Norway Oil & Gas, tt_nrg and Saudi Arabia Oil & Gas

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2008 – Issue 10

Brazil oil & gas

Inside

The Project Cognitus II

Petrobras Tupi

Petrotrin - Ex-President Operations Interview

Courtesy of Petrobras


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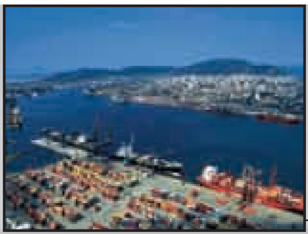

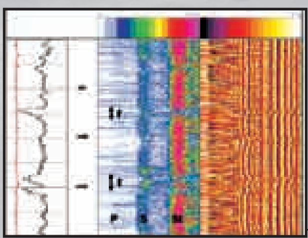

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RECRUITMENT

ROV Engineer in Brazil

The Engineer will have technical responsibilities in the execution of projects undertaken. He/she will contribute to a multi-discipline project team. These projects vary from engineering, procurement, manufacture and test projects, to engineering projects in support of ROV and/or construction engineering activities.

DUTIES & RESPONSIBILITIES
- Understanding of, and ability to co-ordinate other engineering disciplines
- Health, Safety, Environmental and Quality awareness
- Understanding of the practical aspects of design with regards to manufacture and operation
- Able to mentor and provide technical support to graduates and project engineers
- Technically responsible for mechanical engineering aspects of projects
- Budgetary planning
- Technical contact with Oil company
- Design of mechanical systems
- Preparation of design specifications
- Preparation, checking or approval of manuals and procedures
- Preparation, checking or approval of design calculations
- Manufacture, testing and commissioning support
- ROV and construction project support

DESIRED SKILLS OR EXPERIENCE:
Technical Experience:
Experience in a subsea engineering environment
Self Managerial Experience:
Ability to work to deadlines and budgets

REQUIRED QUALIFICATIONS:
- BSc in mechanical engineering or experience in subsea engineering
- Continuing Professional Development
- Ability to articulate learning experiences

Please e-mail applications to
recruitment@braziloilandgas.com

Drilling Engineer in Saudi Arabia

DUTIES & RESPONSIBILITIES
Conducts technical reviews of well plans and well profiles helping with technical specifications and costings. Investigates and troubleshoots daily drilling related problems,finds appropriate solutions and establishes new procedures to prevent reoccurrence of problems. Evaluates new drilling practices, equipment and technologies and makes sound conclusions and recommendations to reduce cost and enhance drilling efficiency. Conducts technical and economic studies as directed by management. Reviews service contracts related to drilling & workover, as required, or to incumbent's area of expertise. Conducts revisions of drilling engineering well menus pertaining to area of expertise.

MINIMUM REQUIREMENTS
Education:
BS Petroleum Engineering or equivalent technical field. MS or PhD is desirable, but not required; intensive industry training including appropriate specialized courses and seminars is expected.

Experience:
15 years experience in the drilling industry out of which 10 years are in drilling engineering. Extensive knowledge and experience in the design of horizontal and multilateral oil or gas wells. Knowledge and experience in the application of new drilling technologies and under-balanced drilling are desirable. Must be clearly recognized by both his supervisors and colleagues as thoroughly qualified and highly competent in areas of expertise. Must have demonstrated ability to communicate ideas clearly to work effectively with others, and to utilize this technical knowledge to achieve practical results. Supervisors and Oil company must have confidence in judgment and recommendations.

Please e-mail applications to
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Petrobr

The volume of oil and natural gas in the Tupi accumulation may place Brazil in the select group of petroleum exporting countries.

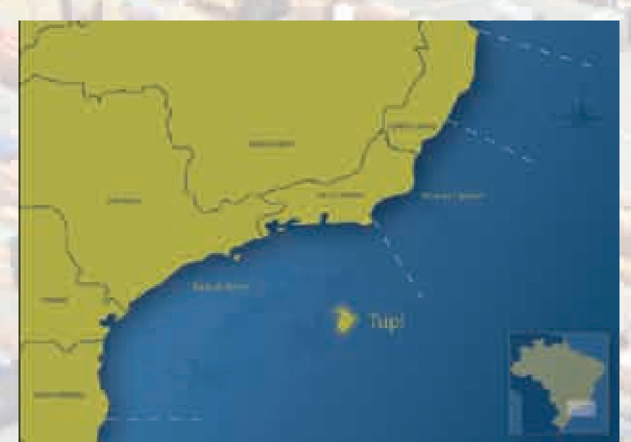
The recent discovery of a gigantic accumulation of oil and gas off the southeast coastline of Brazil, named Tupi, marks the beginning of a new era in the history of oil in Brazil. After all, what apparently seems to be part of a new oil province, is, up to now, the largest deposit in the country and may elevate Brazil in the ranking of the biggest petroleum producers in the world (in which Brazil currently occupies the 24th place) to join the select group of countries exporting "black gold." In addition, the oil province is located in a new exploratory frontier, in pre-salt rock formations, at depths of 3,000 to 4,000 meters below the seabed.

The Giant Tupi

Located in the Santos Basin, the Tupi accumulation has recoverable reserves estimated at five to eight billion barrels of oil and natural gas, a total volume, which, if confirmed, will mean an increase of about 50% in proven Brazilian reserves, now calculated to be 14.4 billion barrels.The 28º API light oil has a high commercial value in the international market. Petrobras is the operator, with a 65% stake in the working area, while the English company British Gas holds 25%, and the remaining 10% is held by the Portuguese company Petrogal-Galp Energia.

Cutting-edge Technology

Two wells were drilled in Tupi, going through the pre-salt layer, and were the object of tests using the best specific technology currently available. Other unprecedented technologies will also be used. "Tupi provides an excellent opportunity to develop cutting-edge technology and improve what already exists. New concepts for the more economical transportation of natural gas have been studied in Brazil because of the discovery of this accumulation. The outflow of the fuel through a gas pipeline would mean very high costs since the accumulation is located 300km from the coast of São Paulo. Injecting and storing the gas in salt caverns until it is needed is a solution that has been evaluated and adopted successfully abroad. Generating energy at the site and transmitting it onshore through electric cables is another alternative. The possibility of having a thermoelectric plant on a floating platform at the site or the use of gas liquefaction ships is also being studied, so that the fuel could be sent



The location of the Tupi accumulation.

as Tupi

Keystone Group

to the terminals in Guanabara Bay, in Rio de Janeiro, and to Pecém, in Ceará, where the product would be returned to gaseous form and injected into the grid that supplies the Brazilian natural gas market," explains Guilherme Estrella, the director of Petrobras' Exploration and Production area.

Tupi Production

According to Petrobras' proposal, currently under discussion with its partners, the production in Tupi should start on an experimental basis by the end of 2008, when the so-called Long Duration Test (LDT), which will last approximately six months, will begin. According to Estrella, a medium-sized ship, moored on site, will produce approximately 30,000 to 40,000 barrels of oil and gas per day and will provide Petrobras with data on the potential of the accumulation. In a second phase, which will last two years starting between the end of 2009 and the beginning of 2010, the plan is to produce, in a pilot project, 100,000 barrels of oil and natural gas per day, which is equivalent to 5% of the current Brazilian production. During this period, a gas pipeline will be installed connecting Tupi to the Mexilhão platform, which will be installed in shallow waters in the Santos Basin. Between 2011 and 2012, after Tupi's commercial viability has been established, the definitive system of production will be determined and the project will include nearby blocks. Only then will the volume of the daily production be estimated.

Golar LNG Archive

A gas liquefaction ship.

Drilling wells and producing in the pre-salt layer implies risk investments and billions of dollars. However, the economically feasible production makes it an attractive undertaking for investors. "Due to cost constraints and the risks, we took more than a year to drill the first well in the pre-salt layer. Now, we have a better understanding of the technology and take only a few months to drill new wells. We are working, however, to further perfect this technology in Brazil. In association with the Universidade Estadual Paulista, in Rio Claro, we will create quality centers in Brazil for the study of microbiolites, which are rock formations found under the salt layers. An agreement for this purpose was signed in early January," Estrella points out.

Tupi should contain more than 70 billion recoverable barrels of oil equivalent.

Mexilhão Platform

Promising new areas in the pre-salt layer

The new exploration frontier where the Tupi deposits are located, a petroleum province running from the Espirito Santo basin to the Campos and Santos basins in the pre-salt layer and covering an area 800 km long by 200 km wide, is an area of great promise. It should contain more than 70 billion recoverable barrels of oil equivalent.

Adding the petroleum and gas volumes of the pre-salt layer to the existing reserves should elevate Brazil to the eighth or ninth position in the ranking of the major oil-producing nations. "To indicate what this means, it is enough to say that the North Sea reserves total about five billion barrels of oil equivalent," exults Estrella.

Also in the new petroleum province, in the deep waters of the Santos Basin, the presence of light oil has been confirmed in the block known as "Caramba" or "Baco," in block BM S-21, operated by Petrobras with an 80% participation, in partnership with the Portuguese company Galp, which holds the remaining 20%. "This confirmation was achieved by the drilling of well 1-BRSA-

P-34

"To indicate what this (Tupi) means, it is enough to say that the North Sea reserves total about five billion barrels of oil equivalent," exults Estrella.

526-SPS, located 280 km off the coast of the state of São Paulo at a water depth of 2,234m. The depth of the well is 5,350m. below the seabed. The extent of the strike and the characteristics of the reserve remain to be determined, which should happen in the first quarter of this year," says Estrella.

In the same accumulation, a well called Bem-Te-Vi, in block BM-S-8, and, close by, a well provisionally known as Jupiter, in block BM-S-24, promise to be just as prodigious as Tupi. A drill is already in operation in each block.

Finally, tests in another pre-salt layer location, the ES-103 well in Espirito Santo, are scheduled for the first semester of 2008. The well will be connected to platform P-34, already in operation in the Jubarte field.

Taking into account the relevance of the new discoveries, the development potential, and the wealth it will be possible to generate, it is no exaggeration to say that Petrobras will help write another chapter of success in the history of Brazil. After all, if previously the company guaranteed self sufficiency in oil for the country, it will now make the nation less dependent on imported light oil and natural gas and will provide greater bargaining power in future negotiations involving fossil fuels.

The Project Cognitus II

Petrobras and its partners develop cognitive tools for environmental management in Amazonia.

Aware that operating in Amazonia, in the Urucu petroleum province, in the Isac Sabbá Refinery, and in the Solimões Terminal requires all possible care to guarantee successful operations and to preserve the environment, Petrobras, together with its partners, is implementing the Cognitus II Project. The objectives are to develop cognitive tools, with the help of cutting-edge technology, for managing the environment in the region, for perfecting environmental sensitivity charts, and for defining the ecosystems to be protected in the event of an oil spill.

"Derived from a project by the artist Wagner Garcia and fine-tuned in partnership with Petrobras, the Cognitus Project – The Application of Cognitive Tools for Environmental Management in Amazonia, now in phase II, proposes new theories and intellectual tools to measure and interpret the quality and complexity of the natural phenomena found in the Amazon region. After all, traditional scientific methodology did not provide the degree of resolution necessary for the understanding of, for example, the seasonal variations in the complex Amazonian ecosystems and the hydrological scenarios of drought, rising waters, flooding, and receding waters.

Historical environmental data regarding the region were also scarce. Therefore, the decision was made to invest in cutting-edge research such as robotics and nanotechnology to satisfy the existing needs and to analyze Amazonia on scales varying from the microscopic to information obtained from satellites," explains the Petrobras geologist and general coordinator of Cognitus II, Fernando Pellon de Miranda.

The Cognitus II Project is being carried out in partnership with the Centro de Pesquisas Renato Archer (Renato Archer Research Center) in the state of São Paulo, The Instituto Nacional de Pesquisas da Amazonia (Amazonia National Research Center) in the state of Amazonas, and the Laboratório de Métodos Computacionais em Engenharia (Computer Method Engineering Laboratory) of the Universidade Federal do Rio de Janeiro (Federal University of Rio de Janeiro) in Rio de Janeiro. In ad-

dition, there is an interface with the PIATAM Project (Potential Environmental Impacts and Risks of the Oil and Gas Industry in Amazonas), co-managed and mainly financed by Petrobras. There are three lines of research in the project: AmazonBOTS, Nanobiotechnology, and Hypersigns.

The research line known as AmazonBOTS deals with the development of robotic systems for the active monitoring of Amazonian lakes, which are often inaccessible to man. Besides, it facilitates the compilation of series of historic data gathered in real time, including details on the dispersion of oil in lowland flat areas with flooded vegetation and the direction and the intensity of the flow of water. The research line also includes robots projected to monitor the microbiotics of the region.

“We are looking at a series of fixed, autonomous Kwata robots for environmental monitoring, such as the Kwata Eros, which will monitor the vulnerability to erosion in the region of the Coari-Manaus gas pipeline and the Urucu oil province, deep in the Amazon forest; the mobile, autonomous robot Porake, equipped with an electrical localization system similar to that of electric fish, excellent for use in cloudy waters where optical systems are ineffective and which will monitor the waters of the Solimões and Negro rivers; the Biobots robot, still in development, whose design is inspired by the biological evolution of animal species in general, and which can change shape in order to surmount obstacles; and the Hybrid Environmental Robot, a mobile robotic vehicle for field work,” explains Pellon.

“The Hybrid Environmental Robot, named after Chico Mendes, in honor of the Brazilian environmentalist who lived and worked in Amazonia defending the sustainable use of its natural resources, can operate with a crew or by remote control, in the water, on land, in the marshes, in flooded regions, and over the Amazon aquatic vegetation. Powered by electric batteries and alternative energy sources, it is equipped with two electronic arms for collecting material in the water and in the forest and is able to carry two TV cameras which record images and transmit them to a base. In emergencies, it can transmit data in real time directly from the forest, 24 hours a day. It also has the advantage of being neither polluting nor invasive, as it does not destroy the vegetation and it is silent. The equipment is unprecedented in the world. The most similar robots are the ones used in space, which travel over much less complex surfaces,” says Pellon.

