GEOPHYSICAL EXPLORATION

By Professor Aftab Khan

Geophysical exploration methods continue to be refined and used in innovative ways to enhance their usefulness in all stages of exploration programmes, ranging from aerial reconnaissance to evaluation from measurements in boreholes.

Aerial Surveys

Regional compilations of airborne geophysical data are becoming increasingly important in mineral exploration but problems occur with merging data sets from a variety of surveys made over a long period of time. Minty (*Exploration Geophysics* 31, p.47) has described how automatic merging of gridded airborne gamma-ray spectrometric surveys for about two thirds of Australia is being done. There are many advantages in having a single coherent data-set. Large tectonics features and geological provinces can be mapped reliably. Signatures mapped in one area can be compared with those in another, and the significance of broad geochemical and other geological features can be better appreciated.

Time domain airborne electromagnetic (AEM) systems are used primarily in the exploration for massive sulphides. However, the systems have been developed to the point where they can be used to map the geology. Bedrock lithologies weather differently and produce layers of different conductance Smith (*Geophysics* 65, p.1124). This conductance can be determined if the integral of the step response from zero time to infinite time (the ideal resistive limit) can be determined. Smith discusses how the reliable resistivity limit (RRL) can be estimated from the finite-time data, and develops a new concept for mapping geological features spanning conductances over an 8-decade range from 0.0015 to 100,000 S. His field example shows many structural features and lithologies not visible on maps using off-time data. With the greater variation shown in conductive areas, more geologically meaningful features become apparent. A further advantage is that artefacts associated with current migration near the edge of conductive features are less evident.

Among the applications of airborne resistivity and susceptibility mapping are metallic mineral prospecting and kimberlite identification. The apparent resistivity is obtained from the measured in-phase and quadrature of the EM system and assume free space magnetic permeability. In highly magnetic areas the resistivities are enormously high. Conversely, susceptibility can be computed in the absence of conductors. Huang and Fraser (*Geophysics* 65, p.502) have now developed a method for obtaining permeability and resistivity in magnetic conductive half-space. The responses at the lowest frequencies are used to obtain the permeability as the conductive signal is a minimum. Once this is known, the apparent resistivity can be computed at all frequencies. They illustrate the application of this elegant idea by producing useful magnetic and resistivity maps in a variety of areas in Canada and Africa.

Gravity Methods

Gravity surveys are used at all stages of exploration surveys and the value of data is enhanced as more information about the geology becomes available. A model of what can be achieved is provided by Fullager, Hughes and Paine (*Exploration Geophysics* 31, p.17) who use drilling information to constrain densities and the positions of interfaces in their modelling. The object of the survey was to locate large, high-grade zones of Cu-Au mineralisation in the basement of the Perth prospect in the Benagerie Ridge area of South Australia, about 100 km northwest of Broken Hill. Over 35,000 gravity stations were recorded in an area of 13 km x

23 km at 50 m intervals along lines 200 m apart or on a 100 x 100 m grid using a Scintrex CG3 gravity meter and Trimble real time GPS. Densities were obtained from calibrated gamma-gamma logs. 3D density models were constructed from close-packed vertical rectangular prisms with internal contacts. Prism tops follow the topography so terrain effects are actually modelled.

In the first stage of the interpretation a 'regional' density model was constructed to satisfy coarsely gridded data. Then a local density model was created on a fine mesh using the drilling data. In the third stage the detailed density model was inserted into the regional model. In the final stage, constrained inversion was performed to adjust the local starting model until a fit to the free-air gravity data was achieved. This model will continue to be refined as new drilling and density information become available.

An interesting new method for the 2-D inversion of gravity data using sources laterally bounded by continuous surfaces and depth-dependent density has been developed by Garcia-Abdeslem (*Geophysics* 65, p.1128). The forward solution is obtained by combining analytical and numerical methods of integration and the non-linear inverse problem is developed in a numerical context. Both remodelling and inversion methods are illustrated with several examples using synthetic data and two field data sets, one of which is the base-metal sulphide Mobrum orebody near Noranda. The geometry of the interpreted source is similar to that obtained from the drilling data and the density of 4.56 Mg/m^3 is in good agreement with the average for the ore determined from the core samples.

