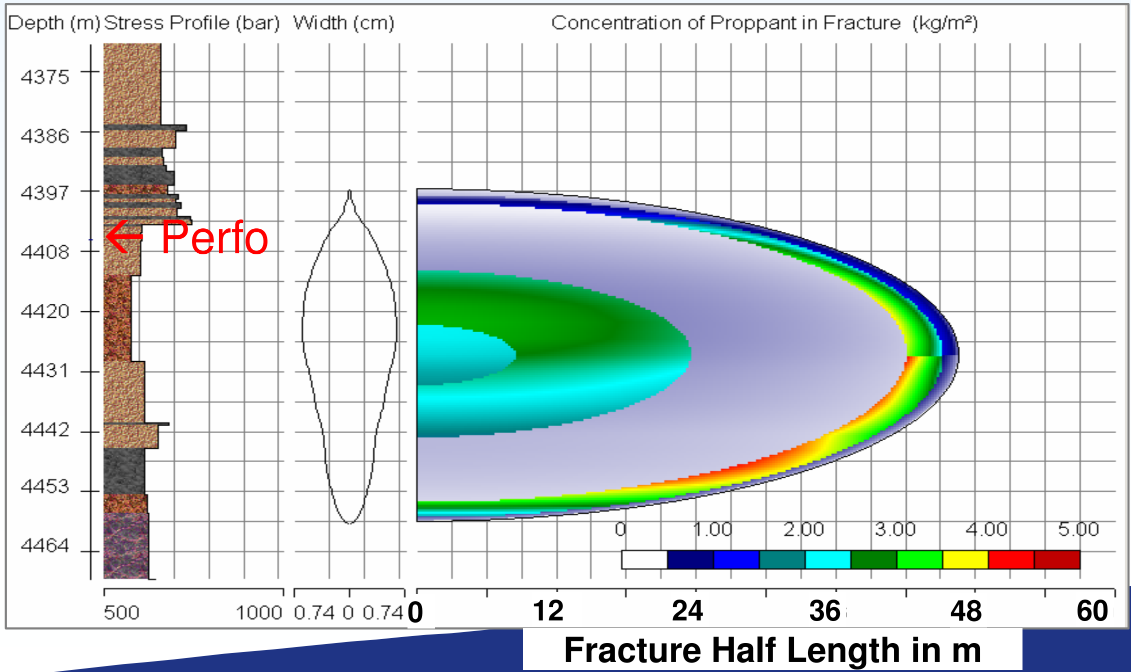
Formation Breakdown
Near Well Bore Friction
effective Perforation



LEER Z4: Data Frac 1:
Breakdown Step Rate Down Test from Frac 4







- **Design of PAD volume to access securely the vertical fracture height.**
  Investigation of erosion potential with x-linked gel and low concentrated proppant slugs.
- **1-2 slugs (prop. conc.: 1-3 ppg – 120-360 g/l). Slug stages are placed to be effective after stabilization of fracture propagation.**
- **If two proppant slugs are pumped a sufficient buffer of x-linked gel is essential.**
- **General Leer problem: To initiate a fracture from a high stress regime to a low stress regime → low fracture width @perforation.**

LEER Z4: Mini Frac: Example: Frac 4

LEER Z4: Fracture Treatments - Friction Results

Frac	Treatment	Perforation Friction bar	Totuosity Friction bar	total Friction bar	Ratio Tortuosity on total Fric.	Ratio Perforation on total Fric.	effective Perfo. PEG	effective Perfo. Halli.	effective Perfo. selected	Ratio eff. Perfo. selected	total Number of Perf.	Remarks
1	SRDT	180	47	227	21%	79%	4		4	20%	20	pre Mini Frac
2	SRDT 1	95	93	188	49%	51%	3	4	4	20%	20	pre Mini Frac
2	SRDT 2	51	81	132	61%	39%	4		4	20%	20	post Mini Frac
3	SRDT 1	227	18	245	7%	93%	2	3.7	3	15%	20	pre Mini Frac
3	SRDT 2	60	69	129	53%	47%	3	5.3	4	20%	20	post Mini Frac
4	SRDT 1	108	25	133	19%	81%	2	4.5	4	20%	20	pre Mini Frac
4	SRDT 2	81	41	122	34%	66%	3	4.5	4	20%	20	post Mini Frac
5	SRDT	144	45	189	24%	76%	7	12	9	30%	30	pre Mini Frac

LEGEND:

SRDT 1 = Step Rate Down Test before Mini Frac.

