Collaborative Geological-Engineering Integration for Unconventional Reservoir Development

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Investigating Wellbore Stability Challenges Resulting from Pyrite Oxidation-Induced Elevated Temperatures in Unconventional Shale Gas Drilling

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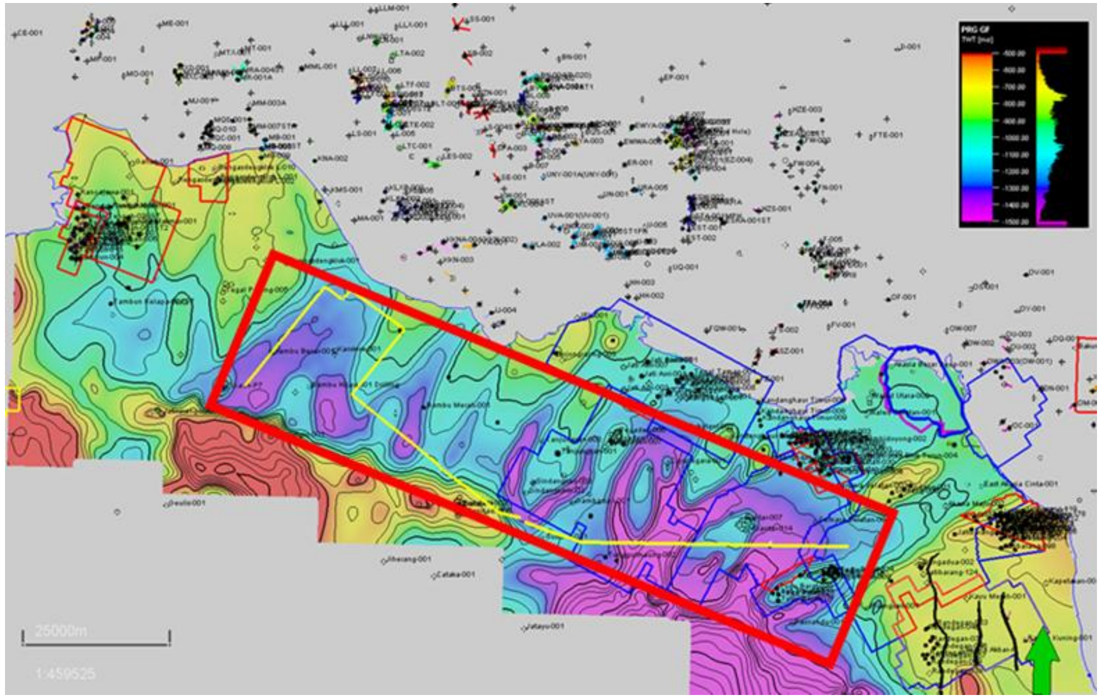
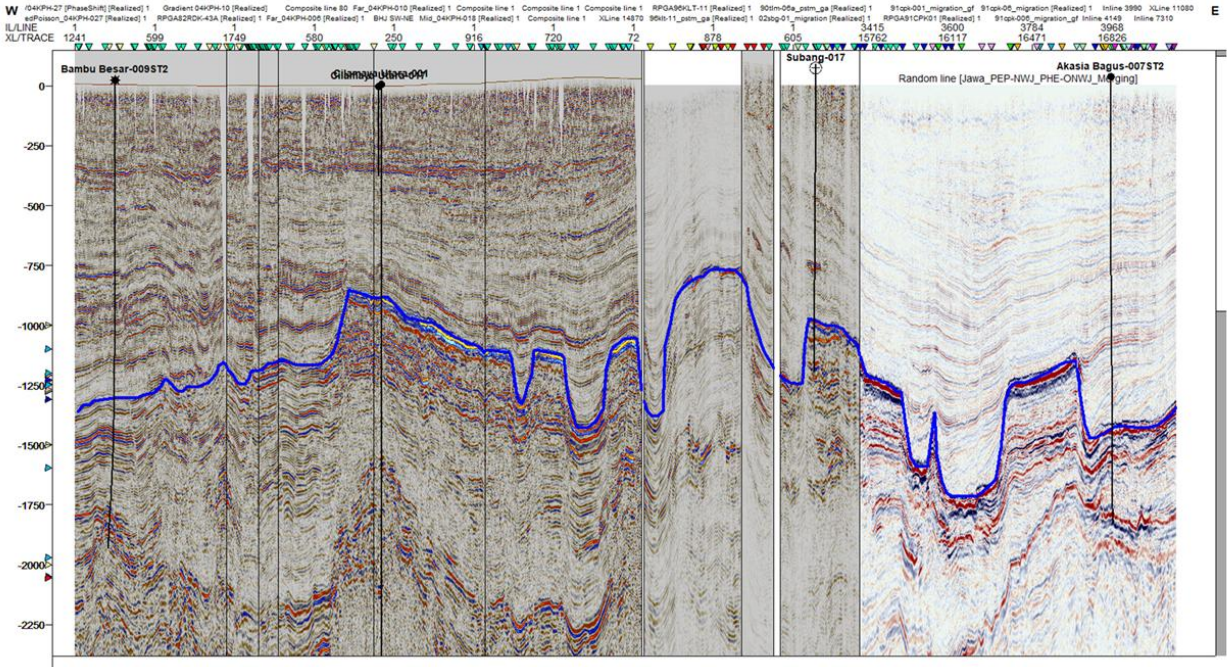
Introduction



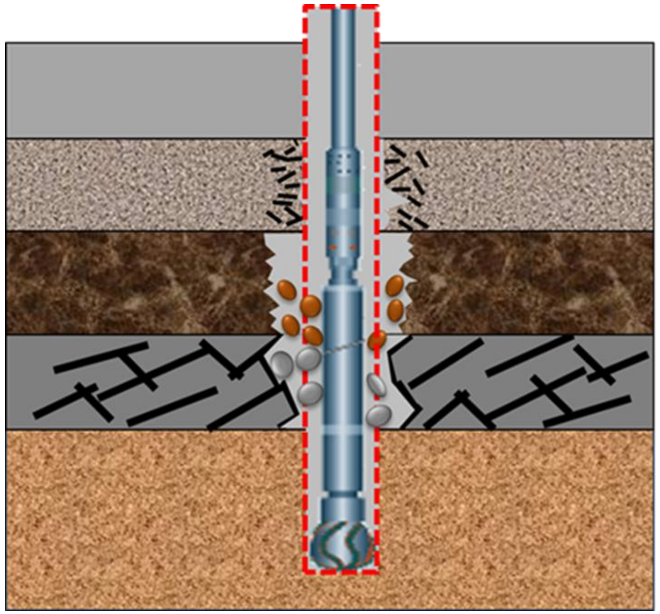
Bottom structure depth of Cisubuh Formation, Onshore North-West Java Basin. The red rectangle is the study area (Bambu Besar, Subang, and Akasia Bagus fields). (Figure courtesy PT Pertamina Hulu Energi, 2025)



