

# **Steam Piloting in the Aruma Reservoir, Awali Field, Bahrain\***

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## **Abstract**

The Aruma Reservoir is the shallowest hydrocarbon-bearing reservoir in the Awali Field, found at depths of between 600 and 800 feet. It is a shallow water carbonate reservoir that contains very viscous tar and bitumen. It thins over the crest of the Awali Anticline, varying in thickness from 800 feet on the crest to 1,200 feet on the flanks. The principle characteristics of the Aruma Reservoir are: Fractured limestone and dolomite reservoir with karst caves and vugs, high oil viscosities, and low pressure Heterogeneous saturation. There are two principal types of hydrocarbons found in the Aruma - a liquid form of tar with API gravities of between approximately 4 to 8 degrees, and bitumen that is a solid under in situ conditions. Both the tar and the bitumen have viscosities low enough to be mobile at temperatures of 200° C.

The best analog reservoir for the Aruma is the Grosmont Bitumen Carbonate Reservoir in Alberta, Canada. Both reservoirs have a wide range of hydrocarbon viscosities, ranging up to 10's of millions of cP at reservoir conditions, and both have similar heterogeneous distributions of tar and bitumen due to the fractured and karsted character of the reservoirs. In January, 2015 Tatweer Petroleum began a steam enhanced-oil-recovery (EOR) pilot in the Aruma Reservoir. Cyclic-steam-stimulation (CSS) in a single vertical well is being attempted to demonstrate that tar and bitumen can be mobilized in the reservoir and produced to the surface. Three separate high-porosity zones in the upper Aruma will be tested sequentially. The lift system utilizes an all-metal progressive-cavity-pump in combination with diluent injection. Specialized surface testing and production facilities have been constructed for the very viscous tar/bitumen. Early results from the steam EOR pilot show that steam confinement in the vicinity of the CSS well is a challenge.

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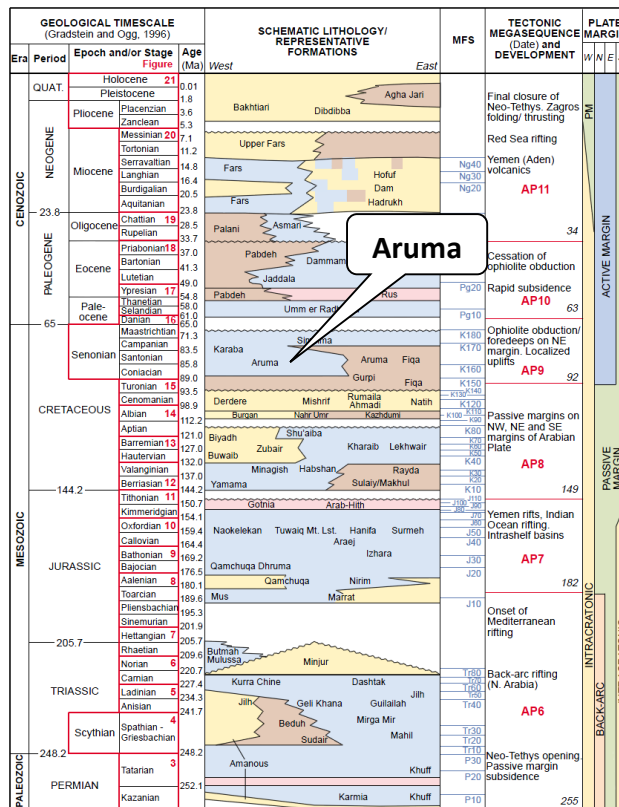
Society of Exploration Geophysicists  
*The international society of applied geophysics*



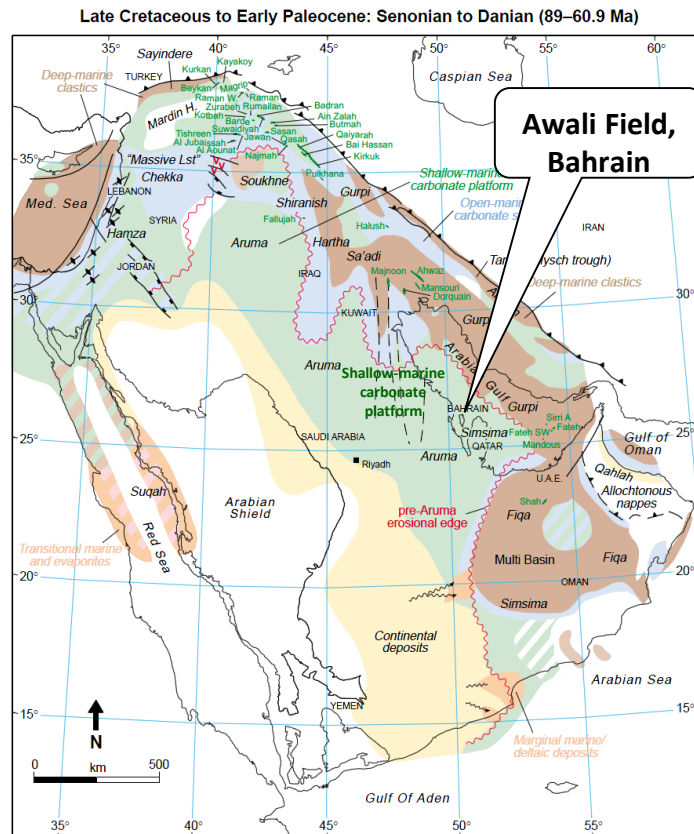
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Arabian Exhibition Management

### Aruma Regional Geology

- Upper Cretaceous.
- Deposited on top of the regional mid-Turonian unconformity.
- Shelf and platform limestone on the eastern flank of the Arabian Shield in a passive margin to foreland basin setting.
- Repeated subareal exposure with extensive karsting.