An important application of gravity surveys in mineral exploration is in the calculation of the masses of bodies. Camacho, Montesinos and Vieira (*Geophysics* 65, p.95) have developed an inversion method to determine the volumes of bodies with pre-established density contrasts. The subsurface volume is divided into a fixed 3-D partition of prismatic elements and the anomalous volumes are constructed using an 'expansion approach'. The possibilities of the method are nicely illustrated with a simulated example and also to real data from the volcanic island of Gran Canaria.

Understanding emplacement mechanism of the Linglong granite complex which hosts the largest gold field in China, has an important bearing on the exploration strategy there. Zeng *et al* (*Geophysics* 65, p.421) have taken a step forward by trying to determine the 3-D geometry of the 100 km x 30 km granite from 2-D forward modelling of gravity data. They estimate that the complex is a sheet-like body 8 km thick rather than a deeply rooted batholith as previously thought.

Magnetic Data

Reduction to the pole (RTP) greatly enhances the value of total field magnetic data in geological studies and has been increasingly used ever since the introduction of wave number-domain data processing. Problems occur if the magnetisation is not in the direction of the geomagnetic field and the differential reduction-to-the pole (DRTP) method was introduced to deal with situations in which the field and magnetisation directions differ. Swain (*Exploration Geophysics* 31, p.78) has been investigating the application of DRTP to regional magnetic grids at low latitudes where interpretation is most difficult. He gives a good illustration using data from Brazil, of what can be achieved on a small work station with careful coding.

One of the problems of interpreting total field magnetic anomalies near the magnetic equator is that N-S anomalous bodies are invisible. Beard (*Geophysical Prospecting* 48, p.745) discusses this problem and notes that folding, faulting, differential erosion, or other structural deformation can result in anomalies. Although these patterns are more complicated than those at high latitudes, he shows how insight can be gained by numerical modelling. He also shows how reduction-to-pole and analytical signal filters can aid interpretation if applied with care. This useful discussion is illustrated with data from Burkina Faso.

Magnetic anomaly data are often used to estimate shape and depth of magnetic orebodies and a variety of methods have been developed for this purpose. The most sophisticated model method is that of Euler deconvolution which is based on a relationship involving the source depth and a structural index. The ambiguity in determining these is discussed by Abdelraham and Hassanein (*Geophysics* 65, p.126) who have developed a similar method which solves for shape and depth independently. It involves using a relationship between shape factor, depth and a combination of observations at symmetrical points with respect to the coordinates of the source centre with a free parameter (graticule spacing). The relationship represents a parametric family of curves which are used in the interpretation. They illustrate the method convincingly using theoretical profiles due to a thin dyke and a horizontal cylinder as well as on a field example from Brazil.

Resistivity Information

In recent years there has been a major change in the acquisition of DC resistivity data due to the emergence of computer controlled multi-electrode arrays which permit complex data acquisition strategies which would be inconceivable using manual methods. In these systems, electrodes are used as either current or potential electrodes during data acquisition. Dakin (*Geophysical Prospecting* 48, p.181) points out that electrode charge-up effects can be orders of magnitude greater than the induced signals and can persist for tens of minutes. It is therefore important to avoid procedures in which an electrode is used for measuring potential soon after it has been used to inject current, even when the positive-negative type of measurement cycle is used.

Li and Oldenburg (*Geophysics* 65, p.149) show how geological dip information can be brought into geophysical inversions. It is achieved by applying a rotation matrix to the horizontal and vertical derivatives of the model so that the derivative in an arbitrary direction is obtained. Formulations for both 2-D and 3-D cases are presented and they are illustrated using resistivity and IP data acquired over a gold deposit in Ontario which is associated with a steeply dipping sulphide body embedded in metasedimentary rocks surrounded by volcanics. They convincingly demonstrated that inversions carried out using known dip information produce a model that has higher resolution and provides a better representation of the true structure than those which do not.

The determination of the strike direction of buried structures, like fracture sets which may control mineralisation, has been addressed in the past using variously aligned linear electrode arrays or the square array in resistivity surveys. Busby (*Geophysical Prospecting* 48, p.677) has made a timely assessment of the effectiveness of azimuthal apparent-resistivity for determining the strike direction of sub-vertical fracture sets. He notes that heterogeneity in the rock mass may also produce an effect. He recommends that the offset-Wenner array is used and that a new parameter is introduced, the homogeneity index, which defines whether the variations due to homogeneous anisotropy such as fracturing are greater than those due to inhomogeneity.

