Geosteering horizontal wells on Ross Field using heavy mineral analysis

When biostratigraphy component fails

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Geosteering of horizontal wells is usually achieved by the integration of biostratigraphy, measurement while drilling (MWD) and geological evaluation of ditch cuttings. This combination is compromised if the biostratigraphic component of the geosteering toolkit lacks resolution (for example, in red-bed continental sequences), and by the use of polychrystalline diamond compact (PDC) bits, which causes severe deterioration in sample quality. Such circumstances require the application of alternative, less conventional geosteering methods.

Heavy mineral analysis (HMA) is one possible approach that can be applied to sandstone reservoirs, since heavy minerals are ubiquitous in sandstones and are frequently used in reservoir correlation. The technique involves optical microscopic analysis of heavy mineral residues from ditch cuttings at the well site, with data acquisition taking approximately two hours from receipt of sample at the surface. Wellsite HMA was pioneered on appraisal wells in the Clair Field, west of Shetland, in 1996-1997, but its first application in a field development program was on the Ross Field in the North Sea.

The main reservoir in the Ross Field (Moray Firth, North Sea) consists of shoreface sandstones of the Ross Formation, with significant reserves in the underlying alluvial/fluvial Parry Formation (both Upper Jurassic). The Ross Formation, which was deposited during progressive transgression, is informally subdivided into four units (R1, R2, R3 and R4 in ascending order). Each unit is approximately 20 ft thick, and represents a basal transgressive event followed by shoreface progradation.

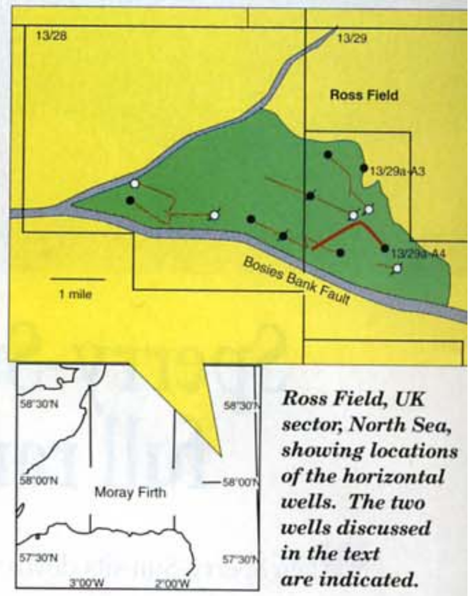
Reservoir quality

Reservoir quality in the Ross Formation is strongly dependent on depositional facies, the best quality being associated with the more proximal marine facies (middle/upper shoreface) and the poorest quality with the most distal (offshore) facies. The distribution of good quality reservoir across the field is therefore dependent both on stratigraphy and paleogeographic setting.

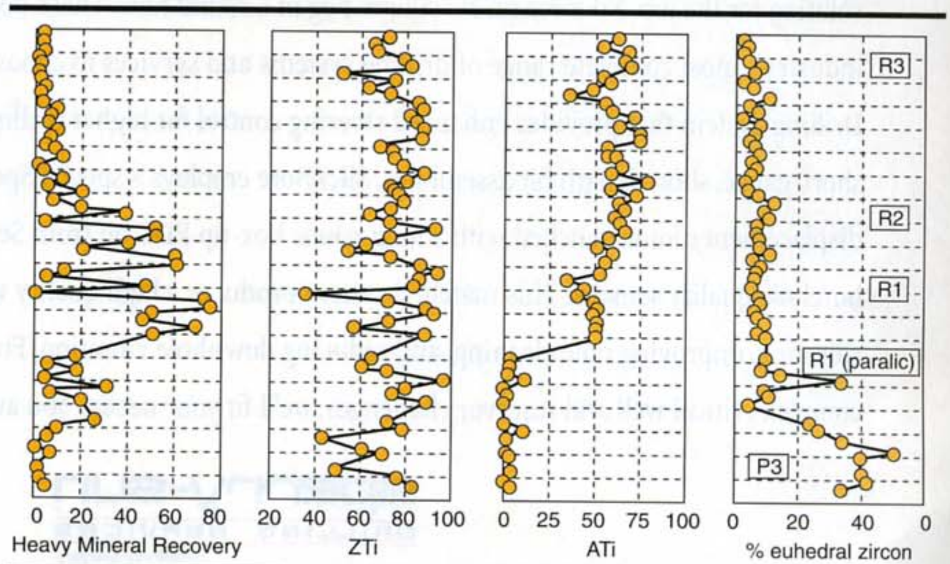
Exploitation of the Ross Field requires drilling horizontal wells that target relatively thin pay zones. Since biostratigraphy lacks sufficient resolution to distinguish R1, R2, R3 and R4, HMA was considered to have greater potential for geosteering in this context.

