Progress in Electrical and Electromagnetic Exploration Techniques

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Reviewing a broad subject area is like photographing a landscape; the scene can only be recorded from one's own particular vantage point. Thus, readers should consider this paper a personal view and not become too incensed if some statements are orthogonal or opposed to their own perceptions.

APPRAISING THE DECADE

As I see it, progress during the past decade (1987–97) in electrical (E) and electromagnetic (EM) exploration methods has been very different from developments in the previous one. In the 1977–87 decade, there was a dramatic transition in geophysical E and EM — a widespread turning to time-domain technology for deep EM exploration, to broad spectrum IP techniques for better geological discrimination and EM coupling removal, and a general acceptance of ground penetrating radar and magnetotellurics as regular exploration tools. In contrast, this decade has largely been a period of consolidation — a decade in which many incremental improvements have occurred but relatively few major new trends or novel technologies have become established. The reasons are not hard to discern:

1. During 1987–97, the mineral exploration industry underwent a period of global consolidation and regroupment in which many of the major corporate players were reorganized and downsized. The remaining active participants were much more interested in obtaining improved cost efficiency with existing methodology than in financing risky novel methodology for possible long term advantage.
2. The new technologies adopted in 1977–87 had many technical and operational "loose ends" associated with them, and it has taken time to "tie up" some of these problem areas. And partly because of the restructuring of the exploration industry, it has also taken a relatively long time for changing exploration personnel to learn how to use all the new technologies effectively.
3. E and EM methods have been in widespread use in mineral exploration for more than 40 years, so the technology is relatively mature from a conceptual point of view. More than ever, progress has become dependent on the technology developments arising outside mining geophysics — on factors such as major improvements in electronic instrumentation, much increased computer power, etc. — than on internal factors such as the scientific ingenuity of a few geophysical pioneers and researchers.

Thus, as I see it, a geophysical Rip van Winkle who overimbibed at Exploration 87 and awoke now at Exploration 97 would not likely find themselves in very unfamiliar surroundings. When wandering through the current geophysical displays, the initial impression would be only that the computer graphics are much larger, more colourful and widespread; and that desktop and laptop computers are marvelously more powerful, smaller, and relatively cheaper. Perhaps a reading of the conference program might discern this decade's chief new trend: a widespread interest on the part of base metal mining companies in the possible use of geophysical methods in mine planning and grade control. But, in trying to resume geophysical practice, I believe our sleepy geophysicist would indeed find himself seriously out of touch in many respects.

The papers of this session on electrical and electromagnetic methods do their best, in confined time and space, to provide you with a rapid update on E and EM methods for the decade. They try to point out the most important points of progress. Rather than attempting to presage their content, I shall concentrate here on a few of the more general aspects of how E and EM geophysics is evolving; also on pointing out the areas I believe we need to focus to make next decade of development really productive.

DIVERSITY, AND THE EFFECTIVENESS OF ELECTRICAL AND EM METHODS

Diversity is both the strength and the weakness of E and EM geophysics. No other branch of exploration geophysics offers such a huge and diverse variety of tools. Certainly, E and EM techniques have long

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proven themselves useful in exploration—even indispensable for a wide range of exploration tasks. Although debates can rage over which is the optimum methodology for any given application, explorationists now routinely rely on E and EM methods of one kind or another as key elements of their exploration programs. In fact, acceptance has reached such a level that a geophysicist today needs frequently to explain the real limitations of the various techniques in specific exploration circumstances to overenthusiastic geologists who are expecting miracles. And while the wide variety of available methods offers at least a theoretical possibility that one of them likely will be suitable for any required application, the enthusiasm of a keen but impatient explorationist rapidly cools off once faced with the complexity of the selection process.

The diversity of E and EM methods is today so great and the technology of each method so ramified, that not even a geophysical specialist in E an EM can be expert in all of them. It is even more difficult for a geologist or exploration manager to be well informed on how to use the variety of techniques we are providing. Certainly, the underlying principles are common. Electromagnetic fields continue to obey the laws of physics (i.e., Maxwell's equations) and all E and EM methods use the electrical properties of geological materials as the proxy by which geology can be remotely sensed. But, it is a long step from understanding the common factors to doing quality geophysical exploration with any specific technique.