From Ziegler, 2001



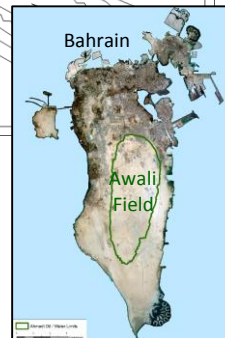
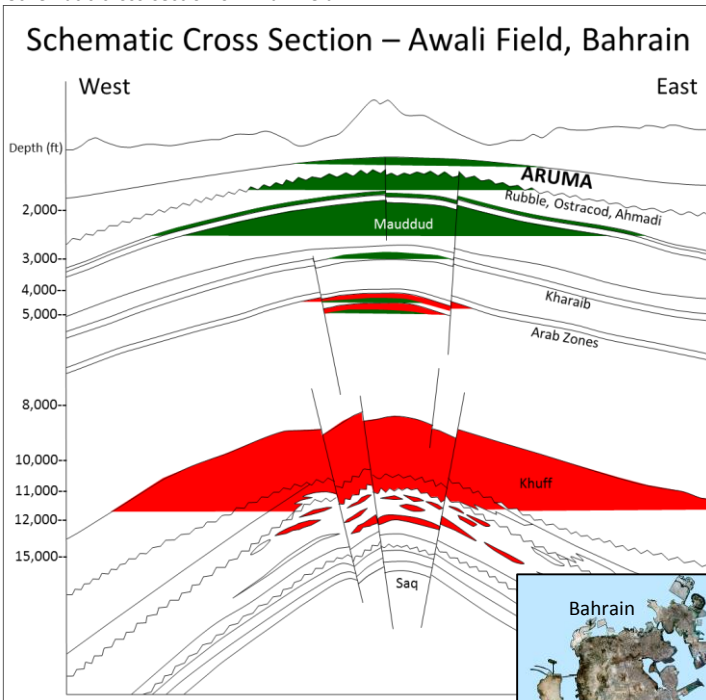
From Ziegler, 2001



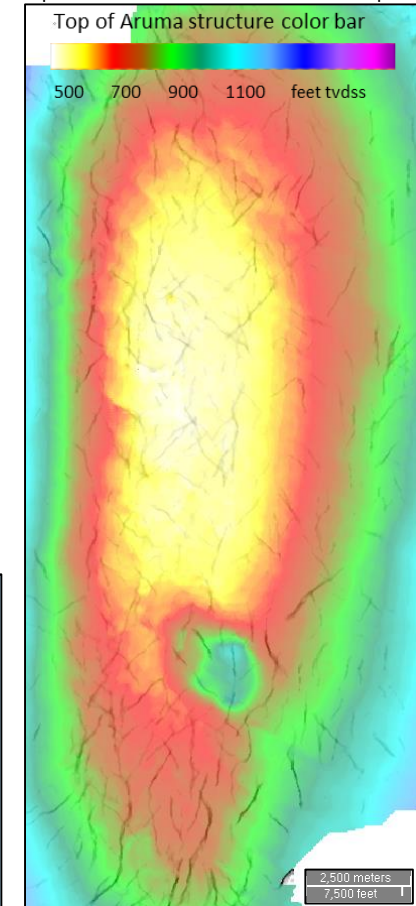
### Aruma Local Geology

- Broad faulted anticline.
- Separated from the Mishrif (Rubble) by the regional mid-Turonian unconformity.
- Shallowest hydrocarbon-bearing reservoir in Awali Field.
- Depth ranges from 500 to 800 feet.
- Thickness ranges from 800 feet on the crest to 1200 feet on the flanks.
- Top seal is the A0 shaly limestone, also known as the “Black Shale”.

Schematic cross-section of Awali Field



Depth structure and “Ant Track” fracture proxy



### Aruma Karst Geology

- Heterogenous fractured limestone and dolomite with karst caves and vugs.



Karst outcrop in Malta, Mediterranean Sea



Karst fracture filled with karst debris and calcite cement



Open vertical fractures



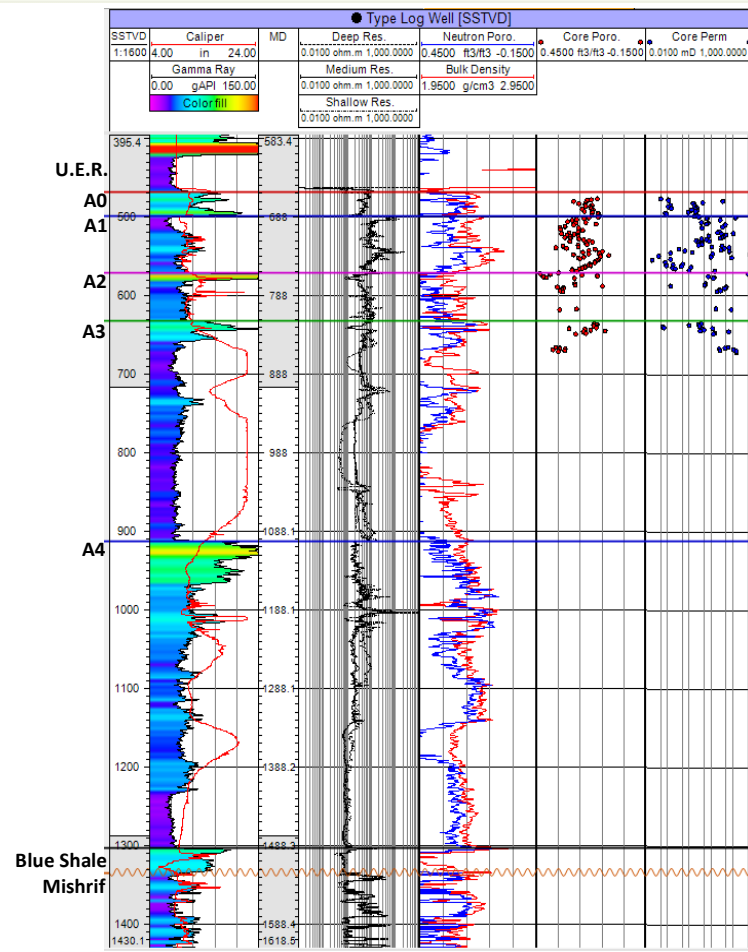
Irregular karst-etched surfaces and infilling carbonate sediment



