Baker Hughes

MR eXplorer

Magnetic Resonance Logging Service

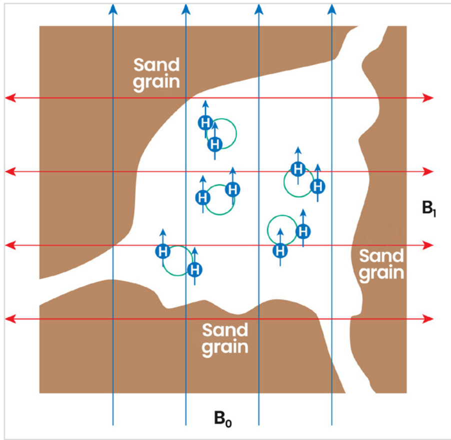
How NMR works

The Baker Hughes **MR eXplorer™ (MReX™) instrument** responds to hydrogen protons in the pore fluids present in the formation. The MReX instrument uses static and pulsed radio frequency (RF) magnetic fields to make downhole spin-echo magnetic resonance measurements. Initially, the MReX instrument aligns, or polarizes, the hydrogen protons in the formation fluid to its static magnet. The MReX instrument then applies an RF magnetic field to rotate or "tip" the protons. The initial, or α, pulse "tips" the protons perpendicular to the static field. The instrument then applies a secondary, or β, pulse to rephase the protons, generating a measurable signal called a spin echo at a time designated as TE. The MReX instrument continues to apply a series of secondary pulses at equal time intervals, with each pulse generating a spin echo. The important information measured by the MReX instrument is contained in the echoes.

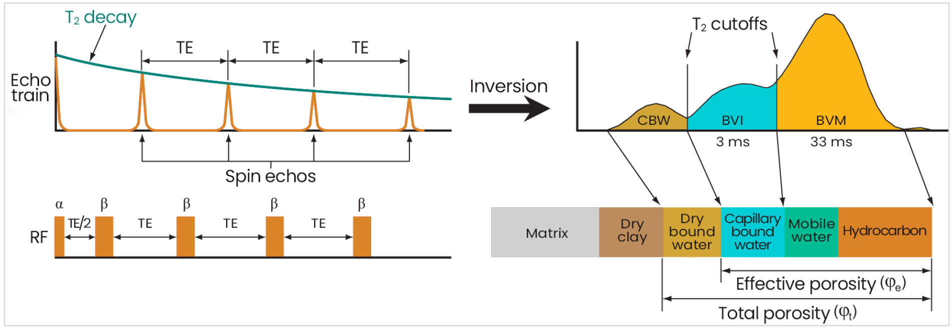
The amplitude of each echo and the time at which the echo was generated is measured and recorded. The initial amplitude of the train of echoes is related to the volume of fluid present in the formation and is used to determine formation porosity. The echo amplitudes decrease, or decay, with time. The decay rate of the echo train (T_2) provides information about pore sizes and the types of fluid present in the pores.

Basic NMR principle

The hydrogen protons in the pore space are first polarized by a static magnetic field (B_0), then subjected to an oscillating magnetic field (B_1) oriented perpendicular to B_0.



The echo train data is processed using an inversion technique to create a T_2 spectrum. The T_2 spectrum represents the distribution of T_2 decay rates at the depth the data was acquired. For 100% water-saturated rocks, T_2 decay rates are directly related to the pore sizes present in the formation; hence, the T_2 distribution is also representative of the pore size distribution. Fluids contained in smaller pores have faster decay rates than fluids contained in larger pores, enabling the T_2 spectrum to be partitioned by pore size into volumes of clay-bound water (CBW), bulk volume irreducible (BVI) and bulk volume movable (BVM). T_2 cutoffs are used as boundaries for the partitions. Typical T_2 cutoffs used are 3 ms for CBW and 33 ms for BVI. In reservoir intervals at irreducible water saturation ($S_{w,irr}$), BVM is a direct measurement of the hydrocarbon storage capacity of the reservoir. The T_2 relaxation times of



BVM, which may be on the order of seconds, are representative of the bulk properties of the fluid present in the pores and can be used to help identify the fluid type. The area under the T_2 spectrum represents the total volume of fluid present in the formation, or the total porosity (f_t). Effective porosity (f_e) is calculated by summing BVI and BVM.

$$k_{NMR} = \left(\frac{\phi_e}{C}\right)^m \left(\frac{BVM}{BVI}\right)^n$$

Coates-Timur permeability model.