NWJB – Cisubuh seismic cross section: Bambu Besar, Cilamaya Utara, Subang, Akasia Bagus (Figure courtesy PT Pertamina Hulu Energi, 2025)

Cisubuh Formation in Akasia Bagus (ABG) and Subang (SBG) fields has potential unconventional resources

Challenges



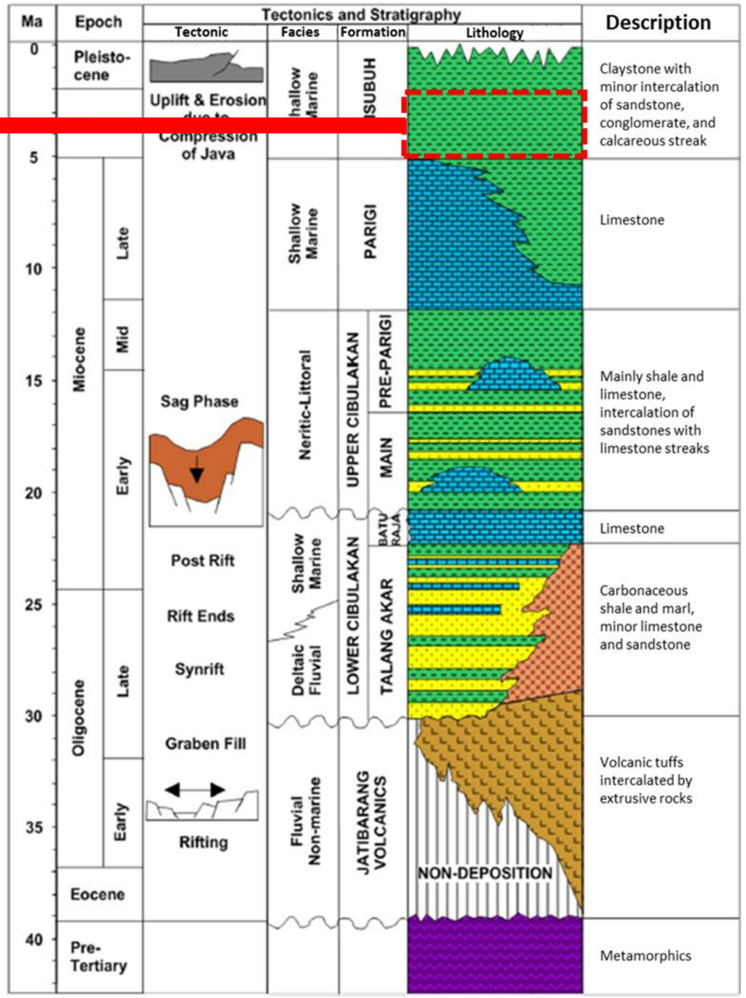
High temperature ➕ Physico-Chemical ➕ Time-dependent

↓

Poro-visco-elastic

Cisubuh Formation Significant features:

- ✓ Hot → ~95°C
- ✓ Swelling, sticky
- ✓ Sloughing
- ✓ Brittle



Common stratigraphy of NWJB. The Cisubuh Formation, particularly its middle and lower section (red dashed rectangle), is the focus of this study within the North West Java Basin. (figure modified after Putra et al., 2016)

Questions

- What cause(s) the elevated temperature in Cisubuh?
- How clay minerals content affect the poromechanics of mudrock in Cisubuh Formation?
- How to determine time-to-failure for Cisubuh Formation?

Hypothesis

Elevated temperature from pyrite oxidation accelerates clay mineral instability in Cisubuh Formation mudrocks, altering poromechanical behavior and causing time-dependent wellbore instability during drilling operations.

Methods

Samples from available cores and drilling cuttings collected from 3 fields, 6 wells

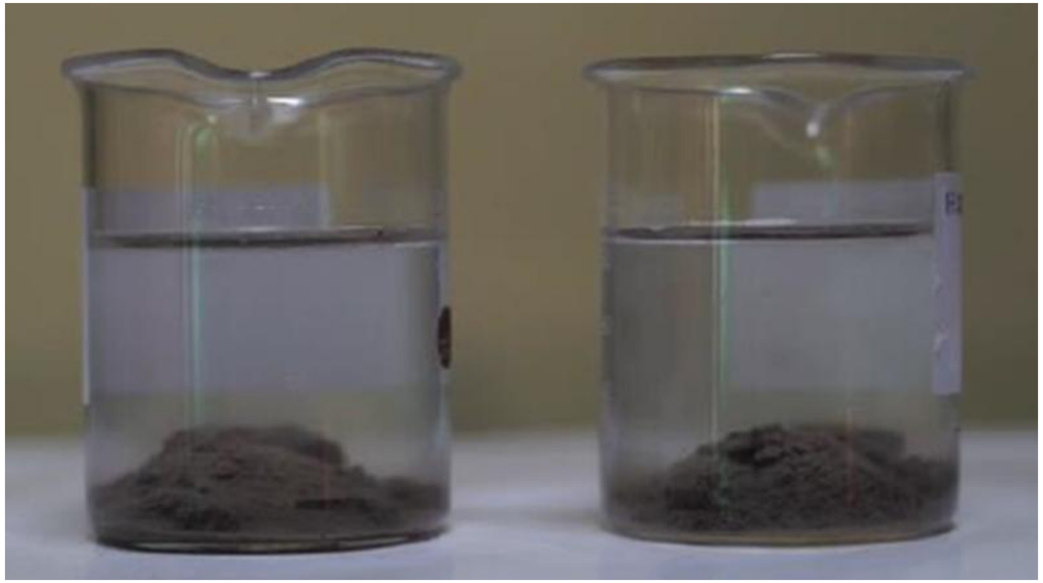
XRD Test

- ✓ To identify the mineral composition
- ✓ To determine pyrite content and clay mineral types and quantities

Triaxial Test

- ✓ To measure the mechanical properties of mudrock under controlled stress conditions
- ✓ To evaluate strength parameters relevant to wellbore stability

