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The Art and Techniques of Microfrac Tests using Conventional Formation Tester in Challenging Salt Formations – First Case Study from Salt Dome, Abu Dhabi, UAE

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Abstract

This paper addresses the challenges to measure the fracture closure pressure and microfrac testing of Paleozoic Hormuz Salt in Abu Dhabi Onshore salt Dome structures in UAE. This study includes the process, results and experience of a recent successful wireline microfrac campaign to measure fracture closure pressures in pure and impure salts along with intercalated clay layers, provided critical insights into the minimum horizontal stress distribution across the interval, essential for evaluating structural integrity and storage feasibility. This emphasizes the critical role of integrating pre- and post-job geomechanics workflows with real-time microfrac monitoring to achieve confident closure measurements and a calibrated Shmin profile.

Introduction

This salt structure is located towards the southwest of the Abu Dhabi City on a peninsula on the south coast of the Arabian Gulf. This is the only onshore salt diapir in the United Arab Emirates. The nature of the rock salt study in the area was conducted for multiple purposes considering its impermeable properties.

The lithological Structural profile showed that the cap rock is about 200 meters from surface. It consists of older saliferous sediments, mainly anhydrite, carbonate, and igneous blocks from the Hormuz Formation. In the lower flank, there are also sedimentary blocks composed of Miocene-age limestone and sandstone. Below this, the salt section extends down to ±1000 meters, interbedded with various sediments and volcanic rocks.

Reservoir Data Availability

Technically there was no data available about reservoir and fluid properties. Cap rock and Salt are the two formations which were under study and target in these wells. The formation pressure value forecast was not precisely known due to the lack of data. The average pressure gradient of 0.5 psi/ft was used. Moreover, some offset wells drilled far earlier in this region indicate that it has zero H_2S with some CO_2 but no recorded value available.

Planned Work Program

Initially four wells (Well-A, B, C & D) were planned and drilled with special well design for various purposes. The conductor was 30″, surface casing 18-5/8″ and 13-3/8″ intermediate casing. One pair was completed with 10-3/4″ tubing using 12-1/4″ hole size with another 7″ tubing inside it for 8-1/2″ open hole and one pair with 7″ tubing string only across 8-1/2″ open hole all the way down to total depth (TD) across the salt section. Two of the wells' sketches are shown in Figure 1.

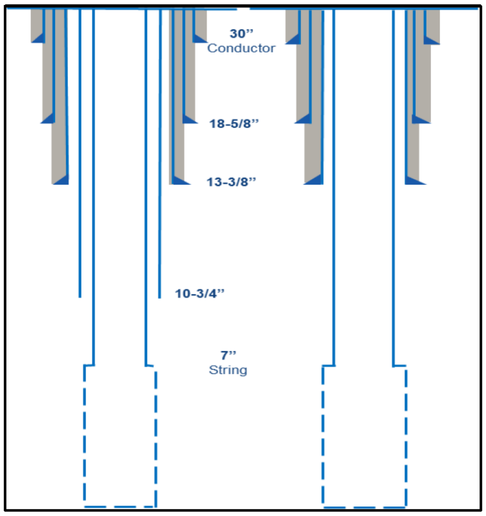

Figure 1—Well A, & B Sketch

Methods, Procedures, Process

Preliminary wireline logs derived Geomechanical model was developed to guide tools selection based on modeled breakdown pressures. Microfrac tests were conducted at different stations across three different wells using a wireline straddle packer. Each test consists of a minimum of three cycles, capturing formation breakdown, reopening, and a definitive fracture closure pressure. Real-time monitoring, from packer inflation to deflation, allowed for real-time operational interventions by the geomechanics team. In impervious salt layers, limited fluid leak-off and flat fall-off pressure responses necessitated using flowback pressure during the induced closure phase to determine the salt closure gradient. Detailed methodology, pre-job planning, real-time execution and post-job analysis are presented in the subsequent sections.

Open Hole Logs Data Recording

Although some old well logs were also available like DT, NPHI, RHOB & PEF etc. which were used initially for micro frac feasibility study/analysis. Comprehensive sets of open hole wireline logs, both the basic and advanced, near and far field, were acquired for their certain objectives in cap rock and salt section like (Triple Combo (GR-Resistivity-Density-Neutron), Dipole Sonic, Spectral Gamma Ray, 6-arm Caliper, borehole Resistivity & Acoustic Imager- borehole Acoustic Reflection Survey/ Deep Shear Wave Imaging log, Elemental Capture Spectroscopy-Nuclear Magnetic Resonance, 3D Borehole Electromagnetic Reflection Survey (Georadar), Vertical Seismic Profiling (Walkaway & Zero-offset)).

