REVITALIZING THE USE OF SPONGE CORE FOR THE DETERMINATION OF REMAINING OIL SATURATIONS IN CARBONATE RESERVOIRS

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ABSTRACT

After a twelve year hiatus, Saudi Aramco revived the use of sponge core as a technique for the determination of remaining oil saturations (ROS) in the Arab-D reservoir. Combined with a well planned analysis and logging program, the technique provides an excellent method for establishing core baseline parameters to interpret log based oil saturations. This paper describes procedures and results for a successful application of sponge coring.

Optimized planning and procedures including redundancies in the use of tracers, multiple core imaging techniques, and complementary analyses are key elements for a successful run. In this recent well, complete whole core and sponge analyses were initiated following x-ray CT scan of the core and digital imaging of the core and sponge. Tracer analyses for iodide and bromide were used to chart fluid profiles and final results were compared with NMR log-inject-log determinations of remaining oil saturation. NMR results were used in combination with fluid sampling to assist resistivity evaluations in this mixed salinity environment. Compared core and log results indicated areas where combined petrophysical tools and core measurements improve saturation determinations.

INTRODUCTION

The introduction of the sponge core barrel as an alternative to pressure coring [1] has provided a cost effective comparator for the determinations of reservoir saturations. In common practice sponge cores are used to validate the precision of other methods that determine remaining oil saturation [2], including laboratory tests [3,4], logs [2,5] and tracer tests [3,6].

A multi-disciplinary project team focused on applying the best available technology to the Ghawar field revived the sponge coring process as a key component in the evaluation of remaining oil saturations. The Ghawar Integrated Appraisal and New Technology (GIANT) team selected a scheduled power water injector replacement as an optimal well candidate. The well is in a portion of the same reservoir described in the 1989 work of Freeman and Fenn [5]. The reservoir had been supported by peripheral water drive since the early 1960’s. Building on the previous work, additional measurements and analyses were added to further investigate the mixed salinity environment and to establish the suitability of carbonate NMR for ROS determinations.

The planned well provided an opportunity to optimize data acquisition and minimize ROS uncertainties with a detailed schedule that included:

- Sponge coring
- Initial logging including Modular Dynamic Tests (MDT)
- Under-reaming with tracer laced mud
- Re-logging

The successful completion of the project was judged by good core recovery, low coring filtrate invasion and sound petrophysical data and comparisons. This success required solid initial planning and some operational flexibility during implementation. Analyses of the results relied on standardized tests as well as application of advanced core imaging.

Core Planning

Conventional coring provides the data necessary for the direct measurement of various petrophysical parameters such as effective permeability, relative permeability, capillary pressure, porosity, and formation factors. In addition, sponge coring [1] gives the added advantage of directly quantifying the fluid saturations within the reservoir.

A series of meetings with all interested Departments was conducted to discuss the coring details and handle problems as they developed. Typical logistic and technical requirements were addressed and responsibilities were assigned. A sample of the pre-core planning issues that were discussed is shown in Table 1.

Coring System and Core Preservation

Implementation of the successful coring program required that low invasion coring methods and equipment be used to minimize, and verify, the amount of flushing from the drilling mud filtrate, which may have occurred during coring operations. Associated with the mechanical components of the system are traced fluid systems designed to minimize contamination of the sponge and to determine the depth and degree of filtrate invasion.

The low invasion coring system used was composed of three main components that provided optimal core recovery and oil phase capture. These included:

- Core Barrel
- Absorptive Liner
- Inner Barrel and Piston Assembly

An illustration of the system with the included sponge saturant is shown in Figure 1.

Tracers

Initial designs for the traced fluid systems incorporated redundant tracers (D_2O and KI) in the primary mud, sodium bromide (NaBr) tracer in the brine used to saturate the sponge, and doped secondary drilling mud ($MnCl_2$). These provided a method for tracking and identifying fluid sources and transport directions as well as conditioning the NMR response of the well.

