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Borehole Nuclear Magnetic Resonance Study at the China University of Petroleum

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ABSTRACT

The research of borehole nuclear magnetic resonance (NMR) began in the 1950 s, but the maturity and large-scale applications of relevant instruments started in the mid-1990. To date, borehole NMR is an important means for borehole in-situ analysis and oil and gas evaluation, which significantly improves the success rate of exploration and the evaluation accuracy of oil and gas reservoirs. Its development has also contributed importantly to low-field and industrial NMR theories and experimental methodologies. Companies and individuals in the United States, China and other countries have developed the capabilities to engineer and deploy borehole NMR instruments and measurements independently. NMR imaging and evaluation of heterogeneous reservoirs and unconventional oil and gas are worldwide problems, involving the innovation of borehole NMR and the advanced manufacture of instruments and equipment.

The commercial technology of borehole oil and gas exploration is highly competitive and proprietary. It is difficult to gain full insight into the details of the technologies and development from published literatures. Based on the research of the author's NMR laboratory at the China University of Petroleum (CUP), this paper reviews the core technologies of borehole NMR and its applications, discusses selected important issues that have not been fully solved, and looks forward to the direction and prospects of future development.

1. Introduction

Oil and gas, buried in tiny pores of the reservoir rock formations under subsurface, are invisible and untouchable fluid deposits. Oil and gas well logging technology, invented by the Schlumberger brothers in France and first applied in 1927, puts well-designed probe and electronics into wells thousands of meters deep, to obtain information about porosity, permeability, water saturation and lithology of Earth formations and answers "Where's the oil and gas? How many? How much can be extracted? In what way?". It is vividly known as the "**eyes**" for oil and gas exploration and development. Well logging runs through the entire life cycle of oil and gas wells and fields, and it has become one of the core technologies in modern petroleum industry. In a vertical well, wireline logging devices are applied to open hole, cased hole and production well to acquire information regarding the formation outside of the borehole or fluids properties inside the borehole. In a high angle or horizontal well, however, wireline devices were not able to be delivered to the objective zone for measuring the formation properties outside or inside the borehole.

Many conventional logging methods, which includes resistivity with deep, medium and shallow depth of investigation, acoustic travel time, formation bulk density and neutron porosity, spontaneous potential, gamma ray and caliper, have long been used in petroleum industry and achieved good results in the early non-complex conventional oil and gas reservoirs. However, with issues like "how to explore oil and gas in deep formation layers, deep-water or unconventional reservoirs" having become the mainstream of oil and gas exploration and development, the characterizations of reservoirs are gradually transferred to the descriptions and evaluations of tight and the complex pore structure and even the fractures [1]. The resistivity, acoustic, and nuclear logging methods used for reservoirs with tight and complex pores structure, have low sensitivity to the investigation of fluids and their states resulting in poor accuracy. The nuclear magnetic resonance technique is sensitive to fluids and their physical properties in tight and complex pores in reservoirs, providing key, rich and unique information about fluid content, fluid type, pore properties, and even wettability [2].

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Exploratory research of borehole NMR began in the 1950s, with Varian [3], Brown [4,5], Jackson [6] and Miller [7], Coates [8], Kleinberg [9] and many other contributors. It only really made a breakthrough in the 1990s, and soon became a popular and "mainstream logging technology" highly valued in oil and gas explorations. The borehole NMR provides a lot of information with high accuracy and has large market demand with high technical threshold requiring major instrumentation and advanced manufacturing technology. China National Petroleum Cooperation (CNPC) purchased the first set of NMR logging instrument in 1995 from NUMAR Corporation. By applying this technique, several oil and gas reservoirs missed by conventional logging techniques were found, resulting in remarkable application effects. However, the imported instruments are very expensive to maintain, limited in technical performance and subject to various restrictions from the manufacturer such as that the purchased instruments were not allowed to operate outside of China. In addition, the application conditions and methods and the actual situation of China's continental stratum complex oil and gas reservoirs are often very different. To solve key technical problems of oil and gas exploration and development and achieve the purposes of expanding application scale, reducing operation costs, and addressing unconventional oil and gas fields, there was an urgent need to develop independently new instrumentation and application technology of borehole NMR. These issues are included in the strategy of the Chinese national science and technology development and have been continuously supported by major national oil and gas projects and the National Natural Science Foundation of China.

Nowadays, the borehole NMR has become a mature technical field in oil and gas industry. As illustrated in Fig. 1, the NMR technology can be split into three key scientific areas, including instrument design and implementation, data acquisition and processing, and interpretation and application. However, the borehole NMR is totally different with medical MRI in laboratory. The instrument design of high field MRI is based on superconducting magnet with "Outside-in" architecture, which can only be operated in a controlled environment with a highly homogenous static magnetic field and gradient magnetic field leading to high SNR. The data set is often collected in k-space with frequency encoding and phase-encoding methods and images are reconstructed by using Fourier transform. Unlike medical MRI, borehole NMR is operated in extremely harsh environment to measure NMR signals in the formation outside the instrument. The magnetic field is much weaker than that in MRI, and operational environment is complex and continuously varying with depth leading to lower SNR. The signal of borehole NMR is almost always detected by echo trains and analyzed by using Laplace transform methods. The measured T_2 spectrum and T_2-D correlation map are often used to evaluate the petrophysical parameters of reservoirs, characterize the fluids and assess the oil recovery.

Our laboratory has been working on borehole NMR principles, instrument design and implementation since 2003 [10,11]. The first NMR well logging tool prototype was completed in 2007, and field testing and establishment of operation and data standards were both accomplished in 2008. In cooperation with COSL (China Offshore Services Limited), CPL (China National Petroleum Corporation Logging), Sinopec (China Petrochemical Group Co., Ltd.) and other enterprises, EMRT (Eccentric Magnetic Resonance Tool), MRT6910 (Magnetic Resonance Tool 6910) and other borehole and desktop MRI instruments were successfully developed and deployed to the industry. In addition, recent developments are in the areas of high temperature (200 °C) borehole NMR tool [12], borehole three-dimensional NMR scanning tool [13,14], logging while drilling NMR tool [15], NMR fluid analysis laboratory [36,37] and other NMR analysis tool in inhomogeneous and unstable magnetic field [16].

