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BOREHOLE GEOPHYSICS: EXPLORING THE THIRD DIMENSION

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ABSTRACT

The application of borehole geophysical techniques to mineral exploration has become more widespread in the last decade. There have been a number of significant technological developments in hardware (probes, sensors, cables and winches), and software (modelling, interpretation and data display). The use of borehole EM techniques in base metal exploration has become routine. Several new three-component borehole EM systems have emerged and new advances have taken place in the area of orientation of the three-component probes and in borehole directional surveying. New generation three-component magnetometer probes with orientation are available. Improved interpretation has led to increased requirements for physical property logs, especially magnetic susceptibility and resistivity/conductivity measurements. Logging for other physical rock properties is also receiving more attention in mining and mineral exploration. This has been supported in part by the Geological Survey of Canada's work aimed at documenting borehole geophysical signatures of major deposits and establishing test sites for downhole measurements.

A multiparameter approach to borehole geophysics provides the best data required for interpretation and for imposing constraints on models. Great strides have been made with respect to inverse modelling of surface data, and extensions of these inverse methods to the borehole environment are currently being developed.

Acoustic velocity logging is now being used to provide data for new high resolution seismic surveys in mineral exploration, and when combined with density logging, for geotechnical information. New technology aimed at in situ assaying has been developed and tested in Canada and Australia, and elemental measurement technology developed for petroleum exploration is now being evaluated.

In addition to acoustic and electrical tomography, the RIM (radiowave imaging method) has been introduced for tomographic imaging of ore bodies. Directional capabilities have now been developed for borehole radar. Borehole probes are available to measure induced polarization, inductive conductivity at several frequencies, and capacitive as well as galvanic resistivity. There are high sensitivity flowmeters and temperature probes, and new tools for viewing the interior walls of boreholes optically, electrically or acoustically. A whole new range of multiparameter borehole probes is also available from several manufacturers.

INTRODUCTION

Borehole geophysical measurements are made by sensors (receivers/detectors) which are housed inside a probe or 'tool' which is lowered down holes in which the measurements are to be made. Usually a series of continuous measurements (logging) are made with the data (signal) transmitted to the surface recording instruments via a logging cable. The cable also serves to send power to the downhole sensor instrumentation, although some probes are powered by batteries in the probe, and in some cases the data are stored in memory in the probe for later retrieval. The primary components of a geophysical logging system include the probe, cable, winch, wellhead pulley assembly at the top of the hole, a depth counter, and the surface recording instrumentation which displays the data, and usually supplies the power to the probe (see Figure 1). Several types of measurement configurations are possible, as summarized schematically in Figure 2.

1. The probes may measure a physical property simply with passive sensors in the probe as in the case of magnetic susceptibility or natural radioactivity measurements.
2. Some measurements require an active source or transmitter in the probe in addition to the sensor, as in acoustic velocity measurements with a transducer (energy source) in the probe, or in density

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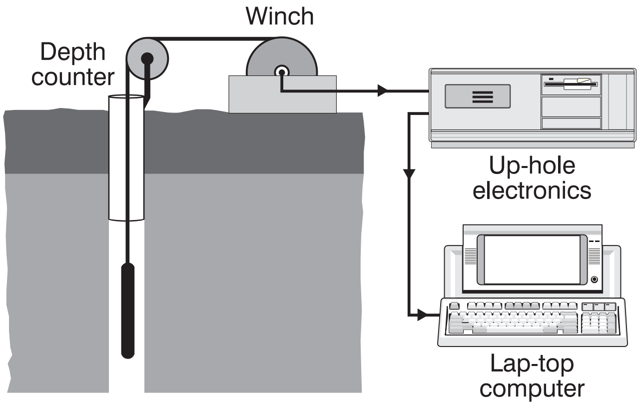

Figure 1: *Components of a typical borehole geophysical logging system.*

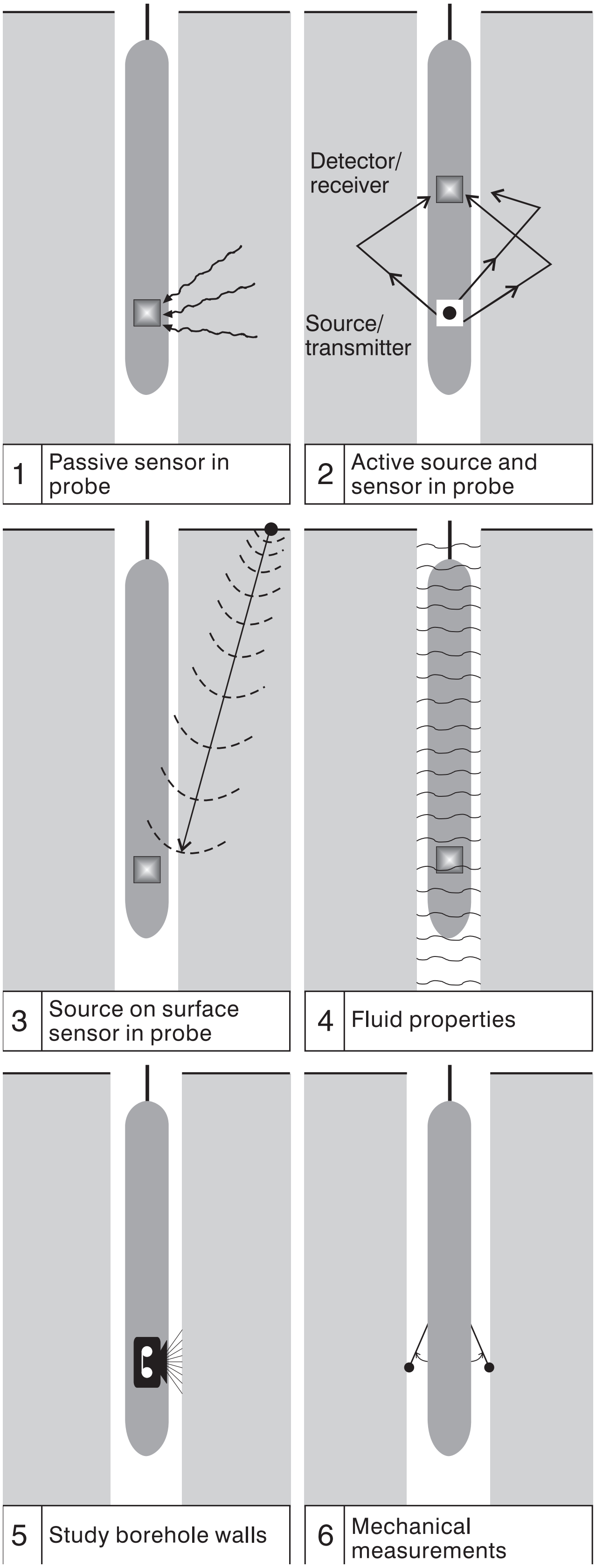

Figure 2: *The six types of measurement configurations possible for borehole geophysical measurements (excluding hole-to-hole).*

measurements with a radioactive source in the probe. Type (1) and (2) configurations generally measure the physical properties in the near-hole environment, ranging from a few centimetres to a few metres radius around the borehole.