Table 1- Pre-Core Planning Items

Well - Core Requirements	
Well	A-48 Sponge Core
Coring Proponent (s)	Reservoir Management Department
Core Diameter	3.25”
Inner Core Barrel/ Sleeve	Aluminum with sponge insert
Feet of Core / Formation	180’ (RMD may request extra footage)
Depth of Formation (s)	6500’ TVD approximate
Coring Contractor	Christensen - will supply well site personnel.
Well Site Operations	
Well Site Geology informed	Yes. Well site will supply one geologist
Date Coring to Begin	July 2001
Core Cradles	Yes, as per short form contract
Special Field Handling	Core 30’ per run. Breakdown of the inner sponge barrel.
Tripping Schedule	In progress
Transportation	Refrigerated truck, chill (not freeze!),transport as recovered.
Required Analyses	
CT Scanning	Yes. Core delivered to R&D first, then Core Storage
Full Diameter Samples	Yes.
Plugs/ft.	To be determined by RMD
Special Core Analysis	Rel. Perm, Cap Pressure, Wettability, Electrical Properties
Thin Sections	To be determined.
NMR Core Analysis	Yes

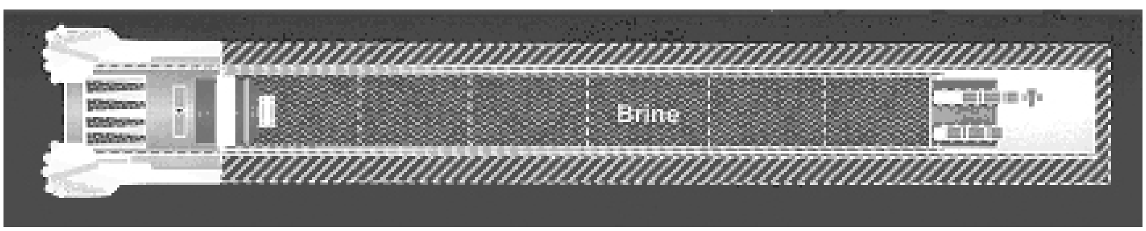

Figure 1- Sponge core system with traced sponge saturant

Tracers were added at the mud pit and concentrations were monitored at selected intervals during the operation. Table 2 lists the target concentrations and locations for the various additives. Since sufficient supplies of D_2O could not be obtained prior to coring this tracer was not used.

Table 2 - Traced and Mud Doping Components and Concentrations

Tracer	**Location**	**Target (ppm)**	**Average (ppm)**
Potassium Iodide (KI)	Primary mud	600	580
Potassium Bromide (NaBr)	Sponge saturant	450	442
Manganese Chloride ($MnCl_2$)	Secondary mud	1870	618

Optimized operating parameters while coring were selected in accordance with the objectives of low invasion coring. These were designed to achieve the fastest possible rate of penetration. A tripping out procedure was recommended for staging the core barrel out of the well to moderate the rate of gas release from the oil saturation in the core.

On arrival at the rig, the coring engineer checked equipment and briefed Company representatives, contractor tool pushers and engineers on the core acquisition process and procedures. Safety requirements were reviewed. Site preparations insured a well lit processing area of sufficient size to conduct the operation in an efficient manner. Prior to coring, the hole was cleared of junk, BHA was checked and mud samples were collected.

Lay down of the core-filled inner tubes at the surface used equipment and procedures to minimize mechanical damage to the core. The core-filled inner tubes were carefully packaged into one meter lengths for transport to the core analysis laboratory.

Once recovered, core barrels were sealed in **ProtecCore™** and then placed in PVC tubes. A CT image illustrating the preservation is shown in Figure 2.

Logging Program

The logging program consisted of a standard suite of logs including spectral gamma-ray, three porosity logs, and resistivity. In addition, the wire line program called for MDT, NMR (regular and with $MnCl_2$ doped brine) and elemental capture spectroscopy (ECS) logs. This logging suite provided the best opportunity to compare the sponge core determined ROS values with the corresponding log derived values.

