High Resolution Unconventional Reservoir Modeling of Devonian Strata in Oklahoma Utilizing Rock Volatile Analysis

Collaboration project between Baker Hughes, Advanced Hydrocarbon Stratigraphy

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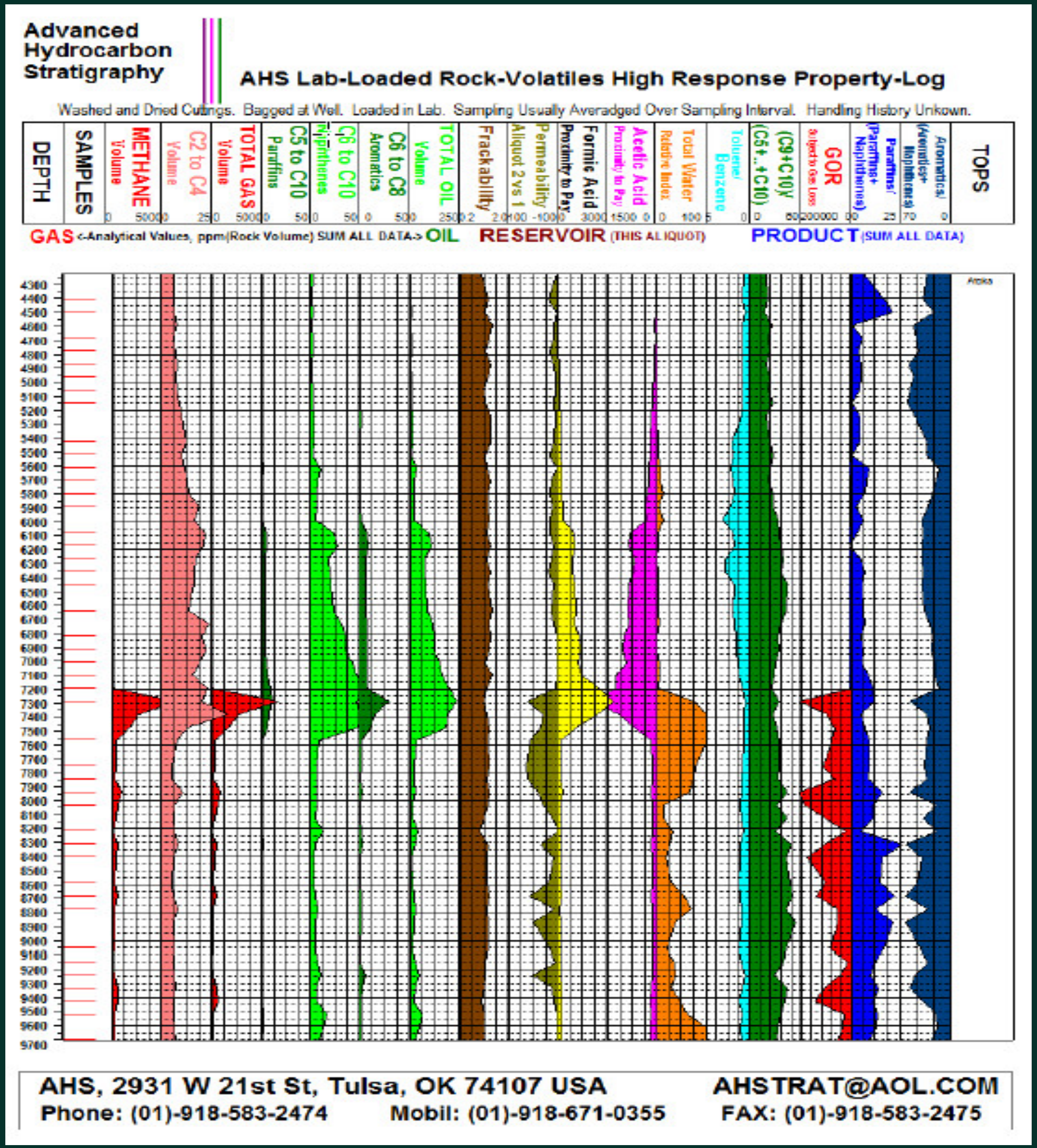
Outline

- Location Maps
- Geologic Background
- Structure & Reservoir Characteristics
- VAS Methods & Data Sets
- VAS Reservoir Modeling
- Conclusions



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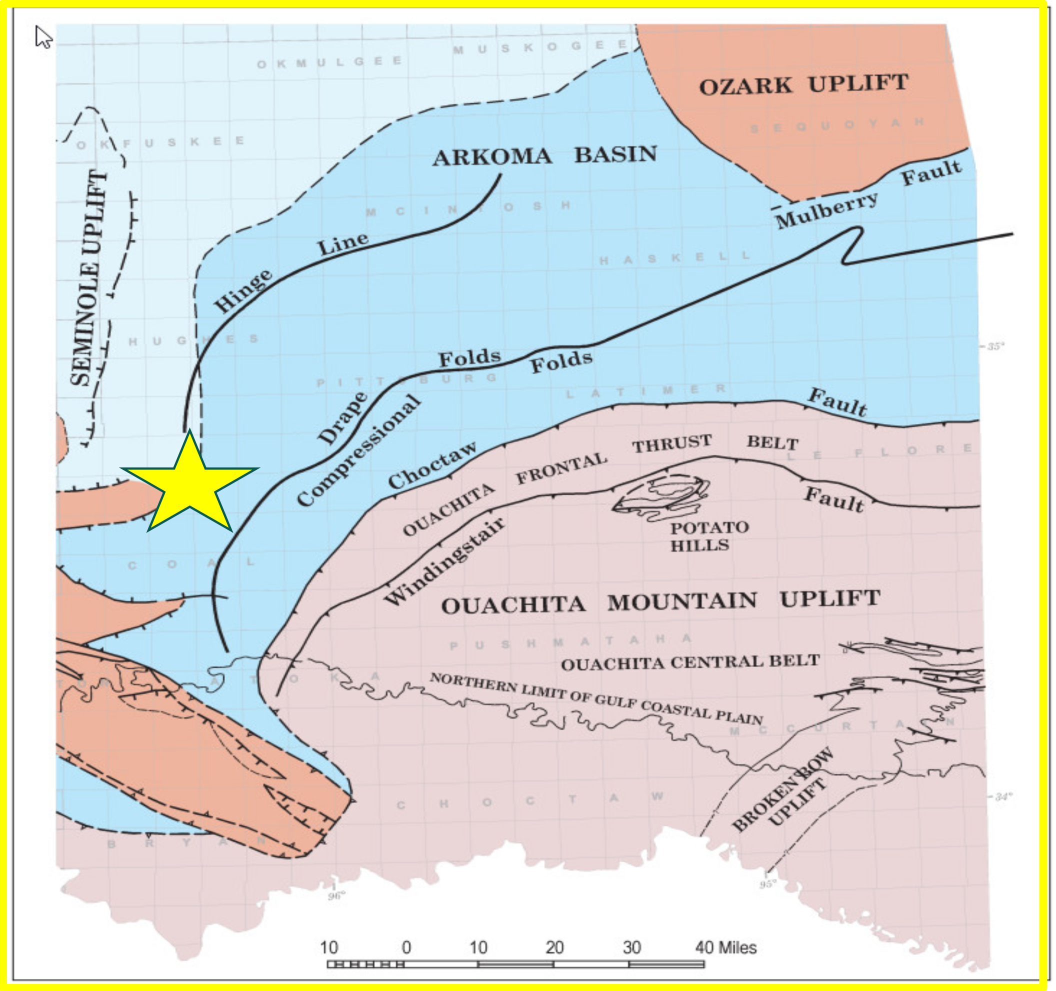
Location & Geologic Map



Western Arkoma Basin – Southeast OK

- Yellow Star/Box = AOI located in Hughes and Coal Co. OK.
- Complex faulting related to Pennsylvanian - Ouachita Orogenic Event

