Paper 14

Electrical Geophysical Systems – Review and Outlook

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ABSTRACT

The induced polarization and direct current resistivity method measures both chargeability and resistivity, and enjoys a wide and varied application in several industries. From the earliest work in 1830 to the current rapid expansion of the 3D implementation of the method, electrical geophysics has consistently delivered significant value to the mineral exploration industry.

Following on from the introduction of distributed array systems in the late 1990s, the industry is now exploring the benefits of full-azimuth 3D surveys. These surveys yield high volume, dense data sets that have minimal directional bias, and that produce high accuracy, resolution and depth search. As time series data acquisition becomes more widespread, significant advancements have been made in the signal processing of data sets. Sophisticated noise reduction strategies, and advances in real-time and post-processing have improved the overall data quality to underpin more accurate modelling and greater depth search. A move to higher power transmitters of up to 200 kW with remote operation has improved performance and safety. Many new distributed array systems are now available, some with cable-free networking and built-in GPS for synchronization and timing. Several contractors are able to field well over 150 receivers in a single array. 3D inversion modelling has advanced to the point where data sets with over 1,000 transmitter points and over 1,000,000 dipoles can be input to a single inversion.

The application of high channel count, full-azimuth 3D surveys will continue to grow and new markets will be addressed that benefit from the accurate, high resolution models that are produced. These 3D systems will be able to field thousands of receivers and high power transmitters will be developed to address larger survey areas and greater depths. A wider range of sensors will be available for use, expanding application to new environments. Noise at long offsets will be addressed through common voltage referencing, time-series acquisition and DSP. It is likely that underground deployment of electrodes will develop in the mining business. Similarly, time-lapse monitoring will allow for better management of leach piles and in situ reservoirs. Integration of electical data sets with other data sets will improve, and further development of joint inversion methodology will refine exploration targeting. Work will continue on the joint processing and interpretation of the electromagnetic signal in the induced polarization response. It is also likely that spectral analysis of the induced polarization waveform will yield better characterization of the target volume.

INTRODUCTION

The induced polarization (IP) and direct current (DC) resistivity method has the advantage of providing two physical property measurements from one survey. While the measurement of the resistivity parameter is not unique to the method, the effective measurement of IP is unique to this ground and borehole geophysical method. Through the direct injection of a time-varying electrical current into the ground, the measurement of subtle Earth responses can be used to derive 3D and 2D model images which provide valuable insight into the distribution of these electrical properties of Earth.

The DCIP industry has seen significant change over the last 10 years. We have seen the introduction of 3D surveys to the mineral exploration industry, the growth of high channel capacity systems, advance of time-series data acquisition, and further development in the processing and interpretation of 3D data sets. These new developments are being added to an already robust suite of survey methodologies that can address a wide variety of exploration applications.

Recent advances in the DCIP method serve to provide heightened accuracy, broader application, elevated safety, and greater operational efficiency. Heightened accuracy is driven by the march towards higher and higher density data sets and the introduction of 3D data sets. Safety is enhanced by new purpose-built technologies. Efficiency is gained through the upgrade of systems and in the introduction of new technologies and approaches. And these advancements together create opportunities to address new applications and markets.

HISTORY

From the earliest work with electrical methods by Robert Fox (1830) and the first recorded discovery using the method in 1835, to the current rapid expansion of 3D acquisition and modelling, electrical methods have contributed significantly to success in mineral exploration. The earliest work on the active resistivity method was carried out by Conrad Schlumberger in 1912 and this was quickly followed by borehole applications in 1913. The majority of resistivity surveys during these early

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years deployed sounding arrays developed by Schlumberger and Wenner.

Schlumberger (1920) first recognized the IP effect, but not until Dakhnov (1941) and Seigel (1949) was the IP method recognized as a viable exploration tool. Seigel (1959) produced the mathematical formulation of the IP effect, and Halverson (1967) describes the phase angle concept and introduces methods to defeat electromagnetic (EM) coupling. The method rapidly gained commercial application in the 1950s predominantly through N=1 dipole-dipole surveys.

