Magnetic Anomalies
Near Ore Bodies and Mineralized Zones
in the Troodos Ophiolite of Cyprus

by

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Abstract

The Troodos ophiolite in southwestern Cyprus has been a major producer of copper since the Bronze age. As such, the area has been studied and mapped extensively, and most known mineralized areas have been studied. Preliminary magnetic work with careful analysis and interpretation shows some promise of being able to characterize these areas.

Accordingly, a model is developed for the magnetic structure in the vicinity of massive sulfide ore bodies. The magnetic anomaly for this three dimensional model is calculated at several altitudes. 2.5 dimensional magnetic modelling is compared to actual survey data.

The results show that a typical anomaly consists of a northwest high coupled with a pronounced southeast low centered on the mineralized body. Total anomaly magnitudes measured at ground level are approximately one thousand gamma for a non-magnetic cylinder surrounded by rock with a magnetization of 10×10^{-4} emu/cm^3. The anomaly magnitudes are approximately an order of magnitude less at low-level aeromagnetic altitudes.

An attempt was made to apply these results to aeromagnetic data, which is available for most of the area of interest. Several major problems were encountered with this data. Explanations for these problems were investigated.

After examining the strengths and weaknesses of these methods, an attempt is made to identify promising areas for future magnetic work.

Acknowledgements

I wish to thank Dr. J.M. Hall for his ongoing discussion and suggestions, and for critically reading the rough draft of this report. Jing-sui Yang and Dr. P.J.C. Ryall contributed useful discussions. Mrs. S.L. Hall, Mair Hall and James Hall were essential partners in the collection of the field data. Finally, I would like to thank the Geological Survey Department of Cyprus and the people of Palekhori, Cyprus for their support during the field work.

Magnetic Anomalies Near Ore Bodies
and Mineralized Zones in the Troodos Ophiolite of Cyprus

Introduction

This study describes an examination of the nature and possible origins of magnetic anomalies near known and possible ore deposits. The region of interest lies in and near the outcrop area of the extrusive sequence of the Troodos ophiolite of Cyprus.

The study consists of two parts:

1. The modelling of anomalies associated with both idealized and known ore bodies to determine possible origins for these anomalies, and, consequently, reasonable forms for the ore bodies or associated mineralized zones.

2. The examination of magnetic anomalies in the area of known ore bodies and mineralized zones using the aeromagnetic maps published by the Cyprus Geological Survey and ground survey data as available.

It is anticipated that from the results of this study, the prediction of the location of other, previously unrecognized, mineralized zones may be possible.

Location

The island of Cyprus is located in the eastern end of the Mediterranean Sea approximately seventy kilometers south of Turkey (see figure 1).

The southwestern half of the island is dominated by the Troodos Mountains, consisting of

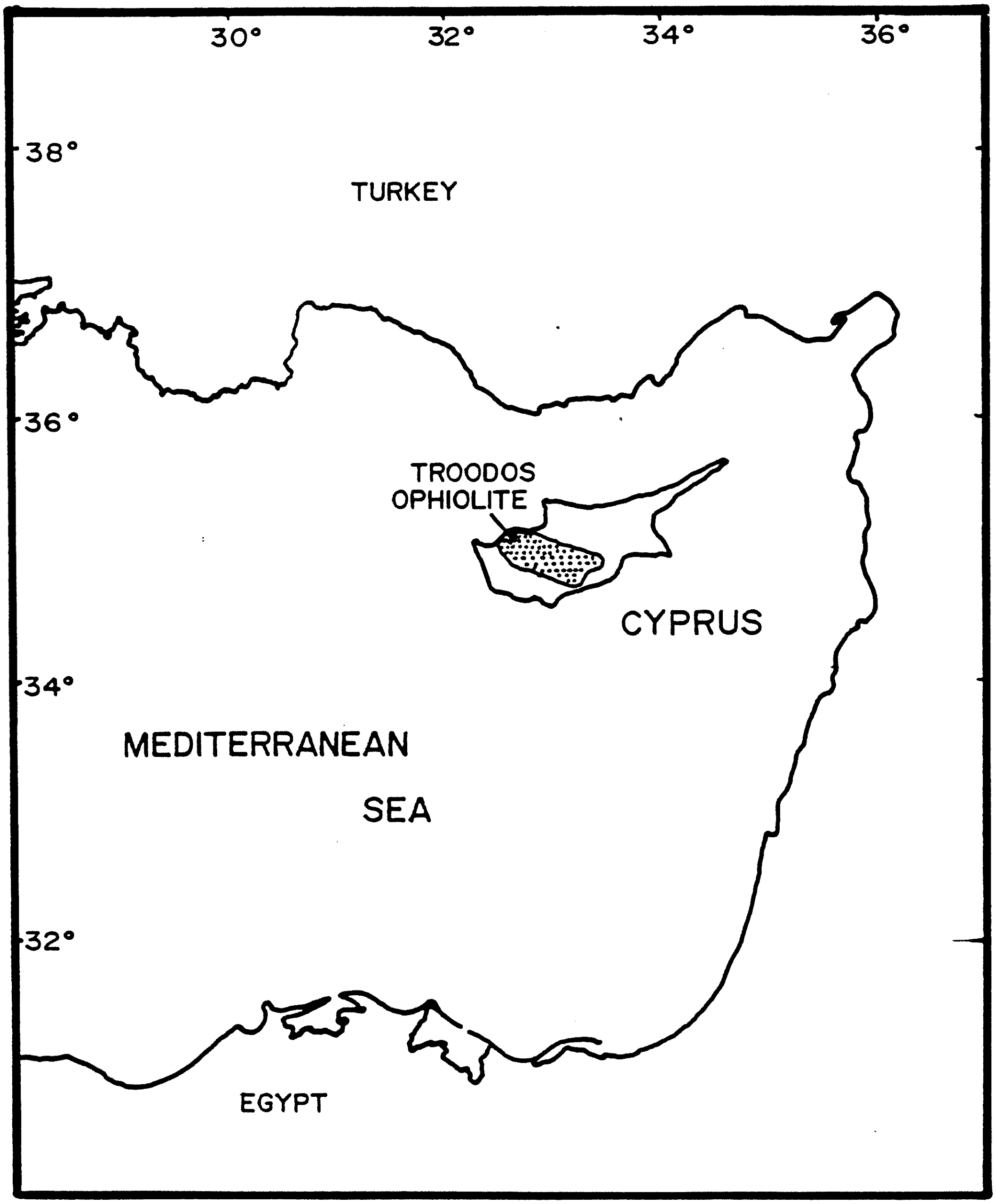


Figure 1. Location map showing Cyprus in the eastern Mediterranean.

a relatively intact piece of a type of oceanic crust (ie. an ophiolite). The ophiolite sequence is domed and eroded to expose the deeper units in a pattern of concentric ovals (see figure 2). Thus, as one moves up into the mountains from the north, oceanic sediments are first encountered, then pillow lavas and sheet flows of the extrusive sequence, then occasional dikes, grading into sheeted dikes. These give way to plutonic rocks thought to be typical of the deep oceanic crust and upper mantle. The southern flank of the ophiolite is cut by a large east-west trending transform fault and is generally less regular than the northern flank (Gass, 1980).

The Troodos ophiolite is interpreted as having been formed at some form of spreading ridge, with the direction of spreading now aligned roughly east-west (Robertson and Woodcock, 1980). The formation is approximately 85 ma in age and was rotated by about ninety degrees, deformed and emplaced comparatively recently (Shelton and Gass, 1980).

Exposure is best in river valleys and along road cuts, with much of the remaining area covered by overburden. Good roads provide access to most areas. Mine pits, road cuts and rivers give limited exposure to ore bodies and to mineralized zones.

Previous workers have divided the ophiolite into a series of geological mapping units (Ingram, 1959). The extrusive rocks are divided into the Upper Pillow Lavas and the Lower Pillow Lavas. The distinction between the two units is not always clear in the field. Both units consist of both pillow lavas and sheet flows. The Upper Pillow Lavas are usually identified by being free of intrusive material, where the Lower Pillow Lavas are commonly cut by a few dikes. The Lower Pillow Lavas are the more magnetic unit, with typical values of $\sim 70 \times 10^{-4}$ emu/cm^3, compared to typical values of $\sim 10 \times 10^{-4}$ emu/cm^3 for the Upper Pillow Lavas (Vine

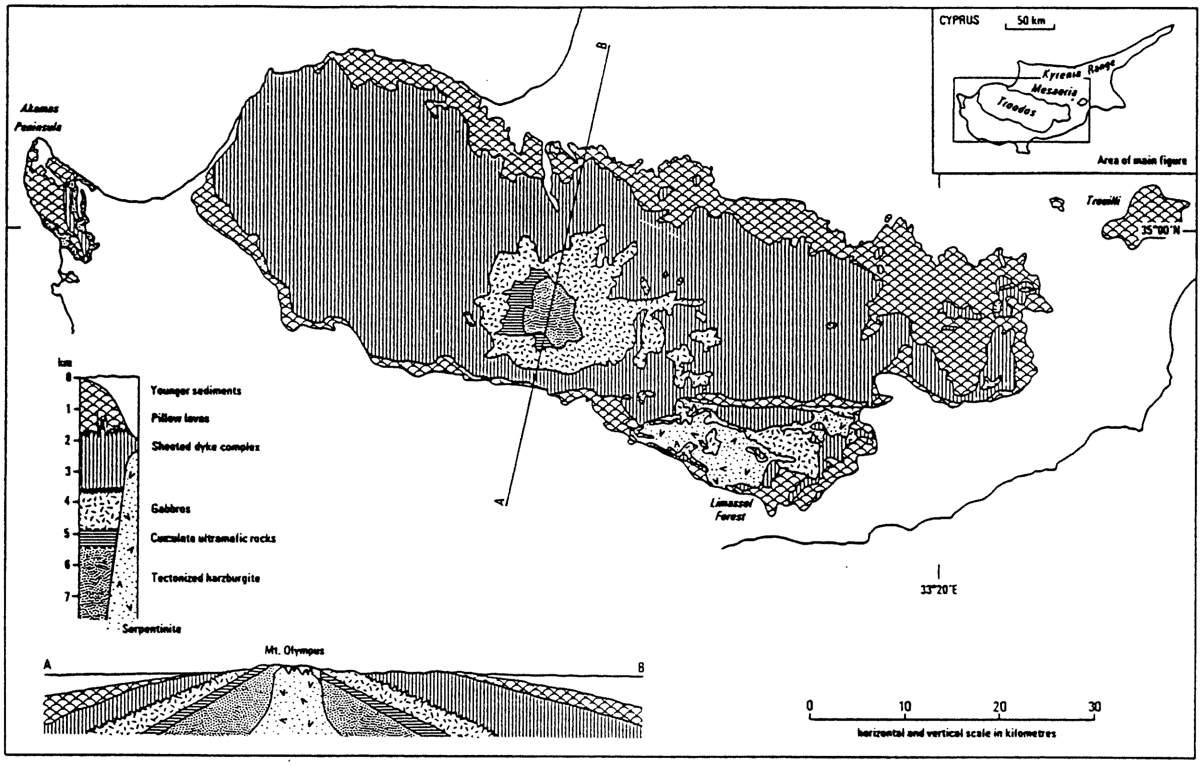


Figure 2. The geology of the Troodos ophiolite, from Gass, 1980.

et al., 1973).

The Basal Group is found immediately beneath the extrusive units. It consists of a varying percentage of dikes, intermingled with pillowed and sheet flow screens. There is a gradational contact with the overlying extrusive.

The Basal Group grades downward into the Sheeted Complex, which is defined as being one hundred per cent dikes. The two units are often most easily distinguished in the field by their weathering characteristics, as the dikes are harder and more indurated in the lowest part of the Basal Group and the Sheeted Complex. A typical magnetization value for the Troodos dikes is 7.6 x 10^{-4} emu/cm^3 (Vine et al., 1973).

The deepest rocks in the Troodos sequence consist of a suite of ultrabasic rocks exposed at the top of Mount Olympus, the highest topographic point in the ophiolite. They form a dome approximately eight kilometers in diameter. Between the ultrabasic suite and the Sheeted Complex is a sequence of gabbros. They are exposed in a continuous belt surrounding the central dome and are related to the base of the Sheeted Complex in a variety of ways. Both the ultrabasic suite and the gabbros have generally low magnetizations, with extremely high values only where the rocks are locally serpentinized.

Mineralization in the Troodos Ophiolite

Four types of ore deposits are commonly found in the Troodos ophiolite: chrysotile asbestos, podiform chromite deposits, small Fe-Cu-Co-Ni sulphide deposits, and massive volcanic hosted Cu-Zn-Fe sulfide deposits. The first two occur exclusively in the deeper plutonic rocks, while the third occurs in small veins throughout the deep to middle sections of the ophiolite.

The massive sulphide deposits, which are commercially valuable and form the subject of this report, are found exclusively in the extrusive sequence.

The chief constituents of the massive sulphide ores are sulphur, iron, copper, and zinc, found consistently in all of the major mining areas. These deposits overly deep stockwork zones enriched in similar minerals at less than commercial levels (Constantinou, 1980).

The island of Cyprus has been a major producer of copper since the Bronze Age, and was famous in antiquity for its exports of this metal. This activity has continued throughout recorded history with many fallow periods. Production of copper recommenced most recently in 1927, and continued in a major way until the 1960's (Adamides, 1980). At this time, a decline in the industry occurred, mainly due to a depletion of known reserves. Presently, production only occurs in small quantities from several existing mines.

The ore bodies are accepted as examples of hydrothermally formed, deep sea mineral deposits. They were formed by precipitation of minerals at or near the sea floor from fluids enriched by circulation in large hydrothermal convection cells. The stockworks represent the path of the upward movement, under buoyancy forces, of high temperature hydrothermal fluids towards the sea floor. Similar systems are known to be widespread at active ridges in the deep oceans (Lydon, 1985).