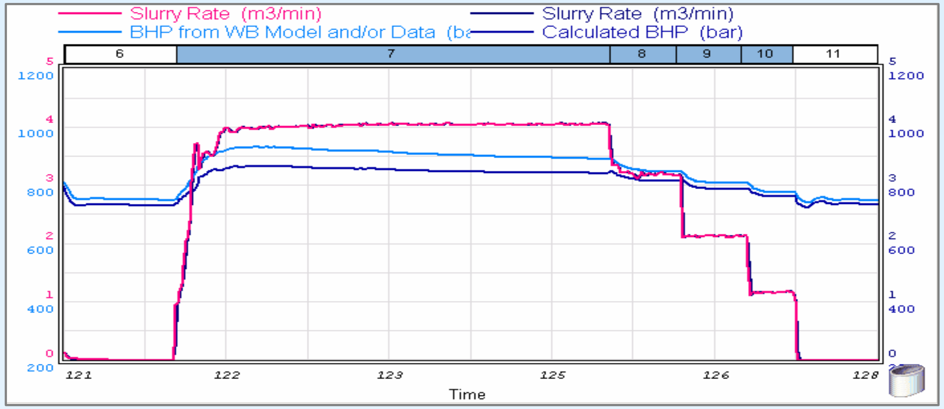
SRDT 2 = Step Rate Down Test after Mini Frac.

High perforation friction before Mini Frac, even with „big holes“.

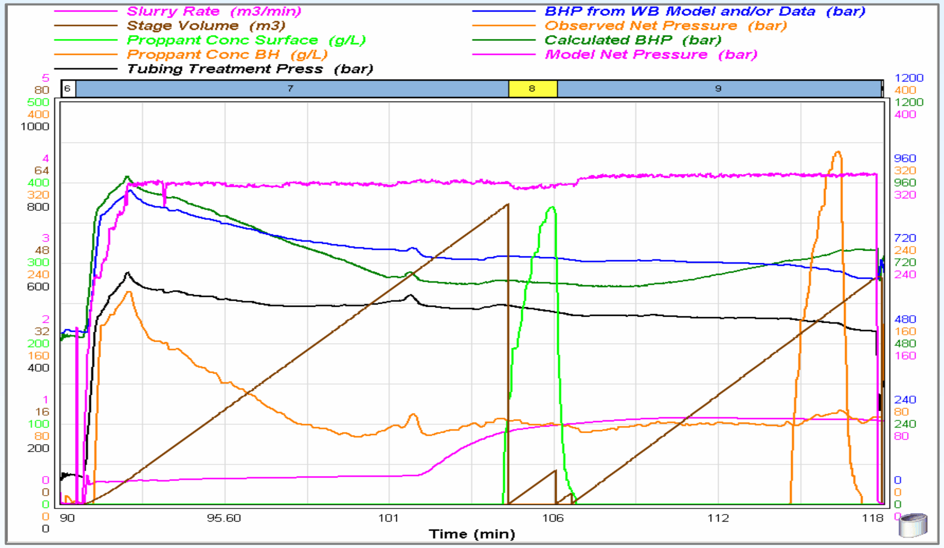
Significant lower perforation friction after Mini Frac, due to erosion (x-linked gel and proppant slugs).

Tortuosity is relatively low: Transverse fractures are expected (suitable well direction: ENE)

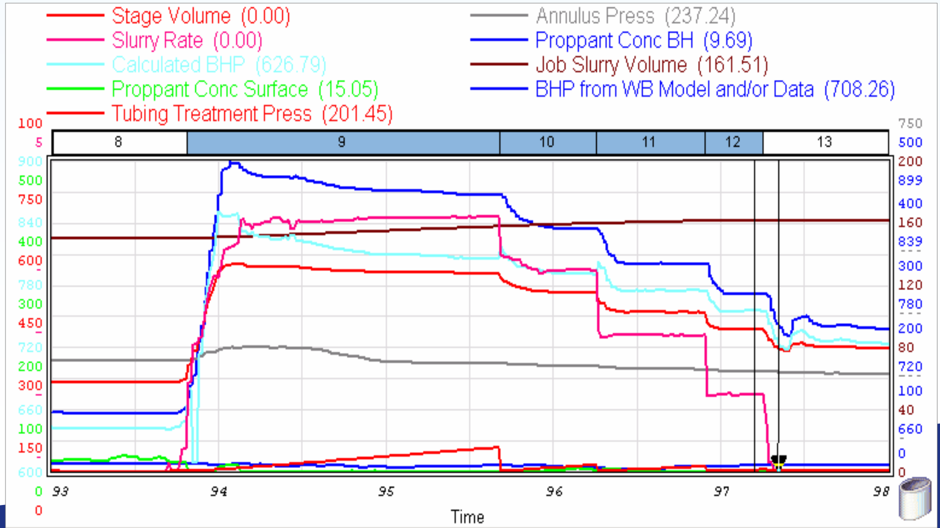
Observed perforation friction and tortuosity
LEER Z4: Comparison: Data Frac 1 und 2 of Frac 2 to Frac 4



Breakdown volume must be scheduled to reach a stable vertical fracture status, where a step rate down can be performed.