This paper will focus on the design and implementation of new NMR instruments, fast and reliable inversion methods, new experimental methods and applications for borehole NMR applied to conventional and unconventional oil/gas reservoirs.

2. Borehole NMR instruments

The borehole NMR instruments, including wireline logging and logging while drilling (LWD) NMR probes, and fluid analysis laboratory have been developed. NMR instrument for pipeline fluid property measurement and analysis in the petroleum industry has be made and will be brief mentioned below.

2.1. Wireline NMR probe and spectrometer

Borehole NMR probe is the key component of the borehole NMR instrument and often regarded as the core trade secret of the technique, which are protected by intellectual property rights. Early attempts were tried to use Earth magnetic field for NMR exploration [4,5], and this technology is still used in some Russian oil

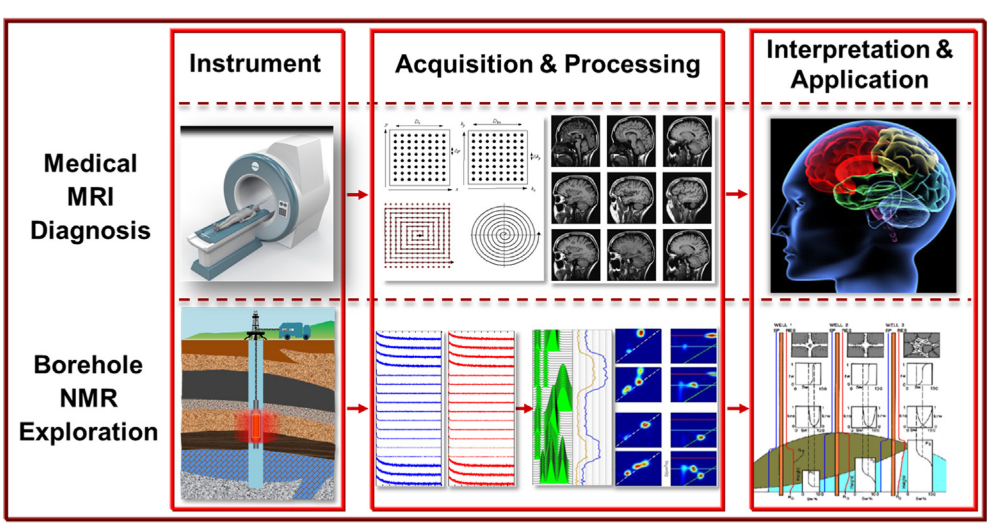

Fig. 1. Three innovative aspects around borehole NMR: instruments, data acquisition and processing, petrophysical fundamentals and software for interpretation and applications.

fields. Based on Earth magnetic field, a huge coil is constructed to excite the polarized protons and receive the NMR signals, as shown in the first column of Fig. 2. However, due to the strong influence of borehole drilling fluid to the received signal, Earth field magnetic resonance logging has not been commercially applied in other parts of the world. In 1980, Jackson proposed the "Inside-out" concept [6] to break through the restrictions of logging tool based on Earth magnetic field and made borehole NMR large-scale commercial applications possible. This new design demonstrated how permanent magnets can be used to generate a relatively homogeneous magnetic field outside of the NMR instrument to improve SNR and adaptability in borehole condition. As shown in the second column of Fig. 2, there are two cylinder-shaped permanent magnets placed in opposite directions to produce a magnetic field stronger than Earth magnetic field in a region outside the instrument. To date, there are two categories of NMR logging tools available in the market, centralized type probe like the Halliburton NUMAR MRIL-Prime [17], and pad-type probe like the Schlumberger CMR/MR-Scanner [18,19] and Baker Hughes MREx [20], as shown in the third column of Fig. 2. The former one adopts hollow cylinder shape as the structure of main magnet to produce omni-directionally distributed static magnetic field, which has demonstrated excellent performance with strong signal intensity, SNR and good repeatability, but not suitable for applications in highly angle wells and horizontal wells. The latter ones are based on the single-sided design by using at least two magnets with the same magnetization direction to realize a focused static magnetic field on one side and have demonstrated better vertical resolution, but poor SNR and repeatability. Many case studies have shown that both centralized and pad-type NMR probes are successfully applied to the discovery of oil and gas. However, neither are suitable for the investigation of heterogeneous reservoirs and unconventional oil and gas reservoirs. Usually, NMR application is based on the hypothesis that the formation is homogeneous. However, in many reservoirs, especially for unconventional reservoirs, pores or fractures [21] and even fluids of rock formation exhibit different properties not only along the depth and radial direction, but around the borehole. These situations will result in unexpected errors in porosity and permeability values, as well as incorrect evaluation of oil/gas location and perforation based on NMR measurements. Early trial of borehole NMR azimuthal measurement was suggested by Prammer [22] to rotate the single saddle coil or tool in 90°increments to acquire additional directional information so that the system is capable to differentiate the petrophysical parameters from four azimuthal regions with special post-processing. Rotating the tool, however, is difficult in borehole conditions, and the precision of corresponding processing is easily affected by overlapping sensitive regions. Therefore, this suggestion was not adopted. Due to the strong demand on heterogeneous formation exploration with NMR technology, a new three-dimensional NMR logging tool has been designed, and corresponding wellbore MRI logging instruments and equipment with scanning function have been developed firstly in the author's group recently [13,24], as illustrated in the right column of Fig. 2.

The three-dimensional NMR probe was designed and configured with a special-shaped magnet array and a coil array, as demonstrated in Fig. 3. The magnet array can produce multi-pole magnetic field outside of the probe [23]. Combining with coil array with azimuthal selection, operation independency and measurement consistency after capacitive decoupling [24], the static magnetic field and RF magnetic field of the probe can be controlled and are orthogonal everywhere in the pre-set areas of the formation outside the wellbore, which is the condition to achieve three-dimensional NMR measurement. The excited sensitive region can have an aperture of 90° or 360° in cross-section by controlling excitation of the coil array. This design made three-dimensional NMR theory and instruments adaptable and applicable in vertical wells, horizontal wells, and other types of wells with different borehole shapes and different drilling fluids, to obtain information regarding fluids properties of the reservoirs and three-dimensional spatial information of heterogeneity of the formation outside of wellbore.