Some new technologies were also deployed for the first time in the region, like 3D Borehole Electromagnetic Reflection Survey (Georadar) for defining lateral and vertical extent of salt / insoluble in 1D & 3D space, to determine salt heterogeneities and bedrock structures (faults, layers) etc.

Geomechanical Modelling for Microfrac Test

Initially all the old wells recorded open logs were evaluated and interpreted with the following major outcomes. The estimated formation breakdown pressure was 1000 psi higher than mud hydrostatic. Stress contrast and magnitude of minimum horizontal stress/ estimated breakdown pressure are higher. Rock properties like Young's Modulus of elasticity within optimum window are too high, as well as too low to avoid latter plasticity effects. Unconfined compressive strength is a crucial parameter representing the maximum compressive stress of a rock sample which can withstand before failure under uniaxial/ unidirectional loading, without any lateral confinement which is not high along with its tensile strength in the below case.

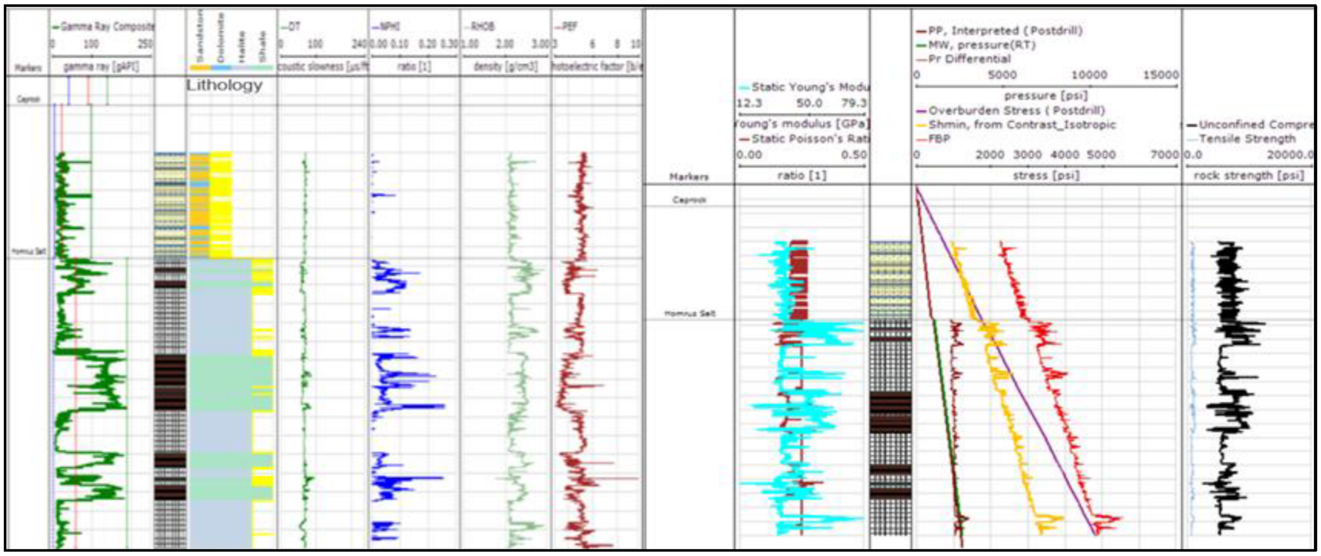

Figure 2—Old well, showing the wireline log responses across Hormuz salt, with the estimated rock-mechanical properties, Pore pressure, in-situ stresses, expected breakdown pressure.

The formation breakdown pressure (FBP) is not an in-situ stress property and is subject to be influenced by external factors also, including mud properties. Thus, the estimated breakdowns could have ±10-15% uncertainty. Based on the old logs evaluation and geomechanical modeling across 8-1/2″ hole the different points were selected for formation breakdown pressure jobs. Although there is a contrast between pay and non-pay zones. The less poro-elastic effects in reopening and closure resultantly small volume fracture & Low injection rate.

Pre-Job Planning

A preliminary geomechanical model, derived from wireline logs, was developed to guide tool selection as well as identifying the test intervals. The pre-job geomechanical modeling integrated wireline logs, regional geological information, drilling and mudlogging data. Available logs include gamma ray, resistivity, caliper, neutron porosity, acoustic and shear slowness. Image log was recorded in the target intervals. Uranium, Thorium and Potassium concentrations from spectral gamma ray suite along with cutting lithology data from mudlogging services helped identify the lithology model. It was a critical step to distinguish between salt and the non-salt lithologies (shales, carbonates). Assessment of density data (with relevant density cutoffs) and image log helped to fine-tune the differentiation between pure and impure salt layers within the Hormuz complex. Rock-mechanical properties were estimated based on the well logs and regional correlations, these include static Poisson's ratio, Young's modulus, coefficient of internal friction and unconfined compressive strength and tensile strength.

