Carbonate Reservoirs

Meeting unique challenges to maximize recovery
<table>
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<tr>
<th>Carbonate reservoirs: <strong>the future</strong> of world oil and gas production</th>
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<td>Carbonate reservoirs: <strong>heterogeneity</strong> at all scales</td>
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<td>Carbonate reservoirs: a <strong>continuous focus</strong></td>
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Although most energy experts agree that the world’s energy resources are adequate to meet this projected growth, more reserves will be needed to delay a peak in production. This means the petroleum industry will have to increase recovery factors significantly from all types of reservoirs. This increase in performance can be accelerated at the same time as reducing the technical risk.

From the statistics below it is clear that the relative importance of carbonate reservoirs compared with other types of reserves will increase dramatically during the first half of the 21st century. Therefore, so will the value of this market for oilfield services companies. However, there are significant challenges in terms of recovery due to the highly complex internal structure and specificity of carbonate reservoirs.

**MARKET SIZE**

More than 60% of the world’s oil and 40% of the world’s gas reserves are held in carbonates†.

- The Middle East has 62% of the world’s proved conventional oil reserves§; approximately 70% of these reserves are in carbonate reservoirs†.

- The Middle East also has 40% of the world’s proved gas reserves§; 90% of these gas reserves lie in carbonate reservoirs‡.

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† World Energy Outlook 2006
‡ Schlumberger Market Analysis, 2007
§ BP Statistical Review 2007
TECHNOLOGY OPPORTUNITIES

Techniques that were initially developed to characterize sandstone reservoirs are being applied to carbonate reservoirs, yet we know that these types of reservoirs have different requirements. The issues of addressing all of the uncertainties and variables in carbonates present great opportunities to develop tailored technology.

Schlumberger is committed to understanding and addressing the specific challenges and technical risks carbonates present. We are at the forefront of technology development into the challenges of carbonate reservoirs, and our continuous investment in R&D has led to a number of product and service introductions that are helping our customers optimize and improve the characterization, the production and the management of carbonate reservoirs.

World Distribution of Carbonate Reserves
The average recovery factor—the ratio of recoverable oil to the volume of oil originally in place—for all reservoirs is about 35%.

However, it is recognized that recovery factors are higher for sandstone reservoirs than for carbonates. Carbonate reservoirs present a number of specific characteristics posing complex challenges in reservoir characterization, production and management.

THE FUNDAMENTALS

Carbonates are sedimentary rocks deposited in marine environments with clear, shallow, warm waters and are mostly of biological origin. They are made up by fragments of marine organisms, skeletons, coral, algae and precipitation, and consist mostly of calcium carbonate, which is chemically active compared to the sand which makes sandstones.

Another key difference between clastic and carbonate rocks is the distance between the site where the sediment was created and where it was deposited. While sand and silt may travel hundreds of miles down river systems before deposition and lithification, the grains that comprise carbonate sediments are usually deposited very close to the place where they were created. This local deposition contributes significantly to the heterogeneity of carbonate grains. Once carbonate rock is formed, a range of chemical and physical processes begins to alter the rock structure changing fundamental characteristics such as porosity and permeability.
as porosity and permeability. This is known as diagenesis. At deposition, carbonate sediments often have very high porosities (35%–75%) but this decreases sharply as the sediment is altered and buried to reservoir depths. As a result, carbonate reservoirs exhibit large and abrupt variations in rock type distribution.

**COMPLEX STRUCTURES**

The porosity of carbonate rocks can be grouped into three types: connected porosity, existing between the carbonate grains; vugs, which are unconnected pores resulting from the dissolution of calcite by water during diagenesis; and fracture porosity which is caused by stresses following deposition. Diagenesis can create stylolite structures which form horizontal flow barriers, sometimes extending over kilometers within the reservoir, having a dramatic effect on field performance. Fractures can be responsible for water breakthrough, gas coning and drilling problems such as heavy mud losses and stuck pipe.

Together, these three forms of porosity create a very complex path for fluids and directly affect well productivity. This heterogeneity also has an impact on the response of logging measurements and therefore on the determination of oil in place.
WETTABILTY AND ITS EFFECT ON FLUID FLOW

In addition to the variations in porosity, wettability is a further heterogeneous characteristic in carbonates. The great majority of sandstone reservoirs are strongly water-wet. However, the aging of carbonate rock containing water and oil turns initially water-wet rocks into mixed-wet or even oil-wet rocks. This means that oil can adhere to the surface of carbonate rock and it is therefore harder to produce. Most carbonate reservoirs are believed to have mixed wettability or to be oil-wet.

