37.

EXPLORATION FOR MASSIVE SULPHIDES IN DESERT AREAS USING THE GROUND PULSE ELECTROMAGNETIC METHOD

Duncan Crone
Crone Geophysics Limited, Mississauga, Ontario

Crone, Duncan, Exploration for massive sulphides in desert areas using the ground pulse electromagnetic method; in Geophysics and Geochemistry in the Search for Metallic Ores; Peter J. Hood, editor; Geological Survey of Canada, Economic Geology Report 31, p. 745-755, 1979.

Abstract

Examples of ground Pulse electromagnetic surveys from Arizona, the Sultanate of Oman, and Australia, show that both massive and fracture-filling sulphide bodies can be detected in desert conditions. The wide frequency spectrum of Pulse EM equipment, and its capability of defining the shape of the conductor, enable the method to differentiate between oxidized sulphides and conductive surficial layers, even though the conductivity contrast is slight. It is important for exploration purposes to retain the high frequency portion of the Pulse electromagnetic spectrum. Low sulphide content marker horizons and narrow oxidized sulphide zones are usually detectable only at high frequencies. New detailed and deep penetration methods utilizing the ground Pulse EM are being developed to locate accurately the position of the sulphide body; as exploration methods reach greater depths of penetration, this becomes increasingly important. Borehole Pulse electromagnetic equipment has been built that will detect sulphide bodies 100 m to the side of a borehole. The capabilities of Borehole Pulse EM surveys in detecting and defining the position of sulphide bodies, should encourage deep exploration in the vicinity of known mineral deposits.

Résumé

Les exemples d'études électromagnétiques au sol en Arizona, dans le Sultanat d'Oman et en Australie, montrent que les corps sulfurés massifs et ceux remplissant les fractures peuvent être décelés dans les milieux désertiques. La vaste gamme de fréquences de l'appareillage et la capacité de celui-ci à définir la forme du conducteur, permettent de distinguer les sulfures oxydés des couches superficielles conductrices, même quand le contraste de conductivité est faible. Il est important pour l'exploration de garder seulement la gamme de hautes fréquences. Les horizons repères à faible taux de sulfures et les étroites zones de sulfures oxydés sont normalement détectés seulement aux hautes fréquences. On a mis au point de nouvelles méthodes détaillées, de prospection profonde utilisant les ondes électromagnétiques au sol, qui permettent de localiser avec plus de précision les minerais sulfurés; cet aspect de la prospection prend de l'importance, à mesure que les méthodes d'exploration permettent une exploration plus profonde du sous-sol. On a construit un appareil de prospection EM utilisé dans les forages, pour repérer les minerais sulfurés dans un rayon de 100 m à partir du sondage. Les possibilités offertes par la méthode de levés EM à partir de forages pour déceler et délimiter les sulfures, devraient encourager l'exploration profonde à proximité des gîtes minéraux connus.

EXPLORATION OBJECTIVES AND PROBLEMS ENCOUNTERED IN DESERT AREAS

A ground geophysical survey for mineral exploration normally has three specific objectives:

- to locate an airborne electromagnetic anomaly on the ground, or to discover an anomaly that could be an orebody;
- to provide sufficient information to permit an evaluation of the anomaly in comparison with other anomalies;
- to obtain results that allow determination of the dip, depth and width of the target with sufficient accuracy to position an exploration drillhole.

When an exploration program for massive sulphide deposits is carried out in a desert region, attaining these objectives becomes increasingly difficult. The primary difficulty is surface weathering that gradually reduces the conducting sulphides to resistive oxides. This is a highly variable process whose effect may range from a few metres to 200 metres in depth from surface. The oxidation weathering process also tends to break down the inter-crystal electronic connection within a sulphide body. The presence of even minor oxidation can drastically reduce the conductivity of a massive sulphide body. Targets in desert areas are therefore usually deeper and are weaker conductors than those encountered in unweathered areas. The desert climate also produces large areas of high surficial conductivity that may consist of brackish groundwater or conductive rock formations such as conglomerates or limestones. This surficial conductivity reduces the penetration of electrical and electromagnetic (EM) methods and creates a background of confusing spurious anomalies.

Induced polarization has traditionally been the most effective geophysical method in the exploration for sulphides in desert areas. The method is suited primarily for the detection of large disseminated deposits, but it is not effective in the exploration for smaller, massive sulphide bodies (Dolan, 1967). Most conventional EM systems have been designed for use in resistive environments and can be usefully applied, only in nonconductive desert areas. Thus suitable ground geophysical equipment that would be effective in the search for massive sulphides in desert areas has, in the past, not been available.

DEVELOPMENT OF THE GROUND PULSE EM METHOD

The Pulse EM system was selected by Crone Geophysics Ltd. as an exploration tool since it appeared to have the most likely capability of providing conductivity, depth, dip and width information for subsurface conductors. The wide frequency spectrum of measurement of a Pulse EM system is capable of resolving the variance of conductivity encountered under desert conditions, and the low frequency portion of the spectrum can penetrate through the surficial conductive layer. Crone Geophysics Limited initiated a Pulse EM development program in 1972 with the co-operation of Newmont Mining Corporation. Newmont held the original Pulse EM patents (Wait, 1956) and had developed a large Pulse EM instrument which had been used successfully in Cyprus (Dolan, 1967). The Crone equipment (Crone, 1975) consists of a moving horizontal loop system; two persons operate the transmitter and one the receiver. The transmitter-receiver coil separation is 50 to 150 m. The transmitter is a multiturn loop of wire 6 to 15 m in diameter laid out in a rough circle on the ground. The current waveform is 10.8 ms on, 10.8 ms off with a 1.4 ms ramp shut-off. Eight delay time-windows, or channels, of the secondary field are sampled after the current shut-off at 0.15, 0.30, 0.55, 0.90, 1.45, 2.40, 4.00, and 6.40 milliseconds to the centre of the sample. The sample amplitude is normalized by setting to 1000, a sample taken of the maximum shut-off voltage amplitude measured at the receiver. The sample measurements are therefore without dimensions. The first sample (0.15 ms) is in units of 1/1000 of the shut-off sample, the eighth sample in units of 1/10 000 of the shut-off sample, with a logarithmic dispersion in between. Unlike conventional horizontal loop EM surveys variance in coil separation and elevation effects are not critical with this time domain method.

Field Examples of Ground Pulse EM Surveys of Poor Conductors

The following are case histories and recent developments in the application of a ground Pulse electromagnetic system designed for exploration in desert areas. Figure 37.1 is a typical example of the response from a narrow (width less than 3 m), weathered, massive sulphide zone using the Crone Pulse EM technique. This profile was obtained over the Ghayth copper-zinc showing in the Sultanate of Oman. Narrow, massive sulphide zones such as this tend to weather to considerable depths. This zone is therefore a poor conductor and is detected by the first Pulse EM sample only. Figure 37.2, also from the Sultanate of Oman, represents the type of anomaly obtained from a zone of disseminated sulphides. In this case, the weathering is shallow (only 30 m), with the lack of conductivity being caused by a low sulphide content of approximately 5 per cent. The important factor illustrated by these two examples is the necessity of retaining the high frequency information generated by a Pulse EM system. This information enables the operator to detect and trace out narrow or weakly mineralized zones that are favourable geological horizons. These zones may expand into larger, more massive bodies along strike.

The conductivity-thickness (σt) of these sulphide zones often is the same order as that of the conductive surficial layer. The sulphide zone is detected only because of the geometrical presence of both vertical and horizontal conductive sheets. The importance of detecting weak conductors is illustrated in Figure 37.3, which shows the discovery Pulse EM profile over the Bayda copper-zinc orebody in Oman. The Bayda showing consisted of an ancient exploratory pit in a small gossan zone at the side of a hill. This showing produces a weak two-sample anomaly that was traced downhill until it strengthened to a six-sample anomaly on line 1+00N. Drilling this section intersected high grade massive mineralization.

Response of Wide Massive Sulphide Conductors Using the Pulse EM Technique

One supportive aspect of desert weathering, we soon discovered, is that wide (greater than 10 m) massive sulphide bodies often self-seal themselves against further oxidation.