Zonge et al. (1972) describe the similarities and differences of the three fundamental measurement methods – pole-pole, pole-dipole, and dipole-dipole. Hallof (1974) begins the period where EM coupling could be isolated from phase IP. In 1976, the first 3D electrical resistivity system, E-Scan, was introduced. Pelton et al. (1978) include mineral discrimination and the Cole-Cole model in the method. Dey and Morrison (1979) provide the seminal paper on numerical modelling that provides the fundamental basis for array comparison and inversion. In 1981, Halverson et al. introduce the Halverson-Wait model for IP and introduce hybrid time and frequency domain systems. Rudimentary dipole-based telluric cancellation is introduced.

In 1981, the state of the art was a 2D survey that acquired N=1 to N=4, and in the late 1980s this expanded to N=6. Bibby and Hohmann (1993) describe a rapid reconnaissance method that came to be variously call RIP, TIP, and VIP. In 1994, Oldenburg and Li forever changed the interpretation of electrical data when they introduced an affordable and available 2D inversion code. Fullagar et al. (2000) introduce halfspace modelling for removal of EM coupling in the time-domain while Routh and Oldenburg (2001) demonstrate similar techniques for the frequency domain. White et al. (2001) carry out the first offset 2D survey which provides 2D coverage, but required 3D inversion for accurate interpretation. In the early 2000s, 3D inversion code was introduced. LaBrecque et al. (2010) followed up with joint inversion for IP and EM coupling. Zhdanov (2008) introduces the GEMTIP formulation that further integrates EM and IP for the purposes of both separation of EM coupling effects and mineral identification.

The first distributed array (DA) system was developed by MIM Exploration Pty during 1994–2003 partly as a result of ‘The John S Sumner Memorial International Workshop on Induced Polarization in Mining and the Environment’ held in Tucson in 1994, and work done at Anaconda Minerals by McAlister and Halverson. Sheard et al. (1998) introduce the MIMDAS system. In the early 2000s the MIMDAS system and the Titan24 system, a DA system introduced in Canada in 2002, create a new capability for deep DCIP exploration. Goldie (2007) demonstrates the effectiveness of the methodology for deep IP.

In separate papers, some early work with 3D inversion was published including Collins and White (2003) who demonstrate an offset pole-dipole array; and Webb et al. (2003) who show the capabilities including building dipoles from a snaking DA. Gharibi et al. (2012) show that 3D acquisition that incorporates orthogonal dipoles and very high channel counts (296) produce a significantly better model resolution in deep investigations. Loke et al. (2013) illustrated the capability of 3D software to manage disjointed arrays. Webster and Wondimu (2013) showed the value of adding subsurface electrodes.

Commercial full-azimuth surveys are introduced in 2011 with the Orion3D system completing a survey with 296 dipoles active for each injection. In 2010, single-channel DA architecture is introduced in the Volterra technology. Deployable on surface or in boreholes, this receiver architecture provides for full flexibility in array design. The gDAS24, whose use in commercial surveys commenced in 2012, was designed for unmonitored data acquisition in both regular and highly distributed, combined IP and magnetotelluric (MT), arrays. The DIAS32 system, introduced in 2015, employs common voltage referencing (CVR), in which a receiver is placed at each sensor and time-series measurements are taken with reference to the CVR wire which extends throughout the survey area. Any two sensor responses can than be differenced to generate dipoles. The method allows for the acquisition of much larger data sets than conventional DA systems that measure dipoles directly.

ELECTRICAL SYSTEMS

Historically, IP and resistivity systems have largely followed similar development paths, but with two main branches. The first branch is the small-scale resistivity mapping systems that are designed to provide high resolution mapping of the near-surface. These systems can be generally described as ‘switching’ systems. In this type of system an array of electrodes are laid out through the survey area, whether it be in a 2D or a 3D application, and are connected to a single receiver/transmitter system. The operator then has control of the entire array and can transmit from any electrode and receive in any electrode. The pattern of transmitting and receiving is normally pre-determined. The principal limitation of this type of system is in the inability to transmit a large signal. Because these ‘switching’ systems do not scale sufficiently to what is normally required for acquiring IP in a mineral exploration project, we will not discuss this branch of systems any further.

The second branch is comprised of those systems that are designed for IP and resistivity surveying in larger-scale applications. These systems generally have separate electrical circuits for the transmitting and receiving functions, and are most often utilized in deeper applications such as mineral exploration.

Reconnaissance mapping is well-served by the RIP/TIP/VIP methods. These methods efficiently map IP and resistivity over large areas but at the expense of depth discrimination and resolution, although this may be enhanced with the use of multiple transmitter bipoles. As a result, RIP is effective in the initial detection of porphyry systems and other large deposit types. The gradient method provides more continuous coverage than RIP, but also lacks depth discrimination. The gradient method enjoys a broader application, but is normally also considered as a reconnaissance method.