Methods



Swelling and reactivity test

- ✓ To observe the swelling behavior and disintegration rate of mudrock upon fluid exposure
- ✓ To quantify the time-dependent physical response of shale to aqueous environments (time-to-failure)

Methods – Geomechanics Model

Pore Pressure
(DEMSE by Majidi et al., 2017)

$$PP = PP_N \times \delta DE \times MSE \times \frac{1-\sin\phi}{1+\sin\phi}$$

Minimum Horizontal Stress
(Uniaxial Strain)

$$\text{Shmin} = \frac{\nu}{1-\nu}\left(S_v - \alpha P_p\right) + \alpha P_p$$

Maximum Horizontal Stress
(Zhang et al., 2018)

$$\sigma_H = 3\sigma_h - P_b - P_p + \sigma_T + kT_0$$

$$\sigma_T = \frac{\alpha_T E\left(T_m - T_f\right)}{1-\nu} \qquad k = \sqrt{2}$$

Collapse Pressure
(Kirsch with Jaeger Weak Bedding Plane)

$$P_c = \sigma_v \cdot \sin^2(\beta) + \sigma_H \cdot \cos^2(\beta) - (\sigma_H - \sigma_v) \cdot \sin(\beta)\cos(\beta)\cos(2\alpha) - S \cdot \tan(\phi_w)$$

Fracture Pressure
(Matthew and Kelly)

$$\mathrm{P}_f = P_p + K_i \sigma'_v$$

Time-to-Failure
(Arrhenius-type relation)

$$t_f = t_0 \times e^{\left(\frac{E_a}{R(T-T_0)}\right)}$$

Overburden Pressure
(Density calculated)

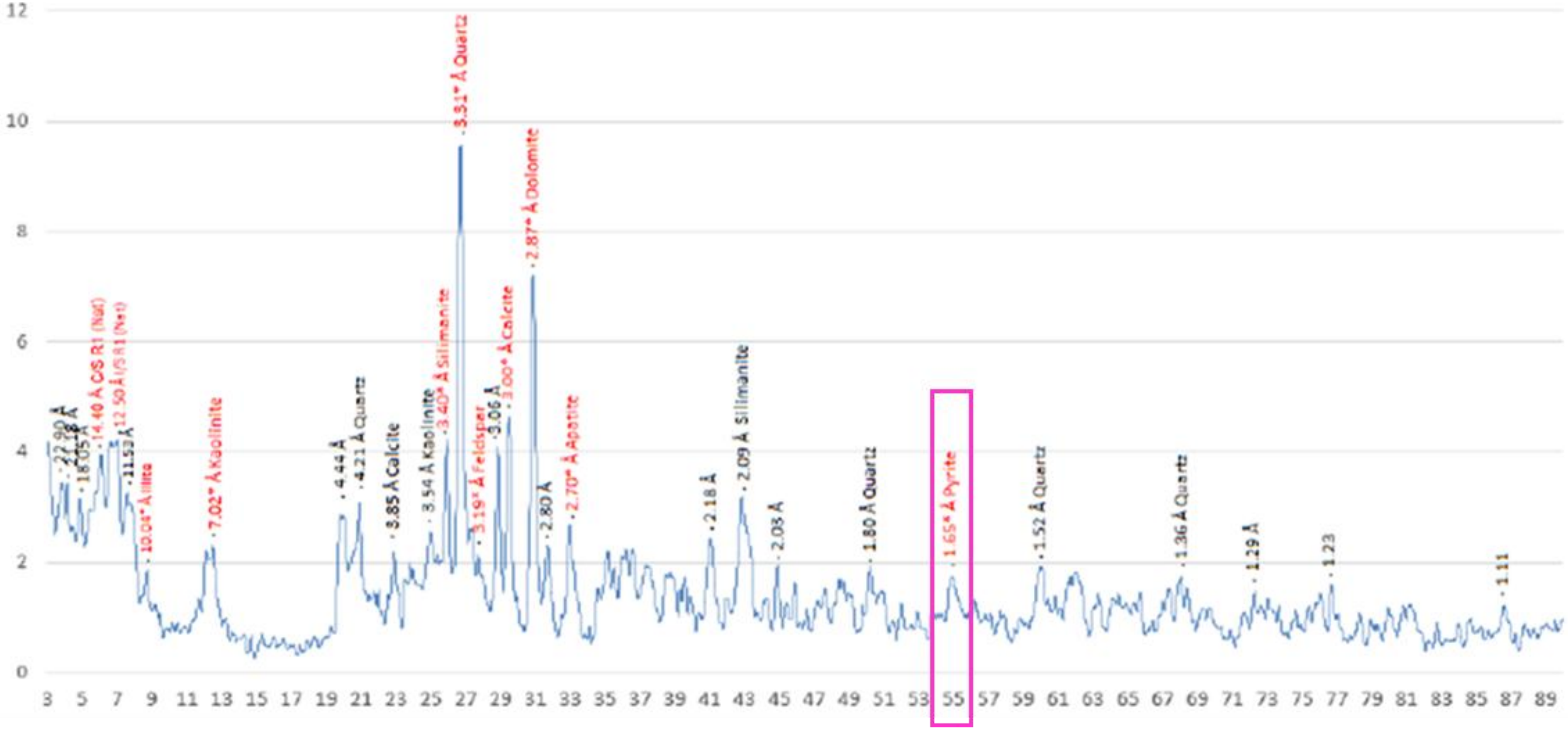
$$\sigma_v(z) = \int_0^z \rho_b(z)\mathrm{g}dz + P_{atm}$$