Correspondingly, a multi-dimensional NMR logging calibration device for simulating in-situ conditions of formations and fluids was built [25]. This device has three key uses: first, as a calibration tool, it will determine the 90-degree pulse and quantitatively calibrate porosity (0–100%) and relaxation time (0.3–3000 ms) in eight azimuthal directions, and to achieve calibration conversion between measured NMR signal and the formation parameters. Second, as a debugging and trouble-shooting tool, it can assess performance of probe and each module of the electronics and state of overall instrument. Third, as a research tool, it can be used for the development and test of pulse sequences and activations based on nuclear spin quantum coherence, which can develop new observation mode for the borehole NMR logging instruments, establish

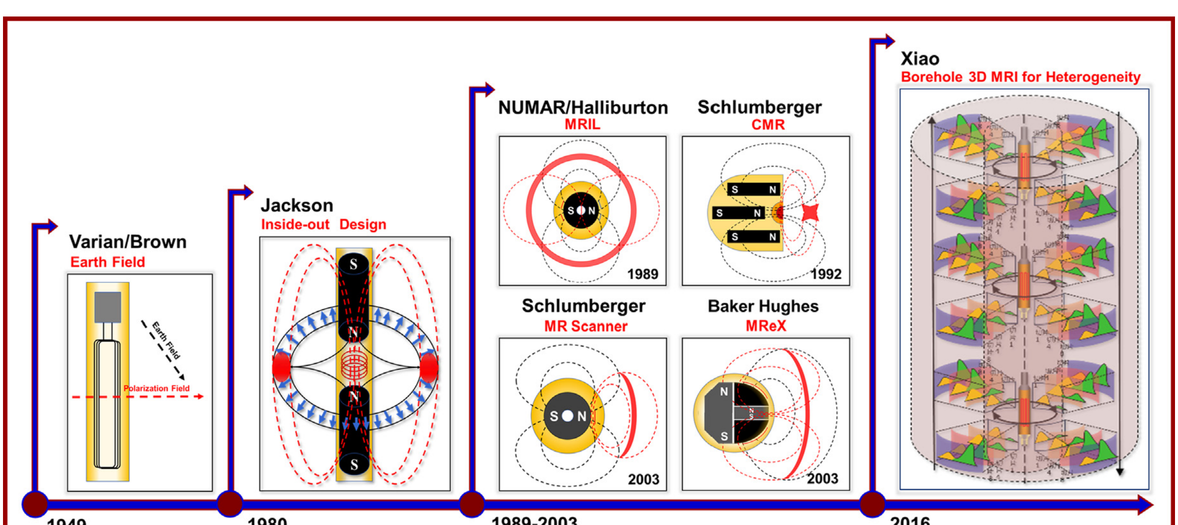

Fig. 2. Development of the concept design for borehole NMR probe.

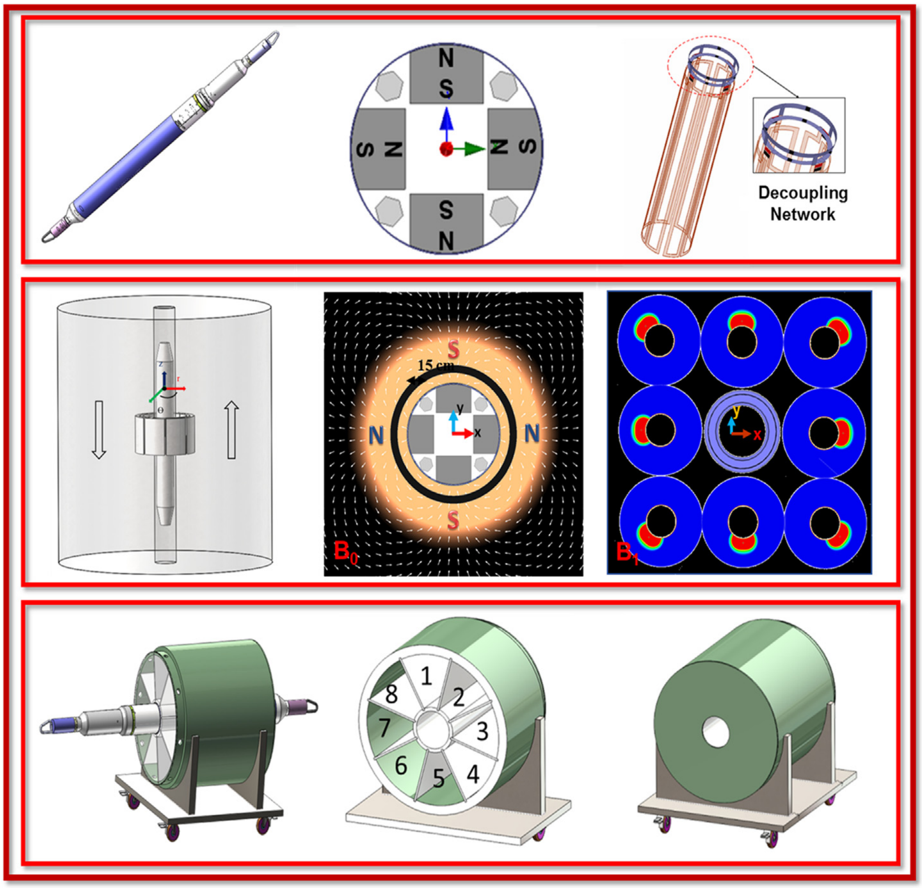

Fig. 3. The illustration of borehole 3D MRI probe and a sophisticated calibration device. The first row is the construction of probe including magnet and array coil, which is implemented to capture 3D spatial NMR information (depth, radial and azimuthal) of the borehole. This design is different from the method used in medical MRI with the "Outside-In" design. The second row is the magnetic field distributions of both the magnet and the RF array coil. The static field is a quadrupole (two north and two south poles) to azimuthally polarize the formation samples as well as ensure the configuration consistency of RF coil elements. The coil elements are decoupled to retain the operation independency in order to acquire azimuthal NMR data, which is key to achieve 3D borehole image reconstruction. The last row is the calibration device which can be used to build a formation model with azimuthal heterogeneity around borehole. The device is divided into eight sectors to build desirable models to calibrate the new designed instrument and to test the pulse sequences as well.

quantitative relationship among borehole NMR measurements, rock physical and chemical characterizations and fluid properties, and develop and validate the theories and methods of borehole MRI. For the study of motion effects on the instruments, an NMR motion platform [26] is also established to simulate the relative motions between instrument and different samples, which can achieve the motion effect corrections [27] with dynamically acquired data from borehole NMR instruments.