More numerous than actual ore bodies are scattered mineralized zones which, while showing evidence of hydrothermal circulation, are not sufficiently rich in minerals to be ore deposits. These may in some instances represent the stockworks of ore deposits now removed by erosion. They typically occur at the surface as yellow-coloured, oxidized mineralized zones known as gossans. The location of known ore bodies and mineralized zones is shown in figure

3.

Previous Work

The Troodos mountains were recognized as an uplifted piece of ocean crust even before the term ophiolite was used to represent such associations. The geology of the island was mapped and described in some detail in the 1950's and 1960's by the Cyprus Geological Survey Department. The results of this work are summarized in a set of 1:31,680 geological maps and accompanying memoirs. Some geophysical work was also conducted during this period and a set of aeromagnetic and electromagnetic maps was published (Hunting Geology and Geophysics Ltd., 1969).

As the understanding of the oceanic nature of ophiolites increased, the Troodos was adopted informally as one of the standards for such sequences, largely due to its completeness and lack of major post-constructional deformation. The theory of plate tectonics, as it developed during the 1960's and 1970's, increased the already considerable interest in the island as a place to study different features of the ocean crust.

This period of interest culminated in the early 1980's with the Cyprus Crustal Studies Project, which was responsible for the drilling of five research drill holes in the ophiolite, and was accompanied by major field studies. The field work confirmed or corrected many features of the original mapping, which was conducted before the geology of the ocean crust was generally known.

Hall et al. (in press - a) have recognized and quantified the cyclical spacial occurrence of massive Cu-Zn-Fe sulfide ore bodies and mineralized zones in the extrusive sequence of the

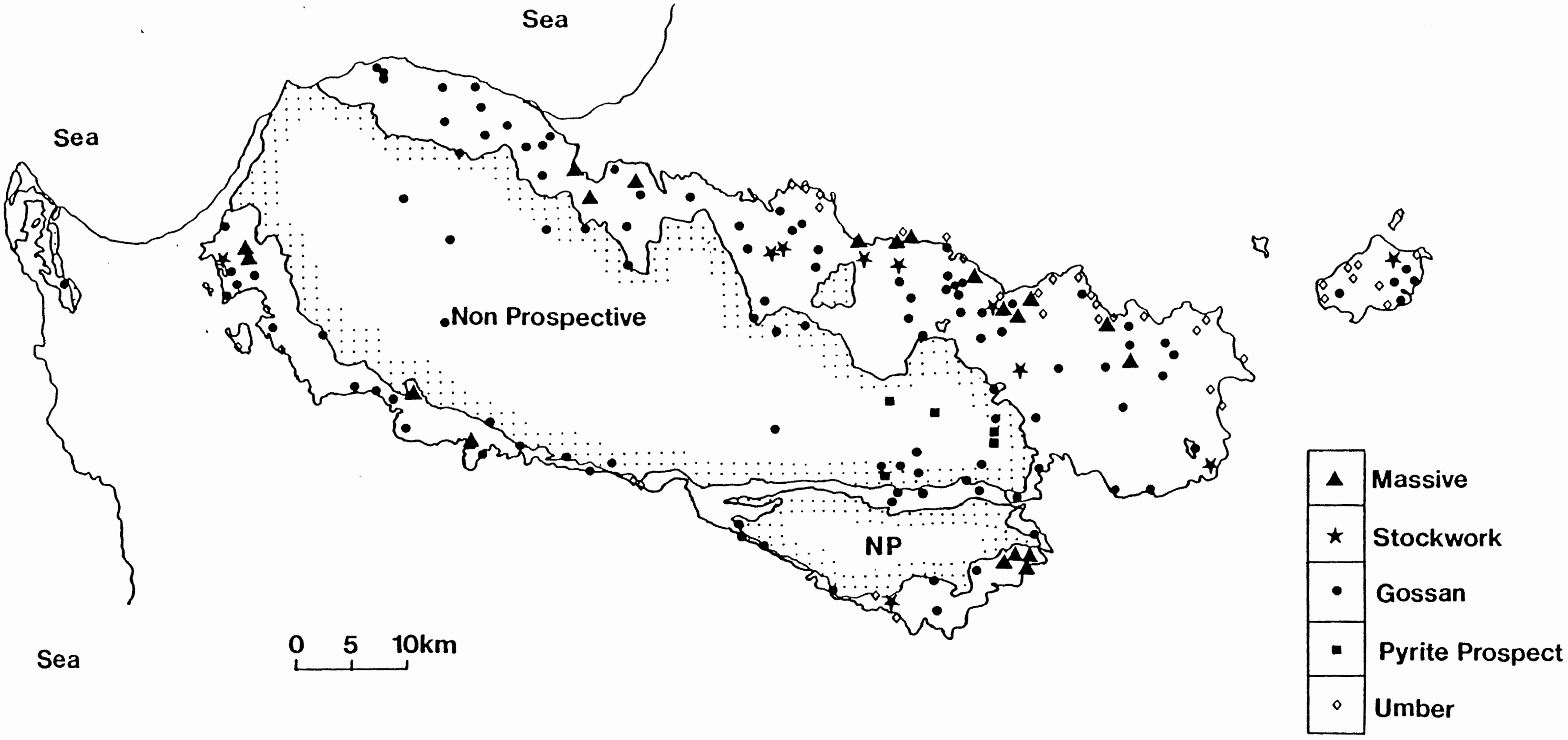


Figure 3. Sulfide mineral occurrences in the Troodos, from Hall et al., in preparation.

ophiolite. They have also demonstrated a conjunction between the mineral occurrences and a regular variation in the thickness of the extrusive units. A model outlined in this paper demonstrates the grouping of ore bodies in prospective zones characterized by several features: the proximity to the original surface of the dikes of the Sheeted Complex, an increase in the concentration of dikes and sills, the occurrence of numerous gossans, the presence of umber and topographic depressions in the surface of the volcanics (figure 4).

Very recent work indicates that ore bodies tend to occur at the level in the extrusive sequence where the rocks are composed of twenty five per cent dikes (Yang, personal communication). The search for further economic ore bodies may be restricted and simplified by these results and further rapid methods of exploration are desirable to pinpoint the most promising targets within prospective zones.

One possible method to pinpoint previously unknown bodies is magnetics. The basis for this approach is that the hydrothermal circulation associated with the ore body formation might cause a characteristic reduction of magnetization as a result of the replacement of magnetite by sulfides. Encouraging evidence in favour of this was given in a survey of the Agrokipia mine site described in Johnson et al. (1982).

Small scale magnetic and electromagnetic surveys were conducted in the summer of 1987 across mineralized zones and old mines. Examples of the results are summarized in figure 5. The most obvious conclusion from these profiles is that distinct negative magnetic anomalies are associated with these sites, as at the Agrokipia site. Further work is required to more carefully differentiate the anomalies from the surrounding noise.

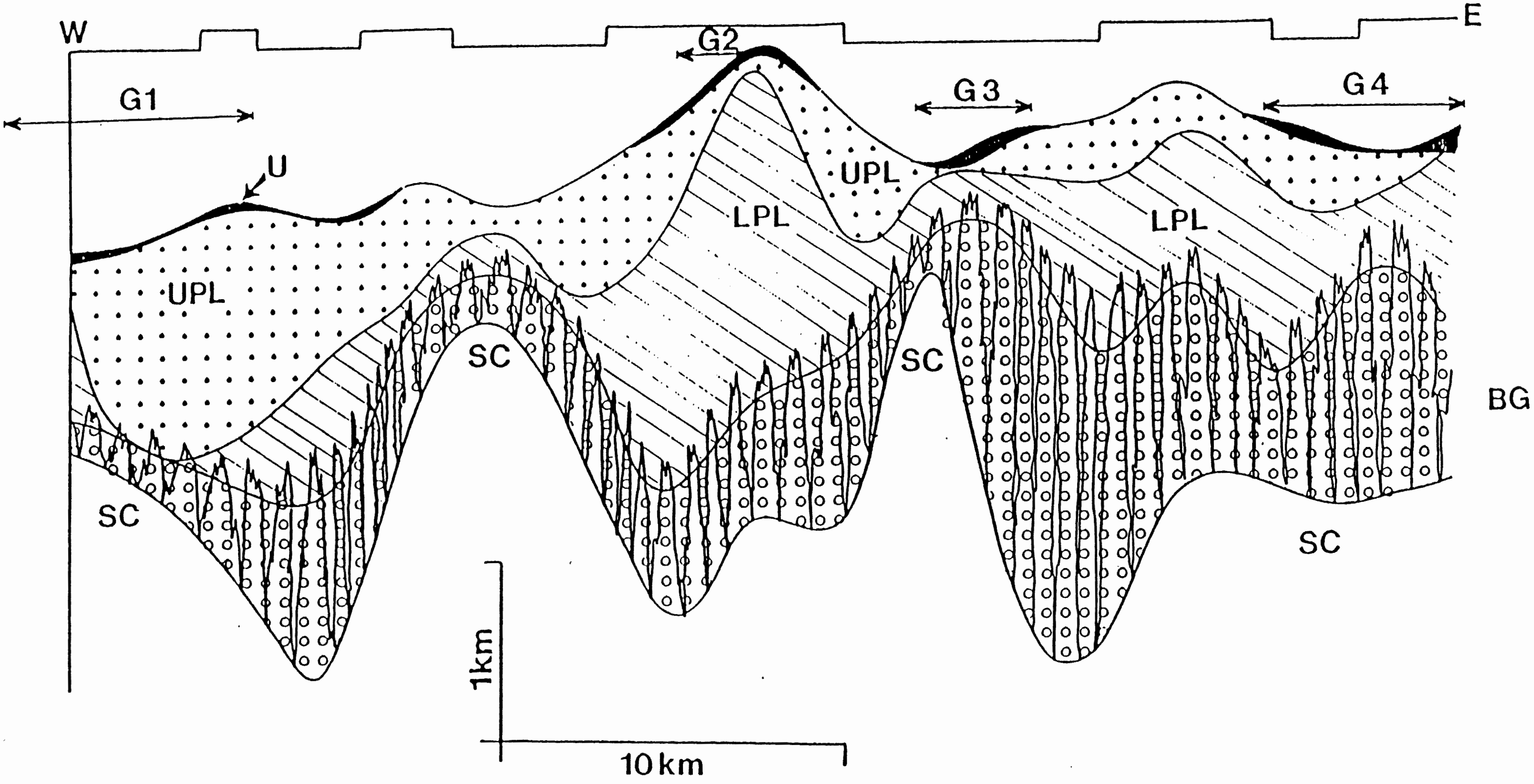


Figure 4. Regular variation of the thickness of upper units in the Troodos ophiolite, and associated features, from Hall et al., in press.

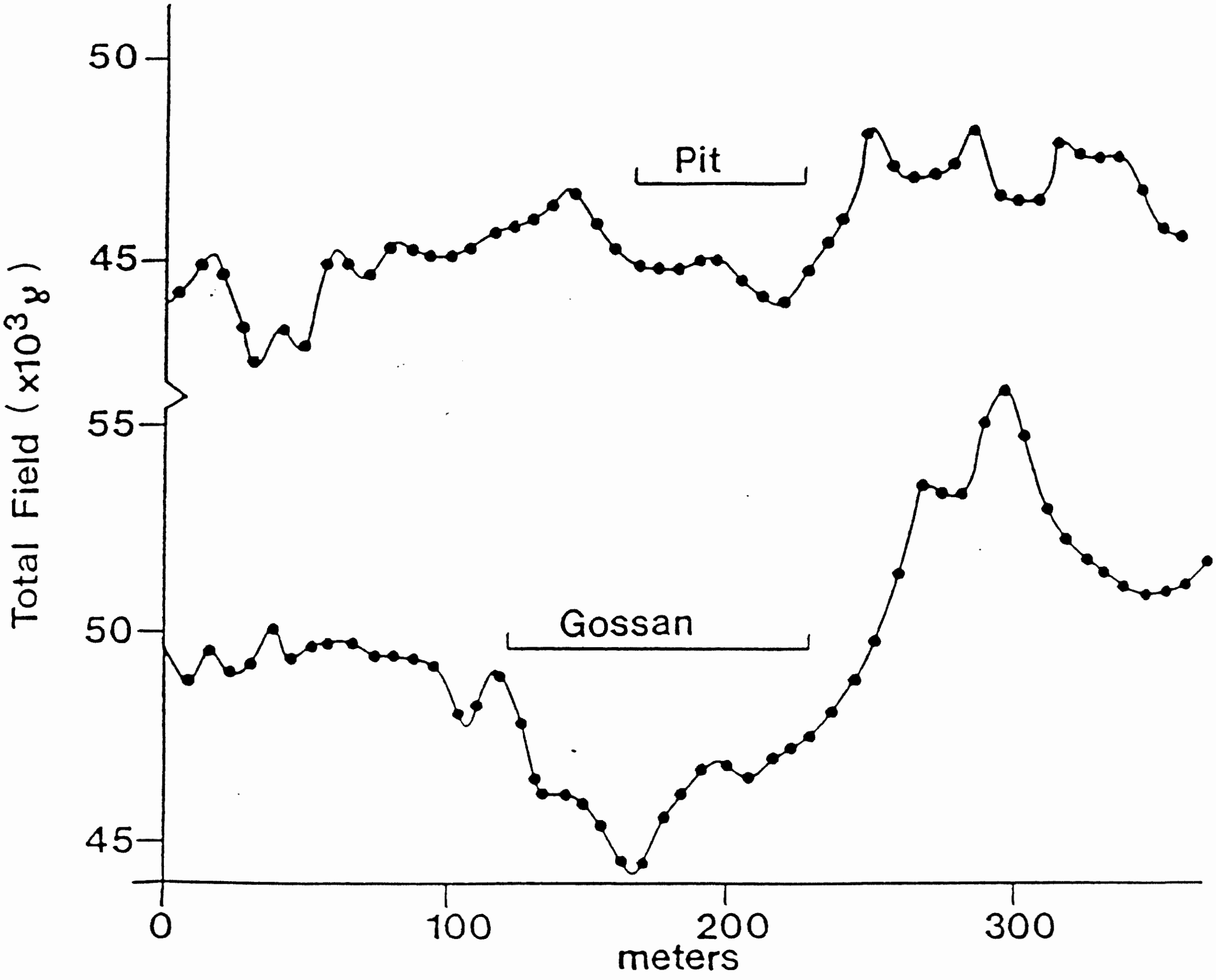


Figure 5. The magnetic field as measured across a mine pit and a gossan on the northern flank of the Troodos ophiolite.