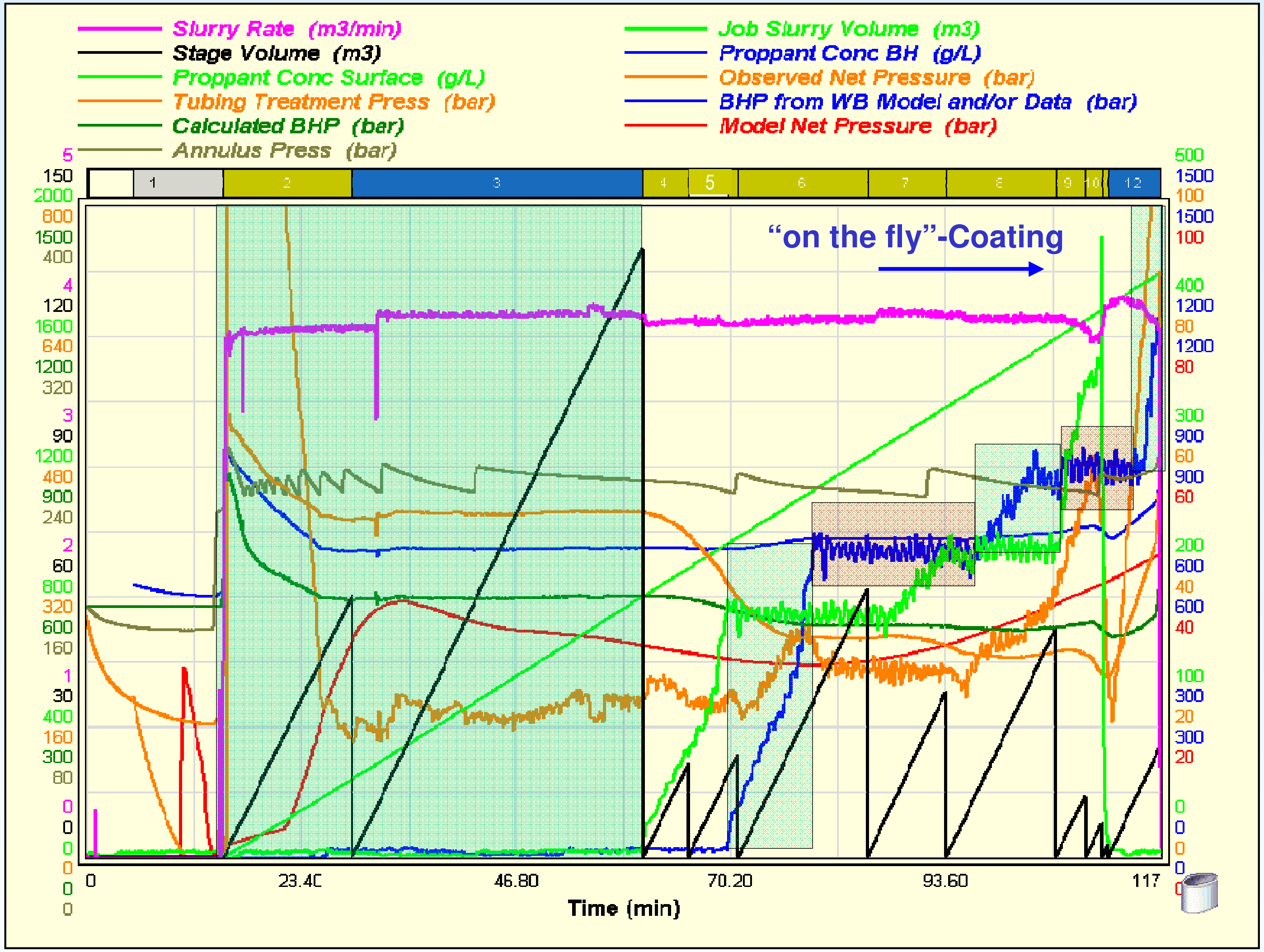


The Mini Frac must be designed to reach the main vertical sequence and thus to examine the vertical stress profile.
1 slug test from 1-3 ppg should be sufficient.

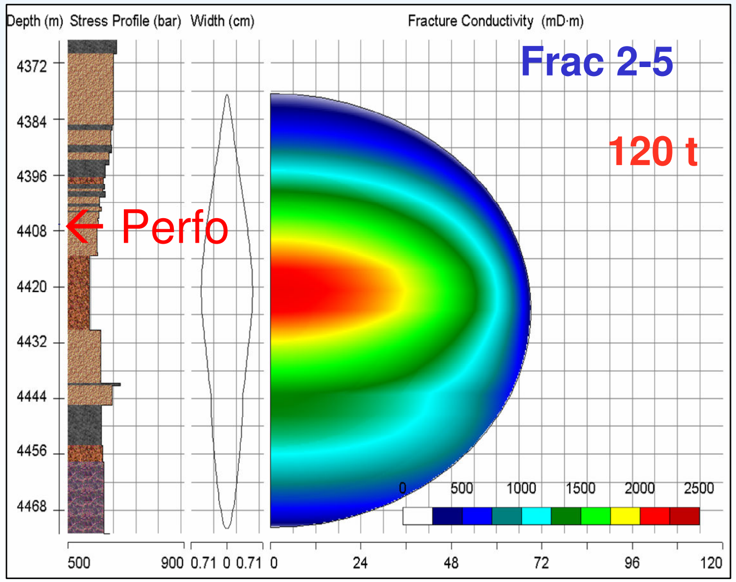


A step rate down test post Mini Frac should be performed as a standard to investigate the curability of the NWB friction.