The MReX service provides permeability (K_{NMR}) using the Coates-Timur equation, an empirically derived relationship between ϕ_e, BVI and BVM. NMR permeability may be derived using other techniques upon client request. The Coates-Timur model has proven to be a good indicator of permeability in clastics but, for accuracy, should always be calibrated to core permeability.

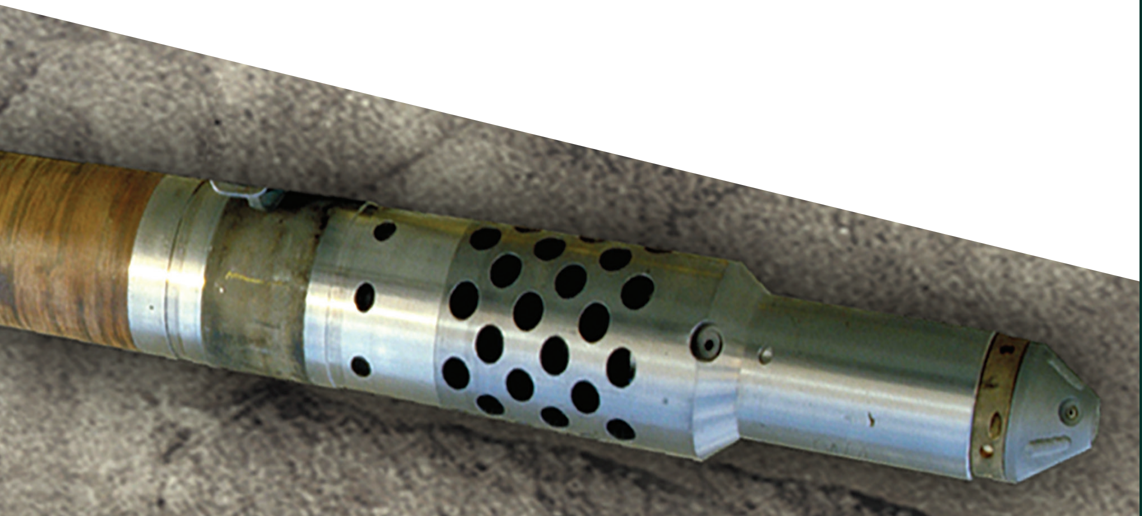
MReX service

At Baker Hughes, our **MR eXplorer™ (MReX™) service** uses the latest-generation nuclear magnetic resonance (NMR) openhole wireline logging device to acquire data more quickly and provide higher-quality results in almost any borehole environment. The data we deliver through our MReX service helps you reduce your uncertainty when evaluating reservoirs and identify hydrocarbon-bearing intervals to maximize your recovery.

A pioneer in NMR logging, we provide more than two decades of data acquisition and interpretation expertise on every NMR logging job. We leveraged this experience to develop the proprietary technology known as the MReX service to provide the best-in-class NMR answers that your wells demand. The strengths of previous NMR logging technologies have been combined with new features to improve performance in the downhole environment by increasing acquisition efficiency and enhancing data quality.

Key features of the MReX service

- Side-looking antenna and a gradient magnetic field for formation evaluation measurements and fluid analysis - delivering reliable data in almost any borehole environment, regardless of borehole size, borehole deviation or borehole conductivity
- Multiple-frequency operation for multiple simultaneous NMR experiments in a single logging pass - saving valuable rig time
- New NMR acquisition techniques - improving NMR data accuracy and providing superior hydrocarbon typing and fluids analysis
- T_1, T_2 and diffusivity measurements continuously recorded by all hydrocarbon-typing acquisition sequences - acquiring comprehensive datasets to minimize the formation evaluation uncertainties
- 2D NMR imaging data acquired as part of the regular logging pass without station-stop requirements - saving valuable rig time



MReX service benefits

- Less rig time
  - Faster logging speeds
  - Comprehensive data sets in a single logging pass
  - No station stops for 2D NMR imaging
- Simplified planning and execution
- Reduced uncertainty in petrophysical interpretations
- Accurate reserves determination with minimal uncertainty

Side-looking data acquisition

Expands operating envelope

Our MReX instrument employs a side-looking magnet-antenna design that offers many advantages over centralized NMR systems. Rather than logging a cylinder around the borehole, the MReX instrument measures an arc of approximately 120° to one side of the borehole - minimizing the effects of borehole condition on NMR measurements.