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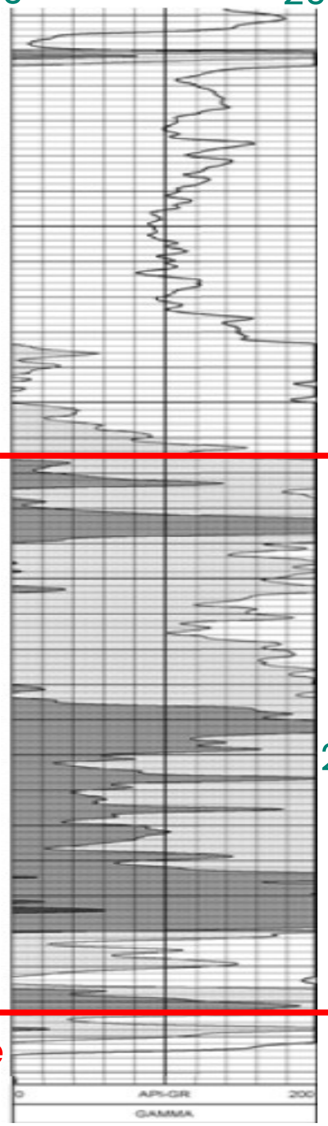
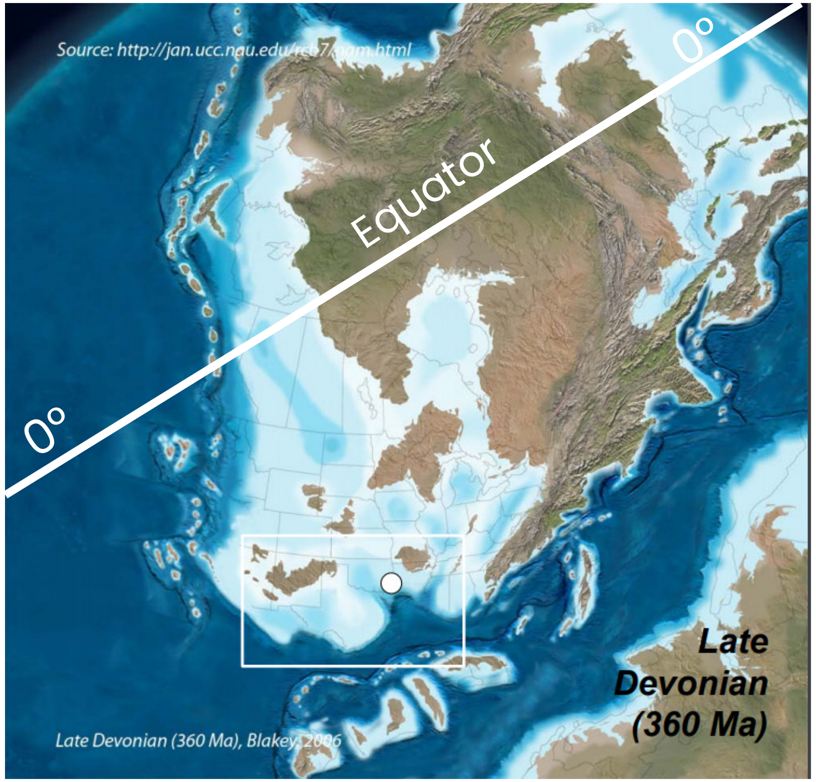
Geologic Background

Woodford Deposition

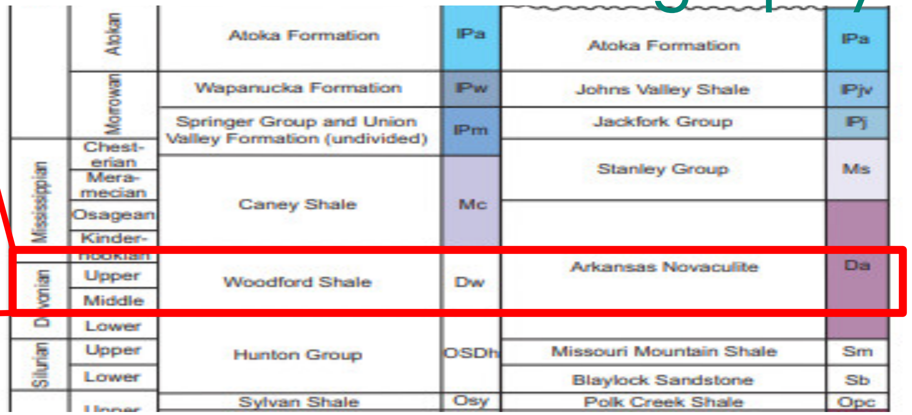
- Paleogeographic map during the Late Devonian – 360 Ma, AOI represented by white dot
- Project area located ~20° S latitude on the westward margin of Laurussia
- Red box = targeted stratigraphic interval, Devonian – Woodford (WDFD)
- Gamma Ray Type Log of the WDFD Formation with API units ranging between 100-650.
- Lower gamma ray intervals contain higher concentrations of silica-rich facies.
- Higher gamma ray intervals contain facies enriched in TOC, phosphate, and clay mineralogies

Gamma Ray Type Log





Arkoma Basin Stratigraphy



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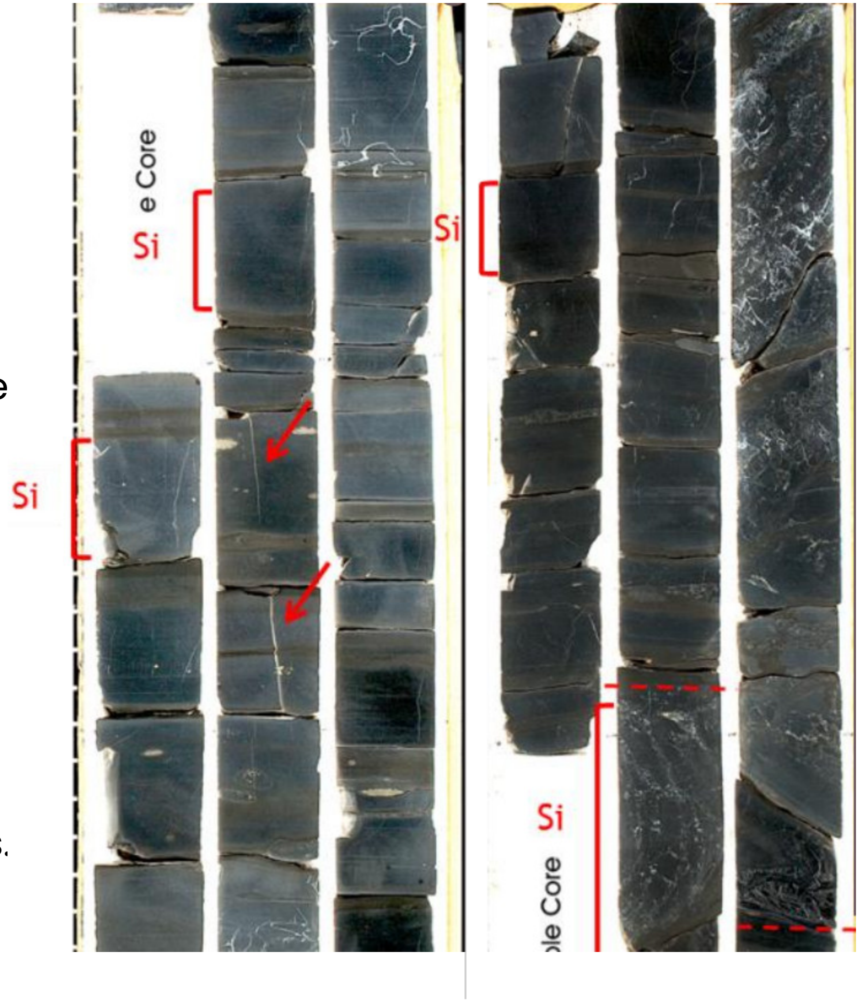
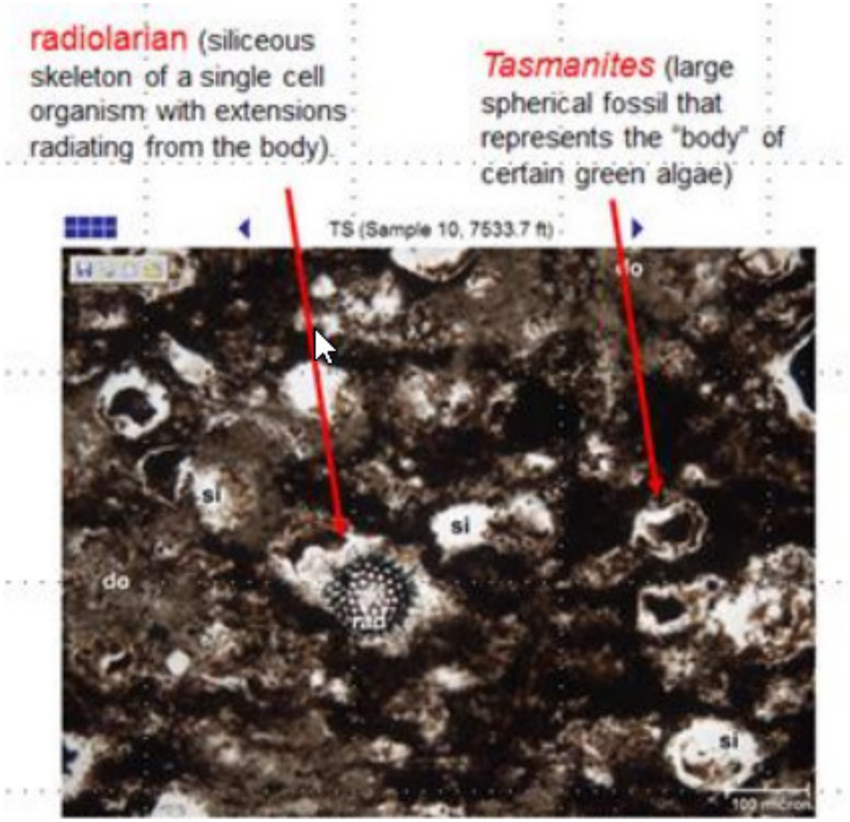
Reservoir Characteristics

WDFD Reservoir Facies

- Core photograph on the left demonstrating interbedded silica rich mudstones (Si brackets) with TOC-rich mudstones.
- Photomicrograph on the right demonstrating constituents of the Si-rich beds: abundant radiolarians and tasmanites.
- Dominated by biogenic silica rather than detrital quartz grains.
- Si-rich beds preferential fracture due to more brittle behavior than interbedded TOC-rich mudstones.





