Les Mines Selbaie—25 Years of Discovery and Definition of a Polymetallic Base Metal Sulphide Ore Body

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ABSTRACT

The Cu-Zn-Ag-Au sulphide ore body now known as Les Mines Selbaie was discovered in 1974 as a result of following up a 1971 airborne INPUT survey. The mine continues to produce significant amounts of concentrates. Geophysics has played a continuing role in defining and discovering ore on the site. Detailed ground magnetic, electromagnetic, electrical and gravity surveys carried out early in the development phase have made possible this continued use of geophysics. For the most part these were uncorrupted by surface installations. The ore body responds to and has been defined by electromagnetic, electrical and gravity methods, as the ore which is made up of massive and stringer veins of conductive chalcopyrite and pyrite. Sphalerite adds to the density response. Surface and underground borehole time-domain electromagnetic surveys have found ore as well as adding to the definition of sulphide lenses. The original analogue data now upgraded to digital data have been used to create modern images that enhance the view of the responses and permit new interpretations.

INTRODUCTION

Les Mines Selbaie is a polymetallic base metal sulphide mine located in northwest Québec (Figure 1) in the northern part of the Abitibi Subprovince of the Canadian Shield (Deptuck *et al.*, 1982; Lacroix *et al.*, 1990; Bouillon, 1990). The deposit that was to become the Selbaie ore body was discovered in 1974 as a result of drilling a ground horizontal loop (Slingram) electromagnetic anomaly identified first in an airborne Input survey flown in 1971 (Reed, 1981). Les Mines Selbaie is currently one of the largest producers of zinc, copper, gold and silver concentrates in Québec. By the end of 1996, underground operations in the A2 and B zones (now closed) had mined 7.0 million tonnes of ore, and open pit operations in the A1 zone had mined 23.8 million tonnes of ore. Average grades were 2.02% zinc, 1.22% copper, 0.65 g/t gold, and 43.24 g/t silver. There remained 16.3 million tonnes of proven reserves of 1.83% Zn, 0.54% Cu, and 0.44 g/t Au and 35.61 g/t Ag (J.J Bouillon pers. com.). In 1996, 3.09 million tonnes of treated ore produced 47,081t Zn, 25,989 t Cu, 125,017 kg Ag and 1,771 kg Au. (Mining Journal, London, 1997).

The deposit consists of moderate to steeply dipping mineralized veins of sphalerite, chalcopyrite and pyrite which cut the local stratigraphy and a stratiform massive barren pyrite. This ore body is not one of the volcanogenic massive sulphide (VMS) ore bodies that are typical of the Archaean volcanic terrain in the Abitibi, however it has affinities to them. Only the massive pyrite, which may have been a precursor to the development of the ore, might be considered to be a VMS deposit. Selbaie is hosted by felsic, pyroclastic volcanic rocks of the Harricana-Turgeon belt (Faure *et al.*, 1990). Age dating of rocks in the mine sequence place an upper limit on the age of the ore at 2.729 Ga (Barrie and Krogh, 1996).

Geophysics has played a significant role in the discovery, definition, and continuing search for ore within the mine (Reed 1981; 1989; 1991; 1993). The presence in the ore of electrically conducting chalcopyrite and to a lesser extent pyrite, made possible the direct detection of the ore body by electromagnetic and electrical techniques. The availability of digital processing since the discovery has created the opportunity to look at the previous analogue data in new ways, to draw out aspects of the data not easily seen in the earlier analogue forms. This paper represents a summary of the data collected and the results achieved, with presentations using digital formats and processing developed since the discovery. The airborne maps are plotted here at a scale of 1:100 000 while most of the ground plan maps are presented at a scale of 1:20 000, so that comparisons between data sets may be easily made.

Other geophysical techniques used at Les Mines Selbaie that will not be reported in this paper are seismic (Milkereit *et al.*, 1992; Eaton *et al.*, 1996; Perron *et al.*, 1997) and borehole physical properties (Reed *et al.*, 1997a; Reed *et al.*, 1997b). Seismic reflection surveying did not image the ore, but did image bounding faults at the east end of the ore body, as well as faults within the mine sequence rocks. Borehole physical properties are shown to correlate with mineralogical and chemical re-interpretation of the geological logs.

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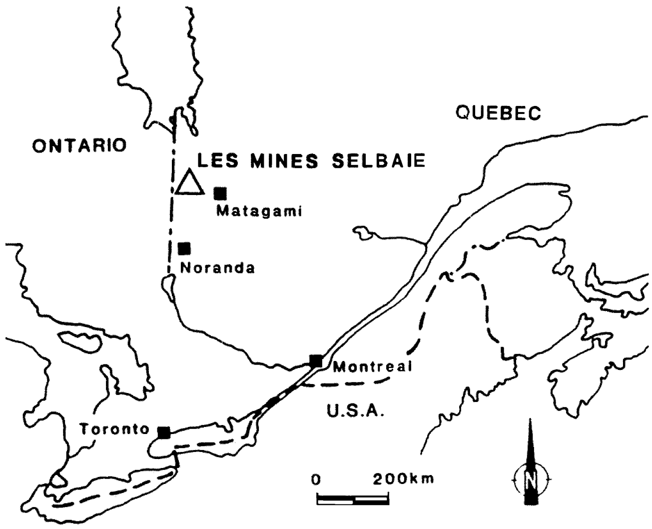

Figure 1: *Location of Les Mines Selbaie.*

AIRBORNE SURVEY

An airborne Mark VI Input survey in 1971 led to the discovery of the ore body as noted above. All of these data remain in analogue form. A Mark VI Input survey over the area by the Québec government in 1979 (Brouillan-Manthet, DP-866) is available in digital form. Magnetic and electromagnetic data from this survey are used here, as images developed with Geosoft software. The anomalies were digitized from the government anomaly maps by High Sense Geophysics. All plan maps are registered in UTM coordinates (NAD 27). Digital topography used on the maps is from the Canada Centre for Geomatics 1:250 000 scale map of NTS Sheet 32E.

Figure 2 shows the Input anomaly map with contours of the channel 1 amplitudes. The conductor at Selbaie is seen as a fairly large response (the A zone), about 1 km long with a small satellite just west (the B zone), making a 2 km long response isolated in an area of resistive high (or conductive low). Other features on this map include: another isolated response 4 km west (known as the Silver zone for its silver and very little else), which is caused by barren pyrite and graphite; an extensive series of linear conductors to the southwest caused by bedded and structurally controlled pyrite and graphite; a few scattered anomalies just north of the long formational features; and several events seen only in the contoured channel 1 response and not picked as anomalies. There is a strong northerly striking event east of Selbaie that coincides with a magnetic diabase dyke. This poor conduction event probably arises from faulting identified with the dyke, as well as overburden clays trapped by the paleotopography caused by the dyke. Southwest of