Prior to its use at the well site, the applicability of HMA was investigated by analyzing existing cores of the Ross Formation from vertical or subvertical offset wells. The studies showed marked downhole variations in a number of key parameters, including overall detrital heavy mineral recovery, mineral ratios, and mineral grain attributes. These variations provided confidence that the method would have sufficient resolution to identify and distinguish the various stratigraphic units during drilling of horizontal wells. The most useful parameters proved to be:

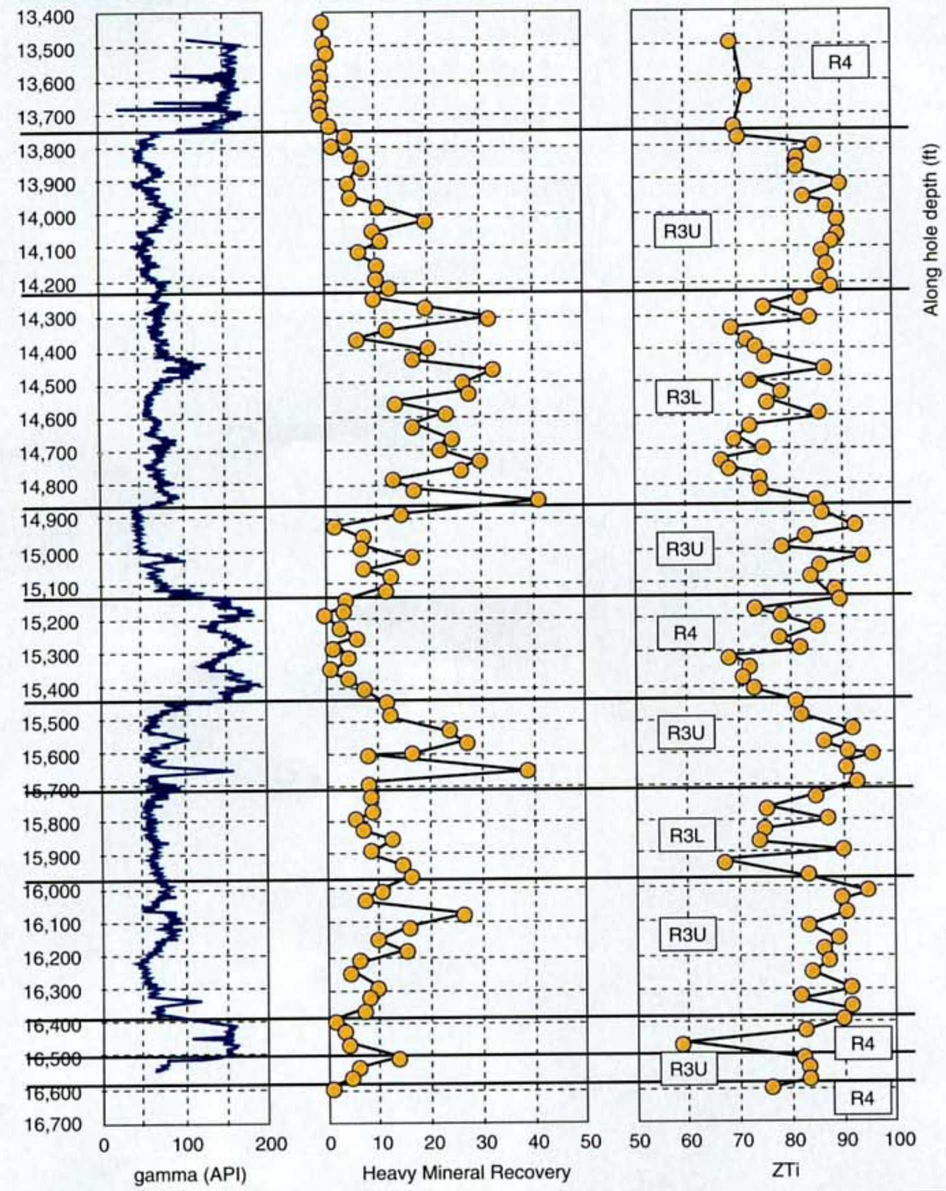
• Heavy mineral recovery, which is very low in distal offshore sediments, but increases with proximity to the paleoshoreline. The decrease in recovery in the more distal sediment is due to the reduction in clastic sediment supply.



Ross Field, UK sector, North Sea, showing locations of the horizontal wells. The two wells discussed in the text are indicated.