Resistivity inversion aims to produce a resistivity distribution in the subsurface from measurements made using electrodes at the surface. The true distribution can never be obtained due to the continuous nature of the resistivity variations, instability, noise, and the problems of non-uniqueness. Olayinka and Yaraminci (*Geophysical Prospecting* 48, p.293) have assessed the reliability of 2-D inversion by calculating systematic apparent resistivity pseudosections from a variety of models and then inverting then using a common scheme based on a smoothness – constrained non-linear least squares by optimisation, for the Wenner array. They find that for vertical structures, the models are sharper than the measured data but the resistivities can be outside the range of the true resistivities.

The authors also find that a reduction in the data misfit during the inversion is not always accompanied by a reduction in the model misfit which can remain unchanged for successive iterations. It can also increase with iteration number, especially where the resistivity contrast at the bedrock interface is greater than about 10. Here the optimum model is obtained at a low interation number. The largest misfits occur near contacts with large resistivity contrasts. Further work is encouraged as it provides a useful insight into the limits of what can be achieved by resistivity inversion.

Induced Polarisation

Although the induced polarisation method is a primary exploration tool, there are deficiencies in the models to describe low frequency electrical polarisation or rocks. Dias (*Geophysics* 65, p.437) has been refining his work on total conductivity functions to account for the phenomenon in the 1 MHz to 10^{-3} Hz range. He has replaced his original five parameters by new ones which have clear petrophysical and electrochemical meanings. His analysis of various models to explain well-selected experimental data show that only the Cole-Cole and Dias models provide satisfactory fits. The work has an-important bearing on the interpretation of IP data and in mineral discrimination studies.

A primary consideration in the design of IP surveys in exploration programmes is the depth of investigation, defined by Apparao *et al* (*Geophysical Prospecting* 48, p.797) as the depth below which the target cannot be detected by an array, assuming a minimum detectable anomaly 0.1 in the apparent frequency effect. In their physical modelling with various arrays, the authors find that the depth of detection of a highly conducting and volume polarisable target agrees closely with the depth of detection for an infinitely conducting and non-polarised body of the same shape and size. The greatest depth of detection is obtained with a two-electrode array, followed by the three electrode array, while the smallest is obtained with an in-line Wenner array. Interestingly, they find that the depth of detection with a Wenner array improves considerably and is almost equal to that of a two-electrode array when the spread is broad-side.

One of the problems with IP data is contamination with EM coupling. Many schemes for overcoming this problem have been presented for frequency domain surveys but not in the time domain. Fullager, Zhou and Bourne (*Exploration Geophysics* 31, p.1340 have now devised a fast simple procedure in which the coupling is represented as a half-space decay. The EM resistivity is adjusted is the inversion until it fits the observed transient voltage. These are then subtracted from the measured voltages to yield a de-coupled ‘IP transient’. They demonstrate their useful procedure with dipole-dipole IP data from the Yandal greenstone belt of Western Australia.

Electromagnetic Methods

Controlled source electromagnetic methods are extensively used in exploration as they provide a means of getting good data quickly and they can be designed to optimise resolution. They are, however, restricted by the difficulty of modelling 2-D or 3-D structures with a finite source and by the problems of allowing for topography and near-source inhomogenites. These problems have received much attention in the past and a new method is presented by Mitsuhata (*Geophysics* 65, p.465) using the finite-element method with a dipole source and topography. It uses a pseudo-delta function to distribute the dipole source current, and does not need the separation of the primary and secondary field. He also presents the response of topography for the long-offset transient electromagnetic and the controlled-source magnetotelluric measurements. This '2.5-D' algorithm is a notable advance.

A variety of tool configurations (horizontal or vertical co-planar, coaxial, perpendicular) can be used in EM surveys to probe the earth in different ways. Zhang *et al* (*Geophysics* 65, p.492) show how complementary information from different configurations may be used to produce 1-D conductivity models, if only a limited number of frequencies are available. Their tests with 3-D synthetic data show that 1-D inversions can be used as a fast approximate tool to locate anomalies in the subsurface.