Operational benefits

Using this method, our MReX instrument can log boreholes 5.875 in. (14.9 cm) in diameter or larger without reducing logging speed to accommodate the borehole size — a significant improvement over centralized tools that require logging speed reductions in both large and small boreholes. This improved logging speed results in measurable rig-time savings for you when using the MReX service.

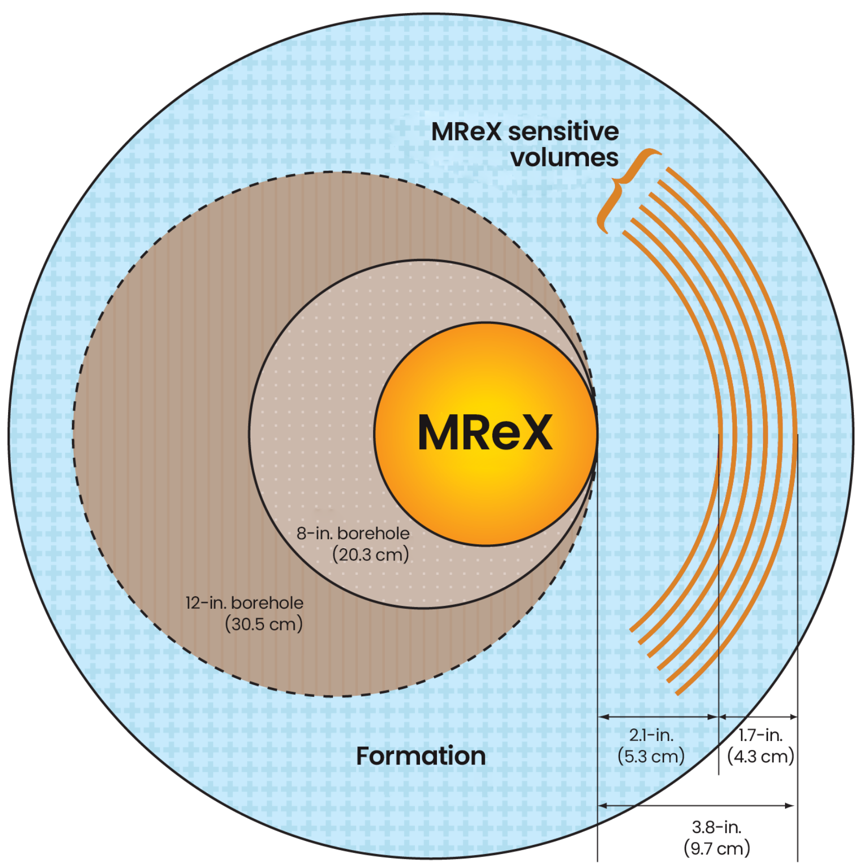
In addition, our MReX instrument's side-looking antenna enables the same 5-in. (12.7-cm) OD tool to be used in all hole sizes. No special equipment is needed for large or small boreholes, which results in the same high-quality data being acquired regardless of borehole size, and eliminates the costs associated with mobilizing special tools and equipment.

Another benefit of the side-looking MReX instrument is that it runs eccentered in the wellbore, making it ideally suited for logging deviated wells. This results in more successful NMR logging jobs and higher quality NMR data, even under the most difficult logging conditions.

The side-looking design of our MReX instrument mitigates the effects of conductive drilling mud on the NMR data quality. The instrument works as its own mud excluder by displacing the mud directly in front of the antenna. Far less radio frequency energy is lost in the drilling fluid column compared to previous NMR systems, resulting in a higher signal-to-noise ratio in high-conductivity mud systems.

