EFFECTIVENESS OF TRANSIENT ELECTROMAGNETICS IN MINERAL DEPOSIT EXPLORATION: A CASE STUDY OF THE KERRY ROAD Cu-Zn-Au SULPHIDE DEPOSIT, NORTHWEST SCOTLAND

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ABSTRACT

It is well known that mineral deposits with surface showing have long been discovered and only 'blind' and deeply buried deposits are yet to be discovered. It is equally well known that the global economic growth is dependent upon non-renewable resources, particularly minerals, and will continue doing so for sometime to come. The global population is projected to grow by about 1.6 billion from 6.1 to 7.7 billion people by the year 2020, with most of this growth taking place in developing nations. The demand for minerals in developing nations will equally increase. Finding new deposits to satisfy this demand is therefore a challenge and requires not only the use of more effective exploration techniques but also combining a number of methods to increase the chances of discovery. This paper discusses the Transient Electromagnetics (TEM) method and its effectiveness in mineral exploration using the stratiform volcanogenic massive Cu-Zn-Au sulphide deposit at Kerry Road in northwest Scotland as a case study. This deposit is hosted in the Proterozoic Loch Maree Group (LMG) composed of metagreywackes and metabasalts. The ore occurs in a quartz-carbonate horizon composed of 15-20% pyrite, pyrrhotite plus chalcopyrite, sphalerite, marcasite and galena. Earlier geophysical studies and drilling of the deposit had detected mineralisation at a depth of about 9 m. Exploration with TEM detected the same mineralization at a depth of about 8 m with a dip of 88-90^o thereby demonstrating the effectiveness of the technique.

INTRODUCTION

The global population has been projected to grow from 6.1 billion people in 2000 to 7.7 billion people by the year 2020 (www.wikipedia.org). This represents a growth of about 1.6 billion people in 20 years. Over 90% of this growth is expected to take place in developing countries, which are at the same time striving for economic development. It has been shown that the degree of economic development is correlated with demand for mineral resources. For instance, the USA, which only has 6% of the global population, consumes 30% of the minerals produced per annum globally. Such high consumption of minerals has compelled developed nations to increasingly import mineral commodities. This, coupled with the desire by developing nations to better their economies, will increase the demand for non-renewable resources in general and for minerals in particular. This increase in demand for minerals increases the need to search for mineral resources. It is now evident that most of the mineral deposits with a surface showing have long been discovered. Today, exploration activities are targeted at those deposits that occur at depth with little or no surface showing. The search for such deposits is sophisticated and requires methods that are effective and capable of locating such deposits. Besides, such investigations also require the application of a combination of different methods and techniques to raise the certainty of finding mineral deposits located at depth. In fact, a combination of several geophysical methods such as magnetics, electrical, and radiometricts is known to be more effective in locating mineral deposits (e.g. Sikazwe, 1992). This paper deals with TEM and its effectiveness in mineral exploration using a known sub-economic stratiform volcanogenic massive sulphide (VMS) copper-zinc-gold (Cu-Zn-Au) deposit at Kerry Road in northwest Scotland as a case study. This deposit, located about 5 km southeast of Gairloch Village (Fig. 1, after Jones et al. 1988), was discovered by Consolidated Goldfields and its extension has been found 11 km southeast at Flowerdale (Coats et al., 1997). Sulphide-bearing and banded iron formations have been found with significant gold values of up to 4 g/t (Coats et al., 1997).

Kerry Road is one of the mineral deposits hosted by the Proterozoic (2.0 Ga) Loch Maree Group (LMG) (Fig. 1), which also contains banded iron formations (BIFs) and manganese-rich sediments. The LMG, underlain by an Archean Lewisian Gneiss Basement, is believed to be a remnant of an originally much more extensive supracrustal sequence of metagraywackes and metabasalts of volcano-sedimentary origin (Jones et al., 1987). The LMG is unconformably overlain by the Neoproterozoic (1.0 Ga) flat-lying continent-derived Torridorian Sandstone, which is in turn overlain by horizontal Cambrian Quartzite (Fig. 1).