LEER Z4: Stimulation and Strategy Breakdown & STDT 1, Mini Frac and SRDT 2

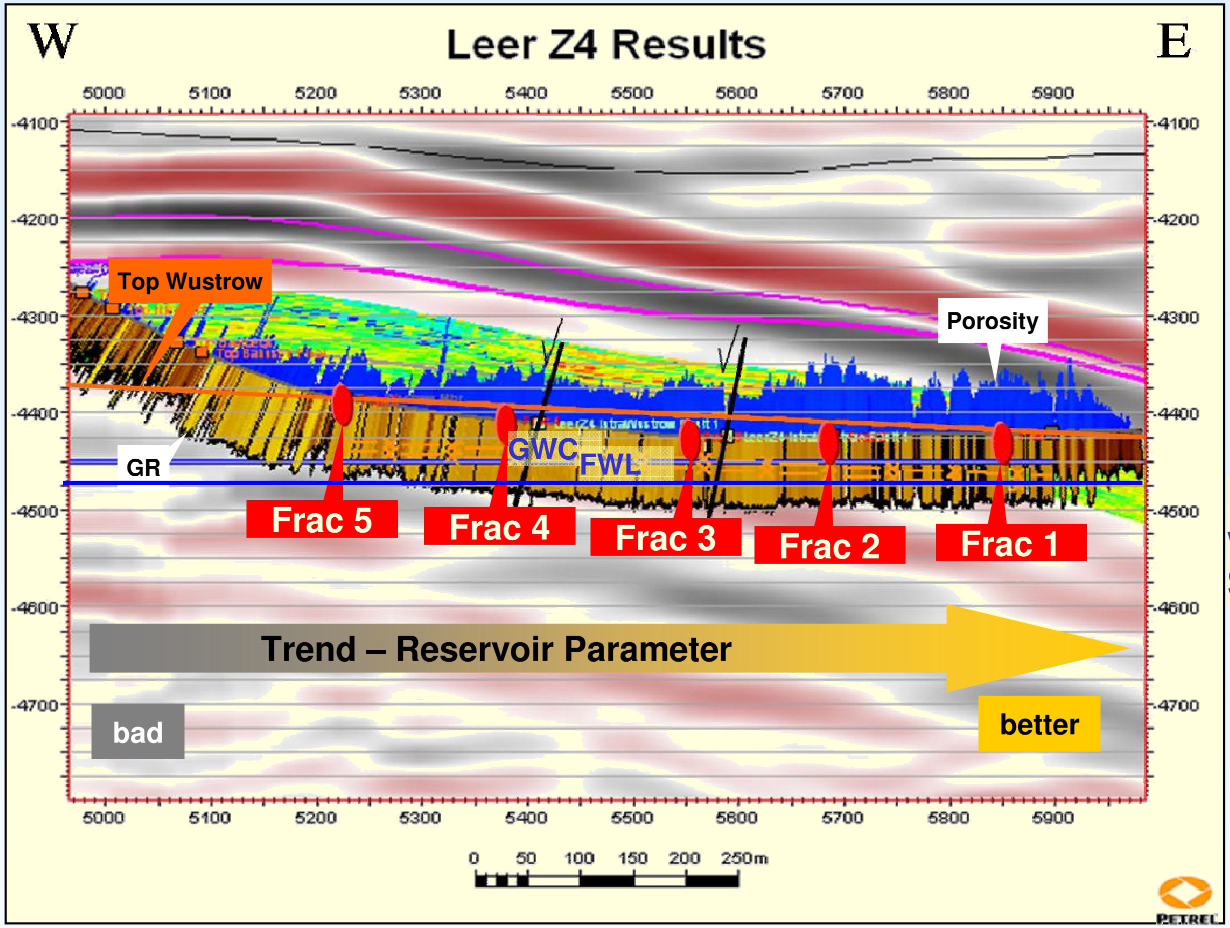


- Plateau @6 ppg: Begin "on the fly"-coating @50% proppant quantity.
- Smooth transfer to the next plateau.
- Plateau @8 ppg
- Tail of treatment: Problem with limited number of perforations → Screenouts can occur.