This provides two important benefits:

- The NMR acquisition programs do not need to be curtailed in conductive mud environments. The MReX instrument acquires its full echo sequences and complex hydrocarbon-typing sequences over the entire range of mud conductivities
- The MReX instrument acquires NMR data at much higher logging speeds in conductive muds than earlier-generation systems



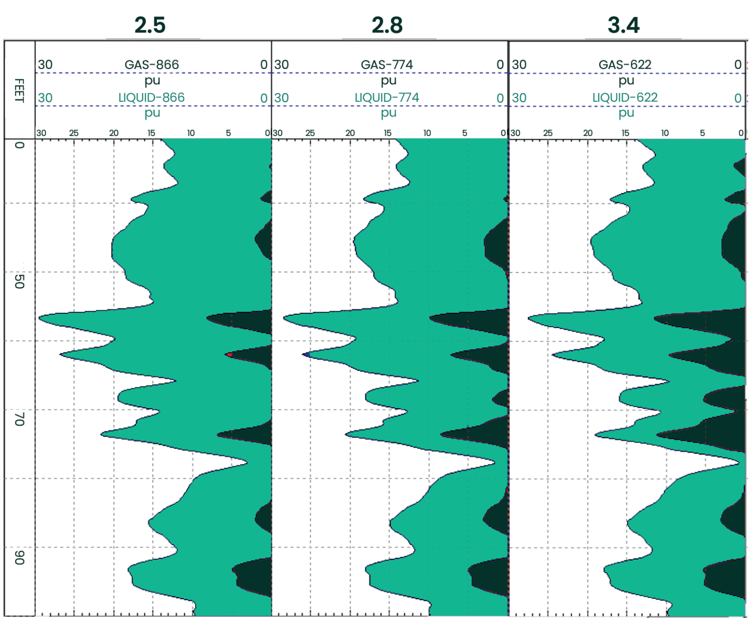
Side-looking MReX allows the NMR reading into the formation in both small and large sized boreholes.

Multiple depths of investigation for faster and finer NMR measurements

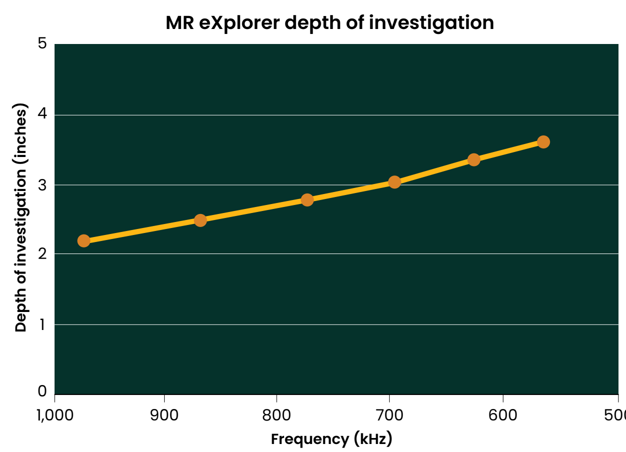
Our MReX instrument's side-looking design provides a constant and well-defined sensitive volume with the measurement zone always located 2.1 to 3.8 in. (5.3 to 9.7 cm) in front of the antenna. The 2.1-in. (5.3-cm) minimum depth of investigation is sufficiently deep to provide valid NMR data in rugose boreholes or when mudcake is present. By operating at multiple frequencies, our MReX instrument provides multiple, independent and continuous NMR measurements that minimize the tool's idle time in your wellbore for increased efficiency and reduced risk.

Invasion profiling

One of the added benefits of having multiple depths of investigation is illustrated in the figure at lower right. The example reveals how you can use our MReX data for determining the extent of flushing that has taken place at each independent "slice" of formation investigated by the instrument. The green shading represents water-filled porosity, and the black shading represents gas-filled porosity. Measured 2.4-in. (6.1-cm) deep into the formation, the data in the left track are from one of the sensitive volumes closest to the tool, indicating the largest volume of water-based mud filtrate. Measured 2.8-in. (7.1-cm) deep into the formation, the data in the center track are from one of the intermediate sensitive volumes; and, measured 3.4-in. (8.6-cm) deep into the formation, the data in the right track indicate the smallest volume of water-based mud filtrate. Gas-filled porosity increases as the depth of investigation increases, indicating that the volume of mud filtrate decreases across the volumes of formation sampled by the instrument. An invasion profile can be constructed by evaluating the changes in gas saturation at the different volumes. It is only applicable to gas reservoir. We do not acquire enough data to provide invasion profile for oil.



MReX data determine the extent of flushing.



This chart illustrates the relationship between the depth of investigation of the multiple independent volumes the MReX instrument measures and the radio frequency. Each independent slice is separated approximately 0.3 to 0.4 in. (0.75 to 1.0 cm) from the adjacent slices.