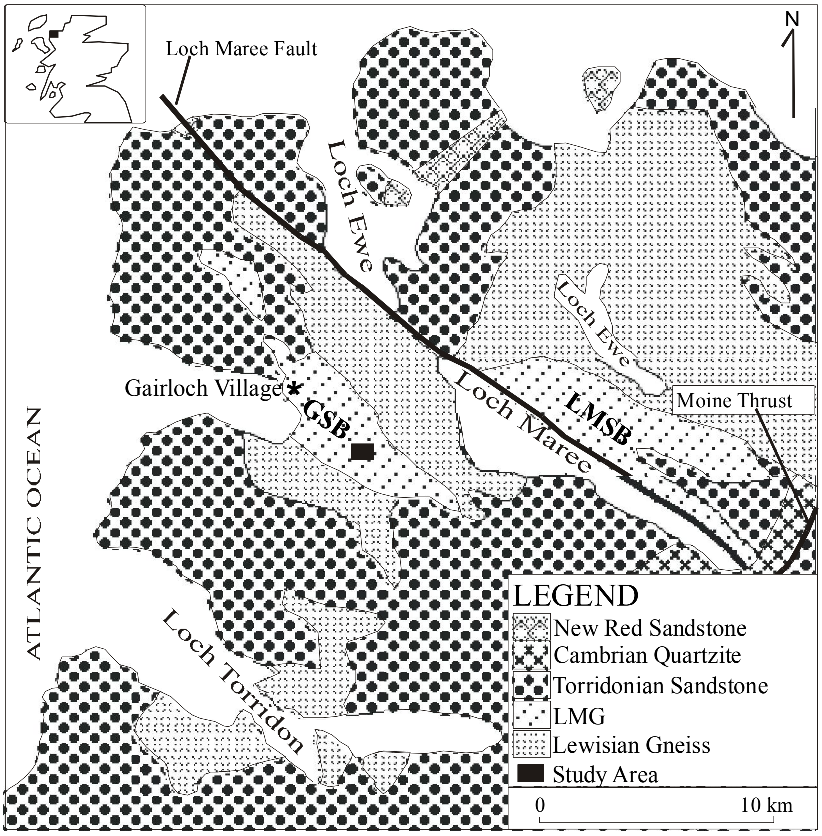

Fig. 1 Location, regional geological and tectonic map of the Kerry Road Cu-Zn-Au massive sulphide deposit, Gairloch, northwest Scotland. LMG - Loch Maree Group; GBSA - Gairloch Schist Belt; LMSB - Loch Maree Schist Belt.

Fig. 1 Regional Tectonic and Geological Setting

The 250 Ma horizontal New Red Sandstone caps the sequence in the region. The deformation and metamorphic history of the area is complex and related to the Caledonia Orogeny, which occurred between 450 and 400 Ma when the Iapetus Ocean closed (Sutton and Watson, 1951). Despite the complexity, several tectonothermal events have been recognised (Sutton and Watson, 1951). The early Scourian episode, the main gneiss-forming event, was accompanied by granulite facies metamorphism. A later deformation event, the Laxfordian, produced a complex synclinorium of steeply inclined NW-SE trending linear greenstone belts, the Gairloch Schist Belt (GSB) and the Loch Marie Schist Belt (LMSB) (Fig. 1), and was accompanied by retrograde metamorphism to amphibolite facies. The LMG is bounded to the east by the NW-SE trending Loch Maree Fault (Fig. 1), formed during the period of crustal extension between 2.4 and 2.0 Ga. The synclinorium has been confirmed by gravity studies, which indicate the occurrence of metabasites to a depth of between 4 and 6 km (Thompson and Westbrook, 1982). The positive gravity anomaly of 150 gravity units over the Gairloch Structure has been interpreted as metabasalts and metasediments folded and faulted into the Basement Lewisian gneisses on which they were originally deposited (Thompson and Westbrook, 1982).

GEOLOGY OF THE KERRY ROAD Cu-Zn-Au DEPOSIT

Locally, the LMG comprises a series of hornblende schists, quartz-mica schists, quartz-carbonate schists and other minor rock types e.g. graphite schists, quartz-magnetite schists, and garnet-cummingtonite schists. According to Park (1964) and Winchester et al. (1980), the most predominant rock types are the hornblende schists and quartz-mica schists, which are derivatives of mafic volcanics/mafic dykes/mafic sills and greywacke, respectively. Figure 2 (after Winchester et al. 1980) shows the distribution of the above rocks. The mineralization is directly hosted in the quartz-carbonate schist horizon, which contains about 15% of the ore. It forms a sheet-like body generally striking NW-SE and dipping nearly 80°NE (Fig. 3; after Jones et al. 1987). The mineralisation is generally shallow although it has also been encountered to a depth of 420 m may be due to thrusting. The footwall sequence comprises the Southern hornblende schist, the quartz-feldspar-hornblende schist and the chlorite-hornblende schist (Table 1). The hangingwall sequence consists of the Lower hornblende schist, the quartz-mica schist and the Upper hornblende schist (Table 1). The deposit lies beneath a 3 m cover of till and peat, which tend to present special geochemical problems (Peacock and Michie, 1975).