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Modeling Data Sets

RNS & VAS Data Integration

- **Baker Hughes – Reservoir Navigation Services (RNS)**
  - ✓ Well Surveys & Trajectories
  - ✓ Formation Tops along the lateral
  - ✓ Gamma Log along the lateral
  - ✓ Key structural observations – faults, dips, etc.

- **Arkoma Data – 2D grids, offset well data (surveys/logs).**

- **VAS Data – Sealed and Lab Loaded Analysis Sets**
  - ✓ **Comparison of like samples for accuracy**

    Ex. sealed vs sealed samples, not sealed vs crush loaded samples
  - ✓ **Sum all data used in reservoir modeling**

    Total Gas Vol, Total Oil Vol, Permeability, Mechanical Strength, Acetic Acid

✦ **Disclaimer: Following models based on data from 2 wells. Geologic uncertainty increases away from 2 sampled wells.** ✦

RNS Surveys & Reports

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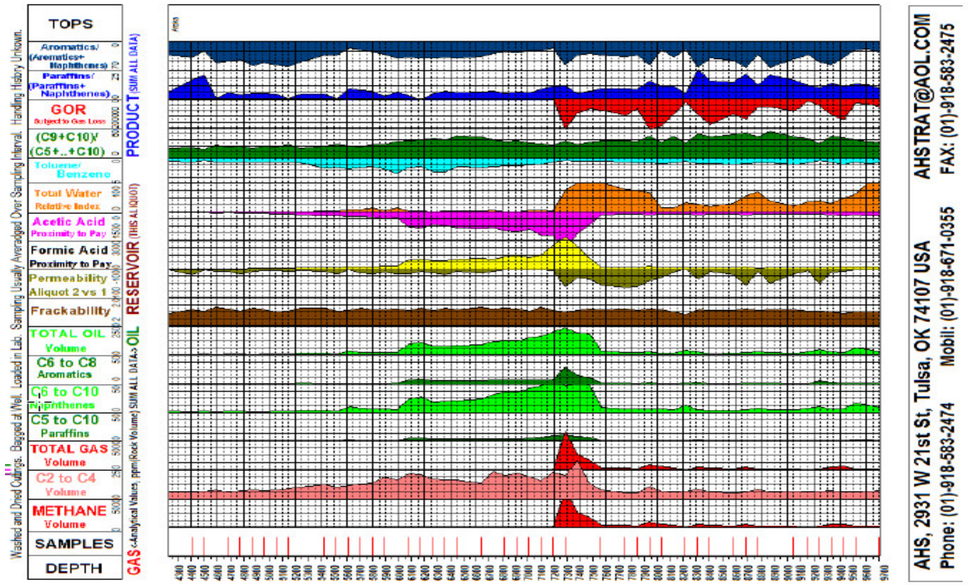
Company:		Job Number:	
Well:		Magnetic Decl.:	
Location:		Grid Corr.:	
Rig:	Cactus 145	Total Grid Corr.:	

Calculation Method	Minimum Curvature		
Proposed Azimuth	354.07		
Depth Reference	DF	Plan #	3
Tie Into:	Surface		

Survey Tool Type	Survey Depth (ft)	Inclina-tion (deg)	Azimuth (deg)	Direction	Course Length (ft)	True Vertical Depth (ft)	Vertical Section (ft)	Coordinates N/S (ft)		Coordinates E/W (ft)		Closure Distance (ft)	Closure Angle (deg)	Dogleg Severity (d/100')	Build Rate (d/100')	Walk Rate (d/100')
Tie In Coordinates																
Tie In	0.0	0.00	195.91	S 15.9 W	0	0.00	0	0.00	N	0	E	0	0	0	0	0
Gyro	23.0	0.00	195.91	S 15.9 W	23	23.00	0.00	0.00	N	0.00	E	0.00	0.00	0.00	0.00	0.00
Gyro	100.0	0.30	195.91	S 15.9 W	77	100.00	-0.19	0.19	S	0.06	W	0.20	195.91	0.39	0.39	0.00
Gyro	200.0	0.10	155.98	S 24.0 E	100	200.00	-0.51	0.53	S	0.09	W	0.53	189.88	0.23	-0.20	-39.93
Gyro	300.0	0.10	138.56	S 41.4 E	100	300.00	-0.67	0.67	S	0.00	E	0.67	179.85	0.03	0.00	-17.42
Gyro	400.0	0.23	123.58	S 56.4 E	100	400.00	-0.87	0.85	S	0.23	E	0.88	165.01	0.14	0.13	-14.98
Gyro	500.0	0.32	135.82	S 44.2 E	100	500.00	-1.21	1.16	S	0.59	E	1.30	153.06	0.11	0.09	12.24
Gyro	600.0	0.22	142.34	S 37.7 E	100	600.00	-1.60	1.51	S	0.90	E	1.76	149.20	0.10	-0.10	6.52
Gyro	700.0	0.28	108.93	S 71.1 E	100	699.99	-1.86	1.74	S	1.25	E	2.14	144.36	0.15	0.06	-33.41
Gyro	800.0	0.28	104.21	S 75.8 E	100	799.99	-2.05	1.88	S	1.72	E	2.55	137.61	0.02	0.00	-4.72
Gyro	900.0	0.32	123.46	S 56.5 E	100	899.99	-2.31	2.09	S	2.19	E	3.03	133.77	0.11	0.04	19.25
Gyro	953.0	0.35	137.51	S 42.5 E	53	952.99	-2.53	2.30	S	2.42	E	3.34	133.50	0.16	0.06	26.51
ATC1	1082.0	0.66	116.30	S 63.7 E	129	1081.99	-3.25	2.92	S	3.35	E	4.44	131.02	0.28	0.24	-16.44
ATC1	1208.0	3.03	268.32	S 88.3 W	126	1207.94	-3.39	3.33	S	0.67	E	3.40	168.59	2.88	1.88	120.65
ATC1	1239.0	3.89	274.33	N 85.7 W	31	1238.88	-3.14	3.28	S	1.19	W	3.49	200.02	3.01	2.77	19.39
ATC1	1333.0	8.16	280.53	N 79.5 W	94	1332.34	-0.68	1.82	S	10.94	W	11.09	260.56	4.59	4.54	6.60

VAS – Rock Volatile Properties Data/Logs



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Project Sampling

- **Lab Loaded = crushed samples at start of extraction.**
  - ✓ Provides opportunity to run VAS on DUC & Legacy wells.
  - ✓ Opportunity for post mortem assessments.
- **Sealed at Well = extraction without crushing of sample.**
  - ✓ Provides opportunity to preserve downhole reservoir fluid conditions.
  - ✓ Dynamic insights on fluid migration/charging effects related to faulting.
- **Sampling methods and intervals are customized to project specific needs. AHS consultation & recommendations are provided.**
  - ✓ Recommended to capture samples above reservoir zone for baseline geochemistry of hydrocarbon system.
  - ✓ Sealed vs Lab Loaded dependent on SOW and lateral/vertical level of investigation.

Well ID	Sampling Method	Sampling Interval	Measured Depth Drilled
Well 1	Sealed at Well	10 ft.	4270-5260 ft.
		90 ft.	5260-14530 ft.
Well 2	Sealed at Well	30 ft.	5310-5700 ft.
		90 ft.	5700-13500 ft.
Well 3	Lab Loaded - Crushed	100 ft.	4700-6500 ft.
		300 ft.	6500-12470 ft.
Well 4	Lab Loaded - Crushed	400 ft.	5000-11700 ft.
		100 ft.	11700-13765 ft.