Modules

Twenty years ago, it seemed appropriate to make an analogy between a geophysicist and a carpenter: and liken the different geophysical methods to the numerous hand tools in the carpenter's tool box. Implicitly, the carpenter was assumed to be personally skilled in the use of each. Today, I believe a more appropriate analogy is to consider the variety of E and EM methods like machine tool stations in a flexible manufacturing organization, and the exploration geophysicist as the chief engineer of the factory. Each machine tool station may have a set of specialists associated with it, who (hopefully) have enough detailed knowledge of the system to predict accurately what their tool can do and know how to get the best performance from it. The chief engineer's job is to assign manufacturing tasks appropriately (and only accept work that the factory can execute satisfactorily), and make sure that the specialist groups are operating optimally.

Thus, I believe geophysicists running substantial exploration programs that need "high tech" geophysics must gradually change their role. Competing geophysical techniques need to be treated as alternative modules in the web of exploration methodology, with performance specifications being available for any module. Geophysicists, instead of focussing their attention mainly on the various field observation techniques and rating their specific advantages and disadvantages under an implicit assumption that whatever data the method provides will be optimally interpreted, should consider alternative field techniques together with their associated data analysis methods as integrated systems that in specifiable circumstances can produce useful exploration information products of various kinds. These delivery products need to be in forms that ordinary explorationists can understand and can directly apply in their exploration programs, not raw or somewhat processed observational data that require the recipient to have a detailed understanding of electromagnetism and the instrumentation used in the survey. And this "systems approach" is as necessary in selection of the most appropriate geophysical technique (or combination of techniques) as it is in performance of the exploration. It should be possible to predict quantitatively the performance of any proposed system for the known (or hypothesized) conditions of any proposed surveys.

Simulation

During the past fifteen years, a major area of advance in E and EM methods has been the devising of practical computer methods for modelling (simulating) the response of electromagnetic geophysical systems to hypothetical models of the earth (described in terms of physical properties such as electrical conductivity). Many research groups have contributed, but the pioneering work of the late Gerry Hohmann and his graduate students at the University of Utah and the more recent work of Greg Newmann at Sandia and of Art Raiche's group at CSIRO Australia deserves special note. Undoubtedly, this technology eventually will have a huge influence on how observational data are interpreted, and it may provide the basis of future computerized data inversion methods that can handle realistically complex case.

Realistically, the current methods and computers are not yet entirely adequate for regular interpretation work. Nevertheless, computer modelling has certainly reached the stage where, with good judgement and care, systematic modelling of many very useful cases is practical. Thus, it is disappointing to discover how little the technology is little used so far, since it could accelerate progress towards the "systems approach" I have espoused above. For instance, few proponents of specific methods have yet made comprehensive model studies that could provide a quantitative description of their method's exploration capability over a usefully broad range of exploration scenarios (quantitatively described in terms of hypothetical geometries and physical properties). Usually, a prospective user still has to estimate exploration capability empirically, by analyzing available case histories together with some very limited modelling of highly simplistic cases. Perhaps the problem is that the purchasers of these softwares (largely) are not the organizations that have personnel with the free time and aptitude to experiment with their use. Or, even more likely, the proponents of various systems see little competitive advantage in accurately specifying the capabilities of their systems unless customers demand it and other suppliers also do it.

Furthermore, the purchasers of geophysical surveys frequently complain of being submerged by the quantity of data from modern high tech geophysical systems. However, the interpretative data products provided by the contractors still are often distrusted relative to the basic observational data. Possibly, this is because current interpretative products fail to extract enough of the information that actually is contained in the field data, or perhaps because the steps used to obtain the product typically are only vaguely described. On the other hand, the exploration geophysicist commissioning the survey work is often too limited in time and facilities and has insufficient experience with the vagaries of the specific field system to do a better job himself. Too often, the geologist whose budget paid for the survey and who must make exploration decisions based on the results ends up doing his own *ad hoc* analysis.

Thus, although I can easily point out many ways in which the exploration capabilities of E and EM methods recently have been improved, I also believe we have a long way to go in interfacing our geophysical tools effectively with the people that need them in real exploration. It is heartening to see that research efforts in a number of leading organizations now are directed on this problem.