The research line known as Nanobiotechnology deals with the construction of microscopic sensors and chips designed to collect series of historic data in the Amazon region. These data will serve as support in the analysis of fresh water and the creatures living therein discovered by the robots of the AmazonBOTS research line. They will also characterize indicators and detect chemical compositions foreign to the organisms of these creatures or found to be at levels higher than normal, conditions which might be connected to pollution caused by oil spills. "This line of research includes some sub-projects. One of them, for example, the Metagenoma, researches the development of methodologies for carrying out taxonomic, genetic, and functional analyses of microbionic flora. Another sub-project, called Clothing Earth with Mind, deals with the observation of the interaction on a nanoscale, that is of one millionth of a millimeter, between proteins of any organic composition in microbionic processes. The objective is to validate sensors on a micro scale, of one thousandth of a millimeter, for this observation, which may indicate, for example, the action of specific biogeochemical processes of the floodplain of the Solimões river. Still another sub-project, known as Liquid Computation, covers the development of an unconventional computational model, inspired by molecular biological processes, for the optimized analysis of data provided by the Metagenoma and Clothing Earth with Mind sub-projects," explains Pellon.

As for the Hypersign line of research, it includes the development of semi-optic instruments and technologies that will make possible the application of the series of environmental data used in the seasonal variations of water levels in the hydrographic sub-basins located in the Urucu- Manaus stretch in Amazonia.

The work of Cognitus II has produced results.The versatility of the Hybrid Environmental Robot, for example,

The engineer Ney Robinson heads the team that is developing the Hybrid Environmental Robot, created to record and transmit images of the Amazon Forest in real time

drew the attention of the riverside dwellers, who proposed that it could also be used as an ambulance and as a means for transporting food and the local population. After all, in the ebb season, large extents of land remain soaked in the Amazon region and mud hampers the passage of personnel and vessels for many days. Ney Robinson, the engineer in charge of the robot project, is already engaged in making possible the social use of the vehicle, as well as its mass production.

In addition, today more facilities are available to obtain information on Amazonia than were available in any past period. Thanks to the Cognitus II Project, cutting-edge technology is definitively at the service of the region, its specific characteristics, Petrobras' sustainable activities, and, consequently, the progress of science.

Kwata Robot

A Hybrid Environmental Robot

Focus on NOC • Focus on NOC • Focus on NOC • Focus

Petroleum Company of Trinidad

Ex-President Ope

Before his retirement in January, Wayne Bertrand, President Operations, took time out from his busy schedule to speak to Brazil Oil & Gas about Petrotrin's activities and plans. Mr Bertrand speaks about the Company Plan for the next 5 years, Petrotrin Operations, Training & Recruitment and J2E, the company's Journey to Excellence Programme.

Petrotrin President Operations – Wayne Bertrand

OPERATIONS

***Q: Brazil Oil & Gas** - Can you detail the Company Plan for 2008-2012?*

***A: Wayne Bertrand** -* A significant increase in total capital expenditure is expected as we intensify our search for more indigenous crude oil and natural gas. Some of our Major exploration and development projects include:

- Enhanced marine exploration, increased joint venture partnerships
- Enhanced oil recovery
- Increased development drilling and several infrastructure upgrades both on land and offshore.

To sustain E&P Growth there will be major investment through joint ventures with international companies including a major partnership with British Gas, Petro-Canada, and Canadian Superior, as well as a consortium that comprises BHP Billiton, Total, and Talisman, on the East Coast.

There is also new Corporate building underway, with estimated completion scheduled for 2009.

Under Refining & Marketing, a major 4-part upgrade of the refinery, which began in 2006, is expected to be complete in 2009. The refinery upgrade - Gas Optimization Unit - involves the construction of five new plants at the Pointe-a-Pierre Refinery at an estimated cost of US$800 million. This key project will enable the refinery to produce greater quantities of cleaner and environmentally friendly fuels, increasing specification that can satisfy the stringent demands of the international market place.

The Refinery upgrade consists of 4 parts:

1 - The 2006-2009 Gasoline Optimisation Programme, which will improve the quantity of finished gasoline

and Tobago Limited

rations Interview

Overhead view of the Point-a-Pierre refinery

products by 25%, and meet full international gasoline specification.

2 - To achieve the same high quality and specification with diesel, to be completed by 2010.

3 - Joint venture of gas to liquid plant is also currently in progress with estimated completion in mid 2008.

4 - New Road Tank Wagon Terminal, Refinery office, Lab and Workshops.

Q: Brazil Oil & Gas- *What major challenges are foreseen for the period 2008-2012?*

A: Wayne Bertrand - The main challenges are Inflation (rising cost of production in cost of services and supplies, increased cost for utilities, and further labour costs rises), lower production, increasing competition for skilled labour and loss of key personnel due to natural attrition, more stringent market specification changes, as well as retaining old markets and entering new markets.

Q: Brazil Oil & Gas- *What plans have been developed to overcome these challenges?*

A: Wayne Bertrand - To deal with Inflation we have embarked upon several initiatives examining the cost management problems and have identified inefficiencies in

The Fluidised Catalytic Cracking Unit is also to be upgraded as part of Petrotrin's Gasoline Optimisation Programme. The upgrade of this unit, which incorporates an increased capacity of 35,000 BPD will enable Petrotrin to produce more gasoline with improved octane ratings for its gasoline pool and reduce the production of less valuable heavier distillates.

The Fluidised Catalytic Cracking Unit

the system or processes, which can be improved upon. As for the increased competition for skilled labour we have taken the following initiatives:

- Enhanced our already competitive compensation package,
- Identified and implemented intensive training programmes aimed at getting the right people for the job,
- Introduction of an Executive Leadership Programme (ELDP) that specifically deals with succession planning for the managerial skills we are about to lose over the next five years due to natural attrition.

For retaining old markets and entering new markets, the GOP upgrade would address some of the specific issues of clean fuels and fuel specification changes.

***Q: Brazil Oil & Gas** - What is the average Lifting Cost for Oil and LNG today?*

A: Wayne Bertrand - The average direct lifting cost for Oil is US$9.44/boe. LNG cost is approximately US$2.50/mcf, which includes processing fees, tug and port charges, pipeline tariffs, shipping, fuel cost, etc. If HH is US$7.00 Netback at wellhead is about US$4.50.

***Q: Brazil Oil & Gas**- Could you provide figures for current Production and Reserves?*

A: Wayne Bertrand - Sure, the figures are:

Production - 2005/2006 Fiscal Year – 85.6 BOEPD Total, which is made up of 60K barrels of oil per day and 140 Million cu ft per day of gas.

Reserves - End of 2006 Fiscal Year – 538 oil and gas MMBBLS Total, which is made up of 424 Million barrels of oil and 660 Billion cu ft of gas.

***Q: Brazil Oil & Gas** - Is any growth in production foreseen?*

A: Wayne Bertrand - Yes we do expect increased production and reserves as a result of increased investments. We always expect at least a marginal increase in production and should have a little more than 100% reserves replacement.

... we do expect increased production and reserves as a result of increased investments. We always expect at least a marginal increase in production and should have a little more than 100% reserves replacement.

UMLE Steamflood

Crude oil - New Joint Ventures, Lease operatorships and Farmouts, EOR projects and increased drilling plans should result in marginal reserve increases.

Natural Gas - By participation in new gas prone blocks (Block 22, 1a/b and NCMA 2) we expect to sell more gas from these areas. We intend to have a production portfolio aimed at increasing gas production for the lucrative gas trade.

***Q: Brazil Oil & Gas** - Have there been any significant new finds recently?*

***A: Wayne Bertrand** -* The joint venture with BHP Billiton resulted in a new find on the East Coast, and we continue to have small ones all the time, contributing to overall figures.

***Q: Brazil Oil & Gas**- Can you speak about Petrotrin's E&P and R&D activities and any new technologies being implemented?*

***A: Wayne Bertrand** -* E&P has several opportunities in the form of JVs, in new current and proposed blocks and in incremental production contracts. The South West Soldado and Galeota Areas are two of our more interesting and promising potential areas.

We also continue to use new technologies and techniques such as 3D Seismic and Horizontal Drilling, and new logging techniques and technologies supplied by the major service companies, as well as participating in R&D activities with universities. New technologies are used to enhance production as the company has mature fields and must undertake frequent EOR projects.

The Upper Morne L'Enfer (UMLE) Steam Flood project continues to bring in successes for Petrotrin's Exploration and Production Division. Beginning with a pilot project in 2004, it was initially conducted on a 23-acre area in Middle Field. The success of this initiative pushed the enhanced oil recovery team to begin the commercial phase of the project and expand over a much wider acreage. The project involved the conversion of recently drilled wells to injectors, the relocation and retrofit of a 30 year old steam generator from an adjacent oilfield, the construction of a gathering station and the installation of gas, water, steam, and crude oil pipe lines with associated tie-ins.

UMLE Production has been increasing consistently from month to month. During the last fiscal period the UMLE Expansion Project averaged 365 bopd in production beginning from May 2007 and this reached a peak of 675bopd in September. The Pilot Project averaged 300 bopd for the fiscal period.

***Q: Brazil Oil & Gas** - How has Petrotrin contributed to the development of local content and capability?*

***A: Wayne Bertrand** -*

• Contracts - Petrotrin employs local service contractors for a significant amount of projects. The number of registered local contractors used is 1153 and there are 1600 registered local suppliers. Even when international EPC companies are contracted most of the construction is by local sub contractors. In the area of major maintenance, Petrotrin works with local contractors to build capacity and capability

Petrotrin Training & Recruitment Exhibition at Macoya

• Competency Development - Investments in academia directly related to the energy industry – University of the West Indies (UWI) and University of Trinidad and Tobago (UTT). Additionally, there are several opportunities for internships for young persons.

Q: Brazil Oil & Gas- *Can you tell us about the J2E Programme?*

A: Wayne Bertrand - Following a below average rating, by the international benchmarking company Solomon & Associates, in the late 1990s, our 'Refining and Marketing Management Team' sought the assistance of energy consultants Shell Global Solutions Inc (SGSI). SGSI's responsibility was to assess Petrotrin's R & M business and identify new ways of working that would enhance our economic and operational performance, thereby laying a strong sustainable foundation in the face of intensifying global competition. An integrated business improvement programme 'The Journey towards Excellence' (J2E), was jointly developed to optimise Petrotrin's economic returns. SGSI was then contracted to "walk hand in hand" with us along the journey.

Since November 2003, the company supported by Shell Global Solutions, has been implementing this ambitious five-year business-improvement programme at its Pointe-a-Pierre refinery. The refinery's economic performance has demonstrably improved and by the end of Q2 2007 the J2E initiatives have contributed in excess of US$110 million to Petrotrin's bottom line. The latest ratings indicate increases in practically all benchmarked indices and that our Plant Utilization, Maintenance Index and Turnaround Performance have moved up one full quartile in the Solomon rankings since the implementation of the initiatives mentioned above.

At the end of 2006, Petrotrin and Shell Global Solutions also entered into a Technical Services Agreement (TSA), which runs concurrently with the J2E, so that new opportunities for improvement can be identified and appropriately implemented. The major provisions to Petrotrin as stated in the agreement are:

• Technical support for existing operations

• Basic best practices sharing

• Access to technical training / conferences

• Benchmark / performance analysis

In order to ensure continued improvement and increased profitability it was necessary to strengthen inter-departmental relationships. The undertaking of further enhancement and integration of refinery processes; improved internal communication and controlled documentation achieved this. This program covered 4 themes: *'Health, Safety and Environmental', 'Asset Integrity and Reliability', 'Margin Improvement and Operations', and 'Operational Excellence and Organizational Change Management'*. Additionally the program focused on further developing Petrotrin's capabilities and skills to sustain these performance improvements. Petrotrin's refinery operators, maintenance technicians, process engineers, managers, union officials, and others have been involved in and continue to contribute to the journey. Petrotrin is reaping considerable benefits from the programme. It has delivered improvements in safety performance; the company celebrated one million safe work-hours in 2006, and has improved plant availability and utilization. Indeed plant Turnarounds are now better managed and newer, more efficient work processes such as Structured Operator Rounds, that monitor the health of critical equipment, are also up and running in all units. This feeds into a more dynamic and efficient routine maintenance planning process.

Although, significantly impacted by World prices, the enhanced refining margins currently being realised, can be directly linked to operational improvements in the processing units. Measurement and reviews of business performance drives actions to sustain the performance improvements. In support of the new organizational path, all Stakeholders roles have been clearly defined. Many intangibles achieved through our change culture programs, such as effectively working across organizational boundaries and increased focus on results is equally important. This has been made possible through the imbedding of principles taught in the 'Coaching for Performance' and 'Managing Own Performance' programs.

The plan has been to train us in best practices and work with us to change our method in order to achieve best practices, and in this final year of the programme we have completed some audits to see where we are in implementing best practices. We have the new practices in place, are implementing them all and are in the process of making them sustainable.

Workforce / Training & Recruitment

The oil & gas industry has recognised there is a need to both attract new talent and make the industry more attractive to newcomers.

Q: Brazil Oil & Gas- *How does Petrotrin recruit new talent?*

A: Wayne Bertrand - We have very significant recruitment and training programmes, and as a state company we often over recruit. As well as job training, we offer some Internships, a summer programme for Graduates and a 2-year programme for Under Graduates. Petrotrin's recruitment strategy involves growing talent (long-term) and buying talent (short-term). This strategy includes:

• Corporate programmes that actively seek to showcase the energy sector as a viable career path to students.

• Scholarships and internship programmes.

• Actively - seeking required talent locally and overseas

• Passively - where persons send in their application without a direct advertisement for a vacancy.