Summary of the Aims of the Present Work

The aim of this work is to investigate the potential for the identification of previously unknown ore bodies and mineralized zones by careful, computer assisted analysis of magnetic survey data.

The work is presented in the following sequence:

1. Computer modelling of the magnetic anomalies associated with reasonable shapes for ore bodies and stockworks to identify the most likely forms of magnetic anomalies,
2. Interpretation by computer modelling of magnetic survey data from mines and mineralized areas in Cyprus,
3. Extension of these results to allow comparison with the aeromagnetic data, for which there is extensive coverage of the ophiolite, and
4. Application of the results to parts of prospective areas in which no ore bodies are known.

EXPERIMENTAL PLAN

The overall objective of this work is to determine if massive sulfide ore bodies can be identified by their characteristic magnetic anomalies, or by the anomalies related to associated structures. In order to proceed with this task, we must first identify a reasonable general form for the ore bodies and their peculiar surrounds within the magnetic structure of the Troodos ophiolite. Only then will it be possible to generate models, refine them and apply their results to the search for as yet undiscovered ore bodies.

Firstly, we need to review the magnetic structure of the Troodos ophiolite. The geological structure consists, as noted earlier, of pillowed and sheet flows, grading into sheeted dikes, which in turn grade into plutonic rocks. As indicated by the results of the Cyprus Crustal Study Project (Auerbach and Bleil, 1987, Hall et al., in press -b), which are consistent with earlier work (Vine et al., 1973), the most intensely magnetized rocks are concentrated in the upper layer (ie the Upper and Lower Pillow Lavas) and in the serpentinized ultramafics. The Basal Group and Sheeted Complex show a marked drop in magnetism. The serpentinized rocks do not occur in the vicinity of ore bodies and so are not considered in this study. The Konigsberger ratio, the ratio of remanent magnetization to magnetization due to susceptibility, is also high (predominantly >10) for this upper section. Figure 6 shows the distribution of these magnetic parameters in the CY-2a drill core. A similar situation, that of a sharp decrease in the magnetization at depth, occurs in the CY-1 and CY-1a drill cores. Thus, we

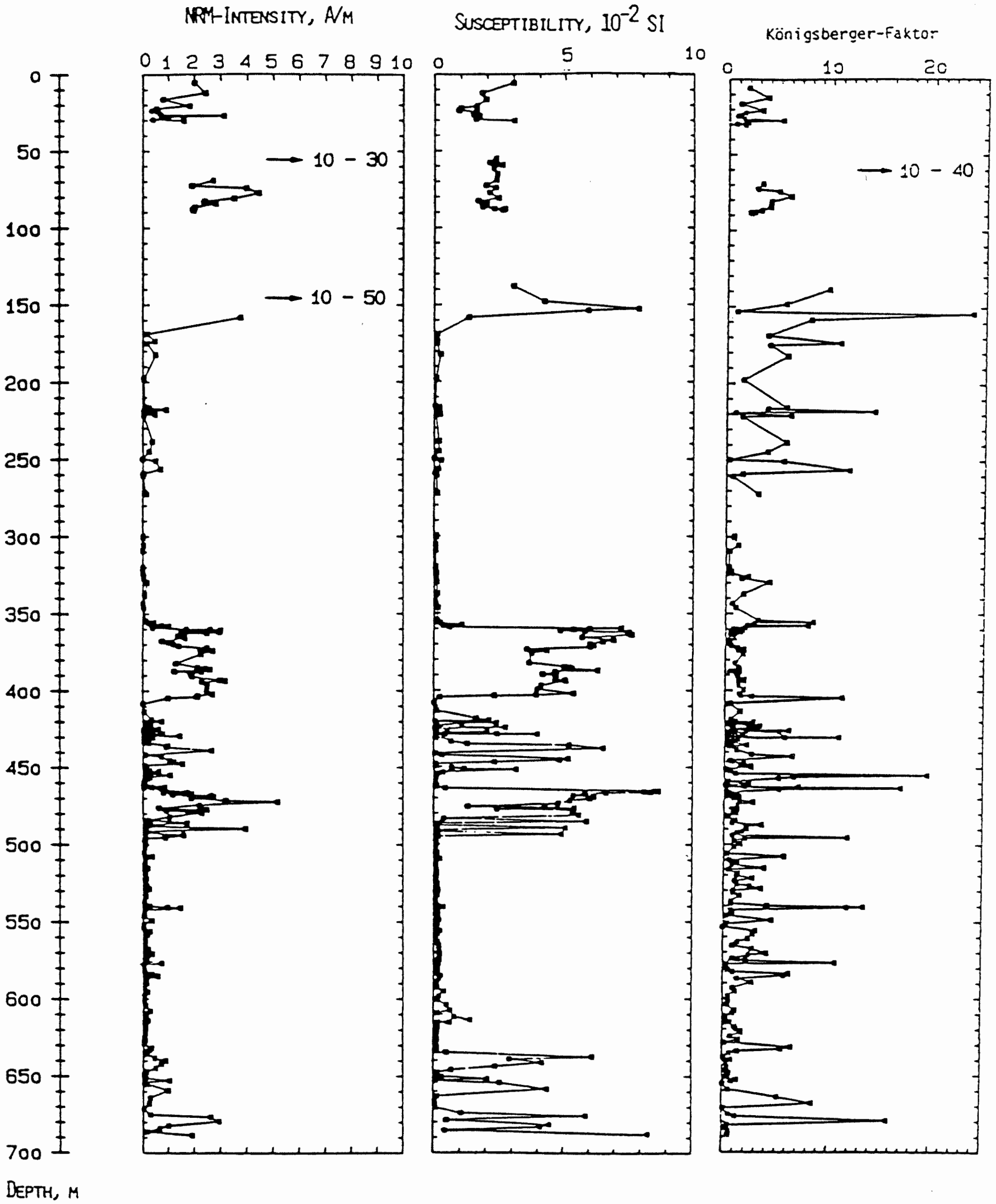


Figure 6. The variation of natural remanent magnetization (NRM-Intensity), susceptibility (K) and Q (Konigsberger Ratio) with depth in the CY-2a drillcore, combined from Auerbach and Bleil, 1987 and Auerbach, 1984.

may conclude that the place to look for the sources of most of the magnetic anomalies will be in the upper extrusive layer of the ophiolite. The effects of contacts within this layer, and contacts between this layer and others, will be exaggerated in surveys taken at lower altitudes due to the very close proximity of the magnetic material.

Secondly, what general assumptions may we make about the shape of a massive sulfide orebody and the surrounding alteration zone? Limited data is available on this, mostly derived from mine surveys (Bear, 1963, Constantinou, 1980). A typical structure consists of massive sulfide, underlain by disseminated sulfide, grading into stockwork which may be rooted in the Sheeted Complex (see figure 7). It is significant that the edges of the mineralized zones are fairly sharp, with little indication of the presence of the ore body in the surrounding country rock (Hall, personal communication).

All of the rock types which make up the ore body and mineralized zone are essentially non-magnetic. Typical magnetizations are much less than ten emu/cm^3, as opposed to the extrusive magnetizations of greater than one hundred emu/cm^3 Auerbach and Bleil, 1987).

Thus a reasonable, simplified model shape for an ore body is that of a vertical non-magnetic cylinder surrounded by strongly magnetic country rock to a depth of several hundred meters (ie. a magnetic "hole"), then dissipating at depth into rock of uniformly low magnetization (see figure 8). It is, of course, unrealistic to assume that the real orebody and stockwork will form a perfect cylinder, or that this will be perfectly vertical. This model will however allow us to predict a general type of anomaly, which real situations may resemble.

The assumption of a magnetic "hole" model is supported by preliminary analysis of field data collected in Cyprus (see figure 5). Orebodies are immediately associated with a significant

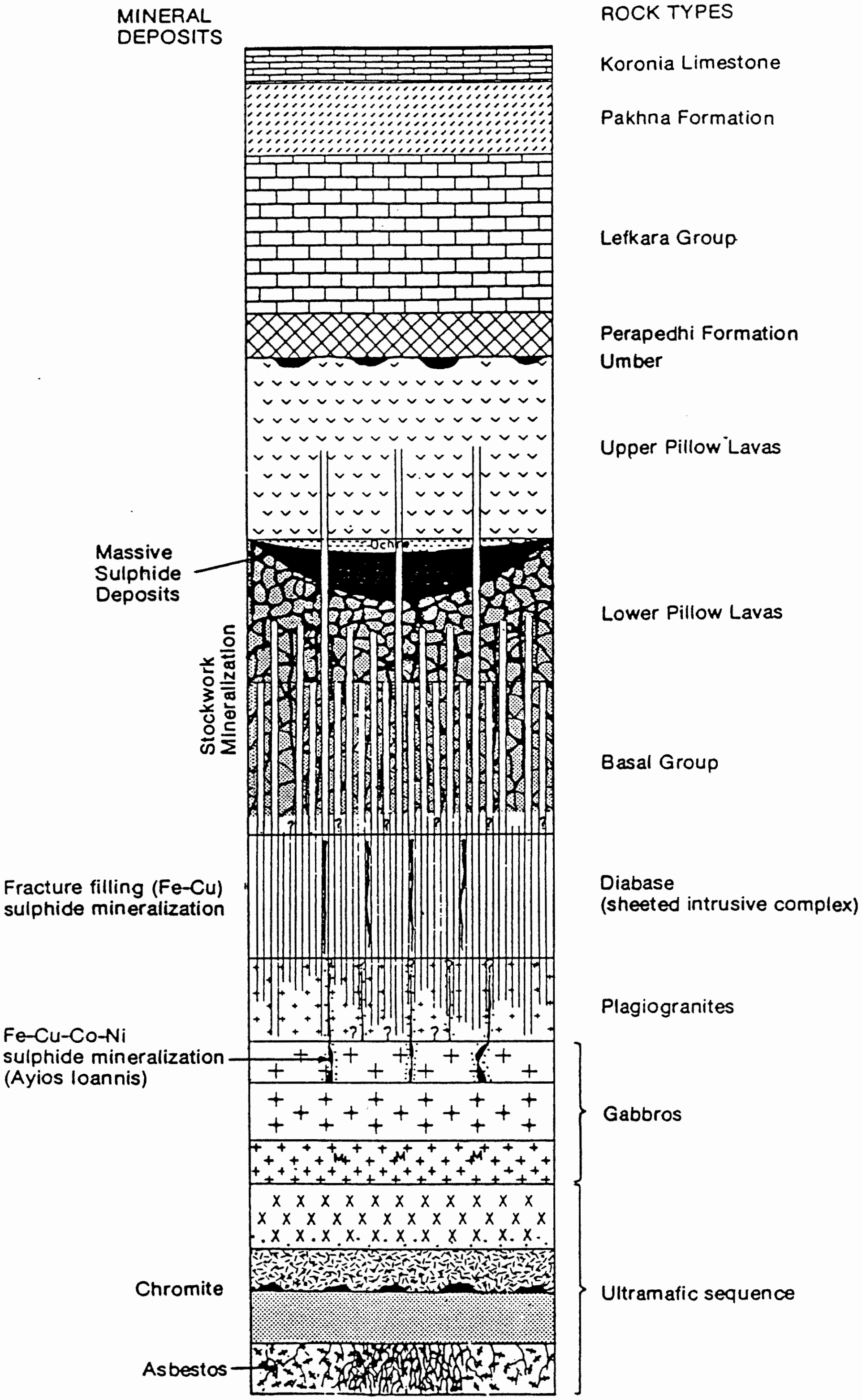


Figure 7. The general structure of massive sulfide ore deposits in the Troodos ophiolite, from Constantinou, 1980.