The spectrometer is one of the core parts of the borehole NMR instrument for activation control, pulse sequence transmission, pre-processing of the received NMR signals, power supply and communication. The key issues of downhole spectrometer system include high-power transmission (up to kW), weak echo signal detection (down to sub-uV), fast energy discharge, high voltage isolation and protection, and time-sequence control [28]. The three-dimensional downhole NMR multi-channel control module with high voltage and data transmission of the spectrometer system is still one of the major challenges [29–31]. The control module consists of three main parts including coil array control circuit, fast recovery circuit and tuning circuit. It is used to eliminate the coupling phenomenon of the coil elements, release the stored energy in the coil, tune operation frequency and to select the corresponding coil to perform azimuthal measurement. Owing to the development of control module, the coil elements in an array can be arbitrarily selected or combined to transmit and receive NMR signals from azimuthal objects or omni-directional objects. In addition, the system is able to complete the collection and processing of amplified echo signals, command transmission, communication with the surface system, and data encoding and decoding for communications.

The designed transmitter and receiver circuit in the spectrometer consists of power amplifier driver, power amplifier, duplexer, preamplifier and receiver. The power amplifier driver is constructed with half-bridge switch to provide high-current control signals for the power MOSFET under the high temperature condition. The power amplifier is built with dual full-bridge switches and RF transformer, which are directly connected to the high-impedance antenna. Amplitude of the output signal can be up to 2800 V. The duplexer circuit is set before the signal reception circuit, which protects the reception circuit during the high voltage RF pulses. To protect the receiver and also further decrease Q value of the antenna, duplexer controlled by MOSFETs is employed so that the recovery time of antenna can be efficiently reduced. The reception circuit uses an input transformer for impedance transformation, which effectively changes the source resistance, so the noise can be neglected. The first stage of receiver with instrumentation amplifier architecture has a differential input built on ultra-low noise wideband operational amplifier. Programmable attenuation is employed to widen the dynamic range of circuit, the maximum gain is 110 dB and the input-referred noise is 0.92 nV/ Hz.

2.2. LWD NMR probe

With the rapid growth of the number of horizontal wells for enhanced oil recovery, offshore, and unconventional oil and gas, there were more and more applications needed in the oil industry to provide real-time measurements and evaluations while drilling.

NMR LWD has the ability to carry on real-time measurements during drilling to the target zone and is compatible with the operation environment in horizontal or high angle wells. Compared to wireline NMR, there are advantages for LWD that the original measurements before the deterioration of the drilling fluids invasion could be acquired by LWD instruments. Nowadays, the representative LWD NMR tools were Halliburton MRIL-WD [32] Schlumberger pro-VISION [33], Baker Hughes Mag-Trak [34]. MRIL-WD has the similar magnet configuration compared with MRIL-Prime, to produce a dipole magnetic field with a field gradient of about 14 G/cm. Due to the thinner sensitive region, T_2 could only be measured when the tool is in a sliding state (without strong radial vibrations) while T_1 measurement can be performed while drilling which is less sensitive to the radial vibrations. The Jackson design [6] was introduced into pro-VISION and Mag-Trak, which could produce relatively homogeneous magnetic field with field gradients lower than 2 Gauss/cm. The advantage was obvious with high formation resolution, wide resonant volume and less sensitivity to the radial variations when T_2 measurements were conducted.

One of the biggest challenges of LWD instruments was the vibration effects on the relaxation measurements, although some methods were suggested to suppress these effects [35]. One way to reduce the effect of vibration was the optimization of sensor design and also ensured the mechanical integrity of the magnet, as shown in Fig. 4. The LWD probe was mainly consisted of magnet, antenna and drill collar. Different from the previously mentioned probes, in our design the double hollow cylinder magnet (DHCM) [15] configuration was introduced as an alternative to the Jackson magnet. The magnet consisted of an outer-layer magnet (fixed on the drill collar) and an inner-layer magnet (fixed on the inserted part of the drill collar). The antenna assembly was also fixed on the drill collar, and its position was in the middle of the gap of the outer-layer magnets. The drill collar and its inserted part had been colored in light green and yellow, respectively. For the Jackson magnet, the fraction of the drill collar and the magnets in the cross-sectional area was 37.5% and 52.73%, respectively. In the DHCM structure, the fraction was 46.88% and 43.36%, respectively. Compared to the Jackson magnet, the fraction of drill collar in the DHCM structure was increased by about 25%, while the proportion of the magnet was decreased by about 18%. Thus, the mechanical strength and reliability of the drill collar were greatly improved. The sensitive region in longitudinal cross-section was a spider-liked shape and the resonant region was about 53 mm. The B_1 field produced by solenoid RF coil was quickly attenuated along the radial direction leading to the non-uniform excitation region half of the whole sensitive region and SNR was about 120 for 16 PAPs scans in the calibration device (copper sulfated solution with T_2 of 320 ms was filled in the calibration device).

2.3. Fluid analysis laboratory

The properties of downhole fluids may change when they are extracted to be analyzed in the laboratory. Those properties, such as oil gas ratio, viscosity, molecular structure [36] etc., are very difficult to be recovered into the original state with the high temperatures and pressures downhole. In-situ fluid analysis is significant to the evaluation of reservoir contamination, fluid characterization, oil and gas quantification and the oil recovery estimation. That is why a multi-functional fluid analyzer that can be used to analyze the reservoir fluids in situ at real-time is a long-term goal of petroleum scientists. Early fluid analysis devices were developed by service companies, like Halliburton's Reservoir Description Tool (RDT) [40], Schlumberger Modular Formation Tester (MDT), Baker Hughes Reservoir Characterization Instrument (RCI). The methods used for fluid analysis were optical [41] and NMR. The former one performed not well in the cases that drilling fluid filtrate was oil-based or the fluids in the pores were mixed phase. In contrast, NMR is sensitive to fluids, which makes it suitable to test with different drilling fluids. The schematic of borehole NMR fluid analysis laboratory is shown in Fig. 5. Moreover, downhole in-situ fluid analysis is only one of the applications for NMR fluid analyzer laboratory. Expanded applications on the ground, includes drilling fluid monitoring for oil content detection [38] and multi-phase flow separation detection system [39] for flow velocity monitoring, fluids quantification and characterizations for pipelines.