SOME SPECIFICS

In the following paragraphs, I try to illustrate some of the above generalities. The first paragraphs concern developments in the well-established techniques that have been in common use in exploration for a long time. Later ones concern methods that still are considered experimental or focus on applications outside mineral exploration.

Global Positioning System (GPS)

Before considering E and EM itself, we should remind ourselves of the profound benefits to all forms of exploration geophysics that are arising from the easy, quick accurate, three dimensional positioning that can be provided by GPS methods. This technology is an essential key to a fruitful exploitation of the high precision geophysical measurements that are enabled by new digital instrumentation techniques.

IP/Resistivity

Conceptually, little has changed in the use of resistivity /IP methods during the 1987–97 decade. But, in reality, the field has moved closer to providing a "systems implementation" than others. It certainly continues to be a mainstay of exploration for porphyry copper-style mineralization and a common tool in gold exploration where the geological effects of mineralizing processes are sought. Although apparatus is improving and effective regional reconnaissance techniques have been devised, a more significant change arises from increased use of computer modelling and of computer data analysis and inversion techniques. These have advanced to the point where EM coupling problems can be well predicted and ameliorated, where at least some information about the spectral character of any IP response is routinely determined from the data, and where the effects of severe topography on the resistivity /IP data can be fully taken into account.

Analysis of data by inversion methods rather than model fitting on pseudosections has also released the method from always having to record data with a fixed geometry of source and receiver points so pseudosections can be constructed. This means it can be used effectively in a much wider range of field circumstances than formerly. Overall, the performance of any proposed resistivity/IP survey is predictable in advance if there is prior knowledge of the terrain, access, and typical physical properties of the bedrock and surficial deposits, and the survey results are understandable by the geologists who must used them. Description of IP response in terms of Cole-Cole parameters has made it easier to integrate results from surveys carried out with different instrument systems.

Of course, these virtues do not change the fundamental factors that control whether a given type of resistivity/IP survey can successfully perform a required exploration job. But they increase the probability of a successful outcome comparably with an increase in instrument sensitivity or use of an improved transmitter or a better noise reduction algorithm.

Surface and borehole EM for ore exploration

Consolidation of practice around the main, well known, survey methods, along with incremental improvements in the hardware and software is a "nutshell" description of the 1987–97 decade. Surface-to-borehole EM has become an absolutely standard technique in deep exploration for base metal sulphides in igneous-metamorphic host rocks, and the emergence of oriented three-axis receivers is making it an even more effective technique. Advances in interpretation techniques and accumulating experience have cleared up a good deal of misunderstanding about seemingly "odd" phenomena such as IP and viscous magnetic effects, the filtering effects of conductive overburden, the effects of system waveform (for time domain systems).

Instruments and sensors are improving, becoming more flexible, and have better noise rejection capabilities. Time-domain response measurement out to delay times of a second or more are now being recorded in some production exploration surveys using "pulse" waveform systems. Although such measures are a pragmatic way of discriminating small highly conductive targets from the persisting responses of larger more poorly conductive interfering bodies, the need to do this (to me) is symptomatic of a larger, more recalcitrant problem:- the limitations and confusions that are inherent in the many different ways EM response is observed and recorded.

It is impractical to think that we currently can forego the various unique advantages associated with each different approach to measuring broad spectrum EM response: be it via selected phase components in the frequency domain or time domain measurement with a favourite transmitter current waveform. However, we should also be aware of how many (and different) limitations go with each choice. For those who remember the days of trying to understand and integrate induced polarization data recorded with diverse measurement systems before spectral representations became standardized, it is "deja vu". A lot of the potential exploration effectiveness of EM is being lost because geophysicists and geologists cannot easily compare experience with EM in different types of geology and terrain because different systems used to acquire the field data and it is too difficult to compare the results quantitatively.

As we move into the next decade, where fully digital signal processing will become common in person-portable ground survey instruments, it should be possible to do something about this problem. I would not be too surprised if there was a renaissance in frequency-domain representation of EM response, as there are powerful advantages when interpreting complicated response data. Borehole and aero-EM systems will be the first to go fully digital, since these equipments are less weight-limited than surface survey systems. Whatever analysis methods gain acceptance there will likely establish the standards for a new generation of surface EM.