An interesting development in TEM methodology is discussed by Smith and Balch (*Geophysics* 65, p.476) who capitalise on the ability of modern systems to make measurements in the transmitter on-time. They note that a very good conductor gives small response due to the slow rate of change of the magnetic field, even though it is a large field. So methods using SQUID magnetometers to measure the magnetic field are being developed. Smith and Balch's alternative is to integrate measurements taken during the transmitter switch-off with those in the off-time to give an estimate of the primary field and the inductive limit response, anomalous values of which are diagnostic of highly conductive ore bodies. PROTEM data collected in a drill-hole near the Reid Brook zone, one of the Voisey's Bay nickel sulphide deposits in Labrador, showed anomalous values due to an off-hole conductor. Another drill hole there encountered 20.4 m of mineralisation including 8.25 m of massive sulphide.

Karnetsky and Oelsner (*Geophysical Prospecting* 48, p.983) observe that due to distortion, there is a minimum depth of investigation using EM transients. They estimate that with the single-loop or coincident-loop configuration, loop sizes from 10 m x 10 m to 40 m x 40 m, and resistivities of 1-100 ohm, the minimum time-delay beyond which we can use a standard interpretation is in the range 2-10µs. This is equivalent to a minimum depth of investigation in the range 1-30 m.

Smith and Annan (*Geophysics* 65, p.1489) discuss using an induction coil to obtain the magnetic field by integrating the response. They compare this with results obtained using a SQUID magnetometer and get very similar results. The conventional voltage and the new magnetic field data have different characteristics. The magnetic-field data are better for identifying, discriminating, and interpreting good conductors while suppressing the less conducting targets.

There have been many illustrations of the effectiveness of the TEM method in the detection of nickel sulphide deposits in Australia. Craven, Revina, Grammer and Styles (*Exploration Geophysics* 31, p.201) describe the discovery of the Cosmos deposit in a drill hole to test a TEM anomaly of short strike length. Modelling suggested a steeply dipping conductor at 50-75 m depth which was confirmed by the drilling. It is interesting to note that detailed ground and aeromagnetic data defined the ultra-mafic host well but not the massive sulphide zone which was highlighted and quickly drilled on the basis of the EM data. The Maggie Hays and Emily Ann nickel deposits, about 500 km east of Perth, were found following IP, AMT and TEM surveys. Further detailed TEM surveys led to drilling and discovery while evaluation was aided by follow-up TEM surveys in the drill holes. The general problem of deep TEM exploration for nickel sulphides beneath a deep regolith has also been addressed by Stolz (*Exploration Geophysics* 31, p.222).

Seismic Information

One of the great advances in methods of investigating the subsurface at the shallow depths in which mineable deposits occur in that of high resolution 3-D seismic reflection surveys. A good illustration of what can be achieved is provided by Büker, Green and Horstmeyer (*Geophysics* 65, p.18) who have been using a dense distribution of source and receiver positions to obtain subsurface sampling of 1.5 m x 1.5 m at depths between 15 m and 170 m, with more than 40-fold coverage in a Swiss mountain valley. They used a variety of common processing techniques to enhance the reflections relative to source-generated noise. They were able to map features less than 80 m wide and map the interfaces between five lithologic units identified in boreholes. The well-illustrated presentations provide an excellent model for anyone wishing to apply the methodology.

Modern developments in shallow reflection make it possible to use the method underground to investigate steeply dipping sheet like deposits or deeper subhorizontal ones. The first such experiment in an Australian gold mine was attempted by Greenhalgh and Bierbaum (*Exploration Geophysics* 31, p.321) in the Revenge gold mine of the Kambalda area in an attempt to map a shear-hosted ore lode approximately 100 m below the tunnel floor. They fired 140 small explosions, mainly electric detonators, at an average depth of 7 m, in holes filled with water for tamping. They used a 24-channel Bison 7024 seismograph and a nominal geophone/shot spacing of 2 m. The data quality was good, with frequencies of 1-2 kHz propagating over distances of more than 100 m. Strong P & S arrivals were observed but no reflections were observed from the shear zone. This was due to the lack of sharp velocity contrasts and should not deter further experiments of this kind. It is a most encouraging and laudable initiative.