Simulations show that in reservoirs under-going water flooding only limited amounts of oil can be recovered from oil-wet layers because the water tends to flow mainly through the water-wet layers. In fact, recovery factors can be less than 10%††.

Characterizing the distribution of wettability and understanding its effects on fluid flow within a complex reservoir is crucial in estimating the producible reserves and determining production strategies to maximize recovery.

Gravity-dominated flow in water-wet reservoir

Capillary-dominated flow in layered wettability

Simulations generated using ECLIPSE* software.
Sustaining global oil and gas demands requires advanced and appropriate oilfield technology in carbonate reservoirs.

Schlumberger recognizes the specific challenges of carbonate reservoirs and has a network of research laboratories and technology centers which is actively involved in carbonate projects. In the Middle East, the Dhahran Carbonate Research Center is entirely dedicated to carbonate research. Significant research activity in flow modeling, fracture detection and seismic services is also taking place in research centers in Cambridge, Stavanger and Moscow, while our research center in Boston is engaged in geology and petrophysics, and our technology centers in Clamart and Sugar Land are developing logging-while-drilling (LWD) and stimulation services targeting carbonate reservoirs.

Our long-term commitment to research into carbonates is enabling us to develop and introduce solutions that are improving characterization, productivity and recovery in carbonate reservoirs. Our regional technology centers support this commitment. The center in Abu Dhabi is focused on carbonates and enables customers to work alongside our experts to solve specific regional challenges.
Most carbonate reservoirs are naturally fractured. The fractures exist at all scales, from microscopic fissures to kilometer sized structures called fracture swarms or corridors, creating complex flow networks in the reservoir. As a consequence, the movement of hydrocarbons and other fluids is often not as expected or predicted. Just a few very large fracture corridors can be highways for fluids in the middle of a carbonate reservoir; therefore, knowing their exact position is critical for planning new wells and for simulating and forecasting reservoir production.

In fractured reservoirs our ultimate goal is to provide a complete geometric and dynamic characterization of the fracture network. Recent advances in seismic technologies for enhanced reservoir delineation, characterization and monitoring is doing much to bring us closer to that objective. Q-Technology services, combined with new processing methods, allow 3D detection of the position of fracture corridors within the reservoir.

One of the preferred workflows used across the industry is discrete fracture network (DFN) modeling. This is the approach Schlumberger has taken with Petrel seismic-to-simulation software. The Petrel workflow combines information from multiple domains into a unified representation of the reservoir.

DFN realistically models the connectivity of fractures and joints that give rise to irregular flow behaviour, combining a wide range of data from maps, outcrops, reservoir...
geomechanics, 2D and 3D seismic, well logs, well tests and flow logs, as well as structural or depositional conceptual models. The reservoir model combines the DFN workflow and fracture corridors that are directly imaged through seismic using a mathematical procedure called ant tracking.

**DRILLING TECHNOLOGY AND WELL PLACEMENT**

Directional drilling technology also plays a large part in improving and enhancing oil recovery. Today, using the PeriScope* bed boundary mapper service, specialists are able to geosteer horizontal drains to the most favorable spot of the reservoir using measurement-while-drilling (MWD) and LWD technology. It is possible to drill wells faster, more accurately and longer than ever before with rotary steerable systems, providing increased efficiency and reducing risk.

**ACCURATE POROSITY MEASUREMENTS**

The evaluation of hydrocarbon in place relies heavily on the accurate determination of fluids saturation and of total porosity. These characteristics exhibit great variability due to the heterogeneity of the rock and the influence of wettability. Accurate porosity measurements in carbonates require complete mineralogical characterization.