Q: Brazil Oil & Gas - *What does Petrotrin have to offer?*

A: Wayne Bertrand - There are many great benefits to working in a company such as Petrotrin. We provide the opportunity to work in a fully integrated company (the only one in the country) with an exploration & production, and refining & marketing environment. We also offer highly competitive compensation.

Petrotrin is in a position to offer its employees an exciting and rewarding career.

Employees in partnership with the organisation are able to chart their career; either geared toward supervisory/managerial positions or through the technical/expertise paths.

Q: Brazil Oil & Gas - *Which department/s is Petrotrin actively recruiting for?*

Focus on NOC • Focus on NOC • Focus on NOC • Focus

Employees in partnership with the organisation are able to chart their career; either geared toward supervisory/managerial positions or through the technical/expertise paths.

A: Wayne Bertrand **-** Petrotrin's recruitment thrust is focused on professionals and semi-professionals/technicians in key disciplines to support its core business of Exploration and Production (E&P) and Refining.

Exploration & Production

• Exploration & Development - Geologists, Geophysicists, Reservoir Engineers, Geological Assistants and Engineering Technicians.

• Production - all the major areas of engineering including Project, Petroleum, Mechanical, Electrical, Drilling, Civil, etc.

Refining

• All the major areas of engineering including Project, Process, Mechanical, Electrical, Civil, etc. as well as Senior Process Plant Operators and Process Plant Operators.

Q: Brazil Oil & Gas **-** *How many new employees have been recruited over the last 5 years and in which divisions?*

A: Wayne Bertrand **-** Over the last five (5) years, recruitment focus has been on mission critical jobs. A mission critical job is defined as a pivotal position that impacts other positions that have a direct impact on the achievement of organizational strategies and goals. These jobs are either difficult to fill because of the need for specific expertise and knowledge or because the skills take a long time to develop.

These positions include:

• Management positions (vice presidents, general managers, managers, etc.),

• Professional technical positions (engineers, geosciences, etc.)

• Semi-professional positions (refinery operators, technicians, etc.).

For the period 2004 - 2007, **357** critical job vacancies were filled, 79 of which were on contract.

Q: Brazil Oil & Gas **-** *Are any new Training & Recruitment initiatives being implemented?*

A: Wayne Bertrand **-** We have completed a job organisation review and are in the final stages of a job evaluation review. Each job now has proper performance criteria in place. The performance criteria and competency criteria for each job is as quantitative as possible, thus allowing proper performance evaluation on an annual basis.

Petrotrin's two-pronged approach to strategic recruitment (grow or buy talent) is supported by our myriad of people development strategies.

• Executive Leadership Development Programme (ELDP),
• Management Development Programme (MDP)
• Supervisory Development Programme (SDP)
• Technical Development courses and assignments

These programmes target specific employees, that either function in an executive, managerial or supervisory level throughout the organisation or high-performing employees showing the relevant enthusiasm and potential. The program premise is to create experiential learning and developmental opportunities through a series of rotations across various aspects of the organisation, which take place over a prolonged period.

As well as the Leadership and Development Programmes in place, there are another 2 major programmes – Coaching For Performance for middle management and Managing Own Performance for other employees. Both programs seek to develop interpersonal skills and provide a more in-depth understanding of the Performance Appraisal process. Employees in non-supervisory positions are encouraged to adopt a proactive approach to managing their own productivity and those in management and supervisory capacities are guided on more proficient coaching techniques to maximize their respective employees' performance potential.

Petrotrin Graduate Trainees at induction ceremony at Paria Suites, La Romaine

HORIZONS - Petrotrin has re-engineered, re-energised and re-branded its Undergraduate and Graduate Trainee Programmes. The main objectives of Petrotrin's Graduate Trainee Programme are to strategically build capability within the organisation and to assist in developing the region's human resource base by providing opportunities for learning within the oil and gas industry.

The graduate trainees are strategically placed to meet the needs of the developing organisation. This move to promote capability building within the organisation stemmed from a need to ensure that there is a transfer of knowledge and to fill vacancies, which may arise from natural attrition or migration to other organisations. During the training period, the graduates are also given the opportunity to learn new skills driven by technology.

Major disciplines in which there is a heavy concentration include:

- Geosciences
- Environmental Science
- Information Systems
- Engineering - Mechanical, Electrical, Reservoir, Process and Chemical

General

***Q: Brazil Oil & Gas** - Has Petrotrin won any major Awards recently?*

A: Wayne Bertrand - Yes, Petrotrin is committed to achieving, maintaining and delivering the highest standards at all times, and I am pleased that our efforts have been recognised and our teams rewarded by various prizes and awards. A number of these outstanding achievements include the following:

2003 - GSTT Most Outstanding Corporate Member

2004 - COSTAATT Partnership Award

2004 and 2005 - Society of Petroleum Engineers (SPE) – Local Chapter - Corporate Sponsorship Award

2006 - STCIC Upstream Achiever Award

2006 - Corporate Apprenticeship Award

2007 - Outstanding Contribution to Scouting

Individual Awards (SPETT)

2007 - Outstanding Engineer Award – Dr. Malcolm Jones (Executive Chairman)

2007 - Outstanding Engineer Award – Lorna Mohammed-Singh

2005 - Outstanding Member Award – Wayne Bertrand (President Operations)

2005 - T. Boopsingh Young Engineering Award – Burt Sinanan

2005 - Distinguished Member Award – Deonarine Jaggernauth

Our Executive Chairman, Malcolm Jones, has also received 2 major awards during the 5 years he has been here. The awards received were National Award Chaconia Gold, and Hon Doctorate from the University of T&T.

***Q: Brazil Oil & Gas** - Does the company have any partnerships with other international companies?*

A: Wayne Bertrand - Petrotrin has a number of Joint Ventures both onshore and offshore. The Joint Venture Partnership table lists the many companies, along with the relevant area, the equity involved and the type of partnership in place. In addition to the many E&P Joint Ventures shown, Petrotrin also has a 49% partnership with World GTL Inc. in a Gas to Liquids plant at Point-a-Pierre.

Petrotrin Joint Venture Partnerships

Blocks	Equity Interest	Type	Joint Venture Partners
ONSHORE			
Moruga West	40.0%	Exploration Carry	Neal & Massy Energy Resources Ltd.
Central Block	35.0%	Exploration Carry	British Gas Trinidad Central Block Ltd.
SW Peninsula	27.5%	Exploration Carry	Trinidad Exploration & Development Ltd.
Parrylands 'E'	25.0%	Carried Investment (SAGD)	New Horizon Exploration Trinidad & Tobago
Eastern Block	35.0%	Exploration Carry	Talisman (Trinidad) Ltd.
OFFSHORE			
East Brighton (Sub-Area B)	30.0%	Exploration Carry	Primera East Brighton Limited
Brighton Marine (Sub-Area A)	35.0%	Exploration Carry	Venture Production
Pt. Ligoure	50.0%	Exploration Carry	Venture Production
Trintomar	80.0%	Exploration & Development	National Gas Company of Trinidad & Tobago
SECC	16.0%	Exploration & Development	EOG Resources/NGC
NCMA Unitized Area	19.5%	Development/Expl.	British Gas/ENI/Petro-Canada
TSP	15.0%	Development/Expl.	Repsol YPF S.A./NGC
Block 1a	20.0%	Exploration Carry	Petro-Canada
Block 1b	20.0%	Exploration Carry	Petro-Canada
Block 3a	15.0%	Part Exploration Carry	BHP Billiton/Talisman/Anadarko/Total
Block 22	10.0%	Full Participation	Petro-Canada
GMB	30.0%	Exploration Carry	Canadian Superior

***Q: Brazil Oil & Gas** - How important is Corporate Social Responsibility to Petrotrin?*

A: Wayne Bertrand - Petrotrin views its social and environmental responsibility as paramount to the direct growth and development of Trinidad and Tobago and to Petrotrin's attainment of set strategic goals and long-term existence…

Brazil Oil & G wishes Wayne Bertrand all the best for 2008 and beyond. Having completed 30 years at Petrotrin, including 23 years at senior executive level, Mr Bertrand is currently lecturing at the University of the West Indies (as a Distinguished Fellow) and consulting following his retirement earlier this year.

Drilling Fluids

An Innovative Manganese Tetra-Oxide/KCl Water-Based Drill-in Fluid for HT/HP Wells

By A.S. Al-Yami, H.A. Nasr-El-Din, Saudi Aramco, A. A. Al-Majed and H. Menouar, King Fahd University of Petroleum & Minerals, All SPE members

Reservoir Characterization

Ginest showed reservoir characterization of Pre-Khuff Unayzah reservoir. The pre-Khuff Unayzah gas reservoir is sandstone formation with two sand units Unayzah-A and B with a siltstone in the middle of them. The Unayzah-A reservoir is around 200 ft thick consisting of fine to coarse grains. Also cross bedded dunes sands are presented that prograding toward the east possibly due to winds blowing east to west. The prograding results in strong permeability anisotropy. Quartz overgrowth is observed in Unayzah-A reservoir, which results in reduction in porosity. Some literature states 7-8% average porosities. The average permeability in the Unayzah-A ranges from 1 to 6 md.

The siltstone unit that varies Unayzah–A and Unayzah–B has different range of thickness from 10 to 155 ft. It is composed of fine sandstones and siltstones. It is considered to be a barrier between the two reservoirs.

Below this barrier, Unayzah-B reservoir is present. It has a gas water contact. The depth of the Unayzah-B reservoir depends on the varying of well bore penetration compared to the gas water contact. Unayzah-B reservoir composed mainly from sandstone of fluvial origin. Sandstones are the main components of the reservoir with extensive quartz overgrowth and very frequent horizontal to low angle fractures. Unayzah-B has slightly lower porosity than Unayzah-A. However, it has lower content of clays and thus it is considered to be more productive than Unayzah-A reservoir. Low content of clays in general means more permeability. It is not clear that the fractures in the Unayzah-B improve productivity. Average permeability of Unayzah-B ranges from 10 to 30 md.

The condensate to gas ratio averages 150 bbl/MMSCF. The initial reservoir pressure is 6,300 psi and the gas dew point is 300-400 psi below that. When bottom hole flowing pressures falls below the dew point, condensate banking will result in a short time. Due to the above two reasons, MRC wells were drilled to to reduce draw down. Also the MRC wells will reduce water conning by isolating Unayzah-B from Unayzah-A.

In general, the bottom hole static temperature of this pre-Khuff reservoir ranges from 280 to 305°F. The reservoir depth is greater than 14,000 ft and the initial reservoir pressure is almost 8,500 psi. Wells drilled in the Unayzah reservoir have the potential to deliver large quantities of sweet gas and condensate, but surely can be damaged during drilling.

Results and Discussion

In this article, the characterization of the typical drill in fluids is discussed. The typical water based drill-in fluids discussed are potassium formate/$CaCO_3$ and KCl/$CaCO_3$/barite fluids. Then, the designing steps of the KCl/Mn_3O_4 water-based drill-in fluids are explained. Several KCl/Mn_3O_4 water-based drill-in fluids were designed and their performances were compared to the the typical drill-in fluids mentioned above. The performance characterization of the three drill-in fluids included testing of rheological properties, filtration (API and HT/HP) and thermal stability.

KCl/$CaCO_3$/Barite Drill-In Fluids

Although the use of barite is not recommended to drill reservoirs, it is used to formulate high density drill-in fluids. Table 1 shows a typical drill-in fluid's formulation used to drill Unayzah-B reservoir. The table also shows the function of each additive used and its amount to formulate one bbl.

Additive	Function	Field Unit	Field Amount	Lab Unit	Lab Amount
Water	Base	Bbl	0.8	grams	280.0
Deformer	Anti-foam	Gal	0.01	grams	0.83
XC-Polymer	Viscosifier	Lb	1.0	grams	1.0
Starch	Fluid loss	Lb	6.0	grams	6.0
PAC-R	Fluid loss/ Viscosifier	Lb	0.75	grams	0.75
KCl	density and shale inhibition	Lb	41.0	grams	41.0
KOH	pH control	Lb	0.5	grams	0.5
Lime	pH control	Lb	0.25	grams	0.25
Barite	Weighting Material	Lb	205.0	grams	205.0
$CaCO_3$ (fine)	Weighting Material	Lb	7.0	grams	7.0
$CaCO_3$ (medium)	Weighting Material	Lb	3.0	grams	3.0
Sodium Sulfite	Oxygen Scavenger	Lb	0.75	grams	0.75

Table 1 - Conventional $CaCO_3$/barite drill-in fluid formulation used to drill Unayzah-B reservoir.

$CaCO_3$ medium and fine were used almost in 1:3 ratio. A previous study suggested that a use of 1:3 ratio is recommended to rapidly bridge the reservoir.

The presence of oxygen in drill-in fluids can accelerate corrosion rates. Oxygen scavenger can be to remove the oxygen. Sodium sulfite is an example of oxygen scavenger as shown in equation 1:

$$O_2 + 2\ Na_2SO_3 = 2Na_2SO_4$$

The drill-in fluid properties were measured. These properties include: PV, YP, Filtration (API and HT/HP), filter cake thickness, and drill-in fluid pH. Table 2 gives the properties for the $CaCO_3$/barite drill-in fluid before hot rolling.

To assess thermal stability, the drill-in fluid was aged for 16 hours at 300 °F and the properties were measured again as shown in Table 3. Exposure of drilling fluids to temperature might change the fluid's rheology and filtration. After aging the $CaCO_3$/barite drill-in fluid, its rheological properties (PV, YP and gel strength) were reduced. PV was reduced from 29 to 15 cp and YP from 29 to 12 lb/100 ft^2. Gel strength reading for 10 seconds was reduced from 8 to 4 lb/100 ft^2. Gel strength reading for 10 minutes was reduced from 15 to 4 lb/100 ft^2. However, the drill-in fluid was used to drill reservoirs at 300°F with success. A previous study showed similar range of rheological values at 300°F for drilling fluids used in the field. The filtration increased from 7 to 10 ml/30 minutes as a result of the reduction in the rheological properties. Phase separation was observed after hot rolling the drill-in fluid sample for 16 hours.