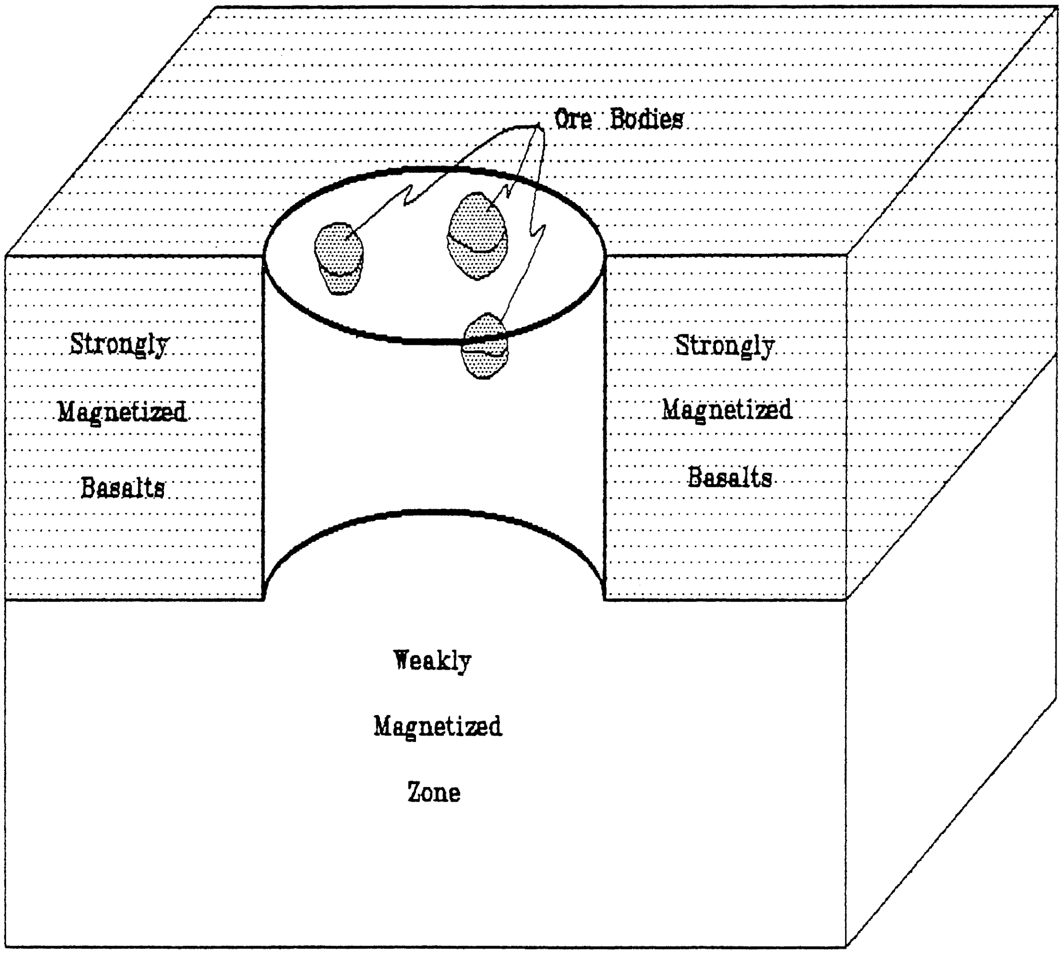


Figure 8. Proposed model for the magnetic structure around Cyprus ore deposits.

magnetic low, suggesting a local absence of subsurface magnetization. These ground profiles will be considered later in more detail.

Proceeding from this general model shape, computer modelling was conducted to generate a typical anomaly for this distribution of magnetization. Three dimensional mesh plots and contour diagrams of the magnetic anomaly associated with holes of different sizes and shapes were compiled for a range of measurement altitudes. The results of this work are summarized in chapter three.

These results were confirmed by constructing principal profiles through these anomalies and modelling them with a 2.5 dimensional modelling program. This method allows more detailed analysis given the limitations of computing equipment and programs.

At this point it was useful to apply the results to real data. Profiles taken from the contour maps of H.P.Johnson (Johnson et al., 1982), and others measured in the field during 1987 were analyzed using the 2.5 dimensional modelling program. This again confirmed the general validity of the model, and suggested variations found in the real geology.

At this stage it was possible draw conclusions as to the value of the model and its associated typical anomaly and to set limitations on how it may be applied to other data, specifically that contained in the aeromagnetic maps. Accordingly, the anomalies for the models were recalculated for a series of higher altitudes, the maximum being that at which the aeromagnetic survey was flown.

The good spatial coverage of the aeromagnetic data invited the search for anomalies of the expected type. Problems associated with this data were identified, and areas of known mineralization examined to evaluate the validity and consistency of predictions from the model work.

The conclusions of this thesis will be drawn from the above analysis. Key questions to be answered are:

1. Is there a typical anomaly associated with known ore bodies?
2. How consistent is the anomaly from body to body?
3. What kind of data and analysis is necessary to isolate such anomalies from other anomalies recorded in the aeromagnetic data?
4. What areas are most promising for further magnetic surveys or analysis of existing magnetic data?

MAGNETIC MODELLING

Modelling of a reasonable magnetic structure for an orebody and its hydrothermally altered surrounds was conducted using computer programs for both three and 2.5 dimensional situations. Both forward and inverse modelling was conducted. Forward modelling calculates the anomaly for a specified distribution of magnetization. Inverse modelling defines, for set constraints, the distribution of magnetization consistent with an observed anomaly. The three dimensional program, due to the length of time required for computation and display of results, was used only for forward modelling. The 2.5 dimensional program was used in both directions, first to confirm the results of the three dimensional work, then to analyze actual field data. It is referred to as a "2.5" dimensional program, as it allows the user to specify the strike length of the model as well as the shape in a vertical plane.

Three Dimensional Modelling

The program used was based on that developed by Vine (1965). The method is described as a special case of that used by Talwani (1965), on which the explanation below is based. Minor modifications were made to conform to the type of computer equipment and software used. The results were displayed using programs developed at McGill University (Crossley, 1988).

Given the situation in figure 9a, the magnetic potential Ω measured at a point O from a

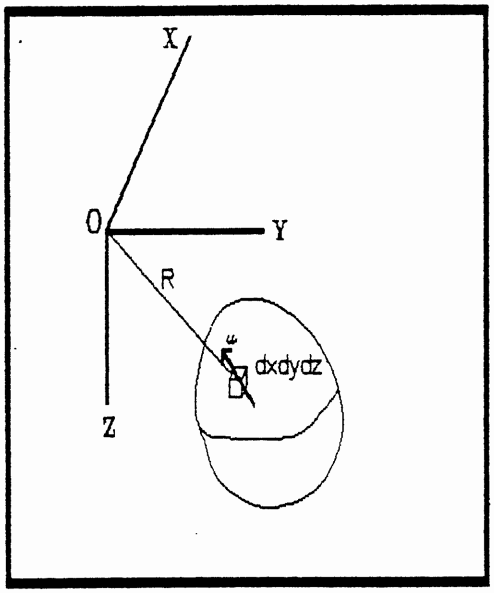
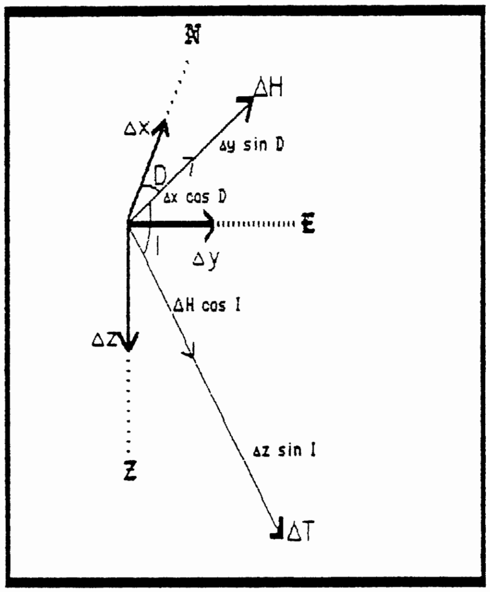


Figure 9a. The magnetic field at 0 from volume element dxdydz.

Figure 9b. Vectors ΔX, ΔY and ΔZ related to the total field anomaly ΔT by the declination, D and the inclination, I. ΔH is the horizontal component of ΔT.



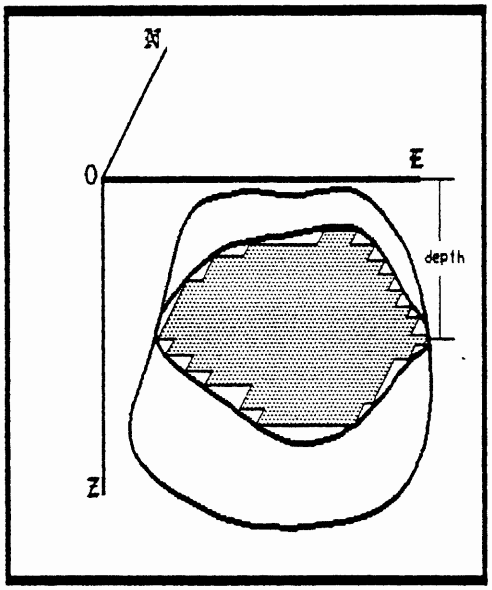


Figure 9c. Method used by Vine, 1965 to define a model using horizontal laminae approximated by rectangles.

volume element dxdydz at a distance R in a body V will be

$$\Omega = \frac{\mu \cdot \mathbf{R}}{R^3}$$

where μ is the magnetic moment of the volume element. As rock magnetization is specified in terms of J, the intensity of magnetization, this may be related by the equation

$$\mu = J\,dx\,dy\,dz$$

The three components of the anomaly created at O by the body V will be

$$\Delta X = \iiint_v \frac{\partial \Omega}{\partial x}\,dx\,dy\,dz$$

$$\Delta Y = \iiint_v \frac{\partial \Omega}{\partial y}\,dx\,dy\,dz$$

and

$$\Delta Z = \iiint_v \frac{\partial \Omega}{\partial z}\,dx\,dy\,dz$$

integrated over the entire volume of V.

The measured anomaly in the total field will depend on the direction of the earth's magnetic field, specified by the declination D and the inclination I. This measured anomaly is related to ΔX, ΔY and ΔZ by the equation

$$\Delta T = \Delta X \cos D \ \cos I + \Delta Y \sin D \ \cos I + \Delta Z \sin I$$

assuming the magnitude of the earth's field is large compared to the size of the anomaly and thus no appreciable distortion of direction occurs. This relationship is shown in figure 9b.

It can be shown that the total field anomaly can be expressed in terms of the intensity of magnetization J

$$\Delta T = J_x f_1 + J_y f_2 + J_z f_3$$

where J_x, J_y and J_z are the components of the intensity of magnetization of the body and f_1, f_2 and f_3 are functions evaluated for each observation point. Simply expressed, f1, f2 and f3 are the x, y and z components respectively of the total field anomaly calculated at a given point for a body of specified shape and unit magnetization in the specified earth's magnetic field. They are calculated by integrating over the volume of the body. This can be performed by any combination of numerical or analytic integration with the analytic integration being more accurate but in many cases excessively lengthy. The body on which the integration is to be performed is specified in such a manner as to simplify this as much as possible.

Vine has chosen to specify the body as a stack of horizontal laminae. The volume integration is performed by integrating analytically over the surface of each laminae, and then integrating vertically by a numerical method to give f_1, f_2 and f_3 for each observation point.

The program was originally designed for modelling magnetic anomalies arising from seamounts. A model of the structure is constructed by specifying depth contour levels (corresponding to laminae) approximated by rectangles (figure 9c). While more modern programs have been written, they contain substantially the same calculations (Plouffe, 1975).

This program was expedient in terms of its simplicity, and the consequent speed of computation and ease of modification, and as it was ready to hand. However, the program did exhibit several weaknesses. Firstly, the required method of entering the model coordinates, being designed for seamounts, was therefore awkward for specifying a magnetic hole. Also, only one magnetization vector can be entered for the model. Knowledge of the magnetization of the Troodos lavas, based on a large number of samples, (Vine et al., 1973, Clube et al., 1985) suggests that a single vector, with a normal inclination and a westerly declination, is appropriate. Accordingly, approximate values of 280 degrees declination and forty degrees inclination were used throughout this study.

A more serious problem concerned the relationship between the absolute units of input magnetization and output anomalous field. The program required both of these quantities to be specified in gammas. This is the normal unit for anomaly measurements but is not usual for the intensity of magnetization. More commonly, emu/cm^3 or amperes/meter are used. This uncertainty was overcome by confirming the three dimensional results with the 2.5 dimensional program. In addition, the three dimensional program was only used to generate shapes for the anomalies while amplitudes were taken from the 2.5 dimensional work.

Results

The results for various models are summarized in figures 10 to 12. The square hole models are included as they allow ease of comparison with the 2.5 dimensional work. The cylindrical hole model provides a better idea of the general shape of the anomaly, and consideration of both give an idea of variations expected from less regular shapes. Results

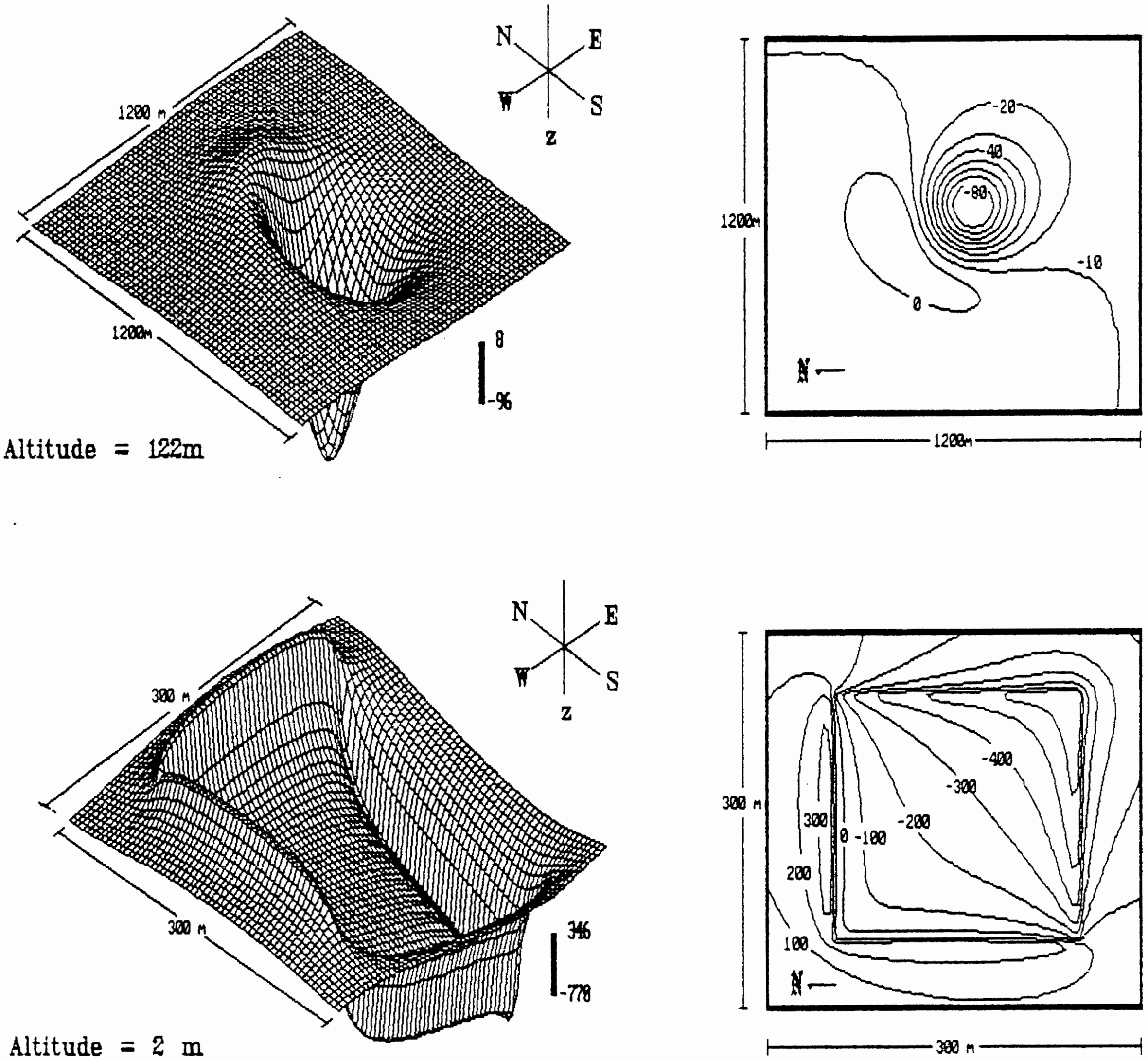


Figure 10. Three dimensional modelling of a square "hole" at two altitudes. The magnetization of the surrounding rock units is 10×10^{-4} emu/cm^3. A scale bar is shown for each set of plots giving the maximum and minimum values (in gammas) for the anomaly. Contour interval is 10 gamma for the upper plot and 100 gamma for the bottom. Note the difference in horizontal scale.