Aero EM

In countries where the target geology is usually not deeply covered or deeply weathered, airborne electromagnetic methods have established themselves as an indispensable tool for direct base metal ore exploration, for kimberlite exploration, and for exploration of igneous metamorphic terrains via structural mapping. The systems are being steadily improved in their capabilities. Naturally enough, the exploration capability provided by these techniques is sorely coveted by explorationists working in other, less suitable terrain. Thus, much research and development effort is being invested in devising systems that can much better accommodate deep weathering and more conductive cover, and also more mountainous terrain. The main emphasis has been on pushing the spectral coverage of the systems to lower limits, increasing the transmitter moment and measuring more parameters in order that complicated patterns of response from surficial and deeper targets will be interpretable, and it has focussed especially on towed bird, time domain EM systems.

As efforts towards penetrating conductive cover have progressed, so has the ability to describe the surficial conductivity structure. A growing variety of data analysis techniques have been devised for this, and system hardware configurations have been upgraded to make it more possible. There is no doubt that the barrier of surficial cover barrier to successful mapping of bedrock structures with aero-EM is being steadily pushed back by the advances in equipment. More problematic is progress with the data analysis techniques. With 50 to 100 channels of information being recorded along the flight profile, geophysicists and geologists who need to make exploration decisions about the area they have flown understandably want to be assured that they will receive a only a few maps that succinctly summarize most of the valuable information in the flight data. At this point in time, I am less than confident that they can be assured of this, but I can reliably report that a lot of effort is being devoted to the problem.

If I could make a suggestion as to what interpretative products are wanted: it would be nice to receive one map with an estimate of a laterally averaged overburden thickness and cumulative conductance, another giving local variations in the cover sequence that might indicate differential weathering, etc., and another set indicating (as well as possible) the conductivity structure of the bedrock. This set would hopefully look much like the mappings possible in thinly covered terrain, but necessarily would be variably masked by the thickness and conductance of the actual cover. My personal guess is that current instruments are easily capable of delivering useful bedrock exploration beneath 50 meters of cover and 2 Siemens of conductance, and in some circumstances may be able to search usefully beneath 80 m and 8 S, but they are not yet capable of penetrating the 120 m and 25 S of cover present in some parts of Australia.

Inversion vs. Interpretation

Much as I would like to see the data product from an EM or resistivity survey be provided as a 3-D data volume of estimated earth conductivity through the surveyed region, this is still an impractical goal in many cases. The reason is that we have not yet found adequate ways to handle ambiguity. Where surveys are very systematic and comprehensive, and simulation methods are adequate as in some cases of resistivity/IP exploration, and where the confusing effects of small scale, high contrast, local structures with complicated geometry are not too prevalent, the reduction in spatial resolution with depth is systematic, and alternative inverse solutions that satisfy the field data do qualitatively resemble each other to a large degree. Then, a single inversion which is carefully conditioned by *a priori* considerations can express the exploration results clearly. However, there are many other situations: for instance where the data are consistent with several qualitatively different earth structures, or where the data require a highly contrasting local feature be present but are imprecise about its location and are inconsistent with a smoothed out version. In such cases, it is difficult to know how to express this information in one or a few pictures of probable conductivity structure.

Inversion methodology will undoubtedly be a growth area for E and EM exploration geophysics in the coming decade, inspired especially by the great progress made in the past few years by the University of British Columbia group headed by Doug Oldenburg. Nevertheless, the road will not be easy in inductive EM. I expect some rather different paradigms will be needed there.

Magnetotellurics

A more cogent title would be "broad spectrum, impedance-measuring methods", as it is not fundamentally important whether the utilized excitation is from natural sources or a man-made transmitter, or what spectral range is utilized. Instruments for impedance measuring systems have improved so markedly that surveys providing a relatively dense grid of observations can now practically be carried out, without having to resort to crude simplifications such as scalar impedance approximations. Interpretation theory has greatly improved, in part due to improved computational modelling techniques. Thus, MT has become an operational rather than a research technique. In the web of E and EM methods, it offers a resistivity depth-sounding capability that is not limited by the dimensions of feasible electrode arrays or the size of practical resistivity transmitters. It is beginning to become a modular technique like standard, controlled source, resistivity and IP methods.