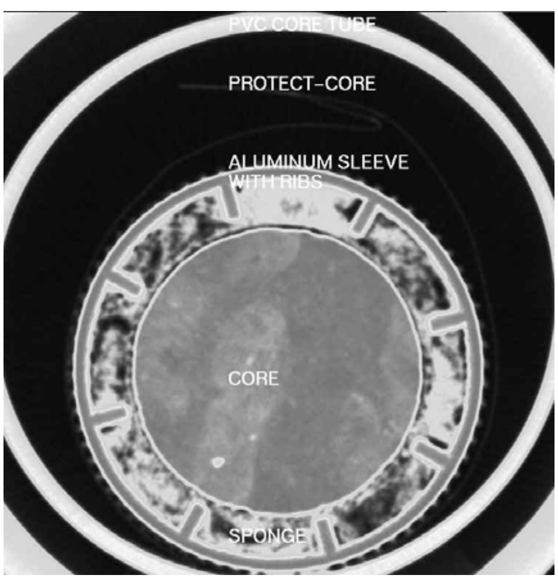

Figure 2- X-ray CT image of sponge core preservation system

MDT

The MDT was run to establish pressures, vertical permeability variation and to obtain fluid samples. The tracer program provided the opportunity to establish that fluid samples collected from the MDT were representative of the formation fluid rather than mud filtrate.

NMR Logging

Following the initial NMR log, the well was reamed ½" with a mud containing $MnCl_2$. The doped mud effectively reduces the water signal relaxation time enabling a more precise measurement of the remaining oil saturation.

ECS Logging

The ECS log was selected to establish mineralogical variations within the formation. Previous experience with sponge core determined remaining oil saturations had established that subtle changes in lithology have a large impact on rock properties and remaining oil saturations.

Core Analyses

The associated analyses of sponge core can be classified into five categories:

- Core Quality Assessment
- Sample Preparation
- Core Analyses
- Sponge Analyses
- Tracer Analyses

Core Quality Assessment

The best method currently available to assess overall core quality prior to testing is x-ray CT scanning. In the case of a sponge core the technique provides critical data to assess the preservation and quality of the core, including the possibility of core re-arrangement. It provides information on sponge integrity and the coincident transposition of adsorbed sponge oil and core. As an added advantage CT scans provide lithological variations for later correlation with remaining oil saturations.

In this study sponge cores still preserved in their well site preservation state were CT scanned for pilot views and slices. Examples of these are seen in Figures 3 and 4. Figure 4 shows sections of high quality sponge core that ultimately provided four (4) to five (5) whole core and corresponding sponge samples per tube. Figure 4 also illustrates the lower quality interval in the bottom of Core #5 and the top of Core #6 that provided only two (2) whole core samples. The slice images for the tubes illustrate the petrophysical and lithological differences (red/yellow to blue/black slices) that the CT data is able to highlight.