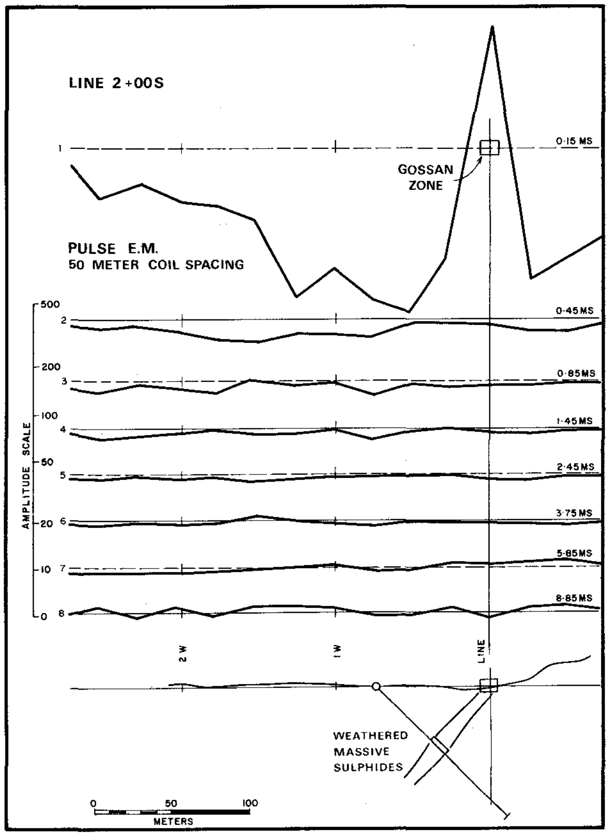

Figure 37.1. *Pulse EM profile, 50 m coil spacing, moving coils method, Ghayth showing, Sultanate of Oman.*

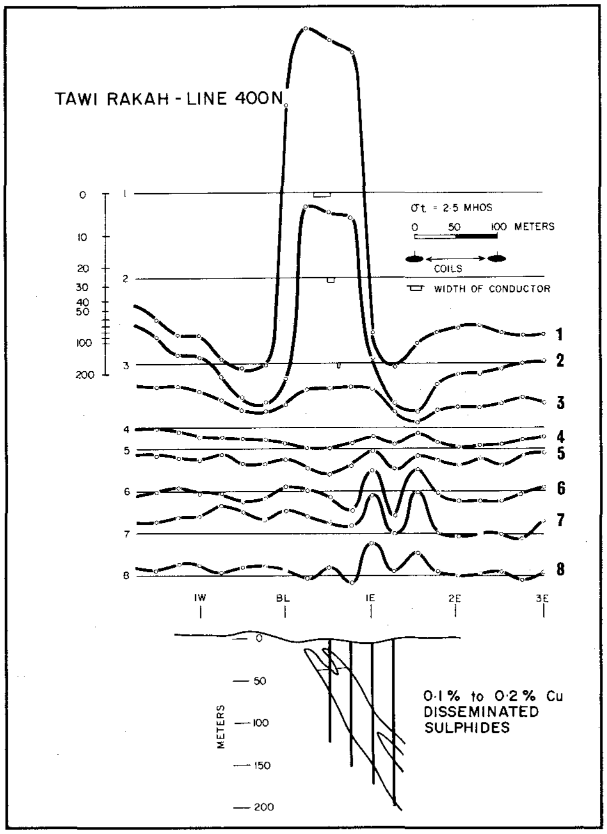

Figure 37.2. *Pulse EM profile, 100 m coil spacing, moving coils method, Tawi Rakah, Sultanate of Oman.*

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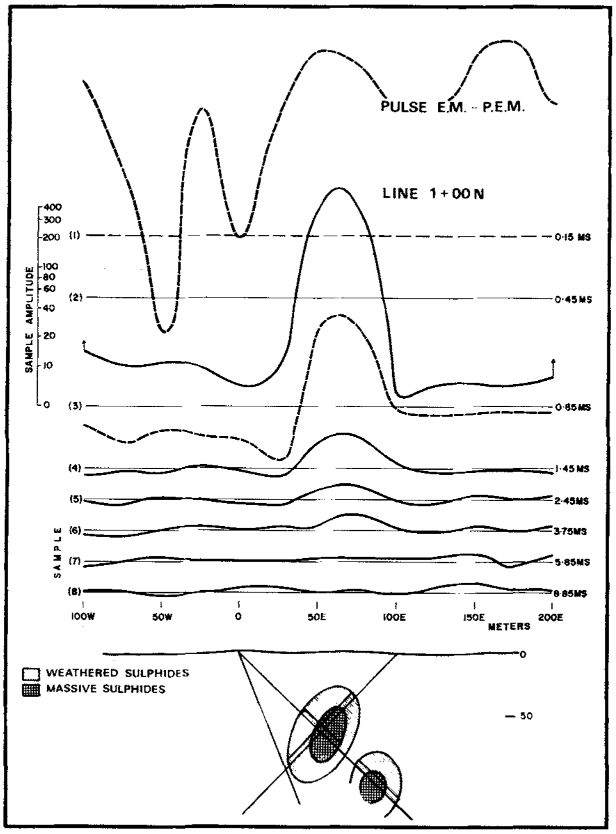

Figure 37.3. *Pulse EM profile, 50 m coil spacing, moving coils method, Bayda showing, Sultanate of Oman.*

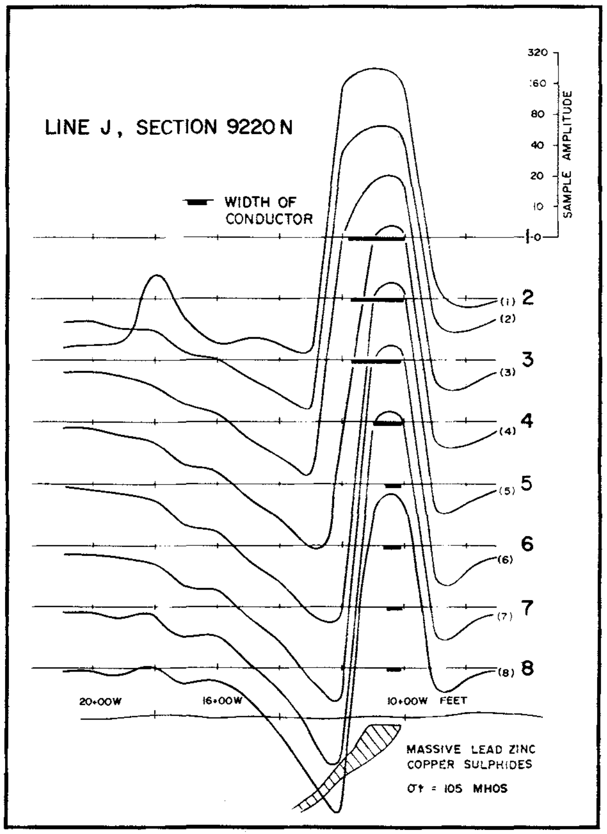

Figure 37.4. *Pulse EM profile, 200 ft coil spacing, moving coils method, Jododex, Woodlawn deposit, Australia.*

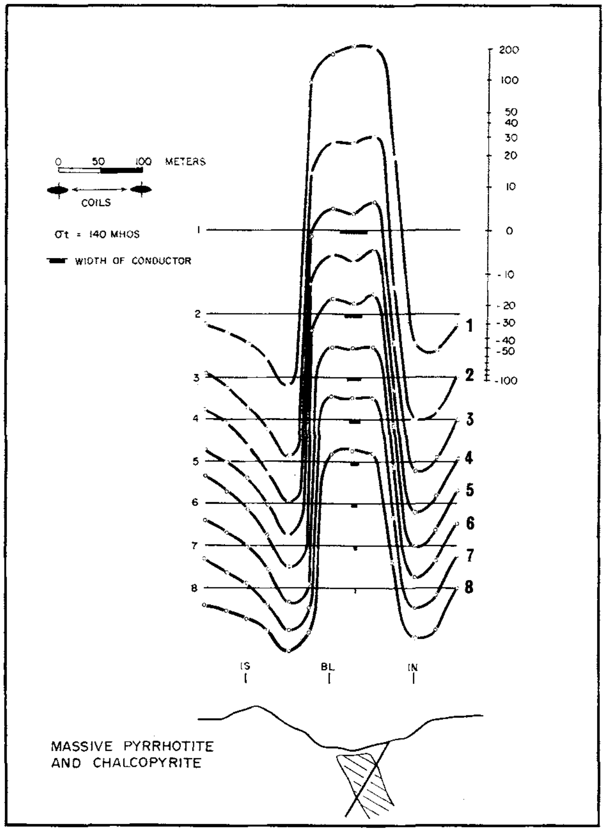

Figure 37.5. *Pulse EM profile, 100 m coil spacing, moving coils method, Maydan deposit, Sultanate of Oman.*