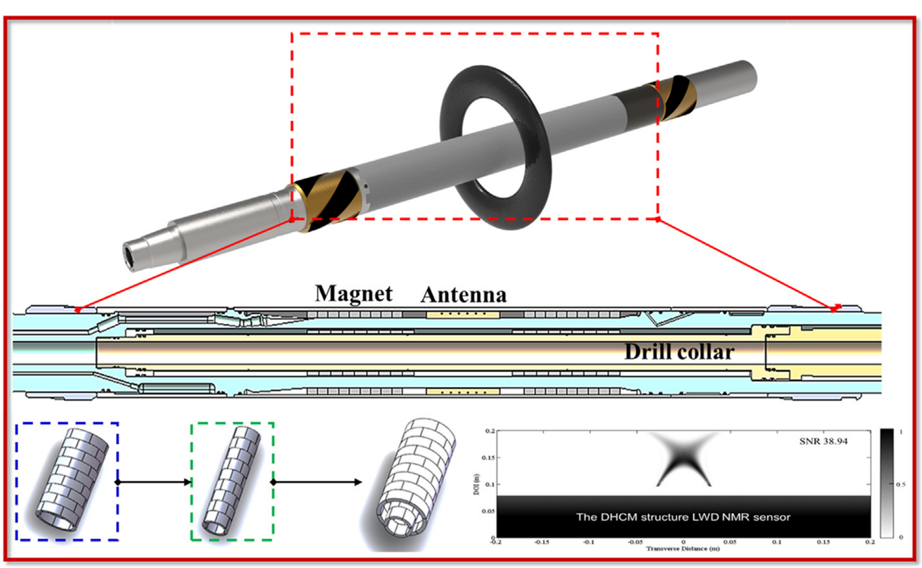

Fig. 4. The illustration of the LWD NMR probe. The design was based on the Jackson magnet but improved by the double hollow cylinder magnet (DHCM) with high mechanical reliability.

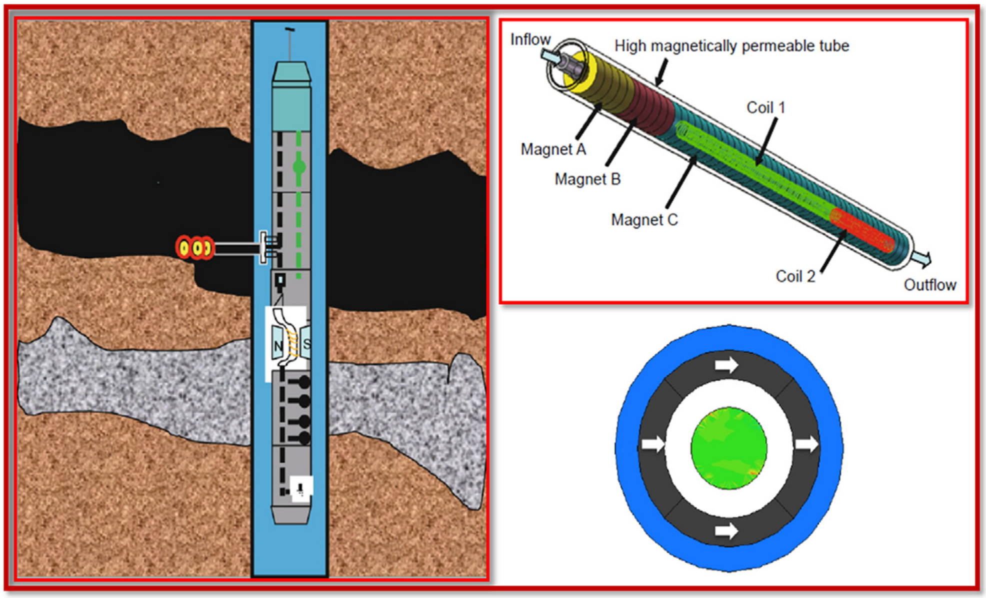

Fig. 5. The illustration of in-situ NMR fluid analysis laboratory working at downhole. The formation fluids are extracted into the NMR tool by the suction probe at fixed depth. The requirements for fast and dynamic measurements necessitate the sensor to have higher magnetic field for better SNR. In addition, two coils without coupling effects were introduced to realize dynamic measurements for different flow velocity, as shown in the right-top panel. A dipole magnet is used with a high permeability material as the outer shell to restrict the magnetic fluxes and improve the strength of static magnetic field.

3. Borehole NMR data acquisition and inversion processing

Borehole NMR instruments work at harsh environments with high/variable temperatures and pressures, to observe complex objects and detect ultra-weak signals down to the sub-microvolt levels. Usually, the collected echo trains are addressed by using time-domain processing method, namely, the echo trains are processed by using inverse-Laplace transform, to obtain the NMR relaxation time distribution at a single depth point. In order to increase the signal-to-noise ratio, it is necessary to combine echo trains at different depth points together and increase the repetition times. In addition, ringing noise will seriously affect the noise level and decrease the signal-to-noise ratio. The phase alternate pairs (PAPs) of different echo trains, often used to eliminate the ringing effects, will result in a trade-off among measurement efficiency, signal-to-noise ratio and spatial resolution. Sigal [42] et al. suggested a phase alternate method among echoes to reduce the effect of ringing. Song [43] et al. studied the uncertainty of Laplace inversion to improve the spectrum resolution. Sun [44] et al. used an inversion method along depth dimension to improve the inversion efficiency. All these efforts have improved the quality of data acquisition and processing.

The introduction of the third-dimensional NMR information, which is the key part of borehole three-dimensional NMR data body, will increase the difficulties of data acquisition and processing. The acquisition speed, the vertical resolution of T_2 spectrum and the inversion efficiency and precision may be dramatically affected. To solve these problems, related data acquisition methods, depth-dimension inversion, and borehole NMR visualization have been developed, as demonstrated in Fig. 6.