2D surveys can be defined as those in which the transmitter and electrodes are all deployed along a single survey line. Where depth discrimination is important, and the geoelectric structure has little variation perpendicular to the line direction, the 2D method is effective. 2D surveys have dominated the IP and resistivity market since their inception in the 1950s. Because of scalability and relatively low cost, this method became a workhorse in many mineral exploration applications.

Any survey array that strays outside the confines of a single line has some component of 3D information, but it is tremendously important to understand the nature of this 3D information. 2D systems have been adapted to acquire partial 3D survey data. The offset 2D method employs two or more receiver lines that are parallel to, and offset from, the current injection line. This method is popular because of operational advantages over 2D surveys. The off-line data content of the offset method requires the use of 3D inversion methods, but because no cross-line dipoles are normally measured in the method, the 3D models are significantly compromised.

Distributed array systems are those that utilize multiple receivers distributed throughout the survey area. DA systems vary from being fully-distributed (single channel receivers) to having up to sx channels per receiver. DA systems may or may not offer real-time communication between the receivers and the operator. More recent systems utilize wireless technology (DIAS32, NEWDAS, ZEN), others use a cabled network system (MIMDAS, TITAN24), and others have no such communication (gDAS24, ORION3D, VOLTERRA). The advantage of DA systems is in the ability to deploy them in any survey configuration. This is particularly true of the single-channel DA systems.

TRANSMITTERS

A summary on the current situation has been given by Woods (2016).

Transmitters vary in power from less than 1 kW to 200 kW, from hand held and battery powered to truck mounted and diesel motor powered. Many have been in the industry for many years and some have been developed more recently in response to the joint demands of increased performance and safety. The GAP range which isolate almost all aspects of the operation from human intervention is a good example of these.

The choice of transmitter for any survey is usually based on a compromise between the highest power unit available, its size and transportability, and its availability and suitability to the recording system. More power means increased size and weight and increased difficulties in navigating the survey area.

An important requirement for some recording systems is that the transmitter is able to be controlled to run on the same time base as the receiving equipment. This is to ensure accurate phase and can be accomplished using either a wire link or GPS timing.

The requirement for a ‘good’ current waveform (stable on-time and fast shut off) still exists for systems that do not monitor the transmitted current but, for those systems that do, this consideration is now of minor importance.

Unlike in airborne surveys where the load is constant, ground transmitters are required to work into an enormous range of loads. This means that it is frequently not possible to get the maximum power available even with increased voltage taps. If the problem is addressed by going to higher and higher voltages, another problem can be created and that is the need for larger current carrying wire and all that is entailed in laying it out and moving it. Consequently, the performance of all the currently-available transmitters in exploration in deep and or covered terrains is ultimately disappointing. In these environments, the secondary voltage, i.e the IP signal is likely to be only a few microvolts per ampere of current. Moving from a readily available say, 30 kVA transmitter to an, as yet unavailable, 300 kVA will give only a three times increase in current because power goes with the square of current. Yet, as mentioned above, the associated logistics are quite onerous.

In many situations, it is more useful to make changes to the electrode array to get equivalent or even greater increases in signal or, as is recommended in the section on electrodes, it may be more fruitful to increase S/N by decreasing noise.

SENSORS

Whereas the importance of good transmitters is obvious and has received a lot of attention, the importance of good sensors is often overlooked. The diminishing rate of returns mentioned in connection with transmitters above does not apply to sensors so any improvements apply linearly to the signal to noise ratio (SNR). So while we have seen that the relatively difficult-to-achieve order of magnitude increase in signal leads only to a S/N increase of three, the relatively more achievable three times reduction in sensor noise produces the same effect.

State of the Art

It is fair to say that opinion is divided over the state of the art. Text books generally recommend, and many operators use, non-polarizing Cu-$CuSO_4$ porous pots. There are other types of non-polarizing electrodes. Ag-AgCl and Pb-PbCl are both popular with the MT fraternity, for example. Their specifications are well understood and documented, as is their performance in tests like the Garchy experiment (Lu and Macnae, 1998).