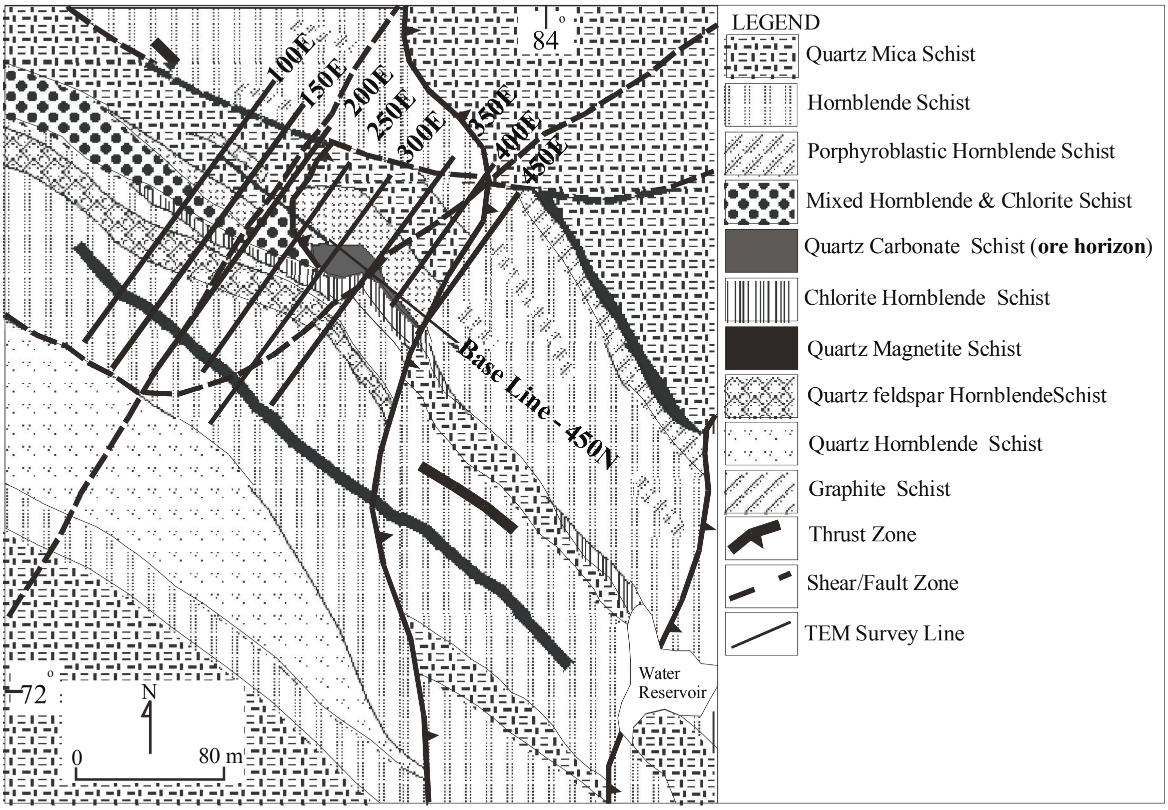

Fig. 2 Geological and tectonic map of the Kerry Road Cu-Zn-Au sulphide deposit, Gairloch, northwest Scotland.

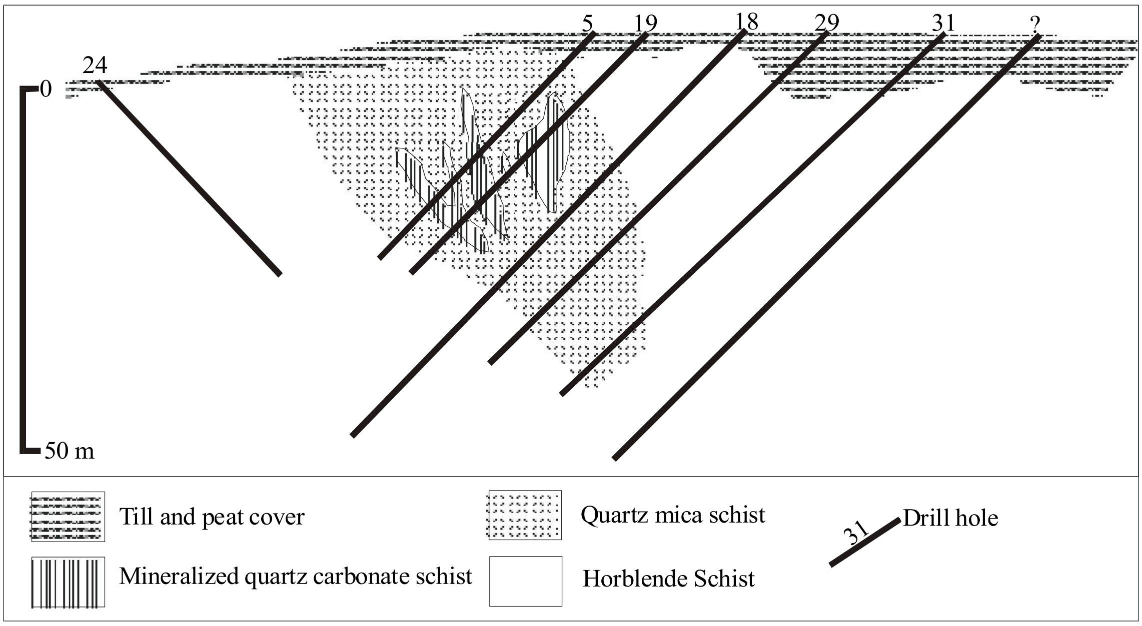

Fig. 3 A drilled section immediately northwest of Survey Line 350E, Kerry Road deposit, Gairloch,northwest Scotland.

Table 1 Stratigraphic sequence of rocks at the Kerry Road Cu-Zn-Au sulphide Deposit (after Jones et al. 1987).

ROCK UNIT	THICKNESS (m)	DESCRIPTION
Upper hornblende schist	-	Massive consisting of minor leucocratic & porphyroblastic schist as wells as thin quartz-magnetite horizons and carbonate schist. Its lower contact is marked by impersistent quartz-carbonate and magnetite schist and siliceous-pyritic graphite schist.
Quartz-mica schist	100	Fine grained, siliceous and contains laminations of pyrhhotite, biotite, muscovite and thin intercalations of graphite schist and hornblende schist. Its lower contact is marked by a pyritic – graphite schist while its upper one by quartzite/quartz-chlorite schist.
Lower hornblende schist	40-50	Fine – medium- grained, massive with bands of quartz-carbonate, biotite, chlorite and quartz-magnetite.
Quartz-carbonate horizon (Ore horizon)	-	Ore horizon which contains about 15% of ore. Forms a sheet-like body striking NW-SE & dipping nearly 80° NE. Has been encountered at a depth of about 420 m but may occur at greater depth southeast-wards due to overthrusting along the Moine Thrust zone.
Chlorite-hornblende schist	20-30	Strongly sheared consisting of deformed quartz lenses, some cummingtonite and sulphide stringers, which decrease in abundance away from the contact with the ore horizon.
Quartz-feldspar-hornblende schist	60	Highly variable in grain size and composed of thin bands of garnet schist and quartz-magnetite schist. Pyrite is common and locally constitutes about 15% of the rock.
Southern hornblende schist	-	Constitutes the rest of the footwall. Massive and consists of minor quantities of the overlying rock unit.