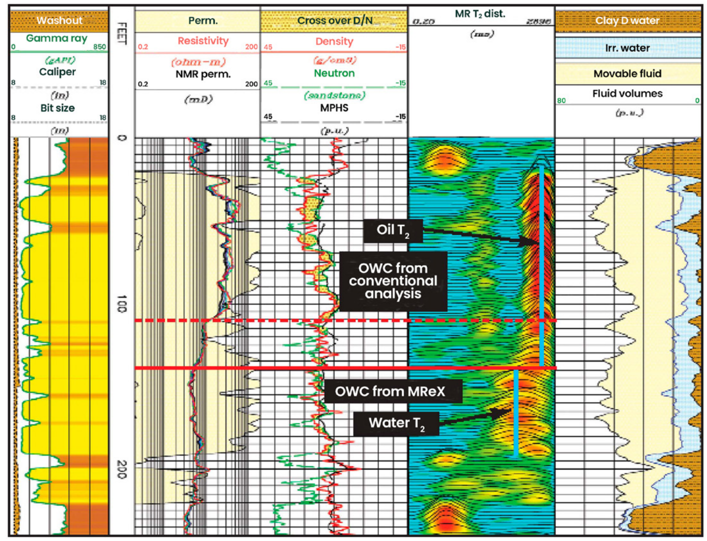
Superior efficiency and accuracy

Faster logging

Because our MReX instrument is the first commercially available, side-looking NMR logging tool that operates using a gradient magnetic field and multiple frequencies, you can now conduct multiple NMR data acquisitions simultaneously on a single logging pass. This helps you improve your operating efficiency and contributes to significantly improved data quality.

Higher quality data

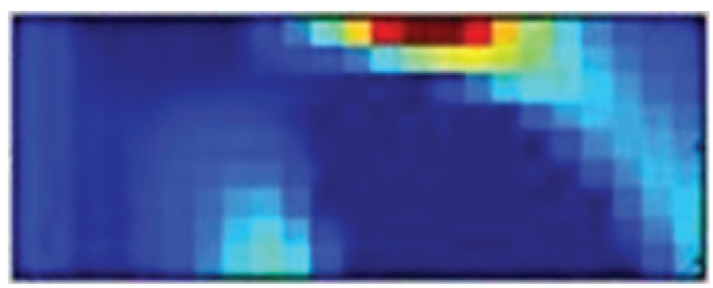
There is minimal dead time associated with fluid polarization wait time when logging with the MReX instrument compared to single frequency NMR tools. All of the time during logging is used to acquire NMR data. This provides high-quality and comprehensive datasets designed specifically to meet the NMR logging program objectives. While single frequency NMR tools required multiple logging passes for advanced NMR logging applications the MReX instrument acquires all hydrocarbon-typing data in a single logging pass. This not only saves you rig time, but also results in higher quality data, as time-consuming and error-prone depth matching is not needed.



Conventional logs indicate a long transition zone, making the oil-water contact point difficult to determine. The MReX T_2 spectrum (Track 4) reveals that the suspected transition zone contains oil, while the MReX fluid volumes (Track 5) indicate that the decrease in resistivity is due to an increase in shale content. The oil-water contact is easily identified by observing the shift in the T_2 spectrum. The MReX instrument identifies movable hydrocarbons in an additional 23 ft (7 m) of the reservoir, proving the value of NMR for accurately quantifying reserves.

MReX service applications

Our MReX service can make significant contributions during formation evaluation, reservoir description, reserves determination, producibility estimation, fluids characterization and completion design. The MReX data help determine reservoir storage capacity, hydrocarbon volumes and permeability. Analysis that integrates MReX data and conventional resistivity and porosity log data is key to helping you understand your reservoirs composed of difficult-to-evaluate shaly sands and low-resistivity pay zones.



T_1/T_2 versus T_2 2D NMR image of a gas reservoir–the large T_1/T_2 ratio characteristic of gas is clearly observed in this 2D NMR image as the bright spot at the top (large T_1/T_2). This image was acquired in a single logging pass with the PoroPerm + Gas OOA at 530 ft/hr (161 m/hr) in a 52° deviated 12¼-in. borehole.