3. In a third type of measurement, the signal from a source on the surface is detected by a sensor in the probe, as in the various borehole electromagnetic methods that utilize a surface transmitting loop, or in VSP (vertical seismic profiling) work in which a surface energy source is used. These methods measure large volumes of rock between the source and sensor and may detect changes in physical properties at several hundred metres from the hole (off-hole anomalies). A variation on this type is the measurement of the earth's magnetic field, which can also detect magnetic effects of bodies hundreds of metres away.
4. The sensors may measure the properties of the fluid in the hole as in temperature measurements which may be related to thermal conductivity of the rock, or fluid-flow measurements which may relate to fractures in the rock.
5. Just as a geologist studies drill core, the borehole walls may be studied, using optical, electrical or acoustic televiewers.
6. Also useful are mechanical measurements such as those made by a caliper probe measuring the diameter of the hole, which may relate to variations in hardness of the rock, or to fracturing. Surveying the path of the hole provides another very useful measurement, since, as with any geophysical measurement, knowing the location is just as important as the measurement itself.
7. Several borehole geophysical measurements (e.g., electrical, seismic, radar) may be made in a hole-to-hole configuration, with a source in one hole and a sensor in another hole. These techniques have been used successfully to construct a tomographic image of physical properties of the rocks between the holes.

This overview of borehole geophysics will touch on most of these types of measurements, giving some indication of the state of the art and future directions. At best, this can be only a thumbnail sketch, since virtually any geophysical measurement made with a surface or airborne system today can also be made in a borehole, and in addition many methods suitable for use only in boreholes are also available.

Passive sensor in the probe

Magnetic susceptibility measurements have become widely used by geologists on outcrop and drill core. Borehole magnetic susceptibility logging provides a rapid and more complete series of measurements than core measurements which may have missing sections. In Figure 3 magnetic susceptibility measurements made on a 40 m length of drill core are compared to a magnetic susceptibility log in the same hole. The two logs are virtually identical, but the borehole log took 7 minutes to acquire the data (about 6 m / min), while the core measurements took 7 hours (Killeen and Mwenifumbo, 1987). The advantages of borehole measurements in a deep hole are obvious.

Gamma-ray spectrometry measurements, both surface and airborne, have become a recognized tool for exploration for gold by virtue of gold's association with potassium alteration (Shives *et al.*, this volume). Other metals (e.g., tin/tungsten) are also associated with characteristic changes in the radioelements potassium (K), uranium (U) and thorium (Th). These are the targets of gamma-ray spectral measurements for the indirect detection of the metals. Likewise, borehole gamma-ray spectral logging can aid in the search for these targets.

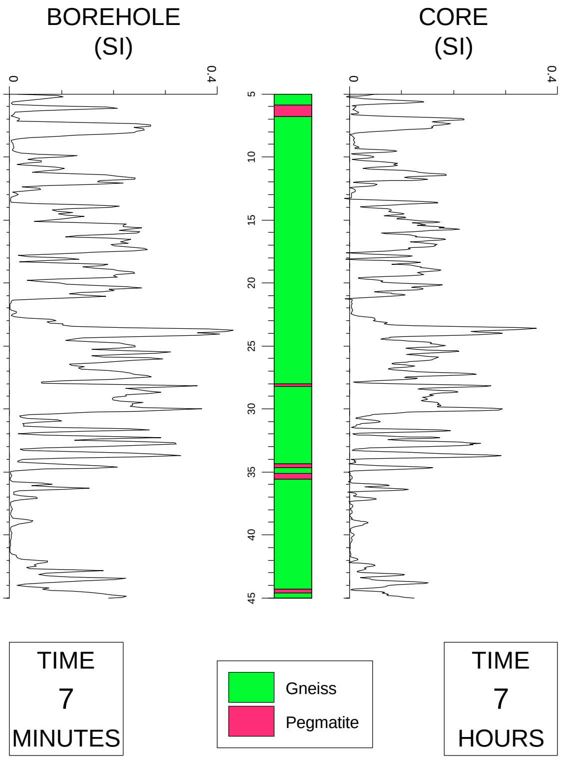

Figure 3: *Comparison of magnetic susceptibility measurements made by logging the hole and by logging the core.*

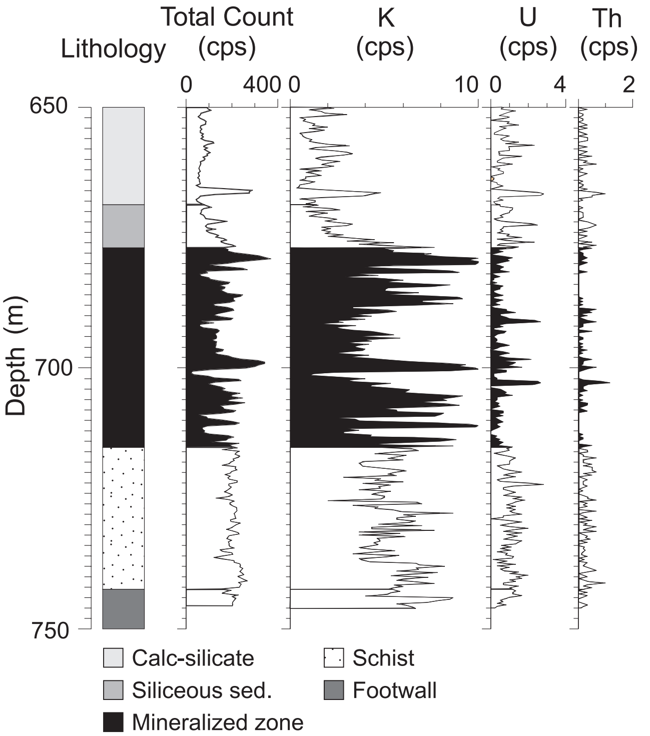

Figure 4: *A gamma-ray spectral log through a mineralized zone in the Hemlo gold mining area showing potassium enrichment.*

A gamma-ray spectral log recorded in the Hemlo Gold mining area of Ontario is shown in Figure 4 (Mwenifumbo *et al.*, 1996a). The increase in potassium in the mineralized zone is easily seen. With proper calibration, the logs could be displayed as % K, ppm eU and ppm eTh.

Active source/transmitter in the probe; sensor in the probe

Resistivity logging is perhaps one of the oldest borehole geophysical measurements. Here, current is passed through the ground between a pair of current electrodes, one or both of which may be located in the probe, and which make electrical contact with the rock via the fluid in the hole. A pair of potential electrodes are used to make the measurements. These also may both be in the probe, or one on the surface. In any case, the objective is to log the variations in the resistivity of the rock as the probe moves along the hole. The example shown in Figure 5 also shows in addition to a resistivity log, a 'spectral IP (induced polarization)' log recorded in a zinc deposit (Mwenifumbo, 1989). The spectral IP log shows six traces, each of which represents a different time window in the decay of the IP waveform. Although the technology exists for these measurements, very little work has been done to interpret the spectral IP data, and this may be an area of activity in the next few years. The same figure shows the result of a spectral gamma-gamma (SGG) ratio log through the zinc-rich zone (see Killeen, 1997). The additional detail on the distribution of zinc, as compared to the core assays is evident. The high IP response in the mineralized zone may be due to pyrite with the sphalerite, but this has not been confirmed. The resistivity log shows low values in the mineralized zone, which would be unusual for sphalerite alone.