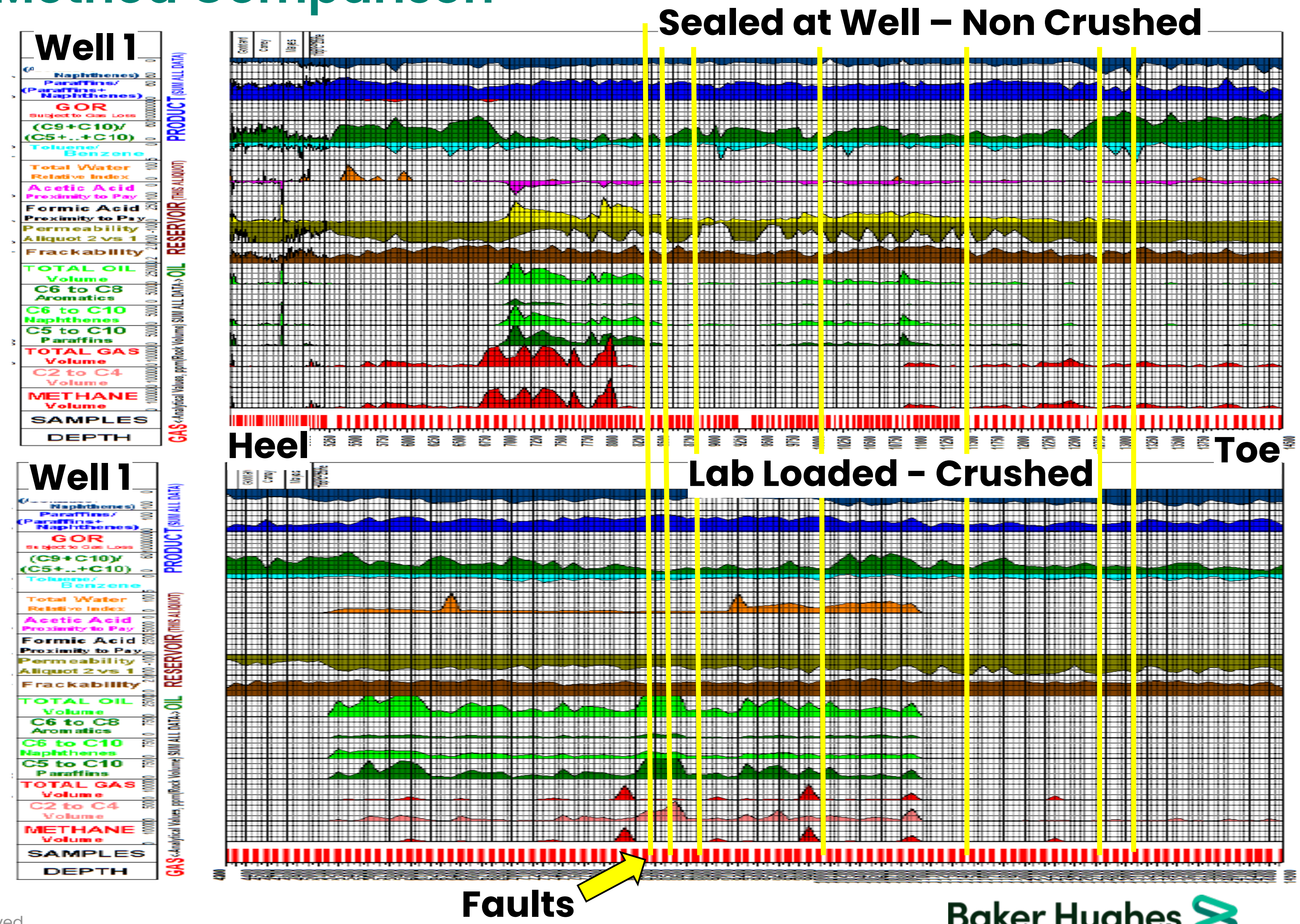
VAS Results: Sample Method Comparison

Sealed vs Loaded Crushed

Different analytical approaches for designated sampling method.

- **Sealed**
  - ✓ Provides more detailed insight into lighter HC and total gas property.
  - ✓ Captures & retains VAS properties used for open faults migrating fluids.

- **Lab Loaded - Crushed**
  - ✓ When used in tandem with sealed method provides insights into water vs oil wetting intervals.



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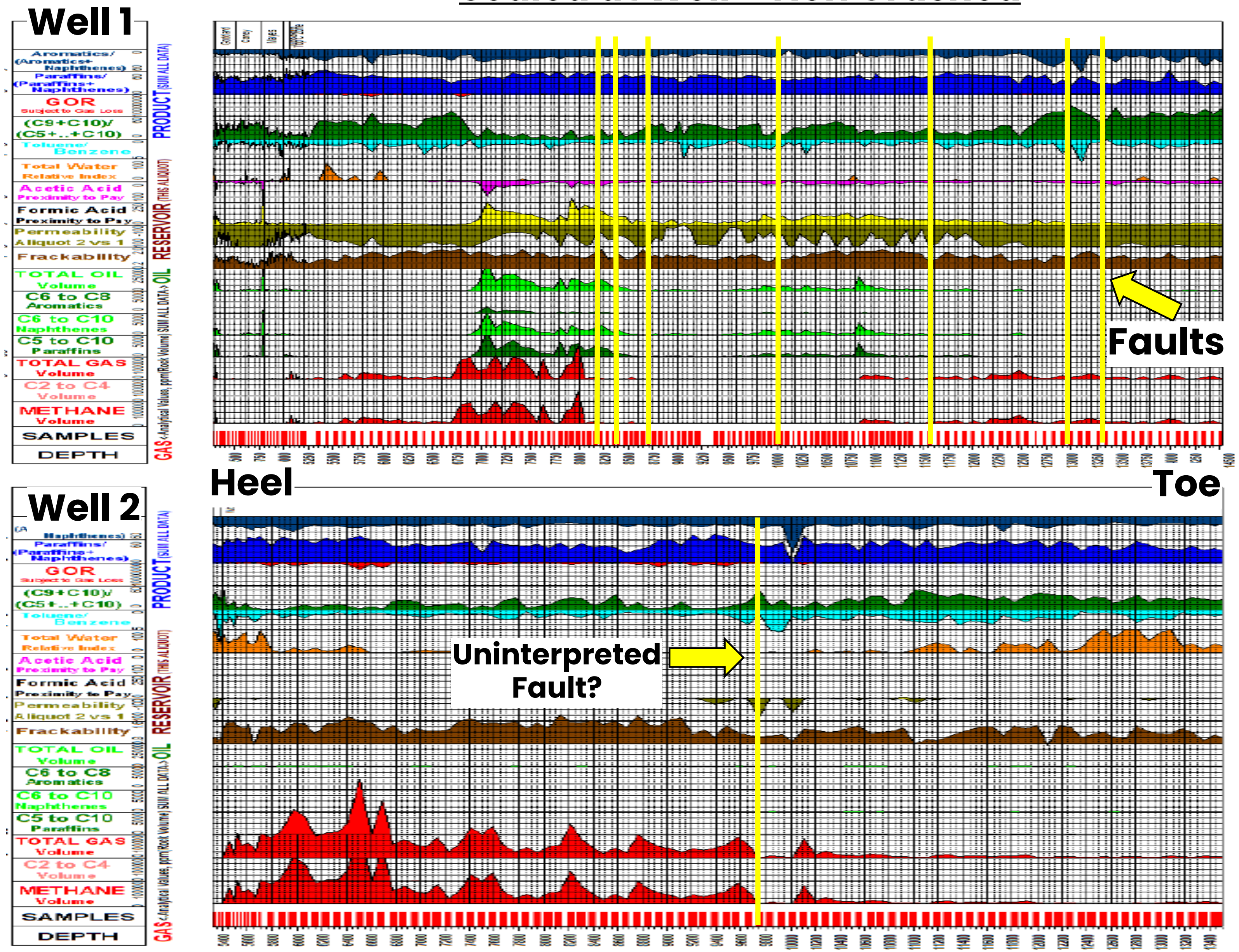
VAS Results

- **Reservoir model uses sealed at well data for more in depth look at reservoir fluid conditions.**
- **Well 1 Analysis:**
  - ✓ More geologically complex with multiple faults encountered while drilling.
  - ✓ Faults are effecting fluid migration and HC charging of fault blocks.
- **Well 2 Analysis:**
  - ✓ Less production potential when compared to Well 1.
  - ✓ Low proximity to pay indicators and low relative permeability.
  - ✓ High total gas zone indicative of tight reservoir rock.

