Ground Geophysics: Advances and Outlook

Roth, J.[1]

1. STRATAGEX Ltd., Toronto, Ontario, Canada

INTRODUCTION

The past decade has witnessed major advances in all aspects of ground geophysical surveys, although such changes have generally been small in any one year but cumulatively significant when viewed over a decade. Key to almost all these advances has been the major and continuing increases in microcomputer capabilities, which have impacted on instrument design and operation, as well as subsequent data processing and interpretation.

It is useful to consider these advances in geophysical capabilities from the wider perspective of the development of ground geophysical techniques over the past 30 years since the first of these decennial conferences was held in 1967 in Niagara Falls. At that time, the appearance of the transistor heralded unprecedented possibilities for miniaturization in instrumentation, although the full range of technological advances ultimately generated by the microcomputer revolution was barely glimpsed, even by the most optimistic prognosticators of future trends. No doubt, any prognostications offered here as to future trends and directions will be similarly in error, when judged from the perspective of some years hence in the 21st century A.D.

Considering the state of the geophysical art from a perspective of three decades, rather than merely one, geophysical techniques are seen to have enjoyed over this period a major diversification and expansion, much like the evolutionary explosions that can be seen in paleontological record. For example, EM techniques have multiplied into more diverse niches, and now span a frequency range from subhertz (MT) to gigahertz (GPR). Conversely, some approaches and techniques have largely fallen into disuse, like the once dominant vertical loop EM (VEM) and fluxgate magnetometers (but which are now, I would note, incorporated into directional devices for DHEM and magnetic compensators in aeromagnetic survey aircraft).

The general impact of the overall technological advances has been and continues to be towards greater flexibility in instrument capabilities and greater simplicity of instrument operations. Thus one can now measure and record spatial variations in the earth's total field magnetic in effectively continuous mode, and without hardly any pause in pace, and with very limited training. Current time-domain EM systems now enable measurement of three orthogonal components of the secondary EM field (each sampled over 20 time windows or channels) in a fraction of the time it once took to measure and record one component in early analog equipment. Instrument troubleshooting and repair are largely done by changing circuit boards.

Similarly, major advances have been achieved in the ability to store, process and display various parameters. For instance, today seismic reflection surveys are routinely conducted for petroleum exploration with hundreds of geophones, and in 3-D seismic surveys with arrays of thousands of geophones, representing an increase of 3–4 orders of magnitude. These data can be filtered, deconvolved, migrated, displayed in plan or cross-section, with calculated seismic attributes in an astonishing variety of ways, all of which have greatly contributed to the improved discovery and delineation of petroleum and gas resources and hence to the decrease in real cost of petroleum over the past three decades that we as consumers have enjoyed.

KEY DEVELOPMENTS

Rather than recapitulate details of new equipment or applications, most of which can be reasonably found in annual summaries such as prepared by Pat Killeen of the Geological Survey of Canada (GSC), it is judged more instructive for the present discussion to focus on those aspects deemed particularly noteworthy in the context of advances sustained over the past decade and the perceived key directions for future developments. Apologies are offered to those whose contributions have been overlooked; the wealth of ground geophysical techniques and applications renders it difficult to encompass all significant aspects and developments, particularly in a limited review undertaken by one person.

In this survey, we will first focus on hard-rock applications of seismic reflection, which offer a paradigm for advances in geophysical technology, and then look at several other geophysical domains more typically applied to mining exploration.

Seismic reflection

The past decade has seen a continuation of efforts to harness the ever more powerful capabilities of the seismic reflection technique developed for petroleum exploration to the domain of hard-rock applications, including exploration for and exploitation of mineral deposits, an effort which has intensified over the past several years.

In "Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration" *edited by* A.G. Gubins, 1997, p. 9–12

Not surprisingly, some of the first and most successful were applications of seismic reflection to the delineation of mining conditions in planning for the development of potash deposits, especially for identifying potential problems such as dissolved salt beds. The loss of several potash mines in Saskatchewan due to water inflowing from undefined faults and solution features, and the ease with which these problems can be detected in advance with 3-D or even conventional 2-D seismic reflection surveys, have served to convince geologists and conservative mining engineers alike.