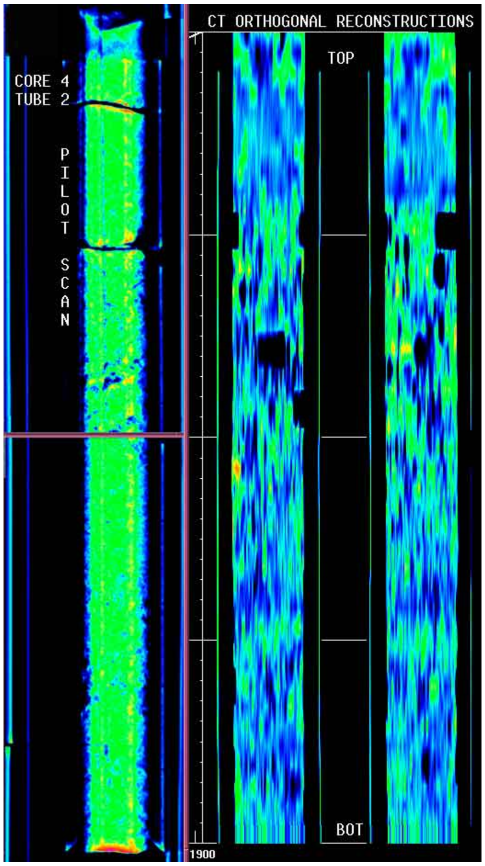

Figure 3-CT pilot scan and reconstructed slice images

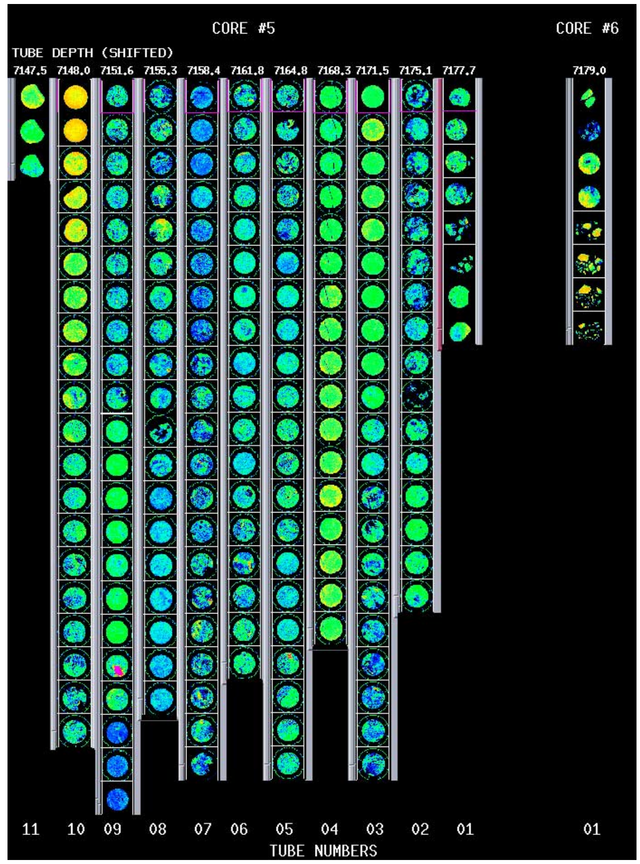

Figure 4-Slice Images taken at 6/ft spacing in Cores #5 and #6

Visual images of the core and sponge provide a second method to assess core quality as well as a semi-quantitative technique to assess rock type specific remaining oil saturations. Figure 5 shows a white light photo of a section of the whole core and sponge. The oil volume adsorbed by the sponge in this section was typically higher than that in other sections of the core. However, a characteristic and unique match of the core lithological structures and the print of the oil in the sponge are apparent.


Figure 5- Sliced Core barrel (bottom) and core (top) illustrating sponge-core oil capture effectiveness

Additional images provided other information including locations of highly permeable zones (inferred from mud cake build-up in Figure 6 and 7) and areas of low remaining oil saturation as shown in Figures 8 and 9.

Figure 6- White light photo of core section (left) and sponge (right).

Figure 8- White light photo of core section (left) and sponge (right)

Figure 7- UV Photo of sponge section showing mud cake formation

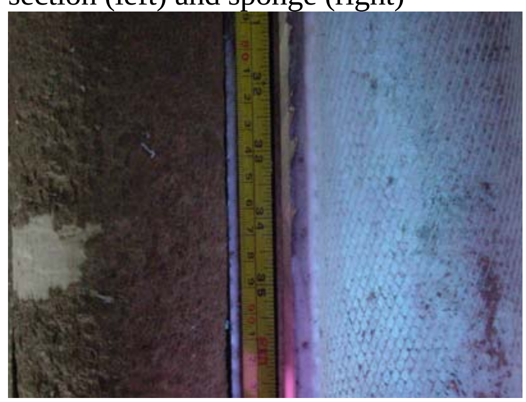

Figure 9- UV photo of cored section illustrating florescence of sponge material

Sample Preparation and Analyses

A step wise procedure for preparation and analyses of the core, sponge, and tracer were designed based on the oil and brine compositions in the Ghawar Field, the expected gas/oil ratio and the type of sponge and sponge saturation fluid. Analytical steps were similar to those recommended in API RP40 and can be summarized as:

- Milling the core barrel open.
- Sample selection and core mapping
- Cutting the core
- Cutting the barrel
- Dean-Stark analysis of the whole core
- Oil in sponge analysis
- Core salt extraction and analyses

Tracer Analyses

Well site tracer analyses for potassium and bromine were done using spectral photometric techniques. Laboratory analyses on the leached salts were done using ion specific electrodes.

RESULTS

Core Quality Assessment

CT scans of the core provided a detailed look at core quality prior to preparation of the core for sponge core analyses. Images such as those seen in Figures 3 and 4 provided significant information related to:

- Assessment of overall core recovery
- Possible locations of damaged sponge
- Mineralogical and bulk density information for characterization and depth shifting

Visual images of the core provided additional information that documented the viability of the technique and identified areas of improvement. Initial plans for the analyses of the sponge included scanning spectral radiometric analyses of the sponge surface to determine adsorbed oil volumes. Although this may have been possible using white light reflectance in some sections with no mud cake such as Figure 8, the high natural florescence of the sponge as seen in Figure 9, precluded similar measurements under UV light.