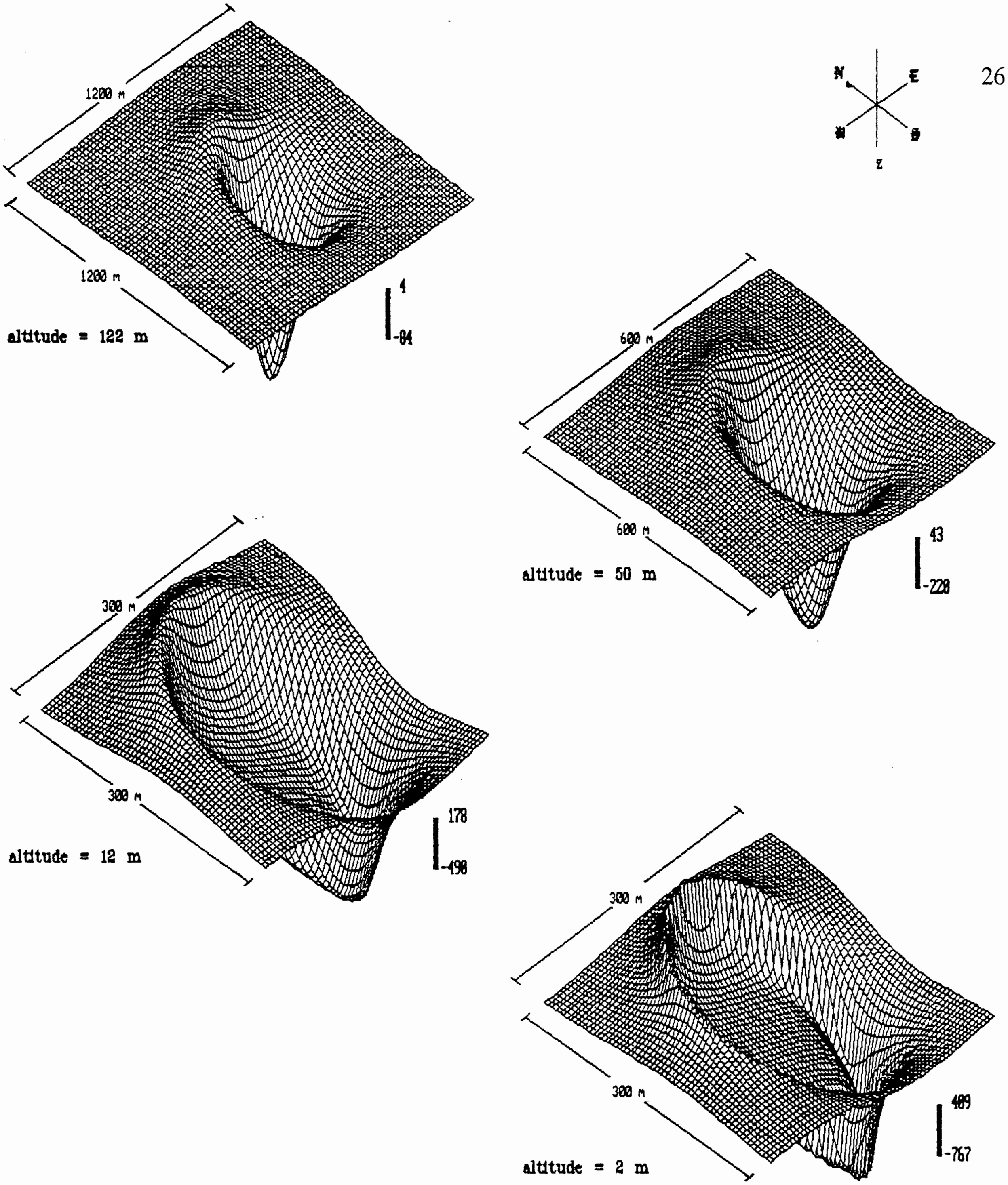
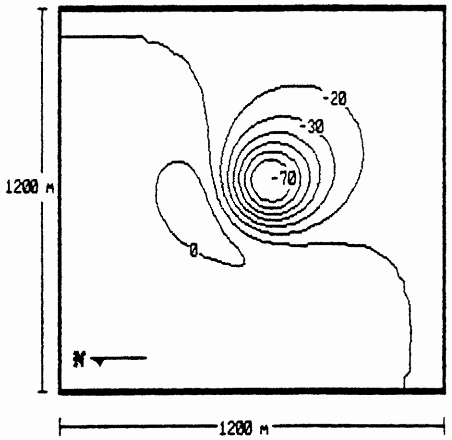
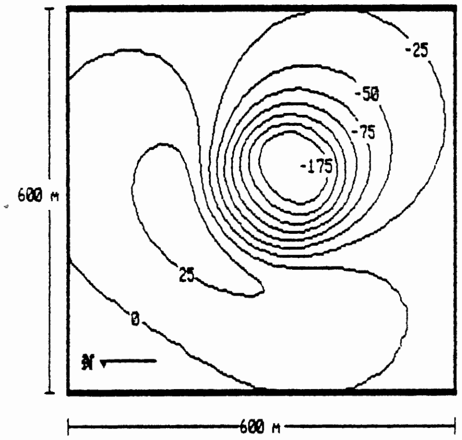


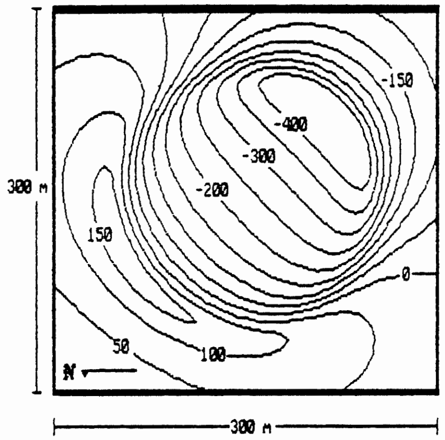
Figure 11. Three dimensional modelling of a vertical non-magnetic cylinder at different altitudes. The surrounding rock unit has a magnetization of 10×10^{-4} emu/cm . Maximum and minimum values (in gammas) for each plot are shown on vertical scale bars. Note the differences in horizontal scale.



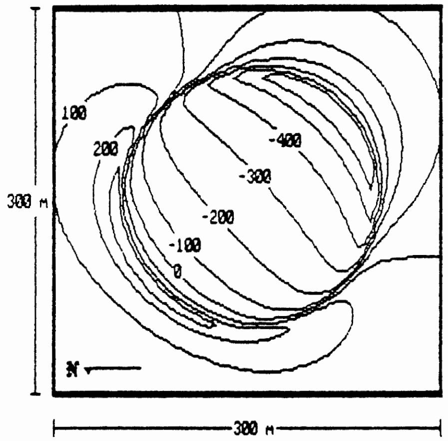
Altitude = 122 m
contour interval = 10 gamma



altitude = 50 m
contour interval = 25 gamma



altitude = 12 m
contour interval = 50 gamma



altitude = 2 m
contour interval = 100 gamma

Figure 12. Three dimensional modelling of a vertical non-magnetic cylinder at different altitudes. Models are the same as for figure 11.

computed for various altitudes give an idea of anomalies that might be expected to be seen in different surveys (ie. ground surveys and aeromagnetic surveys).

Summary of Results

All examples are consistent in showing a northwesterly peak and a southeasterly trough. In the lower level surveys these features quite clearly define the edges of the non-magnetic hole. At higher altitudes, a broadening of the anomaly is seen, and magnitude decreases quickly. The contour diagrams are included for ease of comparison with the aeromagnetic data, which will be considered later.

2.5 Dimensional Modelling

The program used in this analysis was based on MAGRAV2, developed by the Geological Survey of Canada (Broome, 1986). Some modifications were required to use the program on the available equipment.

The theory used in this method of modelling, as described in Shuey and Pasquale (1973), is, in its basic form, similar to that used in the three dimensional program. Instead of horizontal laminae, this program requires the body to be specified by a single vertical polygon, representing the cross section of a horizontal prism whose long axis is perpendicular to the magnetic profile line (see figure 13). The calculation is similar to that performed on a single lamina in the three dimensional situation, and thus may be done by a more accurate method while maintaining a reasonable computation time.

The program allows fairly complex models to be treated, with up to ten separate bodies,

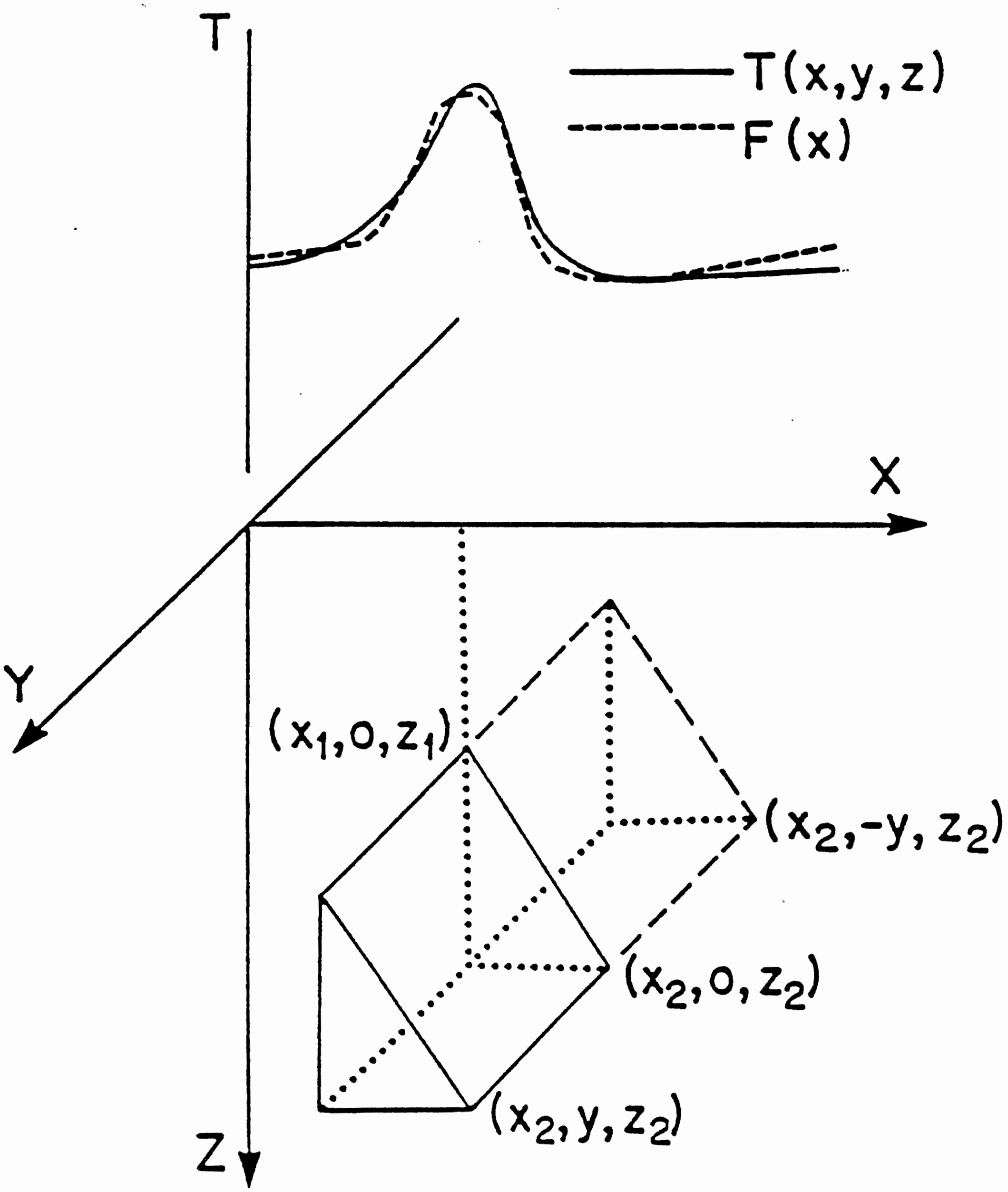


Figure 13. The 2.5 dimensional modelling situation.
T = calculated anomaly
F = observed anomaly

each with its own magnetization vector. Each body is entered by specifying corner coordinates in two dimensions, and a strike extent. It allows a ready comparison of observed and computed anomalies and immediate modification of the model to minimize differences. Automatic optimization of the model was also possible.

