CORE ANALYSIS PROGRAM FOR A GIANT, COMPLEX FRACTURED CARBONATE FIELD IN OMAN: LEARNINGS AND KEY RESULTS

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ABSTRACT

Even after more than 35 years of production, more cores and core analysis are required for this field. In fact, more than ever…why? This is the reality faced by one of the oldest and largest onshore oil fields in Oman. Despite long production history, there remain significant opportunities to realize additional value from the field. However, before this program, the amount of conclusive data was either inadequate or inconsistent and often, the description of the reservoir architecture and properties were perhaps inaccurate. Consequently, the associated scale and complexity of the inherent reservoir uncertainties and their ranges remained high. In most previous coring attempts there had been poor recovery in key reservoir intervals due to the very friable nature of some of the carbonate rock sequences. This necessitated a comprehensive plan for core data acquisition and core analysis to be developed to provide means of assessing the field life recovery under a number of potential development scenarios. A systematic data gathering program has just been concluded which included acquisition of over 1800m of high quality cores. This paper describes the core data acquisition and core analysis program adapted to this field to provide valuable information to help mature the on-going field (re)development study.

The program was designed to address key uncertainties such as capillary pressure, relative permeability, residual oil saturation, level of spontaneous imbibition, wettability, saturation exponent "n" and the effect of overburden stress on porosity and permeability. Special considerations were given to manage known issues such as sample cleaning, sample unconsolidation and bias in sample selection. A recently developed facies classification scheme was used as the basis for sample selection, taking into account lateral facies variations over this large field. A rigorous screening procedure for SCAL sample selection was followed involving routine core analysis results along with a combination of sedimentology, petrography and CT scanning results. Concerted effort was put together to bring in expertise from various outfits to ensure high quality measurements and results. Flexibility is maintained so that future requirements to run special measurements related to EOR, for example, can be accommodated. The core analysis program described in this paper highlights the value of structured approach towards managing uncertainties, and the value of core analysis results themselves to a giant, mature and complex fractured carbonate field such as this field.

BACKGROUND

This giant fractured carbonate field is one of the largest and oldest oil fields in the Sultanate of Oman. It is contained in the Natih Formation, a 450m thick section of Albian to Turonian high porosity, low permeability shallow water carbonates. Over the past 35 years, the field has undergone various drive mechanisms – Gas-Oil-Gravity-Drainage (GOGD) and waterfloods in various parts of this 17km long and 2.3 km wide field. Despite over 35 years of production through various drive mechanisms, there remains an opportunity to realize additional value in the field, i.e. smaller scale waterflood in selected matrix-like layer or area including less convestional cyclic-waterflood and crestal water injection, rim lowering via GOGD, and Steam-Assisted GOGD are few development options being seriously considered for this field. On a large scale, reservoir architecture is layer-cake and well constrained by some 400 wells. However, a close look at seismic, outcrop analogues and performance indicated the likelihood of significant internal heterogeneity and associated uncertainty. Historically, core recovery in this field has been quite low and severely impacted the available core analysis data in the most producible intervals. Also, as most of the GOGD development wells were drilled downflank of the field in order to effectively produce from the oil rim, core coverage in the crestal areas was severely limited. Special core analysis data using state-of-the-art techniques was available only in a few layers in two wells restricted to the NW corner of the field. This led to extrapolation of these results to other layers and areas over this 17km wide field. Effects of lateral and horizontal variations over smaller scales as well as facies variations, which could be quite important in carbonates, had to be ignored while building static and dynamic reservoir models.

UNCERTAINTY BASED APPROACH

Based on an integrated approach, cross discipline data was evaluated early in the study to identify and quantify uncertainties with the highest impact. The scale and complexity of the uncertainties associated with such opportunity necessitated the use of experimental design and response surface methods to provide a framework for evaluating sensitivities and estimating impact of uncertainties on field performance[1]. A set of the most significant uncertainties in the different layers and the associated mitigation options were compiled (Table 1). It revealed that many of the uncertainty mitigation options needed a good core and core analysis coverage.

Uncertainty	Data gathering options
Depositional facies	Core, high resolution open hole logs (Normal suite + spectral GR/BHI/dipole sonic)
Fault distribution	3D seismic, PBU (late time)
Layering	Core, Open hole logs, wireline pressure, dynamic pilot/observation wells, cased hole time lapse, EMI
Diagenesis	Core, BHI, Open hole logs, PBU (late time)
Vertical Barriers	Core, BHI, Open hole logs (including dipole sonic), PBU (interference), MDT
Aquifer	Core through FWL
Hydrocarbon saturation	Core (D&S,SCAL), Open hole logs, NMR, current saturation: cased hole logs
Matrix permeability	Core (CCA), PBU, Open hole logs, NMR, Dipole sonic, PLT, Minifrac
Matrix porosity	Core, high resolution open hole logs
Fracture permeability	PBU, dynamic pilot, tracer injection
Fracture porosity	Core, outcrop analogues
Fracture distribution	Core, BHI, PBU (early time), dynamic pilot, tracer injection 3D seismic
Fault transmissibility	PBU (interference test), wireline pressure, dynamic pilot, tracer injection, core?
Kv/Kh	Core (CCA), High resolution logs, PBU
Fracture gradient	Core (triaxial test), Mini-frac
Stress tensor	BHI (breakouts), Mini-frac
Relative permeability	Core (SCAL)
(Spontaneous) imbibition	Core (SCAL)
Residual oil saturation	Core (SCAL)
Productivity	Well testing (pilot/offset well behavior), PBU/interference test, PLT, BHP/wireline pressure for PI's
Injectivity	Injection rate test, fall-off test (PFO)/interference test, shut-in temperature logs, tracer/water quality monitoring, Mini-frac

Table 1: Most significant uncertainties in the different layers and associated mitigation options. Note that core and core analysis figures in most of the uncertainty mitigation options.