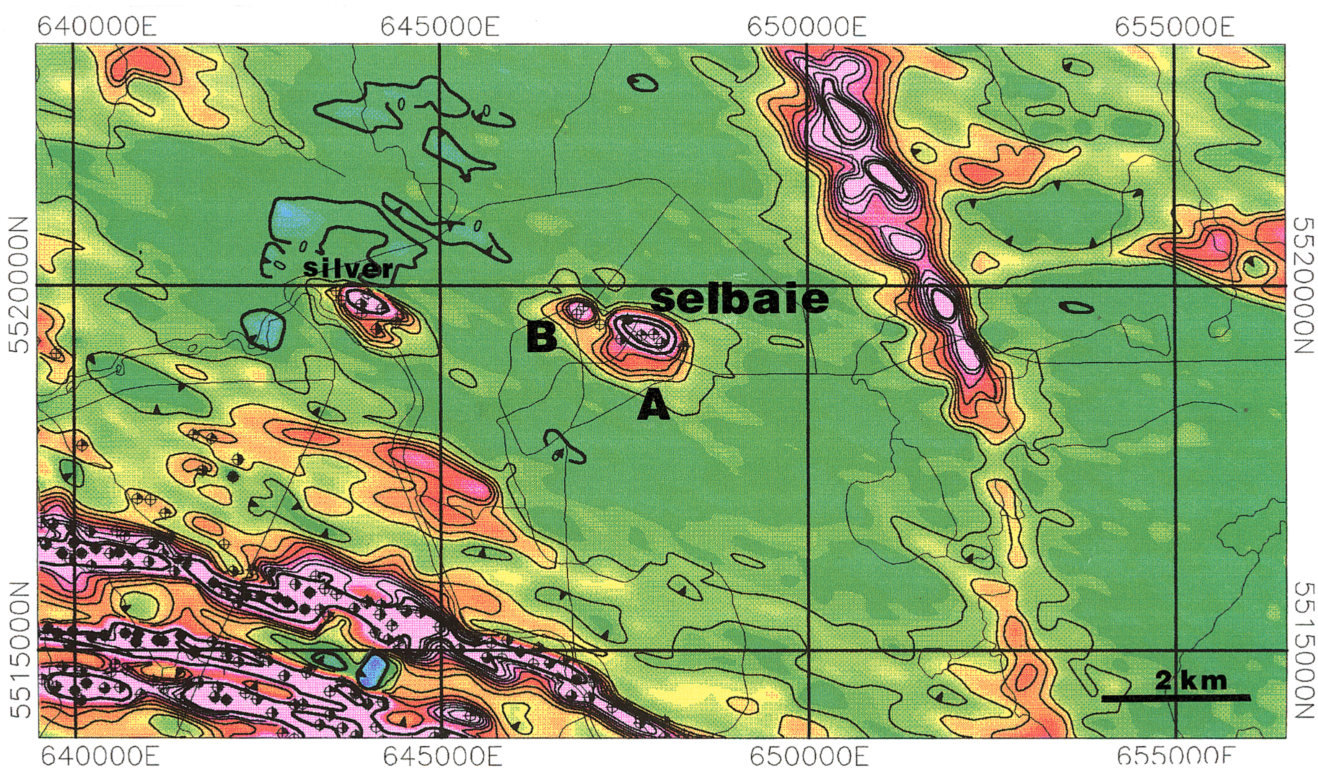

Figure 2: *Contours of channel 1 of the Input airborne electromagnetic response with anomaly indicators, from the Brouillan-Manthet Input and magnetometer survey. The contour interval is 100 ppm of the primary field (ppm). The peak amplitude on the A zone is 3600 ppm, on the B zone 900 ppm.*

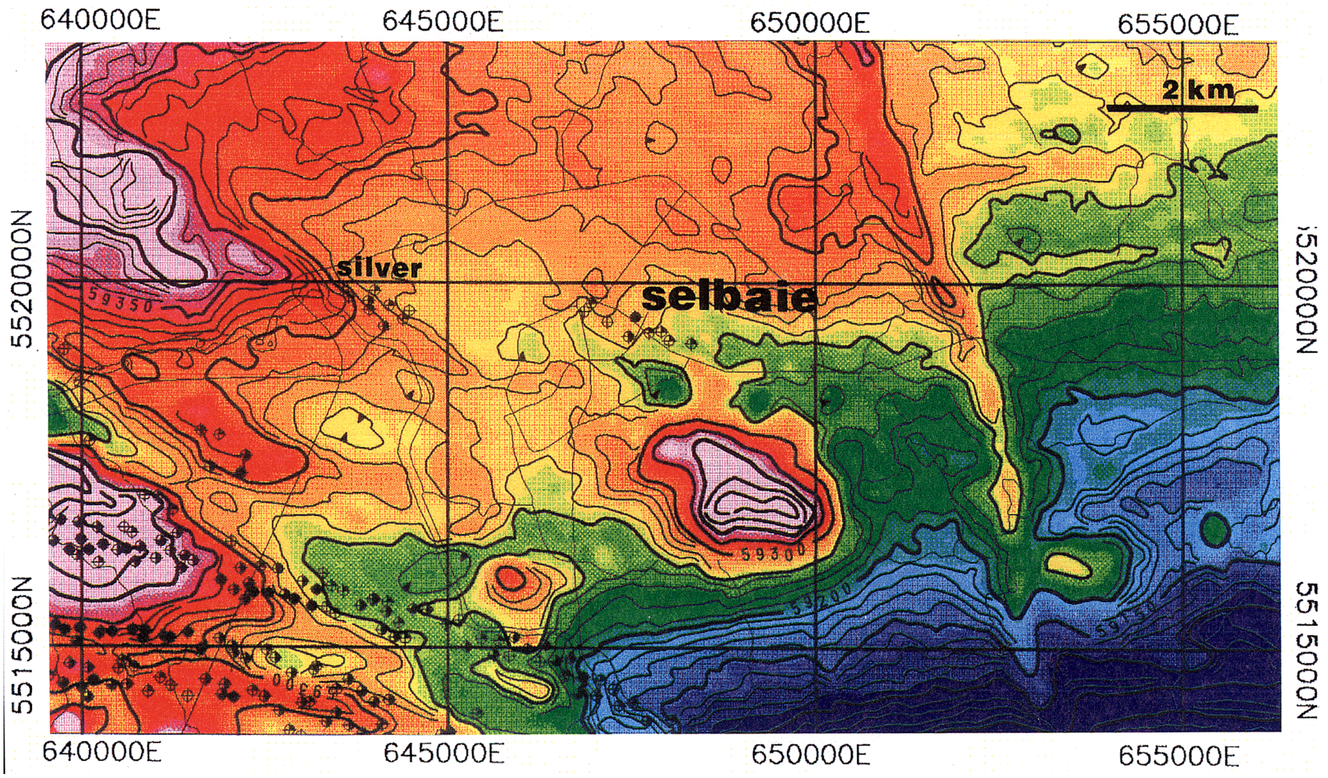

Figure 3: *Contours of the total field magnetic response from the Brouillan-Manthet survey, minimum contour interval 10 nT.*