Tracer Analyses

Results from tracer analyses indicated that maximum flushing of the core either during drilling or during transport to the surface was less than ten percent (10%) based on the concentrations of both iodide and bromide following whole core extraction. As shown in Figure 10, concentration values for the two tracers are generally normally distributed about the mean water saturation value of 65%. They exhibit no trend with permeability or porosity and, as seen in Figure 11, track the concentrations used in the sponge core saturant.

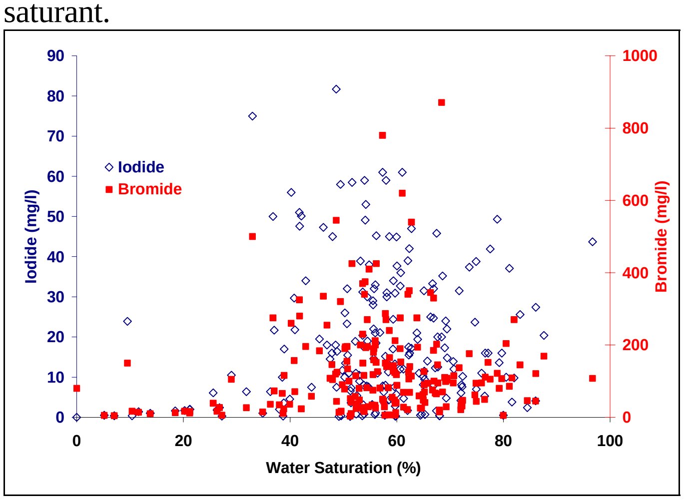

Figure 10- Tracer Concentration distribution as a function of whole core water saturation

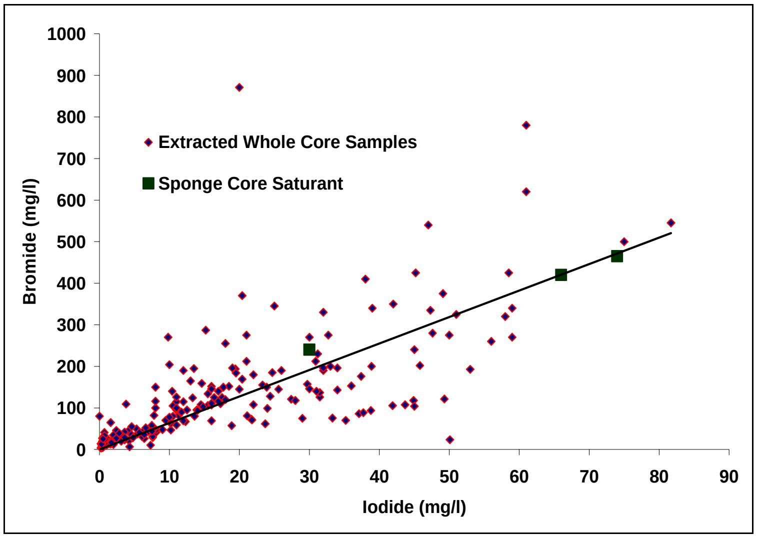

Figure 11- Correlated iodide and bromide concentrations that follow initial sponge barrel saturant values

Whole core analyses

Whole core analyses included processing of 202 whole core samples representing 160 ft. of core material. This represents 90.6% of the targeted 176 ft. Complete analyses also required the processing of 202 sections of whole core sponge. The ranges of values are listed in Table 3.

Table 3- Range of oil volumes in core and sponge

Samples	Maximum Oil (cm^3)	Minimum Oil (cm^3)	Total Oil (cm^3)
Core	158.3	0.12	7705.4
Sponge	2.00	0.00	70.41

In previous wells that were sponge cored, the core and sponge barrel were preserved under de-aerated brine. This provided higher total fluid saturations but made the interpretation of core flushing more difficult. The average fluid saturation of 83% (Track 3 in Figure 14) obtained with **ProtecCore™** preservation reflects the fact that gas expansion in the core probably expelled some brine; not that the core preservation technique was inadequate.

Oil saturations and corresponding bulk volume oil were consistent with those from previous studies and with those reported in the literature. Bulk volume oil is generally bounded as a decreasing exponential or a logarithmic function [2] with RQI as shown in Figure 12.