Well log-based geomechanical modeling of the Hormuz salt complex indicated a mean vertical stress gradient (Sv) of ~ 0.92 psi/ft. A constant 0.5 psi/ft of pore pressure gradient was considered for the entire Hormuz salt interval, including the non-salt interbeds. The entire interval was drilled with a 0.57 psi/ft of drilling fluid gradient. The preliminary in-situ stress modeling predicted an isotropic horizontal stress condition within the salts which translates to a minimum horizontal stress (Sh_{min}) gradient being equal to Sv.

The non-salt interbeds reflected Shmin < Sv, with a mean Shmin gradient between 0.87-0.9 psi/ft. The expected breakdown pressure was modelled based on the rock-mechanical properties and in-situ stresses considering no pressure communication between the wellbore and formation, which provided a conservative estimate of the formation breakdown. Based on this upper bound of breakdown pressure, a high strength wireline straddle packer tool was selected which has a downhole pressure capacity of 5300 psi above mud hydrostatic pressure. The primary objective was to perform microfrac testing against pure/impure salt layers as well as the shale interbeds separating the salts, to quantify the closure pressure gradient across lithological heterogeneities and establish a calibrated Sh_{min} profile for the Hormuz salt complex.

To satisfy the geological objectives, microfrac test intervals selected based on lithology discrimination, contrast in rock-mechanical properties, with a critical consideration of wellbore quality. Caliper log and image log were the key enabler for interval selection, by avoiding breakout, key seats, spiraling, deep tool marks, natural fractures to ensure proper sealing by downhole packers and zonal isolation during the tests. Against the 8.5″ hole size (i.e., bit size), the maximum caliper diameter considered was 9.1″ as a threshold for interval selection. Moreover, based on the caliper enlargement, proposed microfrac test depths were categorized into low, medium and high-risk categories.

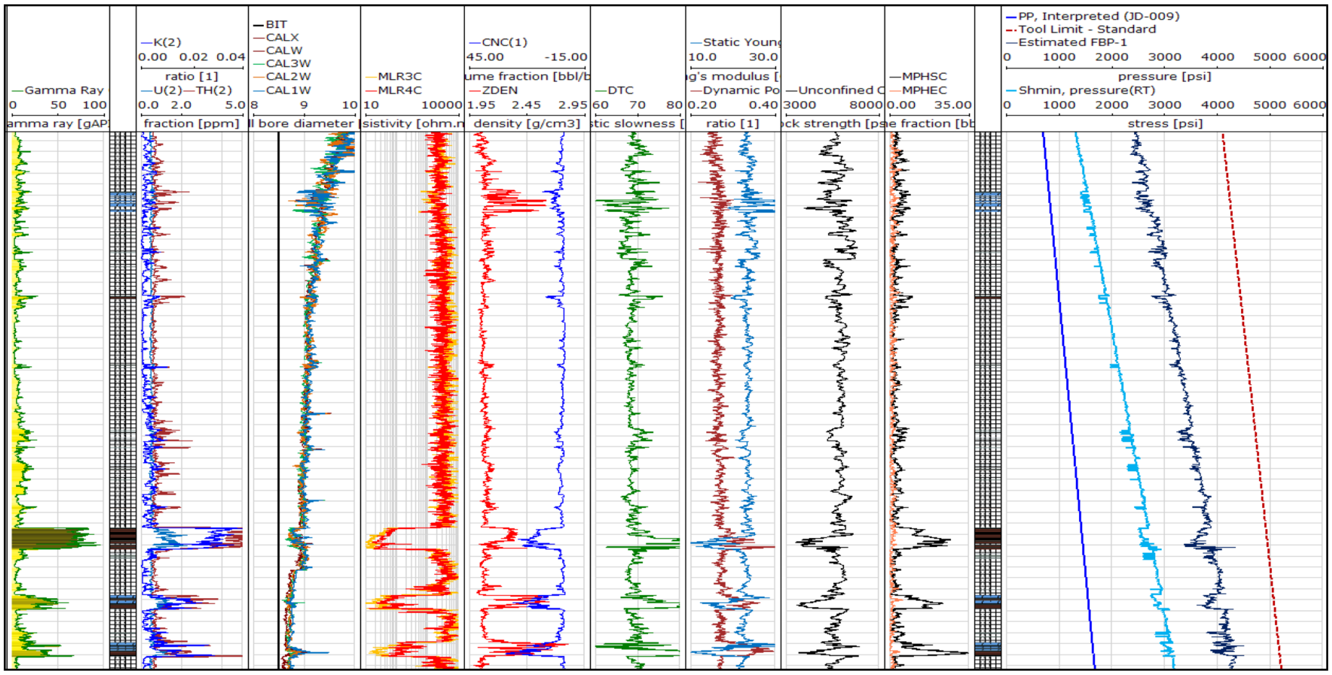

Figure 3—Pre-job geomechanical modeling of one of the wells, showing the wireline log responses across the different lithologies within Hormuz salt complex, along with the estimated rock-mechanical properties, pore pressure, in-situ stresses, expected breakdown pressure vs tool limit.