Concomitantly, in South Africa, where some of the earliest seismic reflection surveys were employed to map faulted blocks of the key Witwatersrand sedimentary sequence, 3-D reflection surveys have been employed to advantage, as we shall hear in greater detail in the subsequent session on seismic techniques.

More recently, in a collaborative effort spearheaded by the GSC, seismic reflection surveys have been attempted in a variety of complex hard-rock mining environments in Canada, such as Ni/Cu deposits at depth in the Sudbury intrusive complex and volcanogenic polymetallic massive sulphide deposits in districts such as Matagami and Kidd Creek in Canada. These efforts will also be discussed in some detail in the subsequent session on seismic reflection; suffice it to say at this juncture that useful seismic definition in these difficult settings, characterized by impersistent reflectors and steep dips, has become achievable only with the recent improvements in multifold instrumentation and the effective processing of high-frequency reflections. For the same reason, effective interpretation in these difficult environments requires reasonably defined seismic velocities, optimally obtained by executing a vertical seismic profiling (VSP) survey in a representative drill hole. Finally, it is worth commenting that seismic reflection costs remain sufficiently high as to continue to be a barrier to great utilization by the mining industry.

Seismic refraction surveying, the poor cousin of the seismic applications, has also benefited from the advances in microprocessor-controlled instrumentation with multi-channel capacity and improved picking and processing.

Projecting these trends, I would anticipate that, with exploration directed at increasingly deeper and/or more subtle targets, efforts to apply seismic reflection to mining exploration and development will intensify but will remain confined to a restricted niche due to complexity and costs.

Potential field methods

Turning to potential field methods, these relatively mature techniques have seen only rather modest improvements over the past decade.

Ground magnetic surveys have benefited from the ability to take measurements in nearly continuous fashion without a significant increase in data acquisition costs, improved and speedier processing and display of the resulting data, and faster means of calculating relevant models and semi-automatic analyses. There have been only limited R&D efforts to yield multi-component ground magnetometers, such as the renewed attention to SQUID devices. However, there has been no marked advance in fundamental measurement technologies nor in the underlying theory of magnetic behavior. Current computer-aided interpretive protocols, such as Euler deconvolution, mainly represent elaborations of ideas already reasonably established ten or more years ago, but now implemented on much faster computing platforms with more useful graphical output.

The one notable exception to the preceding comments about magnetic developments is the effort initiated by Russian researchers to apply nuclear magnetic resonance spectroscopy (NMR), until now principally employed for medical research at scales of millimetres to centimetres, for the direct delineation of water resources by using a large tuned EM loop to excite protons in ground water, and then measuring the precession decay, as if operating a giant proton magnetometer. Given the increasingly critical state of potable water supplies for the world's population as a whole as well as for site-specific mining operations, further practical elaboration of this concept is anticipated in the future.

Ground gravity surveys have achieved improvements in survey efficiency, due to automatic levelling systems such as incorporated in the Scintrex gravimeter, and with the emergence of differential GPS systems with sufficient locational accuracy for regional gravity surveys. Instrument repeatability currently readily attains the 10 microgal levels, as exemplified by the LaCoste and Romberg geodetic gravimeter, and approaches 1.0 microgal in several specialized cryogenic gravimetric devices.

These improved performance characteristics have been exploited in several novel applications, including engineering studies for concealed karsts.

On the other hand, there has been little advance in the fundamental theory pertaining to gravity surveys, or in their applicability. Thanks to improved computer codes and hardware, we can now compute more complex models with ever faster speed; however, the interpretation of the observed gravity variations remains constrained by the large ambiguity inherent in the wide range of permissible models, so that the effective utilization of gravity in such applications as massive sulphide exploration remains limited.