This well is located in one of the 'well-swept' zones described by Freeman [5]. One interpretation of the trend in Figure 12 is that lower remaining oil saturations may correlate with higher vertical permeability. In this case, gravity effects in the high vertical permeability zones are not obscured completely by viscous recovery mechanisms.

NMR Log-inject-Log Comparisons

The well log in Figure 13 shows the results from the NMR log-inject-log measurements in track three compared with the discrete sample points from sponge core. The NMR track represents the NMR signal following the reaming with $MnCl_2$ doped mud. The $MnCl_2$ effectively shifted the water NMR signal providing distinct oil peaks that could be compared with core and RST data. The result is the NMR oil signal plotted in track three which compares very well with the sponge core remaining oil saturations

Resistivity Interpretations

The mixed salinity environment in wells in this area makes use of resistivity difficult. However, with an optimized coring, logging and analyses plan, accurate Rw values can be determined and used to identify lithologies where additional resistivity analyses may be useful. Track 4 of Figure 13 shows the discrete MDT Rw values and a Rwa calculated using the NMR determined Sw , porosity and set values of a, m, and n. In several cases the match is excellent. Samples that show less agreement generally coincide with lithological variations indicating that alternate saturation exponents should be used.

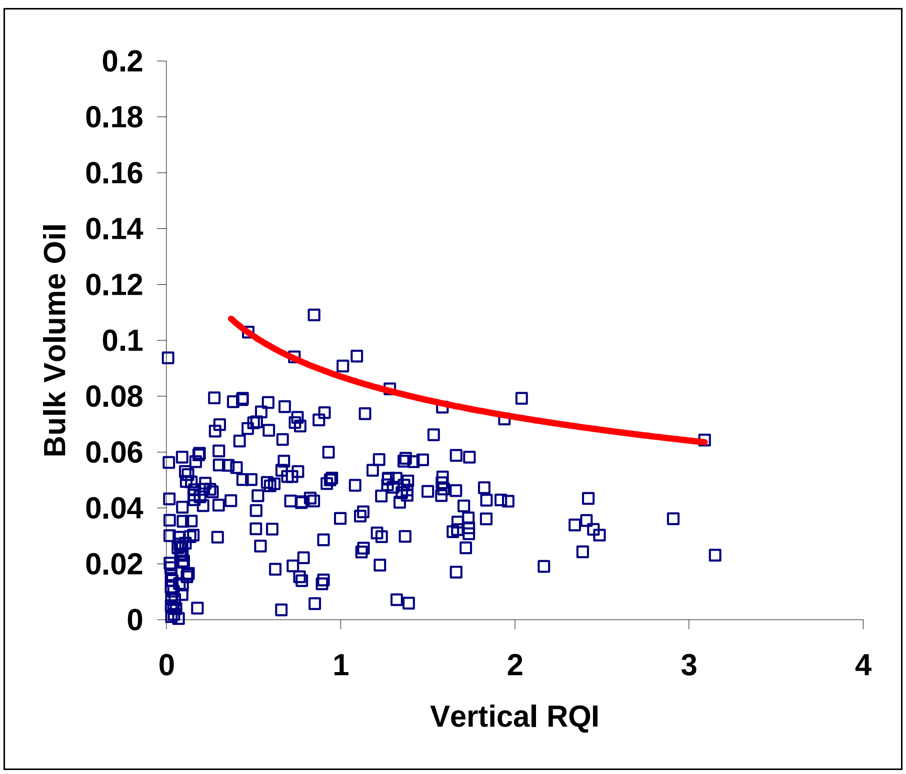

Figure 12- Bounded bulk volume oil as a function of vertical Reservoir Quality Index (RQI)