Real-Time Execution of Microfrac Tests

Microfrac tests were conducted on more than thirty stations across three wells using a wireline straddle packer tool. The chosen straddle packer had a downhole pressure capacity of 5300 psi above the mud hydrostatic pressure, ensuring it could safely withstand the expected injection pressures without compromising tool integrity or data quality. A 434cc pump was used for all injections, providing a consistent and controlled injection rate across all test stations. This pump size was optimal for generating sufficient pressure to initiate fractures while maintaining precise control over injection volumes and rates. Each test included a minimum of three cycles, capturing formation breakdown, reopening, and definitive fracture closure pressures.

Real-time monitoring, from packer inflation to deflation, allowed for operational interventions by the geomechanics team. Following injection, pressure fall-off behavior was monitored during the initial shut-in phase. Across all stations, the pressure declines exhibited a near-flat response, particularly within the first five minutes after the shut-in. The pressure drop rate stabilized between 3 to 5 psi/min, a characteristic signature of low-permeability formations. This behavior strongly supports the interpretation that the tested intervals—whether composed of pure salt, impure salt, or intercalated clay layers are effectively impervious. In impervious layers, limited fluid leak-off and flat fall-off pressure responses necessitated using flowback pressure during the induced closure phase to determine the salt closure gradient. To determine the minimum horizontal stress (Shmin), a controlled flowback method was employed using small volume pump (36cc), allowing for a gradual and measurable pressure decline. This method enabled accurate identification of fracture closure.

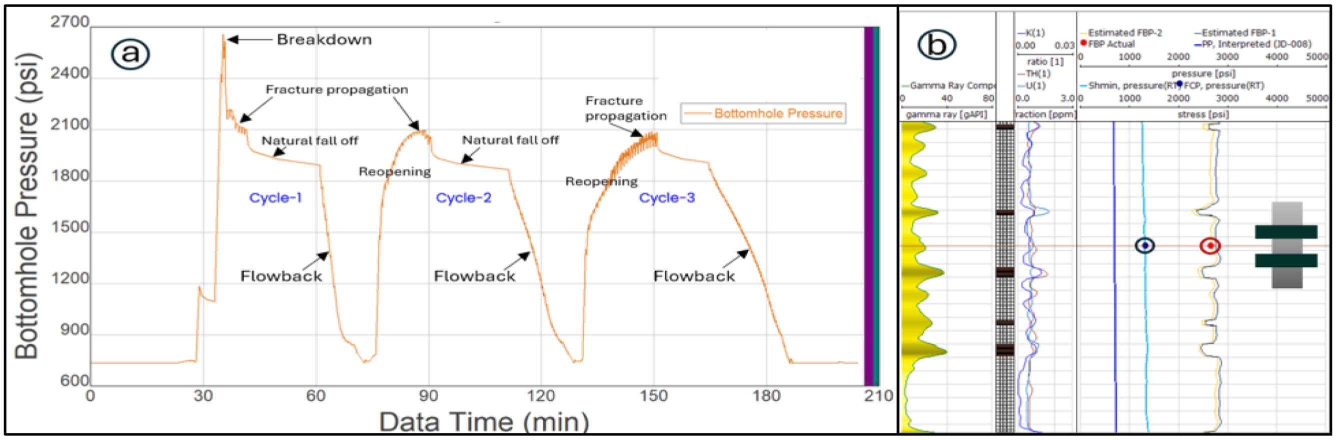

Figure 4—(a) Example of downhole pressure vs time data of a microfrac test interval in a pure salt layer (TVD~ 1406 ft) indicating three injection cycles with clear breakdown at first cycle, followed by reopening in next two injection cycles. Flowback was performed to induce closure. (b) the black and red circles present the corresponding closure pressure (interpreted Shmin) and breakdown pressure (from first injection cycle), respectively.

Post-Job Analysis

Closure Pressure Interpretation and Geomechanical Model Calibration

The breakdown pressure gradients observed across the stations ranged from 1.35 to 1.57 psi/ft, indicating a relatively narrow and predictable pressure window for fracture initiation. This range is consistent with expectations for salt formations, which typically exhibit high mechanical strength and low permeability. The uniformity of breakdown pressures across both pure and impure salt intervals suggests a consistent mechanical response, despite the presence of interbedded clays and other impurities in some zones.