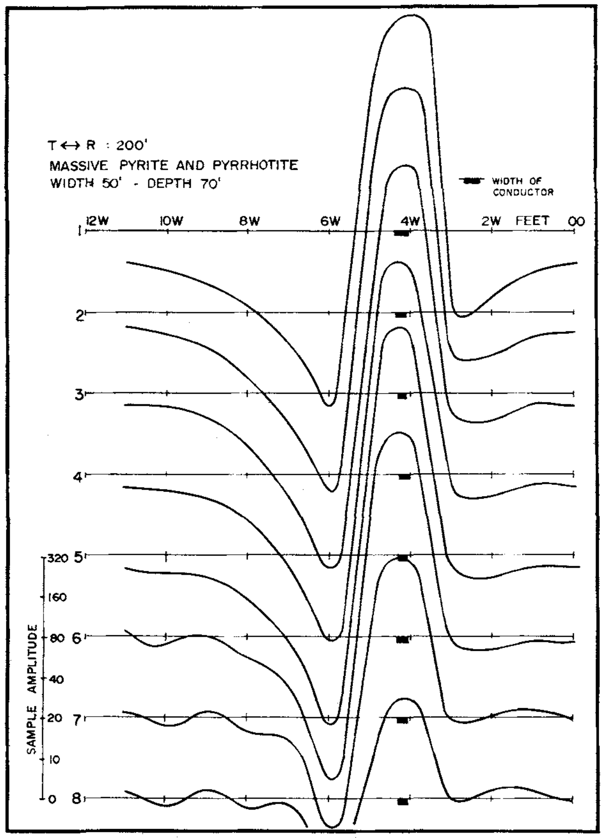

Figure 37.6. *Pulse EM profile 200 ft coil spacing, moving coils method, Massive Sulphide Body, Arizona.*

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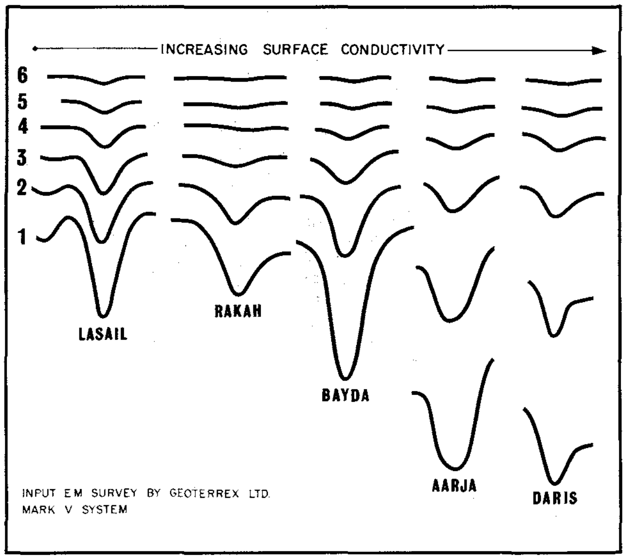

Figure 37.7. Airborne Input EM Anomalies over Massive sulphide orebodies, Sultanate of Oman (Geoterrex Ltd., Ottawa).

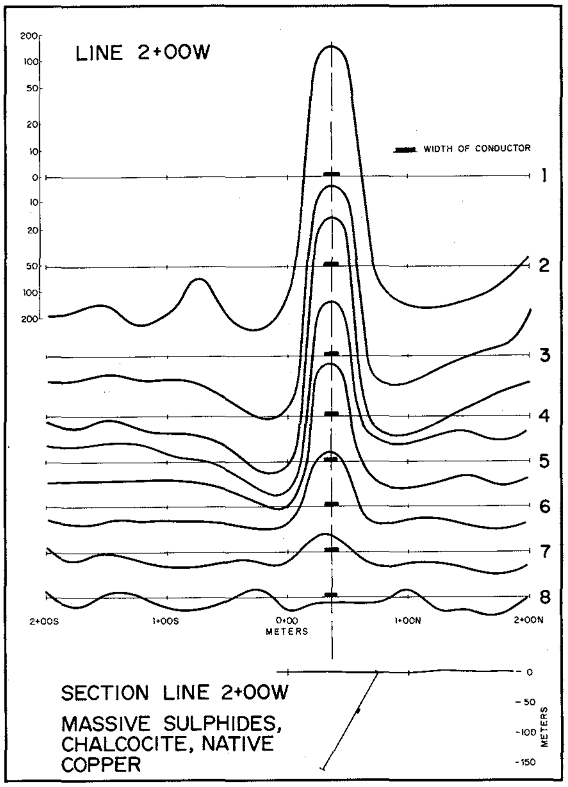

Figure 37.9. Pulse EM profile, 50 m coil spacing, moving coils method, Daris deposit, Sultanate of Oman.

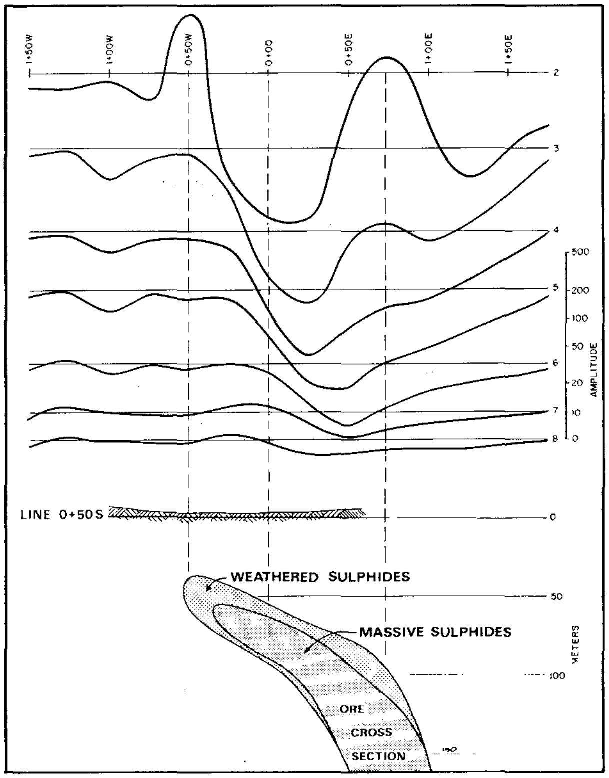

Figure 37.8. Pulse EM profile, 50 m coil spacing, moving coils method, Lasail Orebody, Sultanate of Oman.

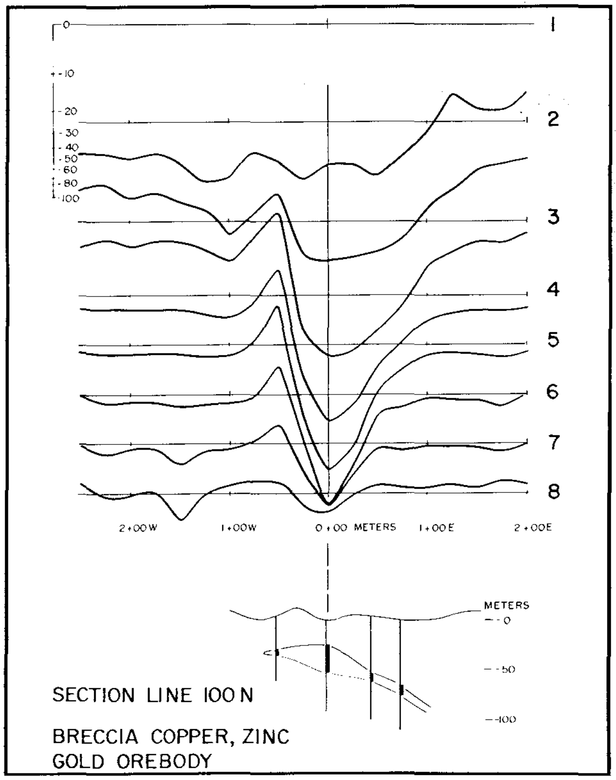

Figure 37.10. Pulse EM profile, 50 m coil spacing, moving coils method, section line 100N, Rakah orebody, Sultanate of Oman.