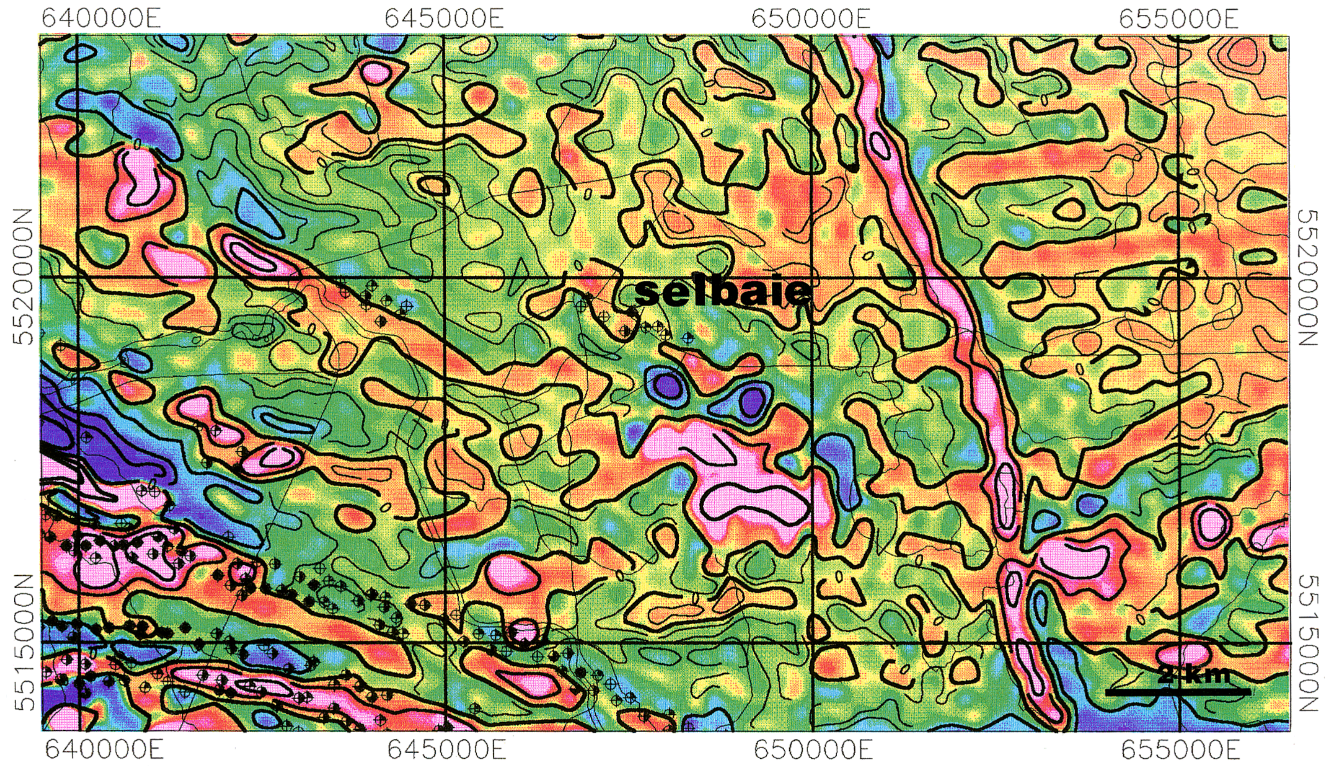

Figure 4: *Contours of the first vertical derivative of the total magnetic field in Figure 3.*

Selbaie, linear conductors appear that are now known to have bedrock origin in stringer and disseminated sulphides. Griding and contouring these weak events improves the resolution of geological events not recognized on the primary anomaly picking.

Figures 3 and 4 presents the magnetics as total field and first vertical derivative. These show a large magnetic high south of the ore body that is a granodiorite intrusion. This is the closest significant magnetic event to the ore body. Its role in the placement of the ore body is problematical. There may be a very subtle northwest striking trend in the magnetics at the ore body. A more significant and separate, northwest striking trend at the Silver zone marks a subtle transition to more mafic volcanics towards the southwest. There are no magnetic minerals in the ore that would produce a magnetic anomaly coincident with the electromagnetic anomaly. The diabase dyke to the east of the ore body is clearly expressed by the north trending magnetic high. The ore body lies at the western edge of a large granitic intrusion, the Brouillan batholith. The ore is in contact with thrusts relating to this intrusion. The magnetics do not differentiate between the Brouillan granite and the mine sequence volcanics. The granite is thought to be a sub-volcanic equivalent of the mine sequence rocks, so that they have similar low iron contents and chemical and metamorphic histories.

GROUND GEOPHYSICS

Electromagnetic

The initial ground location electromagnetic survey has been reported in Reed (1981). The next stage of ground EM employed a Geonics EM-17 in horizontal loop mode. This was run at a coil spacing of 123 m (400 ft) and a frequency of 1600 Hz. The in-phase result is shown in Figure 5. The A and B zones were run on two separate grids, as it was recognized that their principal conductors had different strikes, as may be seen in the figure. The extensive positive shoulder around the A zone was one of the earliest indications that mineralization was more extensive than suggested by the central conductor alone.

Magnetic

The ground magnetics (Figure 6) show no distinctive feature associated with either zone of the ore body, although the subtle north northeasterly trends at the B zone follow the trend of that zone. The locally north northeasterly trends may be reflecting structures that cross the A zone, cause the local emplacement of the B zone and influence bedrock surface topography. It may be that the ground magnetic responses identify sources that are both in the overburden as well as the bedrock. In themselves they are not useful for direct ore identification.

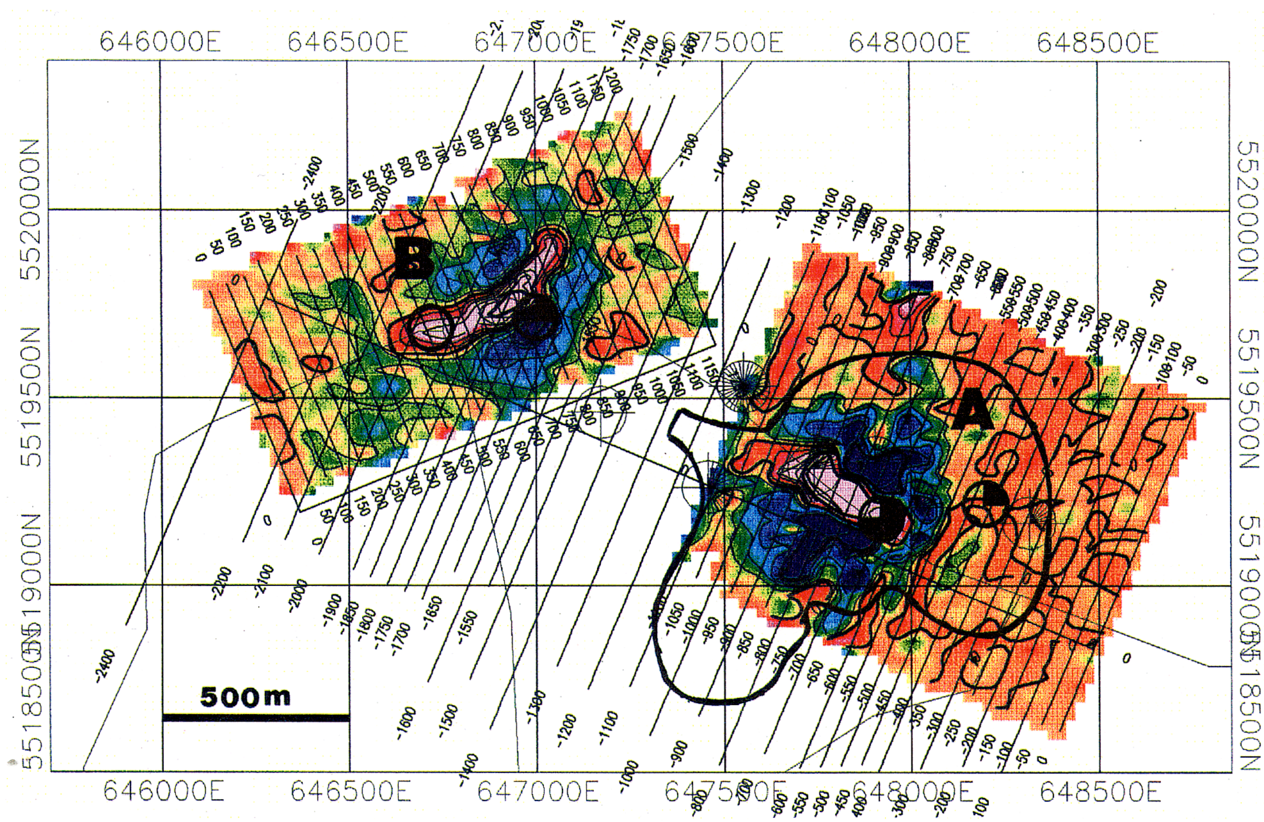

Figure 5: *Contours of the Geonics EM 17, ground horizontal loop EM in-phase response. Anomaly indicators are from the 1971 discovery Input survey. Outline is of the 1996 pit, presented for reference on all the ground drawings.*