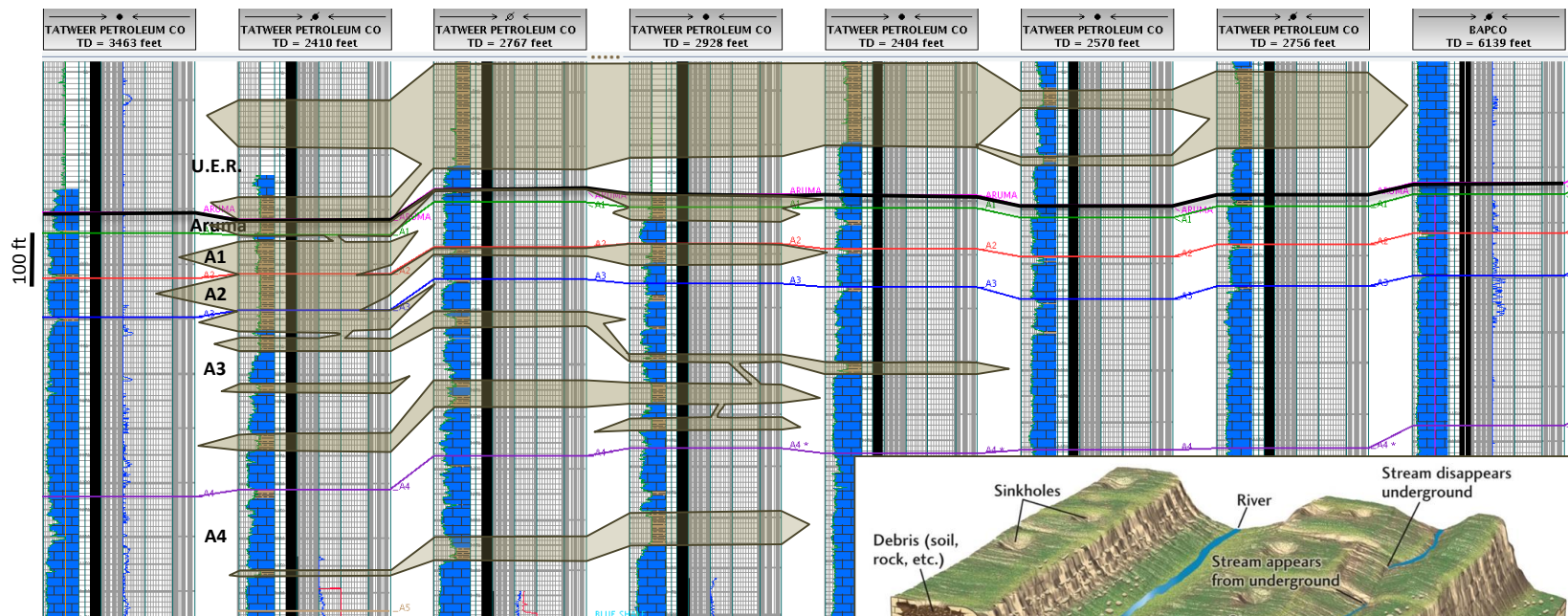
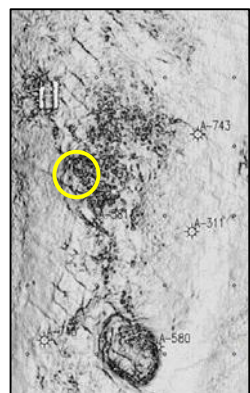
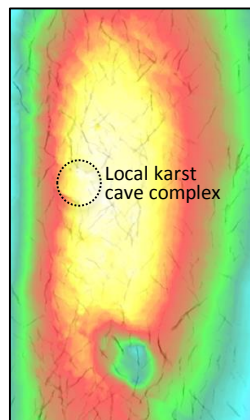
Karst breccia and vugs

### Aruma Reservoir Properties

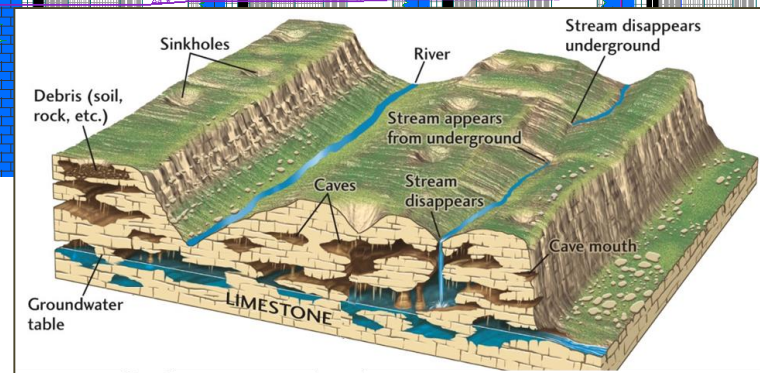
- Subdivided into five zones, A0 to A4.
- Zones targeted for development are A1 to A3.
- Reservoir properties from core analysis:
  - Karsted dolomite (A1, A2) and limestone (A3, A4).
  - Solution-enhanced open fractures and karst vugs.
  - Incomplete core recovery due to large vugs and caverns.
  - Core matrix porosity range is 10 – 37%, excluding large vugs.
  - Core matrix permeability range is 1md – 1 darcy, excluding large vugs.
  - Average core permeability in primary target zones ~ 80 mD.
- Drilling lost circulation zones are common throughout Aruma.



### Aruma Reservoir Properties – Local Stacked Karst Caves

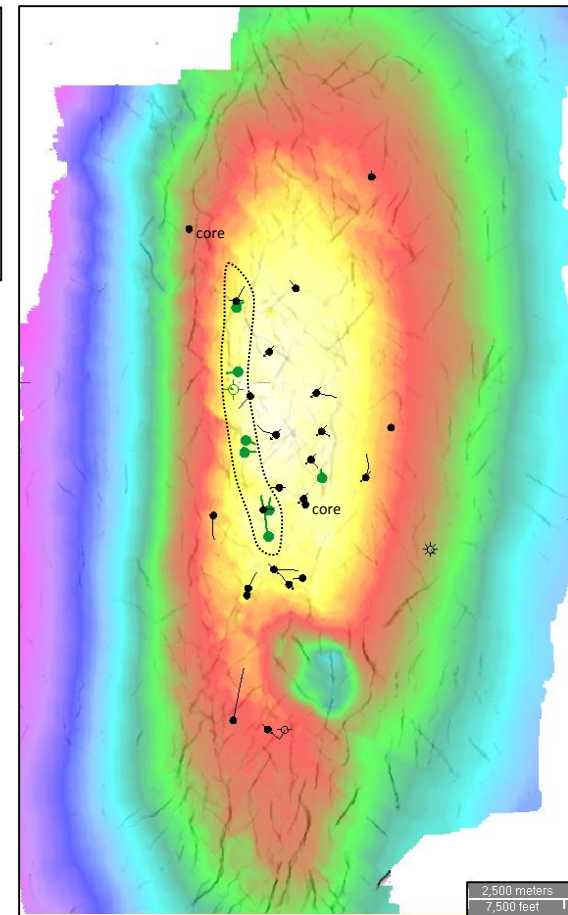
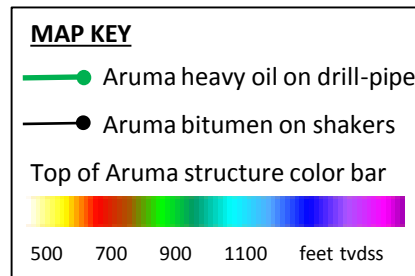


Seismic coherence may be delineating karst features on the Aruma surface.