An inductive conductivity log through a copper ore zone, along with the core assays and geological log are shown in Figure 6. The borehole probe has a transmitter-receiver coil pair which measures the presence of near-hole conductors. The method can be calibrated to produce quantitative ore grades in mine development. Several inductive conductivity probes are now available, in single coil and double coil versions. Each probe covers a slightly different range of conductivities.

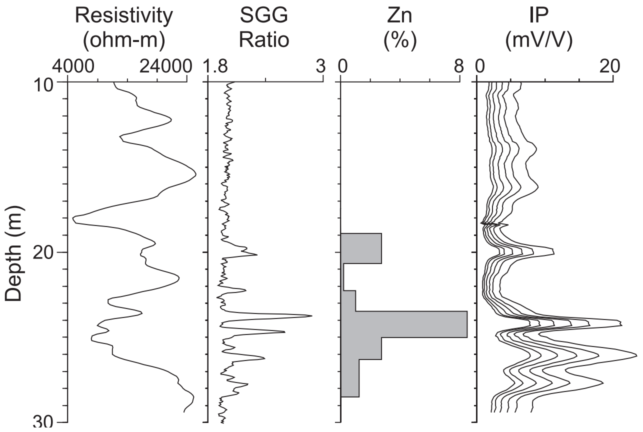

Figure 5: *Resistivity, spectral IP and spectral gamma-gamma (SGG) logs through a zinc-rich zone.*

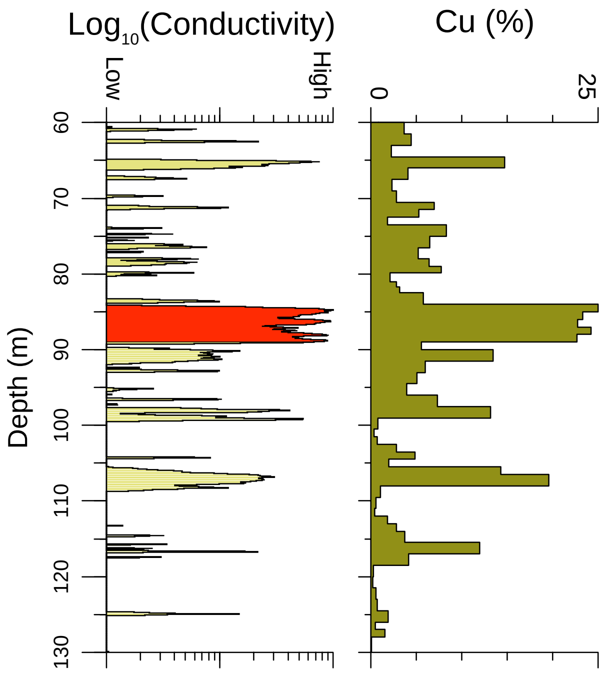

Figure 6: *Inductive conductivity log through a copper-rich massive sulphide zone hosted by cherty breccia.*

The acoustic velocity probe in Figure 7a shows the relative positions of the source and receivers. Velocities are computed from the travel times and distance between the receivers. In this version, the entire waveform is digitized and recorded at each 'ping' of the transmitter, making it possible to pick both P (compressional) and S (shear) wave arrival times from the record. The velocity data may be used to refine interpretation of surface seismic surveys in mineral exploration, or in combination with density logs to compute geotechnical parameters used in mining operations (see Pflug *et al.*, this volume). Figure 7b shows velocity logs recorded in the McConnell nickel deposit, Sudbury area, and at the Kidd Creek polymetallic massive sulphide, Timmins area, both in Ontario.

Source on the surface; sensor in the probe

The borehole electromagnetic methods have become widely utilized since the development of the original Crone pulse electromagnetic (PEM) system around 1975. The concept of the borehole EM system is illustrated in Figure 8. A surface transmitting loop is located near the

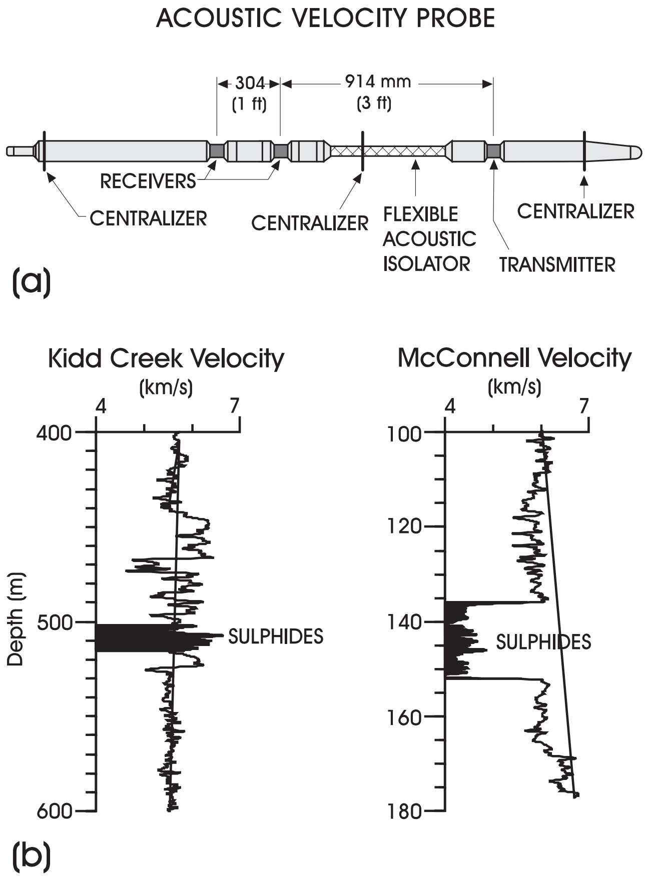

Figure 7: (***a***) *Acoustic velocity probe with transmitter and two receivers* (***b***) *Acoustic P-wave velocity logs recorded in massive sulphides at Kidd Creek (Cu/Pb/Zn + pyrite) and at the McConnell nickel deposit (pentlandite/pyrrhotite).*