Sealed at Well – Non Crushed



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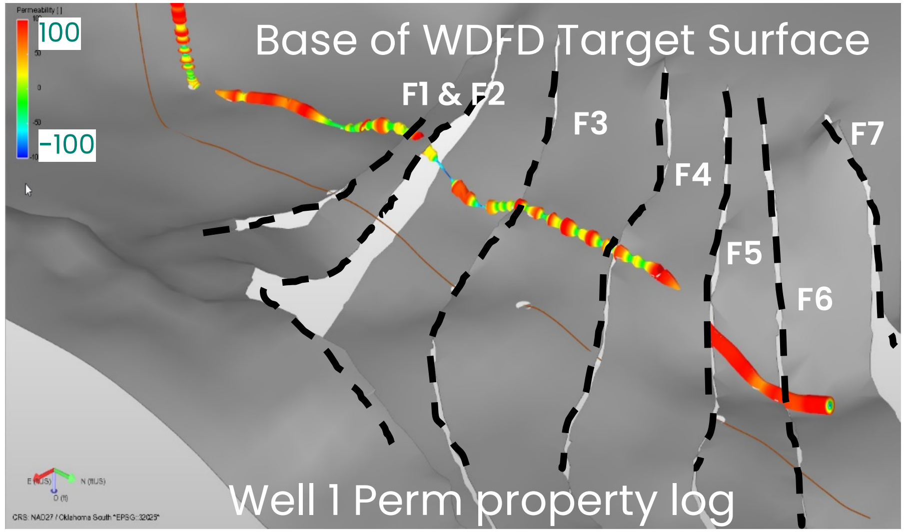
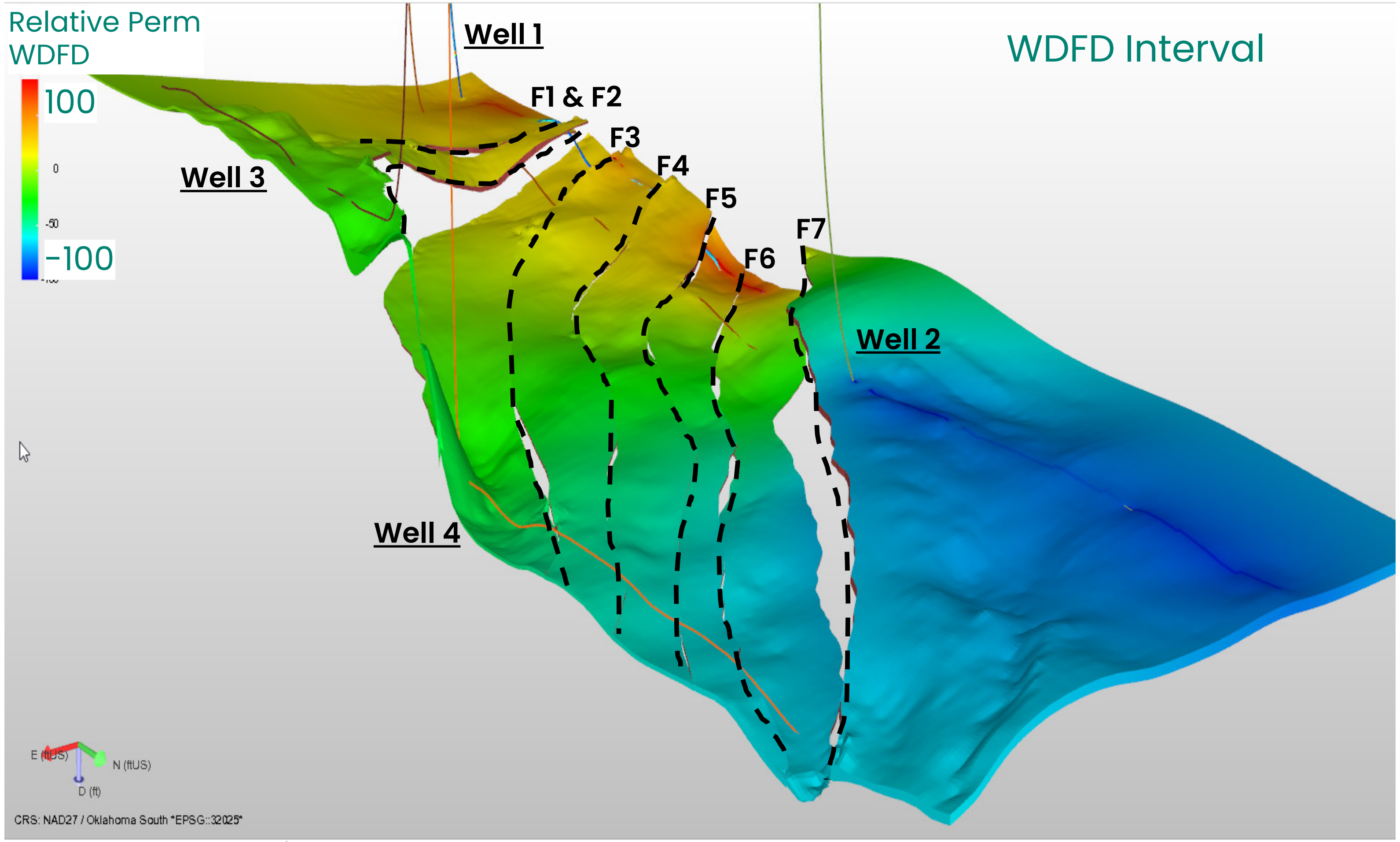
VAS Visualization: Permeability Property

- Permeability measurements are relative and qualitative, not quantitative.
- Northern up thrown fault block contains lowest permeability.
- Highest permeability measurements captured in highly faulted area.





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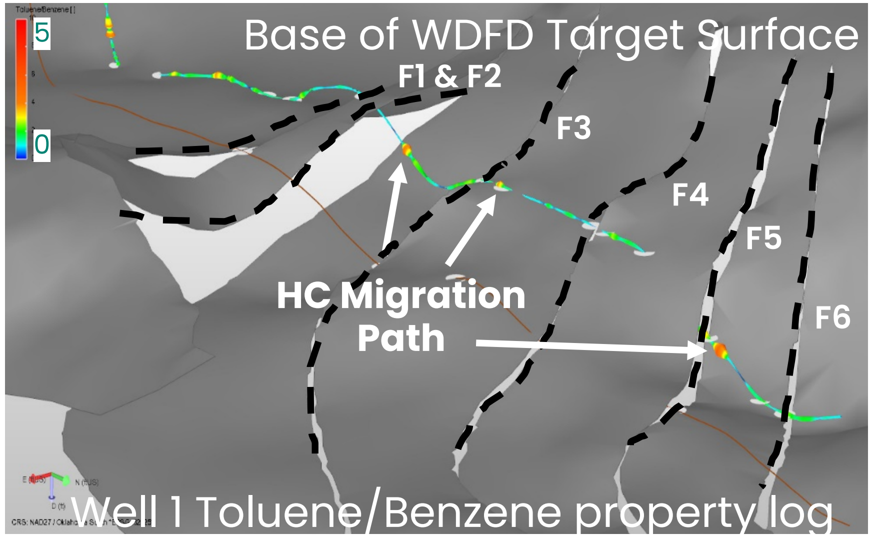
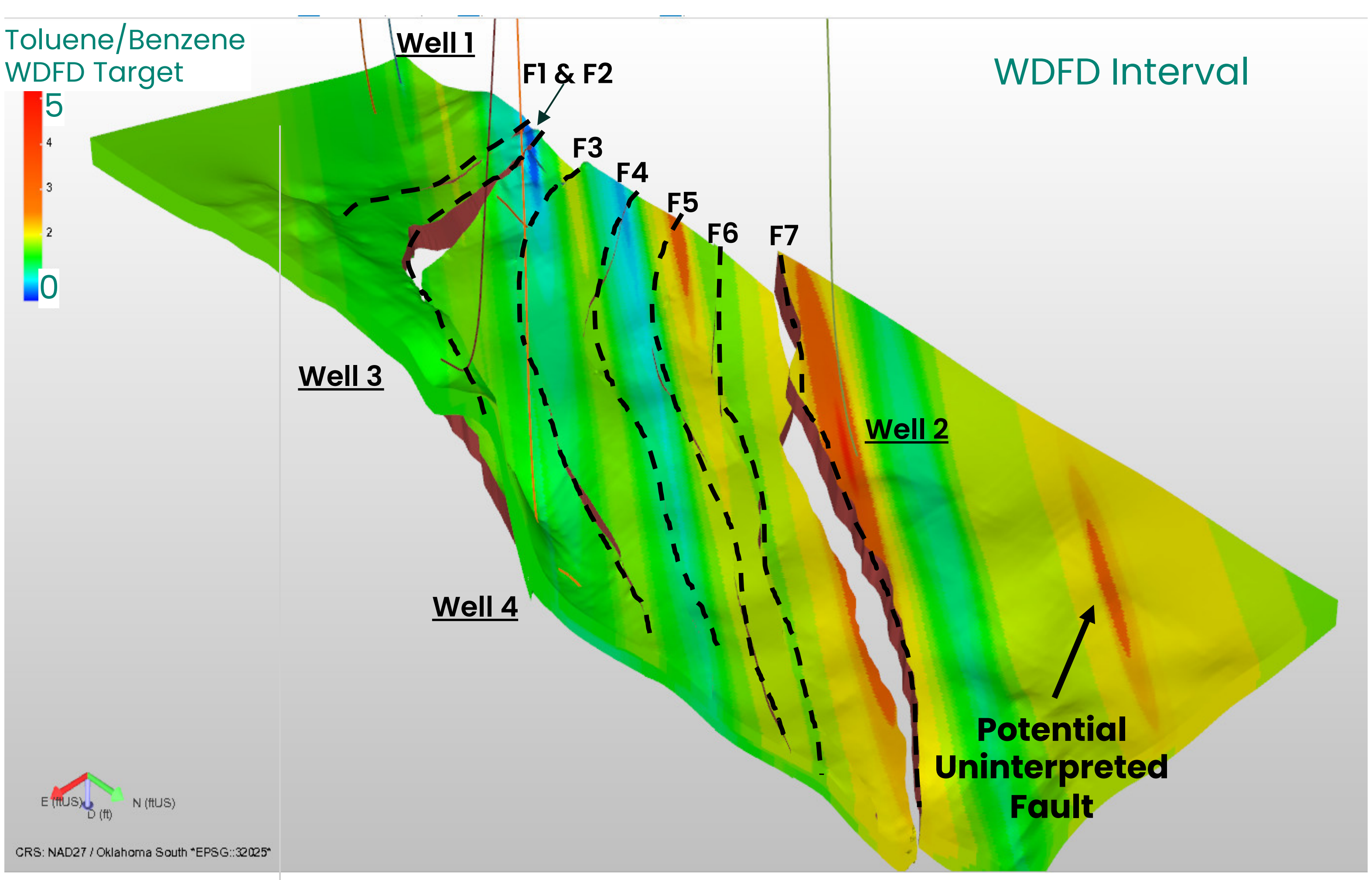
VAS Visualization: Toluene/Benzene Property