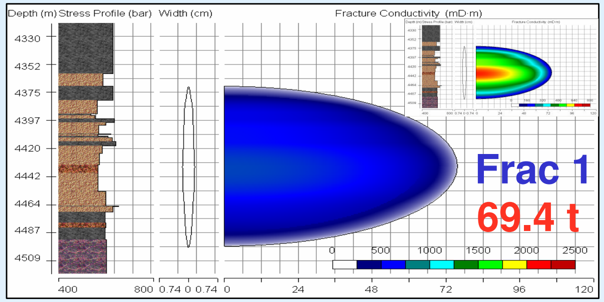


- Pad volume according to stress profile and fracture dimensions, optional with slug stages.
- Smooth enhancement of proppant concentration to reach the first plateau phase with relatively constant proppant concentration.

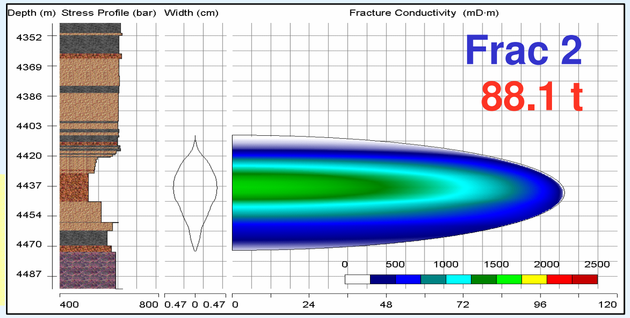
LEER Z4: Main Frac: Example: Frac 4

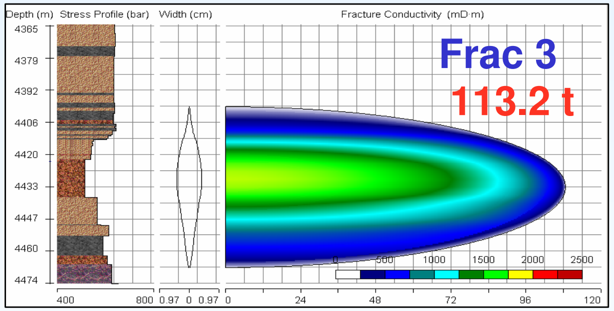


Trial with composite plugs: Temporarily plugged of with: Sand plug



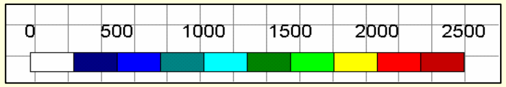
Plugged-off with: Sand plug



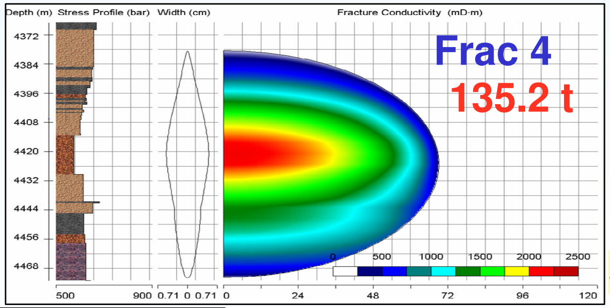


Plugged off: Sand plug „auto-cleanout“ forced to set a new separate sand plug

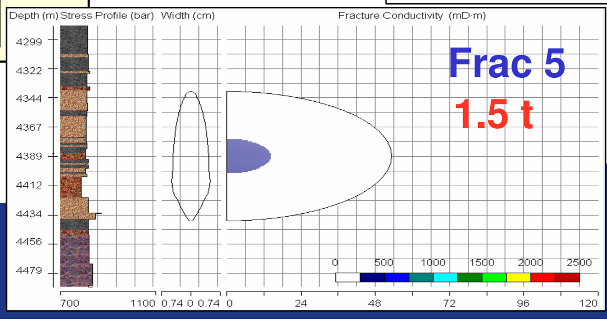
All fractures are shown with the same fracture conductivity kf*wf scale in mD.m
@Fracture damage factor = 50%.