Findings from the core analysis are key elements to constrain ranges of uncertainties incorporated into 3D static and dynamic reservoir models, which were built to assess the viability of various development options.

CORE COVERAGE AND DATA GATHERING PLAN

A review of all the available cores showed that the core coverage before 2003 was quite patchy and essentially consisted of spot cores in different wells. The core recovery was restricted to mostly the tighter and more compact layers in the different sub-units as well as non-reservoir layers. One of the major reservoirs, Natih-E, which is around 100m thick, had almost no complete core throughout the field. Core data availability in this field is shown in Figure 1.

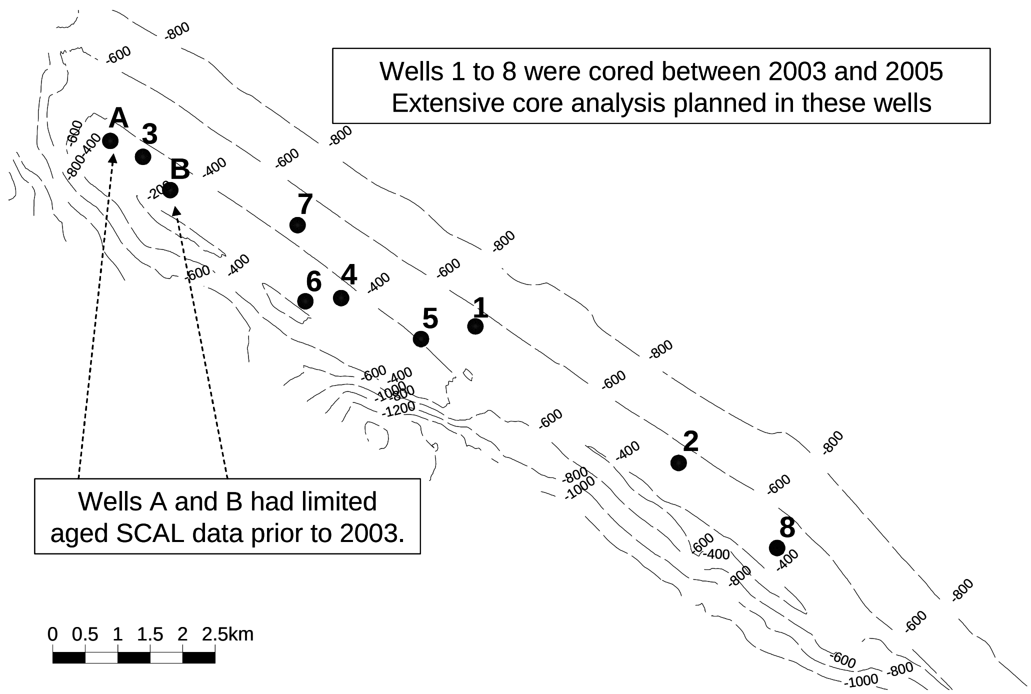


Figure 1: Core data availability in the field

A review of the all available core analysis data came up with the following conclusions:

- No clear Sampling strategy (e.g. based on facies scheme) for SCAL measurements
- Most if not all cores taken before say 1980 were recovered by rubber sleeve method that intrinsically yields damaged cores
- SCAL data is very limited e.g. poor data on porosity/permeability vs. stress, hardly any aged SCAL and relative permeability data
- Problems with sample condition due to stress, interaction with brine etc. only reported as from 1996 onwards

Although extensive numbers of plugs were taken both for routine core analysis (RCA) and SCAL work in the past, the coverage for SCAL with aged samples was quite limited. Data coverage for aged SCAL data before 2003 was restricted to only two wells (Wells A and B in Figure 1) in the North-West corner of this 17 km x 2.3 km wide field.

Data gap analysis was carried out for the field and showed that large data gaps also existed in other static and dynamic data. This led to a comprehensive data gathering plan[2] covering both static and dynamic data requirements as shown in Figure 2.