<table>
<thead>
<tr>
<th>Track 1</th>
<th>Track 2</th>
<th>Track 3</th>
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<tbody>
<tr>
<td>Res ELAN</td>
<td>Sigma ELAN</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>Water</td>
<td></td>
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<tr>
<td>Oil</td>
<td>Oil</td>
<td></td>
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<tr>
<td>Gas</td>
<td>Gas</td>
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</tr>
<tr>
<td>Dolomite</td>
<td>Dolomite</td>
<td></td>
</tr>
<tr>
<td>Calcite</td>
<td>Calcite</td>
<td></td>
</tr>
<tr>
<td>Anhydrite</td>
<td>Anhydrite</td>
<td></td>
</tr>
<tr>
<td>Bound Water</td>
<td>Bound Water</td>
<td></td>
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<tr>
<td>Illite</td>
<td>Illite</td>
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<tr>
<td>Hydrocarbon Volume Using Sigma Elan Volumes</td>
<td>ELANPlus Volumes</td>
<td>ELANPlus Volumes</td>
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<tr>
<td>0.4 ft³/ft³</td>
<td>1 ft³/ft³</td>
<td>0 ft³/ft³</td>
</tr>
</tbody>
</table>

Finding productive low-resistivity pay using sigma: In tracks 2 and 3, water appears in white, and oil in green. Track 2 shows the water and oil saturations calculated from a resistivity log using Archie’s equation. Track 3 shows water and oil saturations derived from EcoScope service sigma-based measurements.

The resistivity measurements (track 2) were pessimistic, while the sigma-based measurements more accurately predicted the oil in place. A subsequent MDT* Modular Formation Dynamics Tester log verified 70% oil in support of the EcoScope service sigma-based determination.
The recent introduction of the EcoScope* multifunction LWD service has allowed more accurate logging of saturation and porosity in carbonates for the first time. This is because it uses a thermal neutron measurement that enables logging specialists to estimate water saturation independently of the traditional resistivity-based measurement.

**STIMULATION AND COMPLETIONS**

Calcite dissolves in hydrochloric acid (HCl). Therefore, HCl treatments have been the most popular stimulation method for wells in carbonate reservoirs. Today, many wells are horizontal and can intersect fractures along their length. The acid tends to be wasted in the first fractures encountered by the well, leaving significant sections without stimulation.

Schlumberger is introducing solutions for optimum stimulation of carbonate reservoirs. An example of this is a new fluid that combines fibers and acid. The fibers temporarily plug the fractures allowing the acid to stimulate the entire well. Another example is StageFRAC* completion technology, which enables the creation of hydraulic fractures in multiple zones along the well.

With our recent acquisition of ResLink, our portfolio of completion technology now includes leading-edge inflow control devices that can be used to design completions for horizontal injectors and producers in order to optimize flow profiles. The effect is long-term; sustained production rates with better control of water cuts; and increased recovery due to the better reservoir sweep-efficiency obtained from the uniform injection flow profile.
ENHANCED OIL RECOVERY

Research into potential EOR for carbonate reservoirs covers the effectiveness of numerous drivers and their ability to target various effects in carbonate reservoirs. Drivers such as carbon dioxide (CO₂), methane (CH₄), surfactants, polymers, fresh water, steam and combinations of them all are used to target effects such as oil volume expansion, viscosity reduction, interfacial tension reduction, wettability change and flood fluid rheology optimization.

Recently, research into EOR has returned to the top of the agenda for most large international oil and gas companies. Schlumberger research is engaged in various projects to enhance oil recovery in carbonates and heavy oil reservoirs.

Our commitment to this ongoing research is supported by the technology we already have in place. The Sensa* fiber-optic distributed temperature system (DTS) continuously monitors the temperature profile along the wellbore, providing information about water and gas breakthrough, zonal isolation and well integrity. Schlumberger electrical submersible pumps (ESP) can be placed in wells deeper than 12,000 ft and hotter than 200 degC—when well conditions are continuously changing, an ESP monitoring system and a variable speed drive can optimize a pump’s performance. The two technologies are key for the monitoring and production of reservoirs using thermal EOR such as steam injection. The ECLIPSE software enables reservoir engineers to simulate the fluid flow characteristics of all types of reservoirs, accurately and quickly, to compare the effectiveness of various production strategies.

INTEGRATING TECHNOLOGY: TOWARDS A DEEPER UNDERSTANDING

Carbonate reservoirs will continue to pose challenges relating to rock type and porosity. A drive towards greater integration of technology will improve performance and lower technical risk through better reservoir characterization and more accurate reservoir models.

We know that solutions to the oil recovery challenge in heterogeneous carbonate reservoirs can come only from increased research efforts and continued collaboration. These will help to refine existing techniques and to develop new and configurable, carbonate-relevant technologies.
Carbonate Reservoirs

Carbonates present us with some of the greatest challenges and opportunities to develop new technologies and processes, or refine existing ones, to maximize their recovery.