This halting of the oxidation process leaves the central core of the body as fresh sulphides of high conductivity. An excellent example of this phenomenon occurs in the Woodlawn lead-zinc-copper orebody in New South Wales, Australia (Fig. 37.4). Weathering of this 50 m-wide orebody stops at a depth of 12 m. The near-surface, fresh, massive sulphides of the Woodlawn orebody were at first considered unusual for Australian climatic conditions. We have since encountered several similar occurrences (without the Woodlawn grade) in Australia and other desert areas. Two examples are shown; the first example presented in Figure 37.5 is a Pulse EM profile across the Maydan massive sulphide body in the mountains of Oman, which is 40 m wide and oxidized to 10 m. Figure 37.6 presents a Pulse EM profile across a massive sulphide body in the Precambrian of Arizona, which is 15 m wide and is weathered to a depth of approximately 20 m. All three bodies occur in areas where oxidation of narrow sulphide zones extends down to at least 40 m. The occurrence of a strong, isolated zone of very high conductivity in a desert area can usually be attributed to a wide, massive sulphide body. Such anomalies are uncommon, but are important exploration targets.

Field Examples from the Sultanate of Oman

Since 1973, Crone Geophysics Limited, has been consulting for Prospection Limited of Toronto, who are managing an exploration program in the Sultanate of Oman. A large area of Oman was flown by Geoterrex, with the Input Mark V airborne EM system. Approximately 70 per cent of this area is covered by surficial conductors that produce a background response down to the lowest Input EM channel. In Figure 37.7, the Input airborne EM response from five massive sulphide ore deposits is shown with background conductivities, varying from low at the Lasail orebody, to high around the Daris deposit. All five orebodies are clearly detected by the airborne EM survey with their signature superimposed on the background surficial conductivity response. The ground Pulse EM profile over the Lasail copper orebody is shown in Figure 37.8. The background surficial response at Lasail is again almost zero. In this section the upper surface of the Lasail orebody is wider than the 50 m coil spacing. Both edges of the body are shown as positive-trending peaks with a large negative response being produced when both coils are located directly over the wide conductor. Figure 37.9 is a ground Pulse EM profile over the Daris deposit which is located on the outwash flats between the coastal mountains and the Gulf of Oman. The surficial conductive overburden in that area produces a large negative anomaly of minus 200 (normalized) divisions on the first sample. With both the airborne and ground EM anomalies, the surficial response in the Daris area in the early samples, exceeds in magnitude the peak response from the sulphides of the Lasail orebody. In both techniques, the Daris body is clearly detected with the sulphide anomaly being superimposed on the surficial anomaly.

The discovery Pulse EM profile over the Rakah orebody, is shown in Figure 37.10. It is a typical response of a flat, dipping conductor with a conductivity thickness of 45 Mhos. The test borehole for such an anomaly was spotted as a vertical hole at the maximum negative response; it intersected 30 m of 3% copper in a breccia sulphide zone. The Rakah body occurs at the foot of a mountain ridge and dips under the mountain. A Pulse EM profile along the steep side slope of the mountain is shown in Figure 37.11. The ore zone under this profile is at a depth of 100 m and is barely discernible with the 50 m spacing Pulse EM profile. This type of anomaly may weakly represent a conductor at this depth, but it lacks the definition required to accurately locate a test drillhole.

Detailed Pulse EM Methods

When a marginal anomaly is detected by a ground Pulse EM survey, a detailed survey is required to first establish if the anomaly is actual or noise, and secondly to provide the additional information required to locate a test drillhole. The deeper the conductive target, the greater the need for accurate position, depth, dip and width information.

The Pulse electromagnetic method has no geometrical restrictions and therefore detailed measurements can be obtained with various transmit-receive coil configurations. The method also has the advantage of being able to measure the secondary electromagnetic fields directly rather than as a resultant field reading in the presence of a primary transmitted field. One of the most effective detailed methods is to measure both horizontal and vertical field components and from these determine the direction of the secondary field. From this information measured at several stations, the induced eddy current paths can be located. The induced eddy current paths within a conductor are shown by Lamontagne and West (1971) to be spaced apart. The distance of separation is dependent on the conductivity-thickness of the body and the frequency of the induced field. For measurement points directly over the induced current path, the field is approximately circular and the eddy current position is located at the intersection point of lines drawn at right angles to the secondary field direction. Figure 37.12, illustrates the eight induced eddy current paths that would occur in a weathered, massive sulphide body. The high-frequency, early-sample current paths will flow along the outside of the body and also within the poorly conductive weathered sulphide and gossan areas. The late-sample eddy current paths will confine themselves to the highly conductive, inner core of the massive body. As an example, a standard, moving horizontal coil Pulse EM profile over a known massive orebody located in Western Australia is presented in the upper part of Figure 37.13. The depth to the top of the body is 100 m. The response of the standard method is within the noise level so that the observed anomaly would normally be considered questionable. A detailed survey was therefore carried out which used a vertical transmitter loop oriented coplanar with the strike direction on a line 120 m from the transmitter loop. The Pulse EM Sample 1 and 2 field directions and orthogonal lines are shown in the bottom part of Figure 37.13. The eddy current path for Sample 1 is located at a depth of 90 m. The slight scatter of the intersection points is caused by surficial conductivity effects. The Sample 2 current position is accurately defined at 96 m depth. The vertical loop survey was used in this case to selectively energize one edge of the sulphide body and to define the location and depth of one side of the body.

THE DEEPEM TECHNIQUE

An alternative detailed method utilizes a 100 m square, single-turn transmit loop out on surface. This has the advantage of a much stronger transmitted field providing greater penetration, consequently the technique is called the Deepem method. The transmitter loop is laid out on one side of the area to be detailed and the survey lines extend away from the loop, starting 50 m from one wire out to a distance of 350 m. Both horizontal and vertical components are measured and the induced current paths are determined as before.

An example of the use of the Deepem technique from a test survey over the Flying Doctor prospect, North Broken Hill area of Australia, is shown in Figure 37.14. In this case the surficial conductivity which is caused by brackish groundwater, has a conductivity of 4.2 ohm-metres to a depth of 7 m and a conductivity-thickness of 1.5 mhos. The massive sulphide body consists almost entirely of galena and

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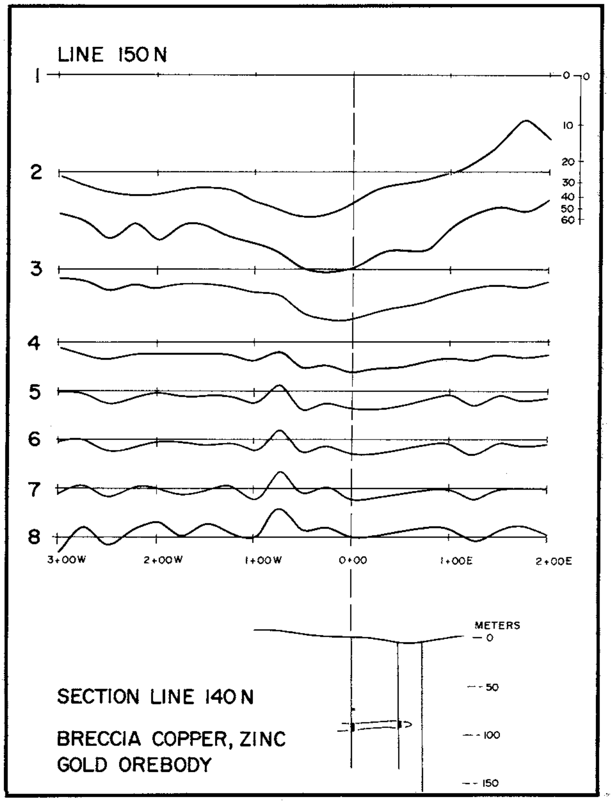

Figure 37.11. *Pulse EM profile, 50 m coil spacing, moving coils method, section line 140N, Rakah orebody, Sultanate of Oman.*