New core data was considered essential to improve understanding of the field and the plan included acquisition of some 1500m of new cores to investigate:

- Depositional environments & architecture (lateral facies variations & cycle stacking patterns)
- Diagenesis (paragenetic sequence, impact of subaerial exposure including lateral structurally related changes and subsequent burial)
- Distribution of petrophysical properties over the field (standard & SCAL)

Static data
- 1800 m core from 8 wells (95% recovery)
  - Complete core description
  - Integrated Outcrop Analogue Study
  - Interdisciplinary Core workshops
- 4400 samples for Conventional Core Analysis; ~300 samples for SCAL
  - CCA: Routine & whole core analysis, thin section, diagenesis
  - SCAL: Wettability, rel perm, saturation exponent, rock mechanics
- 30 wells drilled with consistent log data
  - All wells have: Resistivity, Density, Neutron, BHI, MDT logs
  - Cored wells have additional special logs like NMR for reservoir characterisation
  - Observation wells have EMI/induction logs for flood front monitoring

Dynamic data from four 5-spot vertical patterns for water injection (central injector cored, 4 producers & 2 observation wells)
- Production tests
- Pressure surveys including build-up and fall-off tests
- Cased hole logs: temperature and flow from PLT, EMI/induction logs, saturation logs for monitoring

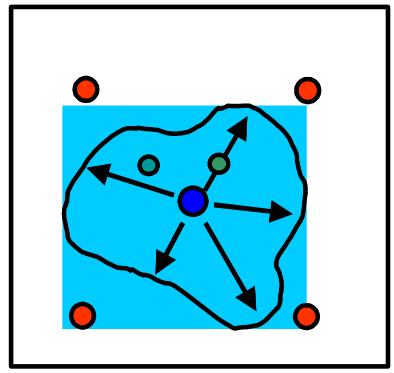


Figure 2: Comprehensive data gathering plan covering both static and dynamic data requirements.

In order to take advantage of the development wells being drilled in 2003, two cored wells were drilled in 2003. Subsequently, a detailed waterflood pilot appraisal plan was formulated in 2004 to obtain SCAL data from different layers and areas in the field. This included drilling of inverted 5-spot vertical waterflood patterns covering different layers and areas in the field. The central water injector in each pattern was planned to be cored to improve characterization models, core-log calibration and SCAL for static and dynamic parameters. A total of 1800m of core was acquired from eight wells during 2003 to 2005 in one of the largest coring campaigns in Oman. An assessment of the available cores in the field showed that out of a total of 18 wells, 11 cored wells had a good coverage whereas 7 wells had core which could be used as supporting data (Figure 3).

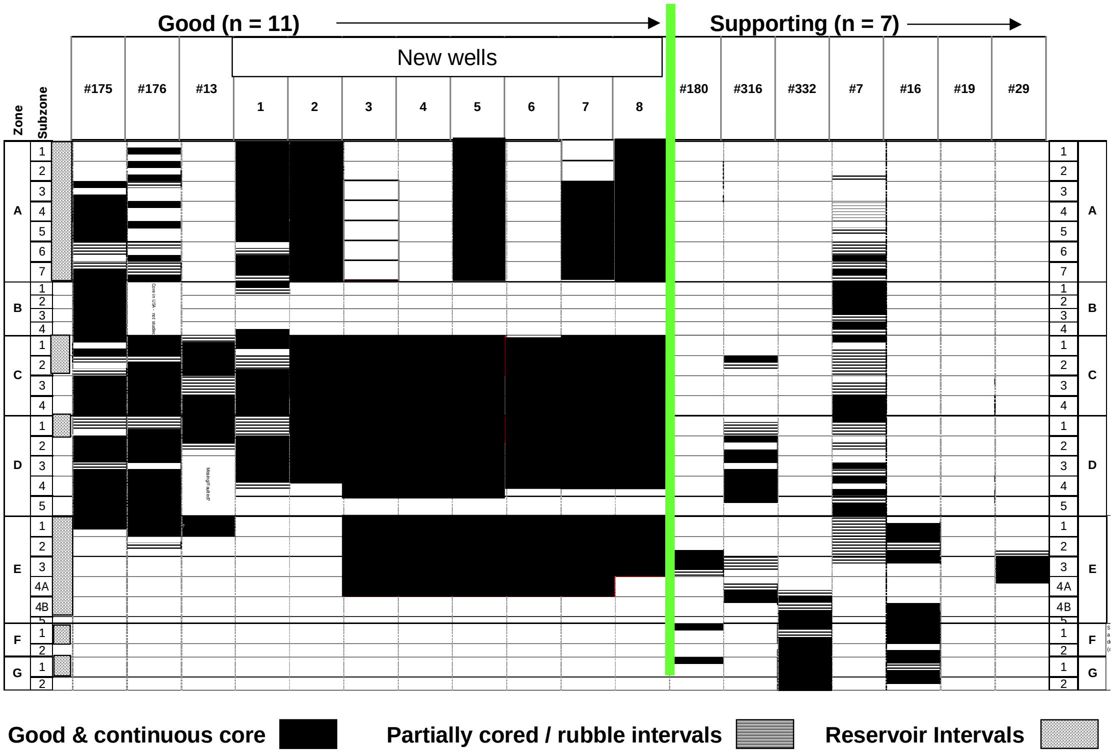


Figure 3: Core coverage and data quality.

Core observations are anchored by extensive outcrop analogue studies, detailed mapping of 3D seismic, a wide variety of logs and the analysis of production behaviour.

CORE ANALYSIS PLAN

Routine Core Analysis

The majority of the RCA work was done by a service contractor located in Muscat while some was done in Abu Dhabi. The typical core analysis workflow followed for these wells is shown in Figure 4. Almost 1800m of core has been acquired resulting in over 4100 plug samples, with the average plug sampling rate of three plugs for every metre. Although recovery has been excellent in this campaign, plug failures were observed both while drilling as well as during the measurement process.