For further suppressing the effects of ringing noise, a new PAPs method called HEPAPS (High-Efficiency Phase-Alternate Pulse Sequence) [45] was suggested and tested with high efficiency, high signal-to-noise ratio, and fast data acquisition. It was based on the theory of PAPs combining with principle of forced recovery pulse sequence. This method can reduce the ringing effect by about 90% during the instrument dead time and improve the vertical resolution with an increase of repetitions. To accelerate data acquisition while ensuring data quality, a sparse sampling and reconstruction method based on compressing sensing [46,47] was developed. In this method, pseudo-random sub-sampling scheme was employed and the spectrum are reconstructed by L_1 minimization with wavelet transform regularization. It achieved a significant reduction of data acquisition time by up to a factor of 5 and reduction of data size by about 90% compared to full data. A multi-stage denoise method and workflow were developed, which can improve the signal-to-noise ratio by up to eight times. It consisted of three stages: before the echo acquisition, phase correction-adaptive line enhancement (PC-ALE) [48] was proposed to noise suppression based on the principle of ALE and NMR spin-echo characteristics; during the echo acquisition, DPSD (Digital Phase Sensitivity Detection) method based on Gaussian low-pass filter was employed to further suppressing the noise in echo data [49]; after echo acquisition, SURE (Stein Unbiased Risk Estimation) algorithm based on wavelet transform was employed to suppress the noise brought by small pores and improve the SNR of NMR logging data [50]. For vertical resolution enhancement to determine formation interface, a joint inversion method based on B-spline base-function [51] was developed, in which the kernel function is determined by petrophysical acquisition parameters and vertical response function, to improve vertical resolution to several times of the sampling rate. In downhole NMR in-situ analysis process, relaxation weighted methods and diffusion weighted methods are usually used to characterize the fluid-typing. However, the inversion process of multi-parameter is complex and time-consuming. To improve inversion efficiency, a multi-dimensional inverse-Laplace transformation method based on dimension-descending theory [52,53] was developed, which improved inversion efficiency.

In addition, based on above progress, NMR data processing and interpretation software have been developed and applied in commercial projects in oil fields, which are fully functional and continuously upgradable. Software copyrights granted include NMR core analysis software (2012SR043222, China), NMR well logging data processing and analysis software (2012SR043756, China) and online multi-dimensional NMR data processing and analysis software (2015SR008533, China).

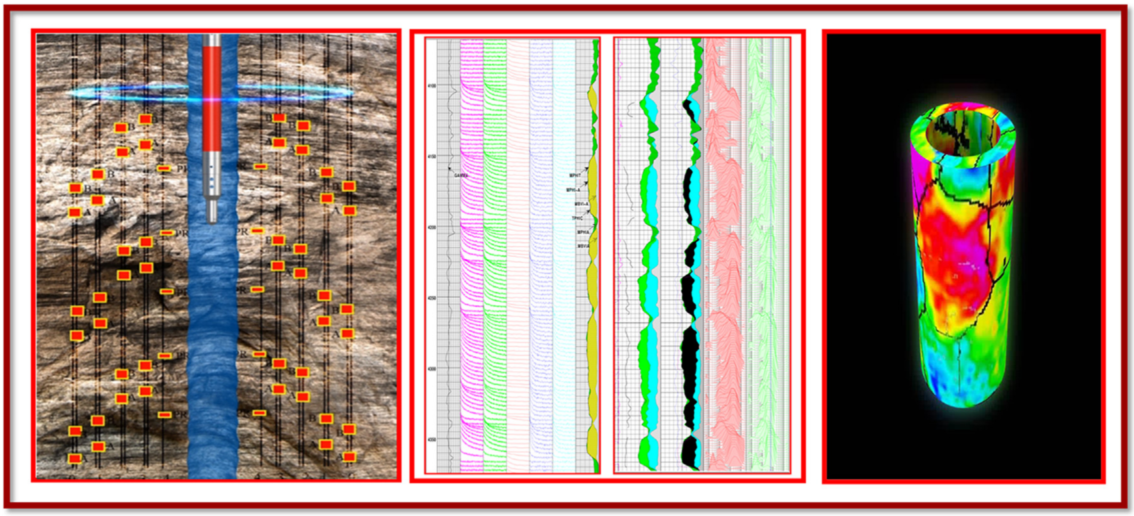

Fig. 6. The illustration of data acquisition, processing and visualization of the 3D borehole NMR. The left column illustrates the operation and activation modes of the NMR probe. The depth, radial profile and azimuthal information were captured by the instrument. The middle one demonstrates that the raw data is consisted of many echo trains with different pulse sequences and parameters. Time domain analysis is often employed to differentiate fluids and petrophysical parameters like porosity, saturation and permeability are derived from T_2 spectrum. The right one is a 3D image of borehole NMR reconstructed by using incremental porosity data with the help of interpolation algorithm, derived from depth, radial and azimuthal data. It is significant to logging interpretation and characterization of borehole properties, which has an ability to give a detailed view of the pore structure, pore connectivity, fracture growth, saturation profile and fluid flow. These are applicable to petroleum engineering for wellbore stability evaluation, perforation and enhanced oil recovery with NMR.

4. Borehole NMR interpretation and application

The well logging methods, such as resistivity, acoustic and nuclear measurements, have made quantitative evaluation of porosity and fluid saturation of conventional oil and gas reservoirs available in past decades. For example, using Archie equations, water saturation can be estimated by resistivity and porosity based on empirical models; the acoustic travel time, bulk density and neutron porosity are usually used to determine the porosity. However, due to the detection sensitivity and evaluation accuracy of these conventional logging methods, reservoirs of low porosity and low permeability and unconventional reservoirs are poorly characterized, resulting in interpretation and application problems. In contrast, the NMR signal originates from fluids themselves so that fluid properties and the interaction between molecules of fluids and the surface of pores may be probed with NMR techniques. Thus, an integration of NMR with other logging methods could potentially improve formation evaluation significantly, for example, resistivity imaging data could be considered as a correction tool to improve the precise of NMR porosity measurement [54].