The minimal fluid leak-off observed during fall-off further reinforces, this conclusion and highlighted the sealing capacity of these formations. The interpreted closure pressures from these flowback tests yielded Shmin gradients ranging from 0.88 to 1.0 psi/ft. These Shmin values are particularly significant because they are very close to, or in some cases equal to, the estimated vertical stress gradient. A closer look at the data distribution indicates Shmin~Sv for salt layers, while the non-salt intercalations indicate Shmin slightly lower than the Sv gradient, although very close to it.

This observation suggests an isotropic stress state within the salt formations, where the horizontal and vertical stresses are nearly equivalent. Such a stress regime is consistent with the known viscoelastic behavior of salt, which tends to redistribute and equilibrate stress. The isotropic stress condition also implies that salt is not currently undergoing significant differential stress, which has important implications for wellbore stability and long-term cavern integrity in salt-based storage or disposal applications. The initial Shmin profile used for planning was derived from elastic property-based geomechanical modeling. This model incorporated parameters such as Young's modulus, Poisson's ratio, and bulk density to estimate stress magnitudes.

However, to improve the accuracy and reliability of the stress profile, the modeled Shmin values were calibrated using the interpreted closure pressures obtained from the flowback data. This calibration process ensured that the final stress estimates were grounded in direct field measurements, thereby enhancing confidence in the geomechanical model and its applicability.

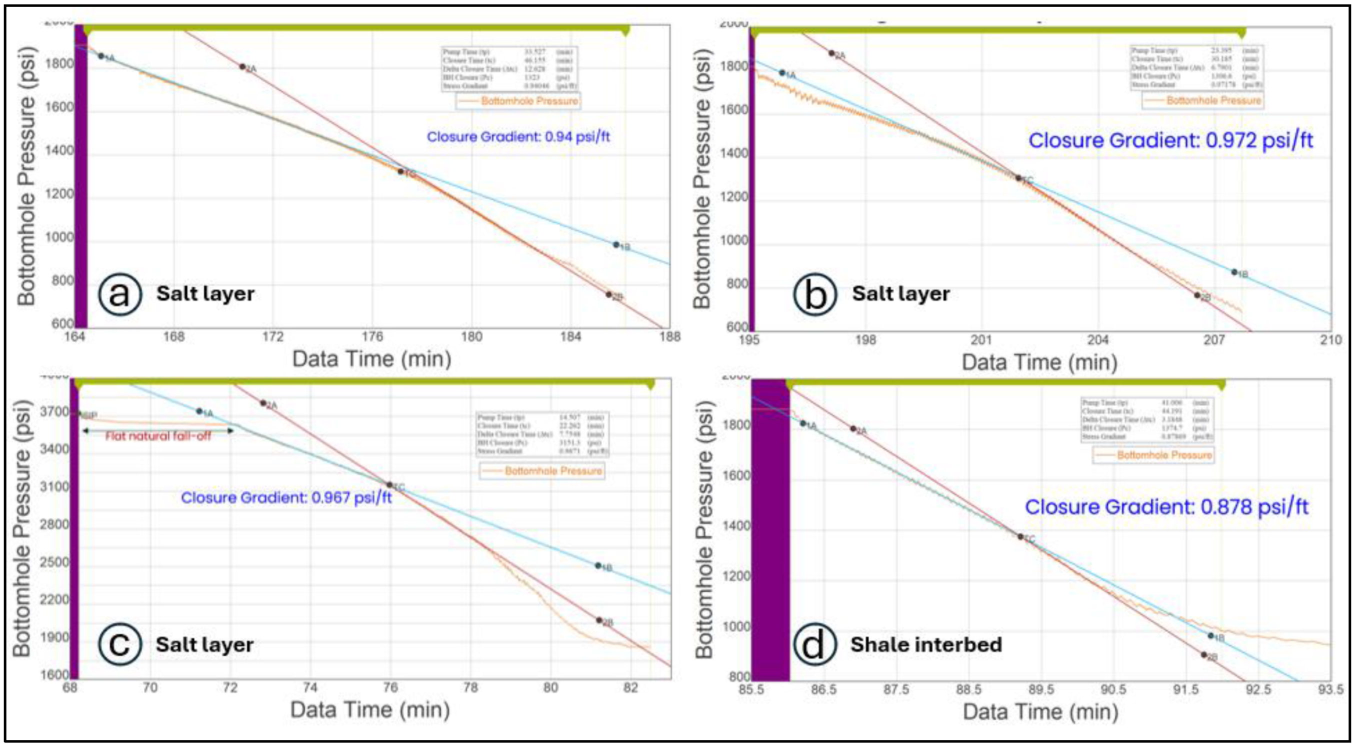

Figure 5—(a, b & c) Closure pressure analysis from flowback data in salt layers indicating Shmin gradient of ~0.94-0.97 psi/ft. and (d) Closure pressure analysis from non-salt layers (shale) exhibiting Shmin gradient ~ 0.88 psi/ft.