One of the major problems encountered during the first few wells in the program was the long time taken to clean the plug samples to extract hydrocarbons. The solvent extraction method was used and cleanliness of the samples was determined from the (dis)coloration of the solvent after many cycles of purging with fresh solvent. In some instances cleaning was ongoing for more than two months and led to delays in the overall program. A pragmatic approach was taken to stop cleaning after a few weeks and carry out the basic measurements. Once a representative set of samples were selected for SCAL, further cleaning was continued on the smaller sample set.

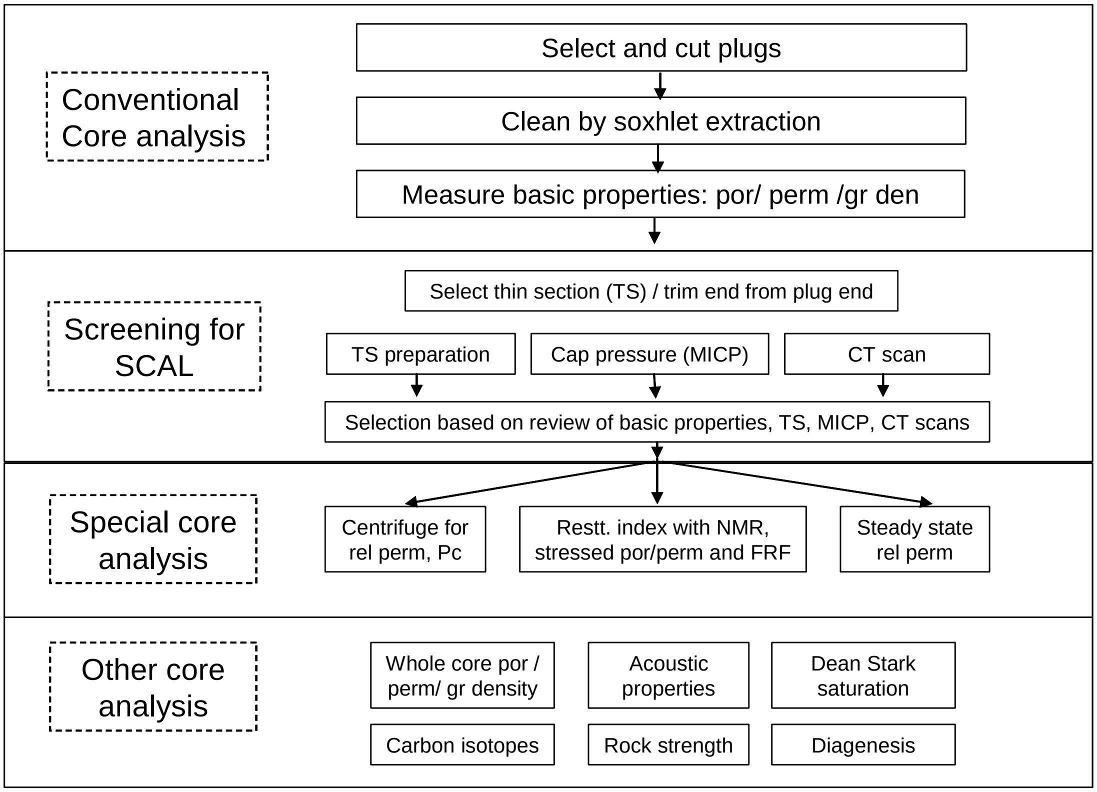


Figure 4: Typical core analysis workflow.

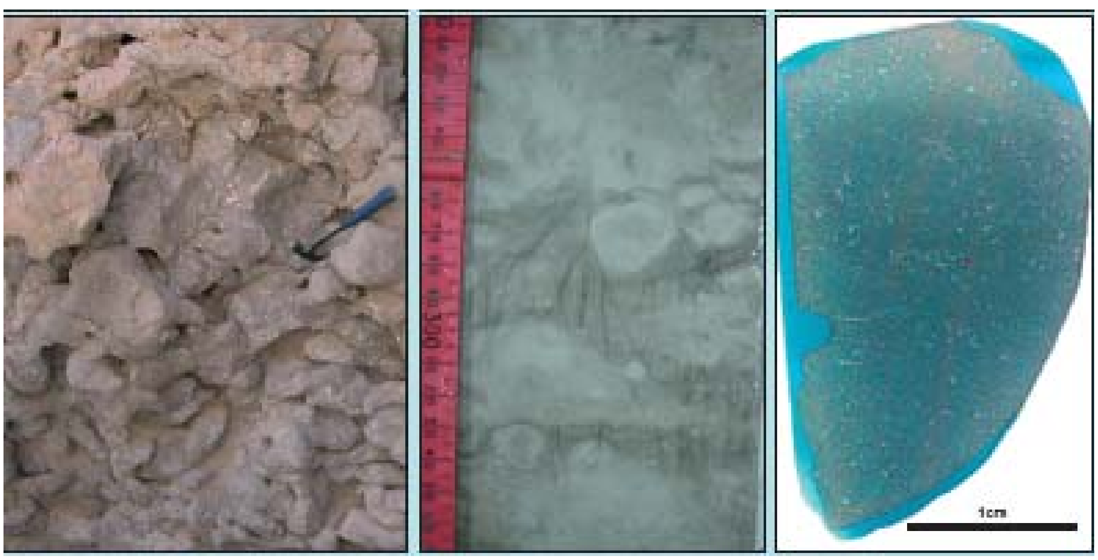
Screening Procedure for SCAL Selection

A detailed sample selection procedure has been set up for picking a representative set of samples for carrying out SCAL measurements. A unified lithofacies scheme[3] was adopted for the field based on sedimentological evaluation of core and petrographic dataset by a service contractor and combined with a study of an outcrop analogue. 14 lithofacies associations (LA) were made based on groupings of genetically related lithofacies (Table-2).