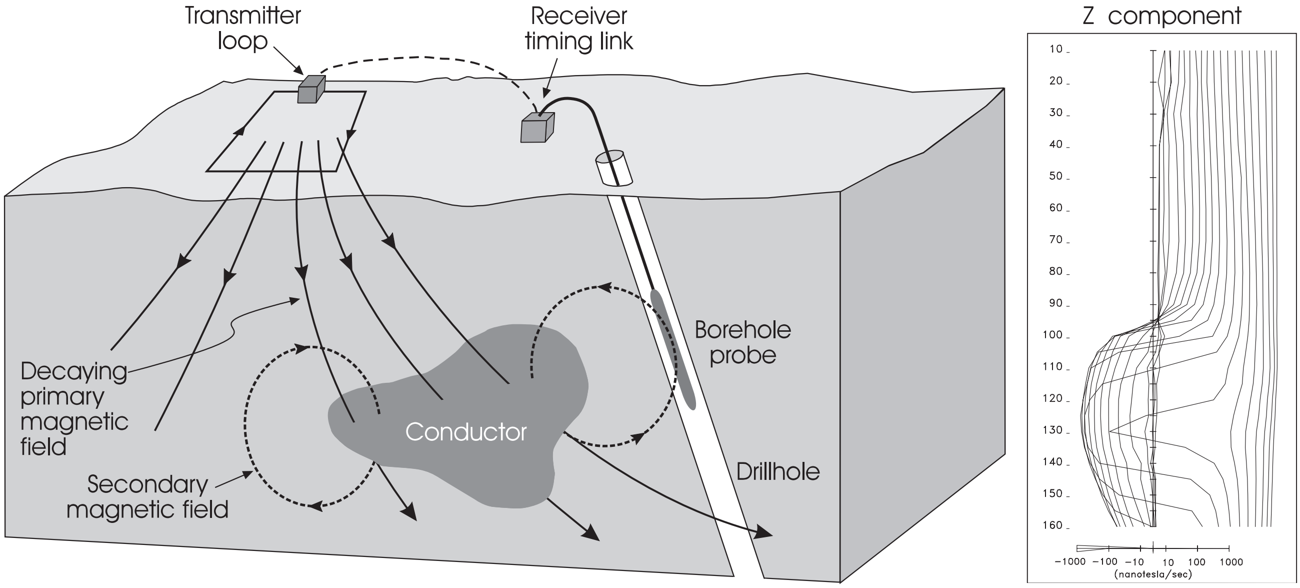

Figure 8: *The concept of a borehole electromagnetic system showing a transmitter loop on the surface and a borehole receiver probe which detects anomalous secondary fields from offhole conductors (modified from Crone Geophysics).*

collar of the hole in which the receiver probe is moving, and the volume of rock between the loop and the path of the hole is investigated for anomalous conductors. The loop is then moved to a new location relative to the hole and the hole is logged again with the receiver. Typically, loop locations may be north, south, east and west of the hole, and possibly one centred on the collar of the hole. There are now numerous time-domain EM systems, including the Geonics system, the UTEM system of Lamontagne Geophysics and the SIROTEM system from Australia, as well as frequency domain EM systems such as the BORIS system introduced in 1996 by IRIS Instruments in France. All of these systems have evolved to where they can now measure three components of the electromagnetic field, at the receiver in the hole. Initially each component required a separate run in the hole, but recently simultaneous recording of all three components has become available for most systems.

In the VSP method (Vertical Seismic Profiling), a surface seismic energy source is used in conjunction with a string of geophones (hydrophones) in the borehole, as shown in Figure 9 (Hunter *et al.*, 1997). The string is stationary during the shot, and moved along the hole by a distance about equal to the length of the string, for each successive shot.

Another possible surface 'source' is the earth's magnetic field or gravitational field. Probes such as the IFG Corp. magnetometer probe shown in Figure 10 are now available which measure three oriented components of the magnetic field. Here, solid state tiltmeters are used as part of the orientation measurement, but some probes use accelerometers or gyros. Although three-component magnetometer probes were available 20 years ago, at that time their orientation was a problem. Figure 11 is a set of logs from a three-component magnetometer probe, showing the x, y, xy cross product, z and total magnetic field values as the probe passes through a massive sulphide. The high magnetic susceptibility of the sulphides distorts the field as the probe passes through them, but those values can be smoothed out. The use of magnetic vectors is illustrated in Figure 12 in which the theoretical vectors recorded in two holes passing to the north and south of a magnetic body are shown. The vectors are the projections in a north-south vertical section. New 3-D modelling software has been developed for interpreting data from the magnetometer probe, some examples of which may be found in this volume (Mueller *et al.*, this volume). As for the gravitational field, Scintrex Ltd. and Schlumberger Technology Corp. have developed a proprietary gravity borehole measurement system, to come into production in 1997. Primarily developed for use in the oil industry, it is hoped that a version suitable for mineral exploration boreholes will follow in the not too distant future.

Measure the properties of the fluid in the hole

Many measurements of the properties of the fluid in the hole such as fluid conductivity, pH, Eh, and temperature are possible. A temperature probe usually has one or more thermisters on the nose or tip of the probe, which measures the undisturbed fluid ahead of the probe in a downward run in the hole, as shown in Figure 13a. Water flows have the largest effect on the measurements as shown in Figure 13b, and these may provide useful data, or mask desired information such as the thermal conductivity variations shown in Figure 14. Here, the high thermal conductivity produces a very low temperature gradient through the massive sulphides. This anomalous gradient may also be detectable in holes that are near misses to massive sulphides (Mwenifumbo, 1993).

Study the borehole walls

Numerous borehole televiewers with black and white or colour recording are now available. Pressure on the camera window, along with

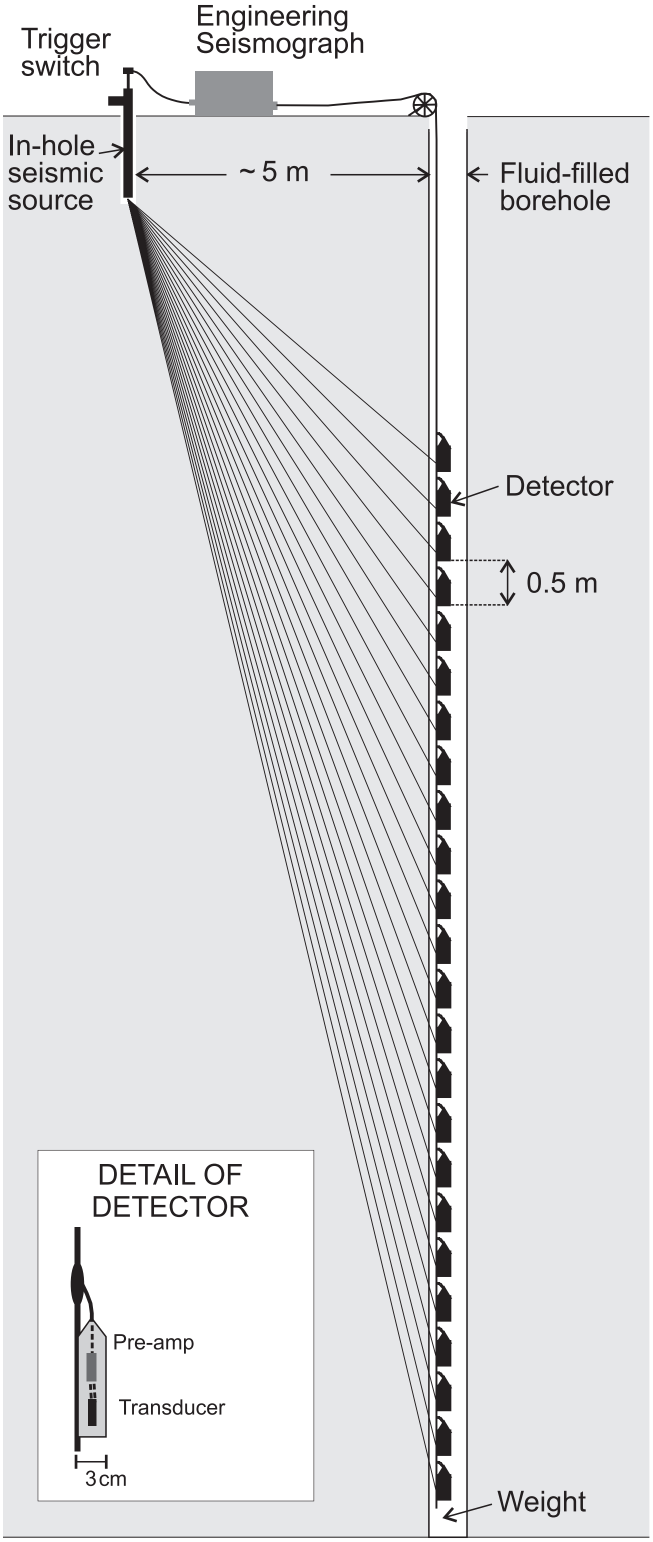

Figure 9: *The concept of vertical seismic profiling (VSP) (after Hunter et al., 1997).*