### Aruma "Tar Valley"

- Heavy oil on drill-strings when tripping out
- Tar coming over the shakers
- 3.9° to 7.8° API gravity
- Viscosity = 200,000 cP at reservoir conditions (40°C, 104°F)

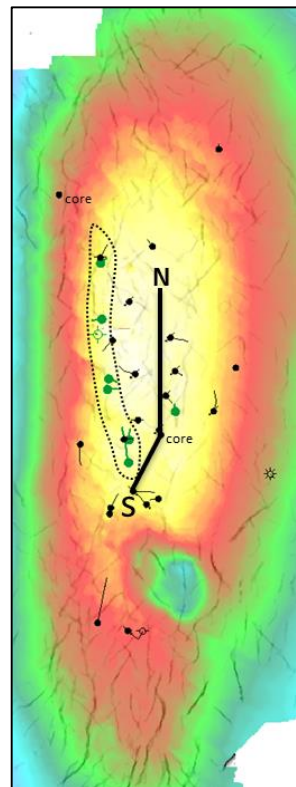


### Variable Tar Saturation – Both Vertically and Laterally

Immoveable HC  
Moveable HC  
Bound + moveable water

North

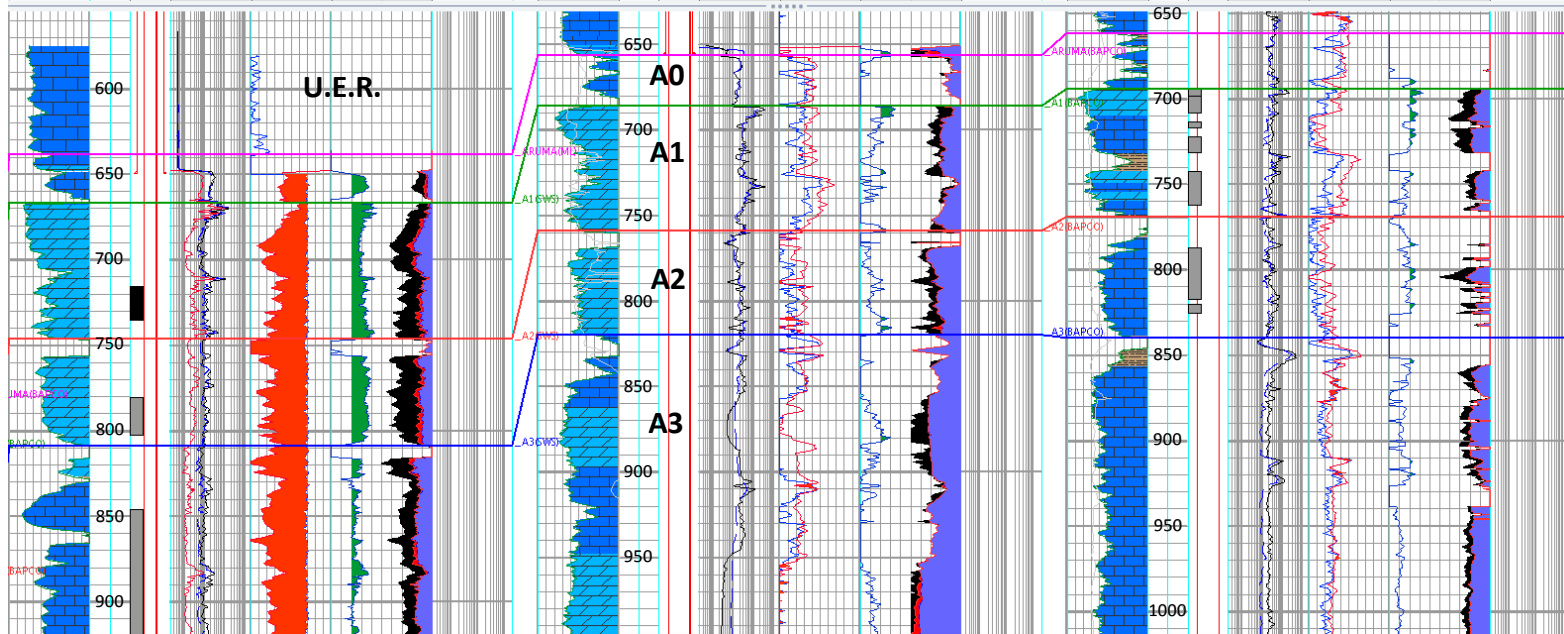
South



TATWEER PETROLEUM COMPANY TD = 1012 feet									
Correlation	Dept	Engin	Resistivity	Porosity	Saturation	Logs			
MD\Linear	MD	Perfs	MD\Log	MD\Linear	MD\Linear	MD\Log			
XGR		ISOLAT	XRES	XRHO	XBVWS				
API			ohm.m	g/cm3	decimal				
0.00	100.00		0.20	2000.0	3.00	0.50 0.00			
		Perfs	XRESM	XNPIL	XSW	XPOR			
		Perfora	ohm.m	decimal	decimal	decimal			

