When drilling for oil, the target may be small and several kilometres from the rig. Drifting off-target is expensive and can be dangerous. **David Kerridge, Susan Macmillan, Christopher Turbitt and Ellen Clarke** describe how drillers find their way around the subsurface.

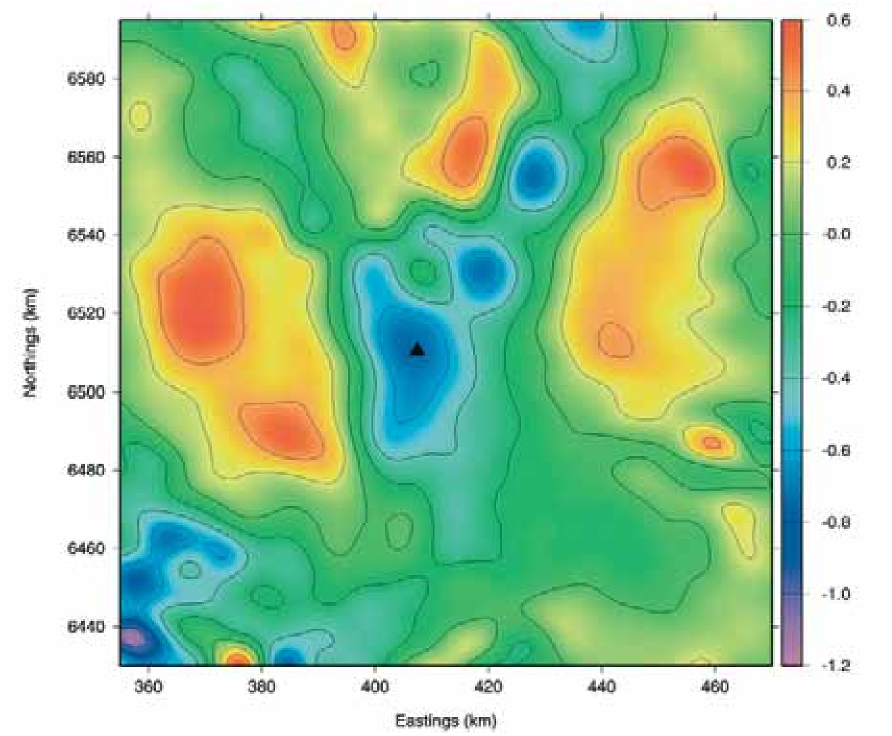
Navigating the subsurface

Modern drilling technology allows wells to be drilled along paths reaching over ten kilometres horizontally and five kilometres vertically. Well paths are often complex by design and the target size may be as small as 100 metres, so high accuracy is needed to navigate to the target. In areas such as the North Sea, the subsurface is congested, with as many as 50 wells drilled from a single rig. This means that the need for accurate drilling is driven not only by economic factors but also by the need to ensure safety by avoiding well collisions. Good accuracy depends on the ability to survey the well path as drilling progresses. Both gyroscopic and magnetic downhole survey tools are used for this purpose. Gyroscopic devices provide a directional reference by sensing the Earth's rotation; magnetic tools use the Earth's magnetic field in a similar way to a simple hand-held compass. However, the desired accuracy in the magnetic field reference direction is about 0.1 degrees, a much more demanding specification than for conventional compass navigation.

The Earth's magnetic field includes contributions from several sources. The major component, referred to as the main field, is generated in the Earth's core, about 2900 kilometres below the surface. It varies smoothly at the Earth's surface and has typical length scales of a few thousand kilometres. At present, there are two magnetic survey satellites in orbit around the Earth providing excellent global datasets, enabling the main field to be mapped accurately. The timescale for significant changes in the main field is months to years and there are about 180 permanent magnetic observatories around the world monitoring its long-term evolution. We make use of the satellite and ground-based observations to produce annual revisions of a model of the main field and its changes with time. This is designated the BGS Global Geomagnetic Model (BGGM).