Potassium Formate Drill-In Fluids

Potassium formate is also considered as a typical drill-in fluid for Unayzah-B reservoir. Table 4 shows a typical drill-in fluid's formulation used to drill Unayzah-B reservoir. The table also shows the function of each additive used and its amount to formulate 1 bbl.

The properties of potassium formate were measured. These properties include PV, YP, Filtration (API and HT/HP), filter cake thickness for each filtration test and pH. Table 5 shows the properties for the $CaCO_3$/barite drill-in fluid.

Similar to $CaCO_3$/barite drill-in fluid, $CaCO_3$/ potassium formate drill-in fluid showed reduction in PV, YP and gel strength, Table 6. PV was reduced from 28 to 20 cp and YP from 22 to 9 lb/100 ft^2. Gel strength reading for 10 seconds was reduced from 4 to 2 lb/100 ft^2. Gel strength reading for 10 minutes was reduced from 6 to 3

Property	Conditions	Unit	Value
Density	75 °F and 14.7 psi	pcf	95.0
600 rpm	120 °F and 14.7 psi	Dial reading	87.0
300 rpm		Dial reading	58.0
200 rpm		Dial reading	45.0
100 rpm		Dial reading	30.0
6 rpm		Dial reading	7.0
3 rpm		Dial reading	6.0
10 seconds gel		lb/100 ft^2	8.0
10 minutes gel		lb /100 ft^2	15.0
PV		cp	29.0
YP		lb/100 ft^2	29.0
API filtrate	75 °F and 100 psi	ml /30 min	3.2
Filter Cake Thickness		inch	1/32
HT/HP filtrate	300 °F and 500 psi	ml /30 min	7.0
HT/HP Filter Cake Thickness		inch	2/32
pH	75 °F and 14.7 psi	------	10.0

Table 2 - Conventional $CaCO_3$/barite drill-in fluid used to drill Unayzah-B reservoir properties before hot rolling.

Property	Conditions	Unit	Value
Density	75 °F and 14.7 psi	pcf	95.0
600 rpm	120 °F and 14.7 psi	Dial reading	42.0
300 rpm		Dial reading	27.0
200 rpm		Dial reading	20.0
100 rpm		Dial reading	13.0
6 rpm		Dial reading	3.0
3 rpm		Dial reading	2.0
10 seconds gel		lb/100 ft^2	4.0
10 minutes gel		lb/100 ft^2	4.0
PV		cp	15.0
YP		lb/100 ft^2	12.0
API filtrate	75 °F and 100 psi	ml /30 min	3.5
Filter Cake Thickness		inch	1/32
HT/HP filtrate	300 °F and 500 psi	ml /30 min	10.0
HT/HP Filter Cake Thickness		inch	2/32
pH	75 °F and 14.7 psi	-----	10

Table 3 - Conventional $CaCO_3$/barite drill-in fluid used to drill Unayzah-B reservoir properties after hot rolling.

lb/100 ft^2. However, filtration control did not change. It showed much lower filtration loss compared to $CaCO_3$/barite drill-in fluid.

Phase separation was also observed after hot rolling at 300ºF the drill-in fluid sample for 16 hours.

Mn3O4 Drill-In Fluid Formulations

The first formula, shown in Table 7, contains 41 lb/bbl of KCl which is the common concentration used in the field. KCl is used for clay inhibition.

Manganese Tetraoxide was used only in the formula without $CaCO_3$ to evaluate its filtration performance. XC-polymer, PAC-R and Resinex were used to evaluate their rheological performance, Table 8.

The API filtrate was almost double the amount of filtrate from the two typical drill-in fluids. Rheological properties (gel strength, PV and YP) were much higher than the typical drill-in fluids' properties. The use of drilling fluids with too high rheological properties can decrease penetration rate, high swabbing and gas flow. Table 9 shows the properties of the fluid after aging for 16 hours at 300ºF.

The API filtrate increased from 7.8 to 11 ml/30 minutes. PV value did not change greatly and YP was reduced from 72 to 55 Lb/100 ft^2. HT/HP filtrate was 13.5 ml/30 minutes compared to 10 with KCl/$CaCO_3$/barite and 7 ml/30 min with potassium formate drill-in fluids. There are two limitations of the formulation. The first one is the high rheological properties that should be reduced to improve drilling performance. The second limitation is the high fluid loss which should be reduced to minimize formation damage.

In order to overcome the above limitations, $CaCO_3$ weighting materials were added in different concetration and in different ratio. Also, different polymers were used such as resinex, soltex and starch to investigate their affects on Mn_3O_4 water-based formulations.

Data Analysis

Yield Point Measurments

Yield Point measurements for 17 formulations tested in designing the Mn_3O_4 drill-in fluids. In formulations (1st-4th), resinex polymer was used. It resulted in high YP values more than 80 lb/100 ft^2 in some formulations. Therma check polymer was used in the 5th-7th formulations resulting in high YP values. Starting from the 8th formulation, using PAC-R, YP values were reduced to acceptable range (30-40 lb/100 ft^2). This indicates that

Additive	Function	Field Unit	Field Amount	Lab Unit	Lab Amount
Water	Base	Bbl	0.14	grams	48.65
Potassium Formate	density and shale inhibition	Bbl	0.86	ml	301.14
Starch	Fluid loss	Lb	6.0	grams	6.0
Deformer	Anti-foam	Gal	0.01	grams	0.08
XC-polymer	Viscosifier	Lb	0.5	grams	0.5
PAC-R	Fluid loss/ Viscosifier	Lb	1.0	grams	1.0
PAC-R-Low	Fluid loss/ Viscosifier	Lb	4.0	grams	4.0
Soda Ash	pH control	Lb	1.0	grams	1.0
Sodium bicarbonate	Buffer	Lb	0.5	grams	0.5
$CaCO_3$ (fine)	Weighting Material	Lb	15.0	grams	15.0
$CaCO_3$ (medium)	Weighting Material	Lb	5.0	grams	5.0
Sodium Sulfite	Oxygen Scavenger	Lb	0.75	grams	0.75

Table 4 - Conventional CaCO3/potassium formate drill-in fluid formulation used to drill Unayzah-B reservoir.

Property	Conditions	Unit	Value
Density	75 °F and 14.7 psi	pcf	95.0
600 rpm	120 °F and 14.7 psi	Dial reading	78.0
300 rpm		Dial reading	50.0
200 rpm		Dial reading	39.0
100 rpm		Dial reading	26.0
6 rpm		Dial reading	6.0
3 rpm		Dial reading	4.0
10 seconds gel		lb/100 ft^2	4.0
10 minutes gel		lb/100 ft^2	6.0
PV		cp	28.0
YP		lb/100 ft^2	22.0
API filtrate	75 °F and 100 psi	ml /30 min	3.5
Filter Cake Thickness		inch	1/32
HT/HP filtrate	300 °F and 500 psi	ml /30 min	6.5
HT/HP Filter Cake Thickness		inch	1/32
pH	75 °F and 14.7 psi	---	10.5

Table 5 - Conventional $CaCO_3$/potassium formate drill-in fluid formulation used to drill Unayzah-B reservoir properties before hot rolling.

using PAC-R provided YP values close to typical drill-in fluids used to drill Unayzah-B.

API filtration measurements for the 17 formulations tested in designing the Mn_3O_4 drill-in fluids. In formulations (1^{st}-4^{th}), resinex polymer was used with different ratios of $CaCO_3$. The filtration did not change significantly due to the addition of $CaCO_3$ with values ranging from 7.2 to 7.8 ml/30 minutes.

Therma check polymer was used with different ratios of $CaCO_3$ (medium and fine) in the 5^{th}-7^{th} formulations. The filtration control did not improve with values ranging from 7.5 to 6.5 ml/30 minutes before hot rolling and 11 to 7.5 ml/30 minutes after hot rolling.

In formulations (8^{th}-15^{th}), PAC-R was used with different ratios of $CaCO_3$ (medium and fine). $CaCO_3$ was added after Mn_3O_4 in the 8^{th}-11^{th} formulations resulting in high fluid loss values up to 13 ml/30 minutes. In the 12^{th} formulation, $CaCO_3$ was added before Mn_3O_4 material. This change in order of addition resulted in a reduction in fluid loss from 13 to 10.6 ml/30 minutes. Mn_3O_4 has smaller particle size than $CaCO_3$, so the efficiency of $CaCO_3$ bridging materials will be less if being added after Mn_3O_4.

Soltex polymer was added in the 14^{th} and 15^{th} formulations resulting in 9 and 8.5 ml/30 minutes. However, the fluid loss values were still high and more filtration control is needed.

Starch was added in the 16^{th} formulation with 3.5 lb/bbl $CaCO_3$ fine and 1.5 $CaCO_3$ medium resulting in 5.5 ml/30 minutes before hot rolling and 6.5 ml/30 minutes after hot rolling. In the 17^{th} formulation, $CaCO_3$ was not added and fluid loss values of 9 ml/30 minutes before hot rolling and 11 ml/30 minutes after hot rolling were recorded. This shows the need of using $CaCO_3$ material with starch to control the filtration in Mn_3O_4 drill-in fluids.

Optimum Concetration of $CaCO_3$ Weighting Material

Additional three formulations similar to the 16^{th} and 17^{th} formulations were prepared. The variable in these five formulations was the amount of $CaCO_3$. The objective of this testing is to find the optimum concentration of $CaCO_3$ needed with Mn_3O_4 drill-in fluid.

Property	Conditions	Unit	Value
Density	75 °F and 14.7 psi	pcf	95.0
600 rpm	120 °F and 14.7 psi	Dial reading	49.0
300 rpm		Dial reading	29.0
200 rpm		Dial reading	20.0
100 rpm		Dial reading	12.0
6 rpm		Dial reading	2.0
3 rpm		Dial reading	1.0
10 seconds gel		lb/100 ft^2	2.0
10 minutes gel		lb/100 ft^2	3.0
PV		cp	20.0
YP		lb/100 ft^2	9.0
API filtrate	75 °F and 100 psi	ml /30 min	3.5
Filter Cake Thickness		inch	1/32
HT/HP filtrate	300 °F and 500 psi	ml /30 min	7.0
HT/HP Filter Cake Thickness		inch	1/32
pH	75 °F and 14.7 psi	-----	10.5

Table 6 - Conventional $CaCO_3$/potassium formate drill-in fluid formulation used to drill Unayzah-B reservoir properties after hot rolling.

Additive	Function	Field Unit	Field Amount	Lab Unit	Lab Amount
Water	Base	Bbl	0.822	grams	287.7
Deformer	Anti-foam	Gal	0.01	grams	0.08
XC-polymer	Viscosifier	Lb	1.5	grams	1.5
PAC-R	Fluid loss/ Viscosifier	Lb	1.25	grams	1.25
Resinex	HT Fluid loss	Lb	6	grams	6
KCl	density and shale inhibition	Lb	41	grams	41
KOH	pH control	Lb	0.5	grams	0.5
Mn_3O_4	Weighting Material	Lb	205	grams	205

Table 7 - Mn_3O_4 drill-in fluid (1st formulation).

The gel strength measurements (10 seconds and 10 minutes). The addition of $CaCO_3$ increased the gel strength of the drill-in fluid. The highest gel strength was obtained with using 5 lb/bbl $CaCO_3$.

The plastic viscosity relationship with the amount of $CaCO_3$. A similar trend to gel strength is observed in the plastic viscosity. The optimum point was obtained at 5 lb/bbl $CaCO_3$. Yield point was reduced by the addition of $CaCO_3$.

The addition of 5 lb/bbl $CaCO_3$ reduced the fluid loss by 39%. However, there was no more reduction as the concentration of $CaCO_3$ was increased to 20 lb/bbl.

The optimum point is using 5 lb/bbl of $CaCO_3$. Using 5 lb/bbl $CaCO_3$ resulted in the highest gel strength and plastic viscosity. It also resulted in a high Yield point and low fluid loss. The highest yield point was obtained with the formulation without $CaCO_3$. However, the fluid loss was higher by 39%. Thus using 5 lb/bbl of $CaCO_3$ formulation should be used in next phases.

Therma check or resinex polymer was selected initially because of their high temperature stability. However, both polymers provided too high YP. As the YP increases, the carrying capacity will increase. However, the pressure losses and equivalent circulation density will also increase and these can cause swabbing and lost circulation. Oxygen scavenger was added to PAC-R to extend its stability and provide good rheological properties. However, the filtration control was not good. The use of PAC-R and XC-polymers did not provide good filtration control. The addition of soltex to PAC-R and XC-polymers did not improve the filtration control. Starch should be added with PAC-R, XC and $CaCO_3$ materials to provide good rheological properties and filtration control.

Property	Conditions	Unit	Value
Density	75 °F and 14.7 psi	pcf	95
600 rpm	120 °F and 14.7 psi	Dial reading	138
300 rpm		Dial reading	105
200 rpm		Dial reading	91
100 rpm		Dial reading	71
6 rpm		Dial reading	25
3 rpm		Dial reading	20
10 seconds gel		$lb/100\ ft^2$	11
10 minutes gel		$lb/100\ ft^2$	14
PV		cp	33
YP		$lb/100\ ft^2$	72
API filtrate	75 °F and 100 psi	ml /30 min	7.8
Filter Cake Thickness		inch	1/32
pH	75 °F and 14.7 psi		9.2

Table 8 - Mn_3O_4 drill-in fluid (1st formulation) properties before hot rolling.