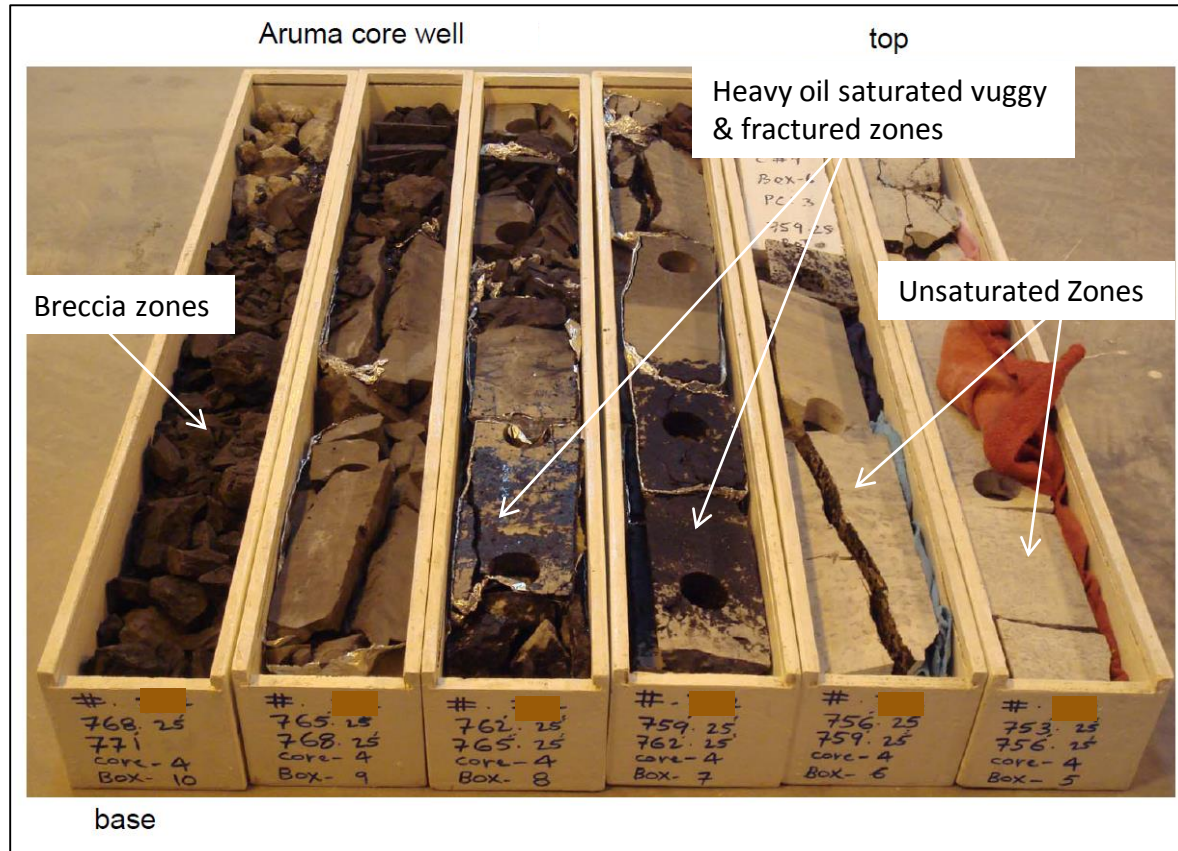
BAPCO TD = 1878 feet									
Correlation	Dept	Engin	Resistivity	Porosity	Saturation	Logs			
MD\Linear	MD	Perfs	MD\Log	MD\Linear	MD\Linear	MD\Log			
XCAL		Perfora	XRESM	XRHO	XBVWS	ZPERM			
inches			ohm.m	g/cm3	decimal	mD			
6.00	16.00		0.02	2000.0	3.00	0.20 200.00			
XGR		Casin	XRES	XNPIL	XSW	XPOR			
API		SURF	ohm.m	decimal	decimal	decimal			

BAPCO TD = 1890 feet									
Correlation	Dept	Engin	Resistivity	Porosity	Saturation	Logs			
MD\Linear	MD	Perfs	MD\Log	MD\Linear	MD\Linear	MD\Log			
XCAL		Squeez	XRESM	XRHO	XBVWS				
inches			ohm.m	g/cm3	decimal				
6.00	16.00		0.02	2000.0	3.00	0.50 0.00			
XGR		Perfs	XRES	XNPIL	XSW	XPOR			
API		Perfora	ohm.m	decimal	decimal	decimal			



### Variable Tar Saturation in Core

- Most fractures are filled with heavy oil and bitumen.
- Larger vugs and caverns are filled with heavy oil and bitumen.
- However, heavy oil saturation of the matrix is highly variable, ranging from no matrix saturation to mottled saturation to fully saturated.



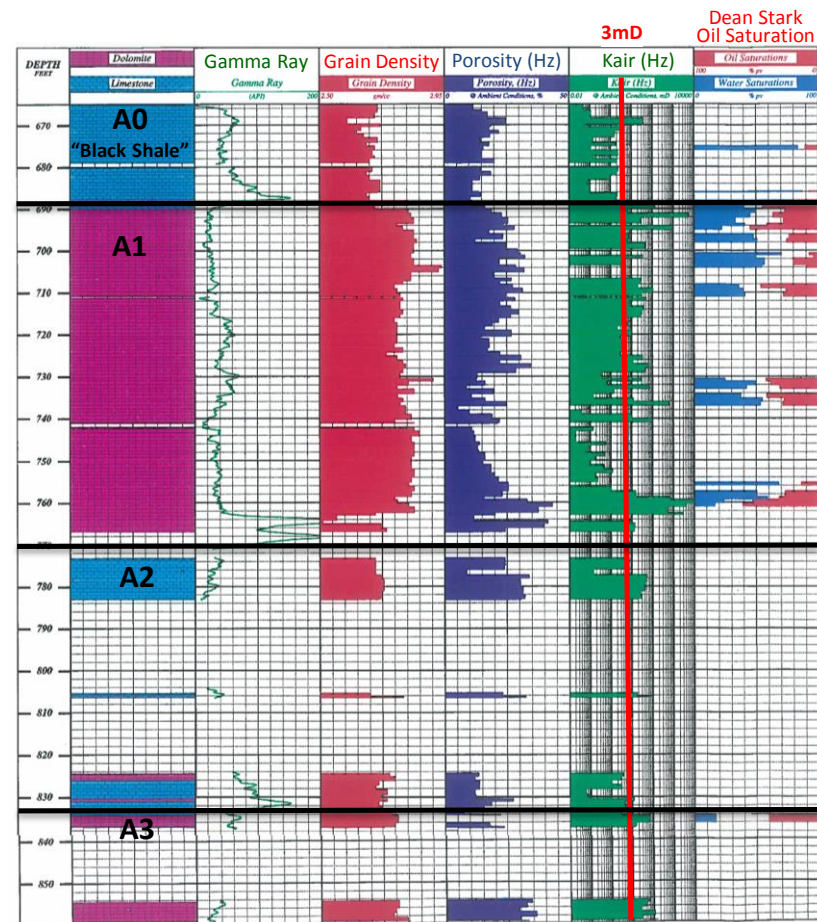
### Variable Tar Saturation in Core

Plug 732.1':  $\phi$  8.9% Kair 70md  
Oil sat 31% Water sat 42%



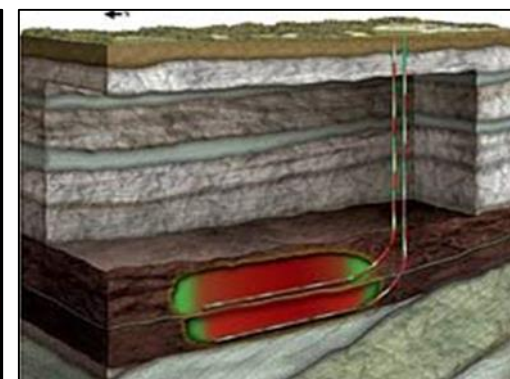
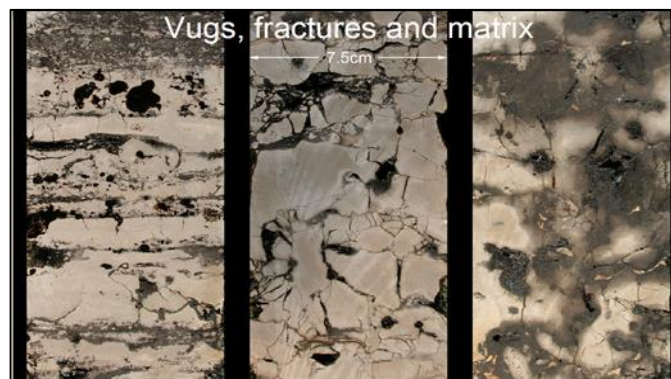
Plug 733':  $\phi$  19.6% Kair 1.4md  
Oil sat --- Water sat ---