The chief weakness of this program was the inability to specify a true three dimensional model of the type desired. This was avoided by using square hole models.

Results

Ground data was available from three sites:

1. the Kambia mine,
2. a gossan between Kambia and Kapedhes, and
3. the Agrokipia mine.

Data from the first two locations was collected by C. Walls and S.L. Hall during the summer of 1987. The third survey was taken from Johnson et al. 1982.

The Kambia mine lies in an area of strongly magnetized basalts (J.M. Hall, personal communication). The topography in the immediate survey area was fairly flat, and the direction of the survey profile was chosen to minimize relief. The data and a possible model are shown in figure 14.

The dike-like gossan was visible in a new road cut between the villages of Kambia and Kapedhes. Again the topography was flat and the surrounding rock strongly magnetized. Results are summarized in figure 15.

Rather more data was available for the Agrokipia area, from more extensive surveys conducted in 1981 (Johnson et al., 1982). A model and a reconstructed profile are shown in

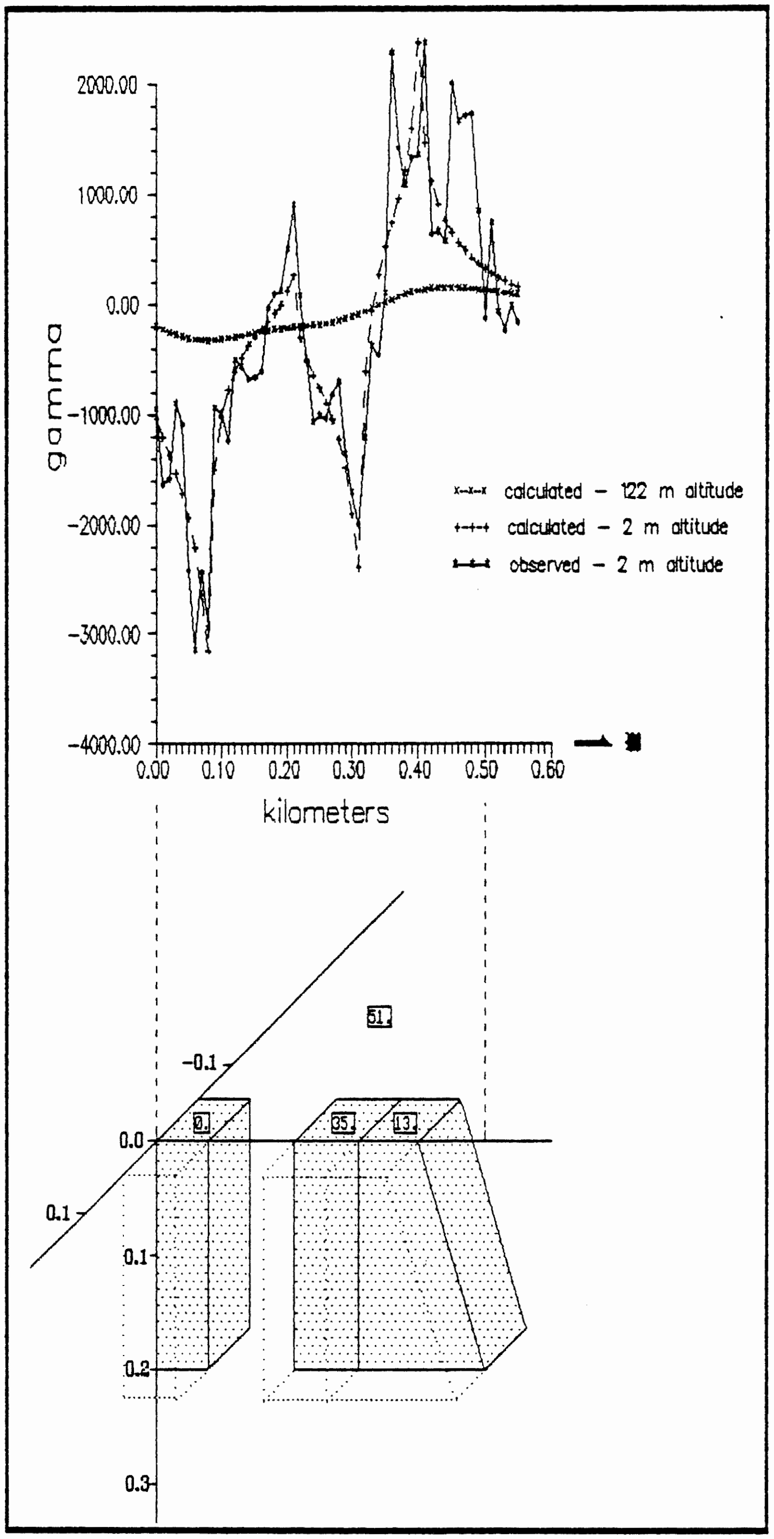


Figure 14. **Kambia mine two dimensional modelling. All model dimensions are in kilometers. Magnetizations for the rock units are shown in emu/cm^3 x 10^{-4}.**

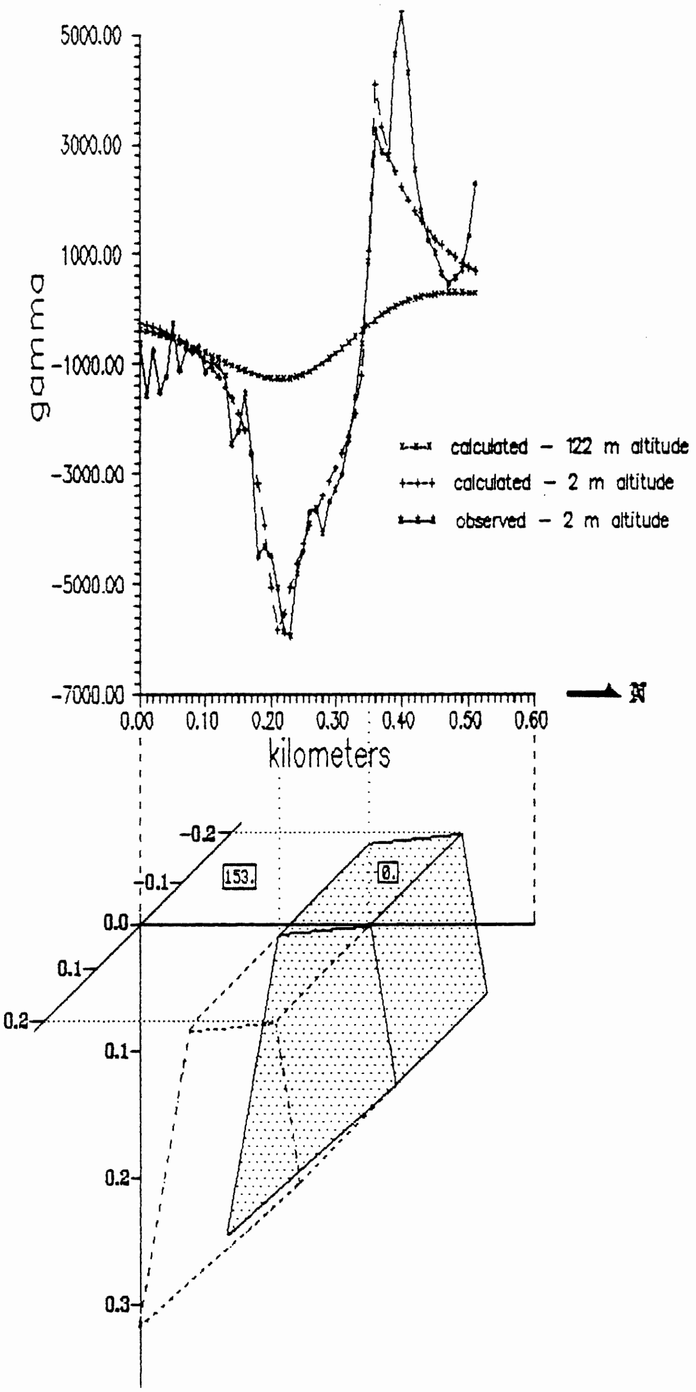


Figure 15. Kambia-Kaphedes gossan two dimensional modelling. All model dimensions are in kilometers. Magnetizations for the rock units are shown in emu/cm^3 x 10^{-4}.

figure 16. This compares well with a model derived independently by Smith and Vine (1987). Detailed geological information is available for this area from the Cyprus Crustal Study Project drillholes and site surveys (Auerbach and Bleil, 1987, Smith and Vine, 1987).

A profile and model generated from the three dimensional modelling of a "square hole" described earlier are shown in figure 17. These are included for confirmation of the three dimensional results and for comparison with the above surveys.

The lower sections of figures 14 to 17 attempt to depict the models used in the calculations. The dotted outline is the projection of the model forward of the plane of the profile. Magnetizations for each body are labelled.

A third site, at the Philani mine, was surveyed during the summer of 1987. The steep walls of the open pit mine made it difficult to collect data in a straight line across the known deposit. As a compromise, readings were taken along a roughly curved line skirting the pit and extending beyond it in both directions. While this made 2.5 dimensional modelling impossible, the results are shown in figure 18 to confirm that they conform to the general shape of the typical anomaly (ie. a large magnetic low). The upwardly domed central section of the anomaly is interpreted as being due to the curved path of the line.

Review of the 2.5 Dimensional Results

All models show a general agreement in shape and magnitude with the observed data. Indeed, other geologically realistic models could not be envisioned. This is taken to confirm the applicability of the "magnetic hole" theory.

The small magnetic high between the two lows in the Agrokipia survey may result either

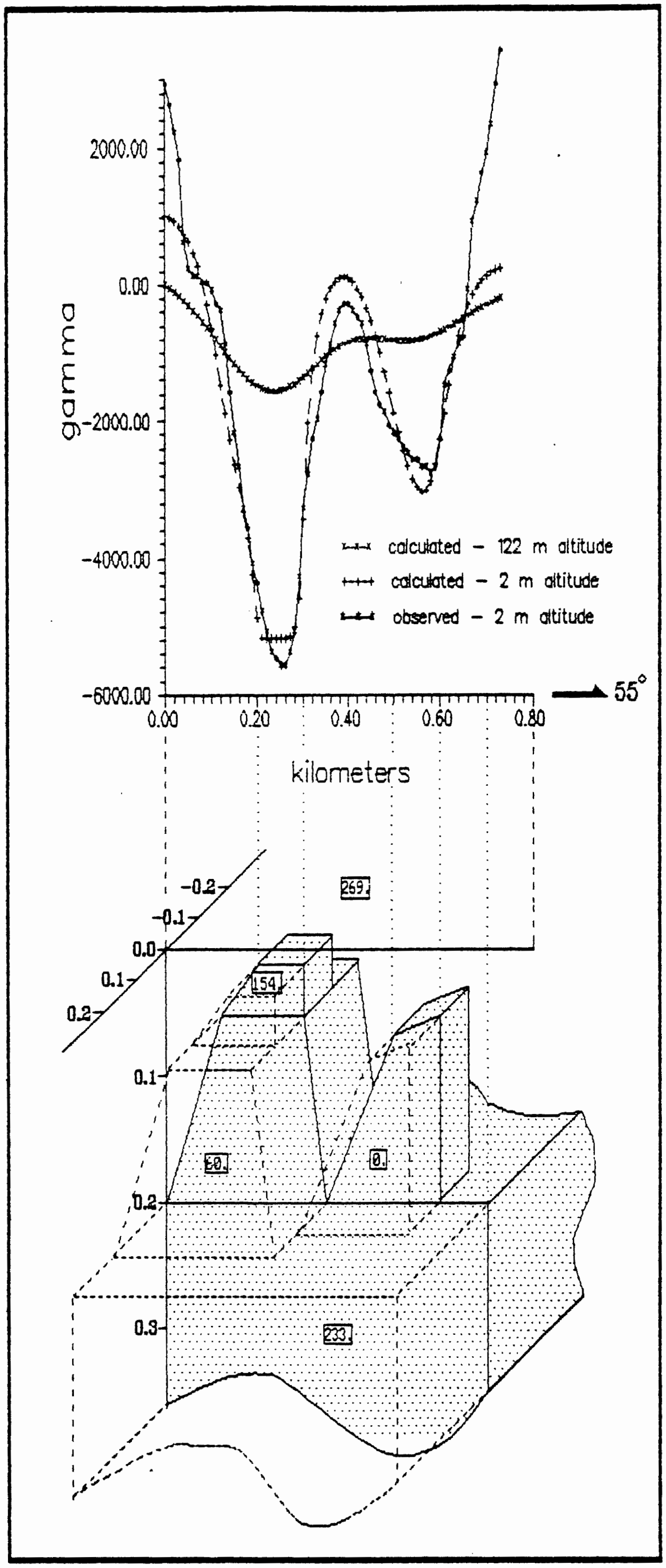


Figure 16. Agrokipia mine two dimensional modelling.
Model dimensions in km. Magnetizations in emu/cm^3 x 10^{-4}.