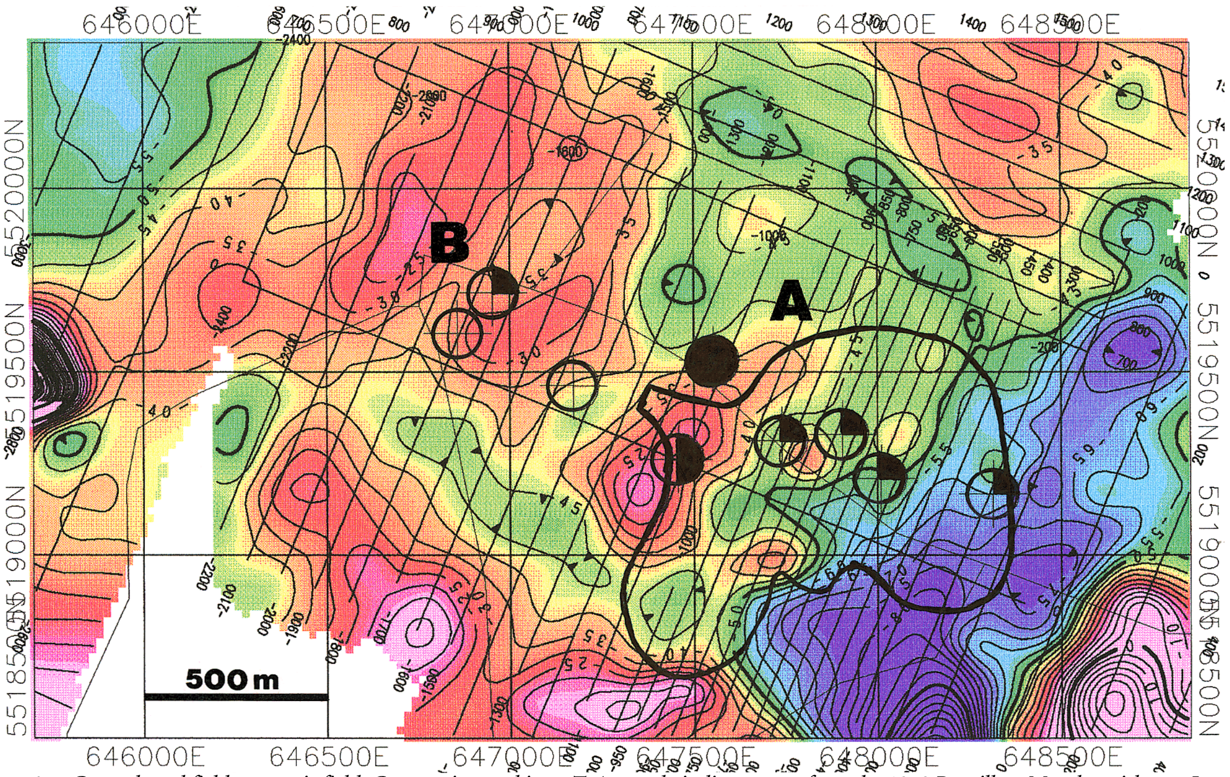

Figure 6: *Ground total field magnetic field. Contour interval is 5 nT. Anomaly indicators are from the 1979 Brouillan-Manthet airborne Input survey. These are in the background for reference on the other ground maps as well as the airborne maps.*

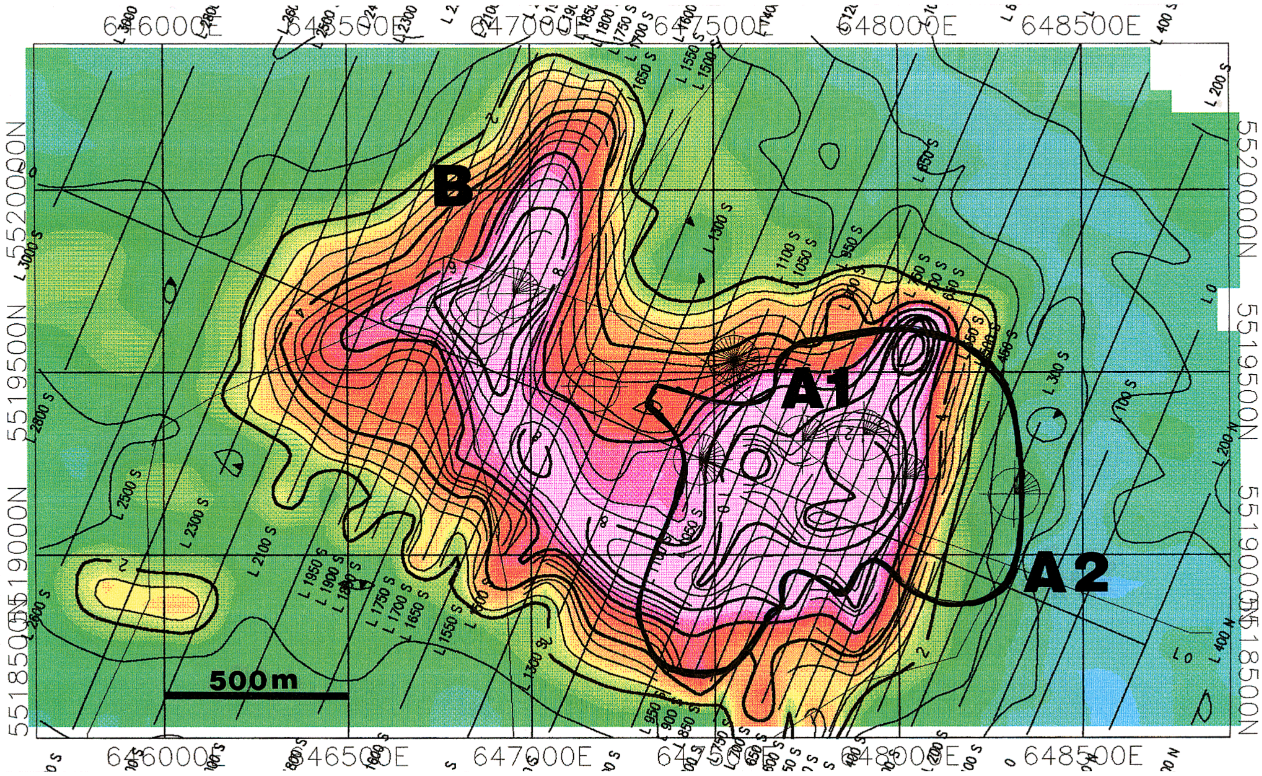

Figure 7: *Induced polarization, contours of pant leg filter, from a=100 m, n=1 to 4, percent frequency effect, interval 0.5 PFE.*