In terms of data quality, the interpreted Shmin values were evaluated using the World Stress Map (WSM) quality ranking scheme for stress magnitude indicators, as proposed by Morawietz et al. (2020). According to this classification, the data acquired from this testing campaign met the criteria for 'A'-quality indicators. This is the highest quality ranking and signifies that the stress magnitude estimates are based on direct measurements with well-constrained uncertainties. Achieving this level of data quality is particularly noteworthy in salt formations, where stress measurements are often complicated by the rock's ductile and time-dependent behavior.

Overall, the results of this diagnostic testing campaign demonstrate a high degree of consistency and reliability. The successful breakdown of all more than thirty stations, the uniform pressure fall-off behavior, and the well-constrained Shmin estimates all point to a robust and repeatable methodology for stress characterization in salt formations. The findings confirm the impervious nature of the tested intervals and provide strong evidence for an isotropic stress state, which is critical for understanding the mechanical behavior of salt and for designing safe and effective subsurface operations.

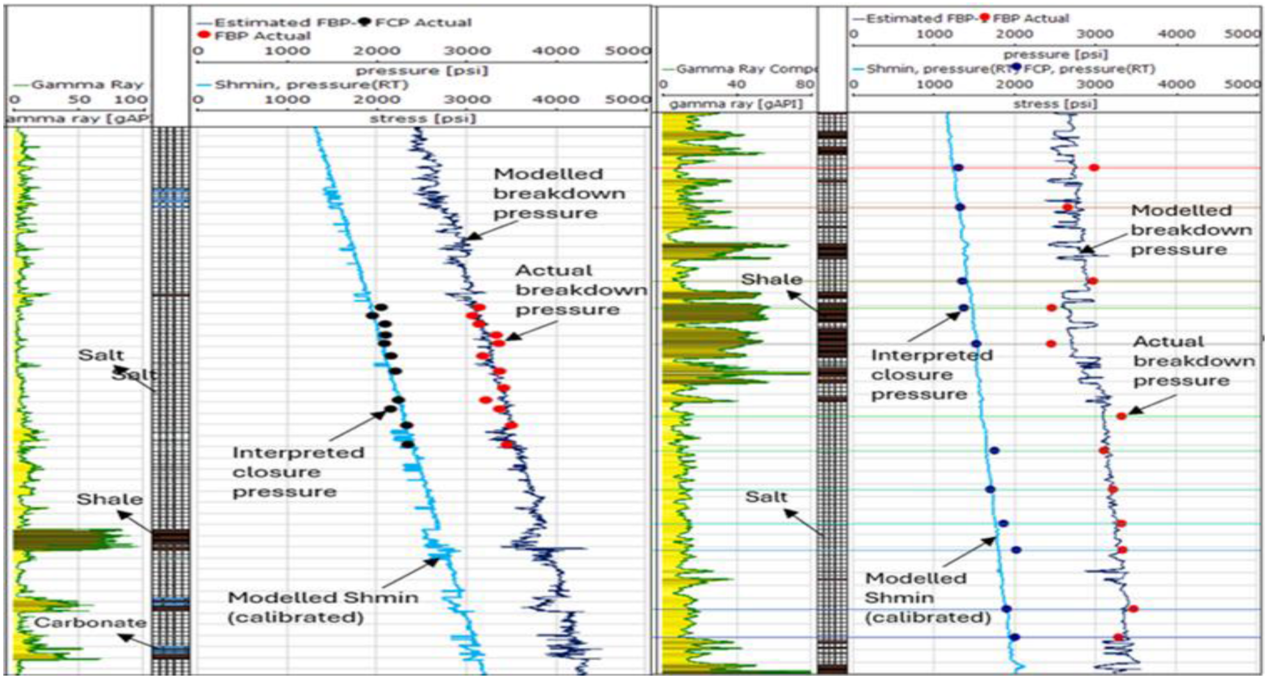

Figure 6—Compilation of wireline microfrac test data including the actual breakdown pressure and interpreted closure pressure (calibrating Shmin) within the Paleozoic Hormuz salt complex in two of the studied wells.

Table 1—Example of closure pressure interpretation summary using flowback method.