Locally, the main field is perturbed by magnetic fields created by rocks containing magnetic minerals. The magnitude of the crustal field is generally less than one per cent of the main field, but it can cause changes in the field direction much greater than 0.1 degrees. There are regular daily changes caused by electric currents flowing in the Earth's upper atmosphere. Additionally, when a solar storm blasts plasma into space the Earth may feel the effects of the changes in 'space weather' one to three days later as various current systems in the near-Earth space environment are enhanced, causing a magnetic storm. Major storms cause short-term changes of several degrees in compass direction in the UK. Because the short-term magnetic field variations have their sources above the Earth's surface they are referred to as external fields.

Instrument housing at Sable Island Observatory.



The estimated anomaly in compass direction (in degrees) at drilling depth over an area of approximately 100 km x 100 km in the North Sea based on aeromagnetic survey data.

For many years well-bore surveys carried out using magnetic tools were thought to be less accurate than gyroscopic surveys because of poor accuracy in the estimates of the Earth's magnetic field at the drilling location. This was because the magnetic reference data were generated from a main field model with no attempt made to account for the magnetic effects of the local rocks or short-term changes in the geomagnetic field. In collaboration with Sperry Drilling Services (Halliburton), we have shown how these effects can be taken into account to provide magnetic reference data tailored to a specific drilling site. The BGGM gives values of the main field. Short-term magnetic field variations are modelled using data from one or more remote permanent magnetic observatories. Estimating the effects of local rocks is a more challenging problem, particularly in the offshore environment. Aeromagnetic or marine magnetic data are often available, but these are usually measurements of field strength, not direction. However, with plausible assumptions, the perturbing effects of the crustal field on the direction of the main field can be estimated from such data.

This method of accounting for the fields from the core, the crust and currents external to the Earth's surface is termed Interpolation In-Field Referencing (IIFR) and it is designed to help achieve the accuracy target of 0.1 degrees. It is acknowledged that there are limitations.

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Estimating the crustal magnetic field, particularly the downward continuation to drilling depths, is difficult when the magnetic field sources are close to the point of observation. During magnetic storms the spatial scale of field variations can be short, and the correlation between the variations seen at a remote observatory and at the drilling site is likely to be less than at magnetically quiet times. Because the effects depend on geographical location, an assessment of the accuracy achievable must be made on a site-by-site basis. Even where it is difficult to achieve high accuracy it is invaluable for well planning to have a proper estimate of uncertainties so that realistic error bounds can be placed on the well path.

Despite these caveats, the success of IIFR for numerous wells in UK waters has gained the confidence of the oil industry, and its application has spread to other parts of the world. With our help, Sperry Drilling Services has installed magnetic observatories on Sable Island, offshore Nova Scotia, and in Prudhoe Bay, Alaska to provide data on external field variations. These observatories are run to high standards and contribute valuable data for scientific studies as well as for application in drilling. A new aeromagnetic survey was flown over the oilfields close to Sable Island, and existing data for Alaska were used to model the crustal magnetic field. The investment in the new observatories and surveys represents a considerable outlay for data acquisition. The demonstrable benefits that IIFR has brought to drilling have made it a commercially sound investment.

Because of its high latitude and proximity to the auroral zone, the external field variations observed at Prudhoe Bay are large almost every day. This means that correcting downhole survey data for external field variations is vital. At low latitudes the external field variations are smaller and, depending on the circumstances, the errors introduced by ignoring the effects may be small enough to be neglected. In these cases it is still beneficial to account for the crustal magnetic field. Examples of oilfield areas where we have recently performed crustal field analyses include Angola, Azerbaijan, the Gulf of Mexico, Kazakhstan, Mauritania, Newfoundland, Sakhalin Island and Trinidad. Even when both the crustal and external fields are ignored, the BGGM is used to generate magnetic reference values for drilling locations worldwide.

For further information contact:

David Kerridge, Edinburgh,
Tel: +44(0)131 650 0220
e-mail: djk@bgs.ac.uk