Target fracture conductivity



Sandout = Sand plug



LEER Z4: Main Fracture Comparison: Frac 1 to 5

LEER Z4: General Fracture Treatment Data

Frac	Treatment	Clean Volume m³	PAD m³	Slug	100-Mesh Sand tonnes	Pumped Proppants tonnes	Formation Proppants tonnes	Sandout tonnes	final BH Prop. Conc. ppg	Remarks
1	Mini Frac	195.94	25	two Slugs		5.42	5.42	0.00		
1	Main Frac	284.33	55+20P+80	7.61 to Slug		98.98	63.98	35.00	7.92	Sandout
		480.27			0.000	104.4	69.4	35		
2	Mini Frac	178.99	60	two Slugs		4.81	4.81	0.00		
2	Main Frac	355.38	200	no		84.59	83.31	1.28	11.26	TSO-shape slight
		534.37			0.000	89.4	88.12	1.28		
3	Mini Frac	157.01	60	one Slug		2.022	2.022	0.00		
3	Main Frac	391.27	60S+140	100 Mesh Sand	0.359	111.78	111.19	0.59	12.45	TSO-trial pnet=80bar
		548.28			0.359	113.80	113.21	0.59		
4	Mini Frac	159.47	60+6P+25+11P	two Slugs	0.359	6.23	6.08	0.15		
4	Main Frac	407.47	60S+140	100 Mesh Sand		138.98	129.12	9.86	10.50	Screenout
		566.94			0.359	145.21	135.20	10.01		
5	Data Frac 1	14.6		Breakdown				0.00		30.09.2005
	Data Frac 2	6		Breakdown				0.00		01.10.2005
	"Erosion Frac"	274.5		Gel-Slug+2 Sand Slugs	1.100			0.00		02.10.2005
	Mini Frac 1	96.5	25	1ppg Slug		0.60	0.60	0.00		03.10.2005
	Mini Frac 2	96	25	0.5-3 ppg Slug		1.04	0.90	*0.14*		03.10.2005
		487.6			1.100	1.64	1.50	0.137		
1-5	Total	2617.5			1.818	454.45	407.43	47.02		

Proppants: 407 tonnes
Clean Fluids: 2 618 m³
(during fracturing treatments)
Total Injection: 3 172 m³

LEER Z4: Fracture Treatment
Fracture Stimulation 1-5: Fluids and Proppants

LEER Z4: Fracture Treatments - Friction Results

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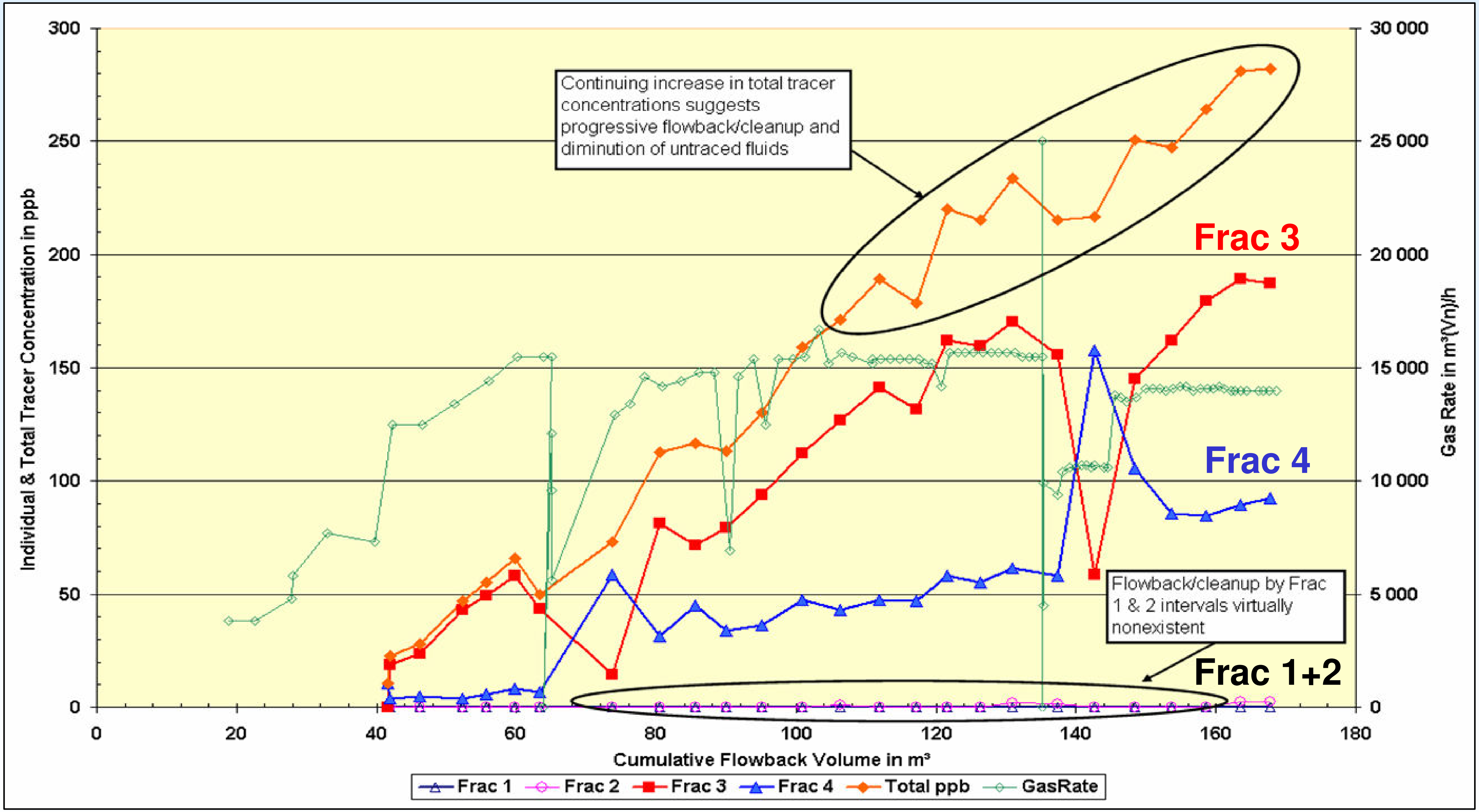
2	SRDT 2	51	81	132	61%	39%	4		4	20%	20	post Mini Frac
3	SRDT 1	227	18	245	7%	93%	2	3.7	3	15%	20	pre Mini Frac
3	SRDT 2	60	69	129	53%	47%	3	5.3	4	20%	20	post Mini Frac
4	SRDT 1	108	25	133	19%	81%	2	4.5	4	20%	20	pre Mini Frac
4	SRDT 2	81	41	122	34%	66%	3	4.5	4	20%	20	post Mini Frac
5	SRDT	144	45	189	24%	76%	7	12	9	30%	30	pre Mini Frac
	Mean Pre	151	46	196	23%	77%	4		4	16%	22	
	Mean Post	64	64	128	50%	50%	3		3	17%	20	