Biot's coefficient
(E-ν relations)

$$\alpha = 1 - \left(\frac{E}{E_s}\right)\left(\frac{1-2\nu_s}{1-2\nu}\right)$$

For Lower Cisubuh shale:
$E_s \approx 49$ GPa and $\nu_s \approx 0.24$

Results – Pyrite Content – XRD Results



Example of XRD result from Bambu Besar well 9

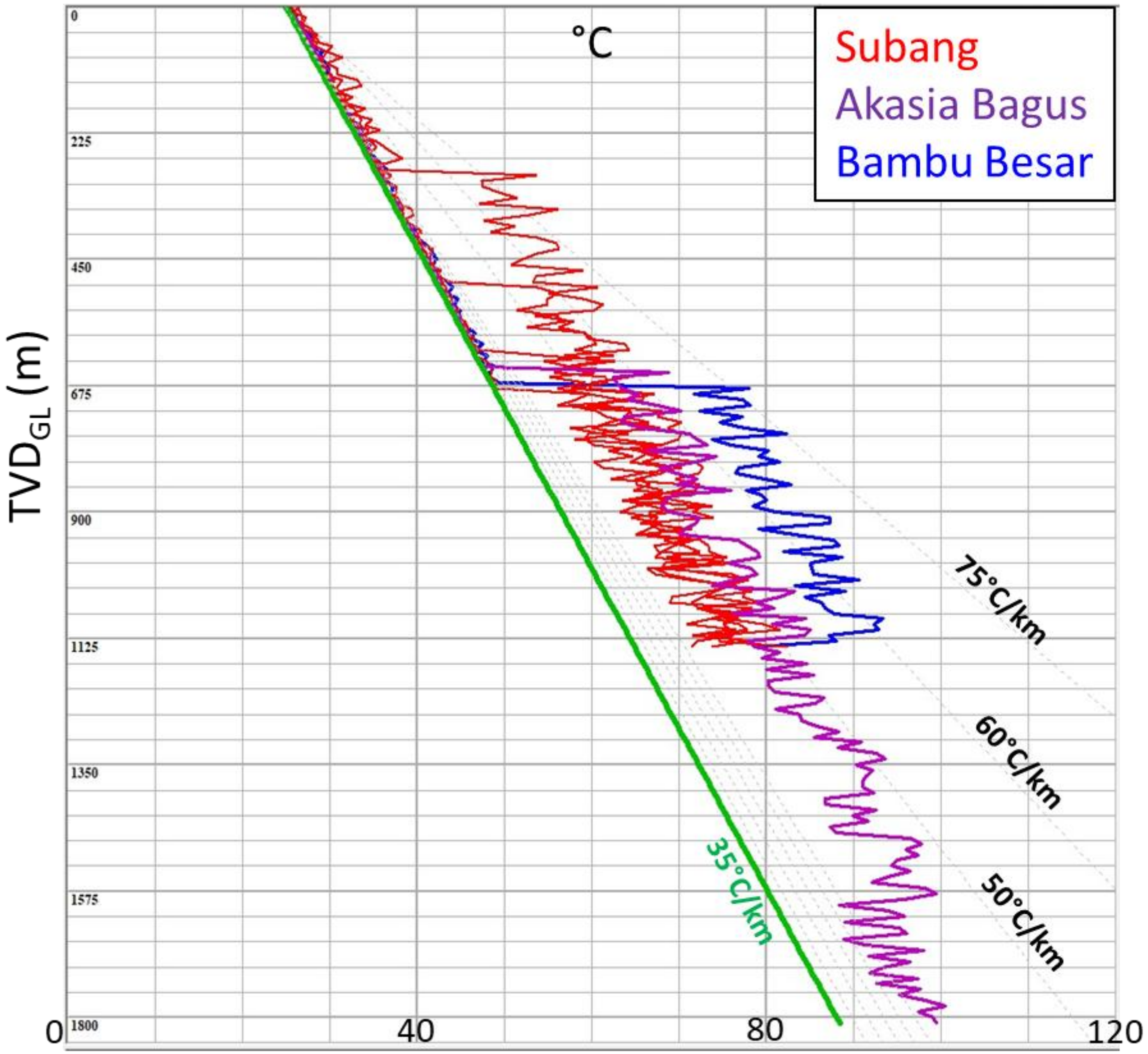
Results – Pyrite content related to BHT

Field	Well	TVD (m)	Pyrite (%)	BHT (°C)	Normal Temp. (°C)	ΔT (°C)
Subang	17	975	2	63	59	4
	20	645	4	54	48	6
	21	945	1	60	58	2
	23	210	1	34	33	1
Bambu Besar	9	1210	16	96	67	29
Akasia Bagus	7	805	6.5	64	53	11