If I might add my dream for the future, it is for multi-receiver measurement systems which could, in addition to the $\mathbf{E}:\mathbf{H}$ transfer function, determine spatial transfer functions between the magnetic and electric fields at nearby sites. This would open up many new interpretational possibilities for the method, including direct identification of highly contrasting conductors by their local induction, and so make it competitive for some exploration problems that now require controlled source EM.

Ground Penetrating Radar (GPR)

The use and acceptance of GPR has grown by leaps and bound in the past decade, mainly focussed on non-ore prospecting applications. On the web of E and EM techniques, it is somewhat isolated from the others. This is partly because its proxies for geological earth properties are dielectric permittivity and dielectric loss factor (local effective conductivity at high frequency). Although these properties are related to the electromagnetic properties of earth materials at the lower frequencies utilized by other E and EM methods, the relationship is not necessarily close. Furthermore, GPR is a true wave method of remote sensing. Thus, it is methodologically closer to seismology than to other E and EM methods which mainly utilize potential or diffusive fields. Its rapid growth in the past decade is partly due to the rapidly increasing power of small computers, and the current feasibility of implementing many simple but important seismic data processing techniques in GPR with only a relatively inexpensive laptop computer.

Environmental E and EM

I refer here to engineering, groundwater and contaminant geophysics using quasi-static or pseudo-static E and EM; also to archeological use, although this is not a subject for this meeting. This has been a growing area, at least in terms of experimentation and novelty, although perhjaps not a large field in terms of budgets for operational surveys. One development is resistivity surveying with large numbers of automatically switched electrodes using non-classical electrode geometries and computerized inversion packages. It is also being applied in cross borehole and borehole to surface geometries. The trends are similar to those encountered in ore prospecting applications, but some of the ideas have been taken much farther. Considerable work is also being done on the effect of contaminants on soil conductivity and conductivity dispersion (IP).

Small controlled source EM units are being used like mine detectors to find waste drums, etc. EM methods are being adapted and invented for use on the ocean floor. Russian work on observing nuclear magnetic resonance to determine water content using audio frequency EM techniques to stimulate free precession of hydrogen molecules in the static terrestrial magnetic field is being revisited in the west. Certainly, the amount of innovation in this broad application area is disproportionally higher, relative to the amount spent on surveying, than in ore prospecting. Ore prospectors would be wise to watch what is happening there for some good ideas.

Radio shadow methods

The mining industry initiatives towards using geophysics at active mines to improve early mine planning and help with final ore delineation prior to excavation is generating a lot of experimental work with what used to be called "radio shadow" methods. It is now often referred to as "EM tomography". Although full of promise, there is a lot of R & D still to be done in terms of equipment development, developing better data analysis and simulation methods, and field testing to confirm or falsify ideas about the electrical properties of ore environments.

New physics

The 1987–97 decade has seen a number of investigations of E- and EM-related methods that have looked for physical effects beyond the standard ones commonly exploited: novel effects that might have some value in ore prospecting, etc. The investigations have been difficult roads for the researchers. In order to have been overlooked so far, any such phenomena are bound to be weak or only observable only in uncommon circumstances. There has been a tendency for an impatient exploration industry to expect dramatic early results and then to loose interest quickly if this does not eventuate. My own feeling is that a lot of useful, exploitable physics and electrochemistry is still waiting to be revealed, but it may take quite a bit of patient exploratory research to uncover it.

Data mining

Geophysical systems generate vast amounts of data of very many types. Although it can help to understand the physics that generates these data, it may take a lot of ingenuity and an iconoclastic frame of mind to devise ways of extracting the desired exploration information from all our data sets and to put it in a compact, understandable form. There are many parallels to be found among analysis methods currently applied to data generated by disparate physics. There is a growing literature about this, and a new discipline located somewhere between mathematics and computational science is developing. I call such individuals "data miners". An analogy is the role of professional statisticians in biological and medical science. I expect to see a rapidly increasing role for "data mining" talents in mineral exploration in the near future, and their input will certainly facilitate the conversion of some of our geophysical field methods into complete exploration systems or components thereof.