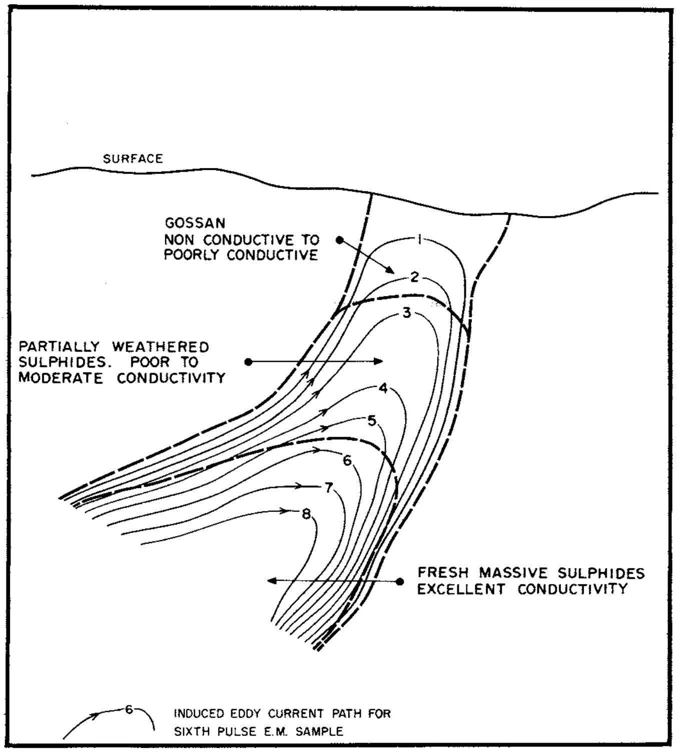

Figure 37.12. *Induced eddy currents in a weathered massive sulphide body from the PULSE EM transmitter.*

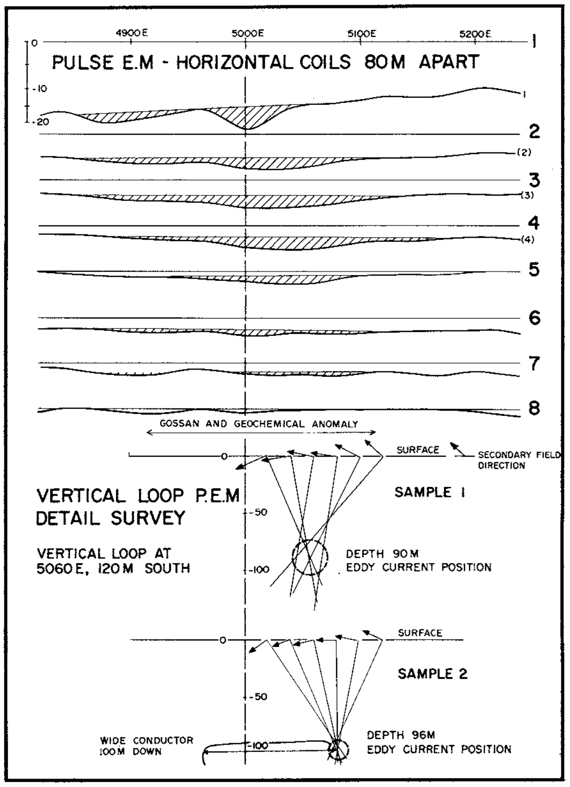

Figure 37.13. *PULSE EM surveys moving coils method and vertical loop detail method. Massive sulphide body, western Australia.*

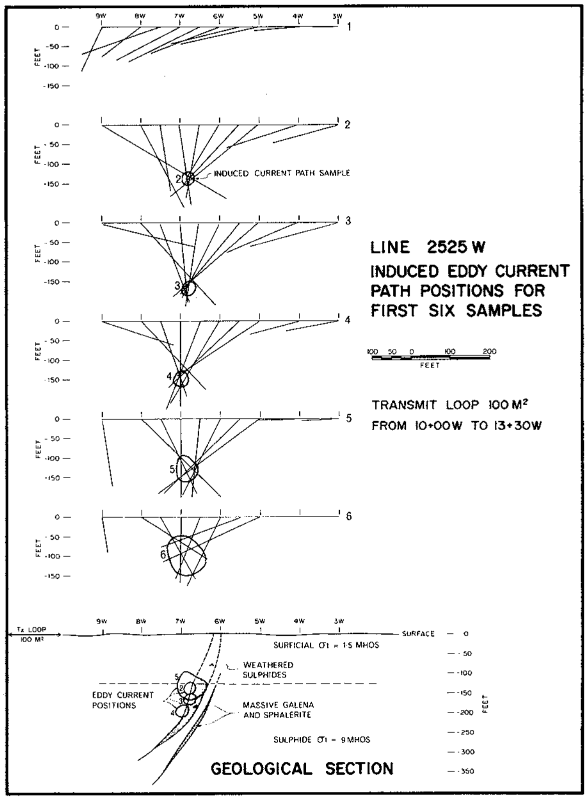

Figure 37.14. *PULSE EM survey, detail vertical loop (Deepem) method, induced eddy current paths. Flying Doctor prospect, North Broken Hill, Australia.*

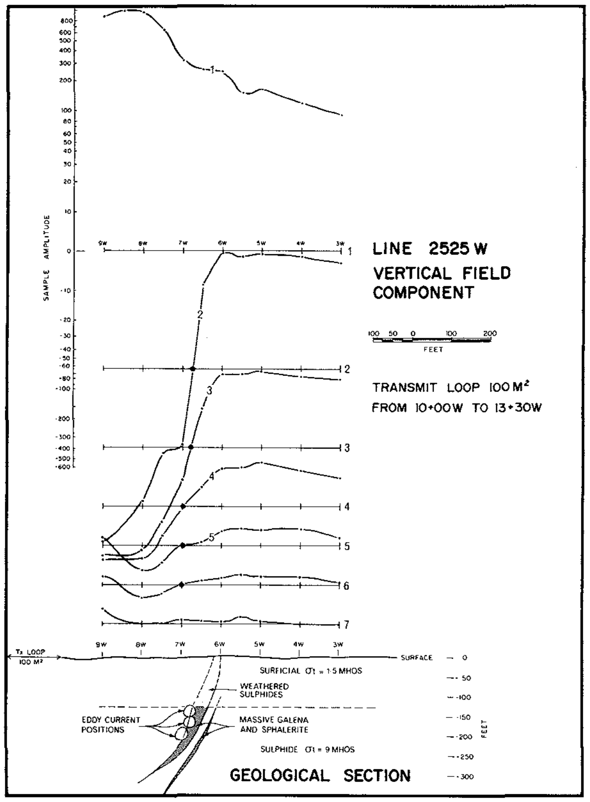

Figure 37.15. *Pulse EM survey, detail vertical loop (Deepem) method, vertical component, Flying Doctor prospect, North Broken Hill, Australia.*

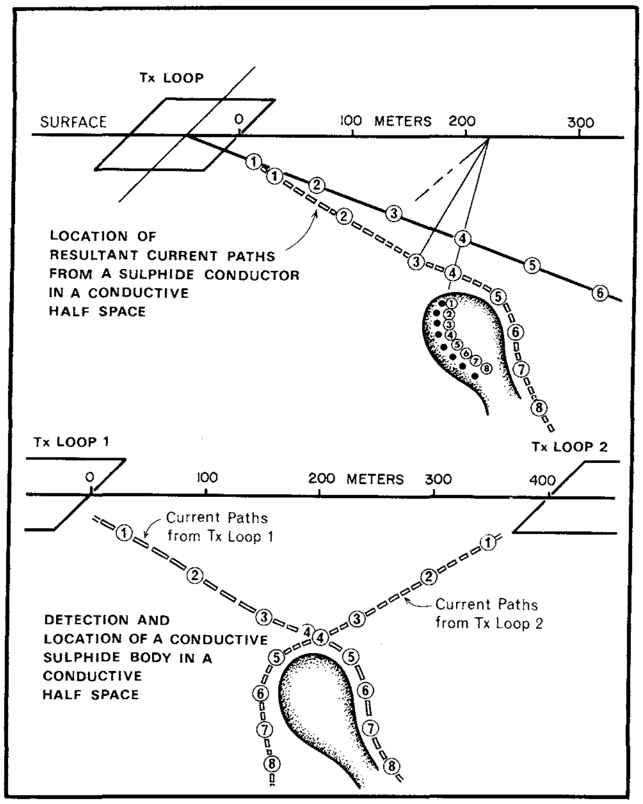

Figure 37.17. *Pulse EM Deepem detail method, induced current paths in conductive half space containing a massive sulphide body and the application of two transmit loops.*