Property	Conditions	Unit	Value
Density	75 °F and 14.7 psi	pcf	95
600 rpm	120 °F and 14.7 psi	Dial reading	111
300 rpm		Dial reading	83
200 rpm		Dial reading	69
100 rpm		Dial reading	52
6 rpm		Dial reading	28
3 rpm		Dial reading	15
10 seconds gel		$lb/100\ ft^2$	10
10 minutes gel		$lb/100\ ft^2$	12
PV		cp	28
YP		$lb/100\ ft^2$	55
API filtrate	75 °F and 100 psi	ml /30 min	11.0
Filter Cake Thickness		inch	1/32
HT/HP filtrate	300 °F and 500 psi	ml /30 min	13.5
HT/HP Filter Cake Thickness		inch	3/32
pH	75 °F and 14.7 psi	-----	9.2

Table 9 - Mn_3O_4 drill-in fluid (1st formulation) properties after hot rolling.

The best formulation to use has 5 lb/bbl $CaCO_3$ fine and medium in 3:1 ratio. $CaCO_3$ material should be added before Mn_3O_4 to improve filtration control.

Performance Comparsion of Mn_3O_4 Water Based Drill-In Fluid to Typical Fluids

The high values of gel strength of Mn_3O_4 fluid before hot rolling might be due to foaming while mixing. Additional deformer concentration can address this problem. The gel strength is a measure of the shear stress required to initiate flow of a fluid that has been quiescent for a period of time. It is indicative of the drilling fluid ability to keep the drilled cuttings and weighting materials in suspension when circulation is stopped. Mn_3O_4 fluid has higher gel strength value than that of typical drill-in fluids after hot rolling for 16 hours at 300ºF and 500 psi.

The plastic viscosity shows the viscosity at high shear rates. All three drill-in fluids showed similar values before hot rolling. However, after hot rolling, Mn_3O_4 drill-in fluid was the only fluid that showed minimum reduction in PV. $CaCO_3$/barite drill-in fluid's PV reduced from 29 to 15 cp, potassium formate's PV reduced from 28 to 20 cp and Mn_3O_4 drill-in fluid's PV reduced from 30 to 27 cp.

The yield point reflects the drilling fluid ability to carry the drilled solids out of the hole. After hot rolling, Mn_3O_4 drill-in fluid was the only fluid that showed no reduction in YP. $CaCO_3$/barite drill-in fluid's YP reduced from 29 to 12 lb/100 ft^2, potassium formate's YP reduced from 22 to 9 lb/100 ft^2 and Mn_3O_4 drill-in fluid's YP reduced from 35 to 38 lb/100 ft^2.

The HT/HP fluid loss test results of the three drill-in fluids. The fluid loss reflects the amount of fluid that will be filtered from the drilling fluid into the formation. The fluid loss values of the three drill-in fluid were similar before hot rolling. After hot rolling, Mn_3O_4 drill-in fluid showed similar results to $CaCO_3$/Barite drill-in fluid's (10 and 11 ml/30 minutes). The fluid loss of potassium formate was the lowest after hot rolling (7 ml/30 minutes).

From the results above, Mn_3O_4 drill-in fluid showed better thermal stability compared to the typical drill-in fluids used in the field since YP and PV values were not changed much after aging for 16 hours at 300ºF and 500 psi. There was no phase separation in the Mn_3O_4 fluid because its gel strength measurements were higher than typical drill-in fluids. The fluid loss result of Mn_3O_4 was similar to the $CaCO_3$/barite drill-in fluid which shows its potential to be used in the field.

LWD Geosteering and Natural Fracture Identification in Horizontal Wells in Unconventional Reservoirs

By Greg Meszaros and Paul Boonen, PathFinder Energy Services

Coal Bed Methane (CBM) production has grown from about 200 BCF per year in 1990 to close to 1800 BCF in 2005. The success of the Barnett shale play, in the making for the past 20 years, has spawned new or renewed interest in a number of similar shale plays such as the Fayetteville and Moore field shales, the Bakken shale play and the Woodford, Floyd, New Albany and Antrim shales amongst others. Naturally-fractured carbonates such as the Ellenberger can be produced as long as horizontal wells can be drilled to intersect as many fractures as possible. Heavy oil reservoirs are produced using multiple horizontal wells or typically using twinned well pairs and Steam Assisted Gravity Drainage (SAGD). All of these reservoir types can be considered to be "unconventional reservoirs".

Whatever the nature is of an "unconventional hydrocarbon resource" or however we define "unconventional reservoirs," one thing they seem to have in common besides a requirement for high oil and gas prices, is that they need advanced technology to be drilled and produced. Horizontal well drilling is one of the prime technologies to access these reservoirs. High angle/horizontal well drilling relates in turn directly to applications of LWD technology. Tools like 3-D Rotary Steerable Systems (RSS) and formation evaluation LWD tools are now being used in onshore drilling to position the borehole in the reservoir and to provide the necessary reservoir data. This has become economically feasible in a high priced oil and gas environment because their relative cost to the total well cost has decreased.

We concentrate in this article on a few applications of LWD tools in horizontal wells in unconventional reservoirs such as the use of at-bit measurements for real-time geosteering in CBM wells and the use of sonic logs for fracture identification in limestone reservoirs.

MWD At-Bit Gamma Ray And Inclination Measurement

An at-bit tool operates directly above the drill bit to provide real-time dynamic inclination and gamma ray measurements. The tool is designed to operate as two separate subs. Data are transferred from the at-bit sensors in the lower sub to the upper sub via an electromagnetic frequency. This allows it to operate with positive displacement motors or 3-D RSS. The upper sub is connected to the M/LWD system which in turn allows the addition of any LWD tools. The combination of continuous, dynamic inclination and gamma ray at-bit provides the data to determine well path placement and bit position while drilling. It is the combination of both at-bit inclination and at-bit gamma ray that makes this tool unique. The at-bit gamma ray and inclination sensors are offset 11-in. and 22-in., respectively, from the bit.

We concentrate in this article on a few applications of LWD tools in horizontal wells in unconventional reservoirs such as the use of at-bit measurements for real-time geosteering in CBM wells and the use of sonic logs for fracture identification in limestone reservoirs.

By providing immediate lithology and inclination data, the at-bit sensors assist in landing high angle/horizontal wells and optimize well bore position. The at-bit gamma ray is an excellent correlation tool by detecting formation changes at the bit. The at-bit inclination allows the directional driller to drill a smoother well path with reduced tortuosity and dogleg severity. Geosteering becomes more accurate and effective by measuring and recognizing the changing conditions that may affect the well trajectory at the bit.

Geosteering

Geosteering integrates MWD / LWD sensors, forward-modeling software, and the expertise of a highly trained geosteering specialist (Jackson, 1997). Geosteering specialists have the training and expertise to interpret all aspects of the drilling and logging operations to steer the well bore.

The first process in a geosteering project is to create a geological earth model derived from basic geologic information and logging data obtained from offset wells. Offset well resistivity data are used to create a true resistivity (Rt) profile. A 'geologic roadmap' is created utilizing offset well data, the proposed well plan and the modeled response from the gamma ray, resistivity, and density-neutron tools. The resistivity tool response is predicted using a forward model (Jackson et al., 1995). This roadmap is then adjusted as the well is drilled, using the actual trajectory. The geologic model is calibrated as the selected formation markers are encountered while drilling. Depth shifts, bed dip changes, and faults can be added to reconcile the real-time log with the geologic model. This allows the geosteering specialist to forward-model the logging response and to predict the formation in front of the bit in order to steer the well bore geologically, relative to the well plan.

Coalbed Methane Horizontal Well Positioning

At-bit sensors have found a niche in the CBM markets of North America, including the San Juan, Arkoma, and Powder River Basins. The integration of at-bit sensors and forward-modeling software has proven to be an ideal match for the nature of CBM horizontal well drilling.

There are a number of reasons why horizontal wells are important in CBM drilling (Maricic et al, 2006). The direction, shape and position of a horizontal well can be controlled so that an almost ideal well position can be achieved. Proper well positioning and borehole length contribute to draining large areas. Drilling horizontal wells is also very important for sweep efficiency. Increasing contact with the coal in longer boreholes, decreases the time for water production and gas flow peak will occur sooner after the well starts producing. Horizontal CBM wells can realize a 10 to 1 increase in production over vertical wells drilled into the same coal seam.

Coalbed Methane Horizontal Well Examples

The following examples show the results of an aggressive CBM drilling program. The drilling program rapidly increased with the success achieved by shifting the drilling focus from vertical wells to horizontal, in order to expose more of the coal seam to the well bore. The horizontal drilling program progressed by moving from

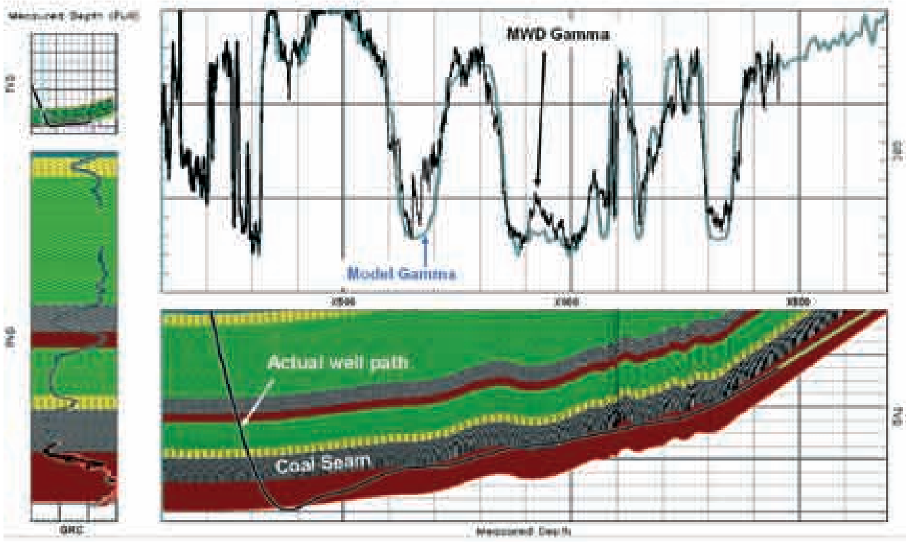


Figure 1 - Post well model of CBM horizontal well drilled with MWD gamma ray. (Vertical Scale Exaggerated.)

drilling with (1) an MWD gamma ray service to (2) utilizing at-bit gamma ray and inclination measurements to (3) utilizing at-bit measurements, LWD resistivity, and forward-modeling software.

Figures 1 to 3 are illustrations of the pre-well modeling and real-time geosteering software screen. The top left panel shows an overview of the well plan and the geological model. The bottom left panel contains the offset well data represented on a true vertical depth scale. RVD is the reference (for offset well) vertical depth. The top right panel displays the modeled and measured log data. This can be the gamma ray only (cyan = model, black = measured) as in the first example. In the second example a modeled resistivity was added. The green blocky curve is the offset well true resistivity modeled along the proposed well plan. The four colored resistivity curves are the forward modeled resistivities for the particular LWD resistivity tool. In the last example, where a resistivity tool was run, the image also includes the measured resistivity data. The bottom left panel shows the well path progression in the geological model. It is in this panel that the geosteering specialist modifies the geological model by changing formation dips or adding faults to match the predicted log data to the real-time log data.

Figure 1 is an example of a horizontal CBM well drilled with MWD gamma ray only, but without real-time forward-modeling software. The model below was constructed after drilling. The coal seam was encountered shallower than expected and the landing point of the planned horizontal well was too deep. From the landing point to total depth of the lateral section, the well was drilled up dip attempting to re-enter the coal seam. The model and log data show that this well penetrated only the bottom of the coal seam approximately 30% of the lateral section.

Figure 2 is an example of a horizontal CBM well drilled with at-bit gamma ray and inclination measurements, but without real-time forward-modeling software. The model below was constructed after drilling. The coal seam was encountered shallower than expected and the landing point of the planned horizontal well was too deep. From the landing point, the well was steered up to 95.0° inclination to re-enter the coal seam. The amount of section lost in zone, due to missing the landing point, was approximately 25% of the total lateral section. Once the well was back in zone, drilling continued at 90°-91° inclination. Without real-time modeling, it was unknown that the bed dip had changed and was now down dip, while drilling continued slightly up dip. The well exited the top of the coal seam and never re-entered before drilling to total depth. The model and log data show that this well was drilled in zone approximately 50% of the lateral section.

Figure 3 is an example of a horizontal CBM well drilled with at-bit measurements, LWD resistivity, and real-time geosteering. Detailed pre-well modeling was prepared in addition to real-time modeling while drilling. The model below was constructed while drilling. The coal seam was encountered deeper than expected, however this was predicted by the on-site geosteering specialist utilizing the forward-modeling software, and the landing point of the planned horizontal well was adjusted. The geosteering model was adjusted to the real-time at-bit and LWD resistivity data while drilling. Prior to reaching total depth

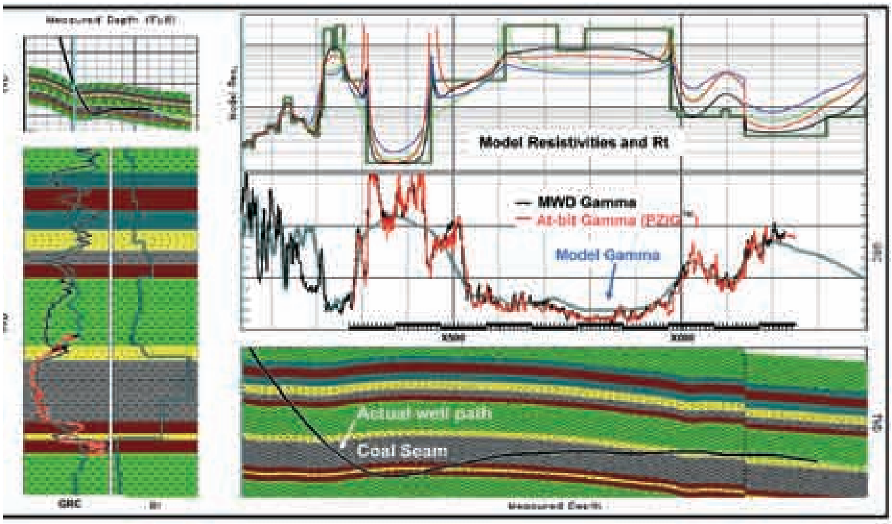


Figure 2 - Post well model of CBM horizontal well drilled with at-bit measurements. (Vertical Scale Exaggerated.)

of the lateral section, the real-time model predicted that the bed dip was changing and would begin to dip steeply upwards. The client chose not to follow the bed dip any further, because the achieved horizontal section had already exceeded the client's expectations for this well. The client did want confirmation that the model was correct and drilling continued until the at-bit gamma ray showed that the well had exited the bottom of the coal seam. This confirmed the bed dip change predicted by the model. The complete geosteering service was successful in steering the well in zone for 100% of the lateral section.