Practical devices measuring the tensor components of the magnetic and gravitational fields, which will likely be available over the next decade, would confer a substantial improvement in resolution and interpretation of causative sources, particularly with the parallel development of effective computer analysis of such data, and might well provide for a significant advance for a variety of applications, particularly when gravity data is complemented and constrained by electrical or seismic data.

Electrical techniques

In the flourishing and diverse realm of electrical techniques, we first examine DC and related methods (i.e., IP/resistivity, SP, CR and Non-linear CR (or Voltammetry), followed by a recital of some notable advances in EM techniques. Many of these topics will receive a more complete exposition in the subsequent session on Electrical Techniques and will be instructively exemplified in the final session on Integrated Case Histories.

In terms of fundamental theory and underlying physical principles, few new advances were achieved in IP over the past decade; not surprisingly, the resistivity method itself has also changed little over this period. In this regard, the fundamental insights achieved by pioneers such as Schlumberger, Stefanescu, Brant, Seigel, Halloff, and various Russian researchers continue to provide primary guidance in our present applications of IP and resistivity.

However, the past decade has seen considerable advances in the practical implementation of these fundamental insights, via the substantial improvements in the efficacy of computer modelling. Most impressive has been the achievement of effective inverse modelling algorithms for IP and resistivity data, with notable contributions by Doug Oldenburg of the University of British Columbia and Scott McInness of Zonge Engineering and Research.

The resulting improved understanding of IP provided by enhanced modelling capabilities has also led to renewed attention to and utilization of several ideas and approaches which had been developed earlier but which had previously seen little or only sporadic application.

These new applications have been aided by improvements to IP instrumentation. In this regard, IP/resistivity has emulated seismic technology, in that the multiplicity of electrodes capable of being measured simultaneously continues to increase. Standard IP systems being manufactured today enable measurement of 8–12 dipoles (although in practice one rarely measures more than 6), while areal arrays such as devised and implemented by E-SCAN of Vancouver or IRIS Instruments of Toronto, enable measurement of voltage differences between as many as 250 dipole pairs in a fixed 2-D array.

IP surveying has also benefited from improved noise rejection attained through intelligent sensors and predictive filtering, providing more accurate measurements of resistivity and polarizability at low signal levels.

Among the new aspects of IP survey implementation, three particular arrays, developed or tried two or three decades earlier but which had seen limited or sporadic use, have received renewed attention.

In particular, the gradient array, used extensively for exploration for shallow porphyry copper deposits in the 1960s and 1970s, has been revived in a mode that employs multiple current electrode separations. Based on research by Perparim Alikaj of the University of Tirana (Albania), Quantec Consulting and Delta Geoscience have adopted a novel mode of gradient data presentation in terms of approximate depth of exploration for a given current dipole distance, termed "RealSection IP." Like other modes of displaying IP and resistivity data measured at the earth's surface, RealSection is a useful convention for portraying gradient data but is not an actual interpreted or inverted depth section. It is also cautioned that a multi-spaced gradient IP measurement such as RealSection, although capable of providing better lateral resolution than dipole-dipole or pole-dipole arrays, does not overcome the inherent decrease in resolution which accompanies an increasing depth of target, a fundamental constraint which governs all surface electrical arrays and surveys.

A second array which has received renewed attention and use is the roving bipole or reconnaissance IP array, originally developed in the 1950s by the innovative group of geophysicists at Kennecott Exploration. The roving bipole array was later used to a limited degree in exploring for active geothermal systems in the late 1970s. Again in this case, improved theoretical understanding gained from more complete and speedier computer modelling has provided added confidence in interpreting the resistivity and IP features observed in roving bipole field surveys. IP surveying employing the roving dipole array contributed to the discovery by Phelps Dodge of the Candelaria porphyry copper deposit in Chile concealed under alluvium, as will be described in detail in the subsequent Case History session.