Closure Pressure Interpretation Summary Using Flowback Method									
Depth (ft)	Break Down Pressure (BPD) & Gradient (Psi/ft)		Cycle #	Closure Pressure (PSI)			Closure Pressure Gradient (Psi/ft)		
	BDP (Psi)	BDP Gradient (Psi/ft)		Flow Back Method	Average	Final Interpr. (Conser.)	Flow Back Method	Average	Final Interpr. (Conser)
X1	4620	1.39	4	3297.4	3297.4	3297.4	0.99	0.99	0.99
X2	4358	1.34	1	3162.5	3125.3	3075.4	0.97	0.959	0.94
			2	3151.3			0.967		
			3	3111.9			0.955		
			4	3075.4			0.944		
X3	4338	1.34	1	2801.4	2787.6	2767.2	0.868	0.864	0.86
			2	2794.4			0.866		
			3	2767.2			0.857		
X4	4506	1.42	1	2842.5	2828.9	2811.2	0.893	0.888	0.88
			3	2811.2			0.883		
			4	2833.0			0.89		
X5	4630	1.47	1	3099.9	3099.9	3099.9	0.98	0.98	0.98
X6	4232	1.39	2	2574.5	2609.9	2603.5	0.84	0.85	0.85
			3	2651.7			0.87		
			4	2603.5			0.85		
X7	4120	1.39	2	2313.3	2309.5	2309.5	0.78	0.78	0.78
			3	2305.7			0.78		
X8	4127	1.41	3	2463.9	2457.9	2452	0.84	0.84	0.84
			4	2452.0			0.84		
X9	4027	1.44	3	2429.2	2324.2	2219.1	0.87	0.84	0.8
			4	2219.1			0.80		
X10	4347	1.57	4	2463.1	2463.1	2463.1	0.88	0.88	0.88

Core Cutting & Geomechanics Study

The coring program was designed to have a complete data set of formation starting from very shallow to till bottom of the wells. Cores were planned and cut in two main sections, 17-1/2″ and 8-1/2″ holes sections. Conventional standardized core cutting, handling and conservation procedures were used to optimize core preservation for special core analysis measurements and mechanical measurements.

Special attention was paid to packaging to avoid damaging the cores during transportation by injecting foam around the cores in the containers prior to transportation. Core was stored in pertinent area, with adequate conditions and labels to facilitate the core photography, descriptions and measurements properly.

Before discussing the core experiments and results, we will briefly explain key stress concepts, including total, hydrostatic, deviatoric, shear, and tensile stresses. Hydrostatic stress is the simplest type, acting equally or nearly in all directions. It can change the volume of the applied object but can't break it down or shear it or cause its distortion. Then the total stress is considered force per unit area but in case of rock body, it will be sum of stress applied by rock structure itself plus the stress or force exerted by any fluid present in it. Shear stress or Deviatoric Stress is simply the difference of total stress value and hydro static stress. Usually, it acts nonuniformly and resultantly de-shape the structure or alter the shape of sample. The tensile stress generally considered as resistance of any samples against applied stretching force by cross sectional area of sample before its breakdown.

Multiple core plugs were cut for UCS and Brazilian testing and core plug with 2.5″ diameter were specifically cut for triaxial compression (TXC) testing. Initially two core plugs were used for Brazilian testing and after its completion further core plug were also used. Similarly, UCS testing was performed for the first Salt and Insoluble samples and then further samples were tested.

During first test at insoluble sample the rate of loading/unloading strain was entirely at 10e-6 per second(/s). For the Salt sample, the first two loading/unloading stages were done at 5e-6 /s and the last loading stage at 10e-6 /s. However, subsequently the protocol to run the entire test was changed, for both Salt and insoluble samples at 5e-6 /s. The yielding value aligns with the inflection on the volumetric plot, theoretically marking the transition from linear elasticity to plastic deformation. However, since unloading reveals residual Visco-plastic strain, it is uncertain whether this inflection truly represents the elastic limit.