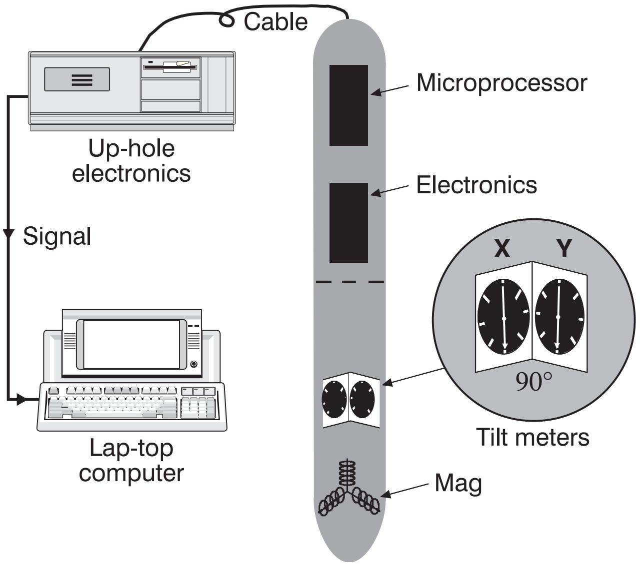

Figure 10: *A three-component magnetometer probe with orthogonal tiltmeters for orientation (modified after figure by IFG Corp.).*

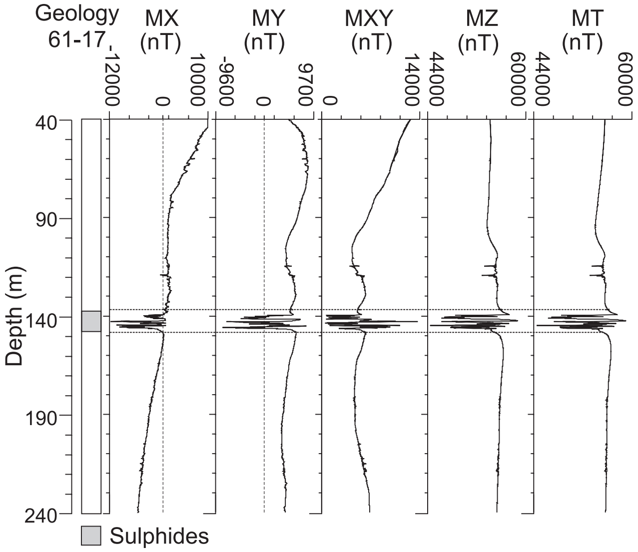

Figure 11: *Logs of the three components of the magnetic field, x,y,and z, and the computed xy cross product and total field. The effects on the logs of the high magnetic susceptibility in the massive sulphides is clearly evident.*

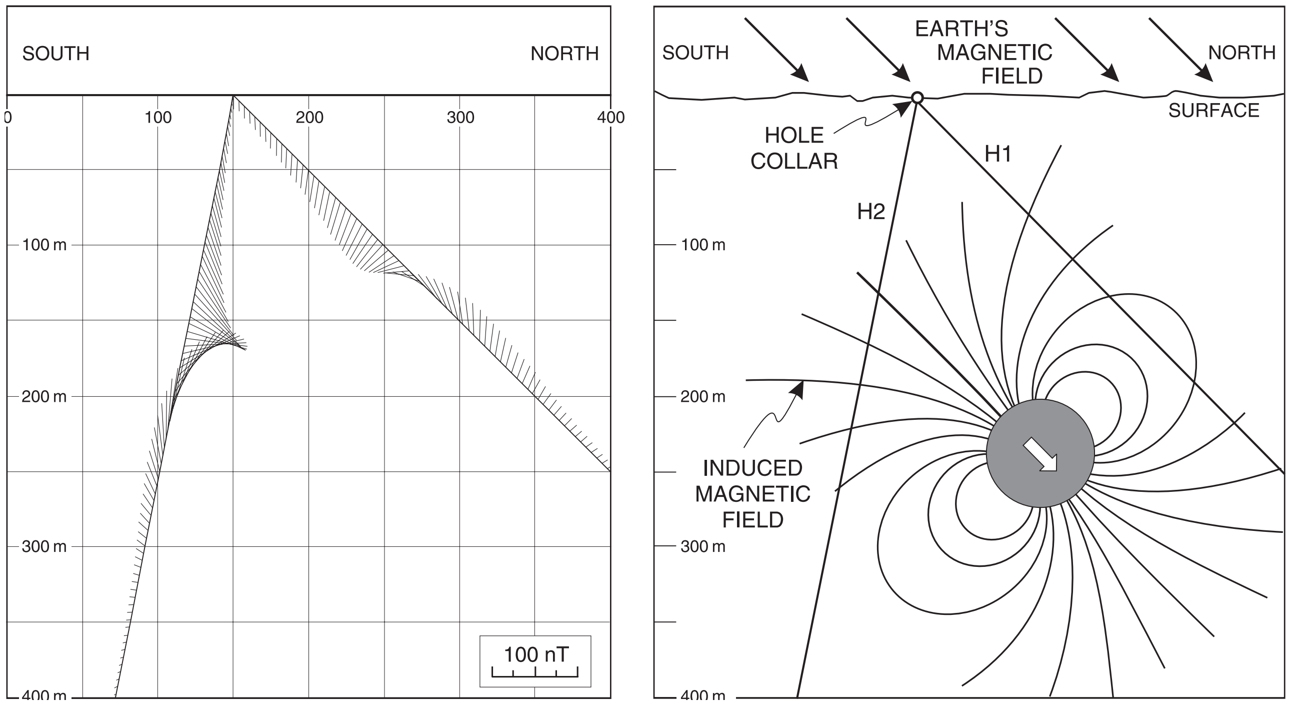

Figure 12: *The concept of using magnetic vector components to determine the location of a body. The magnetic vectors in two holes in a north-south section on the left result from the presence of the spherical body between the holes as shown on the right.*