- Distribution of tar saturation possibly due to a matrix permeability cutoff of ~3mD
- This trend may reflect increasing oil viscosity as the crude migrated vertically from deeper Awali oil reservoirs



### Development Analog

- Grosmont is an analog field located in Alberta, Canada
- Karsted limestone
  - Patchy, irregular distribution of heavy oil and bitumen in fractures and vugs
  - 150-250 mD permeability
- Laricina Energy's thermal pilot
  - Reservoir contains ~ 406 billion barrels of bitumen
  - Steam injection pilot began Dec 2010
  - Three processes:
    - Thermal expansion
    - Spontaneous imbibition
    - Gravity drainage (SAGD is the dominant recovery mechanism)
  - Cum gross bitumen production exceeds 600,000 barrels



C-SAGD: Single horizontal wells in the Grosmont D & C zones.

Aruma heavy oil

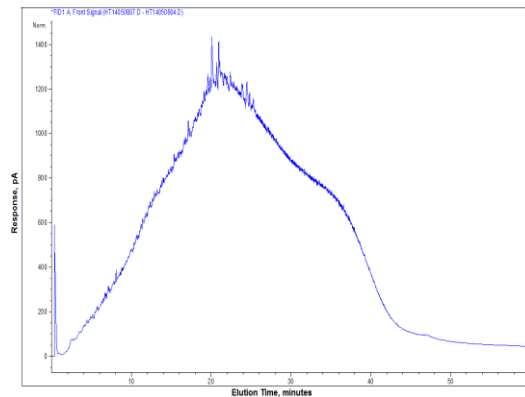
### Aruma heavy oil composition

- HTGC method
- C40 to C90+

### Aruma heavy oil SARA

Description	Lab Method	Result	Unit of Measure
Saturates Content	HPLC	10.05	wt %
Aromatics Content	HPLC	64.37	wt %
Resins Content	HPLC	11.72	wt %
Asphaltene Content	IP 143	13.85	wt %

### Aruma heavy oil gas chromatogram



### Aruma heavy oil viscosity at temperature

	Aruma Heavy Oil method 1	Aruma Heavy Oil method 2	Aruma Heavy Oil method 3
	polynomial fit	linear extrapolation	linear fit of log-log vs log T(deg K)
Temp., °C	Visc., cP	Visc., cP	Visc., cP
20	2.65E+06	1.28E+08	3.67E+06
25	1.62E+06	1.26E+07	1.57E+06
30	8.34E+05	2.34E+06	7.11E+05
35	4.07E+05	6.48E+05	3.41E+05
40	1.99E+05	2.33E+05	1.72E+05
45	102000	102000	102000
50	47872	47872	47872
55	29653	29653	29653
60	16026	16026	16026
65	9267	9267	9267
70	5675	5675	5675
75	3789	3789	3789
80	2679	2679	2679
85	2039	2039	2039
90	1579	1579	1579
95	1212	1212	1212
100	904.5	904.5	904.5
105	624	624	624
110	455.5	455.5	455.5
115	336.5	336.5	336.5
120	263.1	263.1	263.1
125	198.2	198.2	198.2
130	162.1	162.1	162.1
135	126.7	126.7	126.7
140	103.3	103.3	103.3
145	85.1	85.1	85.1
150	70.6	70.6	70.6
155	60.6	60.6	60.6
160	51.8	51.8	51.8
180	30.3	30.9	30.0
200	19.2	20.6	18.8
220	13.1	14.9	12.8
240	9.6	11.4	9.2
260	7.4	9.1	7.0

200,000 cP @ reservoir  
temp 40°C, 104°F

Lab tests 45 °C to  
160 °C using  
Brookfield  
Rheometer.

Extrapolation to  
lower and higher  
temperatures.

19 cP @ 200°C, 392°F

7 cP @ 260°C, 500°F

**Conclusion: A thermal recovery opportunity with production handling challenges at the surface.\***

\* Bahrain average surface temperature ranges from 34°C (93°F) to 17°C (62°F) with corresponding oil viscosities of 400,000 to 2,650,000 cP.

Aruma bitumen

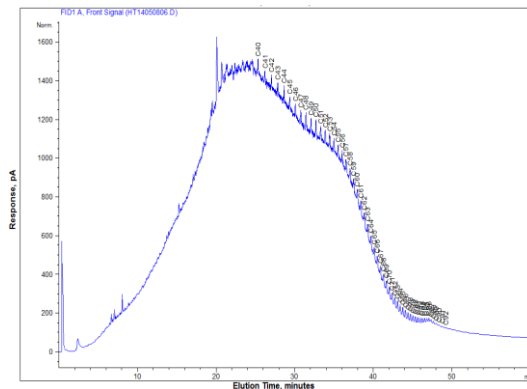
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- HTGC method
- C40 to C90+

### Aruma bitumen SARA

Description	Lab Method	Result	Unit of Measure
Saturates Content	HPLC	8.09	wt %
Aromatics Content	HPLC	53.06	wt %
Resins Content	HPLC	19.26	wt %
Asphaltene Content	IP 143	19.59	wt %

### Aruma bitumen gas chromatogram



### Aruma bitumen viscosity at temperature

Temp., °C	Aruma Tar method 1	Aruma Tar method 2	Aruma Tar method 3
	polynomial fit	linear extrapolation	linear fit of log-log vs log T(deg K)
20	6.49E+11	7.76E+18	1.75E+10
25	7.89E+10	2.89E+15	4.60E+09
30	1.18E+10	1.34E+13	1.33E+09
35	2.17E+09	2.70E+11	4.19E+08
40	4.85E+08	1.38E+10	1.43E+08
45	1.28E+08	1.33E+09	5.27E+07
50	3.90E+07	1.99E+08	2.08E+07
55	1.35E+07	4.16E+07	8.69E+06
60	5.16E+06	1.11E+07	3.86E+06
65	2.17E+06	3.62E+06	1.80E+06
70	9.89E+05	1.37E+06	8.85E+05
75	4.83E+05	5.86E+05	4.54E+05
80	2.51E+05	2.78E+05	2.43E+05
85	139000.0	139000.0	139000.0
90	77909.0	77909.0	77909.0
95	48555.0	48555.0	48555.0
100	29483.0	29483.0	29483.0
105	17536.0	17536.0	17536.0
110	11187.0	11187.0	11187.0
115	7248.0	7248.0	7248.0
120	5171.0	5171.0	5171.0
125	3511.0	3511.0	3511.0
130	2512.0	2512.0	2512.0
135	1837.0	1837.0	1837.0
140	1399.0	1399.0	1399.0
145	1029.0	1029.0	1029.0
150	785.9	785.9	785.9
155	364.8	364.8	364.8
160	275.2	275.2	275.2
180	117.9	231.2	189.1
200	50.9	126.0	91.5
220	25.9	77.2	50.1
240	14.9	51.5	30.3
260	9.6	36.7	19.9

485,000,000 cP @ res.  
temp 40°C, 104°F

Lab tests 85 °C to  
160 °C using  
Brookfield  
Rheometer.