To be able to measure IP signals of microvolts/amp we need electrodes with noise levels less than 100 nV/√Hz. Morrison (?) showed results of both copper sulphate and lead chloride porous pots with noise levels of 20–30 nV /√Hz at 0.1 Hz which is the range. However, their performance in practical situations is less well-known. In general, they are prone to breakage, leakage and are intrinsically high impedance making them often much noisier than their specifications.

Many IP practitioners use metal electrodes, either plates or rods which usually test badly but often work well in practice, and their performance is not so well understood. For example, Lu and Macnae (1998) show results for 4.82 Hz and 0.001 Hz. At 4.82 Hz, stainless steel (rods, not plates), are comparable with the rest but display much more noise at the lower frequency. So, while 4.82 Hz is too high for most conditions, 0.001 Hz is certainly much lower than required. Most IP surveys operate around 0.1 Hz, a full two orders of magnitude higher. So the problems with the tests are:

1) No test at a standard IP frequency
2) No compensation for linear drift.
3) Appear to have tested rod shapes, not plates.
4) Do not discuss contact resistance

Other tests, eg. Ritchie (2015) while not so encompassing but addressing these shortcomings have found stainless steel plates (~30 cm x 15 cm) to test very well. They may drift but do so in a linear fashion which is removed in processing, and they have low noise. They also usually have very low impedance, several ohms or tens of ohms compared to the non-polarizing pots that may be several thousand ohms. Zonge and Hughes (1998) documented the effect that contact resistance had on capacitive coupling in controlled-source audio MT (CSAMT) surveys and Ingeman-Nielsen (2006) showed the adverse effect of capacitive coupling on the measurement of phase in complex resistivity (CR) surveys.

One of the challenges in DCIP surveying is seen in environments where the resistance of the ground at surface is high and establishing contact is difficult. Improvements to analog circuitry has meant that receivers can overcome higher contact resistances, but in some environments, the problem still remains. The use of a buffer amplifier on the electrode has been tested and found to be an effective approach, but no public information is available to quantify or characterize the improvements.

Finally, there are the issues of numbers and handling. For example, while it may be practical to deploy a few delicate Ag-AgCl electrodes it is another matter to transport and maintain 90+ of them. Steel plates on the other hand are almost indestructible and 90 or more are not an impost on cost or handling.

Recent developments

Capacitive electrodes have been suggested and tried for many years. If suitable they would solve many problems associated with emplacement. Recently there have been claims that many or all of the historical problems have been solved but there is no publicly available data to judge.

Opportunities

Probably due to lack of demand it seems that little work has been done on improving electrodes compared to the considerable amount done on developing transmitters and receivers.

There is perhaps an opportunity to improve the S/N in surveys used by better packaging of the superior performing silver and lead chloride sensor types and producing them in quantities that would significantly lower the cost per sensor.

RECEIVERS

The state of the art in IP receivers can be summarized as distributed array receivers with time-series acquisition, GPS, and communication capability. The time-series 'revolution' started with John Kingman, and the DA systems described above. These hybrid systems combined the best aspects of the three main technologies of the time, time-domain chargeability, complex resistivity phase (CR) and frequency domain signal comparison (percent frequency effect or PFE). Time-series acquisition means the recording of a signal sampled at some regular rate from the response of a sensor located at some useful location within the area of interest. The sensor locations are chosen to produce a measureable response expected to be pertinent to the study. These sensors are electrodes, any two of which can be paired to create a dipole of a certain size and orientation sensitive to galvanic measurement of the electric field.

Most receivers measure and record the dipole response from two closely-spaced sensors. This approach is beneficial because the short length of wire between the two sensor electrodes limits the amount of noise that is induced in the wire. A new mode of measurement, called CVR (Rudd and Chubak, 2017), measures the response of each electrode sensor relative to a reference wire. Noise induced in the reference wire is removed when differencing the response from adjacent (or non-adjacent) sensor electrodes when building dipoles through the subtraction of the time-series records.

A sampling rate is chosen that is pertinent to the geophysical parameter being measured. For IP signals that are pertinent to the mining community (Macnae, 2016) the sampling rate must provide a focus on the band from 'DC' (typically 0.1 Hz) to 50 Hz, although in some environments, a lower base frequency of 0.02 Hz may be required.