- **Toluene/Benzene property provides insight into oil migration. Value > 3 = significant migration.**
- **Toluene/Benzene in highest concentrations around northern fault zone and faults with highest offset within the graben zone.**
- **Zones around faults highlighted in red and yellow indicate high potential for oil migration.**





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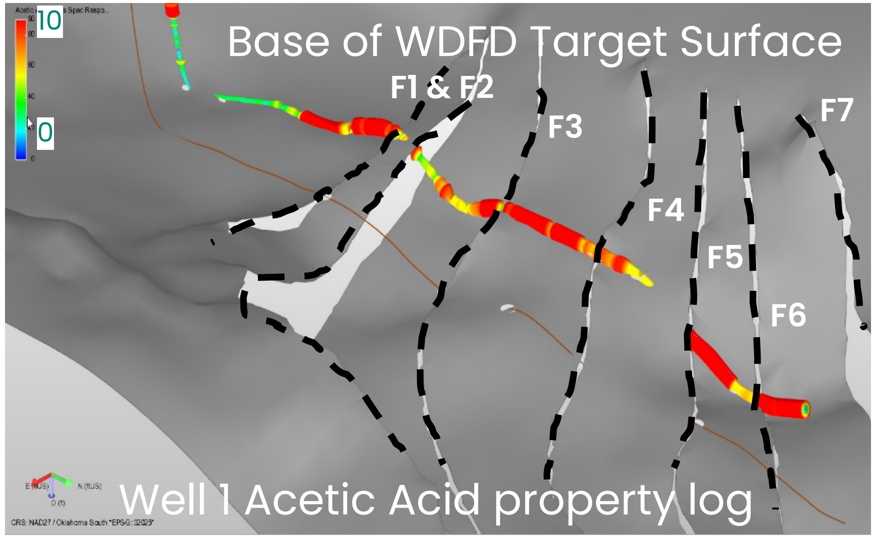
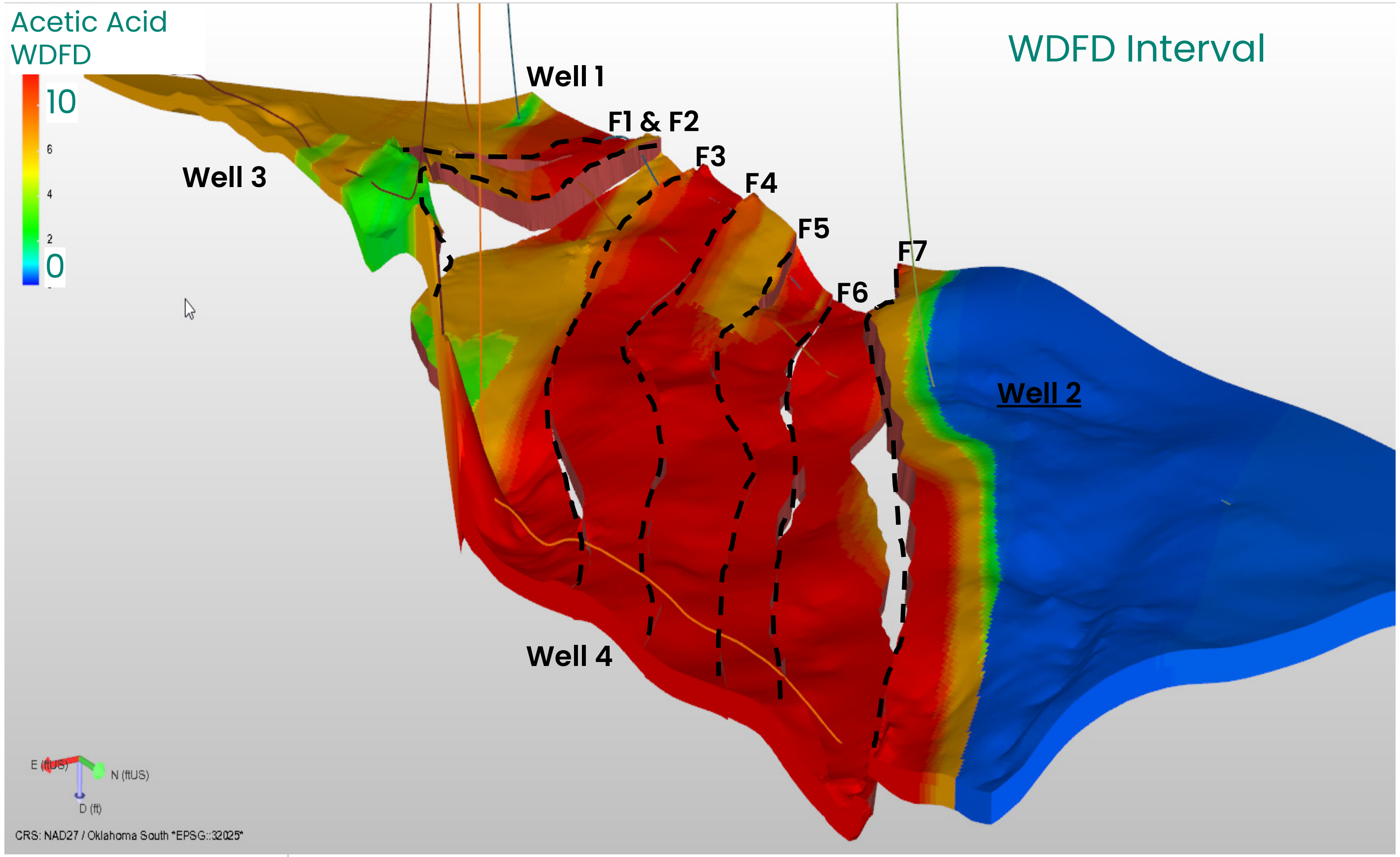
VAS Visualization: Acetic Acid Property

- **Acetic acid property provides insight into proximity to pay related to biodegradation of hydrocarbons.**
- **Acetic acid in highest concentrations within the graben fault zone.**
- **Proximity to pay indicators suggest higher production potential within graben fault zone.**