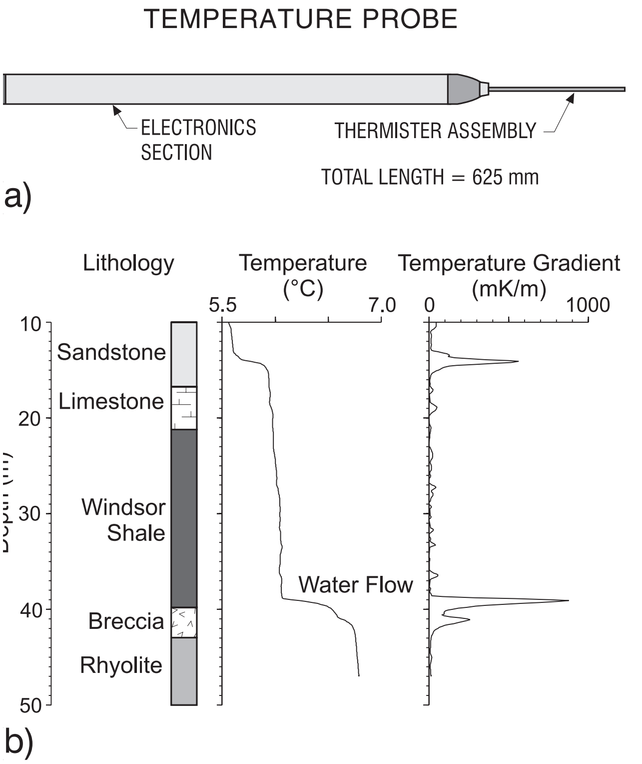

Figure 13: *(**a**) A borehole temperature probe with thermister-tip on the nose. (**b**) Temperature and temperature gradient logs through two zones with water flows in fractures/joints intersected by the hole.*

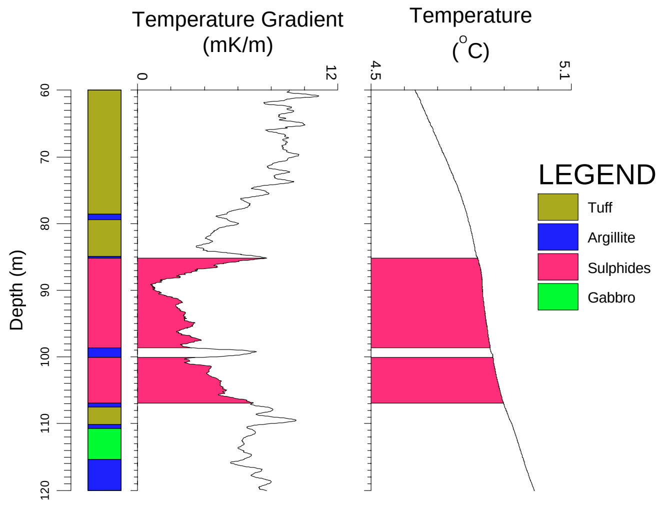

Figure 14: *Temperature and temperature gradient logs through a massive sulphide, showing the near-zero gradient in the high thermal conductivity sulphides.*

the clarity of the borehole fluid are usually the limiting factors. An acoustic televiewer uses sonic waves to scan the wall of the hole from a rotating source in the probe. Thus an image of the wall of the hole, which is almost a topographic map instead of a photograph, is built up by successive scans. Another image of the borehole wall is possible using an electrical method with 32 electrodes equally spaced around the probe (the ELIAS probe, by OYO Corp.). As the probe moves in the hole, the contact resistance at each electrode is measured and used to build an electrical resistance image of the borehole wall.

Mechanical measurements

A caliper measurement is often useful for applying correction factors to data which are sensitive to hole diameter. Single-arm calipers are simple but may not be as accurate as a three-arm caliper in some hole conditions.

Borehole orientation surveys are important, and numerous devices have been developed to survey the path of a hole. The devices may be based on magnetic measurements (i.e., a compass), or on measuring distortion of a pipe as it moves along a crooked borehole (usually by means of light beams and targets inside the pipe), or based on a gyroscope mechanism. An overview of available methods was given by Killeen *et al.* (1995), and by Killeen and Elliott (this volume). Figure 15 shows the result of surveying a 750-m deep hole with five different probes. The path of the hole in plan view, and in an east-west section shows significant differences in results. The truth is not known. The path which deviates most from all the others, may in fact be the most correct.

Hole-to-hole configuration

Measurements between holes may be made with both the source and sensor travelling simultaneously down their respective boreholes as shown in Figure 16, or a tomographic image may be built up from the data obtained from many combinations of source-sensor locations as shown in the borehole radar image of Figure 17. A more detailed image is possible if measurements are more closely spaced, and if surface-to-hole measurements are added to the picture. Tomographic images may be produced from seismic data, radar data, RIM (radiowave imaging method) data as shown in several papers in this volume (McGaughey and Vallee, this volume; Calvert and Livelybrooks, this volume; and Fullagar and Fallon, this volume). Electrical tomography is also possible, almost as an extension of the Mise-à-la-masse (MALM) method (Mwenifumbo, 1987).

Data processing and interpretation

The rapid development of the personal computer (PC), has made it possible to do many computations in the field which 10 years ago were only possible on an office main-frame computer. More elaborate data sets are now also available (e.g., three-component measurements). Software packages are rapidly evolving. An example of a recent 3-D model interpretation of borehole UTEM data is shown in Figure 18. This 3-D image would be much more impressive rotating on a computer monitor screen. This kind of vector modelling is also being developed for magnetic measurements as well as EM.

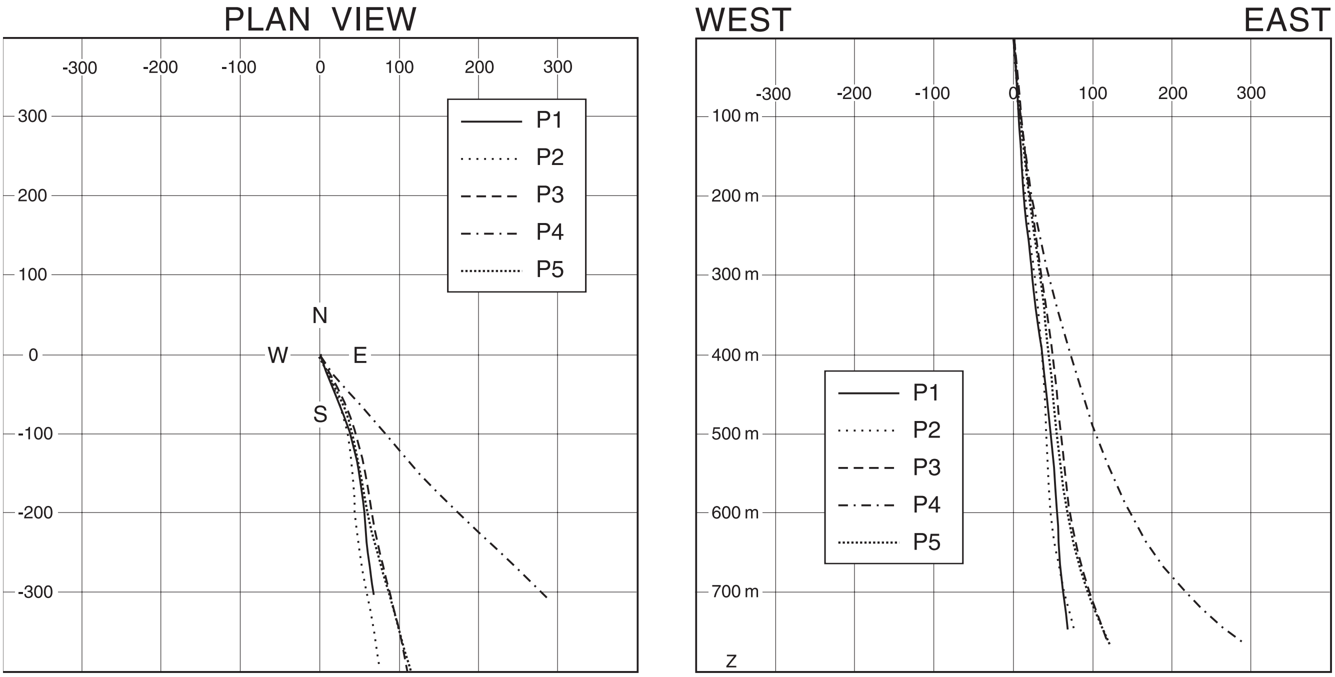

Figure 15: *Plan view and east-west section view of the path of a borehole surveyed with five different probes.*