Extrapolation to  
lower and higher  
temperatures.

51 cP @ 200°C, 392°F

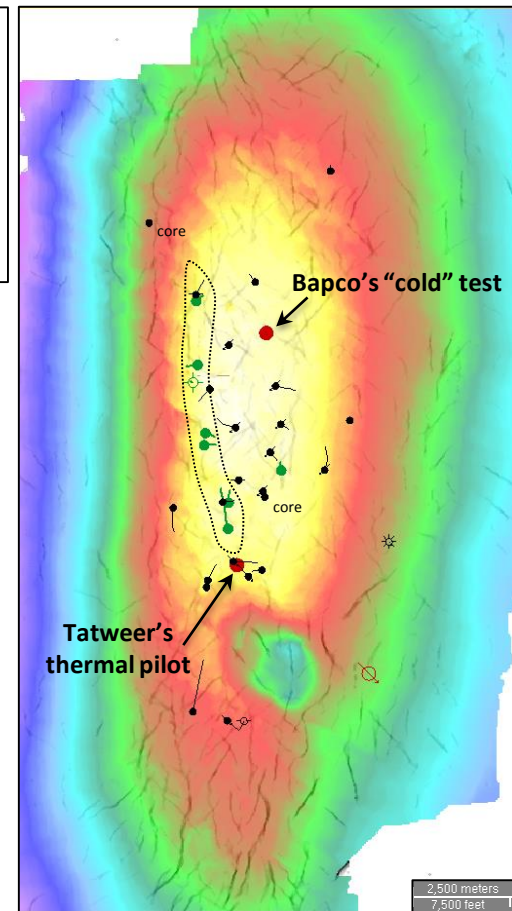
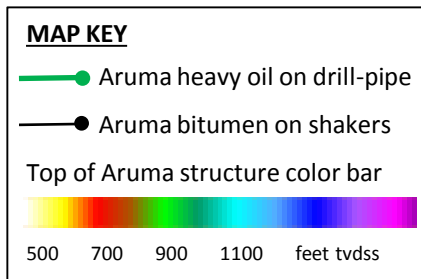
10 cP @ 260°C, 500°F

**Conclusion: A thermal recovery opportunity with production handling challenges at the surface.\***

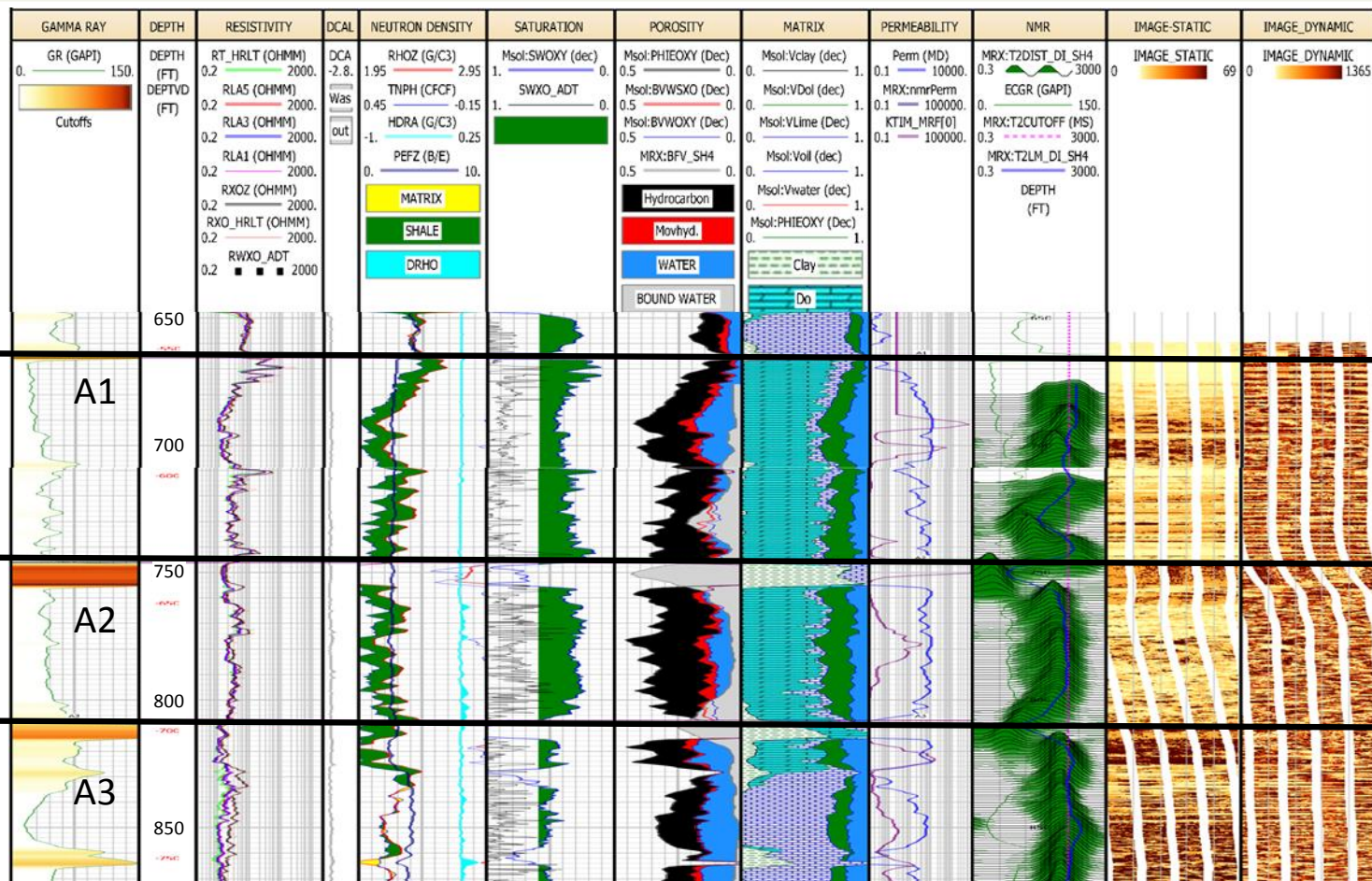
\* Bahrain average surface temperature ranges from 34°C (93°F) to 17°C (62°F) with bitumen viscosities exceeding 2,170,000,000 cP.