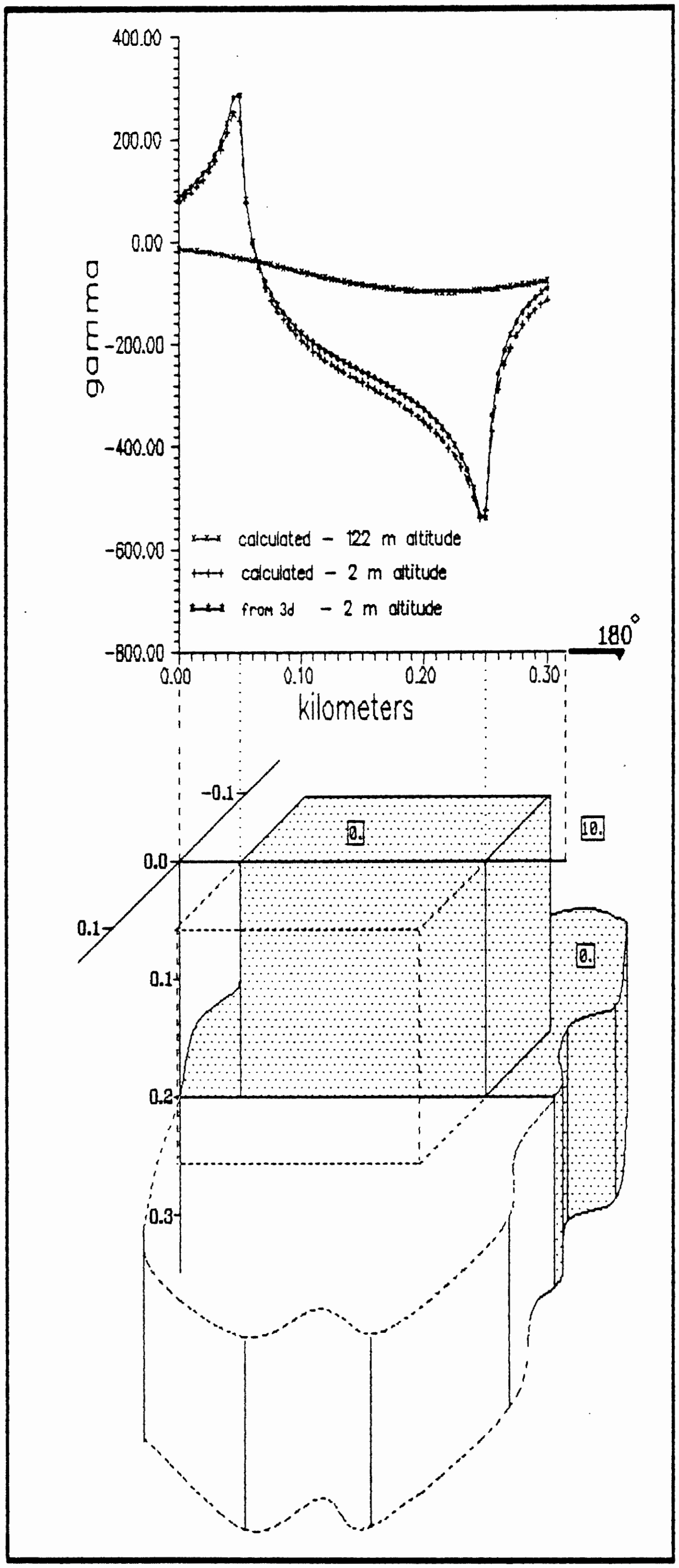


Figure 17. Square "hole" model in two dimensions

Model dimensions in km. Magnetizations in emu/cm^3 x 10^{-4}.

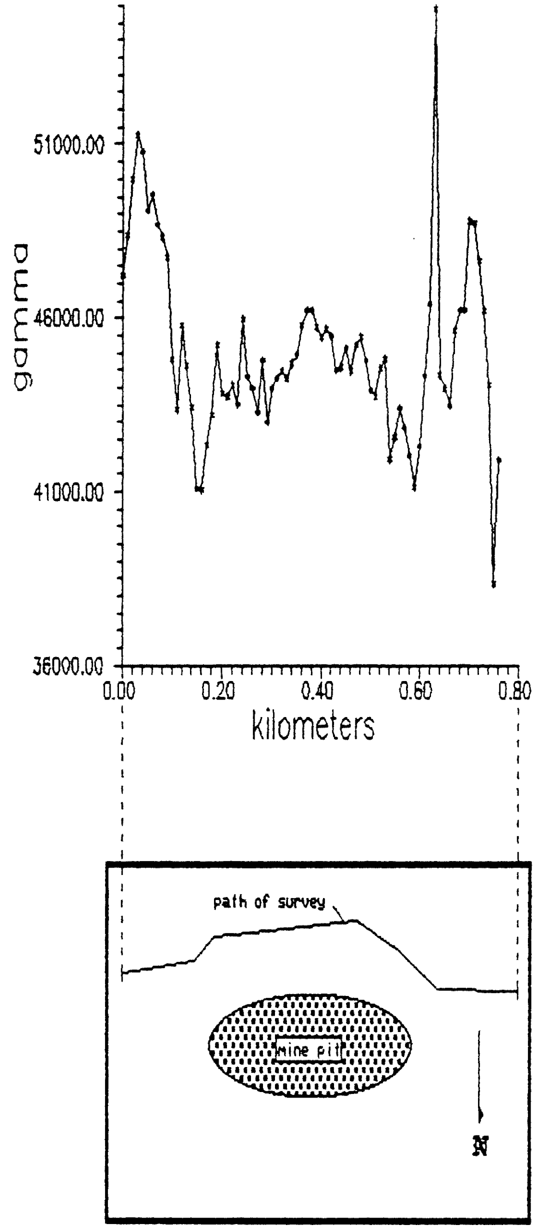


Figure 18. Ground magnetometer survey at the Philani mine showing the abnormal anomaly caused by skirting the mine pit.

from a block of magnetic material located between the Agrokipia A and B orebodies, or from the increased altitude effect of the survey moving over the mine tailings (see figure 14). The actual anomaly shape may be two lows corresponding to the two orebodies (as observed) or alternatively, a single large low. No definite conclusions are drawn.

The Kambia mine also shows more than one low. Detailed local geology is not available, and these anomalies may be due to formations related to the orebody extending to some distance from the mine site. Again, no definite conclusions may be drawn.

The Kambia-Kapedhes gossan shows the best agreement between the model and observed data. This is interpreted as being due to rather simpler geology and geometry, which is more closely approximated by the simple model. This result is rather encouraging, being found in an isolated mineralized zone, presumably with a less complicated form than those in which orebodies occur.

It was noted in Smith and Vine (1987) that the effect on the model anomaly of deeper (>100m) structures was minimal for measurements taken at the surface. This was confirmed by the present model work. Consequently, the configurations of the deeper parts of these models are only poorly constrained, and may be considerably different for the actual situations. Most of the anomaly results from the very shallow parts of the body.

Extrapolation of Anomalies to Higher Altitudes

The anomalies for each of the models were recalculated at higher altitudes to provide a basis for comparison with aeromagnetic data. The results are displayed in figures 14 to 17, together with the original data, and will be discussed in the next chapter. While these anomalies were calculated only for the ground and aeromagnetic altitudes as opposed to the range of altitudes for which calculations were done in the three dimensional case, intermediate profiles may be interpolated. This gives an indication of the shape and magnitude of the anomaly in cases where a formation covered by a thickness of overburden is surveyed by ground magnetometer.

Consideration of the Aeromagnetic Data

While the ground surveys cover only a few very small areas around the location of mines and mineralized zones, low level (122 meter altitude) aeromagnetic data covers much of the extrusives and their surroundings. Using the information generated from models, it is hoped to utilize the aeromagnetic maps to predict likely areas for further exploration.

The three dimensional models have given us a general shape for the anomaly to be expected of a "magnetic hole". Specifically, we would expect a high to the northwest, coupled with a more pronounced low to the southeast. The anomaly corresponds exactly with, and is centred on, the body. The magnitude decreases rapidly with increasing altitude of measurement; the ratio of the magnitude of the anomaly of a shallow body measured at the surface to that measured at 122 meters is an order of magnitude.

The 2.5 dimensional modelling has both confirmed the results of the three dimensional work and has also generated expected amplitudes for the anomalies.

During the course of this modelling work it became apparent that the contribution to an observed anomaly was very dependent on altitude of measurement. This not only causes the expected aeromagnetic anomaly to be much smaller than the ground anomaly, but also causes the contribution to the ground anomaly from more deeply buried bodies to be minimal. In other words, most of the anomaly observed in a ground survey over shallow bodies is due to the near surface magnetization of that body. The decrease in the magnitude of the anomaly with increasing altitude for two simple situations is shown in figure 19. Differences in shape and extent of the body at depth will have little effect on the rate of this decrease.

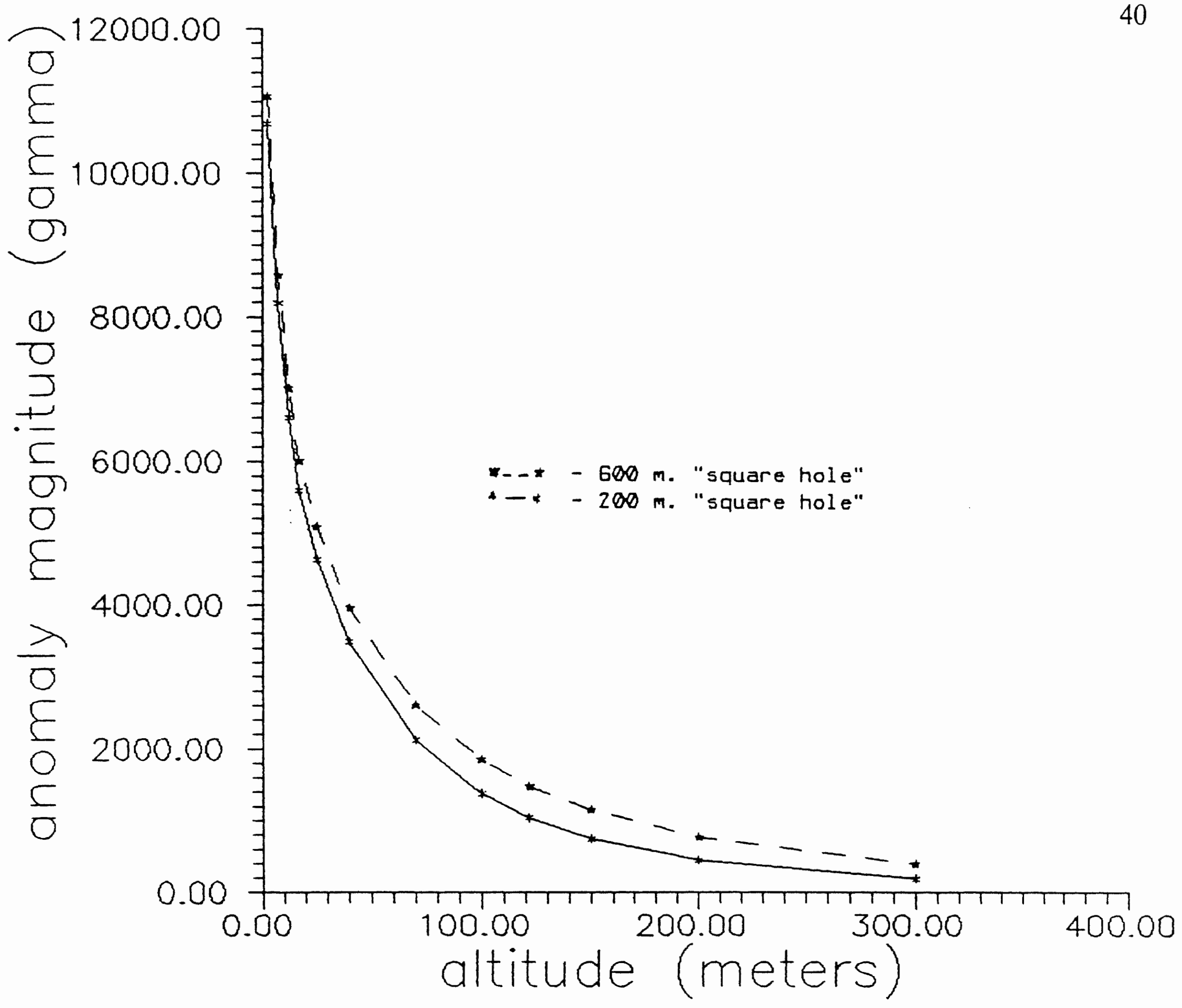


Figure 19. The decrease in anomaly magnitude versus elevation for two simple models.

The situation may be considered intuitively by considering the body to be a single point pole (see figure 20). The anomaly directly above the pole will be given by the equation

$$\Delta z = \frac{m}{a^2}$$

where the magnitude is seen to decrease with the distance a squared (Parasnis, 1971). Correspondingly, a similar, yet less pronounced effect will be expected in the aeromagnetic data, as it was flown at a low altitude.

Thus the expected aeromagnetic signature from a "magnetic hole" will be a magnetic low associated with a high to the northwest. The amplitude at the flight altitude of 122 metres is expected to be approximately one tenth of the ground anomaly.