A further minor innovation that merits brief mention is a multi-spaced pole-dipole array which employs two or more dipole lengths measured simultaneously at a multiplicity of N spacings, taking advantage of the ability to measure up to 12 dipoles. Such an array, designated the Poly-Pole, enables one to expeditiously resolve narrow, near-surface sources as well as larger, deeper targets in a single cost-efficient traverse. For instance, one particular embodiment of this design measured N=1-3 for a=25 m and N=2-5 for a=50 m. A sample of such data, plotted as a single combined pseudo section, is shown for a line which crosses a gold prospect characterized by variable lenses of disseminated sulphides in steeply dipping Archean volcanics near Sault Ste. Marie in northern Ontario.

Surprisingly, little research and innovation were conducted with respect to Complex Resistivity over the past decade, although problems remain in the routine and practical application of this technique. Better modelling capabilities, in particular semi-automatic inversion approaches, will likely stimulate renewed interest in this area, since such modelling offers the possibility of recovering a valid estimate or approximation of the intrinsic CR effect, rather than just the apparent parameter measured at surface, as noted in the recent paper in Geophysics by Yuval and Oldenburg (Geophysics, **62**, 2, 1997, p. 436–48).

The past decade has also seen limited further advances in understanding and utilizing non-linear CR behaviour on a laboratory scale and for limited surveys primarily for mapping the extent of hydrocarbon and other chemical contamination. During the past decade there was also a transient spurt of interest in the geochemical effects created by non-linear electrical processes (e.g., the Russian CHIM technique), but various test programs carried out in North America did not provide a convincing demonstration that CHIM constituted a means of achieving exploration insights not attainable by direct geochemical analyses.

In similar fashion, there has also been sporadic renewed interest in SP processes, of which probably the most notable is the recent PhD study by R.L. von Blaricom of Cominco American, which has sought to link anomalous metal ion distribution with weak but persistent SP processes acting over long periods.

Electromagnetic techniques

Significant changes and improvements have also occurred within the diverse family of ground exploration technologies generally designated as electromagnetics. Only a few key aspects will be briefly described in this paper; considerably more detail will be presented in the subsequent session on EM techniques.

At the lowest frequency range exploited by EM methods (10^{-4} to 10 Hz), the magnetotelluric (MT) method has benefited from improved S/N using remote reference magnetic base stations, and the ability to record electric and magnetic components from two to six sites simultaneously (depending on how many components are measured at any one site). Further advances in modelling, including approximate 2-D inversion, offer enhanced ability to understand the variations in observed MT parameters, which are typically complex in hard-rock environments.

One interesting new development involving MT is the recent effort by Frank Morrison *et al.* of University of California (Berkeley) to investigate a non-contact mode of measuring IP effects by observing residual phase shifts in MT parameters that display a variation with frequency opposite in sign to effects caused by conductive inhomogeneities. This interesting approach, which will likely receive additional discussion in the subsequent session on EM, could provide a useful means of conducting IP surveys in difficult environments characterized by very high surface and/or subsurface resistivities.

CSAMT has also seen substantial advances, via improved instrumentation as with MT, improved understanding of source field effects and how to mitigate them, and improved interpretation through more complete and more efficient modelling. For instance, recent modelling results suggest that under typical geologic conditions, the effective depth of exploration with CSAMT is considerably less than hitherto thought using simple skin depth rules and layer models.

In recent years, combining CSAMT with low-frequency MT has gained favour as a means of overcoming the problems associated with the transition to near-source-field conditions which afflicts CSAMT at low frequencies. Further elaboration and utilization of this approach is anticipated in the future, as well as renewed attention to natural field AMT in an effort to remove the various deleterious source field effects and constraints of CSAMT.

With regard to active EM systems that operate in the range of 10 to 1000 Hz (or its time equivalent), and which are most generally used for mineral prospecting and geologic mapping, incremental improvements over the past decade have yielded EM instrumentation presently capable of detecting large conductive bodies such as the Voisey's Bay massive Ni/Cu sulphide ore body to a depth of 500 m, or smaller, less conductive tabular galena/sphalerite/pyrite bodies, such as the Lisheen deposit in Ireland, to a depth of 300 m, or for geologic mapping of conductive strata to depths of 400–500 m.