Natural Fracture Identification Using Sonic Logs

Full waveform acoustic logging tools record the sonic energy received at an array of receivers over a certain period of time. Unlike conventional acoustic tools that measure only the first arrival of the compressional wave, waveform recording tools offer the opportunity to compute arrival times of compressional, shear and Stoneley waves and to determine the relative amplitudes of the different arrivals.

A plot of the raw waveform can be an excellent fracture indicator. Fractures are indicated by the following combination of features:

- No major change in the arrival time of the compressional and shear waves

- Minor to no attenuation of the compressional waves

- Strong attenuation of shear waves

- Strong attenuation of the Stoneley waves

Lithology changes and particularly shale beds may show similar attenuation patterns; therefore a gamma ray curve or another shale indicator should be included to identify such shale beds. Washed out zones may also have a similar effect on the waveforms. A caliper curve should be included in the plot to check for hole enlargement. However, borehole washout is often a result of the presence of natural fractures and the caliper logs should be examined carefully. Formation gas may attenuate the compressional wave, but it does not affect the shear wave. Fluids do not support a shear wave. Hence a fluid (gas) independent porosity can be computed from the shear wave.

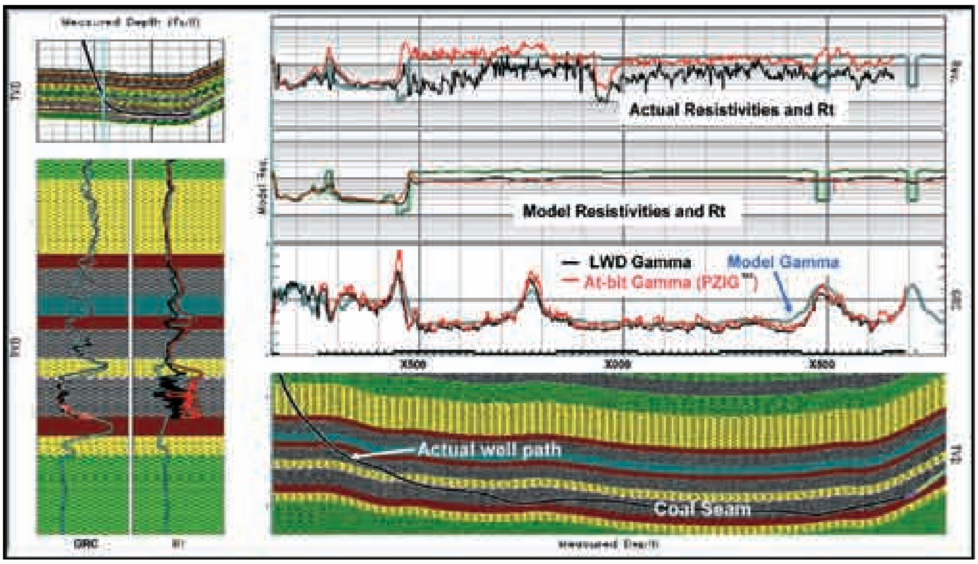


Figure 3 - Real-time model of CBM horizontal well drilled with at-bit measurements, LWD resistivity, and forward-modeling software. (Vertical Scale Exaggerated.)

A series of three examples of geosteering in coal-bed methane horizontal wells shows the importance of integrating at bit measurements with pre-well modeling and real-time geosteering.

LWD sonic tools were introduced in the mid 1990's (Minear et al. 1995). Due to the harsh drilling environment in which LWD tools must operate, LWD sonic waveforms typically are quite noisy as compared to wireline waveforms. They also typically contain tool mode arrivals so that the effects of the presence of fractures may be difficult to interpret using the raw waveforms. A processing technique called Instantaneous Waveform Characteristics is used to enhance the fracture identification capabilities.

Instantaneous Waveform Characteristics (IWC)

Instantaneous Waveform Characteristics (IWC) processing is an application of Complex Trace Analysis (Taner et al, 1976) to acoustic waveforms recorded using a full waveform type of sonic logging tool (Knize and Patton, 1989, Boonen and Flowers, 1996). IWC processing applies a Hilbert transform to the acoustic waveform to separate energy and phase information. An IWC log provides a means of viewing acoustic waveforms in a new way. One of the main advantages of IWC processing is its ability to separate magnitude from phase and frequency. We are now able to look at the energy (magnitude) and energy changes with depth independently from phase changes.

The instantaneous magnitude of amplitude is the portion of the emitted signal that is transmitted through the formation to reach the receiver. It is called the sonic transmissivity of the formation and is defined as the envelope of a complex acoustic response to the formation. The sonic transmissivity is a direct measurement of the attenuation of acoustic energy within the formation. Any structural changes causing absorption or dispersion of the acoustic energy will affect the transmissivity. In particular, shear and Stoneley transmissivity will be lower in the presence of fractures.

The instantaneous phase emphasizes the continuity of acoustic events through the formation. The phase log reveals formation boundaries and their apparent dips, geological discontinuities, like faults and fractures, and broken or hydro-fractured formation as oblique events, splits of phase lines, and irregular patterns. The instantaneous phase is sensitive to effects of formation absorption and dispersion, to the scattering due to structural irregularities and to transitional acoustic impedance changes. It is an effective indicator of fractured zones.

Figure 4 is an example of an instantaneous transmissivity and phase plot from LWD sonic waveforms recorded in a horizontal well in a fractured carbonate reservoir. On the transmissivity plot, the compressional wave shows up as the faint blue colored arrivals at about 200 microseconds. The shear wave is represented by the blue-green colors around 400 microseconds. The Stoneley wave energy is indicated by the red arrivals (high energy). Fractures are indicated by the loss of shear and especially Stoneley en¬ergy from x70 to x75 ft, x135 ft to x145 ft and x150 ft to x157 ft. At the same depth levels, the phase plot shows marked disruptions in the phases.

Maximum Stoneley Energy

The maximum Stoneley energy curve (Figure 4, track 1) represents the relative attenuation of the Stoneley wave computed across the Stoneley arrival window. In a similar way, a maximum shear energy could be computed. It appears however that the Stoneley wave energy responds better to fractures. Strong attenuation (low energy) relates to fractured zones. This computation provides a

Sonic logs have been shown to effectively identify fractured zones in carbonates. The introduction of LWD sonic tools, made this analysis available to the LWD market. Instantaneous Waveform Characteristics processing enhances this open fracture identification process. The analysis has been used to design well completions and acid fracturing operations.

fracture identification curve as compared to a qualitative transmissivity image. The curve can easily be correlated to other log data.

Applications

It is important to remember that the sonic waveforms respond in this manner only to open (fluid filled) fractures.

The interpretation is also qualitative. The sonic energy will be attenuated in the same way by one major fracture as by multiple small fractures. The fractures need to occupy a considerable part of the circumference of the borehole. A vertical fracture in a vertical borehole will probably not be detected, whereas vertical or highly dipping fractures in a horizontal section will cause the sonic energy be strongly attenuated.

Very often these fractured carbonates need to be stimulated to attain economic production. The acid can be spotted across zones of interest indicated by the logs. The IWC logs have been used to design multiple acid fracturing jobs. The packers are set in more competent rock for better seal and the fracturing ports are positioned across fractured zones where the intent is not to create new fractures but to enhance the existing fracture system.

Conclusions

Successful introduction of an at-bit gamma ray and inclination measurement tool has greatly enhanced geosteering capabilities. The combination of continuous, dynamic inclination and gamma ray at-bit provides greater directional control and confidence in geosteering complex sections. This unique tool accurately determines well path placement and bit position while drilling. Integrating these at-bit measurements with LWD data and real-time forward-modeling software is an essential component in any geosteering project.

A series of three examples of geosteering in coalbed methane horizontal wells shows the importance of integrating at bit measurements with pre-well modeling and real-time geosteering. The exposure to the target coal bed increased from 30% of the horizontal section in a well where neither at-bit tools nor steering was used, to 50 % where the at-bit tools were used but without real-time modeling, to 100% exposure where the entire geosteering service was used.

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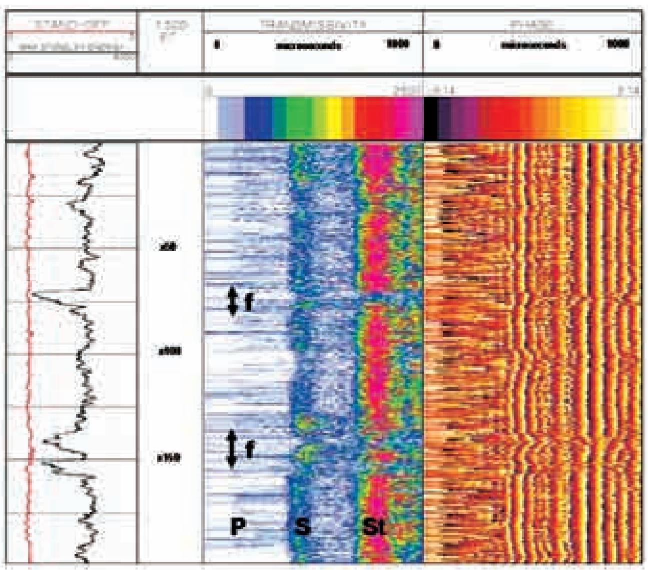

Figure 4 - Instantaneous transmissivity and phase plot.

Pore Network Modeling: A new Technology for SCAL predictions and interpretations

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Abstract

There have been recently substantial advances in Pore Scale Physics Discipline. These advances can now be used for the benefit of special core analysis (SCAL) measurements and interpretations. This article is devoted to explain these improvements from two perspectives: (i) Pore scale imaging and network extraction (ii) Fluid flow modeling applied on the extracted networks in order to predict some key petrophysical properties (capillary pressures, relative permeabilities).

We use either thin sections or X-ray microtomography (micro-CT) to analyze rock cuttings of sandstones from Saudi Arabian oil and gas fields. These cuttings are a few mm across and are imaged with a resolution of 3 to 12 microns. Hence, the details of the three-dimensional pore space can be clearly seen. A maximal ball algorithm[1,2] is used to extract a topologically equivalent pore-throat network: the largest inscribed spheres in the pore space representing the pores, with throats representing the connections between them.

In parallel to this algorithm, thin section images are utilized to build 3D equivalent images, reproducing porosity by a similar spatial variation of the grain sizes obtained from the thin sections. This has been done through the so called process based technique[3] which is based on honoring the geological depositional mode of the rock.

The final aim is to input these network models into pore-scale fluid flow simulators to predict macroscopic properties such as relative permeability and capillary pressure. Blind tests are envisaged to compare the measured petrophysical properties and their corresponding numerical estimations.

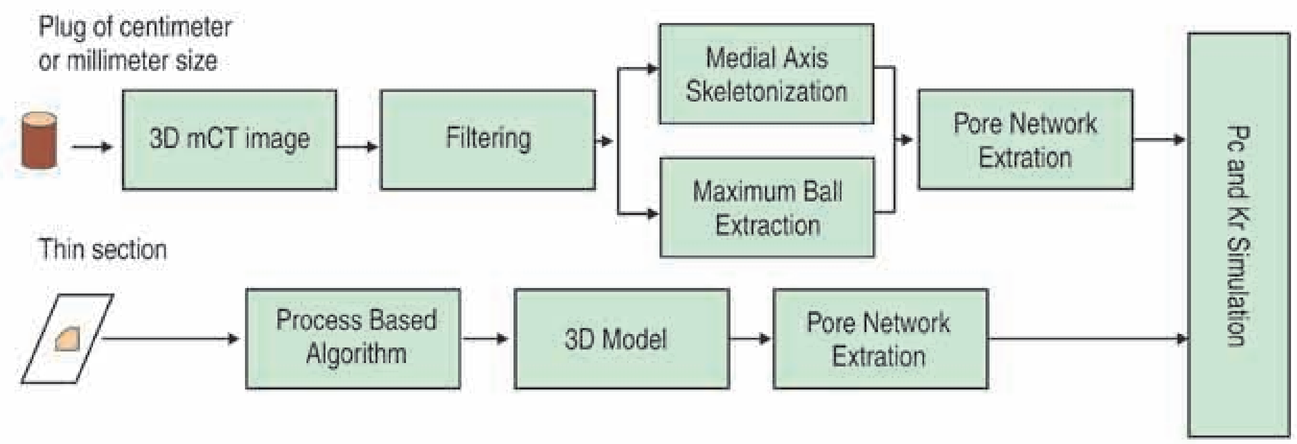

Figure 1 - Steps of the pore network modeling from 3D or 2D imaging to petrophysical properties estimation.

This acts as a valuable complement to special core analysis, enabling predictions of properties – such as three phase relative permeabilities and the impact of wettability trends – outside the range probed experimentally.

Introduction

Obtaining the SCAL data can be very expensive, and even more importantly acquiring, analyzing and integrating the data may take a long time. In order to prevent this expense and even more importantly the wasted time due to the long and tedious SCAL procedures, numerical simulation techniques were developed and deployed in the last few decades.