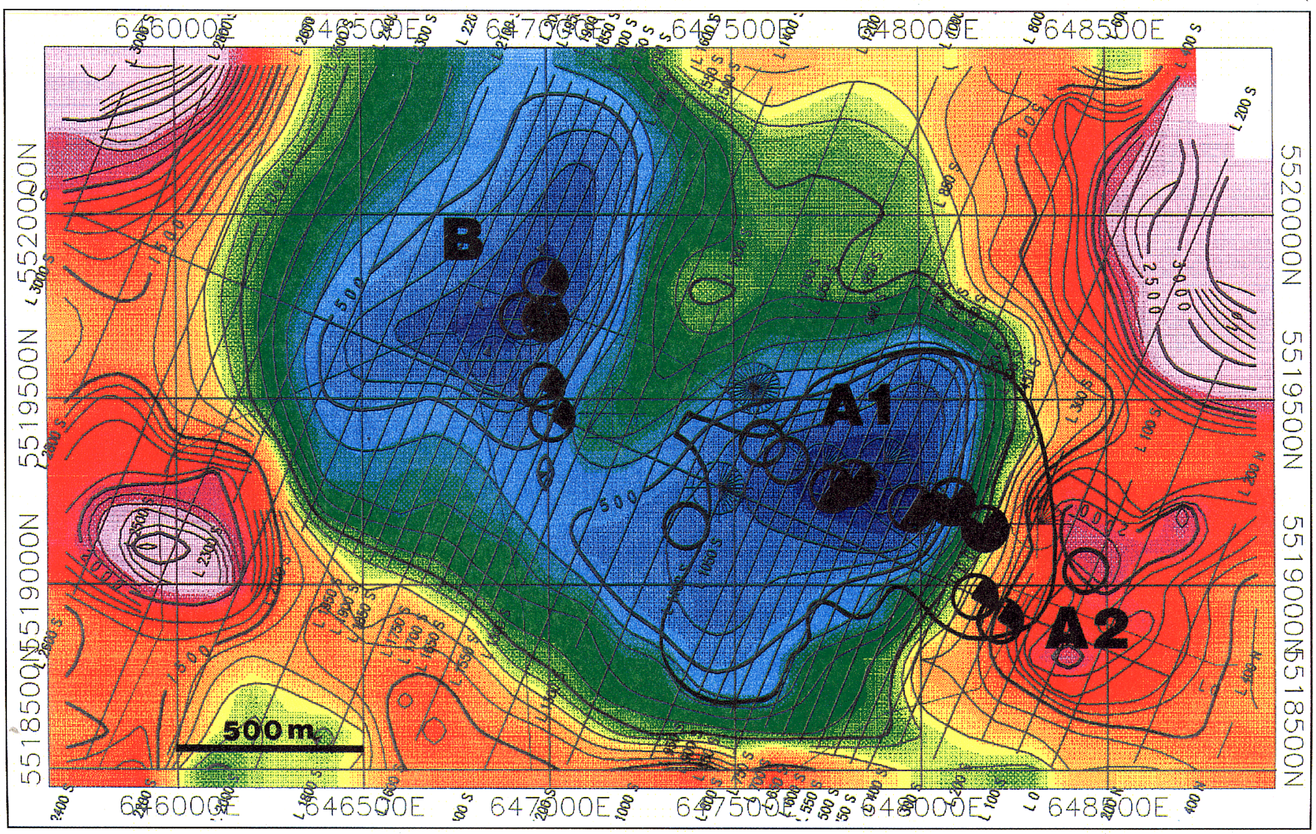

Figure 8: *Resistivity, contours of pant leg filter, interval 100 ohm-m. Resistivities are below 200 ohm-m over the A1 and B zones. Anomaly indicators are from the detail 1971 Input survey. Note that the A2 zone which has an upper lens with a top at 75 m from surface, is seen by the Input, but not by the resistivity or the IP. In section, the widest electrode spacings begin to see this deep zone.*

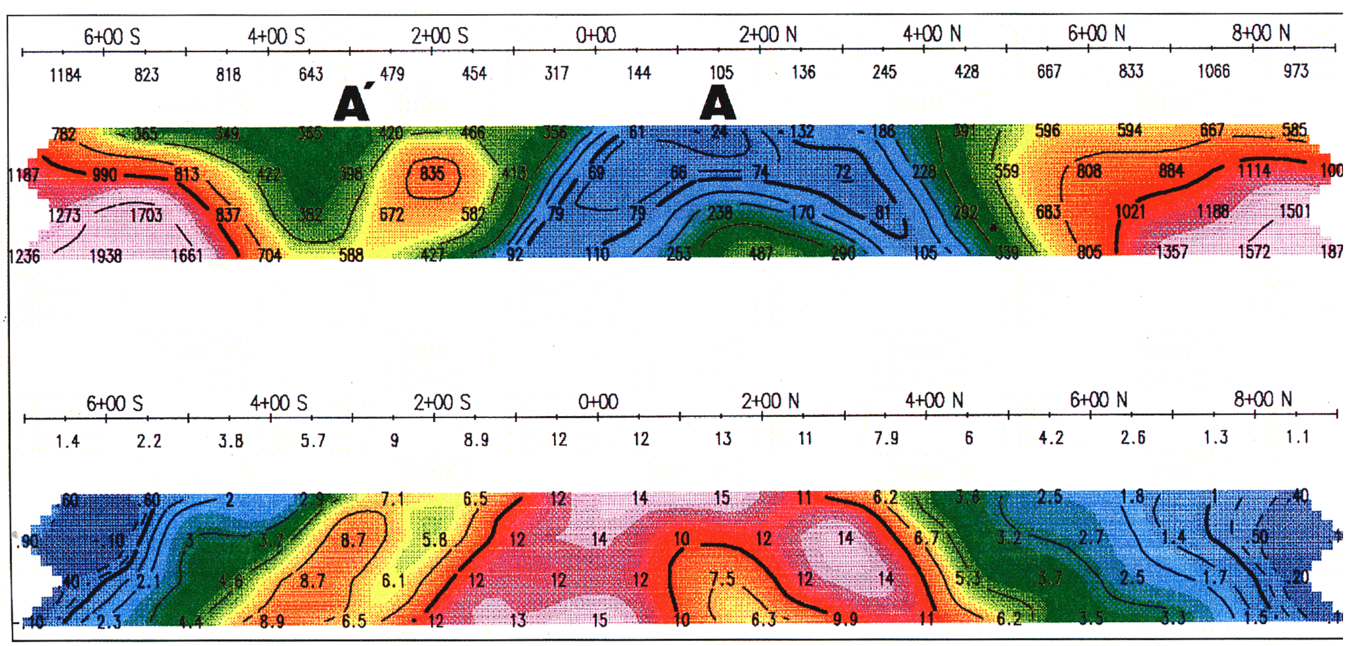

Figure 9: *Pseudo-section of resistivity and induced polarization for line 800W, over the centre of the A zone (A). A´ is a weak anomaly identifying minor sulphides but nevertheless is in ore and within the pit (Figure 7).*

Induced polarization and resistivity

Induced polarization and resistivity surveying using McPhar frequency-domain IP was undertaken on the main grid soon after the drilling of the discovery hole. Dipole-dipole surveys with electrode spacings *(a)* of 50 m and 100 m were undertaken. A single line of a = 25 m run across the A zone found that while considerable detail was achieved, the shallowest n spacing showed the effects of overburden thickness. Even at a = 50 m, the effects of overburden thickness were evident. The electrode spacing of 100 m and dipole separation *(n)* readings from 1 to 4 was adopted for general coverage. Plan maps of the pant leg filter versions of the percent frequency effect (PFE) and resistivity over the ore body are shown in Figures 7 and 8. Both components well describe the A zone as the recent pit outline shows. The B zone is also well described in general even though the lines were run parallel to strike. Details within the B zone such as grid east-west striking lenses at the south end are not apparent in this presentation. There is a connecting bridge in both IP and resistivity response that identifies mineralization, principally pyrite, with lower grades of economic minerals, that are not included in the reserve. There is a narrow extension north on line 700 W (labeled 700 S, an artifact of plotting the rotated line labels), at the north end of the A zone that identifies a grid north striking vein set that is of ore grade. Irregularities along the south edge of the IP high are artifacts of the plotting of the data on the short lines and do not reflect irregularities in the mineralization.

Induced polarization has proven to be the most useful tool for mapping of sulphides from surface. Details within the mineralized envelope are recognized in a general way on the 100 m dipole. Figure 9 shows a pseudo-section through the centre of the A zone (line 800 W) that describes a broad central high from 100 S to 300 N, where PFEs rise to 15, along with a smaller event at 2+50 S, where PFEs rise over to 8.9. The resistivity low drops to 24 ohm-m, although most of the low is in the 70 ohm-m range. All of the IP high response is in ore. The 50 and 25 m dipoles describe greater detail (not shown). The highest IP responses recorded over the A zone are just under 20 PFE.