Variations in key heavy mineral parameters from part of the core in well 13/29a-A3. These parameters were used to build up a template of mineralogical characteristics of the Ross and Parry formations across the field to help calibrate and interpret the parameters determined subsequently at well site.



Along-hole variations in two key parameters determined at well site during drilling of 13/29a-A4, shown against the LWD gamma ray log. The mineralogy clearly identifies penetrations of R4, upper R3 and lower R3, and was used to aid decision-making during drilling.

Recovery also tends to be relatively low in paralic sediments (Parry Formation and R1 coastal plain facies).

- The zircon:tourmaline ratio (ZTi), which varies on a high-frequency basis throughout both Ross and Parry due to a combination of changes in sediment provenance and hydrodynamic conditions during deposition.
- The apatite:tourmaline ratio (ATi), which reflects the extent to which sediment has been weathered during the sedimentation cycle. ATi is high throughout in the marine parts of the Ross Formation (R1-R4) but very low in paralic sediments (Parry and R1 coastal plain facies)
- The abundance of euhedral and brown zoned zircons, which are indicators of sediment derived directly from the Ross granite of the adjacent hinterland. Such zircons are scarce in the Ross Formation but are common in the Parry.

HMA geosteering

To date, HMA has been used to geosteer nine horizontal wells on the Ross Field (13/29a-A3Y, 13/29a-A4, 13/28a-B2, 13/28a-B3, 13/28a-C1Z, 13/28a-C2, 13/29a-D1, 13/29a-D2 and 13/29a-E1). HMA is particularly effective in the Ross Field, since penetration rates (ROP) are relatively slow (typically 10-20 ft/hour), and the logging tools are placed some considerable distance behind the bit.

For example, the gamma ray tool is 54 ft behind the bit. At an ROP of 15 ft/hour, HMA can give an indication of formation change some two hours before the gamma ray log, taking into account cuttings lag time and heavy mineral extraction. Heavy mineral data were used in the decision-making process in a variety of situations, including identification of the 9 5/8 in. casing point, deciding on TD, and whether to maintain angle, to steer up or to steer down.

A typical example of the application of HMA as a geosteering tool for the Ross Field development is well 13/29a-A4. This well targeted the R3 unit, which has the best reservoir quality in this part of the Ross Field.

Heavy mineral data provide a clear distinction between R3 and the overlying non-reservoir R4 unit, and also differentiate the better-quality upper R3 from the poorer-quality lower R3. R4 is distinctive in having a combination of very low recovery and low ZTi. The upper R3 has high recovery and high ZTi, whereas the lower R3 has high recovery and low ZTi.

Consequently, when HMA indicated that the well track had penetrated lower R3 (for example, at 14230 ft and subsequently at 15710 ft), a decision was made to build angle to enable the well track to re-enter better-quality upper R3. Similarly, when HMA indicated that the well track had penetrated R4 (at 15140 ft and subsequently at 16,390 ft), a decision to drop angle was taken. This was successfully achieved after the first penetration of R4 (15,140-15,440 ft).

However, after the second R4 section (16,390-16,500 ft), R3 sediment was encountered only until 16,575 ft, at which point penetration of R4 was renewed. This indicated that it was no longer possible to steer the well, and since the target of drilling 2,500 ft of high-quality reservoir had already been achieved, TD was called.

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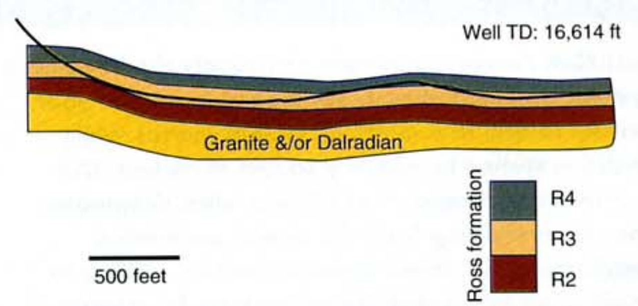
13/29a-A4 well trajectory



Geological interpretation of the 13/29a-A4 well trajectory, showing the extensive penetration of good-quality upper R3 reservoir sandstone.

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strength cable resulted in a 16,000 lb pull. If the capstan and high strength cable had not been available, the logging job would have had to be pipe conveyed costing 3-5 days additional rig time.

- **One-pass drilling:** Five of the eight borehole sections were drilled in one pass as planned.
- **Geological requirements:** All geological requirements, including a minimum acceptable depth of 28,100 ft, plus the ability to drill to 30,000 ft and log a well at that total depth, were achieved.