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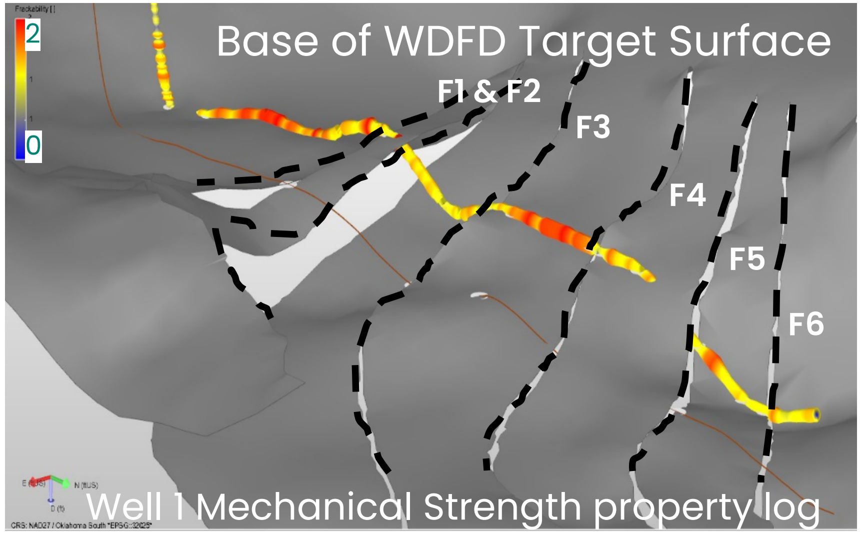
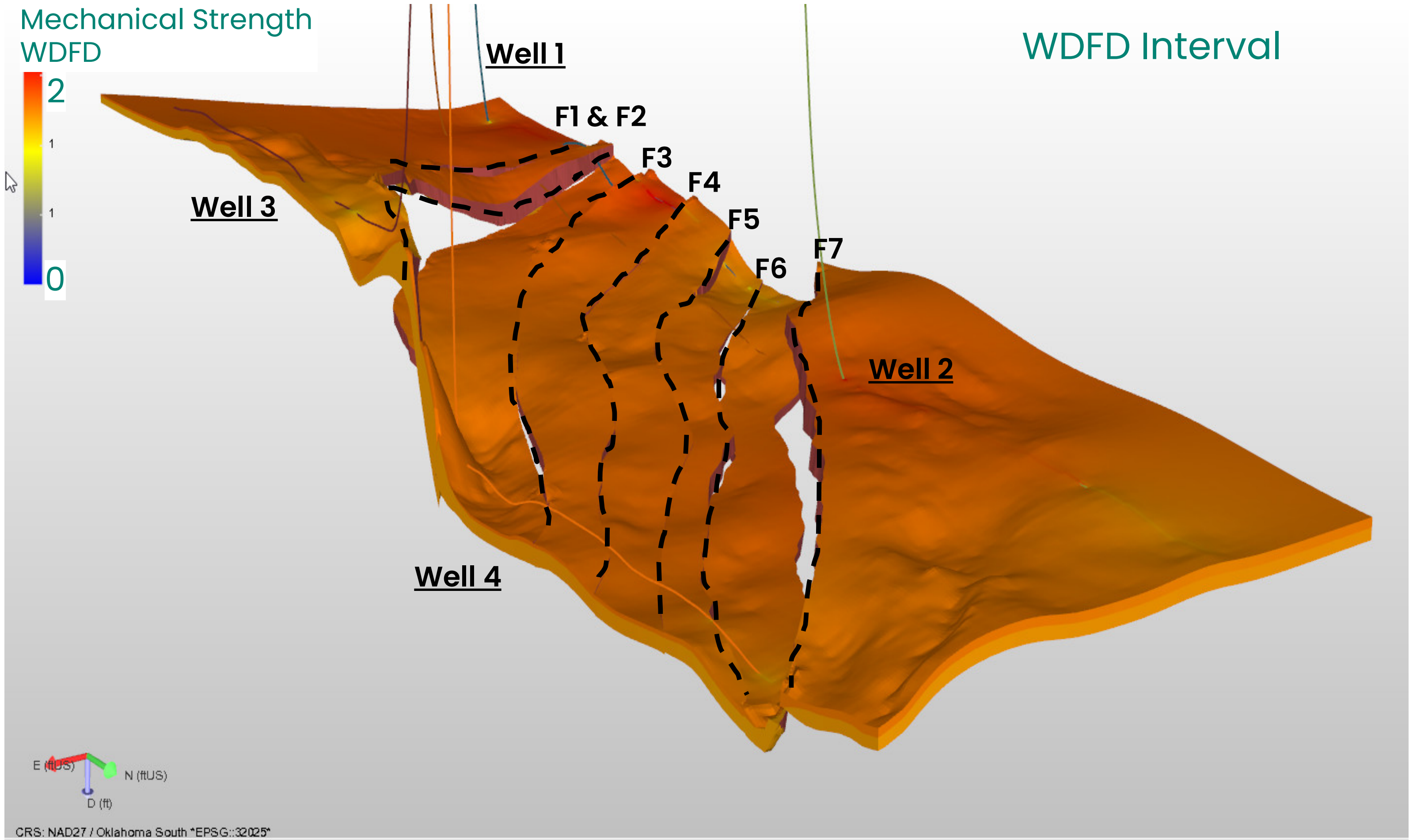
VAS Visualization: Mechanical Strength Property

- Mechanical strength values range from 0-2, and are produced when mechanically squeezing cuttings tubes.
- Consistent measurements within target zone across the field.
- Lowest mechanical strength readings recorded when borehole goes out of target zone.





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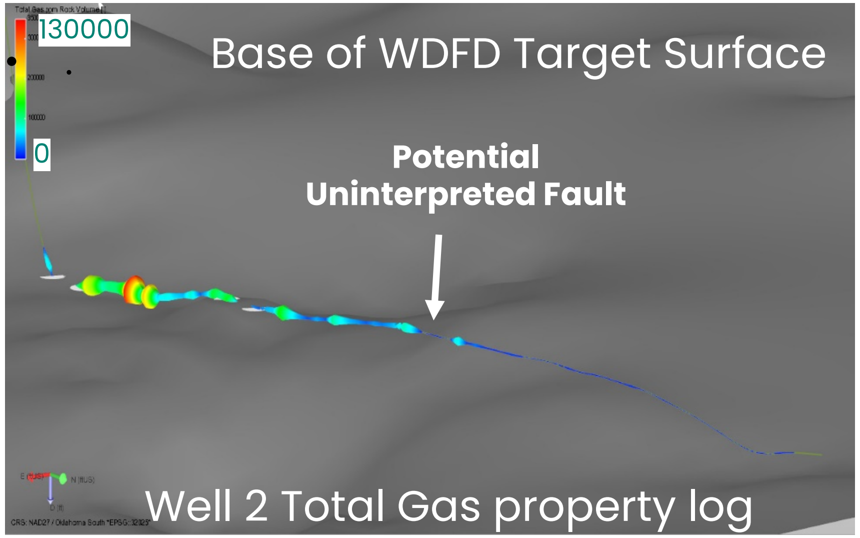
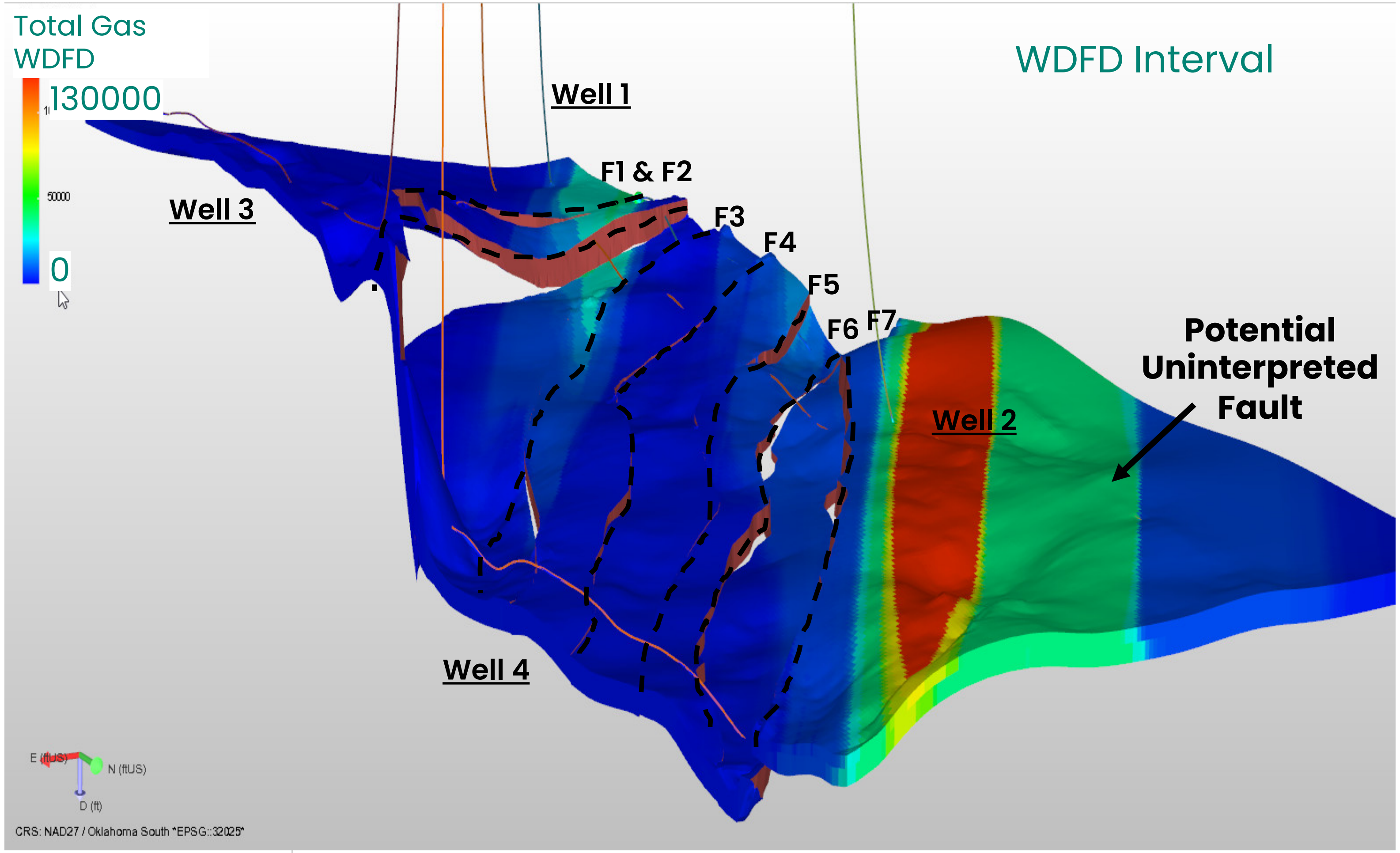
VAS Visualization: Total Gas Volume