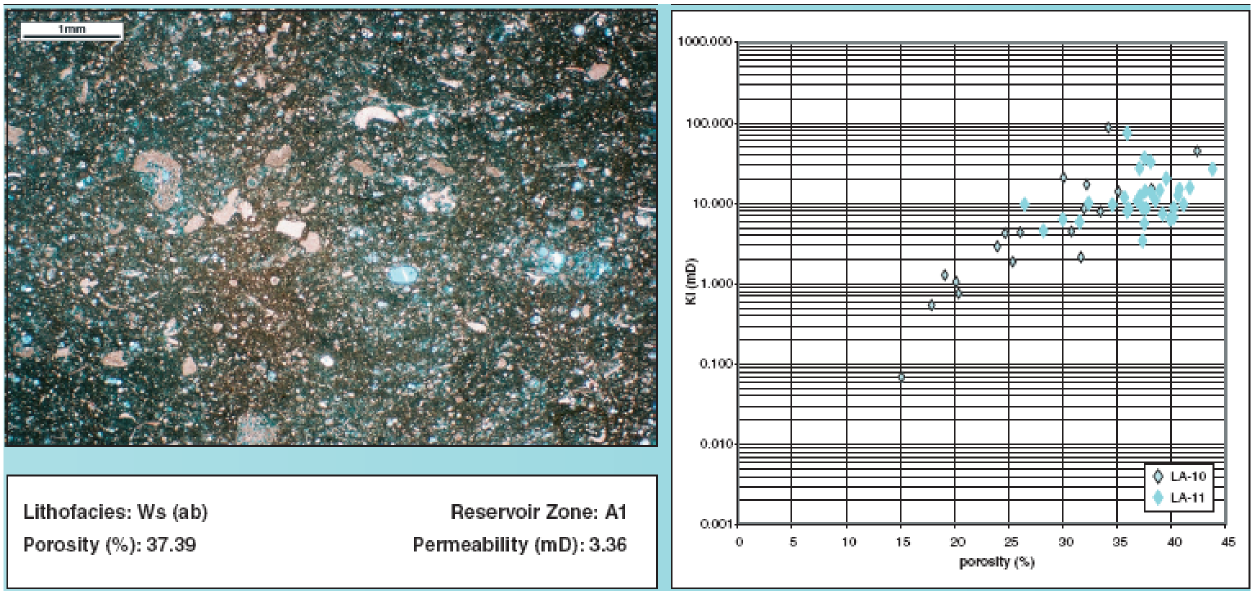
Lithofacies association	Depositional environments	Occurrence	Consider for SCAL
LA1	Clay-dominated, protected inner ramp	Natih-C,D.F.G	No
LA2	Backshoal/lagoon	Natih-E	Yes
LA3	Storm reworked washovers	Natih-E	Yes
LA4	Rudist shoal	Natih-A.C.D.E	Yes
LA5	Marginal/Inter-rudist shoal	Natih-A.C.D.E	Yes
LA6	Foraminiferal shoal	Natih-A.E	Yes
LA7	Marginal/Inter-foraminiferal shoal	Natih-A.E	Yes
LA8	Moderate-energy, protected inner ramp	Natih-C,D.F.G	Yes
LA9	Low-energy, protected inner ramp	Natih-C,D.F.G	Yes
LA10	Moderate-energy foreshoal/mid ramp	Natih-A.E	Yes
LA11	Low-energy distal mid-ramp	Natih-A.E	Yes
LA12	Very low-energy outer ramp	Natih-A.E	Yes
LA13	Carbonate-rich intrashelf basin	Natih-B,E	No
LA14	Organic-rich intrashelf basin	Natih-B,E	No

Table 2: Lithofacies associations considered for SCAL

An example of the integration of different data sources for lithofacies LA-10 and 11 is shown in Figure-5. Reservoir quality is moderate to good and shows a high degree of variability due to cementation (nodules). Although pore volumes are typically excellent, pores are tortuously connected via narrow micropore throats resulting in reduced reservoir quality.



