A novel method of determining
gas saturation has proved
successful in Oman’s Natih Field
where conventional methods
were giving anomalous results in
difficult conditions. Stephen Adams and Johann van Popta of Shell describe how, for the first
time in the Middle East, sensitive borehole gravity measurements,
interpreted as density logs, have been compared with traditional density readings or previous borehole gravity measurements to derive a quantitative estimate for gas saturation changes.

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Fig. 1.2: TRUE LIFE STORY. At discovery, the Natih Field had no gas cap. Through primary depletion the FGOC moved down and the FOWC moved up. Oil was left above the FGOC and below the FOWC in the matrix blocks. Finally, with gas injection, the oil rim in the fracture system is pushed down. This exposes the maximum possible amount of rock to the gravity drainage process. Oil is produced at controlled rates from the oil rim in the fracture system.
The effectiveness of the gravity drainage process depends on a uniform and complete gas-oil contact being maintained in the fracture system. To find out how well the process had been working in the Natih Field, Petroleum Development Oman (PDO) launched a gas saturation monitoring campaign four years ago using conventional and pulsed neutron capture measurements. Readings were taken through production tubings and in workover wells. The estimated secondary gas saturations were not only lower than predicted by material balance calculations but were inconsistent - even within a single well (figure 1.3). As the blocks of reservoir rock between the fractures are relatively impermeable, it is believed that the shallow-reading neutron devices could not see beyond the mud filtrate trapped in the rock surrounding the borehole, giving rise to pessimistic estimates of gas flushing and variable results.

Because of this doubt over the validity of the gas saturation results, an alternative method had to be found for evaluating the reservoir’s gas saturation.

Research by Shell in The Netherlands indicated that the Borehole Gravimeter (BHGM) might be the answer. This is a deep-reading tool which the research team believed would see beyond the invaded zone and could be used to quantify gas saturations (see box right). Extensive modelling studies were conducted at Shell’s research laboratories in Rijswijk, The Netherlands. The study findings confirmed that bad hole conditions, invasion of drilling fluid, poor cement bonds, the presence of perforations and previously acidized intervals would have a negligible effect on the gravity readings.

Two factors stood out as being critical in achieving accurate gas saturation measurements from the BHGM:
- A clear knowledge of the porosity around the well, derived from open-hole logs.
- An accurate depth measurement for the tool at each recording station.

Consequently, the four wells selected for BHGM surveys in the Natih Field were chosen not only for their structural position above the fracture GOC and the completion status but also for the quality of their open-hole porosity logs. Depth control was achieved using a combination of wellhead, manual and downhole measurements. A special odometer was mounted on the wellhead and a casing collar locator log was calibrated with a casing tally.

In addition, the length of cable run down the borehole between measuring stations was checked manually using a steel tape and a high-precision pressure gauge was included in the tool string. This last gauge was added because it was assumed the tool movement downhole could be estimated directly from the difference in wellbore pressure - the borehole being filled with brine, rather than weighted drilling fluid. Each of the three depth measurements were examined in conjunction with the gravity measurement and an optimum depth determined for each BHGM measurement.

The provision of a stable borehole environment is essential to ensure good quality gravity readings with such sensitive equipment. In the depleted fractured carbonate reservoirs of North Oman, heavy fluid losses are encountered when a formation is open to the borehole.

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**Fig. 1.3: CONSTANT CONFUSION**

Gas saturation from Pulse Neutron logs gave inconsistent results - even within individual wells.
EDCON’s gravity meter (manufactured by LaCoste & Romberg) is fundamentally a very sensitive spring balance in which the weight of a hinged beam with a small mass on its free end is balanced by the tension of a spring (figure 1.4). As the gravitational acceleration - and hence the weight of the mass - changes, the spring tension must be changed to hold the beam in a stationary horizontal position. The spring tension is calibrated in gravity units.

Essentially, the BHGM can be used to quantify hydrocarbon saturations by reinterpreting the results to produce a density log. To do this, the earth is modelled as a layered cake with infinite horizontal slabs (figure 1.5).

The change in gravity between the top and bottom of each slab is proportional to the slab’s density and thickness.

The density of each slab is made up of the matrix (rock) density, plus the fluid density. As oil is replaced by gas, the fluid density decreases. This ‘density’ log from the BHGM can then be compared with the original open-hole density measurements. In the Natih Field, where there was no initial gas cap, any differences between the two measurements can be directly attributed to fluid movement and thus gas saturation.

Under normal conditions, measurements can be repeated to within a standard deviation of about 3µgal (three parts in $10^9$ of the Earth’s gravitational field).
Prior to running the surveys, three of the four wells in the Natih Field were being worked over, thus all existing perforations were closed with cement. This prevented fluid movement distorting the results. In the remaining wells, the surveys were carried out before perforating.

As a result of the co-operation agreement between Schlumberger and EDCON, the surveys were conducted using EDCON's Deep Density BHGM sonde in combination with Schlumberger's gamma ray and high-precision pressure gauge tools. Each survey took readings at the geological sub-unit boundaries, producing an average gas saturation for each layer. Typically, 15 to 20 gravity stations were selected in each well from 20 m below the GOC in the fracture system to 20 m above the reservoir. Before each reading the tool had to be left to stabilize for several minutes. Readings at some stations were repeated in order to improve the precision of gravity and depth measurements and to provide monitoring of gravimeter drift. Overall, the logging time varied between 15 hours and 30 hours.

Using a BHGM to determine gas saturation is an innovative use of the tool based on theoretical considerations and experience in sandstone reservoirs in Texas, USA. To ensure the validity of the results in complex fractured carbonate reservoirs, a control test was planned in two new development wells over a gas-bearing formation in the nearby Yibal Field (figure 1.6). The estimates produced by the new tool were compared with gas saturations calculated using resistivity logs. Figure 1.7 shows the similarity of the results produced by the two techniques.

Confidence in the tool is further increased by comparing the BHGM-derived formation densities and the open-hole density log for Natih-48 (figure 1.8). In this example, the calibration intervals above the reservoir and below the fracture GOC show good agreement. The discrepancies between 585 m and 601 m can be attributed to the gas-filled formation's influence on the BHGM.
Gas saturations around the Naith Field have been estimated based on BHGM measurements. When plotted with gas saturation values derived from earlier pulsed neutron measurements the BHGM estimates show consistently higher gas saturation. This ties in with the neutron tool being affected by drilling fluid trapped around the borehole (figure 1.9a and b).

Secondary gas saturations estimated for the Naith Field using the BHGM are now similar to predictions from reservoir simulation studies, according to Shell. Gas/oil gravity drainage will continue to be the primary recovery mechanism in the Naith Field, as will the use of the BHGM for gas saturation monitoring.

**Fig. 1.8:** A comparison between BHGM-derived densities and the shale corrected open-hole density log shows excellent correlation above the reservoir and below the GOC.

**Figs 1.9 (a) and (b):** Comparison of gas saturations predicted by the BHGM and PNL for two different subunits show that an envelope created through the BHGM results completely encompasses the PNL figures. This is consistent with the latter figures being influenced by drilling fluid trapped in the rock matrix adjacent to the well.