Time-series acquisition implies that the recorded signal will be 'nearly raw'—typically a stream of digitizer counts—and all signal processing will occur separately. This means the signal processing may be repeated as often as necessary to ideally separate the signal of interest from the noise. The signal processing may occur long after the fact—e.g. years in some cases where new methods might improve old results, or in real time for QA/QC purposes. The immediate results may be a pertinent subset of methods that provide suitable quality assurance from, for example, lower-capability processing hardware. The new time-series receivers require much less interface hardware and software than previous receivers because they are not designed to display results, however they require capabilities for higher volume data storage (up to several GB depending on application) and can benefit from network protocol communication such as LAN or wireless. Some loggers, however, are completely autonomous and data harvest is performed by physically removing or locally downloading the stored data.

Since significant signal processing is not typically included in a logger, these receivers could be considered more 'array independent' than previous receivers. There may be no attempt to include and calculate geometric factors 'on-the-fly' or internal to the receiver. This flexibility comes at the price that it may be difficult to trouble-shoot the sensor associations and location of a receiver. Therefore, modern receivers are equipped with GPS receivers for location.

In a DA survey, receivers will not typically move during the course of surveying unless they are on water. They will remain stationary for a ‘shoot’ that may take several days or even weeks in the case of a high channel count 3D survey. The loggers are usually configured with a battery that permits from 8 hours to several days of acquisition time. For a DA system, low channel counts are possible, some receivers are configured with a single channel (e.g. DIAS32, Volterra), others may have 2, 4 or 6 channels (MIMDAS, Titan24, gDAS24). However, there are still some high channel count receivers such as GDD and IRIS that may connect to 10–32 channels or more. Certain engineering systems such as IRIS Syscal, AGI Sting and MPT DAS may connect to hundreds of electrodes, although they multiplex through these sensors rather than record all channels at once. The Crone ESCAN and the IPOWER 3D systems also operate by switching.

The quality and parameters of the IP measurement depends less on the receiver than on the perturbation source and the post-processing method. The source may fundamentally be configured as time-domain or frequency domain, usually with a square waveform in either case, and may be imposed using systems with signal strengths that vary from a few 10s of watts to 100 kW. High current (> 1 A) is desirable and some systems can deliver 100 A. Signal processing can occur in the time-domain (referred to as ‘binning and stacking’) or the frequency domain (FFT).

Most modern IP systems use at least one receiver channel to monitor and record the current. This permits deconvolution of the signal at every receiver sampling point. Two current monitors, one placed at the current injection point and one at the transmitter site, are gainfully deployed to sense leakage in the current lead wires, an often significant, and normally undetected, noise source.

PROCESSING AND INTERPRETATION

Data processing is an algorithmic approach to enhancing and extracting the relevat part of recorded information or signal, whereas interpretation is a more iterative process, in some cases requiring the re-processing of data, with the aim of explaining the meaning of the data with respect to the problem at hand.

Data processing was largely rendered within receiver instruments until the advent of large capacity, rapid, and field-worthy memory which has facilitated storage of full time series data at suitable sample rates for processing outside of the receiver instrument itself. As such, data processing options in older receiver systems tended to be restricted, and post-processing was largely limited to selection and rejection of processed data. For many modern receivers, apart from some limited data processing required by the analogue-to-digital converters such as anti-alias filtering, the intention is usually to store the time series that most closely represents the nature of the received analogue signal, leaving the choices of what processing algorithms to apply to an external system. The advantage of this resides in the capability to test alternative processing methods, even at a much later date, where greater computational and presentational power can usually be brought to bear on the processing challenges. Furthermore, data acquired elsewhere in the array, or indeed even more remotely, may be incorporated into the processing to further enhance the relevant part of the signal, or conversely diminish the unwanted part.

Enhancement of the relevant part of the recorded signal with respect to the noise, ie. the remainder of the recorded signal, may be achieved by the subtraction of inferred noise and/or by filtering-out the undesired parts. A manageable graphical user interface that allows for the inspection of the recorded time series signals, inferred signals, and the effects of filters at the level of the time series and processed data is fundamental in making appropriate decisions to optimize processing.

To date, among the most common sources of noise, telluric signals are the most propensive to their inference and subsequent removal. Rowston et al. (2003) describe how this may be achieved through the synchronous acquisition of remote magnetic field data which provides an inferred local electric field though application of the local transfer function, i.e. the impedance through the bandwidth of interest, obtained from MT data acquisition using the same array of receiver dipoles. Utilization of the tensor impedance and orthogonal pairs of magnetic field data further improves the accuracy of the inferred tellurics in areas of complex geoelectrical structure. The extent to which telluric cancelation may improve data quality depends on the relative magnitude and spectral content of other sources of noise.