The power of using seismic, gravity, and magnetic data together has been well-known in the oil industry but with the availability of cheap powerful computers these methods can now be used effectively in the mining industry. A splendid illustration is provided by Roy and Clowes (*Geophysics* 65, p.1418) who have been using seismic and potential field imaging to delineate structures hosting porphyry copper deposits in the Guichon Creek batholith of British Columbia. Interpretation of the gravity data over the zoned batholith suggested a mushroom-shaped structure. Data from one of the lithoprobe seismic reflection lines showed weak east-dipping reflectors in the east in the upper 10 km. Refined interpretation of the data enabled correlation of the images with the geological environment associated with porphyry copper deposits which structurally lie in faulted breciated regions of low velocity.

The seismic images help to define the edge of batholith, its concentric phases and the stem. These results are combined with modelling of the regional gravity and high-resolution aeromagnetic data which show a slow density and low susceptibility region associated with the batholith to more than 10km depth. The mineral deposits are above a circular low-susceptibility at 2 km depth with low velocity above the stem of the batholith.

Borehole Data

Magnetic data on the earth's surface are useful for locating magnetic bodies but are not able to provide depth information unless assumptions are made about the source. A similar ambiguity is present if borehole data are inverted. Li and Oldenburg (*Geophysics* 65, p.540) have demonstrated how the use of both surface and borehole data may be used together to solve the non-uniqueness problem. Their algorithm depends on weighting functions that counteract the geometric decay of magnetic kernels with distance from the observer and is demonstrated with both synthetic and field data over an ironstone formation in Australia. When borehole data are inverted directly, three component data are for more useful than single component data. However, they find that either can be used effectively in joint inversions with surface data to produce models that are superior to those obtained from surface data alone.

One of the interests in borehole logging is that logs may provide information on ore grade and thus save on the high costs of coring. Fallon, Fullager and Zhou (*Exploration Geophysics* 31, p.236) have described an automated interpretation tool, LogTrans, which performs rapid analysis of multi-parameter logs and expedites presentation in a meaningful way. It exploits the contrasts in petrophysical signatures between different classes of rock. They present two examples of grade estimation from Australia, one from the Newlands coal mine and one from the Mount Isa underground operations. In the coal mine, depth and thickness can be identified automatically and coal quality inferred from the pseudo lithology log. In the copper mine, the example demonstrated the use of an ore-to-waste indicator. In both the reliability was >80% compared with core-based information. Most of the discrepancy arose from the differing scales of observations; 0.05 m for the log, and 1-3 m for the core.

There will be considerable interest in the surface and borehole surveys used at the Nkomati mine, at Mpumelanga in South Africa, where a magmatic Ni-Cu-Co-PGM massive sulphide deposit is being mined at depths of around 500 m. Nyoni and Bishop (*Exploration Geophysics* 31, p.521) present data from magnetic, gravity and CSAMT, plus downhole EM and the comparatively new downhole magnetometric resistivity (DHMMR) method. As would be expected, the down-hole methods were the most effective for the deep targets. The sulphides were highly conducting so the standard impulse type time-domain DHEM did not give good results when transformed into step-type data. Strong responses were obtained from frequency-domain measurements. The DHMMR results would be of particular interest. A square wave is transmitted from an IP transmitter to grounded U-shape dipole, with lengths typically 500-2,000 m along strike surrounding the boreholes, several of which can be surveyed from a single dipole. Measurements were made with a standard DHEM probe. The DHMMR method was by far the most useful in locating conductors. Also of interest is that the CSAMT successfully defined the disseminated and massive sulphide at depth and the data were consistent with the gravity and magnetic data which were most useful for outlining shallow mineralisation outside the main complex.

There is growing interest in DHMMR and it is timely to have comparative tests with the well-established DHEM. Bishop, Lewis and Stolz (*Exploration Geophysics* 31, p.192) have made a start with measurements at a nickel prospect in Western Australia. The DHMMR clearly defined a zone of shallow matrix sulphides which were only weakly detected by some of the earlier DHEM survey (in hindsight). Conversely, the DHMMR gave weak responses in massive sulphides which were well-defined by DHEM. The methods are therefore regarded as complementary, with DHMHR responding well to bodies of large cross-sectional area and DHEM to bodies of larger long-sectional area. Although of lower grade, the matrix deposit may be the more economic ore because of its much higher tonnage.