Electromagnetic (2)

Well after development on the site began, a Max-Min horizontal loop electromagnetic survey was run on the main grid across both zones. Figures 10 and 11 showing in-phase and quadrature components for the frequency of 3555 Hz. This contoured representation of the amplitudes like the EM-17 above, is not the usual way of presenting these data, but it is effective here. The coil separation for this survey is 250 m. Five frequencies from 222 Hz to 3555 Hz were collected. Some coverage was accomplished at 125 m and 75 m coil separations. The core conductor of

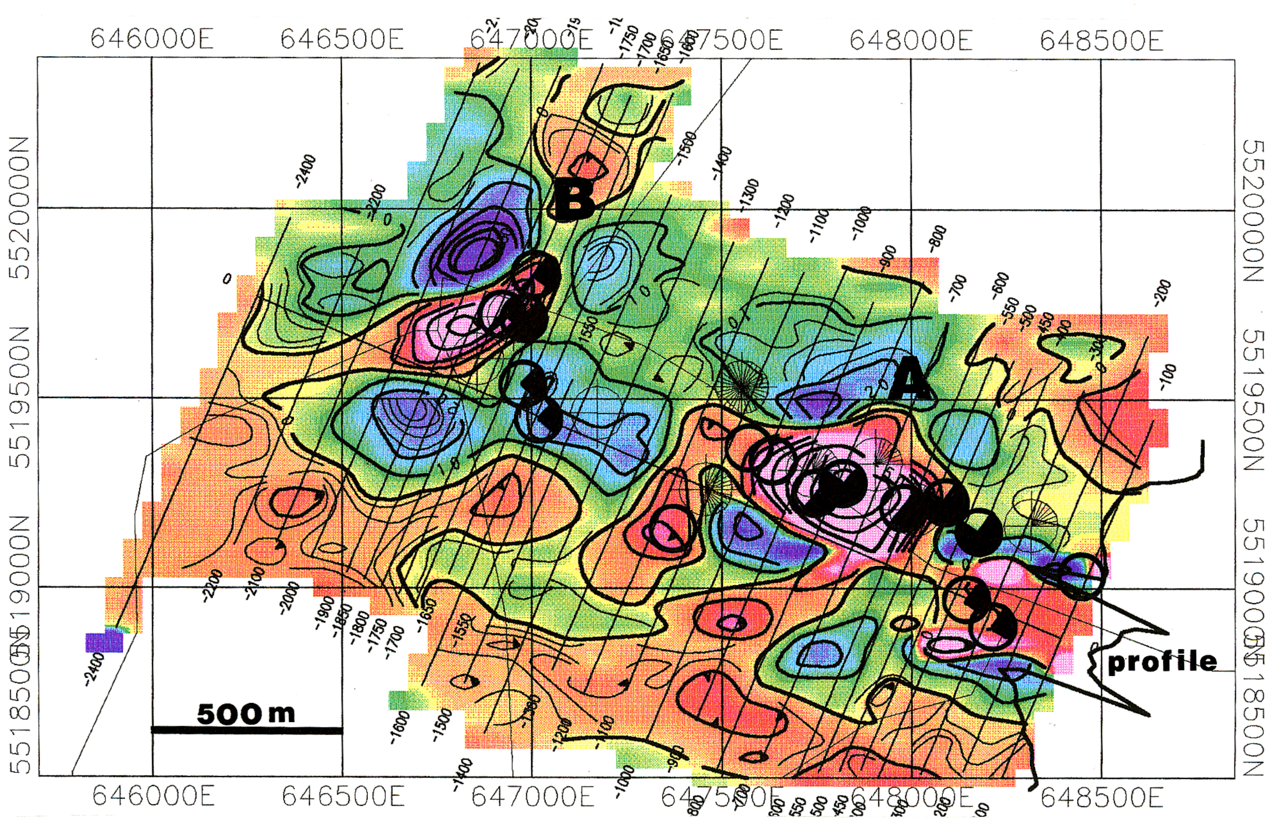

Figure 10: *Contours of the in-phase horizontal loop EM response, 250 m coil separation. Peak amplitudes on the A zone are near –40% of the primary field. Anomaly indicators are from the 1971 Input survey. Less distinct are the anomaly indicators from the 1979 Input survey.*

the A zone, a massive chalcopyrite vein (a relatively good conductor) centred at about 150 m north on the grid, is clearly described on the in-phase component. Similarly, the centre of the B zone from the base line to 400 N, which is predominately chalcopyrite, is well described. The quadrature describes a broad area of response over the A1 zone that describes most of the mineralized area as identified by the pit outline. There is an area of response low in the east side of the pit that will be described below. The B zone in the quadrature is narrow, showing the confined nature of the B zone mineralization. There is a linear event marked 1 on both the in-phase and quadrature responses, lying east-west azimuth. This identifies one of the structural trends in the ore body. The EM identifies narrow vein mineralization that is only hinted at on the IP response. Note response 1 lies parallel to the south end of the B zone. The grid east-west response 2 identifies an overburden trough that appears to be structurally controlled. The trough adds 30 m to the overburden depth along the line of the EM response. A grid north-south response along lines 11 and 12 west follows the line of a structurally controlled trough up to 80 m deep on the west side of the A1 zone.

There is a cultural artifact on both responses from line 100 W (-100 on the plot) to 500 W, along the baseline (0). This arises from a power cable on the surface, and shows as sharp bipolar responses 125 m on either side of the cable. The in-phase profile of this on line 100W is shown. A profile drawn on line 100 W (Figure 10) shows a typical line source response. The source is mid-way between the two bipolar peaks.

Profiles of the 125 m coil separation data are presented for line 800 W (Figure 12). These show two responses. The A response is over the core of the A zone, while the A′ response is on mineralization in the southern extension of the A zone. On both conductors, the quadrature response is larger than the in-phase response. The conductance from various coil separations and frequencies of the good central conductor in the A1 zone is low between 2 to 3 s. The discovery Input showed a similar low conductance of 6 s on the A zone anomaly (Reed 1981). Note that response from some of the vein sulphide mineralization surrounding the core conductor is present in the quadrature profile, but this is more evident on the response from the 250 m coil separation data (Figure 11).

The profile of dip angle VLF-EM response in Figure 12 shows clear crossover anomalies on the two conductors. These readings were taken using the Cutler transmitter. VLF coverage over the central main grid (not shown) did not improve the mapping of the ore zone conductors. The responses that are clear on this profile become lost on adjacent lines in responses arising from the irregularities in the overburden.

Comparison of the EM profiles with the resistivity section (Figure 9) which is plotted at the same 1:10 000 scale, shows the A anomaly directly on the 24 ohm-m resistivity, and the A′ anomaly at a resistivity contrast