The ore mineralogy comprises mainly pyrite and pyrhhotite, which constitute 15-20% of the ore horizon. Other ore minerals include chalcopyrite, marcasite, sphalerite and galena. Magnetite and native gold are also present in minor quantities. Pyrite, pyrhhotite and chalcopyrite occur in several forms including (a) massive, (b) fine disseminations, (c) lenses or thin bands parallel to foliation, and (d) stringers at the margin of the ore horizon.

METHODOLOGY

Background to Transient Electromagnetics (TEM)

The Time Domain Electromagnetics (TDEM) method used in western nations was invented in Russia. It was quickly adopted by Australian geoscientists in the early 1980s when they realized that the TDEM technique was ideal for 'looking through' the typical tropical-zone weathered, conductive surface layer which covers most of Australia. This prompted the development of an Australian TDEM system called Scientific and Industrial Research Organisation TEM (SIROTEM) by the Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) (Buseli and O'Neill, 1977). The system is normally used in the coincident or common loop mode, in which a single loop serves both as transmitter and receiver (Fig. 4; after Fokin, 1971).

The loop size, although generally dictated by the required depth of investigation, may be up to 100 m^2 or greater. The receiver can sample the response over 32 contiguous channels at delay times ranging from less than 0.4 to 165 milliseconds. TEM systems operate on the principle of inducing eddy currents into the subsurface and sampling their decay time to provide information on any conductive bodies lying within the subsurface. The alternating current in the transmitting loop produces a magnetic field in the surrounding environment, which in turn generates eddy currents as shown in Fig. 4. The strength of these currents depends upon the conductivity, shape and size of the target body and its position relative to the loop. When established, eddy currents tend to diffuse inwards towards the center of the target body but these are gradually lost due to resistive heat. If the body is strongly conducting, however, the currents tend to circulate on the boundary of the body and as such decay more slowly. The receiver samples a voltage proportional to the rate of decay of the vertical component of the secondary magnetic filed.

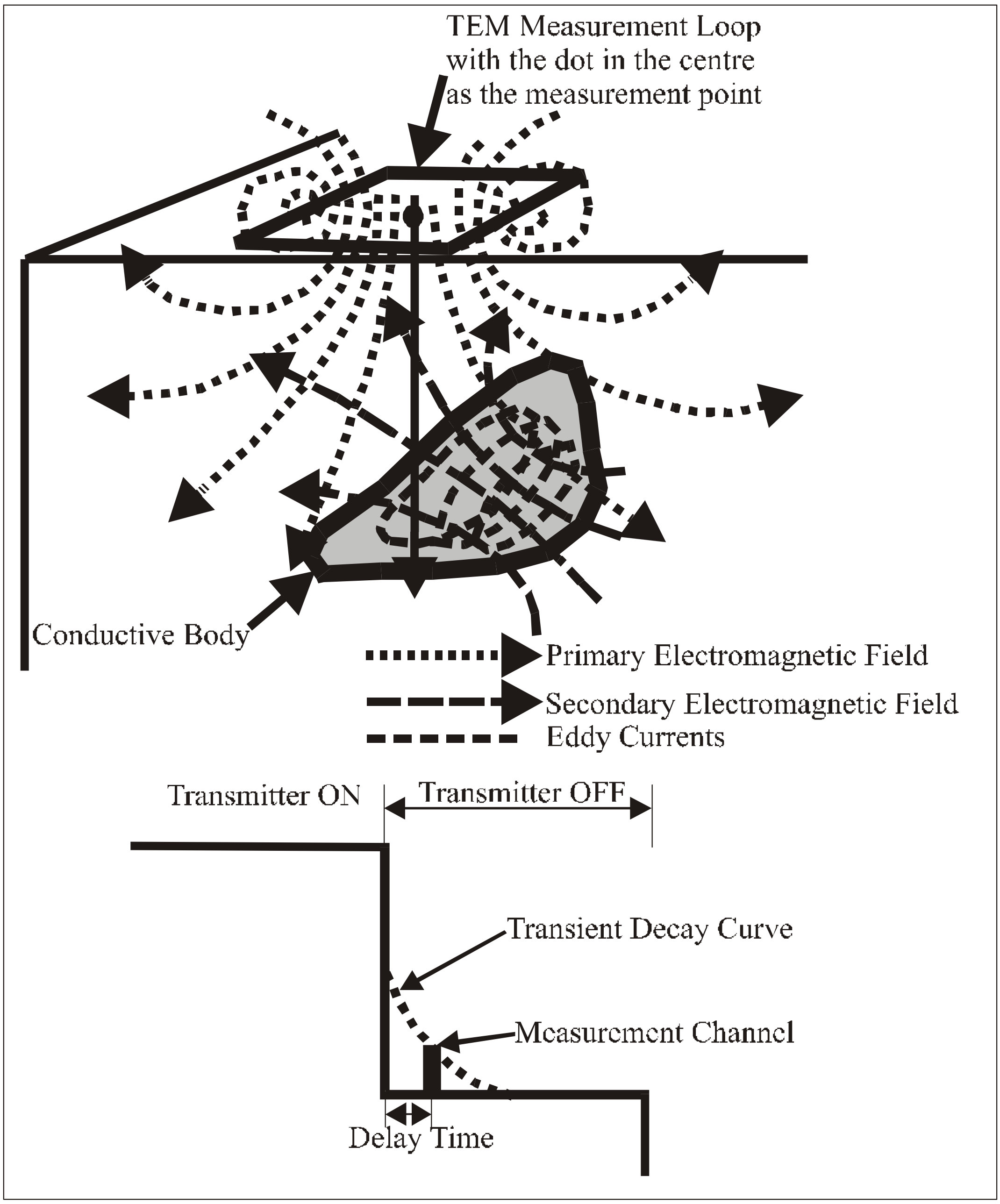

Fig. 4 A schematic diagram of a 25m x 25 m transient electromagnetic (TEM) coincident survey loop.