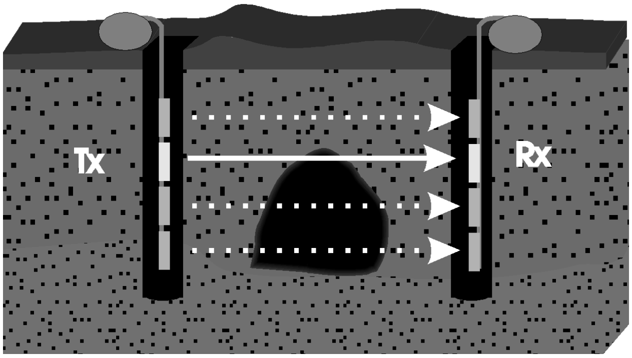

Figure 16

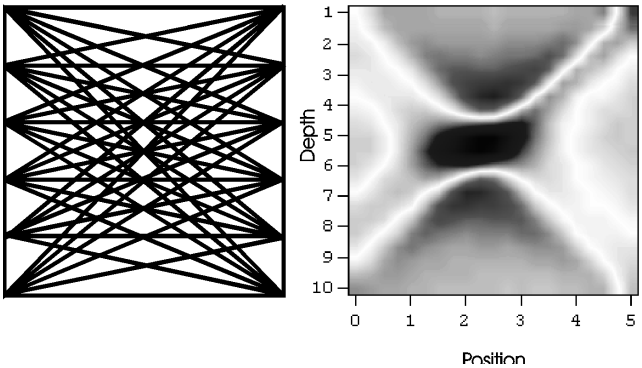

Figure 17

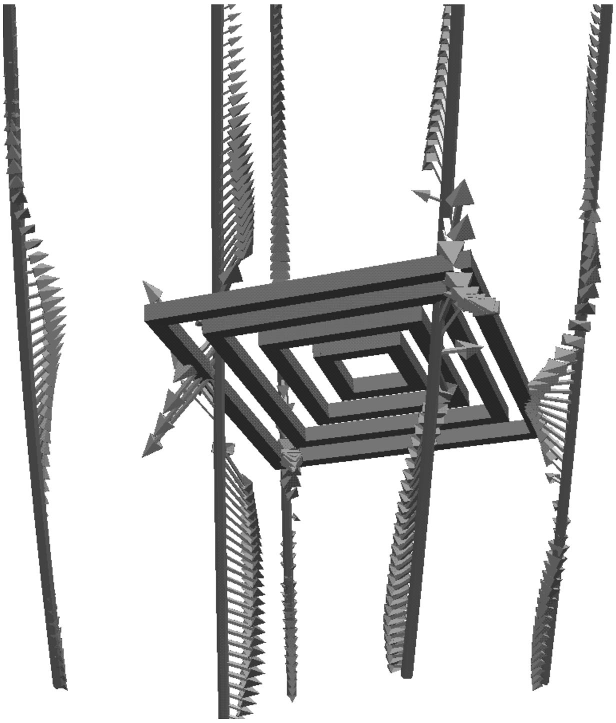

Figure 18

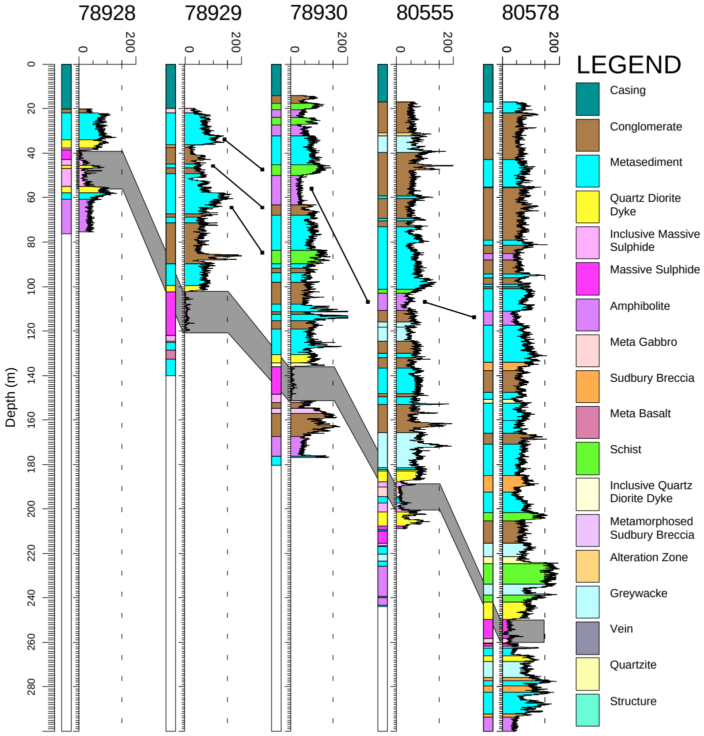

Figure 19

Figure 16: *Hole-to-hole borehole radar measurements with transmitter and receiver moving down their respective boreholes simultaneously to detect anomalous conditions between holes (courtesy Sensors and Software Ltd.).*

Figure 17: *Radar tomography produces an image based on multiple transmitter-receiver paths as shown. Adding surface-to-borehole measurements would enhance the image even further (courtesy Sensors and Software Ltd.).*

Figure 18: *A 3-D model for interpretation of three-component vector electromagnetic measurements with a borehole UTEM system. The four square conductors model the body causing the measured vectors in the five surrounding boreholes (courtesy Lamontagne Geophysics Ltd.).*

Figure 19: *Total count gamma-ray logs in five holes at the McConnell nickel deposit. Lithological correlation is made easier by correlating high gamma activity zones (e.g., schists), and low activity zones (e.g., amphibolites).*

Physical property logs are very useful for lithological correlation between holes, as shown in the five holes in Figure 19. Here the gamma-ray log provides a characteristic signature of many of the rock types, making correlation easier. Correlation between the mineralized zone in the five holes is shown shaded. Other tentative correlations between shists (high gamma counts), and also amphibolites (low gamma counts) are indicated in the figure.

Another method of characterizing different rock units is the use of cross-plots of different parameters. Clustering of points as shown in Figure 20 indicates a rock with characteristic physical properties. In the example shown, different phases of a kimberlite are shown to cluster in different areas of the plot (Mwenifumbo *et al.*, 1996b).