- **Total gas volume recovered consistently low within graben and southern block.**
- **Low gas volume recovery from cuttings potentially indicative of better gas production areas due to open faults.**
- **Northern fault block exhibits zone of high gas volume where minor faulting provides better representation of gas in place.**





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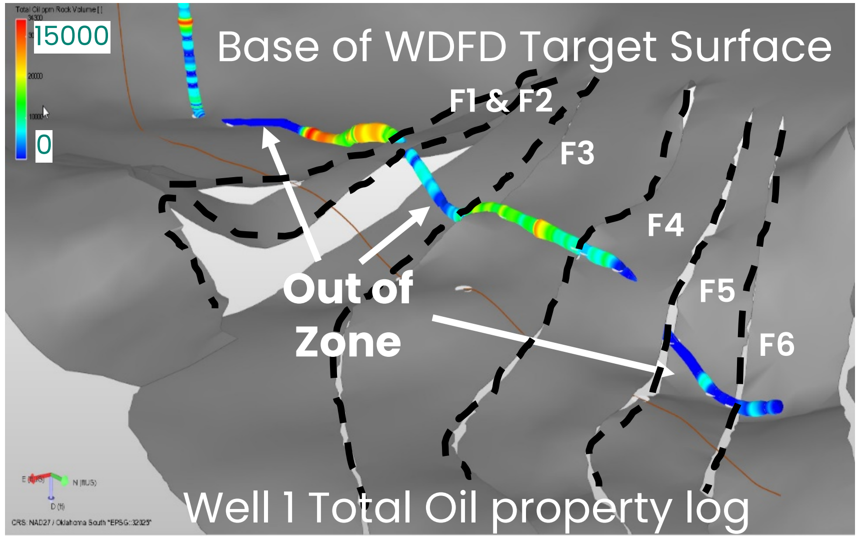
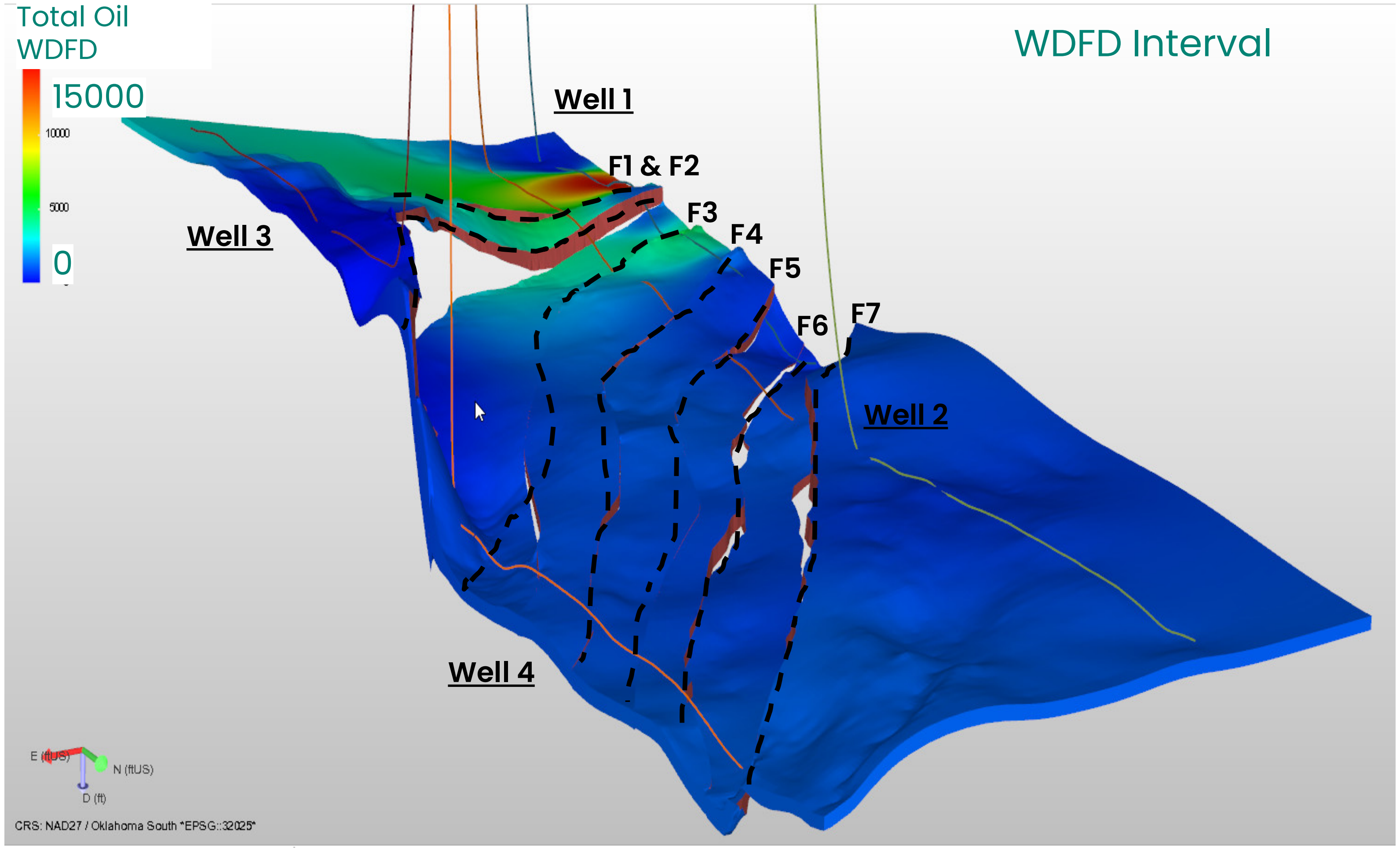
VAS Visualization: Total Oil Volume

- **Total oil volume recovery lowest on the north fault block and where wellbore drilled out of target interval.**
- **Higher oil volume recovery zones due to open faults migrating hydrocarbons.**
- **Oil volume indicators within Well 1 lateral occur along interpreted open faults from toluene/benzene data. Evidence for migration.**





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Conclusions

- **Sampling interval and method dependent on SOW for specified unconventional reservoir & project area.**
  - New wells open to sealed at well sampling method.
  - Legacy wells or DUCs open for lab loaded-crushed method.
  - 3D reservoir modeling requires consistent sampling method across the AOI.

- **3D VAS visualizations offer detailed insights into reservoir fluid conditions within unconventional reservoir targets.**
  - Single well analysis produce 3D visualizations of VAS property distributions along the wellbore and insights on reservoir quality.
  - Multiple well analysis provides insight for 3D reservoir modeling with respect to VAS properties and insights on the relationship with the overall geologic framework of an AOI.

- **Unconventional Woodford reservoirs in the Arkoma AOI are dependent on:**
  - Geologic complexity and mapping of open faults migrating and charging designated fault blocks with hydrocarbons.
  - Reservoir quality insights from VAS show proximity to pay and permeability indicators are highest in the graben fault blocks.

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