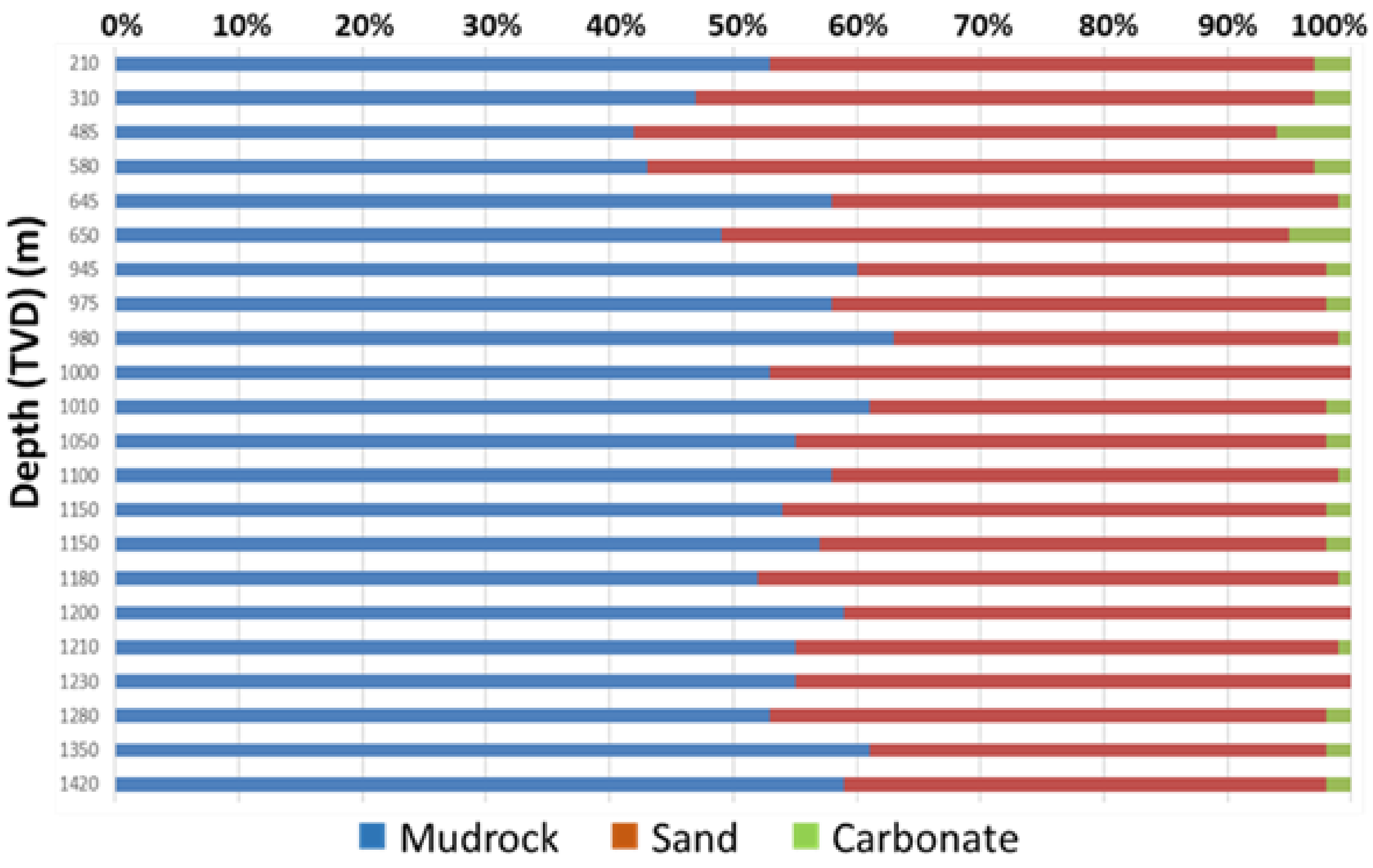
Average surface temperature = 25°C

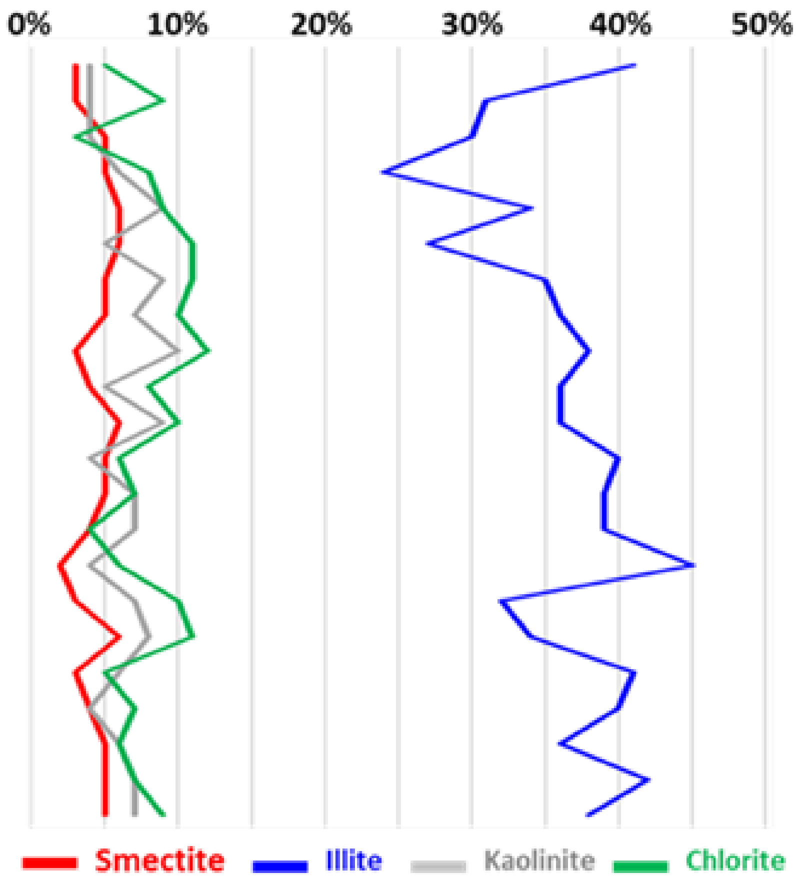
Normal temperature = 35°C/km (Putra et al., 2016)

Results – Temperature Profile



Results – Clay Minerals Content





Results – Rock Properties Cisubuh Formation

Samples from Subang Field, Well 21

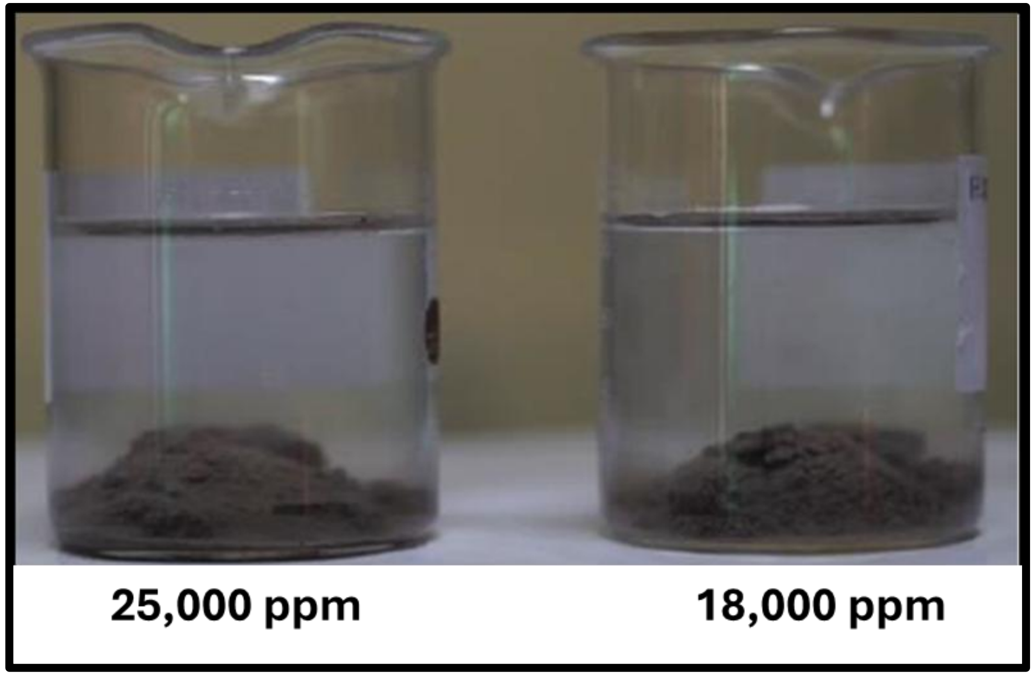
Confining stress (σ_3) (psi)	Poisson's ratio	Biot's coefficient	Young's modulus (GPa)	Bulk modulus (GPa)	Shear modulus (GPa)
528	0.34	0.924	2.29	0.45	0.85
1019	0.35	0.903	2.73	0.53	1.01
1951	0.37	0.843	3.85	0.74	1.41