The Fig. 7 illustrates a forward model for fluids characterization and is very important for NMR logging interpretation. As shown in the first column of Fig. 7, a rock consists of rock matrix, dry clay, bound water, movable water and oil or gas. Each component contains different types of fluids with different relaxation time and diffusion coefficient, which can be estimated from NMR measurements. Usually, T_2 spectrum is the common means for the calculation of porosity, permeability and saturation etc., and it can also be used to differentiate fluids by setting different *TW*

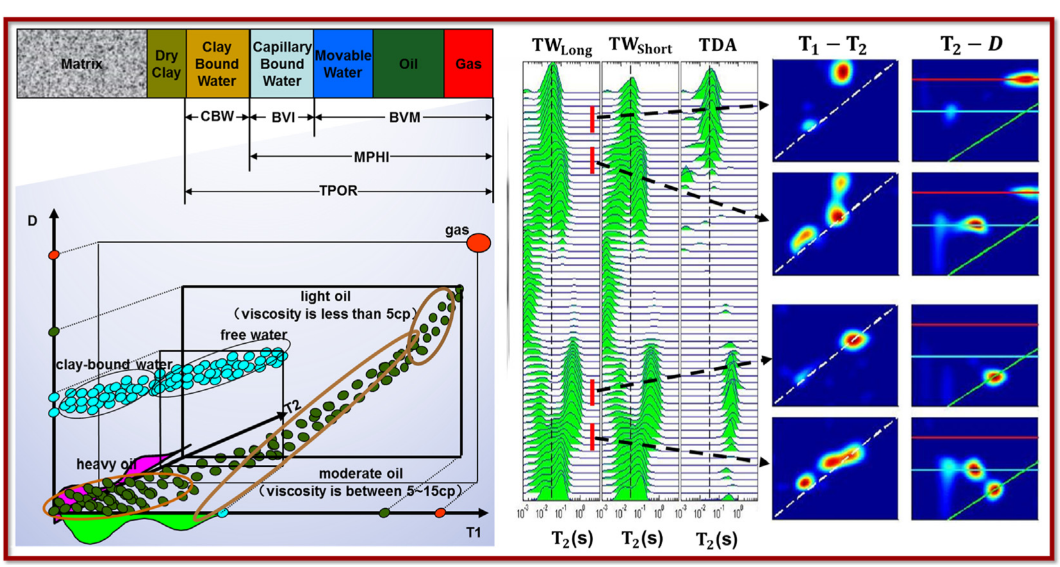

Fig. 7. NMR properties of reservoir fluids and petrophysical forward modelling for fluid identification and formation evaluation.

or *TE* as shown in the second column of Fig. 7. However, if the relaxation time or diffusion coefficients of fluids (bound water, oil or gas) are similar, the single relaxation or diffusion contrast cannot be employed well so that T_1-T_2 or T_2-D correlation map should be introduced to differentiate the properties of fluids (as shown in the third column in Fig. 7) and calculate the saturation, viscosity and other evaluation parameters. It is worth noting that this model should be revised as in-situ conditions of the formation may change.

To further improve the quality of interpretation and application by using NMR technique, new experimental methods were developed. The pore structure of rocks is very important for reservoir evaluation and prediction of production. However, measurements may be seriously influenced by restricted diffusion and internal gradient [55], which are dominated by pore size and different fluid phases in the rock. On the other hand, these effects can be a useful tool for detecting the pore structures. Thus, two methods based on DDIF-PFG and DDIF-CPMG [56,57], were proposed to directly acquire the correlations between pore size distribution and diffusion and internal gradients, respectively. The results gave a better understanding of the behavior of fluid diffusion dynamics and internal gradients in rock pores.

Permeability is a critical parameter directly affecting the production of reservoirs. Most of the permeability evaluation is based on the commonly used models like SDR and Coates. However, the contribution of isolated pores and connected pores to the long relaxation time spectrum cannot be distinguished in the SDR or Coates models, especially for reservoirs with complex pore structures, causing over-estimate of permeability. To solve this problem, an improved permeability model combining Darcy law and Poiseuille equation was built, which was suitable for the macromolecular flow in mesopores[58]. For complex reservoirs such as tight sandstones, the NMR data has low SNR leading to the uncertainty of permeability calculation [59]. A method with integral transforms (ITs) of the NMR echo data [60] was suggested to evaluate bound water saturation and permeability and to avoid the uncertainty brought by inverse-Laplace transform at low SNR condition with improved accuracy. In addition, unconventional reservoirs may have complex pore structure with strong heterogeneity so that it is very difficult to observe the permeability behavior of reservoir rocks. A new relaxation technique [61,62] is applied to rock cores combined with MRI schemes to allow interior structures of rock cores to be recorded along a chosen axis. This method will spatially resolve the permeability profiling and estimate the local porosity and connectivity factor, which is significantly important in petroleum exploration.

The wettability of reservoir rocks is highly important for oil recovery. For the study of wettability, a multi-dimensional NMR method (including T_1/T_2 and T_2-D correlation method) was proposed and the concept of apparent contact angles was introduced as an indicator to characterize the heterogeneous wettability of porous media [63,64]. Correspondingly, an experimental study, integrating Amott tests, X-ray diffraction and SEM, NMR (PFG-CPMG pulse sequence), and a new workflow, was suggested to quantitatively estimate the wettability of tight rocks [65,66], which is more capable of evaluating complex reservoirs.

In another important application, viscosity and composition analysis are of great importance, especially for crude oil. Conventional NMR methods for downhole viscosity prediction need to bring downhole samples back to the laboratory for measurements and the results often need to be corrected by empirical formulas. The changes of environment might lead to variation of the physical properties. Thus, a fast method using a new pulse sequence (DEFIR, Driven-Equilibrium-Fast-Inversion Recovery) [67,68] was proposed and suggested to precisely estimate the viscosity of crude oil over 2 times as fast as that of the traditional methods. In addition, this method may be suitable for online monitoring of oil pipeline for transportation. For molecular dynamics and composition analysis of crude oil, a T_1-T_2 correlation method [69] was suggested and shown to be very helpful to predict the rotational correlation time distribution of crude oil molecules. Furthermore, it would reflect the effects of SARA (saturates, aromatics, resin, asphaltenes) components of crude oils.

Recently, the study of unconventional shale oil/gas reservoir has become a hotspot worldwide. Unlike conventional reservoirs, the large amount of organic matter (kerogen) presents the potential of hydrocarbon generation and storage capacity of shale. However, the common relaxation and T_1-T_2 correlation methods are insensitive and difficult to characterize shale. A T_1-T_2 correlation method based on a novel pulse sequence (PIR-CPMG, Partial inversion Recovery CPMG) [70] was proposed and suggested to improve the contrast over saturation recovery CPMG (SR-CPMG) and reduce T_1 encoding time of inversion recovery CPMG for petrophysical characterization of shale. Moreover, a method combined with spin echo, solid echo, and magic echo [71,72] was developed and suggested to quantitatively determine the organic porosity and total organic carbon of shale, which is a tough problem in shale evaluation.

