Borehole gravity in Horizontal Wells.

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SUMMARY

Gravity can now be measured practically anywhere a drill hole can go. This extends our ability to perform 3D and 4D gravity mapping of the sub-surface with applications in the energy and mineral sectors.

New tools have been developed to perform these measurements. The tools address issues of size, measurement accuracy, stability and ruggedness. The data handling has also changed to address the 3 dimensional nature of the measurements. Whereas previous borehole gravity measurements in near vertical wells could ignore latitude corrections and use simpler terrain correction, surveys in highly deviated wells involve calculating and using 3 dimensional coordinates for each gravity station in the correction process. This all needs to be done preserving the survey accuracy requirements that are often only a few microGals.

Tool location is extremely important, more in the vertical direction due to the vertical free air and Bouguer gradients. Tool location control tends to be more difficult in more horizontal holes. A new high sampling resolution CCL tool has proven very useful for repeat location of the tool for drift calculations and time lapse measurements.

For oil and gas, most applications in highly deviated or horizontal wells are expected to be of a time lapse mode such as monitoring of traditional and SAGD type steam floods.

For mining the tool significantly extends the volume of investigation for deep exploration and development holes.

Key words: Borehole Gravity, logging, petrophysics,

INTRODUCTION

For many years borehole gravity measurements were limited to near vertical wells due to the difficulty in designing a field rugged, sufficiently accurate instrument in a small package to operate in an environment much more hostile than that of surface gravity instruments. With the introduction of the initial Gravilog tool by Scintrex and the Micro-g LaCoste / Scintrex Bluecap tool, the deviation restriction has been removed and surveys can be made up to 105 degrees from vertical. The tools are also slimmer and capable of operations in smaller casing, tubing and drill rod sizes.

With this new capability there are changes in how we acquire, process and interpret the data. Many surveys in near vertical wells were collected to measure density information from large volumes surrounding the well based on the relationship between density and the vertical gravity gradient. This calculated borehole gravity density concept tends away from the simple formation density concept used in vertical wells and near horizontal sediments and must be regarded more as an apparent density as we find ourselves in more complex environments. The density concept breaks down completely for purely horizontal wells and the borehole Bouguer gravity values must be used. The use of Bouguer gravity in multiple wells brings up questions regarding survey techniques, common Bouguer densities for all wells, tying wells together to a useful accuracy level and relocating the instruments with sufficient precision for accurate drift corrections.

DATA ACQUISITION

Both of the current tools use the quartz sensor from Scintrex. This is an adaptation of the sensor in the latest Scintrex CG-6 land gravity meter. There has been quite a long path of experimentation with design minutiae, packaging and environmental control that have produced a sensor with extremely regular drift with very few tares. The sensor has demonstrated repeatability of less than 5 microGals running surveys under a range of conditions. The high temperature tool operates up to 150°C and incorporates active Peltier heating and cooling to control the sensor temperature. The 2.5 inch O.D. pressure housing operates to 15,000 psi. The slimmer 1.9 inch O.D. tool currently operates up to 80°C and 3500 psi. This is the current version of the original mining Gravilog tool. With the trend toward deeper mining exploration and development drilling and to stay within smaller tubing sizes, this tool is being upgraded to higher pressure and temperature ratings with the same diameter. Readings are made with the tool held stationary and the spring and mass levelled to local vertical. MEMS level sensors have proven very stable and the system can level the tool while moving between stations.

Figure 1: The BHG tool in the foreground with a well tractor.

The BHG tools operate on a single conductor cable. There are sufficient extra conductors in a seven conductor cable to run the BHG tool "beneath" a well tractor (Figure 1). Typically the tractor pushes the BHG tool to the end of the horizontal section of the well and gravity is measured as the tool is retrieved using the wireline.

Depth control is important for BHG surveys because a depth error is difficult to differentiate from a change in gravity. In a vertical well with a density around 2,500 Kg.m^{-3} the vertical gravity gradient is about 1 microGal/cm. The BHG tools are relatively light compared to some long combo tools and the resultant different amounts of cable stretch between logging runs can make maintaining good depth correlation over long stretches of well challenging. Our strategy is to establish a master log with a high resolution CCL log that is stretched to match the original established depth reference log for that well. This high resolution master CCL log allows us to reposition the gravity tool to within 2 cm and better on subsequent passes in one well survey. The same repositioning accuracy is seen on returning to a monitoring well after a substantial interval.

As deviation increases the vertical gravity gradient becomes less of an issue but increasing hole deviation is often accompanied by increased stick and slip motion of the tool as the wireline is retrieved. This can become fairly severe and the task of maintaining measured wireline depth to within a centimetre or two becomes more difficult but the errors are of less consequence than in a vertical well. The tools have accelerometers recording at the same sample rate as the CCL and we are working on integrating the accelerometer information to improve the CCL position control. (Figure 2.)

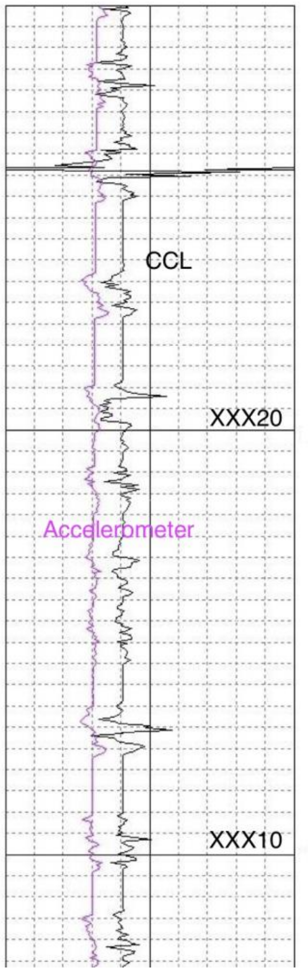

Figure 2: Stick and slip motion shown by CCL (black) and accelerometer (pink) traces.

Data processing is fairly simple in principle with many corrections that are programmed and well understood. The corrections include off level corrections, solar, lunar tidal and ocean loading corrections, atmospheric pressure corrections and position dependent corrections including latitude and terrain corrections. The latter two corrections can be made during recording if well trajectory survey information is available before logging. The minimum curvature method is used to calculate the three dimensional position of the gravity measurements lying between well survey points.

Drift corrections are, in principal, fairly straightforward involving a linear least squares fit of repeated measurements at the gravity stations but these tend to involve most processing time. In practise, the design and execution of a survey with sufficient repeat readings in the zones of interest influence the ease and accuracy of performing drift corrections. The survey design is a function of the survey objective. For example time lapse monitoring of reservoir fluid saturations requires much more precision than salt flank delineation survey. The survey execution can be planned in detail but an experienced engineer on site can avoid many situations that can upset the best made plans.

APPLICATIONS

The main use of BHG logging in highly deviated and horizontal wells is expected to be for time lapse monitoring. Relatively shallow steam floods and SAGD heavy oil programs could be monitored with gravity at much closer range than surface measurements allow, although a combination of surface and downhole gravity measurements would give the most complete picture. Monitoring of CO2 or acid gas disposal into aquifers also benefits from high fluid density contrast between injected and displaced fluids, increasing the magnitude of the time lapse gravity signal.

CONCLUSIONS

Borehole gravity measurements capabilities have been extended to highly deviated and horizontal wells. This involves a shift in focus from the traditional large volume density through casing use of the tool to remote sensing of time lapse reservoir fluid distribution changes. Deep mining exploration and development will also benefit through increased drill hole volume of investigation