Signal processing encompasses a very extensive field of investigation and application, but for IP data it is focussed on despiking and subsequent filtering, usually based on Fast Fourier Transforms (FFTs) but also, more recently, on Wavelet filters as described by Deo and Cull (2016). Wavelet filters are attractive given that they are localized in both time and frequency and can as such provide additional diagnostic information in the case of non-stationary signals. A single optimal recipe for processing is unlikely to be forthcoming given the temporal and spatial variability in noise, certainly between surveys, if not perhaps even within one survey, however, wavelet filters have been shown in some instances to provide improved results over FFT-based filtering, and are less subject to careful preconditioning which is often fundamental to the success of FFT-based methods.

Stacking, for improving SNR, is usually considered as a time domain process, but approaches in frequency domain analysis where the aim is to obtain the magnitude and phase (of the transfer function between the transmitted current and the received voltage) are equivalent. Stacking, and its modifications proposed by Halverson and Kingman et al. (2004), is a filtering method with the modifications aimed at optimizing the spectrum of the filters to best reject noise at all but the desired frequencies. The exclusion of individual cycles, or half-cycles, although something of an anathema to readily understanding the filtering effect of stacking, has been proposed by Paine and Copeland (2003) as a method of removing extreme temporal noise to the overall benefit of the stacked data.

Cole-Cole model-based drift removal, model-based cancelation of harmonic (cultural) noise, and the careful design of tapered windows for averaging portions of the secondary decay into gates are described by Olsen et al. (2016), further extending the toolbox of algorithms that may be brought to bear on processing time series IP data.

Following on from the algorithmic approaches of data processing, the more iterative interpration stage is reached. Interpretation has become inextricably linked with inversion modelling. Inversion has commonly, and often quite rightly, been viewed as a tool to obtain a digital result that matched the experienced interpreters' expectations. However, with the acquisition of ever larger and more geometrically complex datasets, it has increasingly become an advanced "process" that is necessary to obtain images from which the interpretation of the geophysics and derived geology is then based.

Several 2D and 3D inversions, even extending to a fourth dimension in time-lapsed surveys and a fifth when incorporating spectral variation in the analysis, exist in both academic and/or commercial versions. 2D inversions, although still attractive as a rapid imaging method for individual survey lines, are restrictive in the complex 3D environments common in mineral exploration, particularly as highly distributed acquisition systems promote equally highly disrupted and "3D" styles of array, poorly suited to interpretation along simple lines. Surveys conducted in areas of pronounced 3D topographic relief may also be poorly served by 2D inversions.

The formulation of IP that was outlined by Seigel (1959) has been utilized as the basis for several inversion algorithms as described for example by Oldenburg et al. (1994). Although providing valuable models for imaging the location and distribution of the IP and resisitivty parameters, it is ill-suited to modelling the spectral content of IP (and inductive EM) responses. Significant advances have been made in this sense, with for example the 3D inversion of Complex Resistivity (Spectral IP) data described by Commer et al. (2011), and more recently, the 3D inversion based on a generalized effective-medium model of the IP effect described by Zhdanov et al. (2016). These inversion modelling approaches may bring relief to the troublesome effects of inductive EM coupling which are particularly problematic in surveys designed for deep investigation in mineral exploration, particularly in conductive environments, where large dipoles and transmitter receiver separations are required. The capability to model the spectral content of the measured signals is an important step toward discrimination of the source of the IP effects; still a rather elusive, although enticing, goal for IP surveys.

Within this, the estimation of uncertainty (error) in the data that is fed to the inversion model algorithms is tremendously important, especially as the number of effective dimensions of the models increases. To ensure that the error evaluations and measures are appropriate, not only random error needs to be contemplated but also eventual sources of more systemic types of error need to be factored-in and adequately expressed as accuracies for each of the data values. Failure to appropriately define the data's accuracy may lead to erroneous and misleading results from the inversion model. Reciprocal methods of evaluating error suggested by Slater et al. (2006) although readily implemented in near-surface applications and providing a powerful method of error analysis, are more challenging to implement in many large scale, deep investigating, mineral exploration survey arrays.