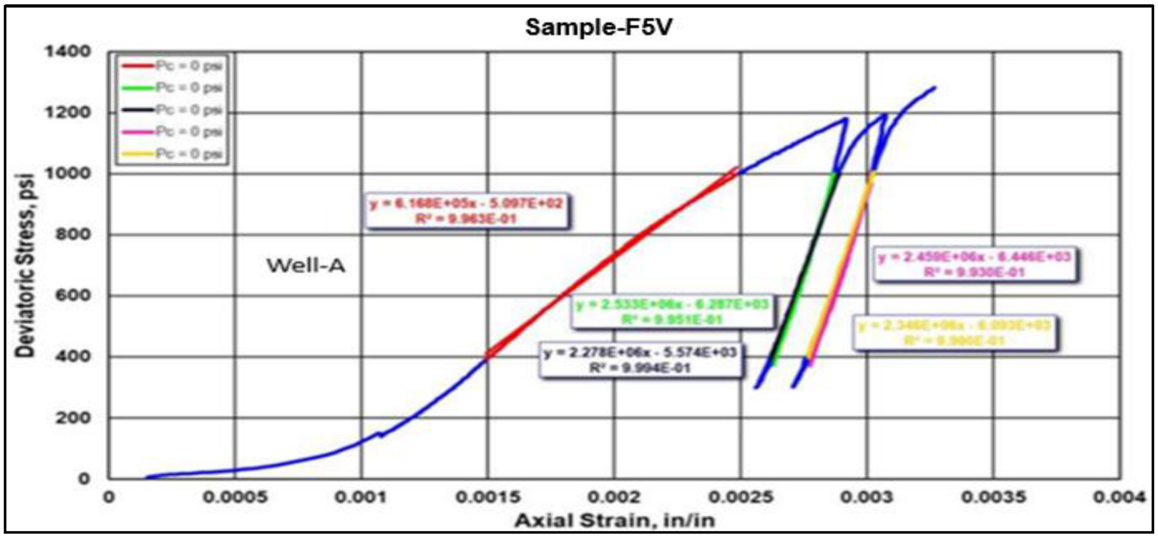

Figure 7—Graph of Sample F-5 showing the yielding value aligns with the inflection on the volumetric plot, theoretically marking the transition from linear elasticity to plastic deformation, since unloading reveals residual Visco-plastic strain also.

The measured Young's modulus values for salt (F5) and anhydrite appear underestimated, as standard values for salt are typically 20–30 GPa and anhydrite to be above 30 GPa. Standard Poisson's ratio is about 0.3 for salt and 0.2 to 0.3 for anhydrite, but the samples measured fall outside these expected ranges. The elastic parameters (Poisson's Ratio and Young's Modulus values) were measured during multiple cycles of unconfined loading and unloading, with exceptional yield points based on the corresponding plots. The elastic parameters obtained from unloading cycle were apparently more reliable, might be due to better representation of downhole compression scenarios. Additionally, the data shows that Poisson's Ratio measured during loading aligns more closely with the range suggested for Salt facies. This study supports the interpreted results of the mini frac tests.

Challenges

The geomechanical properties revealed that the expected pressure differential for breakdown was ~1000 psi above the mud hydrostatic. The formation breakdown pressure is not an in-situ stress property and is subject to be influenced by external factors. Thus, the estimated breakdowns can vary significantly. Stress contrast between pay and non-pay zones demands multiple testing intervals. Bore hole integrity and wellbore wall conditions to avoid breakout, key seats, spiraling, deep tool marks and natural fractures presence etc. The stress contrast was high, so ensure that the packer positions at high stress magnitude area and low stress is in between (dual packer) to prevent sleeve fracturing, with estimated breakdown pressure within tool limits.

Results, Observations, Conclusions

The targeted salt sections were drilled with 8-1/2″ bit size. Based on the estimated formation breakdown pressure from pre-job geomechanical modeling, a high strength wireline straddle packer tool was selected which has a downhole pressure capacity of 5300 psi above mud hydrostatic pressure. A 434cc pump was used for injections. All recorded stations had a successful breakdown with a breakdown pressure gradient ranging between 1.35-1.57 psi/ft. Both the pure and impure salt intervals along with intercalated clays, exhibited near-flat pressure fall-off responses during the initial shut-in phase. It was evident from the pressure drop rate stabilizing at 3-5 psi/min within the first 5 minutes, reaffirming the impervious nature of the analyzed intervals. Closure in these formations was induced using a controlled flowback method with a 36cc rate. The resulting flowback pressure interpretation indicated Shmin gradient of 0.88-1.0 psi/ft, which is very close or equal to the vertical stress gradient indicating an isotropic stress state in salts. The Shmin profile, initially estimated via elastic property-based on modeling, was subsequently calibrated with interpreted closure pressures. Based on "World Stress Map quality ranking scheme for stress magnitude indicators proposed by Morawietz et al., 2020", the interpreted Shmin data was classified as ‘A’-quality.

Novel/Additive Information

This study marks the first regional reporting of extensive microfrac testing in salt formations. The conclusive and reproducible closure results offer vital insights into vertical and lateral heterogeneity in halite characteristics. This emphasizes the critical role of integrating pre-job and post-job geomechanics workflows with real-time microfrac monitoring to achieve conclusive closure measurements and a calibrated Shmin profile in Paleozoic salt intervals. Moreover, this study suggests guidelines for halite formation characterization and geomechanical properties estimation.

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References

Morawietz et al, An open-access stress magnitude database for Germany and adjacent regions, *Geothermal Energy* (2020) https://doi.org/10.1186/s40517-020-00178-5

Ziegler MO, Heidbach O, Reinecker J, Przybycin AM, Scheck-Wenderoth M. A multi-stage 3-D stress field modelling approach exemplified in the Bavarian Molasse Basin. *Solid Earth*. 2016;**7**(5): 1365–82. https://doi.org/10.5194/se-7-1365-2016.