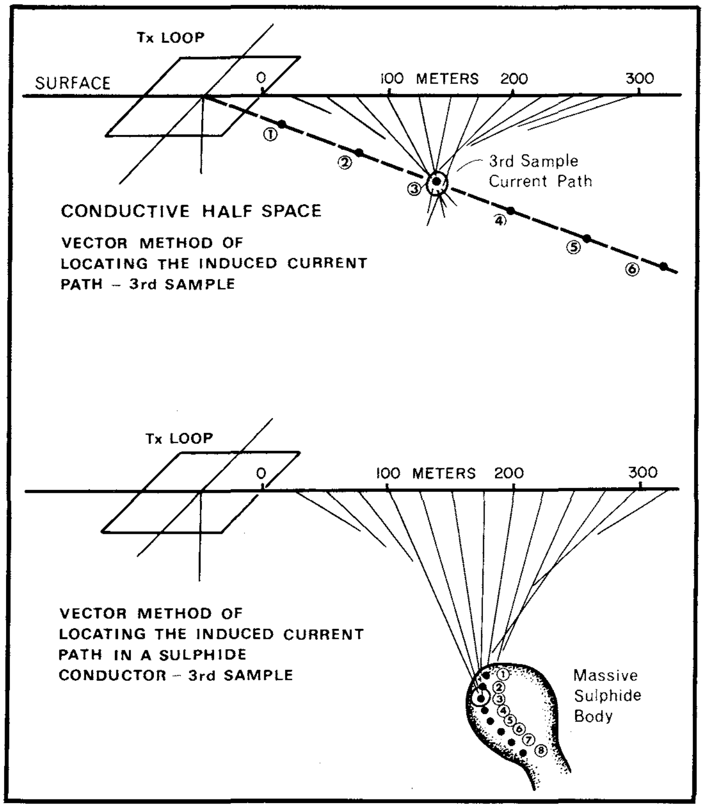

Figure 37.16. *PULSE EM Deepem detail method, Induced current paths in a conductive half space and massive sulphide body.*

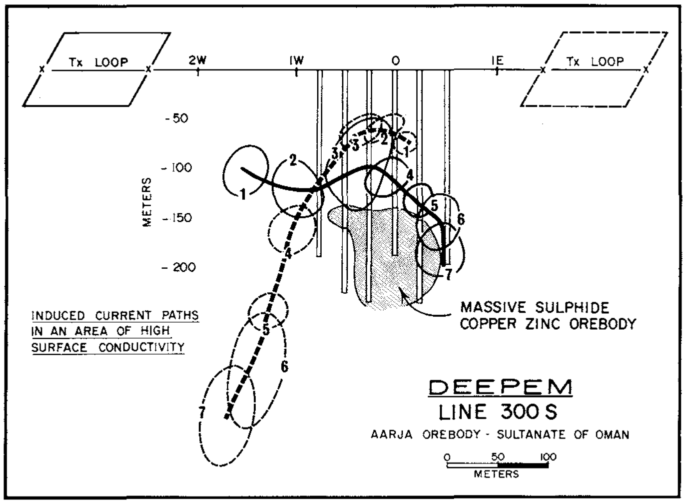

Figure 37.18. *Pulse EM Deepem detail method over Aarja Orebody, Sultanate of Oman.*

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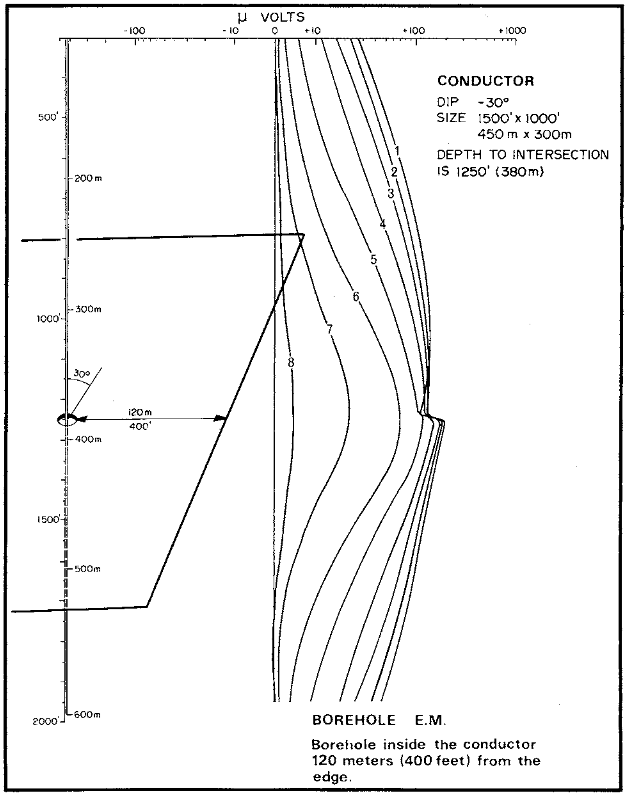

Figure 37.19. *Pulse EM borehole method, model study result from a conductive sheet, borehole intersecting the sheet 400 ft from its edge.*

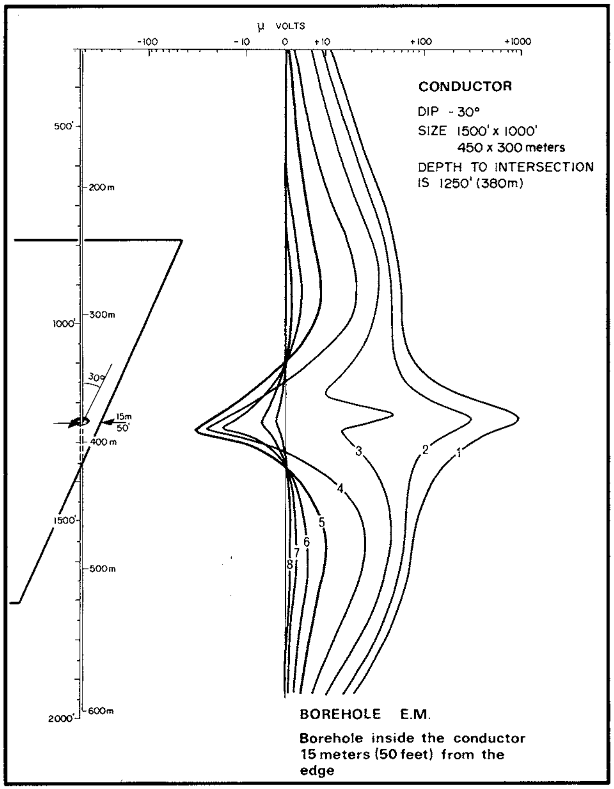

Figure 37.20. *Borehole pulse EM method, model study result from a conductive sheet, borehole intersecting the sheet 50 ft from its edge.*

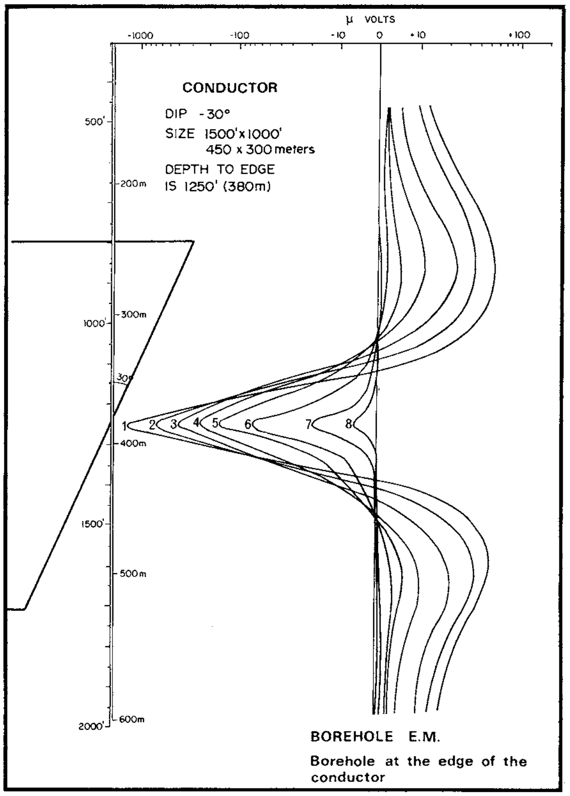

Figure 37.21. *Borehole pulse EM method, model study result from a conductive sheet, borehole just outside edge of sheet.*