These impressive exploration depths, which are comparable to the height of the CN tower (400 m) located adjacent to the Metro Toronto Convention Centre, have been largely achieved in the time-domain, because of its inherent capability to achieve an efficient increase in signal without the limitation arising from errors introduced by variations in coil geometry, as was ably argued by Art Raiche of the CSIRO 20 years ago.

The best known examples of such powerful TDEM systems include the UTEM system of Lamontagne Geophysics, the EM–37/47/57 series from Geonics, and Crone Geophysics' DEEPEM instrumentation, all of Canadian origin, plus the SIROTEM from GEOEX of Australia. Further improvements to the present remarkable capabilities of TDEM can be expected in the next decade.

TDEM surveys will be treated in greater detail, both surface and drill hole instrumentation and applications, in subsequent sessions, with additional interesting examples presented in the case history session.

At the upper end of the EM spectrum (10^7 to 10^9 Hz), we have seen a notable elaboration of ground-probing radar (GPR) devices and applications for engineering and environmental problems. Its capabilities have largely supplanted seismic reflection and refraction for very shallow engineering and environmental investigations, particularly where free water is largely absent (i.e., fresh rock, very dry or frozen). We may reasonably anticipate that these capabilities will be further extended in the ensuing decade, through multi-detector measurements at lower frequencies, enabling one to address a greater range of mining exploration and development applications.

Radiometrics

Finally, with respect to ground spectrometer systems, advances have been modest and limited over the past decade, reflecting the much reduced uranium exploration effort over this period, nor has there been much attention directed at alpha particle detectors, except for environmental monitoring. Recently introduced versions of radiometric spectrometers which enable measurement of radioactive decay energy levels over 512 channels should provide more accurate estimates of key radioelements in ground surveys, particularly for back calibrating old aeroradiometric surveys for reprocessing, as well as for environmental studies of potentially contaminated areas. Several companies, such as Scintrex, are proceeding towards installing these sensors in motor vehicles.

CONCLUDING COMMENTS

Generalizing on the preceding discussion, it is clear that there has been over the past decade a continuation of the trend to integrating multi-sensor capabilities in a single intelligent instrument package. One may expect a continuation of this trend in coming years, given the ever-increasing ability of microcomputers to measure, store and process multi-channel data streams. For instance, prior efforts by Zonge to measure and utilize TDEM effects in conjunction with IP surveys (as well as SP and possibly MT parameters) will likely receive more general attention and utilization.

Similarly, one may anticipate increased integration of the results of various sensors and surveys in a single consistent quantitative interpretation, a theme that will be further illustrated in the concluding session of this conference. One recent instructive example, which merits mention, is offered by a recent exploration program directed at investigating a possible deep ultramafic complex concealed under at least 1.5 km of late Precambrian clastic sediments. This challenging program involved the combined analysis of detailed aeromagnetics, regional and detailed gravity, selected CSAMT traverses and seismic reflection.

Looking into the future involves the usual uncertainties. However, I would anticipate that many of the trends in ground geophysics cited above will have become even more accentuated and developed in the next decade, driven by a need to detect and delineate deeper and/or more subtle targets. In addition to a continuing progression towards more complex instrumentation capable of measuring a greater number of parameters simultaneously, an improved capability to view multiple data sets and to interrogate them usefully with statistical tools and AI protocols, and quasi-automatic inversion of geophysical data and quantitative integrated interpretations consistent with all available data, we should also anticipate the unpredictable, i.e., innovations in methodology and techniques which confer entirely unforeseen capabilities.

All in all, these future directions in ground geophysics offer an exciting prospect, both for those in the mature stage of their professional endeavors, and for those just embarking on careers which will extend into the middle of the next century.