Core test	Confining stress (σ_3) (psi)	Yield stress (psi)	Peak compressive strength (psi)	Mohr envelope	Cohesion (psi)	Internal friction coefficient	Internal friction angle (°)
UCS	0	-	61	τ=0.517σ+19	19	0.517	27.4
MST	528	1630	6356	τ=0.21σ+2281	2281	0.21	11
	1019	2988	7158				
	1951	4631	8557				

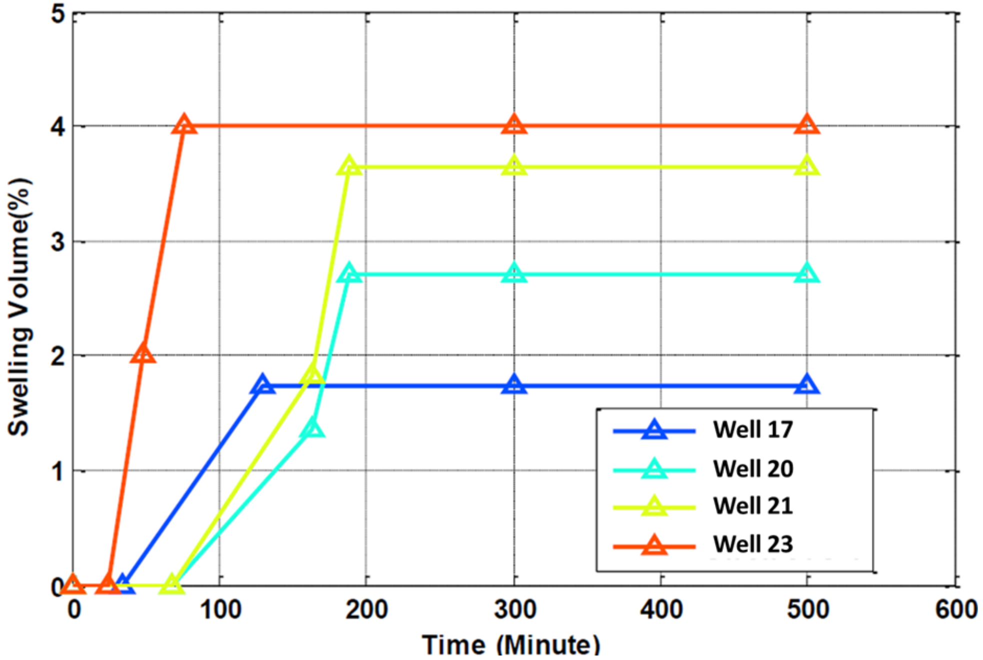
$$V_p = 2700 - \left[120 \times e^{\left(-0.0005\sigma'\right)}\right]$$

$$V_s = 1720 - \left[220 \times e^{\left(-0.0003\sigma'\right)}\right]$$

Results – Reactivity and Swelling Volume

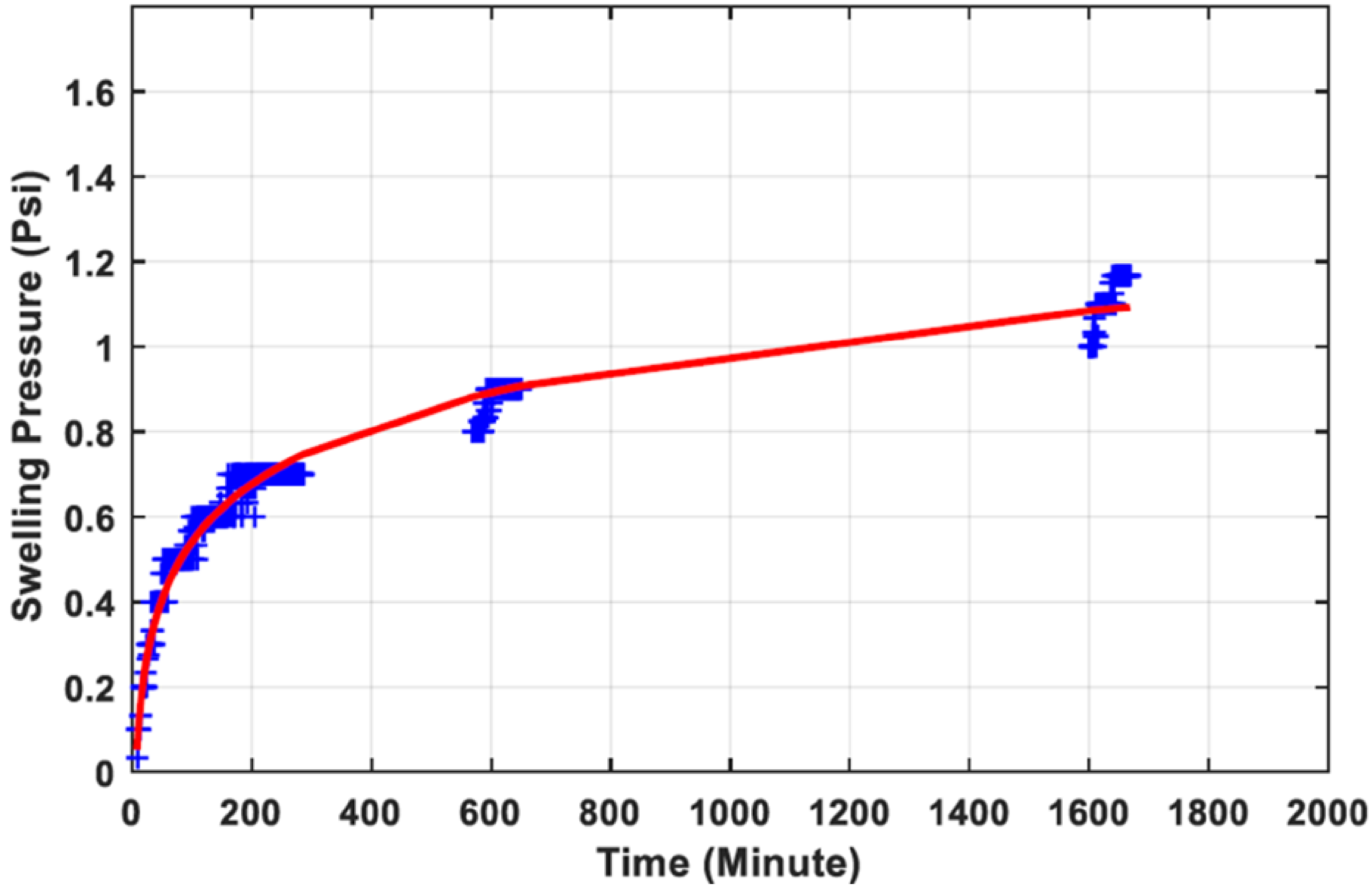


Lower Cisubuh shale reactivity completely disintegrated in 72 seconds both in brine solution with 25,000 ppm and 18,000 ppm salinity, and also in distilled water as control. The samples are from drill cutting samples Subang wells.