TEM can be employed routinely in various geoscientific investigations including (Bowker and Hill, 1987): (a) mineral exploration as metallic elements occur in highly conductive massive sulphide orebodies; (b) groundwater quality assessment, as it is known that groundwater contaminants such as salts and acids significantly increase groundwater conductivity; (c) stratigraphic mapping, in cases where rocks have varying conductivities; (d) geothermal energy assessment because of the presence of geothermal alteration due to hot water which increases the conductivity of the host rock; (e) permafrost mapping as there is a significant conductivity contrast at the interface between frozen and unfrozen ground; and (f) environmental assessment such as to locate buried hazardous metallic drums and tanks. TEM has several advantages over the frequency-based electromagnetic techniques and these include: (a) little interference from the primary magnetic field as measurements are taken when the system is off, which tends to enhance the signal to noise ratio; (b) greater ability to image through the conductive overburden; (c) greater penetration depth; (d) little effect from changes in topography; (d) no direct electrical contact with the ground is needed so that surveys can be equally effective in frozen environments; (e) the same basic techniques can be used to investigate the top few metres of ground or to depths over 1000 m; (f) TEM systems may be used in many different configurations such as large loop Turam style, moving loop Slingram style, and in borehole; (g) generally fast and cost effective for the amount of data generated; and (h) works well in conductive to moderately conductive areas.

Disadvantages are that TEM is poor at resolving shallow layers in resistive areas, may also be logistically cumbersome and is susceptible to interference from pipelines and power lines.

Data Collection and Processing

The TEM data were collected using a 32 channel 25 m^2 coincident loop SIROTEM MK 2SE system along lines 100E to 450E at a 50 m interval (Fig. 2). Sampling stations, always kept at the center of the loop, were at a 25 m interval. Responses were recorded on tape and an output of voltages, with the corresponding time samples (or channels), generated. Processing involved conversion of the measured electromagnetic field (EM) voltage decay (dB/dt) data into apparent resistivities using EXCEL. Using these responses, suitable data files were prepared for the TEM profiles and pseudosections generation as well as modelling as described by Sikazwe (1992).

Computer modeling to produce 1D-layered Earth models was achieved using inversion software developed by Meju (1990; 1992). In this process, a theoretical model was provided and its parameters (i,e the number of layers, their resistivities and depths-to-top of layer) varied automatically through inversion to simulate the actual model. Theoretical responses were then compared with those determined from field data in a process of graphical matching. If the theoretical model is close to the actual model, then the variance should be as small as possible. The closeness of the theoretical model to the actual one is dependent upon: (a) the amount of geological information available as this will provide a control on the generated model as well as allow for a reasonable interpretation; in areas of complex geology, for instance, the modelling will be less effective; (b) the turn-off time, which is employed in correcting for turn-off effects; If this were not taken into account, the shallower parts of the subsurface conductor would not be detected; and (c) the sampling frequency. The modeling presented in this paper used the early-time SIROTEM data rather than the late- or standard-time because the former was appropriate to the depth of interest i.e. 0-50 m. The mineralisation has been defined by drilling to be within the depth of 50 m (Fig. 3).

DESCRIPTION AND DISCUSSION OF RESULTS

Results of exploration with SIROTEM are described in form of profiles, ID-layered Earth models and pseudosections for lines 250E to 400E. Strong TEM responses were obtained along lines 300E, 350E and 400E generally between stations 400N and 500N (Fig. 5). Apparently, the massive sulphide body is located in this zone. Generally, weaker and non-definitive responses occur along lines 100E to 200E and 450E because these lines lie outside the zone in which the conductor lies (Fig. 2). Thus, TEM profiles for lines 100E to 200E are not presented in this paper.

The raw TEM data (i.e. uncorrected for turn-off effects) are plotted as profiles shown in Fig. 5. Each profile line represents a delay time channel. At some stations, the sampled channels were as many as 25, but not all could be plotted, as there were no corresponding channels at other stations. This variation in the number of sampled delay times is a good indicator of lateral variations in the conductivity of the subsurface. In fact, the more conductive the subsurface is the greater the number of sampled channels. Generally, the amplitude of the channels decreases both westwards and southeastwards of line 350E (Fig. 5). This means that either the conductive body is truncated on both the northwest or the southeast ends or it is located at a greater depth at the southeast end than it is at the northwest end such that the response from the former is less strong than from the latter. Both situations apply at Kerry Road and can be explained in terms of thrust faulting through which the orebody is terminated to the northwest by the western thrust zone and to the southeast by the main thrust zone with the former being at greater depth than the latter. The response strength also decreases with increase in time delay on all the profiles (Fig. 5) indicating that the conductor terminates at depth. The termination of mineralisation at depth has been confirmed by drilling (Fig. 3).