NMR data provide answers for:

Formation evaluation

- Effective and total porosity
- Movable water and bound water
- Pc and permeability
- Pore size, microporosity and vugs
- Grain size distributions, rock facies and rock quality

Hydrocarbon typing and quantification

- Low-R, low-contrast pay
- Water, gas, oil saturations or flushed zone saturations
- Oil viscosity and GOR
- Radial saturation profile
- Characterizing unconventional reservoirs such as gas shale, tar and heavy oil

Objective-oriented acquisitions simplify job planning and execution

We have also introduced innovative NMR data acquisition techniques that provide the highest quality NMR data to meet your formation evaluation and fluids characterization needs. Called Objective-Oriented Acquisitions (OOA), these advanced data acquisition sequences, while very complex, are designed to simplify the planning and execution of your MReX logging jobs. All of the OOAs have been optimized to acquire the highest quality data in the least amount of rig time. The choice of OOA is based on your NMR data interpretation needs. For porosity, fluid volumes and permeability answers, the PoroPerm mode is used. If you need further answers the quantities and types of fluids present, one of the fluid typing OOA mode can be used. The mode selected depends on the type of fluid expected to be encountered in the reservoir. There is normally enough overlap between the modes so that only one logging pass is required, should the logging pass encounter an oil zone and a gas zone in the same reservoir section. If the reservoir is expected to contain both oil and gas legs, consult with your Baker Hughes representative for help in selecting the optimal OOA.

Acquisition package	Objectives	Deliverables
PoroPerm	Porosity	Φ_t, Φ_e, CBW, BVI, BVM, k_{NMR}
	Permeability	T_2
PoroPerm + gas	Porosity	Φ_t, Φ_e, CBW, BVI, BVM, k_{NMR}
	Permeability	T_2, T_1, D
	Quantify and characterize gas and light oil (< 1 cp)	HI_g, ρ_g
PoroPerm + oil	Porosity	Φ_t, Φ_e, CBW, BVI, BVM, k_{NMR}
	Permeability	T_2, T_1, D
	Quantify and characterize oil (1 to 20 cp)	In situ viscosity
PoroPerm + heavy oil	Porosity	Φ_t, Φ_e, CBW, BVI, BVM, k_{NMR}
	Permeability	T_2, T_1, D
	Quantify and characterize heavy oil (> 20 cp)	In situ viscosity
Fast BW	Permeability calculated in combination with conventional porosity measurements	CBW, BVI, k_{BW}
	High speed acquisition consumes no additional rig time combined with triple combo	T_2
PoroPerm unconv. + HC 5 frq	Porosity	Φ_t, Φ_e, CBW, BVI, BVM, k_{MR}
	Permeability	T_2, T_1
	T_1/T_2 map	
PoroPerm unconv + HC 4 frq	Porosity	Φ_t, Φ_e, CBW, BVI, BVM, k_{MR}
	Permeability	T_2, T_1
	T_1/T_2 map	

DEFINITIONS

BVI	Bulk volume irreducible
BVM	Bulk volume movable
CBW	Clay-bound water
D	Diffusion coefficient
HI	Hydrogen index
k_{BW}	Permeability calculated from NMR data acquired in bound water mode
k_{NMR}	Permeability calculated from NMR
$S_{g, xo}$	Flushed-zone gas saturation
S_{or}	Residual oil saturation
$S_{w, irr}$	Irreducible water saturation
T_1	Longitudinal relaxation time spectrum
T_2	Transverse relaxation time spectrum
ρ_g	Gas density
Φ_e	Effective NMR porosity
Φt	Total NMR porosity

MReX service aids production facilities design

Accurate viscosity profile derived in a timely and cost-effective manner

Background and project objectives

As an aid in designing lifting and production facilities, Petrobras' objective was to characterize the viscosity variation of the formation oil in a complex reservoir.

The well was drilled in a development field in the Campos Basin, offshore Brazil. The target reservoir comprised high-porosity and high-permeability Oligocene turbidite sandstones. The oil in this reservoir showed compositional variation affecting both the API gravity and the viscosity. Although 14 to 15° API oil was common in the field, 25° API oil had been found in certain areas of the same field. Based on well correlations, it was predicted that both types of oil would be found in this well.

Methodology

To characterize the reservoir oil, data from the Baker Hughes **MR eXplorer™ (MReX™) service** were acquired in the PoroPerm + medium oil mode. The data were transmitted to the client's office in real time, and an initial evaluation was conducted to generate a continuous profile of the reservoir oil viscosity. Based on this profile, reservoir intervals with different oil properties were selected for testing with the **Reservoir Characterization Instrument™ (RCI™) service.**

Three single-phase fluid samples were collected using the RCI instrument and were transported to a laboratory for PVT analysis. While waiting for the PVT results, the MReX data was further evaluated with the Simultaneous Inversion of Multiple Echo Trains (SIMET) package to determine the intrinsic T_2 of the reservoir oil, which was then used to refine the initial estimates of the reservoir oil viscosity.