Swelling volume of **lower Cisubuh** shale formation drill cutting samples taken from 4 Subang wells in brine solution with 18,000 ppm salinity.

Results – Swelling Volume

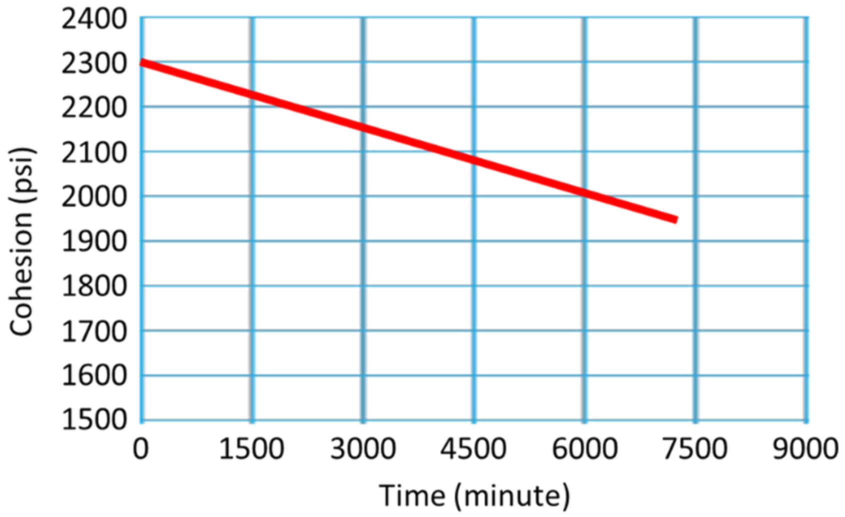


Swelling pressure test on **lower Cisubuh Formation**. Maximum swelling pressure reached **1.1 psi** after 1600 minutes immersed in brine solution with 18,000 ppm salinity. Data samples from all 6 wells.

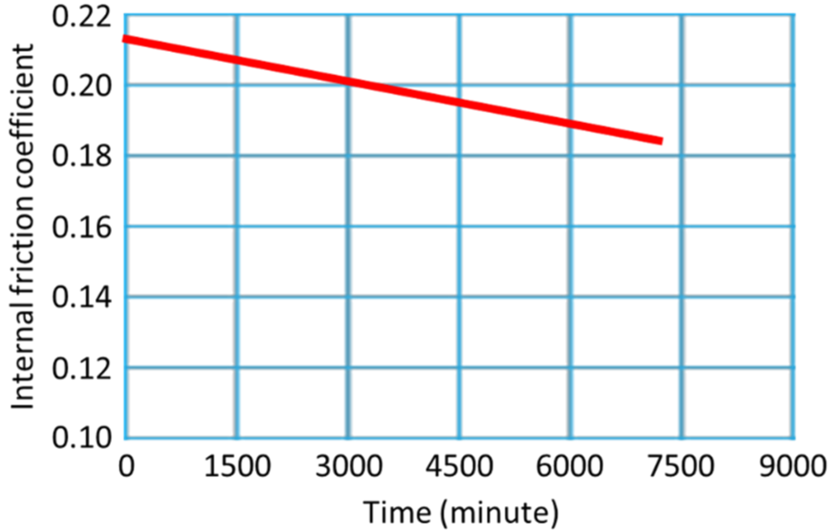
Results – Strength Weakening – time-dependent stability test

Day	Cohesion reduction (%)	Internal friction coefficient reduction (%)
0	0.00	0.00
1	3.28	2.76
2	6.44	5.45
3	9.49	8.06
4	12.42	10.61
5	15.25	13.09

Lower Cisubuh Formation decreased in cohesion and internal friction coefficient



Cohesion



Internal Friction Coefficient

Immersed in brine solution with **25,000 ppm** salinity

Results – Theoretical temperature increase – pyrite oxidation

Pyrite oxidation reactions:

$$FeS_2 + \frac{15}{4}O_2 + \frac{7}{2}H_2O \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ + \Delta H$$

Oxidation of sulfide to sulfate:

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

Oxidation of ferrous iron to ferric iron:

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2}H_2O$$

Sample from Subang well 17

Pyrite content = 2%
Shale density = 2.1 g/cm^3
Shale volume = 1 km^3
Specific heat capacity of shale (c) = 800 J/kg°C
Time = 10 Ma (Late Miocene – present-day)
Pyrite exothermic = 12,300 kJ/kg

Mass of shale = 2.1×10^{12} kg
Mass of pyrite = $0.02 \times 2.1 \times 10^{12}$ kg = 4.2×10^{10} kg

Total heat released from pyrite oxidation (Q_p):
$Q_p = 4.2 \times 10^{10}$ kg × 12,300 kJ/kg = 5.166×10^{14} kJ = 5.166×10^{17} J

Temperature increase (ΔT) over 10 Ma:

$$\Delta T = \frac{5.166 \times 10^{17}\,\text{J}}{2.1 \times 10^{12}\,\text{kg} \times 800\,\text{J/kg°C}} = \mathbf{307.5}\text{°C}$$

Max. adiabatic without losses

Results – theoretical temperature increase – other mechanisms

Natural radioactivity from potassium-rich shales (^{40}K) ≈ **7.83°C**

Ongoing tectonic deformation and fault reactivation ≈ **26.2°C**

Conductive heat flow ≈ **normal thermal gradient (35°C/km)**
(Putra et al., 2016)

Detailed analysis proposed and described in Basuki et al. (2025)
https://dx.doi.org/10.2139/ssrn.5390491