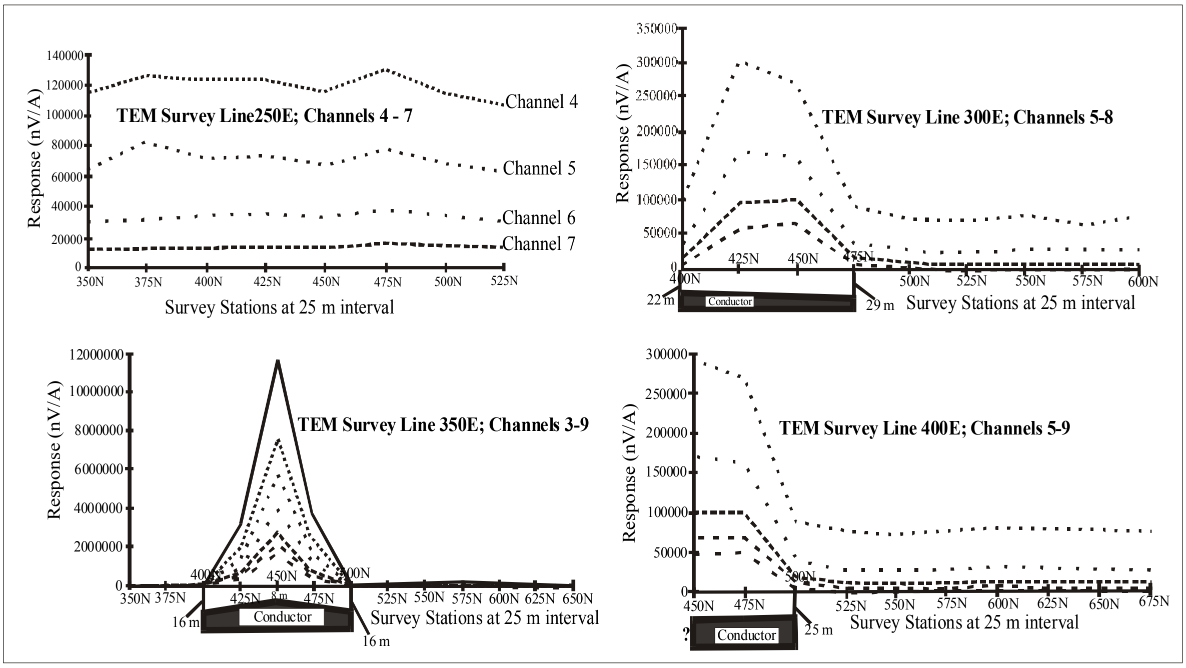

Fig. 5 TEM Profiles for Lines 250E - 400E showing high responses particularly along Lines 300E - 400E. Channels 3, 4, 5,6, 7, 8 & 9 correspond to delay times 0.147, 0.196, 0.245, 0.319, 0.417, 0.515 & 0.613 milliseconds, respectively.

The data used in the modeling were corrected for turn off effects using the turn-off time of 55 microseconds as the correction factor determined using the San Antonio Texas-1 (SATX-1) instrument. Results of modelling are described and discussed in the following paragraphs. Modelling results presented in this paper are only for lines 300E to 400E because along these lines strong responses were recorded (Table 2). Fig. 6 illustrates the graphical representation of the model results.

The variance (represented by the chi squared-CHSQD Error) for lines 300E to 400E is very small ranging from 0.004 to 0.067 (Table 2) suggesting a close simulation of the actual model by the theoretical one. Fig. 6 indicates that the Kerry Road Deposit is best represented by a 3 layered earth model. For example, the top layer of resistivity ranging from 9 to 12 Ωm lies at depth of between 8 and 12 m (Fig. 6). This top layer probably corresponds to the 3 m cover of peat and till plus a variable thickness of the unmineralized part of the quartz-carbonate horizon. TEM has also been used with success in locating "blind" sub-economic sub-massive to massive sulphide mineralisation in Okiep District where the depth of weathering extends to about 40 m (Maher, 1992).

An intermediate layer of resistivity 0.30 to 6.29 Ωm occurs at a depth of between 8 and 100 m (Fig. 6). This layer is the mineralized section of the quartz-carbonate horizon. The mineralized part is known from drilling to occur below the depth of 9 m (Fig. 3). The area in which the massive sulphide body is located has resistivity values of generally less than 20 Ωm. This is in contrast to a resistivity value of 200 Ωm reported by Bowker and Hill (1987) of the same body. If this 200 Ωm body is regarded as conductive, then results obtained with TEM exploration and presented in this paper suggest that the surveyed target area is generally highly to moderately conductive. This is expected in the Kerry Road area, which is mostly underlain by generally conductive hornblende schists, particularly when they are weathered. The high conductivity may also be partly attributed to the presence of graphite schists and chlorite schists although these are of limited extent in the area. Resistivities of igneous and metamorphic rocks range from about 150 to over 100,000 Ωm (Griffith and King, 1988). These values, however, may be reduced by the presence of fissures, groundwater conductivity and saturation.