CONCLUDING REMARKS AND SUMMARY

Exploration geophysics for mining and environmental exploration is a steadily growing and maturing field. E and EM techniques form one of its most important branches. The list of proven technologies within E and EM is getting longer, and the individual technologies are becoming more powerful but more complex. Inexorably, geophysicists involved with the E and EM field are being drawn towards one or other of two poles — either being an exploration geophysicist who is strongly grounded in exploration geology and has a broad understanding and experience of all the geophysical techniques useful in his or her type of exploration, or being a technical geophysicist who has a full knowledge of all the technical details and fundamentals of one (or a few) methods and is involved with improving its technical capabilities. While there is still a need for some applied physicists in E and EM geophysics, of the kind that pioneered the field, they are becoming a rarity. As important now is the contribution of specialists from other fields like theoretical and mathematical physics, computational physics and computer science, electronic engineering, etc. And exploration geophysicist must certainly have a good geological background and a strong enthusiasm for the exploration game.

Once a technical field reaches a certain level of maturity and diversity, for it to be economically successful and competitive with other alternatives, it has to become modular. By this, I mean that the different specialized techniques it uses have to become encapsulated, i.e., describable by specifications and with instructions for their proper use, and having forms of output or outcomes that are readily understood and useable by persons who do not have a profound understanding and lots of experience with the topic. Medical practices are a good example. Once this happens, the various techniques become much more widely useful, because they can be employed without needing a technical specialist at every turn or requiring everything about a project to be carried out by a single individual. Information and responsibility for action can be passed more easily from one person to another. Reflection seismology for petroleum exploration began the process of modularization more than twenty years ago and has almost completed it. Petroleum "explorationists" work closely with seismic data products all the time, but need not be deeply involved with or knowledgeable about the fundamental principles of reflection seismology or all the technological niceties that are needed to give good seismic images.

In my view, E and EM geophysics has more that started down the path to modularization. Perhaps the first example of it was what Jack Betz did in the early 80s for horizontal loop (Slingram) EM when he produced, what amounted to, a manual of how to use it and how to interpret the results. And he persuaded Tapio Vaara to incorporate all the necessary improvement in his "MaxMin" versions of the equipment. However, the concept is an engineering approach to applied science that sits uncomfortably with many of the personalities in the mineral exploration business (perhaps including me) and will not likely be a popular idea among present technology leaders. Nevertheless, its progress will be like osmosis and diffusion — quiet, slow and inevitable. To put a more upbeat face on it by using a computer analogy, we have given up straight down, monolithic, unstructured programming methods, and have adopted the use of structured coding with subroutines and function libraries. but we must now enter the age of object-oriented programming where nearly everything is made of modules that are especially designed to interface with one another.

Technical improvements in E and EM geophysics are appearing everywhere, as the potential of ever improving computational technology, new instrumentation electronics, GPS, and numerous other technical developments are being assimilated into geophysics. The rate is limited by the amount of research and development investment moneys available to the industry, but progress is probably about as fast as the user side of the industry can digest. This is the upside of development in the past decade; the downside is that comparatively little progress has been made in improving the use of E and EM techniques in exploration. This requires improved understanding of the relationships between geological and physical properties of rocks and soils; and as far as I can see, comparatively little effort has been devoted to this subject.

The relationship between geology and physical rock properties is often regarded more as a matter of a geophysicist's acquired experience rather than of documentable science. I largely disagree with this view, but to the extent it is true, the mineral exploration industry has lost a very large and essential technical resource in the retirement and/or transfer to other duties of so many of its older, experienced geophysicists; and it is not doing a great deal to replace the loss with documentable material from which newcomers can learn. I believe that major companies that want to be winners in the exploration business in the future need to give some serious consideration to this point, as do governments that claim to be desirous of mineral discoveries and mining investment, but are downsizing or disbanding geological survey groups that help provide this sort of background.

As a final thought, I believe that we could generate a lot of rapid progress in electrical and electromagnetic geophysics if the exploration company who are its customers were a little more demanding of their geophysical suppliers in terms of written specifications for instrument systems and their geophysical capabilities and in requiring as part of any system they buy or use that there be a well described analysis method for the survey data that will yields a well thought out and well controlled set of geophysical output products. This will cost some money, but would be very worth while in the long run.