Outcrop picture Core Thin section



Thin section

Porosity-permeability crossplot

Figure 5: Example of reservoir quality assessment of LA-10 and 11 lithofacies associations

Based on the routine plug measurements such as Helium porosity, permeability and grain density along with the detailed core description by a service contractor, a representative set of thin sections and trim ends are picked to represent the various facies observed on the cores. At the outset it was decided to use the 1.5” diameter plug samples all through the program, i.e., the same plug is used from the RCA to SCAL. This was necessitated by the large heterogeneity observed at small scales in the core as well as the limited availability of good quality samples for different measurement programs from all the various lithofacies types and layers. The final SCAL sample plugs for each well are picked on the basis of a review of the following data:

- Detailed core description
- Thin section analysis
- Air-Mercury capillary pressure data on trim ends
- CT scans of plugs to check for sample homogeneity, fractures

The following criteria are followed for picking SCAL samples:

- 3-5 points per lithofacies association group in Natih-A,C,D and E; lithofacies association based on Wells-1 & 2
- Full set of SCAL in at least 1 well in NW-N, NW-S, and SE areas of the field
- Centrifuge sample numbers in multiples of 3 as per service contractor equipment capacity

High Level SCAL Program

The SCAL program for the field was detailed after deliberations both within the team as well as with SCAL experts from Shell. The SCAL samples were sent to the service contractor after cleaning and measurement of basic properties.

A high level SCAL program is discussed below.

Combined Wettability And Water-Oil Capillary Pressure Measurements By Centrifuge.

The combined wettability and water/oil capillary pressure measurements were performed using an automated centrifuge. The measurements were performed on cleaned and restored core plugs at 50°C using crude oil from the field as oil phase. The experiments included complete Amott - USBM wettability tests; i.e. capillary pressure curves (USBM indices) and spontaneous imbibition of brine (Amott part A) and spontaneous drainage of brine (Amott part C) before the corresponding forced experiments in centrifuge (Amott part B and part D, respectively).

Water/Oil Relative Permeability Measurements By Centrifuge

Water/oil relative permeability measurements were performed both in the centrifuge and by the steady state technique. The centrifuge relative permeability measurements were performed on plugs at 50°C using crude oil from the field as oil phase. Production of oil as a function of time was measured by the automatic centrifuge system. After completion of the centrifuge run, effective water permeability, $k_w(S_{or})$ was measured.

Steady State Water/Oil Relative Permeability Measurements

Water/oil imbibition steady state relative permeability measurements were performed in a semi-automated steady state rig equipped with γ-ray source and detector for in situ saturation monitoring. The measurements were performed at ambient temperature and doped mineral oil was used as oil phase.

Gas-Oil Capillary Pressure And Gas/Oil Relative Permeability Test By Centrifuge.

Gas/oil capillary pressure and relative permeability measurements by centrifuge were performed on core plugs using mineral oil as oil phase at ambient conditions. $k_g(S_{org},S_{wi})$ was measured at completion of the tests.

Formation Resistivity Factor (FRF), Porosity And Permeability Vs. Stress

Formation resistivity factor (FRF), porosity and permeability versus stress were performed plugs saturated with simulated formation water (SFW) and the effect of net confining pressure was determined.

Continuous Injection Measurements At Net Confining Pressure Combined With Nuclear Magnetic Resonance (NMR) Measurements

Continuous injection to obtain resistivity data was performed on aged plugs and these plugs were also analyzed by NMR to get detailed knowledge about the fluid distribution in the pore system.

Independent verification of results from another lab (Shell) for consistency and QC showed consistent results.

KEY RESULTS TO-DATE

At the time this paper was written, not all of the measurements are completed, available and fully analyzed. An overview of planned SCAL program with number of samples per program is given in Table-3 below.

Well	Core meterage	Total CCA samples	Dean & Stark	CT scan, TS & MICP for SCAL screening	WO Pc Centrifuge + wettability	OW rel perm centrifuge	WO rel perm steady state	Gas-oil Pc + relperm centrifuge	FRF(m) + stressed por & perm	I-Sw + NMR characterisation	WC poroperm
W-1	138	275	70	74	6	6	6	6	7	3	8
W-2	153	355	142	72	5	6	3	5	4	4	11
W-3	250	626	45	99	9	7	6	5	6	6	
W-4	239	494		44	3	6	1	0	0	0	6
W-5	305	753		80	6	6	8	6	3	6	2
W-6	247	642		98	5	6	6	6	6	10	6
W-7	260	407		74	4	3	5	3	5	4	4
W-8	218	578		76	9	9	9	9	10	10	3
Total	**1810**	**4130**	**257**	**617**	**47**	**49**	**44**	**40**	**41**	**43**	**40**

Status

Done

Table 3: Overview of planned SCAL program.

While only limited early results are available, the core data acquisition and core analysis program have already yield important observations to help manage some expectations on how to develop the field. Few key observations and their expected effects on future field (re)-development are summarized below:

1. Wettability measurements both from Amott and USBM Indices indicate more pronounced oil-wet character in all samples to-date. This is a turn-around of initial interpretation based on limited data of a more mixed-wet system. An analysis of trends in wettability across the field in terms of lithofacies/layers would be carried once all the data is available.
2. Very little spontaneous imbibition was observed in all samples to-date. This is a significant finding in that future development option such as cyclic-waterflood or creastal water injection, which relies on imbibition process, will be adversely affected.
3. Residual oil saturation (Sorw) from centrifuge measurements in two wells shows an overall spread around 14-26% (Figure-6). In comparison, initial input into first pass modelling when evaluating various waterflood development options was between 5%-20% (based on limited data and analogs). The higher spread in Sorw data than initially assumed could result in lower oil recovery for any planned waterflood projects, which are being considered for certain part of the field. It is interesting to note though that the Sorw spread from these two wells are quite distinctive, with Sorw in Well 1 from 14-24% and Sorw for Well 2 from 21-26%. One possible explanation is that Well 1 is

located in the NW part of the field whereas Well 2 is in the SE. This observation on the distinction between Well 1 and 2, and the overall Sorw spread will be further validated once more data from other wells become available and analyzed.