LEER Z4: Fracture Treatments - Fracture Results

LEER Z4 - Fracture Geometric Results

Frac	Fracture Half Length xf m	Fracture Height xh m	Fracture Conductivity wf*kf with 50% Damage md.m	Final Proppant Concentration at Perforation g/l	Final Proppant Concentration at Perforation ppg	CarboProp 20/40 Proppants in Formation tons	Fracture Width at Perforation mm	Average Fracture Width mm	Reservoir Pressure @4420 m TVDss BHSIP bar
1	76	77	550	890	7.4	69.4	3	2	531
2	97	62	1000	1300	10.8	88.1	7	3	487
3	105	66	1250	1440	12.0	113.2	9	4	614
4	69	93	1500	1230	10.3	135.2	10	5	606

LEER Z4: Frac 1-4 (5): Fracture Treatments: Friction Results and Fracture Dimensions



LEER Z4: Well Cleanout/ Tracer Analysis
Result of Fluid Flowback

- **The Leer Z4 was designed with a “mono bore”-Cr13-95-completion, which was used during the well simulation and is used as a production string.**
- **Fracture initiation was generated in high stress zones, while the fracture propagates into low stress zones, which were generated by lower reservoir pressures.**
  Problem: Fracture stabilization, fracture width and fracture propagation: Risk of pre-mature screenout.
- **Each fracture has been marked by individual tracers.**
  During well cleanout and later production: Quantitative observation on fracture contribution.
- **On the fly-coating with special resin (Expedite XP) prevents backflow of proppants.**
- **The scheduled temporary shut-off of stimulated fractures with composite bridge plugs was not possible.**
  As an “alternative” sand plugs were used to shut-off the prior stimulated perforation
  → Problems:
  - Well head pressure must be kept in the range of 260 – 300 bar to perform sand cleanout with coiled tubing and to ensure stability of the temporary sand plug.

    Disadvantage applying high back pressure: critical low fluid velocity (limited hydraulic power) and enhanced erosion on the used 2” coiled tubing.
  - In general: Very limited access to the reservoir. Effective number of perforation holes (3-4).
  - Formation breakdown with fracture initiation: Risk of sand blocks due to residual proppants from prior treatments.

LEER Z4: Peculiarities of the Fracture Stimulation

- Despite tectonic and facies insecurities:
  An optimized access of the upper section of the Wustrow-Sandstone was reached.
- Main contribution of successful geo-stearing was the application of LWD-Tools.
- During the construction of the well site a gas connection to the public gas network was installed to ensure energy supply to heat-up the fracture fluids.
- Application of transportable gas-heaters to warm-up the fracture fluids:
  A quick and flexible heating system was created.
- Concept: Fracture treatment with "mono-bore" completed well.
  No workover after stimulation is needed. The aim is to use the completion during the first production years to reach an economic project.
- Sirocco gels and „Expedite (XP)“ applied as „on the fly - coating“ was found to be useful.
- The concept of the fracture treatment was adopted to the local circumstances and improved:
  General strategy: Data Frac 1, Mini Frac, Data Frac 2 und Main Frac.
- The well azimuth (about ENE) reached at least a relative low tortuosity friction.
- Application of individual markers (tracers) were quite successful.
- On the well location the fracture stimulation team was present during all stages of the treatment.

LEER Z4: Positive Experiences

- **Limited access to the reservoir through generally 3-4 big hole perforations with relatively high initial perforation friction.**

- **Problem to maintain fracture width stability during the fracture initiation, especially by fracturing a high stress zone while the fracture propagation will allocate low stress zones.**

- **The Mini Frac gel volume must be enhanced significantly to reach about 2/3 of the main fracture height to ensure more "Main Frac"-treatment-security.**
  This was caused by vertical reservoir pressure changes in the sandstones and thus unexpected vertical stress differences.