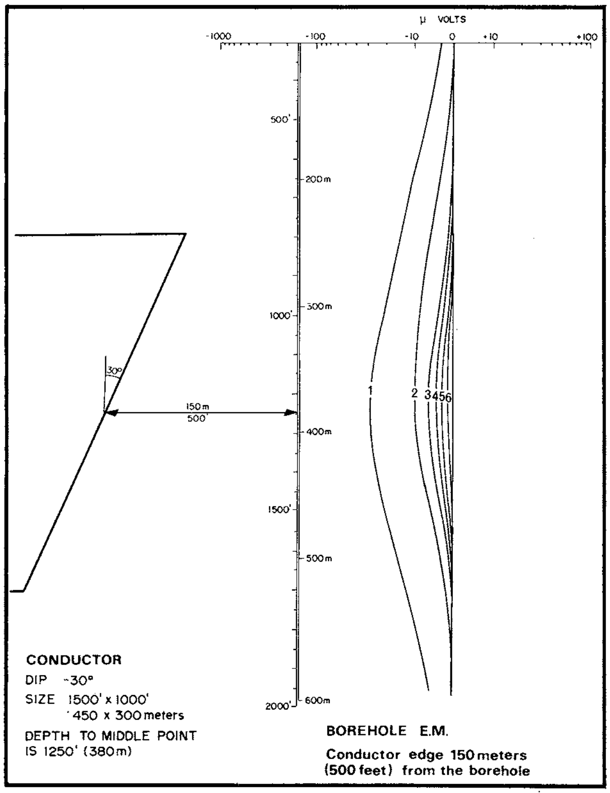

Figure 37.22. *Borehole pulse EM method, model study result from a conductive sheet, borehole 500 ft and outside edge of sheet.*

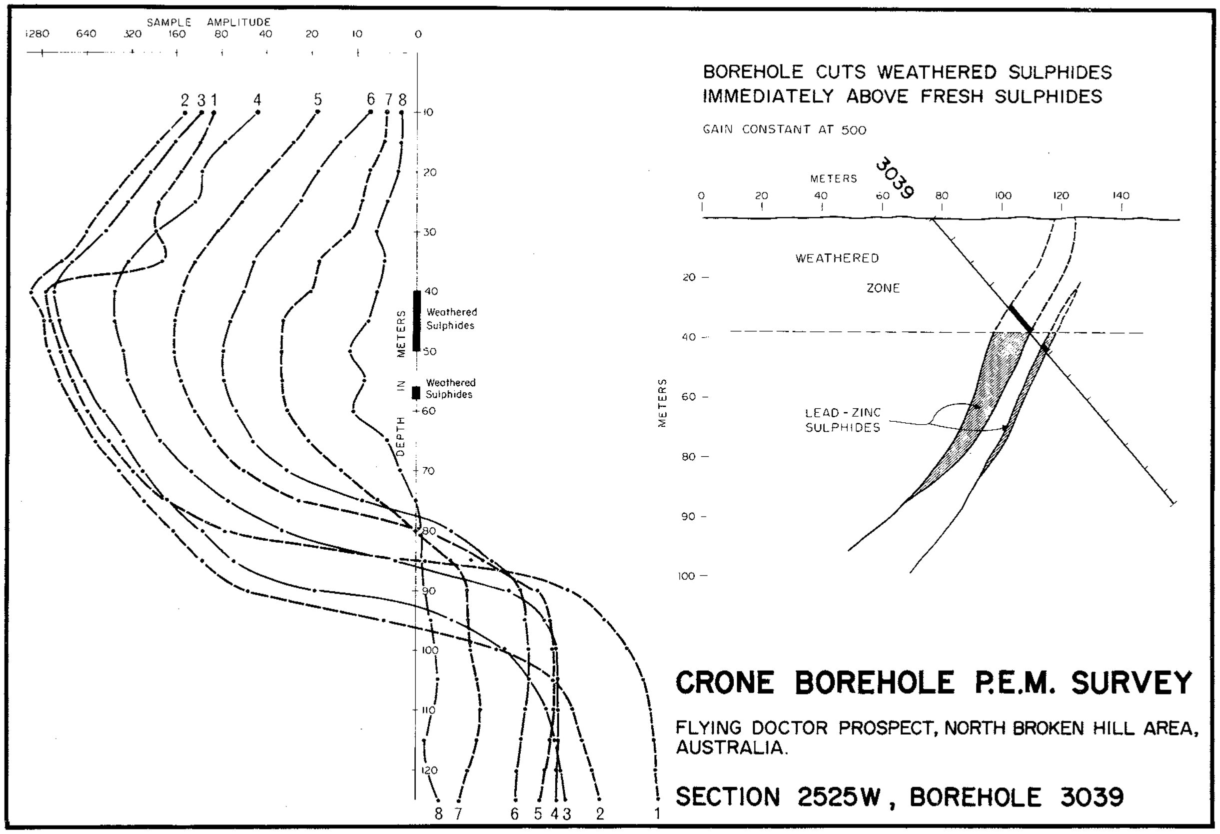

Figure 37.23. *Borehole pulse EM survey, borehole just outside the upper edge of Flying Doctor lead-zinc body, North Broken Hill, Australia.*

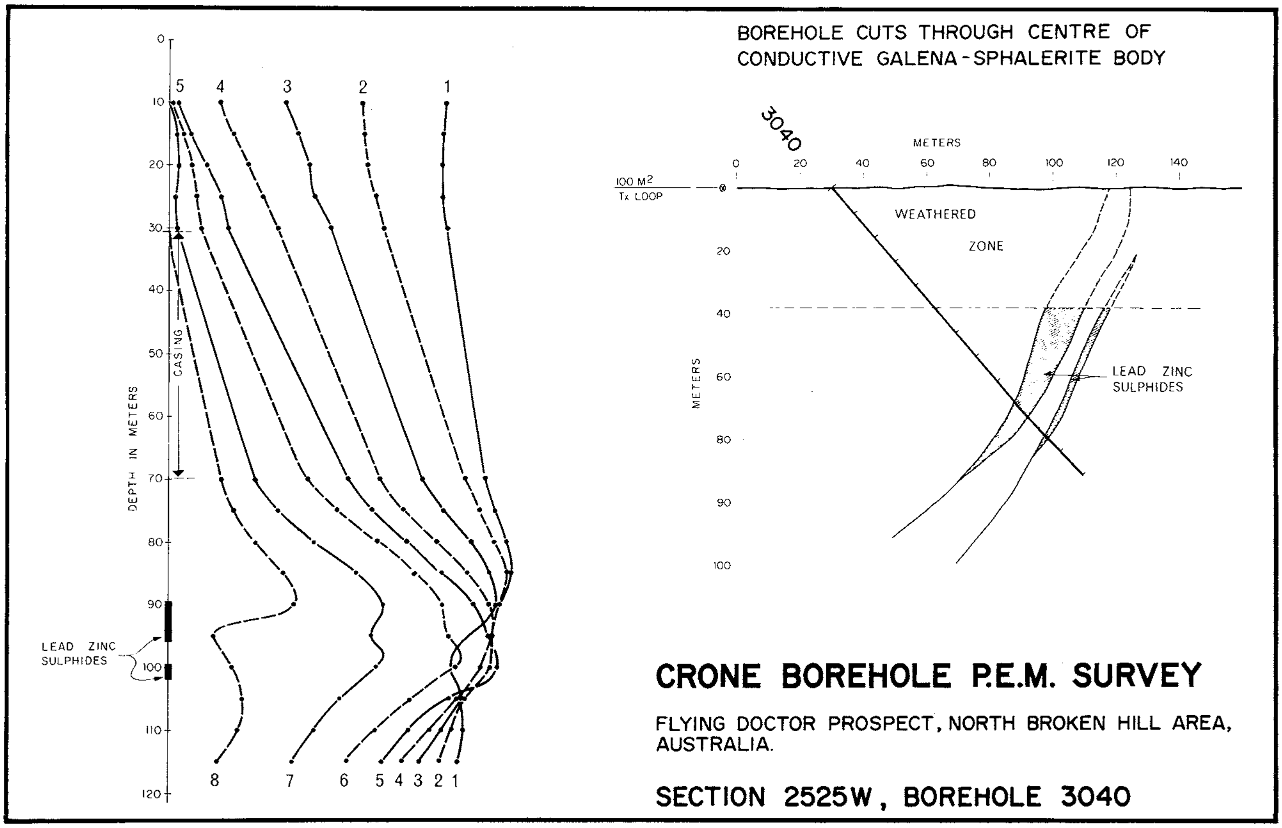

Figure 37.24. *Borehole pulse EM survey, borehole intersecting the middle portion of Flying Doctor lead-zinc body, North Broken Hill, Austraila.*