With the availability of more efficient numerical modeling algorithms and super-fast computing resources, there have been significant advancements in the specific area of "pore-network modeling". Pore-scale modeling which combines an accurate description of the pore space with a detailed analysis of pore-scale displacement physics is a useful tool for understanding multiphase flow in porous media. From a practical perspective it can be used to make predictions for situations that are difficult to study experimentally. Some of the previously conducted studies[4] show that even for rather complex displacements – such as WAG flooding – this approach is able to make accurate predictions while revealing the subtlety of the influence of pore-scale displacement on macroscopic behavior.

In short, the main advantages of such developed procedure for pore network extraction and multiphase fluid flow modeling, are as follows:

• It takes only a few hours of computing time to obtain multi-phase flow properties while it may take a few weeks and even months to get the same properties measured in the lab.

• It is possible to virtually change some input parameters such as initial water saturations, Swi, interfacial tensions, IFT's, and contact angles to conduct sensitivity studies for different fluid and rock systems. It is a well known fact that these parameters are not constant throughout the reservoir, but instead quite varied especially in the transition zone.

In the course of this article, we will first discuss and compare two of the recently developed pore-network generation algorithms (i) Maximum ball algorithm[1,2] and (ii) Process-based technique.[3] Once we obtain the pore/throat network which is representative to the pore space of the real reservoir rock, we can then conduct multiphase fluid flow simulation in order to obtain the macroscopic transport properties such as relative permeabilities and capillary pressures (see Figure 1).

Pore Space Reconstruction

Utilizing pore-network modeling technique and solving multiphase fluid flow equations to predict transport properties not only require a detailed understanding of displacement mechanisms at the pore level but also an accurate and realistic characterization of the structure of the porous medium. Although there have been significant advances in describing the geometry of pore space and several techniques were already introduced in the last few years, we will limit this article with the two recently developed promising approaches; maximal ball algorithm and process-based technique.

Micro-CT Imaging and Maximal Ball Algorithm

We extract pore networks from direct micro-CT images. A micro-CT scanner at Imperial College London and a synchrotron tomographic scanner at ELETTRA, a national laboratory in Trieste, Italy, have been used to image sandstone and carbonate samples (Figure 2). The micro-CT scanners output three-dimensional (3D) arrays of reconstructed linear X-ray attenuation coefficient values (CT numbers), which can be viewed as gray scales in image processing software. The raw images are filtered to smooth the image, reduce noise and improve the contrast between grain and void. We use the median filter which replaces the gray scale value of a voxel by the median value of the nearest 26 surrounding cells. A threshold value is then chosen to binarize or segment the gray scales into two phases: solid and void. The effect of image processing is seen in Figure 3.

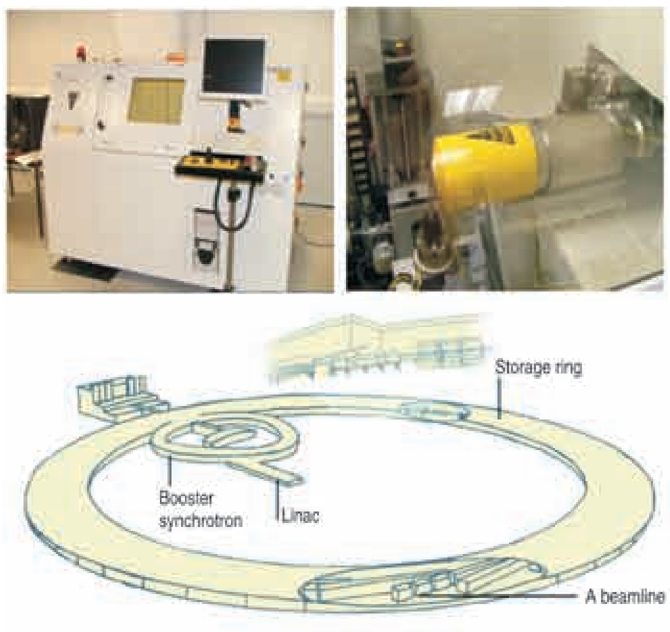

Figure 2 - Micro-CT scanner at Imperial College London and X-ray tube (left), in this scanner and the sample stage. Synchrotron (Above).

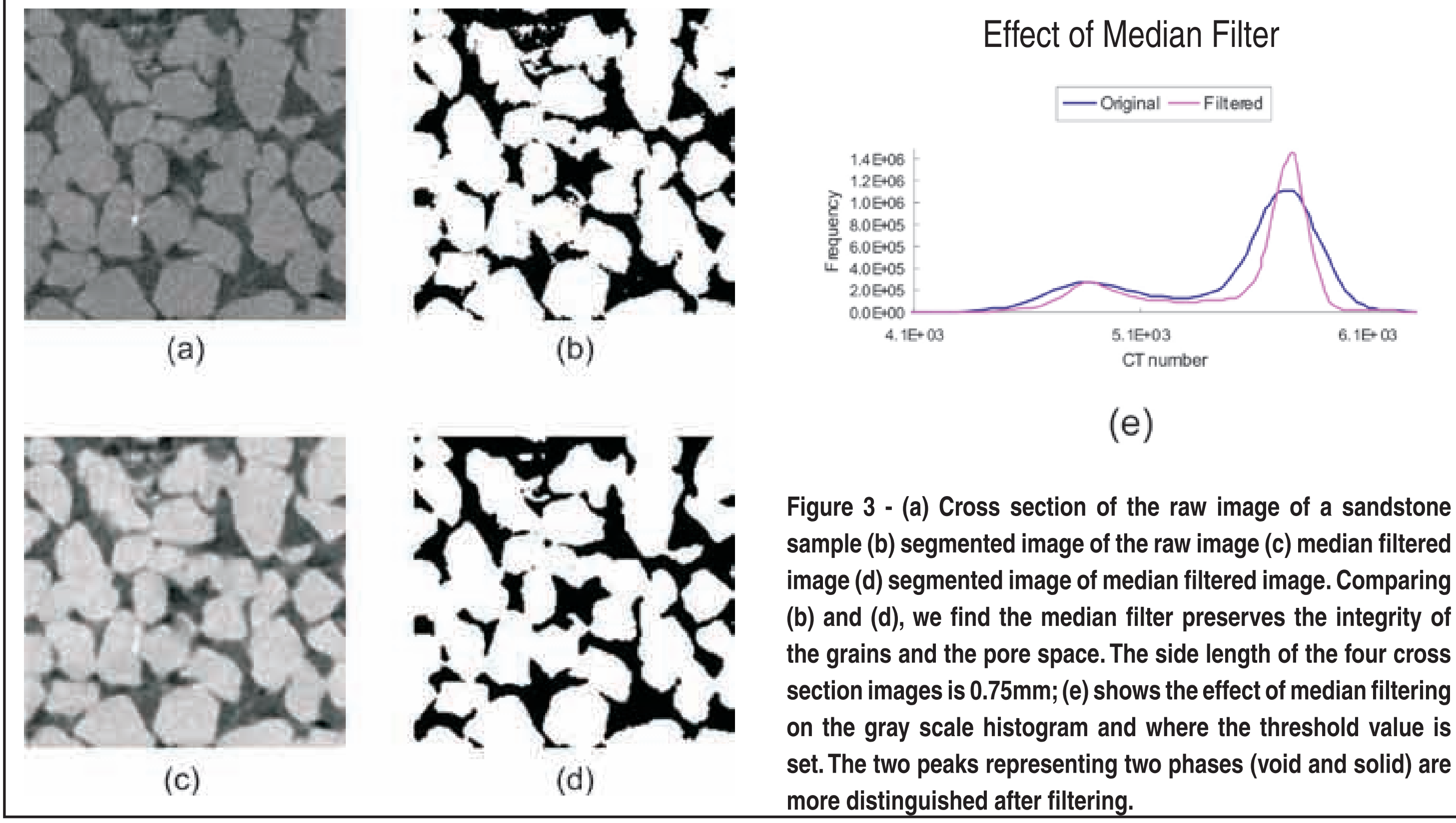

Figure 3 - (a) Cross section of the raw image of a sandstone sample (b) segmented image of the raw image (c) median filtered image (d) segmented image of median filtered image. Comparing (b) and (d), we find the median filter preserves the integrity of the grains and the pore space. The side length of the four cross section images is 0.75mm; (e) shows the effect of median filtering on the gray scale histogram and where the threshold value is set. The two peaks representing two phases (void and solid) are more distinguished after filtering.

Once we obtain the 3-D representation of the void and solid using the micro-CT technology, maximal ball algorithm is used to construct the largest spheres centered on each void voxel that can just fit in the pore space. A maximal ball is one of the spheres not completely enclosed by another. The concept of maximal balls was first introduced and used by Silin et al.1 to study the morphology of 3D pore-space images. A maximal ball that does not overlap any larger sphere defines a pore. Throats are defined as chains of smaller balls connecting pores. The maximal ball method easily and unambiguously identifies pores, but the construction of throats is more tedious, as there may be several different ways to connect pores by overlapping smaller spheres.

Validation of Maximal Ball Algorithm

Ten rock samples of Saudi Aramco have been scanned and fourteen images were obtained using industrial and synchrotron micro-CT scanners. In order to obtain suitable samples for imaging, we drilled cylindrical specimens from the larger cores before scanning. The resolution of 3D images varies from 3 to 12 microns corresponding to specimen diameters ranging from 2 to 8 mm.

Pore networks have then been extracted from two sandstones (named as S1 and S2) and one carbonate sample (named as L1). Cross-sectional views as well as the full 3D representations of the micro-CT images are shown in Figures 4 and 5 respectively. The sandstone sample S1 has measured porosity and permeability of 16.4% and 906 mD. We drilled a 10 mm long, 8 mm diameter cylindrical specimen from the core plug and used a subset of the image (with a bulk volume of 1.73 mm^3) for pore network analysis. The resolution of the image was 8μm. The porosity measured on the image was 16.8% and the permeability was computed using Lattice-Boltzmann simulation as 1400 mD. As the image analysis results were in good agreement with the experimentally measured data, the subset of the image was considered as a representative elementary volume (REV) of the sandstone, S1.

The second image (from sandstone sample S2) was obtained at a resolution of 5μm and is representing a volume of 0.42 mm^3. And the last image (from limestone L1) has a resolution of 3μm. It represents a volume of 0.1 mm^3.

We extracted pore networks from these three samples and list the properties of the networks in Table 1. Since

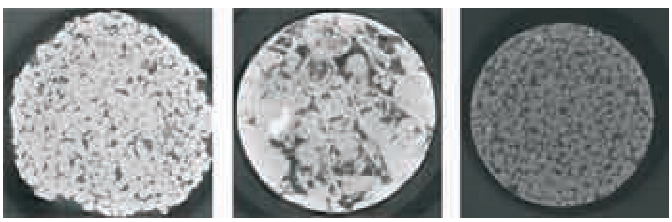

Figure 4 - Cross sections of micro-CT images of Saudi Aramco core samples. The image resolutions are 8 μm, 5 μm, and 3 μm respectively. Each image is 512 voxels across.

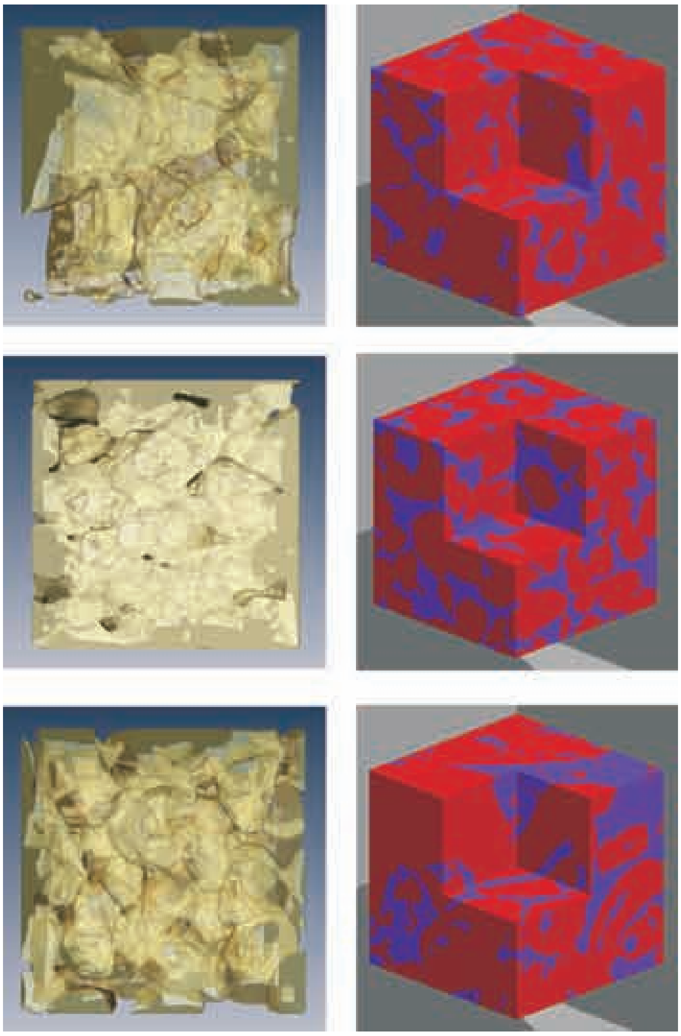

Figure 5 - Transparent view (left) and cutaway view (right) of the 3D micro-CT images. (a) S1, (b) S2, (c) L1.

Properties	Samples		
	S1	S2	L1
Porosity (%)	16.8	25.2	29.8
Number of pores	442	279	347
Number of throats	1018	631	1265
Avg. coordination number	4.71	4.59	8.6
Max. coordination number	14	12	32
Avg. pore radius(μm)	25.0	19.0	22.3
Max. pore radius(μm)	87.7	59.7	117
Avg. throat radius(μm)	19.2	13.1	19.3
Max. throat radius(μm)	78.5	37.2	88.9

Table 1 - Properties of pore networks extracted from Arabian reservoir samples

the minimum size of pores and throats is always the resolution value of the image, we don't list them in the table. We find that the sandstones have average coordination numbers between 4 and 5, which is in agreement with other analyses of granular media.[3,5] However, the vuggy carbonate has higher coordination numbers and a wider distribution of pore and throat sizes than the sandstones, which is also another expected result.[5] Figure 6 illustrates the extracted networks from S1, S2, and L1 samples.