Results and conclusions

Real-time analysis of the MReX data identified reservoir intervals with varying oil viscosities and provided key input into the design of the formation testing program. The quick turnaround time of the initial analysis enabled wellsite operations to continue without interruption.

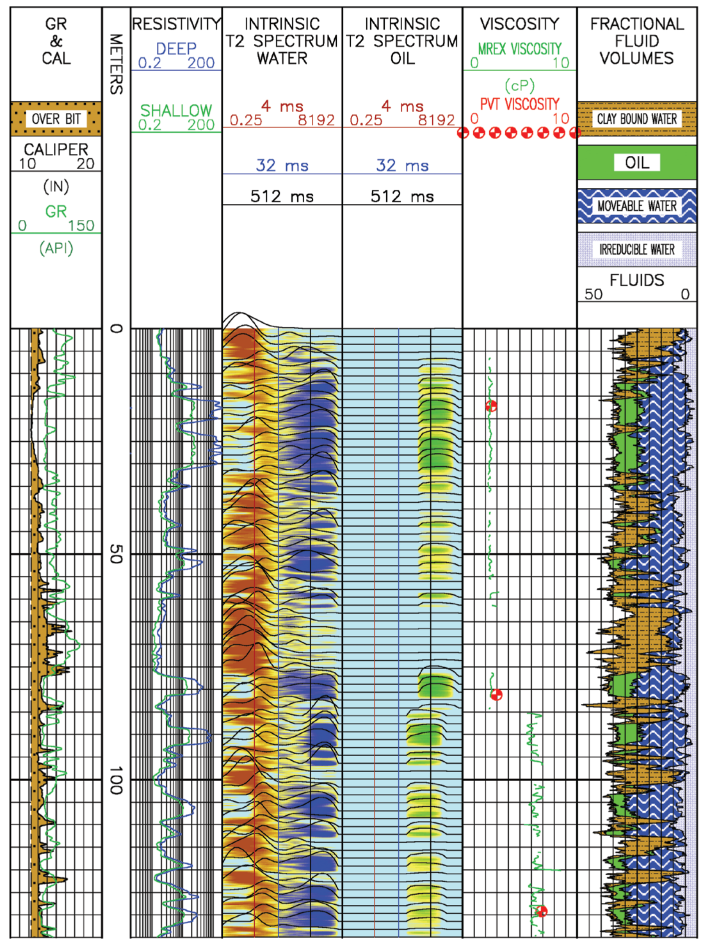
The difference between the viscosity determined from the MReX data analysis and the laboratory-measured PVT data was less than 5%.

The viscosity data was integrated with the real-time mobility data obtained from the R**CI Formation Rate Analysis™ (FRA™)** to determine effective permeability.

Value to client

Instead of collecting formation samples evenly across the zone of interest, a costly and less-efficient operation, the viscosity profile derived from the MReX service enabled the operator to pinpoint sampling locations to measure variation of the crude oil quality. This resulted in considerable cost savings to Petrobras.

While reservoir fluid samples provided high-quality PVT data, they only characterized a few discrete levels of the reservoir. On the other hand, accurate and continuous viscosity information from the MReX service significantly reduced the uncertainty in the formation evaluation in a more timely fashion. Furthermore, the combination of viscosity and permeability results was used in the reservoir simulation program to aid in the design of the lifting and production facilities.



MReX specifications

Diameter	5 in. (12.7 cm)
Length	24 ft, 5 in. (7.4 m)
Weight	622 lbm (282 kg)
Maximum temperature	350°F (177°C)
Maximum pressure	20,000 psi (137.9 MPa)*
Borehole size range	5.875 in. (14.9 cm) and larger
Mud type and salinity	No restrictions for mud type and salinity
Antenna aperture length	18 in. (45.7 cm)
Depth of investigation	2.1 to 3.8 in. (5.3 to 9.7 cm)
Magnetic field type	Gradient
Minimum echo spacing	0.3 ms

* High pressure, 30,000 psi (206.8 MPa) service available.

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