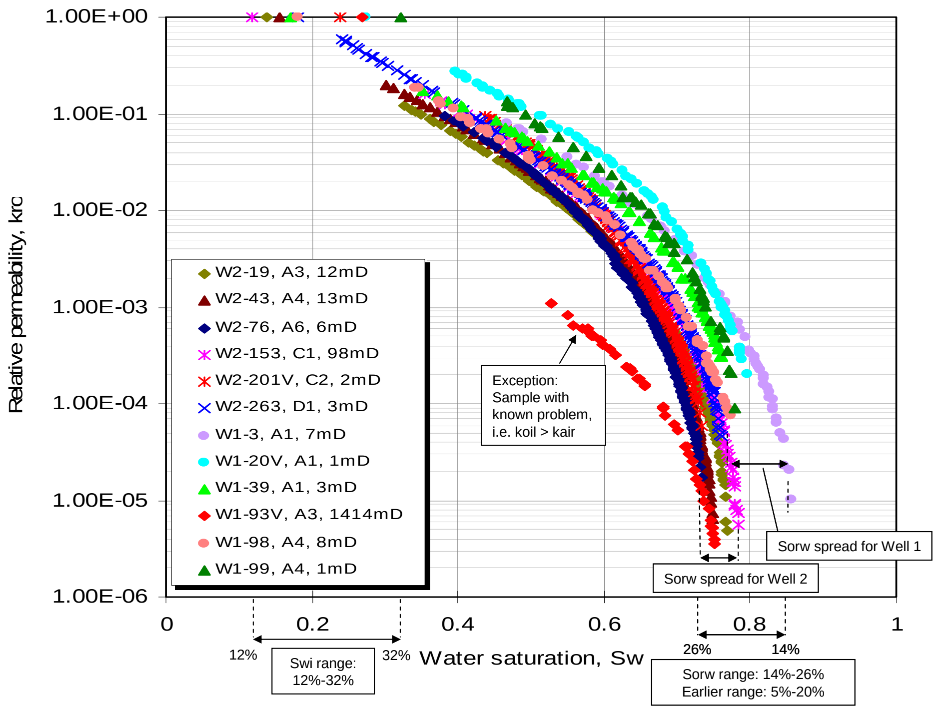


Figure 6: Preliminary water-oil relative permeability data from centrifuge.

4. The residual oil saturation (Sorg) measured from Well 1 and 2 show an overall range of 12-23% (Figure-7). Ranges for Sorg from Well 1 and Well 2 are 13-20% and 12-23%, respectively. Similar to Sorw, the input into first pass modelling work for Sorg was a range from 5%-20%. Potentially higher lower bound of Sorg could impact the projected ultimate recovery for this field considering bulk of production comes from the Gas-Oil-Gravity-Drainage, which is the dominant drive mechanism in the field. This observation will be further validated with additional Sorg data from other wells.

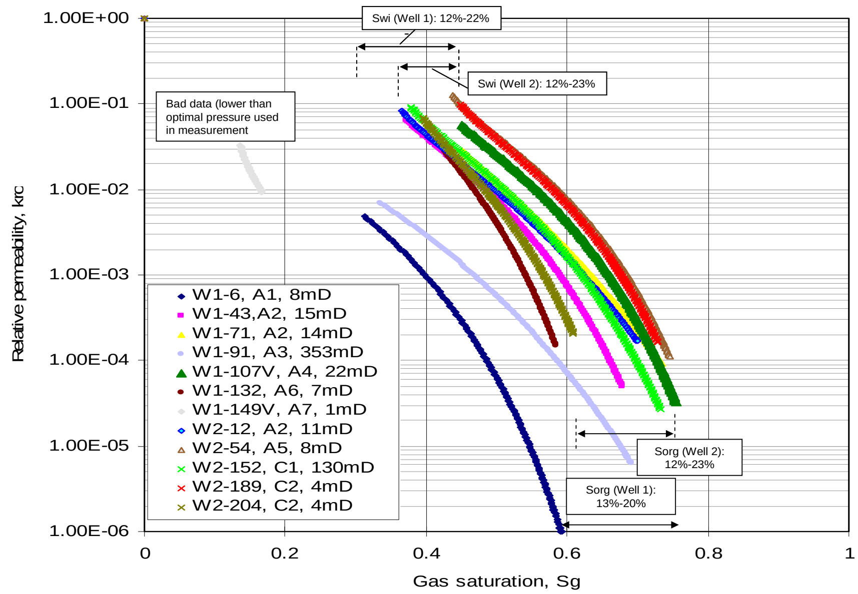


Figure 7: Preliminary gas-oil relative permeability data from centrifuge.