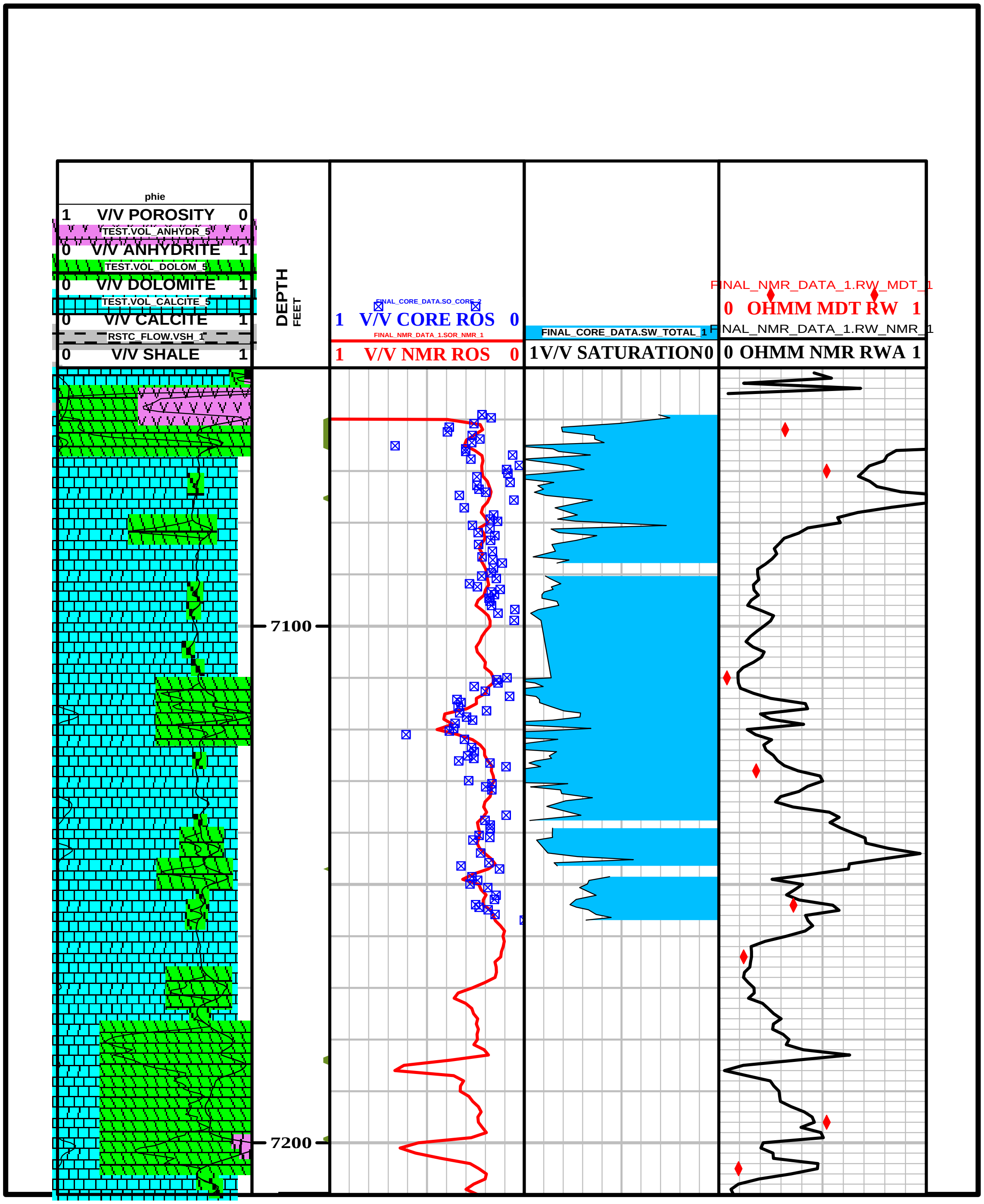

Figure 13-NMR log and Sponge Core comparison – Track 1- litho-log, Track 2- NMR ROS and sponge core ROS, Track 3- total liquid saturation, Track 4 – MDT sample measured Rw and Rwa determined from NMR Sw.

CONCLUSIONS

Sponge core proved an effective tool in benchmarking the remaining oil saturations in this key carbonate well. With the support of tracer analyses and extended imaging of the core material several aspects of sponge coring were verified including:

- Direct contact of the sponge with the core providing adsorption of oil into the adjacent sponge allowing addition to the proper core sample oil volume,
- Low invasion and flushing of the core with the proper use of recommended sponge core techniques,
- The utility of complete core analyses as a part of the sponge core process to optimize the interpretation and to identify key petrophysical parameters in the determination of remaining oil saturation and
- The benefit of combining additional logging and analyses to validate and identify variability of key measurements.

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