### Aruma Thermal Pilot - Objectives

- Viscosity of both heavy oil and bitumen can be reduced to low values with sufficient heat.
- Both heavy oil and bitumen are potential thermal recovery targets.
- However, the high viscosity at low surface or downhole temperatures provides operational challenges:
  - Need insulation, diluent in production facilities
- Aruma thermal test located near existing Mishrif (Rubble) steam flood facilities to minimize costs.

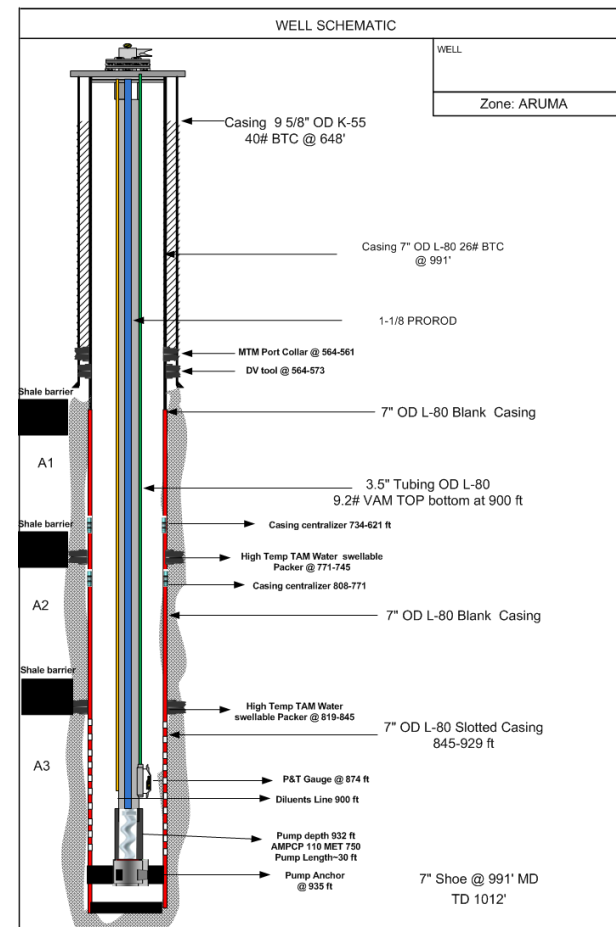


Pilot well spud Nov 2014  
Completed Dec 2014

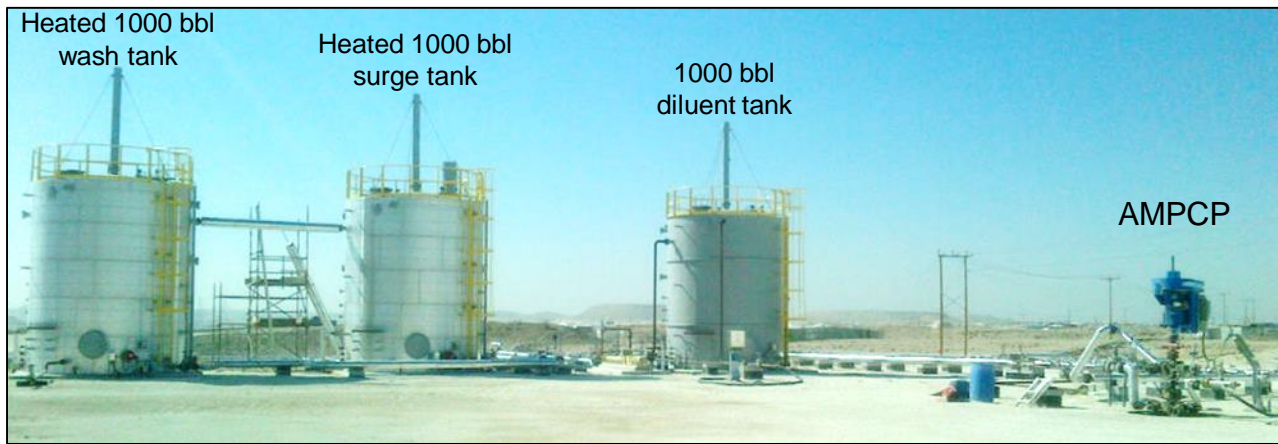


### Aruma Thermal Pilot – Wellbore Design

- Cyclic steam stimulation (CSS) implemented in A3 in January 2015.
- Uncemented pipe due to complete lost circulation during drilling.
- External water-swellaable packers (thermally compatible) to isolate the three test zones: A1, A2, and A3.
- All-metal progressive cavity pump (AMPCP) used to lift high viscosity fluids. Thermally compatible.
- 100 bpd of diluent injected above the AMPCP to reduce viscosity of produced crude for surface handling.
- A1, A2, and A3 are tested separately. Well is plugged back each time and recompleted in the next shallowest zone.



### Aruma Thermal Pilot – Surface Facilities



- Facilities to support the Aruma thermal test are working as per design.
- Diluent injected from the diluent tank into the wellbore reduces the produced oil viscosity for surface handling.
- Produced fluids flow to the wash tank and oil is skimmed and measured at the surge tank.

## Aruma Thermal Pilot – Results to Date

Date	Zone	Bbls of steam cold water equivalent	Average steam injection rate	Average downhole pressure	Injected diluent (to lubricate PCP pump)	Produced Oil
Jan 2015	A3	33,000 bbls cwe	2700 bsp/d cwe	368 psia	579 bbls, 28° API gravity	0 bbls
May 2015	A2	60,000 bbls cwe	2700 bsp/d cwe	315 psia	0 bbls	1948 bbls, 12-18° API
Dec 2015	A1	tbd	tbd	tbd	tbd	tbd

## Aruma Challenges and Opportunities

- **Challenges**
  - Difficult to reduce reservoir uncertainties.
  - Drilling, producing, shipping, and refining are technical challenges.
- **Opportunities**
  - A potentially large resource.
  - CSS Steam piloting demonstrates that it is possible to mobilize and produce Aruma heavy oil.

Thank you