5. Preliminary indications from steady-state relative permeability show that interpreting flooding results will be a challenge for these "difficult / complex" samples. Significant oil end-effects were observed in many samples (Figure-8). Numerical simulation work is deemed critical as a QA/QC tool to validate these phenomena.

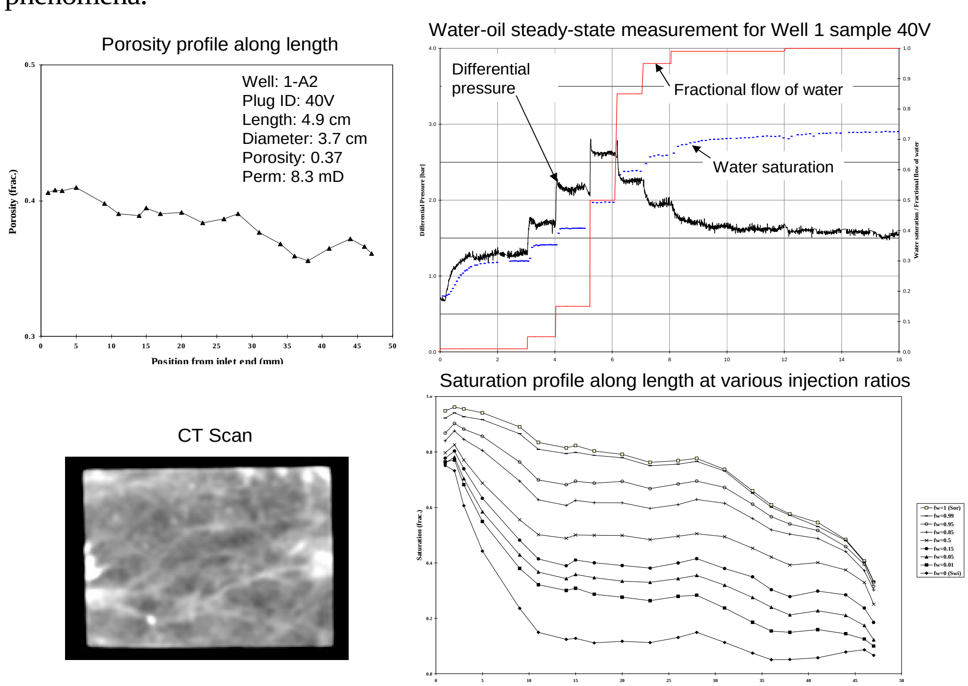


Figure-8: Example of uneven saturation profile observed across the sample length.

6. Some core permeability measurements at stress were hampered by plastic deformation of the samples (Figure-9). Large reduction was seen in high permeability samples whereas low permeability samples showed less change at higher stress values.

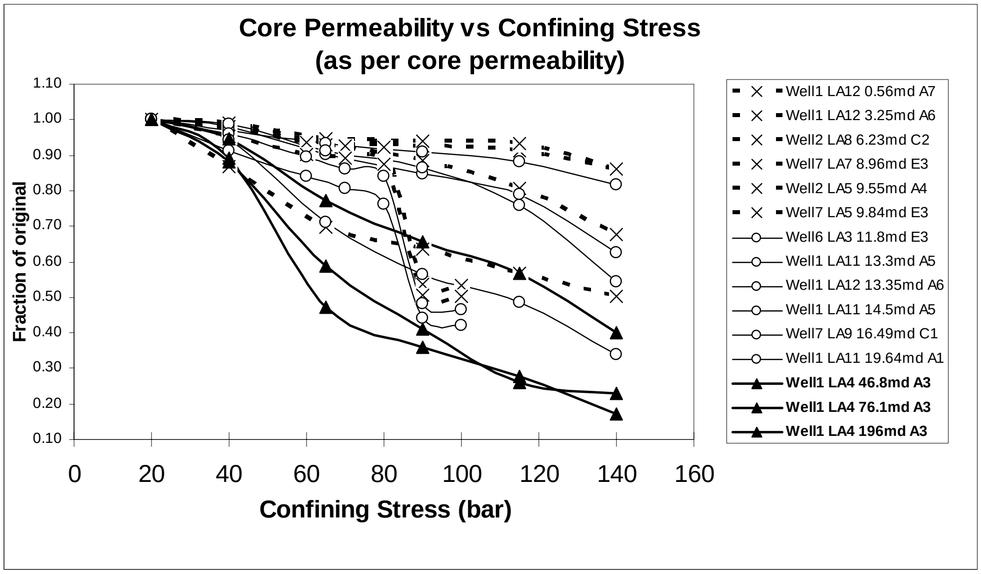


Figure-9: Permeability measurement at confining stress.

Additional remaining measurements and results from other samples will be used to confirm these initial observations and to gauge the extent of these observations (by layer and by area).

CONCLUSIONS

- A systematic data gathering program has just been concluded which included acquisition of over 1800m of high quality cores.
- The core data acquisition and core analysis program was adapted to this field to provide valuable information to help mature the on-going field (re)development study.
- A rigorous screening procedure for SCAL sample selection was followed involving routine core analysis results along with a combination of sedimentology, petrography and CT scanning results. Special considerations were given to manage known issues such as sample cleaning, sample unconsolidation and bias in sample selection.
- Initial results from various SCAL measurements have already yielded important observations to help manage and further develop this field

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