The processing and interpretation eventually needs to be distilled and framed in geological terms, evaluated against other available constraints, such as other geophysical models, geology, geochemistry and hydrogeology, in an iterative manner until an acceptable, consistent result is obtained. In some respects, the mineral exploration applications of IP have been left behind with regard to application in near-surface geophysics as summarized by Kemna et al. (2012) particularly in terms of interpreting the physicochemical sources of IP effects. A better understanding in this area may lead to more effective source discrimination and a subsequent unleashing of enourmous potential benefit.

OUTLOOK

High channel count, full-azimuth 3D data sets using DA technology will proliferate, because this approach provides rich information for 3D characterization, supports high resolution imaging at depth, and can so flexibly be adapted to address objectives and obstacles. These data rich surveys will drive the development of robust algorithms for automated quality control and error tracking. More attention will be given to matching the final processed data from these high-volume surveys to the inversion routines towards optimization of the final model images.

With the growth of high-volume high-density data sets, automation in the acquisition phase will be necessary to manage the data flow and data quality. This automation, much of which will be in real-time will improve the completeness and quality of the final data sets.

A wider range of sensors will be available for use, and sensors will be selected based on the local ground conditions and the survey specifications. Ag-AgCl and capacitive electrodes will become viable options, expanding the application of electrical methods to new envionments.

Safety improvements in electrical methods will manifest in several ways. Remote operation of the transmitter function will become more widespread. Current lockout systems that utilize system radio networks will be added to standard safety protocols. Smaller, lighter equipment, better battery technology, better data visibility, and the resultant efficiency gains in field operations will reduce the overall effort and crew exposure through the data acquisition stage.

Noise at long offsets is a factor. CVR, time-series acquisition and DSP will likely combine to provide the solution. Deo and Cull (2016) explore wavelet processing as a potential new methodology and highlight the importance of time-series acquisition so that raw data are available as improved processing becomes available.

The prospect of airborne acquisition of IP has its roots in 1989, when Flis et al. describe an effect in inductive EM data that is named as an "IP effect". From the early 2000s to the present this effect is seen commonly in data sets produced by helicopterborne time domain EM systems. First treated as noise, more recently this effect is being processed to produce what have been called "airborne IP" products. Macnae (2016) describes how airborne IP is insensitive to the electro-chemical effects of economic mineral IP targets due to the much higher excitation frequency, but very sensitive to 'Maxwell-Wagner' effects due to ionic fluids. We do not foresee any airborne implementation of the IP method.

It is likely that underground deployment of electrodes will evolve and migrate into new practice in the mining business. Similarly, time-lapse monitoring may translate into better management of leach and waste rock piles and in situ reservoirs. Integration of techniques will improve. Already, joint inversion of MT and DC is available. Further improvements in joint inversion methodology will integrate more diverse methods and help refine exploration targeting.

3D inversion modelling will improve with the addition of joint methods and the effective inclusion of a priori information. The impact of the choice of data input to inversion modelling will be understood better, and the inversion results may eventually inform the selection of input data for each inversion run or even from iteration to iteration.

Work will continue towards a better understanding of the EM signal in the IP measurement. Oldenburg et al. (2016) have described a workflow for this. It is also likely that spectral analysis of the IP waveform will yield better characterization of the target volume.

CONCLUSIONS

Electrical geophysical methods provide a wide range of solutions in a host of applications encompassing several industries. From borehole surveys to regional-scale reconnaissance surveying to high resolution, deposit scale full-azimuth 3D surveys, the electrical method can be easily adapted to address the scale, resolution, geometry, depth, and nature of the target and geology.

Electrical methods have seen significant progress in the last 10 years, and similar progress is likely to be seen over the next 10 years. Building on the advances in the late 1990s and early 2000s, the most significant recent progress is the introduction of full-azimuth 3D surveys. The introduction of 3D surveys revolutionized the seismic industry in the 1990s. Accompanying this introduction is the necessary enhancement of time-series acquisition and processing, and 3D inversion routines that can manage high volume, high resolution data sets.

New sensor technologies will make surveying in some challenging environments more feasible. Safety will improve as system hardware becomes more compact and lightweight, automation improves, and the QC function advances through the use of wireless communication. The CVR method shows promise in delivering extremely high data volumes, noise reduction, and operational efficiencies.

We project that the full-azimuth 3D method will both replace and expand on classical acquisition arrays. It will replace some of the work that has been carried out with 2D methods, and it will create new markets where accurate, high resolution models that search to great depth add value.

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