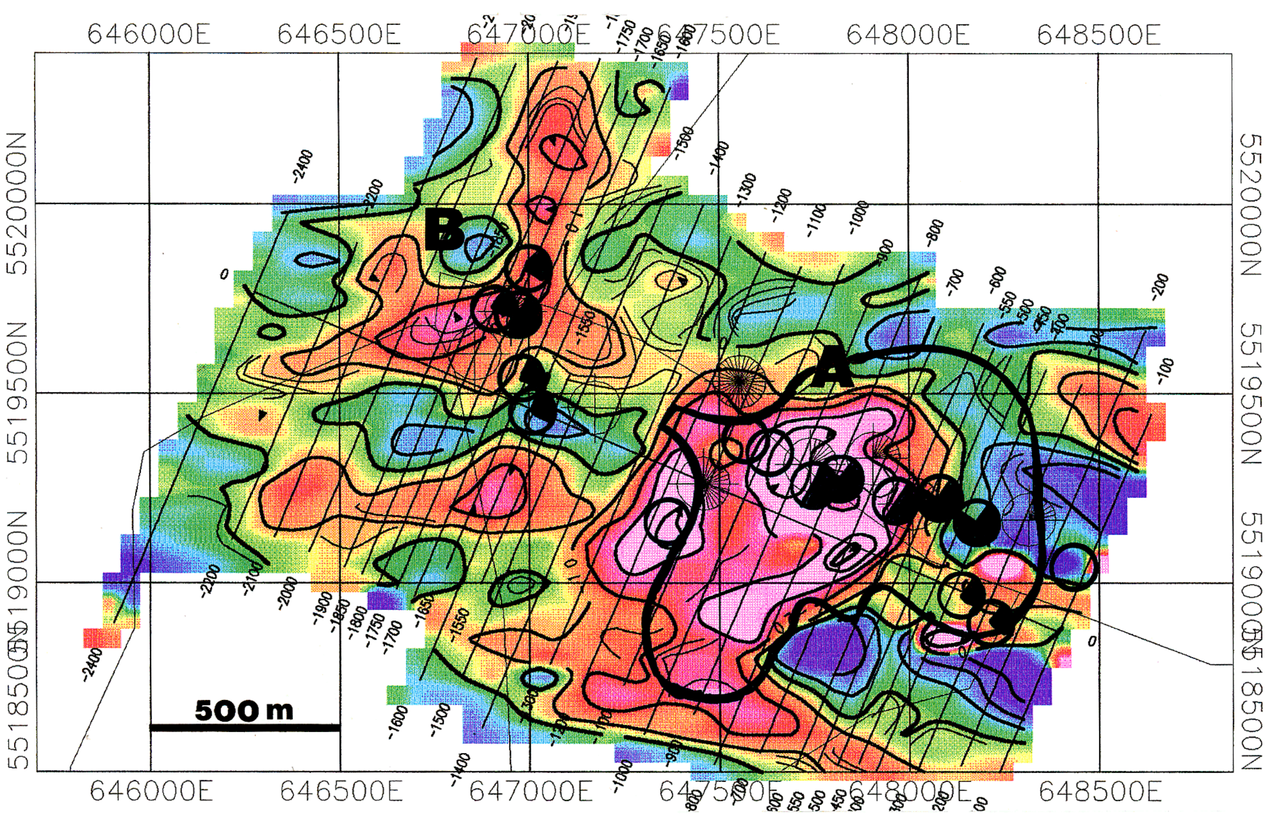

Figure 11: *Contours of the quadrature horizontal loop EM response, 250 m coil separation. Peak amplitudes on the A zone are over –40% of the primary field. The quadrature response well describes the weaker mineralization in the southern extension of the A zone, and shows the narrow width and changes in strike of the B zone.*

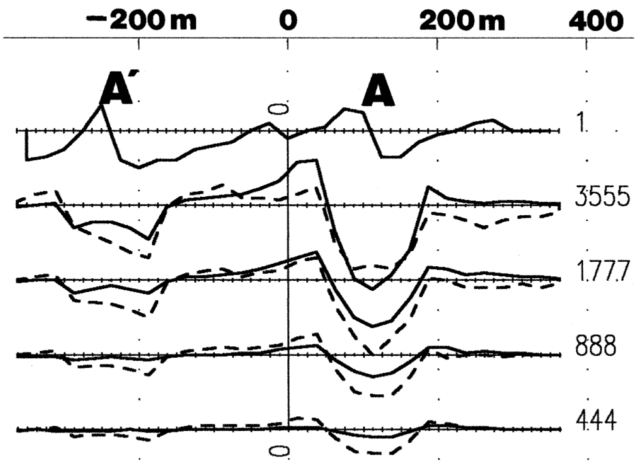

Figure 12: *VLF-EM from Cutler, Mane, dip angle profile (1) on line 800 W, 1 cm = 20°. Horizontal loop MAXMIN EM profiles for frequencies 444 Hz to 3555 Hz, scale 1 cm = 40%. The largest anomalies rise to 40% of the primary field. Anomalies A and A´ are the same as those on the resistivity section (Figure 9).*

rising from 400 to 800 ohm-m. The resistivities do not identify the A´ conductor as well as the EM response does.

Gravity

A gravity survey using a Lacoste gravimeter shows a significant anomaly of over 1.0 mGal over the A1 zone (Figure 13). The anomaly extends to the west along the feature seen in the IP connecting the A zone to the B zone, but there is no anomaly over the B zone. Early estimates of the ore body size from the gravity response suggested a body of 20 million tonnes.

Differences in overburden thickness have a considerable impact on the behaviour of the gravity response. The bedrock surface topography is very irregular, changing tens of metres in elevation over tens of metres in plan distance. The overburden thickness was as little as 2 m at the south edge of the A zone. The overburden thickness increases to 10 m or more toward the north on the A zone, but not in a regular fashion. There was a broad trough along the east side over the A2 zone, then a subcropping hill under the east edge of the pit. This trough is partly the cause of the termination of the A1 gravity high and a moderate low just east (*t1*) before rising gravity over the "hill". The troughs west of the A zone, (*t3*, which is as deep as 80 m) and south (*t2*, where the depth is 30 m), show as gravity lows. *t2* and *t3* were also seen on the horizontal loop EM

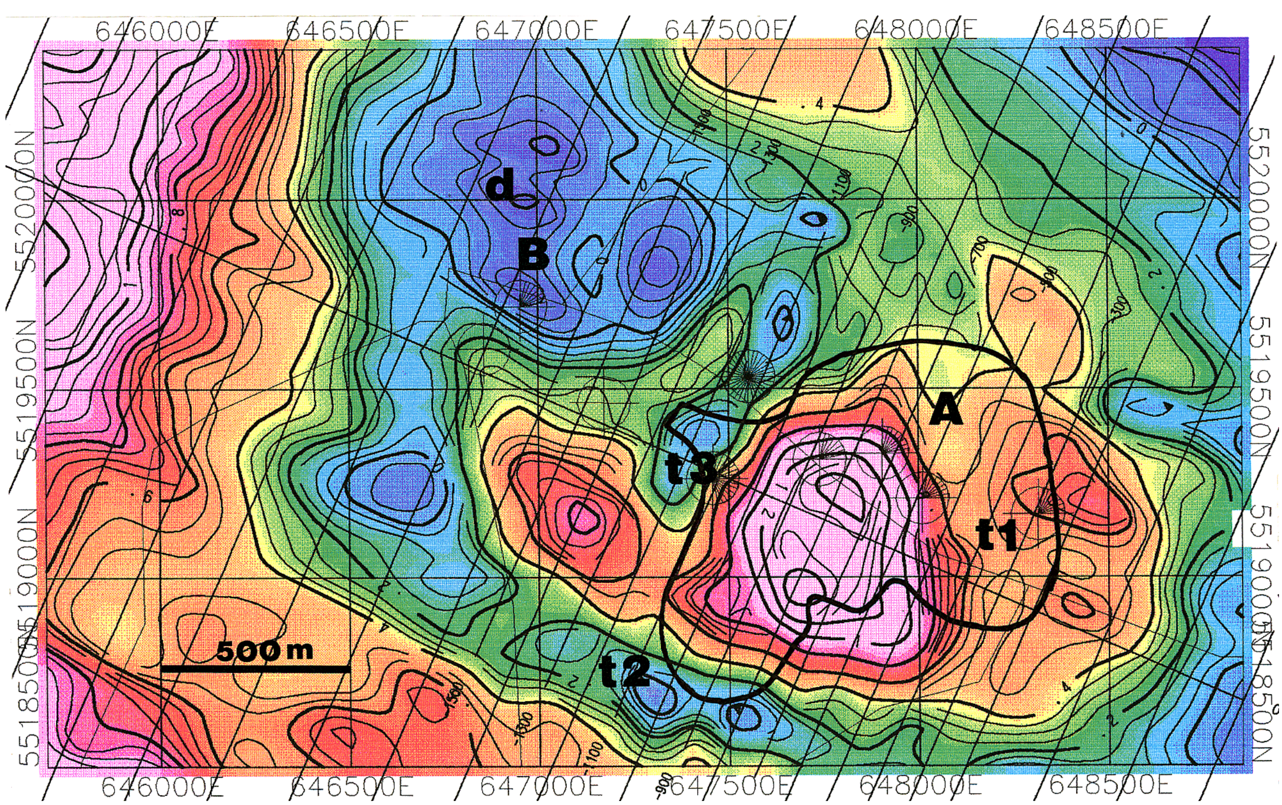

Figure 13: *Contours of Bouguer gravity. The peak amplitude on the A zone is 1.4 mGal out of a local background of 0.2 mGal. t1, t2, t3 and d, are gravity lows caused by depressions in the bedrock surface. The land surface on which the gravity readings were taken was essentially flat, so that all bedrock surface irregularities were filled with low density overburden.*