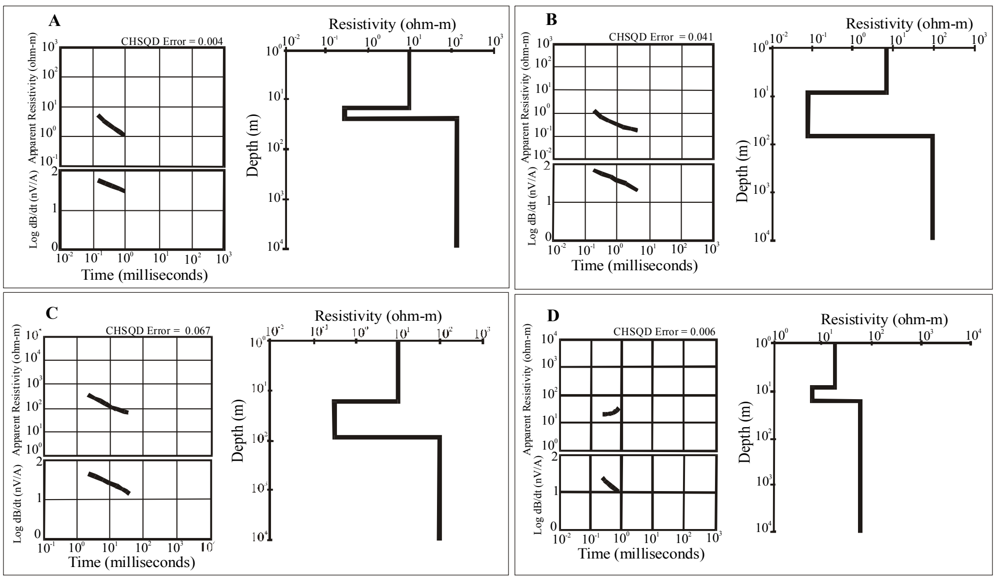

Fig. 6 ID-Layered Earth TEM Models for Survey Line 350E; Stations 475N (A), 450N (B), 425N (C), & 400N (D), Kerry Road deposit, Gairloch, northwest Scotland.

Table 2: A summary of TEM stations where moderately strong to strong conductive bodies are located

LINE	STATION	ρ (Ωm)	CHSQD ERROR	α (m)
300 E	425N	3.76	0.007	22.07
	450N	1.96	0.010	28.71
350 E	400N	6.29	0.006	8.13
	425N	0.30	0.067	15.52
	450N*	0.08	0.041	8.37
	475N	0.30	0.004	15.86
400 E	450N	2.87	0.007	22.84
	475N	2.38	0.012	24.55

*** Station located directly above the massive sulphide deposit; CHSQD – Chi Squared**

The bottom layer of resistivity > 60 Ωm lies at a depth of 12 m and below (Fig. 6). This layer represents the unmineralized part of the quartz-carbonate horizon. The variation in depths to the tops of the three layers reflects the morphological nature of the conductive body and this is clearly illustrated by Fig. 3. TEM data were also plotted as contoured pseudosections for various survey lines (Siakzwe, 1992). In this paper, pseudosections only for lines 300E and 350E are presented (Fig. 7; after Sikazwe, 1992) because along these lines the highest responses were recorded. These figures show that there is conductor defined by the 11 Ωm and less resistivity anomaly lying between stations 400N and 500N of lines 300E and 350E (Fig. 7; after Sikazwe, 1992). The massive sulphide deposit lies in this zone.

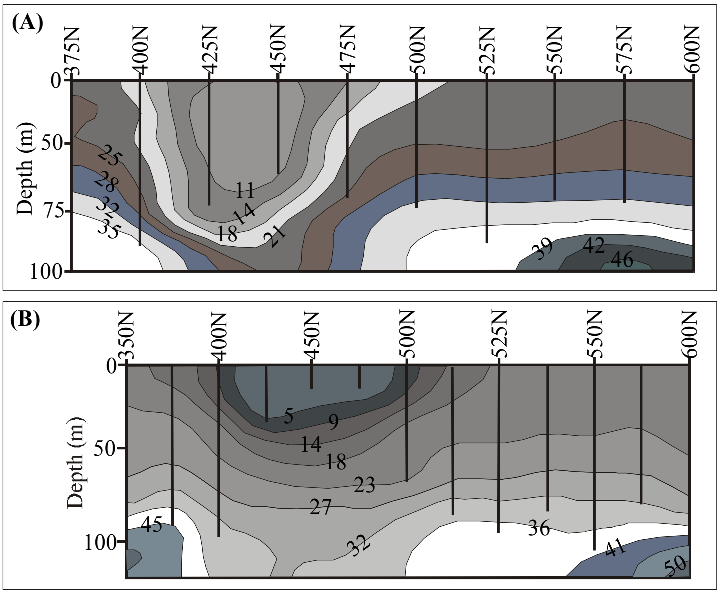

Fig. 7 TEM pseudosections along survey lines 300E (A) and 350E (B). Contours represent resistivity values. A conductor with resitivity of 11 ohm-m and less lies roughly between 400N and 475N along line 300E while along line 350E a conductor of resistivity 5 ohm-m and less lies between 400N and 500N. The Massive sulphide body at Kerry Road is located in this zone.

TEM data can also be used to determine the dip of the target conductor employing nomograms developed by Kamenetskii (1976) or an empirical formula [1] of Fokin (1971);

$$\sigma = 90 - 74.5\left(1.0 - 0.22\frac{\alpha}{\kappa}\right)Log\frac{\nu_1}{\nu_2}.(1)$$

Where σ = dip of the target conductive body (degrees)

α = Estimated depth to the top of the conductive body (metres)

κ = half loop side (metres)

ν_1/ν_2 = ratio of larger to smaller peaks for a selected time sample t in milliseconds

The above equation, however, is only valid for $\alpha/\kappa \leq 2$. Errors in the estimate procedure may be in the order of 10 – 15° for the dip. Dips of the conductive body at the Kerry Road Deposit are estimated to be in the range 88 to 90° (Table 3).

Depths to the top of conductors were determined using apparent resistivities and sample times established from modelling using the formula [2] of Meju (1992) (Table 3).

$$\alpha = \frac{\sqrt{2 * t \times \rho/\mu}}{2} \text{..................(2)}$$

Where: α = Depth to top of conductor (metres)

t = Time delay in seconds

ρ = Apparent resistivity (Ωm)

μ_o = Electromagnetic permeability constant ($4\pi x10^{-7}$ H/m)

The depths to tops of conductors along the lines presented in Table 2 range from 8 to about 29 m, which lies within the targeted depth of investigation of 0 – 50 m.

The TEM survey detected a conductive body at Kerry Road at a depth of approximately 8 m, which agrees very well with that of 9 m obtained by Bowker and Hill (1987), using a 100 m x 100 m horizontal loop frequency-based Pulse EM.