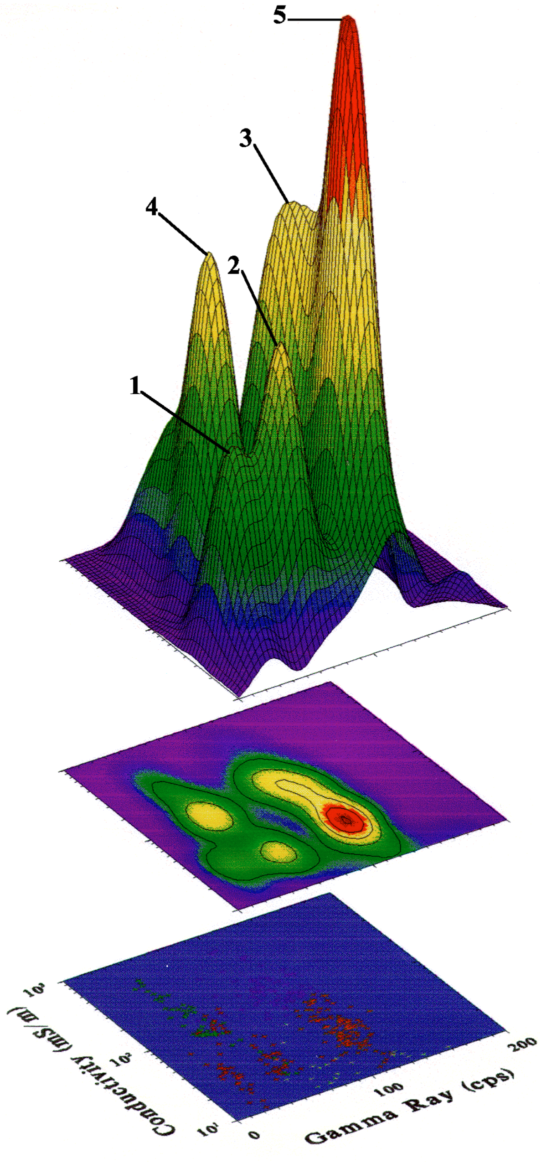

Figure 20: *Cross-plots of two parameters logged in a kimberlite, showing distinct clusters representing mineralogically different phases of the kimberlite.*

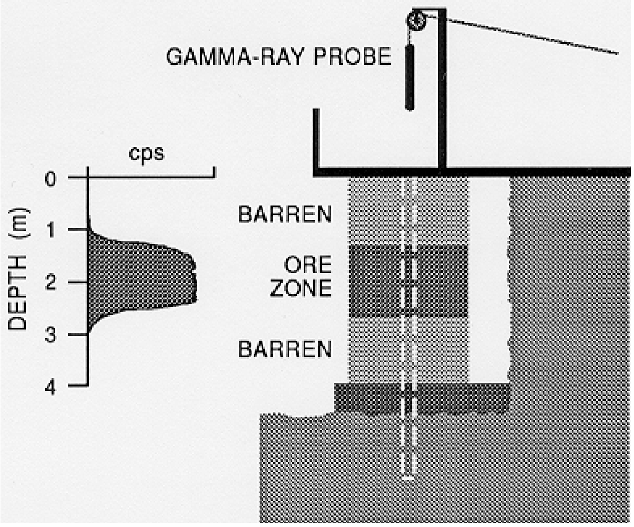

Figure 21: *Concept of a model borehole constructed of concrete with an artificial 'ore' zone containing K, U or Th in known concentrations for calibration of gamma-ray probes.*

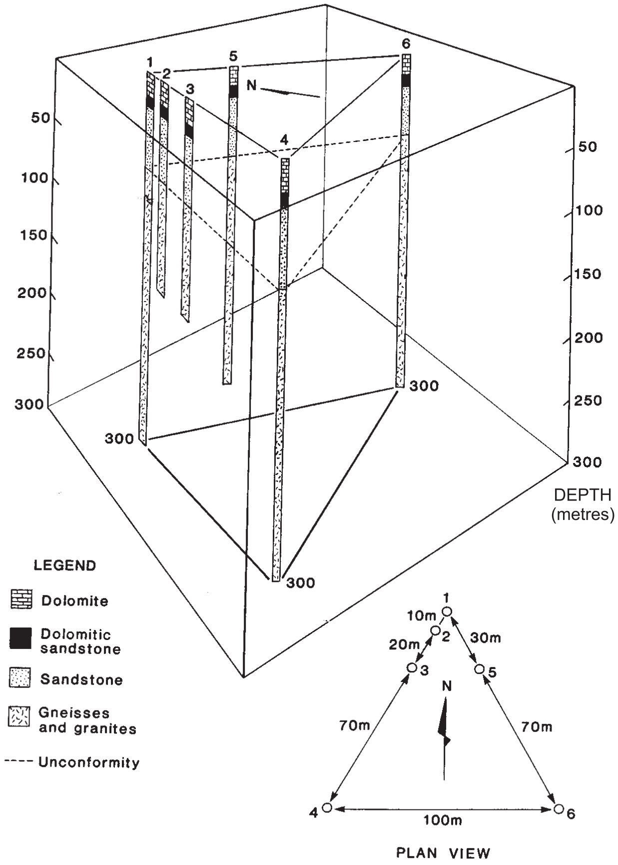

Figure 22: *Configuration of the six drilled test holes at the GSC Borehole Geophysics Test Area at Bells Corners. The top 70 m is sedimentary rock, overlying igneous and metamorphic rocks*

Calibration

To obtain quantitative borehole geophysical measurements necessary for lithological correlation, or to define characteristic signatures, the probes must be properly calibrated. In some cases, physical models are adequate, such as the gamma-ray calibration model borehole shown in Figure 21 (Schock *et al.*, 1991), but for large sample volumes, drilled holes are required, such as the set of six 300-m deep test holes at the Geological Survey of Canada (GSC) Borehole Geophysics Test Area at Bells Corners near Ottawa, shown in Figure 22.

Ore deposit signatures: documenting the target

It is probably not adequately appreciated that in order to locate a target, one must first know the characteristics of the target. Many geophysical methods are developed on very scant knowledge of the physical properties of the ore bodies and host rocks. In 1992 the GSC began a project to provide some new in situ physical property data on major ore deposit types and their host rocks. The borehole geophysical signature of the McConnell nickel deposit is shown in Figure 23 (Mwenifumbo *et al.*, 1993; Killeen *et al.*, 1994). Here, twelve geophysical logs are shown along with the geological log. This figure also illustrates the possibilities for using geophysical logs to predict geological logs, which are described by Killeen *et al.* (this volume). Other deposit signatures are expected to be published in the next few years, some in the form of GSC Open Files. These should provide better data for designing new airborne, surface and borehole geophysical systems.

CONCLUSIONS

This next decade should finally see universal recognition by the mining industry of the importance of borehole geophysics, just as it has been recognized for years, in the oil industry. However, looking back in the Exploration '87 proceedings volume, I noticed that Dr. H. O. Seigel in his review paper stated "Borehole geophysics will come into more general use" (p. 93), and on p. 102 "Borehole logging has the potential to form a very important pillar of mineral exploration practice." Now, in 1997, I can only say that "I second that emotion!"

Figure 23: *The borehole geophysical signature of the McConnell nickel deposit showing the variation in twelve different parameters through the mineralized zone and host rocks.*

ACKNOWLEDGEMENTS

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