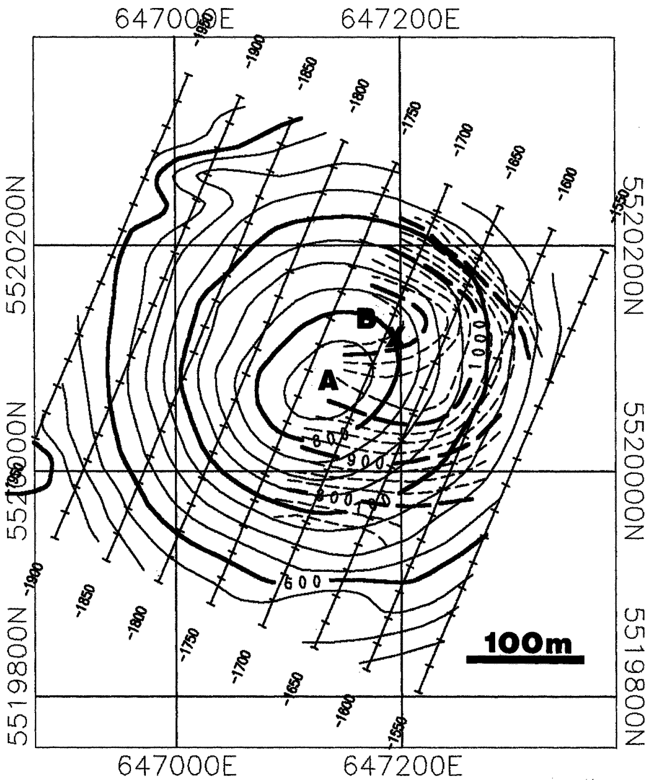

Figure 14: *Mise-à-la-masse in the pipe-like feature at the north end of the B zone. The current source is in a drill hole at X, 300 m below the surface.*

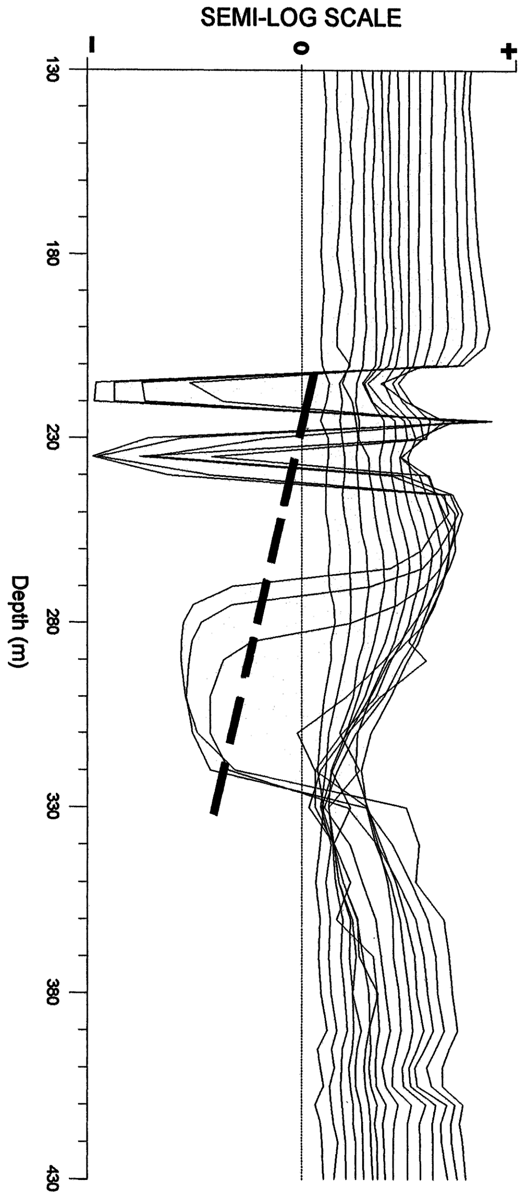

Figure 15: *Complex profiles from a borehole TDEM survey identifying a small irregular lens of sulphides in the south of the B zone. The dashed line represents an interpretation of the source body.*

responses (Figures 11 and 12). The broad gravity low over the B zone correlates with a region of deep overburden that is 45 m on top of the B zone and deepens in a broad depression *(d)* to 60 m further west. The B zone which has open faulting along its length, is neither big enough nor massive enough to overcome the effects of the deep overburden.

Mise-à-la-masse

Extensive mise-à-la-masse surveying in the early phases of the development of the ore body assisted in mapping the complex vein systems (Reed 1991; 1993). This assisted in ore tonnage estimates by identifying continuity or lack of continuity in the veins. The changing strike and lenses at right angles to the main B zone were identified by this method and new drill targets were identified.

The mise-à-la-masse process involved placing a current electrode in mineralization, with the other end of the current dipole at infinity (some distance away). Current was 1.0 A, or was normalized to 1.0 A. for plotting purposes where this fairly high current could not be achieved. Voltage readings on surface, down boreholes and underground were read as point measurements with the other end of the voltage dipole at effective infinity. The example presented here is from the north end of the B zone (Figure 14). Surface and borehole measurements using a single current source, show the movement of the peak voltages, as the body plunges to the north northeast. The centre of the response at surface (A) moves to B at 150 m. This body, known in the mine as "The Cigar", had a pipe-like shape, as the round surface voltages and the migrating peak with depth shows.

Borehole Time-Domain EM (TDEM)

Extensive use has been made of borehole TDEM to map ore lenses and search for ore missed by drilling. Many holes have been surveyed from surface and from underground. Crone Borehole PEM was used for this surveying. One discovery made from an off-hole source TDEM anomaly in the south end of the B zone, was of 400 000 tonnes of ore (Reed 1989).

The example shown here (Figure 15) is of a complex response also in the south lenses of the B zone. Sulphide veins were cut by the hole at about 230 m. The sulphide conductor continues down at a low angle to the line of the hole, and extends to about 330 m. Simultaneously with the borehole TDEM survey, an underground access drift on the 240 m level intersected these sulphides. Some ore was removed, but the lens was largely uneconomic.

GENERAL

The data presented here represent a sample of the geophysics done at Les Mines Selbaie. The general outline of the database has been shown, with some sense being given of the use and contribution these data have made. Considerable discussion could be done, simply comparing various aspects of the results presented here. It is hoped that the perceptive reader can do this on their own. Note how on the regional and on the detail site maps, magnetic, electromagnetic, gravity and electrical components both compliment and contrast each other. Note how different parts of the ore may be detected in different ways or not at all depending on the location and/or method (for example the difficulty of seeing the A2 zone with most methods, or seeing most parts of the A1 zone and non-ore components to the west with gravity, but not the B zone). The outline of the pit is a guide to relatively shallow ore, yet the north and east parts of the pit extend into mineralization seen only by one or two methods.

The early establishment of an extensive geophysical database has meant a lot to the continuing ability of the geophysics to contribute to exploration for and definition of ore on the site. Use has been made of 20-year-old data right up to the present time. In hindsight, a larger database should have been collected to provide even better definition of the broad distribution as well as variations in strike and tenor of mineralization on the site.

Where possible collection of new data has continued through the production period. Borehole TDEM contributed directly to finding ore, while the various seismic and physical properties measurements contributed to the general knowledge of the deposit, which have assisted with new thinking on exploring the deposit.

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