Table 3: Dips of the conductive body estimated from the ratio of responses (V1/V2) and depths to the top of conductor (α) (after Sikazwe, 1992)

Survey Line	Channel	V1 (nV/A)	V2 (nV/A)	α(m)	α/κ	σ (degrees)
300E	5	300000	275000	22.07 (425N)	1.77	88
300E	5	300000	275000	28.71 (450N)	2.30	89
300E	6	175000	160000	22.07 (425N)	1.77	88
300E	6	175000	160000	28.71 (450N)	2.30	89
350E	3	3000000	3000000	15.52 (425N)	1.24	90
350E	3	3000000	3000000	15.86 (475N)	1.27	90
350E	4	2000000	2000000	15.52 (425N)	1.24	90
350E	4	2000000	2000000	15.86 (475N)	1.27	90
350E	5	1000000	1000000	15.52 (425N)	1.24	90
350E	5	1000000	1000000	15.86 (475N)	1.27	90

Using the TEM data, it was also possible to get an idea of how the orebody is disposed. The orebody is roughly steeply inclined at an angle of between 88 and 90º. Bowker and Hill (1987) show that the orebody is subvertical and this was confirmed through diamond drilling (Fig. 3).

CONCLUSIONS

Exploration with the TEM technique revealed that the surveyed area displays resistivity values ranging from as low as 0.08 to as high as 342 Ωm (Sikazwe, 1992). The area in which the massive sulphide body is located has resistivity values of generally less than 20 Ωm.

TEM is also generally a versatile method in the sense that its application is not only in mineral exploration as exemplified by this paper but also in lithological mapping, contaminant mapping, and geothermal energy mapping. From what is presented in this paper, the conclusion is that mineral exploration with TEM is generally effective even in geologically complex areas. However, the effectiveness of this method is dependent upon how conductive the target area is. In general, the more conductive the target area, the more effective the method is.

It is well known that TEM is effective in soundings to depths of over 1000 m even in areas with a highly conductive overburden. In Africa, the overburden is generally thick, highly weathered and conductive and therefore exploring for mineral deposits requires effective and deeply penetrating imaging methods such as TEM. It is however, strongly recommended that, despite its many successes, TEM should be combined with other techniques in mineral exploration to further increase the chances of mineral deposit discovery.

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References

Bowker, A. M., and Hill, I. A., (1987). Geophysical study of the Kerry Road orebody, Gairloch, *Trans. Instn. Metall. (sect. B: Applied Eart Science), 96, B213-220.*

Buseli, G. and O'Neill, B., (1977). SIROTEM: A new portable instrument for multichannel transient electromagnetic measurements. *Bull. Aust. Soc. Exploration Geophysics, 8, 82 – 87.*

Coats, J. S., Shaw M. H., Rollin K. E., and Fortey N.J. (1997). Mineral exploration in Lewisian suprucrustal and basic rocks of the Scottish Highlands and Islands. www.bgs.ac.uk/mineralsuk/exploration/potential/mrpsumm141-146.html.

Fokin, A. F. (1971) The method of transient processes in the search for sulphide deposits. Leningrad, Nedra, 242 pp.

Griffith, D. H. and King, R. F., (1988). Applied Geophysics for geologists and engineers – The elements of geophysical prospecting. Pergamon Press, Oxford, 230pp.

Jones, E. M., Rice, C. M., and Tweedie, J. R., (1987). Lower Proterozoic stratiform sulphide deposits in Loch Maree Group, Gairloch, northwest Scotland. *Trans. Instn. Metall. (Sect. B: Applied Earth Sciences), 96, B129-140.*

Kamenetskii, F. M., (1976). Handbook of applied methods of transient processes in ore geophysics, Leningrad, Nedra, 127pp.

Maher, M. J., (1992). Transient electromagnetic surveys in the Okiep District. *Geophysics, 57, pp.736-745.*

Meju, M. A., (1990). TEMOD: A desktop system for processing and modeling central and coincident loop data. *Unpublished University of Leicester Geophysical Research Report 90/1.*

Meju, M. A., (1992). Iterative most-square inversion: application to magnetoterrulic data. *Geophysical Journal International, 108, 758-766.*

Park, R. G., (1964). The structural history of the Lewisian rocks of Gairloch, Wester Ross, Scotland. *Quarterly Journal of the Geoloical Society of London, 120, pp.397-433.*

Peacock, J. D., and Michie, U. M., (1975). Superficial deposits of the Scottish Highlands and their influence on geochemical exploration. In: Jones, H. J. (Editor) Prospecting in areas of glaciated terrain. *London IMM, pp.40-52*.

Sikazwe, O. N., (1992). An integrated geophysical study of the Kerry Road Cu-Zn-Au sulphide deposit, Gairloch, northwest Scotland. University of Leicester MSc Thesis, 89pp.

Sutton, J., and Watson, J. V., (1951). The pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the northwest highlands and its bearing on the chronological classification of the Lewisian. *Quarterly Journal of the Geoloical Society of London,* 106, pp.241-307.

Thomson, M. W. H., and Westbrook, G. K., (1982). A gravity investigation of the deep structure of the Lewisian rocks of Gairloch, Wester Ross. *Scottish Journal of Geology, 18, pp.177-185*.

Winchester, J. A., Park, R. G., and Holland, J.G., (1980). The geochemistry of the Lewisian semipelitic schists from the Gairloch District, Wetester Ross. *Scottish Journal of Geology, 16, pp.165-179.*

www.wikipedia.org (accessed on 9th July 2013)