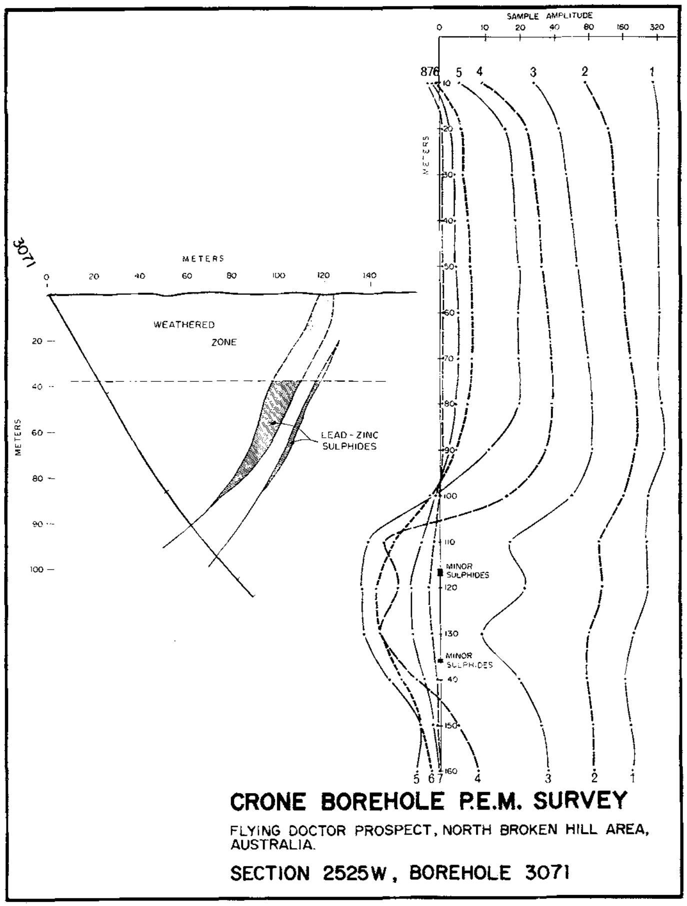

Figure 37.25. *Borehole pulse EM survey 20 metres away from the lower edge of Flying Doctor lead-zinc body, North Broken Hill, Australia.*

sphalerite with a calculated conductivity-thickness from the Pulse survey of 9 Mhos. The body is weathered to a depth of 40 m. The first Pulse EM sample is dominated by the surficial conductivity and does not form an eddy current path position. The second, third and fourth samples produce eddy current path positions along the contact of the sulphide lens that faces the transmitter loop. Because the sulphide lens has a low conductivity, the response of the fifth and sixth samples are weak and the eddy current paths are not accurately defined. In order to show the amplitudes of the responses measured, the vertical component is usually plotted as shown in Figure 37.15. The conductor is located below the cross-over position.

Limitations of the Deepem Detail Method in Areas of High Surficial Conductivity

The presence of a conductive half space below the transmitter loop results in eddy currents that flow in concentric rings around and outside the loop. The first sample eddy current flows close to the loop, with the later samples spaced farther out as shown in the upper portion of Figure 37.16. The interval between the eddy current paths decreases as the conductivity-thickness of the half space increases. The lower portion of Figure 37.16, shows the current paths induced in a massive sulphide body without the presence of a surficial conductive zone. When the sulphide body occurs in a conductive half space, then both surficial and sulphide eddy currents are present as shown in the upper portion of Figure 37.17. In this case, a resultant current path will be detected by the receiver that is shown as a dashed line. This resultant current path for the early or high frequency samples, will be dominated by the surficial conductivity response. The later sample or low frequency resultant response, will be influenced to a greater degree by the more conductive sulphide body. The net effect is for the resultant current path to form a line that lies between the surficial and sulphide current paths. If transmitter loops are employed on either side of the target area, then the approximate position of the sulphide zone can be determined as the area enclosed by the two resultant current paths, as shown in the lower portion of Figure 37.17.

The two-transmitter Deepem procedure was first tested in a profile over the Aarja massive sulphide body in the Sultanate of Oman. The body approximates a cylinder some 50 to 100 m in diameter of massive sulphides that has a shallow plunge of 20° from the horizontal. The test section has a depth to the top of the sulphide zone of 150 m. The surficial conductivity in this area is 9 ohm m to a depth of approximately 30 or 40 m. The resultant induced current paths are shown in Figure 37.18; the eddy current paths from the eastern transmit loop as dashed circles, the paths from the western loop as solid circles with the orebody occurring between.

Further tests with the Deepem method in Australia, indicate that the induced current path method does not outline deep (100 m plus) massive sulphide conductors, when the surficial conductivity-thickness product is of the order of 10 Mhos. In this case the anomalous information is available in the measured readings but the eddy current path method lacks the sensitivity to unlock the sulphide response from the strong surficial response. Computer processing of the observed data to strip off the surficial conductivity background effect is now being investigated.

BOREHOLE PULSE EM METHOD

Crone Geophysics developed in 1976, a Borehole Pulse EM system for the Geological Survey of Canada with depth capabilities in excess of 1000 m. The method uses a large single-turn transmitter loop laid out on the ground and a receiver probe sent down the borehole. The advantages of the Borehole Pulse EM system are; (1) Since the method is free of geometrical effects, anomalies are not caused by variances in the straightness of the borehole. (2) The measurement of the secondary fields directly provides accurate interpretative information. (3) The wide frequency spectrum enables the method to separate effects from weakly mineralized sulphide zones intersected within the hole from large massive bodies located outside the hole.

A model study was carried out (Woods, 1975) as an aid to the interpretation of Borehole Pulse EM data. This study illustrates that Borehole Pulse EM is effective in detecting massive sulphide bodies and also provides an idea of the size, shape and position of the sulphide body. Figures 37.19 to 37.22 illustrate the change in the response pattern obtained when the borehole is moved from an intersection from 120 m inside a conductive sheet to 150 m outside. The response unit in this model study are microvolts of signal received at the downhole probe and are not normalized.

Field results are shown from a survey of three holes in a section from the Flying Doctor prospect. This is the same section that was detailed with the Deepem method. The three holes were all surveyed from a 100 m square, single turn, transmitter loop located immediately west of the collar of borehole 3071. In Figure 37.23, the Borehole Pulse EM results from borehole 3039 are shown. This hole intersects the upper weathered portion of the sulphide zone. The survey curves match those of Figure 37.21 of the model study. This would indicate that the weathered sulphides intersected in the hole are nonconductive, but the hole is just outside the conductive sulphide zone. In Figure 37.24, the downhole results from hole 3040 are shown to produce the typical positive response obtained when a borehole intersects a conductive sulphide zone, with the intersection point located towards the central part of the body (model study Fig. 37.19). Casing in this hole blocked out readings between 30 and 65 m. The survey of borehole 3071 (Fig. 37.25) shows that the minor sulphide zones intersected at 117 and 136 m are both nonconductive but that two conductive bodies are located some 10 to 20 m from the hole. The upward displacement of the negative response peaks from the intersection of minor sulphides, indicates that the massive sulphides occur up dip from the intersection.

CONCLUSIONS

The ground Pulse electromagnetic method is an effective exploration tool in the search for massive sulphide bodies in desert areas. The method is very flexible as far as coil configurations and field component measurements are concerned. A large number of field measurements can be obtained at each observation point. Advancements in the computer processing of such a large data base, should lead to further increased depths of penetration and accuracy of the Pulse EM method. Developments in the Borehole Pulse EM technique have expanded the radius of detection of mineralization from a drillhole from a few centimetres of core up to 150 m. Thus this capability of the Borehole Pulse EM technique will permit exploration at depth in the vicinity of known ore deposits.

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