The last kick was handled at the +/-27,000 depth level, which may be the deepest circulation Chevron has ever performed.

- **Operator trouble time:** Total operator trouble time was 6.7%, including well control incidents. Excluding well control incidents, the operator preventable downtime for the well was 4.9%.
- **Well control operations:** Three well control operations were handled safely and efficiently in the subsea environment. There were no major hole problems or stuck pipe problems. After the three kicks were circulated out, drilling was continued after only a short trip. The last kick was handled at the +/-27,000 depth level, which may be the deepest circulation Chevron has ever performed.
- **Casing operations:** All casing strings were set at planned depth or deeper, as hole conditions allowed. This ensured that the well objectives could be met.
- **LOT/FIT values:** All necessary LOT/FIT (leak-off test/formation integrity test) values needed were achieved with no shoe squeezes.
- **Proven equipment:** Most tools used on the well were proven equipment from the service companies. New items used included the Baker In-Line liner hanger to install the heavy 11-7/8 in. liner, and the Baker High Flow Surge Valve on the 9-5/8-in. liner installation. The In-Line hanger and integral liner top packer performed as expected during the installation. The HF Surge Valve was used to help reduce expected synthetic based mud (SBM) losses when running the deep liner. No mud was lost running the liner and the valve closed as required for the cementing operations. ○

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rotation has long been accepted by the industry as beneficial to primary cementing operations. Moving the pipe has been shown to improve cuttings and filter cake removal, and help break down mud gel.

These advantages continue to hold true when considering horizontal or highly deviated wells. However, due to the nature of the wellbore, pipe tends to lie along the bottom introducing additional torque and drag forces, which must be overcome.

For these reasons most liners are now set and released before pumping cement, and whenever possible, rotated. In addition, when the casing/borehole relationship is severely eccentric, rotation appears to be more beneficial than reciprocation. Rotation of the pipe requires sufficient torque to overcome the downhole forces. These include:

- Weight of the pipe (which is lying on the low side of the open hole with little or no buoyancy)
- Weight of the cement slurry before it leaves the pipe
- The inherent restrictions associated with any centralizers.

Computer simulations

Excellent wellbore isolation has primarily been successful through the application of good cementing practices. Due to the limitations on reciprocation of the pipe and the low fracture gradient of the formation, annular cleaning has been achieved by other techniques. Implementation of the multiple spacers, each with a different flow regime, has allowed improved hole cleaning, while reducing the placement ECD. The thin low fluid loss slurry is easy to mix and pump, yet provides excellent zonal isolation and pipe support.

The ability to simulate the job on computer ensured that the fluid's rheology and density are beneficial to the job objectives and the effects of any changes are accounted for. In addition, the novel use of centralizers with rollers during well 1M-16-SPz allowed this long section of pipe to be rotated for the majority of the cement placement process. ○

Acknowledgement

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***Author's Note:** In the text, reference is made to API Spec 10a dated 1991. Please note that this was the most recent issue of the specification at the start of the project and that test procedures have been continually compared against more recent issues, as they have become available.*

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Other applications

An additional application of HMA in the Ross Field is the identification of the 9 5/8-in. casing point. Since the overlying Heather Formation is frequently unstable and requires a much higher mud weight than required to drill the reservoir, it is important that the casing point is placed in the relatively thin R4 unit.

The R4 can be differentiated from the Heather Formation on the basis of a small increase in heavy mineral recovery and by the appearance of glauconite, as well as its typical high-gamma signature. In one well on the Ross Field, there was an MWD failure during drilling of the lower Heather.

Heavy mineral analysis now has a positive track record for geosteering horizontal wells during a field development program.

This could have necessitated making a trip to change the bottomhole assembly, but the casing point was picked solely on the basis of the heavy mineral data and geological evaluation of ditch cuttings, thereby achieving significant cost saving.

In many of the horizontal wells on Ross, total depth (TD) is called either because the well achieved its target or because mechanical reasons made it impossible to steer adequately.

However, in the water-injector well 13/29a-E1, after drilling over 600 ft of good-quality R2 and R3 sediment, HMA indicated that the well had penetrated an upthrown basement block. In view of uncertainty over the precise throw on the fault, it was unclear how long it would take to drill through the basement back into the reservoir. Since the R2 and R3 section that had been drilled was deemed to be sufficient for the purposes of water injection, it was decided to terminate drilling at this point.

As a result of its application on the Ross Field, heavy mineral analysis now has a positive track record for geosteering horizontal wells during a field development program. The technique can therefore be genuinely considered as an alternative geosteering tool in circumstances where biostratigraphic methods have inadequate resolution. ○

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