Generally speaking, all these suggested methods and techniques have provided a new perspective and experimental approaches for the identification and interpretation of oil and gas in tight and complex reservoirs and unconventional shale oil and gas reservoirs.

5. Summary

With the strong support by the Chinese national major projects to address key problems and demands in oil industry for nearly 20 years, including oil and gas major special projects of China National Development and Reform Commission, the national major scientific instrument projects of the National Natural Science Foundation of China, exploration of borehole NMR principles, innovation of methods, development of borehole tools, industrial promotion, the establishment of standards to commercial manufacturing and large-scale application in oil and gas fields at home and abroad have been achieved. The borehole three-dimensional NMR imaging theory, instruments and equipment and series of interpretation and application methods are established and developed, to address the in-situ analysis of heterogeneous reservoir and in-situ modification of unconventional reservoir. The key progresses are summarized as followed:

(1) *The development of borehole NMR instruments including probes and spectrometers.* For the technical bottleneck of establishing dynamic magnetic resonance conditions in the complex and harsh environment of boreholes, unique configurations of magnet and coil should be designed and implemented to make the B_0 and B_1 magnetic fields orthogonal in the pre-set area. Based on this design theory, the new pad-type NMR instrument, centralized NMR instrument and novel NMR scanning probe were developed. The high-power (kW) soft pulse transmission, and weak (uV) signal reception set up a foundation of NMR spectrometer with high performance. In addition, the multi-channel control module in the front-end of spectrometer was built and tested, which can provide the flexibility for coil array of scanning NMR probe to selectively transmit power and capture three-dimensional "Inside-out" NMR data. Instruments and equipment with a 200 °C temperature specification were completed and tested.

(2) *The study of methods for rapid collection and inversion of borehole NMR data*. Based on the designed borehole NMR and MRI instruments, new pulse sequences, fast data acquisition and inversion methods were developed, including SNR enhancement method, fast data acquisition method, improved depth-based inversion method and fast and robust multi-dimensional Laplace transform method, which were important and necessary for performing logging data interpretation and applications.
(3) *The study of methods for high resolution NMR to capture physical and chemical characterization parameters of oil and gas reservoirs*. Based on the theory of NMR in porous media, methods for analyzing molecular structure, motion and state of fluids, determining porosity, pore-size distribution, bound water, permeability, viscosity, oil and gas saturation, and wettability index have been developed. In addition, the methods for relaxation-based and diffusion-based characterization and quantification of shale organic matter, evaluation of molecular chain length and component of crude oil were developed. Owing to the developed methods, experimental analysis and testing standards and field operation specifications have been established and practiced. Based on these methods, a series of software for the processing, evaluation, interpretation, application and visualization of characteristic parameters has developed and applied in oil fields.
(4) Developed tool sets and methods have been deployed to production and applied in more than 100 oil and gas fields and more than 400 blocks in China and many other countries onshore and offshore, and significantly increased the discovery of reservoir storages and recovery rates. The coincidence rate of fluids identification and the success rate of exploration wells in the investigated blocks are increased by up to 12.8% and 9%, respectively, and the interpretation compliance of tough layers are increased by 2.0 to 2.8 times. They also help to find reservoirs, improve production capacity, and reduce operational cost.

6. Discussions and perspective

As a critical technique for oil and gas exploration, the theory of borehole NMR is in continuous evolution, the instrument is continually improved, and the application is continually expanded. Compared to high-field NMR spectroscopy and medical MRI, borehole NMR exhibits unique scientific, technical, engineering and processing challenges, which will remain significant now and in the future. A few of the challenges are highlighted below.

1). Borehole NMR instruments need to be further improved. The key components of borehole NMR instrument like probe and NMR spectrometer need to have the performance with deeper depth of investigation, shorter echo space, greater signal intensity, and higher SNR. These core issues will be solved once hardware have been optimized or upgraded. With the material improvement and optimization of magnet and antenna, it is possible to achieve deeper depth of investigation and improve the strength for both static magnetic field and RF magnetic field. With the improvement and optimization of electronic components, downhole electronics will be able to achieve miniaturization and integration for shorter echo space and higher sensitivity to weak signal detection with lower internal noise.

2). Data acquisition and inversion need to be faster, more robust and intelligent. With the increased need for exploring complex unconventional oil and gas reservoirs, more data shall be collected quickly and addressed precisely. Downhole NMR data acquisition and inversion need to have the abilities with faster acquisition rate, higher resolution, intelligent quality control, and data-driven inversion to reduce the time and economic cost. With the applications of data driven machine learning technology, it may be possible to redesign the pulse sequences, data acquisition and processing methods for borehole NMR. With compressed sensing and deep learning, potentially new pulse sequences for fast data acquisition, more effective de-noise, intelligent quality control and inversion are possible.

3). The NMR petrophysical model and formation evaluation applications need to be further improved or expanded. The purpose of borehole NMR is to assist the discovery of oil and gas reservoirs and to guide exploration and engineering in an efficient and cost-effective manner. The oil and gas exploration have been shifting to unconventional and deep-water and deep formations. The traditional model-driven methods, single-factor analysis normally employed to establish a deterministic causality to achieve the quantitative evaluation with NMR information in geological exploration and development. And it works well so far. The data-driven methods, which is developing very quickly, may skip the intermediate link of single-factor causality to directly realize the relevant application from the collected echo data and quality control data. But data sets for both training and testing are critical and not available at present. Hybrid methods, driven by data and physical models, are likely to be useful to extend the borehole geophysics measurements with other field data to achieve the optimized decisions for exploration and production.

4). The new technique of inside-out three-dimensional borehole NMR imaging need to be further developed and applied. The key technique of downhole inside-out 3D NMR imaging, with the circumferential phased array and parallel transmission and reception, is capable to collect 3D NMR data body from radial multiple slices, azimuthal multiple regions and multiple depth points to achieve the expansion of 1D to 3D spatial information. It is very important to obtain richer information around borehole and make borehole visualized, especially for reservoirs with strong heterogeneity, which cannot be easily investigated using conventional NMR logging tools. But issues like, the performance to price ratio, still need to be explored.

In addition, the progress in instruments and methodology mentioned above may be adopted to other industrial NMR applications, which will significantly promote and improve the NMR science and technology.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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