- **Due to the dogleg severity and a completion with relatively thick tubing wall the planned composite bridge plugs could not be set.**

- **By applying the "alternative" sand plugs disadvantages occurred:**

  High back-pressure, instable plug settings, additional time loss, insufficient well sandout treatments with coiled tubing (limited circulation rates), higher coiled tubing erosion, formation breakdown with linear gel due to residual sands, risk of sand bridges in the next treatment.

  → For follow-up "tight gas" projects: Changes in the well path design and the well completion.

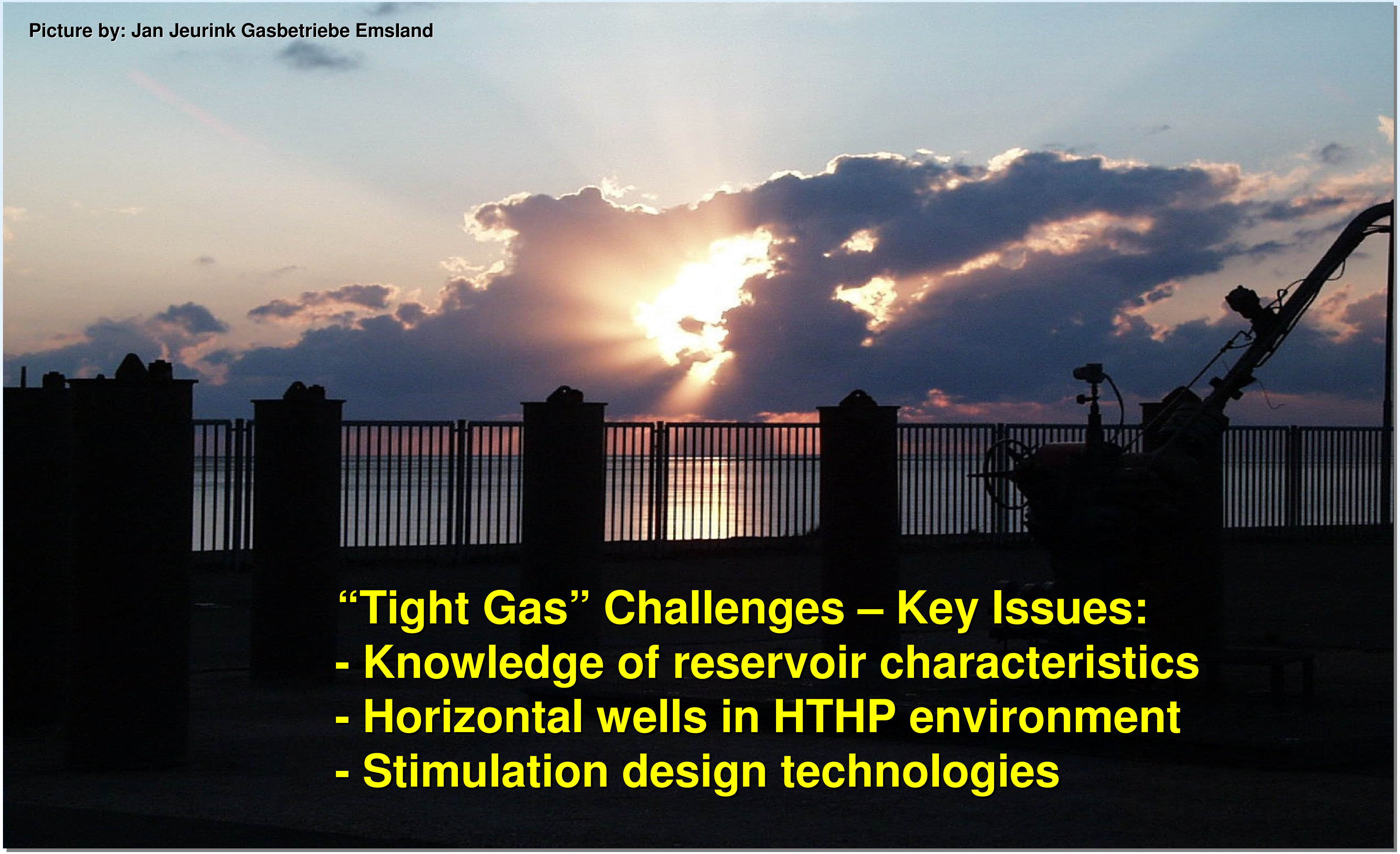
LEER Z4: Negative Experiences

Gaz de France

wintershall

BASF-Gruppe

We like to thank our Leer consortial partner Wintershall AG for the possibility to present this “tight gas” - contribution.


Picture by: Jan Jeurink Gasbetriebe Emsland
"Tight Gas" Challenges – Key Issues:
- Knowledge of reservoir characteristics
- Horizontal wells in HTHP environment
- Stimulation design technologies