Process-Based Network Generation

The process-based technique generates a model porous medium by simulating the packing of grains. The technique was first introduced and used by Øren et al.[3] and based on the simulation of the geological processes that the rock has been formed. The only input for this technique is a thin section image. Using image analysis techniques, sizes of the grains are recorded and deposited to form a 3-D porous medium. In addition to sedimentation process, compaction and diagenesis mechanisms are simulated to obtain a more accurate description of the porous medium in three dimensions. Medial axis algorithm[6,7] is then utilized, which uses a thinning algorithm to erode the pore space from grain surfaces until the medial axis – lines with branches denoting the centers of the pore space – is found. Pores are located at branches in the medial axis, while throats are connecting the pores. The size of the pores and throats can be determined by the number of steps of erosion from the surface of the grains. The medial axis mathematically preserves the topology of the pore space. However, the intrinsic sensitivity to the irregularity of pore space results makes the unambiguous identification of pores that may encompass several branches of the medial axis, difficult[7]. Generally, medial axis based algorithms readily capture the interconnectivity of the pore space but pore identification is tedious.

In this section, we will present the results of 3 blind tests that have been recently conducted on three Saudi Arabian sandstone samples. Thin section images were obtained for these samples to be tested through the process-based modeling approach (see Figure 7). In parallel to this study, the samples have undergone complete routine (RCAL) and a few special (SCAL) core analysis studies. The output properties that were targeted for comparison are the porosity, permeability and capillary pressures.

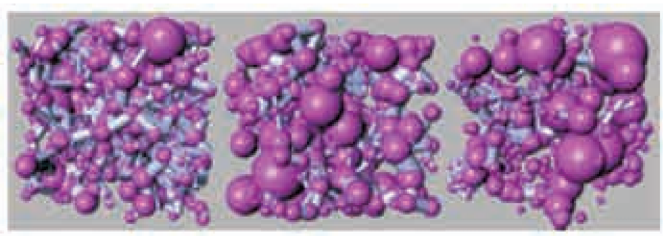

Figure 6 - Pore-throat networks generated from micro-CT images using maximal ball algorithm.

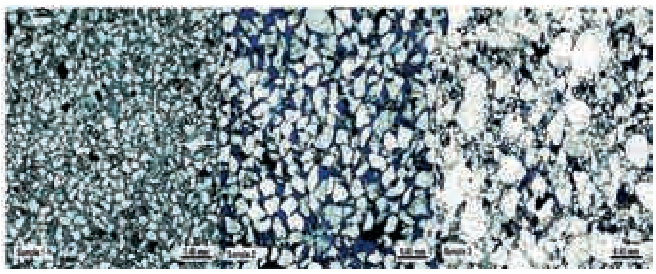

Figure 7 - Thin section images of the three Saudi Aramco sandstone samples which were selected for the blind study in order to test the validity of the process-based modeling technique.

Descriptions of the thin sections reported for the three samples are as follows:

Sample 1: Fine-grained (0.08 - 0.12 mm) quartz, well sorted, angular. Ovoid patches of carbonate cement up to 1 cm across. Visual porosity estimated to be around 25%.

Sample 2: Fine-grained (0.20 - 0.24 mm) quartz, well sorted, angular to subangular. Estimated visual porosity is between 25 to 30%.

Sample 3: Bimodal with fine & medium grained (0.08 - 0.12mm & 0.34 - 0.40mm) quartz. Visual porosity is estimated to be 8 - 10%.

Scanning electron microscope (SEM) images were then generated for each thin section to build a numerical 3D model from which porosities and permeabilities are estimated. The values of the estimated porosities and permeabilities (with the corresponding error margins) as well as the experimentally obtained ones are reported in Table 2.

As can be seen from Table 2, the results obtained through the numerically generated 3D images were comparable with the experimental data. Pore networks were then constructed from the 3D images using the medial axis algorithm. 2D slices of the numerically constructed 3D models as well as the pore-throat networks are presented in Figure 8.

Some of the key characteristics of the numerically constructed rock networks are shown below (see Table 3).

	SAMPLE 1	SAMPLE 2	SAMPLE 3
Measured Porosity (%)	30	34	19
Predicted Porosity (%)	31.5 - 32.1	28 - 30	14.2
Measured Permeability (md)	1265	1789	139
Predicted Permeability (md)	1800	1944 - 3428	9.4 - 15.4

Table 2 - Comparison of the experimentally measured and predicted porosity and permeability values.

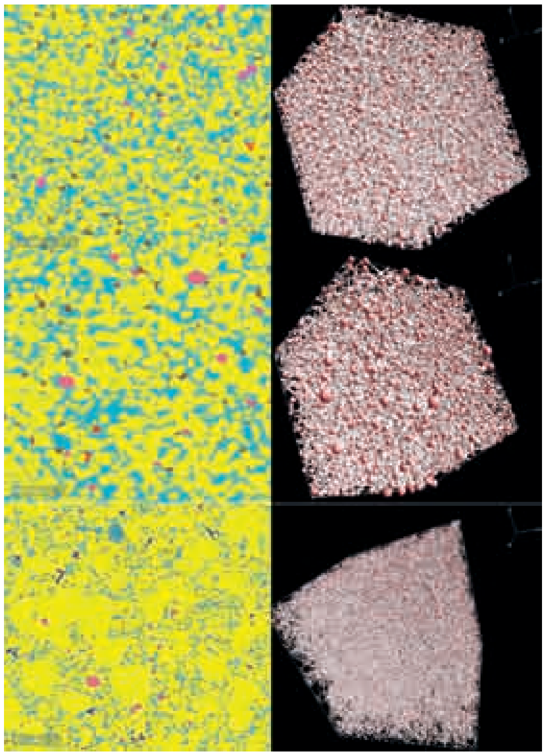

Figure 8 - A 2D slice of the 3D Model (left) and the corresponding pore-network (right) for samples 1, 2 and 3.

Nodes stand as pore-bodies while links are representing the pore-throats. Coordination number is the number of links that are connected to a node element. Note that, statistics are concordant with the porosity and permeability trends of the samples. For example, sample 3 with the lowest pore/throat radii as well as the lowest average coordination number has also the lowest porosity and permeability values. Sample 1 and 2 with similar pore/throat radii and coordination numbers have similar porosity and permeabilities.

Fluid Flow Simulation

Valvatne and Blunt[8] developed a mixed-wet, two-phase pore-network simulator in order to predict the key petrophysical properties such as relative permeability and capillary pressures. The fluids are assumed to be Newtonian,

	SAMPLE 1	SAMPLE 2	SAMPLE 3
Number of Nodes	55048	56448	65137
Avg. Node Radius (μm)	12.6	14.7	7.2
Number of Links	125116	121009	120243
Avg. Link Radius (μm)	6.6	7.7	3.0
Max. Coordination No.	34	53	21
Avg. Coordination No.	4.6	4.4	3.8

Table 3 - Key properties for the pore-throat networks constructed from Saudi Aramco sandstone samples through the so called process-based methodology.

incompressible, and immiscible. The displacements at the pore scale are assumed to be quasi-static and capillary dominated. A displacement is defined as a change in the configuration of an element (pore or throat) in order to satisfy capillary equilibrium conditions. Each displacement has a threshold capillary pressure associated with it. In other words, displacement is carried out only if the invading phase reaches the required (threshold) phase pressure. At a certain phase pressure, all possible displacements take place until there is no more available displacement, which means system is relaxed and capillary equilibrium conditions are satisfied. The analytical computations of the threshold pressures have already been discussed in the literature.[3,8]

We use the model developed by Valvatne and Blunt[8] in order to predict the mercury/air capillary pressure data as well as the water/oil relative permeabilities during waterflooding using the rock networks generated from Saudi Aramco samples. Figure 9 and 10 compare the mercury/air capillary pressure curves for the experimentally measured and numerically estimated data for sample 1 and 2. The interfacial tension between mercury and air was assumed to be 480 mN/m during simulations. Although the match between the predictions and measurements were not perfect, the results were reasonable considering the fact that the only available input was a single thin-section image while constructing the representative rock networks.

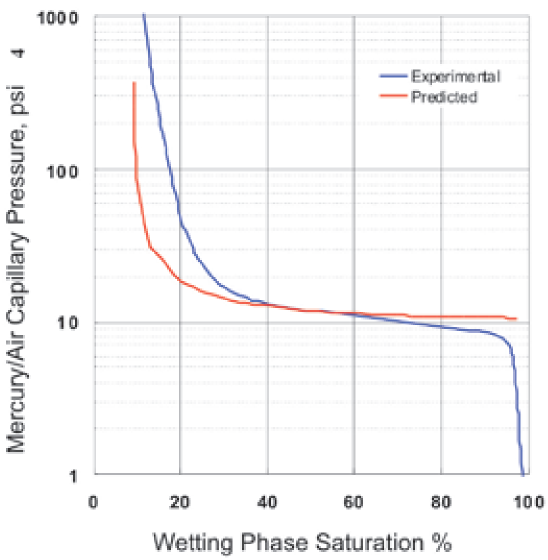

Figure 9 - Experimentally measured and numerically predicted capillary pressure curves for sample 1. Note that interfacial tension between mercury and air is assumed to be 480 mN/m during our simulation.

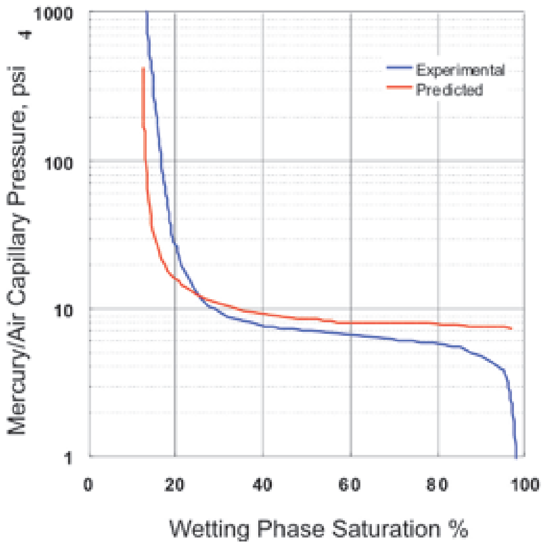

Figure 10 - Experimentally measured and numerically predicted capillary pressure curves for sample 2. Note that interfacial tension between mercury and air is assumed to be 480 mN/m during our simulation.

We then simulate a water injection cycle in order to predict water/oil relative permeabilities. Unfortunately we currently do not have experimental data to validate our findings. However, we are planning to conduct steady-state relative permeability measurements to test our simulation results. Figure 11 compares the predicted water/oil relative permeability curves for a water-wet (oil/water contact angles were distributed between 30 and 60 degrees) and a neutrally-wet (oil/water contact angles were distributed between 70 and 120 degrees) system for the rock network of sample 1. The interfacial tension between water and oil was assumed to be 35mN/m.

The results confirm that water/oil relative permeabilities have strong dependence on the system's wettability (see Figure 11). In a water-wet medium, oil is the non-wetting phase and prefers to invade the larger pores and throats. Thus oil relative permeabilities are significantly higher in a water-wet system. However, it is also shown that the residual oil saturation is lower for a neutrally-wet medium as the oil layers do form and stable throughout the displacements. This is a similar conclusion which was reached by Janahundran and Morrow[9] after conducting a series of experiments with media of varying wettabilities. We are planning to conduct a series of two-phase steady-state relative permeability measurements to validate these results.

Conclusions

We first described two recently developed pore-network generation techniques, maximum ball algorithm and

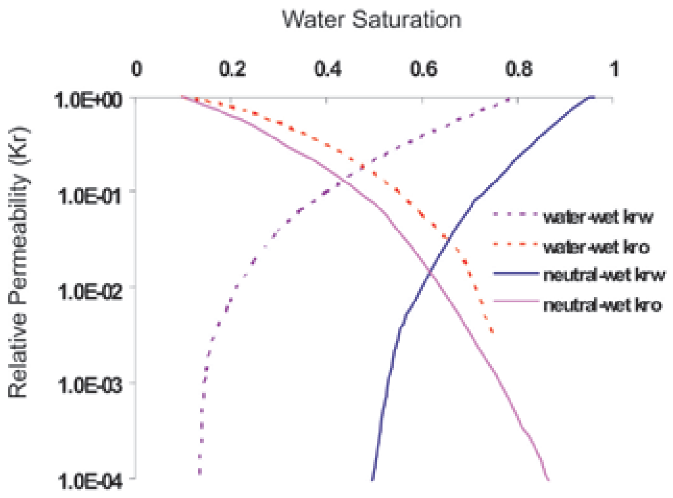

Figure 11. Comparison between oil/water relative permeabilities for a water-wet and a neutrally-wet medium. The simulations were conducted on the rock network of sample 1 and water/oil interfacial tension was assumed to be 35 mN/m.

process-based method. We were able to generate pore-throat networks that are representative to the real rock samples. We then simulated two-phase fluid flow through the rock networks (obtained by process-based technique) in order to test the predicted mercury/air capillary pressure data with the experimental counterparts. The results are encouraging. Considering the fact that the rock network is constructed from a single thin section image, predictions were in reasonable agreement with the measured data. We then simulated a water injection cycle after the primary oil invasion to see the effects of system's wettability on water/oil relative permeabilities. Oil relative permeabilities were higher for a water-wet system, however residual oil saturation was estimated to be lower for a system of intermediate wettability which is in line with previously conducted experiments[9].

Overall, pore-scale network modeling that combines an accurate description of the pore space with a detailed analysis of pore-scale displacement physics is a useful tool for understanding multiphase flow in porous media. From a practical perspective it can be used to make predictions for situations that are difficult to study experimentally.

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