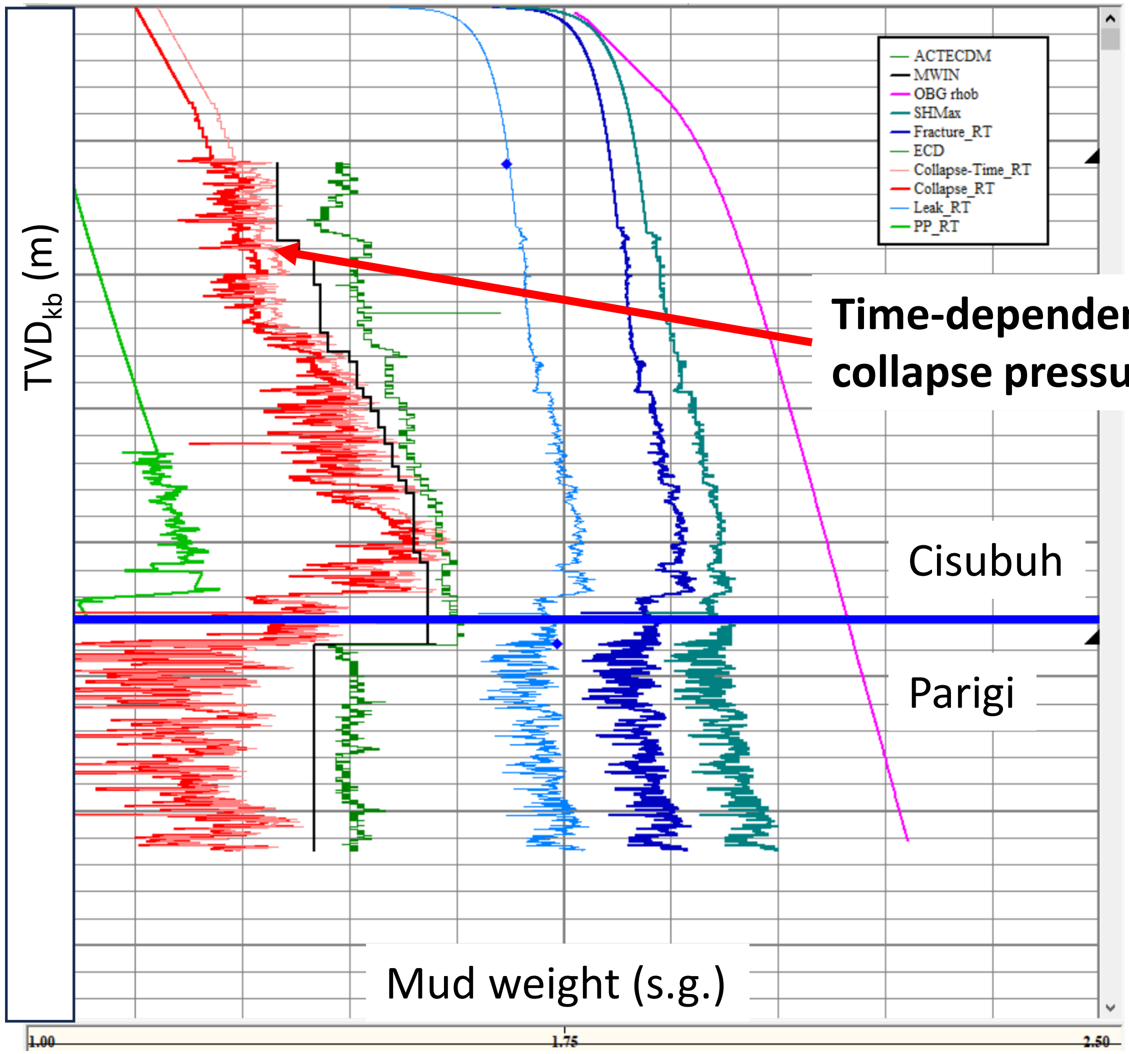
Discussion

The present-day temperature anomaly in the Cisubuh Formation is lower than modeled values due to prolonged heat dissipation. Uplift, erosion, groundwater convection, and conductive transfer into surrounding rocks have progressively diminished the thermal signal.

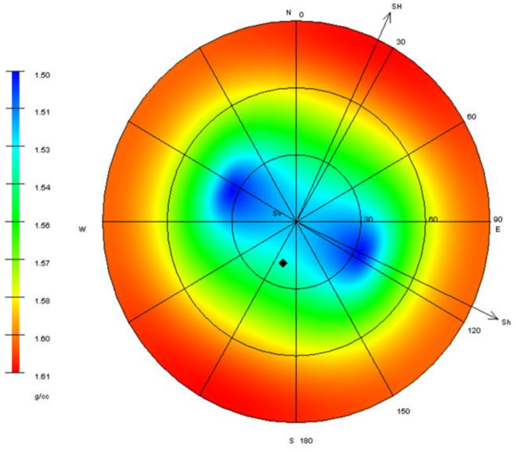
Late Miocene–Pliocene tectonic, sedimentary, and geochemical conditions in the North West Java Basin fostered pyrite formation via microbial sulfate reduction, with rapid burial and acidic Cisubuh environments enhancing preservation and highlighting redox-sensitive mineralization controls.

Reactive clays weaken formation strength and increase pore pressure, with elevated temperatures and fluid exposure accelerating time-dependent chemical and mechanical instability.

Discussion

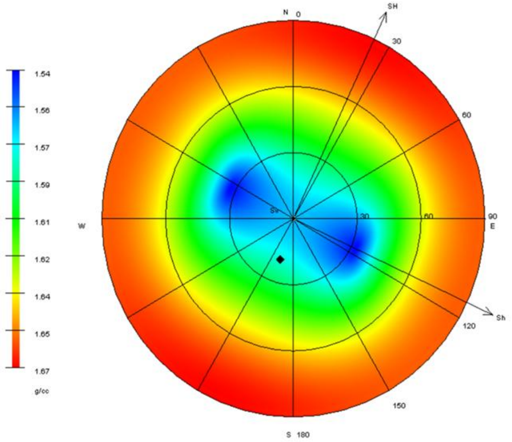


Depth 1170 m



While drilling

Collapse = 1.53 s.g.



With time-dependent effect

Collapse = 1.58 s.g.

Results:

- ✓ No NPT due to geomechanical issues
- ✓ Saves 3 days ahead of plan ≈ $1.2 million

Conclusion

Pyrite oxidation is the main driver of thermal anomalies in the Cisubuh Formation, with uplift, erosion, groundwater flow, and conduction moderating its impact, while minor radioactive and tectonic sources contribute secondarily.

XRD, triaxial, and swelling tests show that **reactive clays** weaken formation strength and raise pore pressure, effects amplified by elevated temperatures. Time-dependent tests confirm progressive loss of strength, indicating wellbore failure develops with prolonged fluid exposure.

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