The Aeromagnetic Maps

The coverage of these maps is shown in figure 21. In general, when they were examined, three significant problems were encountered:

1. Positioning Accuracy. The aeromagnetic data was located using aerial photographs taken simultaneously with the magnetic data. The maps show little detailed ground information, except the major rivers and villages, to check their accuracy. Even these are sparse in some areas. Mine locations and other geological data were located on the aeromagnetic maps using latitudes and longitudes. A comparison between the 1:50000 topographic and aeromagnetic maps of a river junction at latitude 35° 00.3' North, longitude 33° 14.7' East (approximately) shows a location difference of the order of one kilometre. It is impossible to know how widespread and significant these inaccuracies are, and they must be

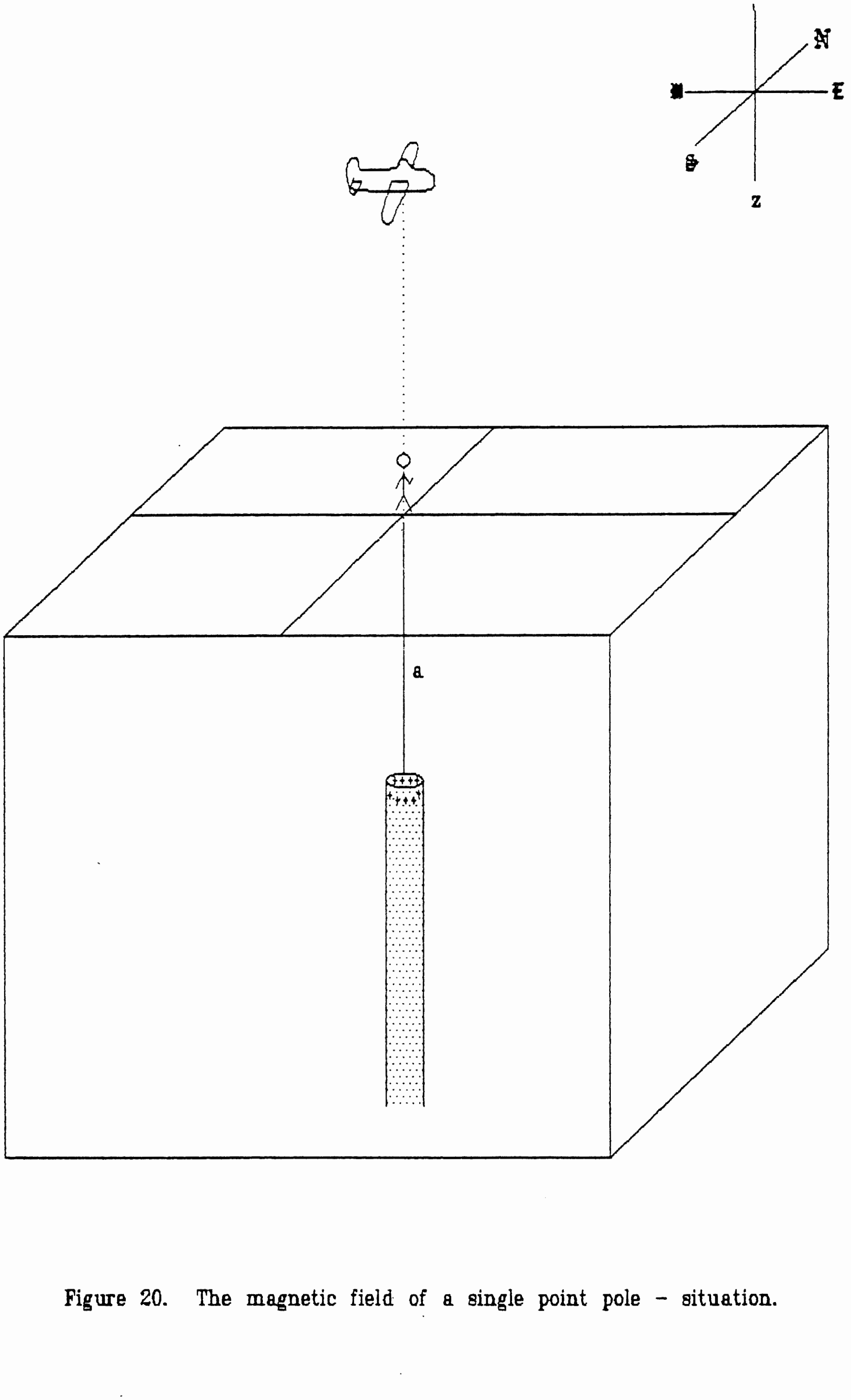


Figure 20. The magnetic field of a single point pole - situation.

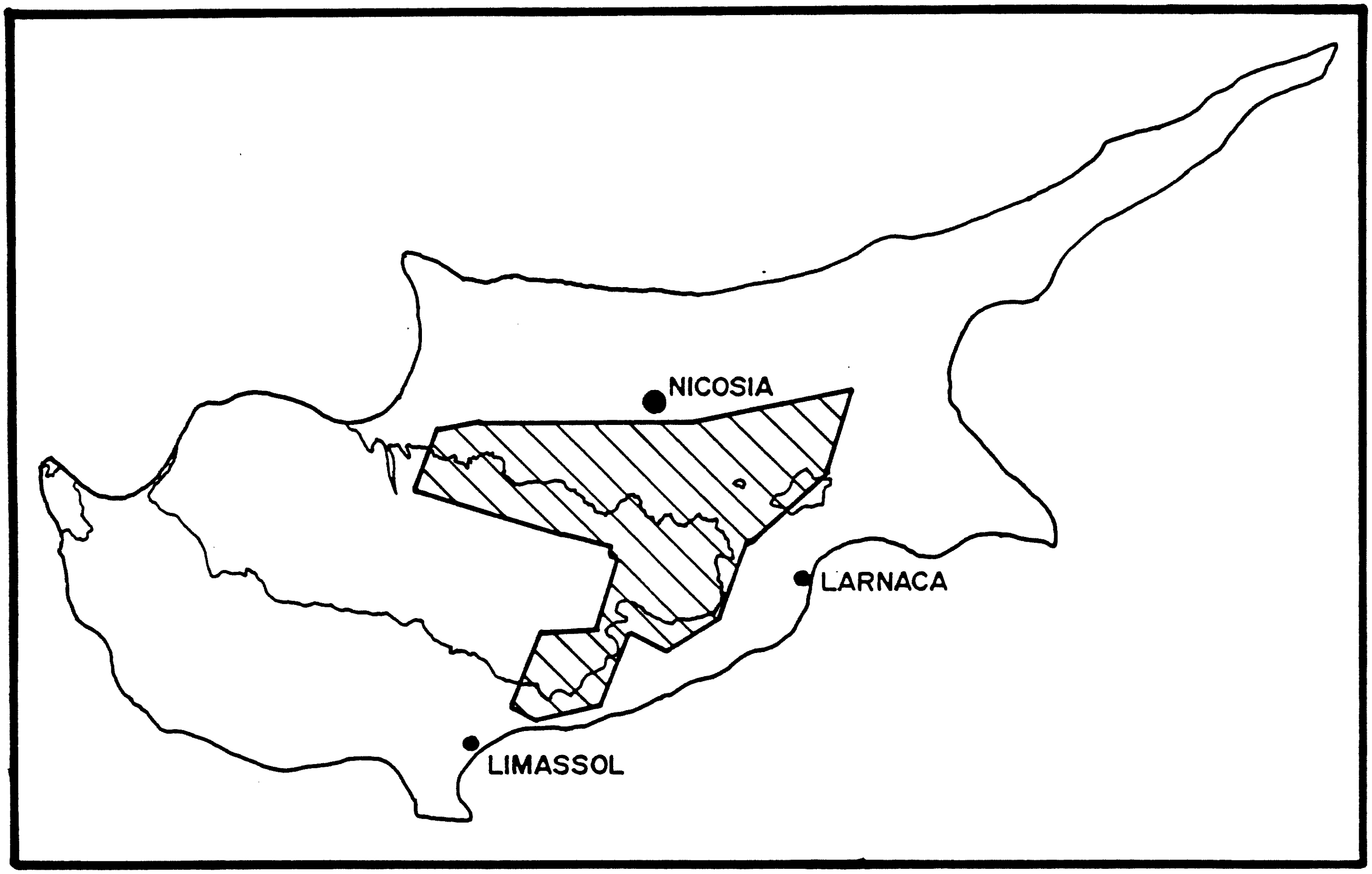


Figure 21. Aeromagnetic data coverage.

considered in the evaluation of the aeromagnetic data.

2. Data Density. The nominal spacing of the flight lines in the survey was one quarter mile (~ 400m). Due to inevitable variations in flight path (which are noted on the maps) in some areas this spacing was larger. The result is that smaller ore bodies and mineralized zones (less than one kilometre across) will be covered by at most two flight lines and finer details of the anomaly will be missed. Indeed, the contouring may be inaccurate or quite incorrect in many areas.

3. Topographic Effects. The airplane used in the survey maintained a nominal altitude of four hundred feet (122 meters) above the ground. While most of the survey was flown over fairly flat terrain where this altitude could be maintained, the effect of steep topographic gradients (eg. gullies, small, steep hills) has not been removed from the data. While it is impossible to do this universally, such features must be considered in the interpretation.

General Observations

Initial examination of the aeromagnetic maps indicates that they can be divided into zones of characteristic magnetic relief. Over the sediments, the anomalies are very broad and less numerous. Over the volcanics, the magnetic topography becomes much more rugged. The sediment-volcanic boundary is defined to within a kilometre by the transition. The minimum width of individual anomalies, determined by the line spacing of the survey, limits the resolution.

Further comparison between the geologic and aeromagnetic maps shows a similar, but less pronounced, variation within the volcanics. Strongly magnetized units show the steepest magnetic gradients, while less strongly magnetized units show broader, more gentle anomalies. Figure 22 shows the differences between three rock types: sediments, Lower Pillow Lavas, and the Basal Group. The weakly magnetized sediments exhibit very broad, weak anomalies. The magnitudes of the anomalies in the volcanics are generally consistent, but those in the more weakly magnetized Basal Group are broader, while those in the Lower Pillow Lavas show steeper gradients.

The minimum contour interval used in the aeromagnetic maps is fifty gammas. Over most of the volcanics, the steep magnetic gradients necessitated increasing this to one hundred gammas, and in places, to five hundred gammas. Typical anomalies over the volcanics vary from five hundred to three thousand gammas. Thus it may be concluded that anomalies of the order of one thousand gammas, to be expected from magnetic holes in strongly magnetized basalts ($\sim 100\text{x}10^{-4}$ emu/cm^3), would be significant but not unique in this data.

Local Anomalies

At this point, individual anomalies associated with known local geological conditions are considered. Figure 23 shows the locations of the sites of these bodies.

Five mine sites and one gossan were considered, each of which had been observed in the field. Three mines and the gossan had been surveyed with ground magnetometers. The observed anomaly magnitudes are summarized in table 1, along with some model data for comparison. All mine sites for which ground data was available showed significant associated anomalies. Four of the sites (Philani, Kambia, Mitsero and the gossan) were associated with significant aeromagnetic anomalies.

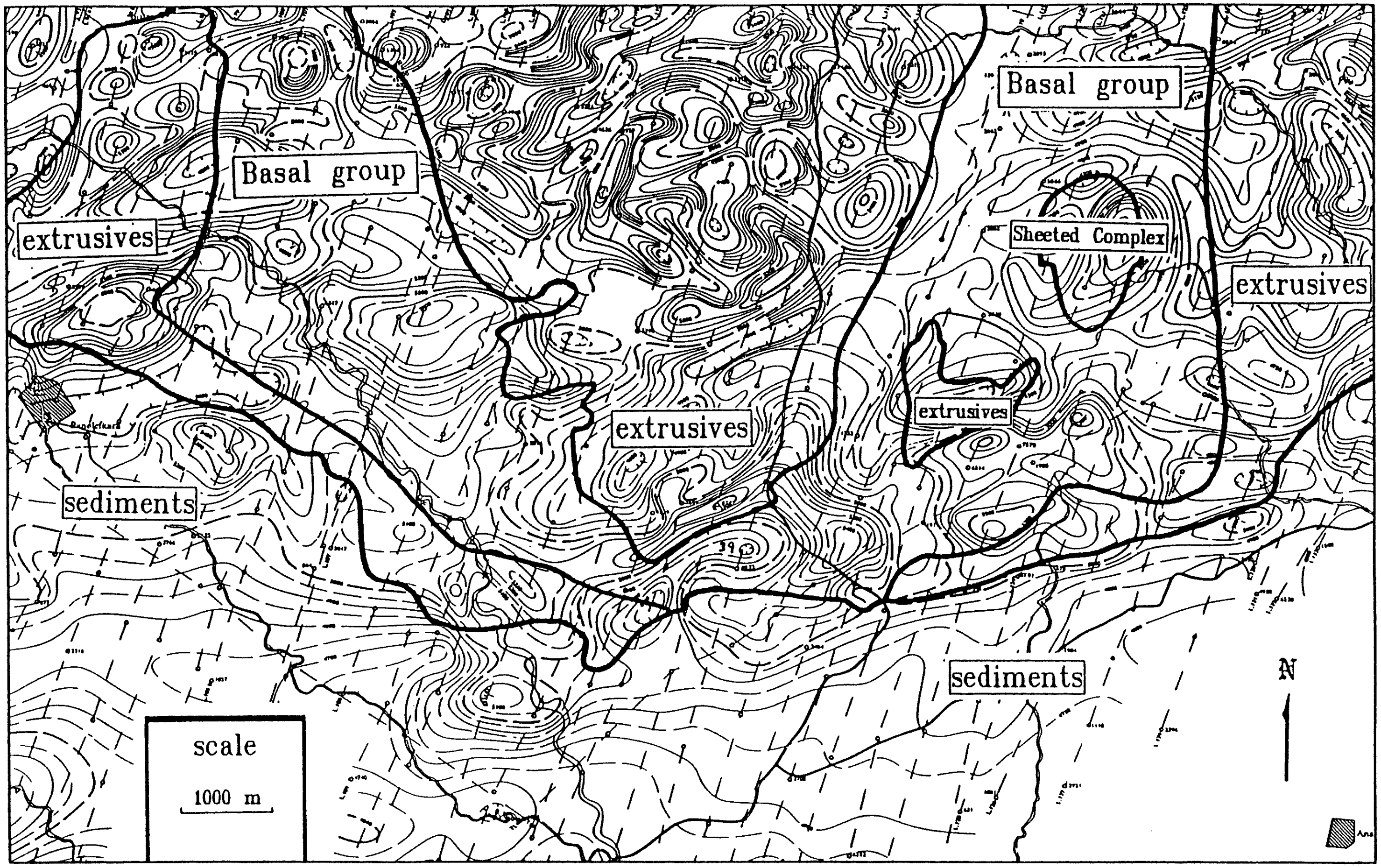


Figure 22. Aeromagnetic map showing differences in anomaly shapes over different rock types.

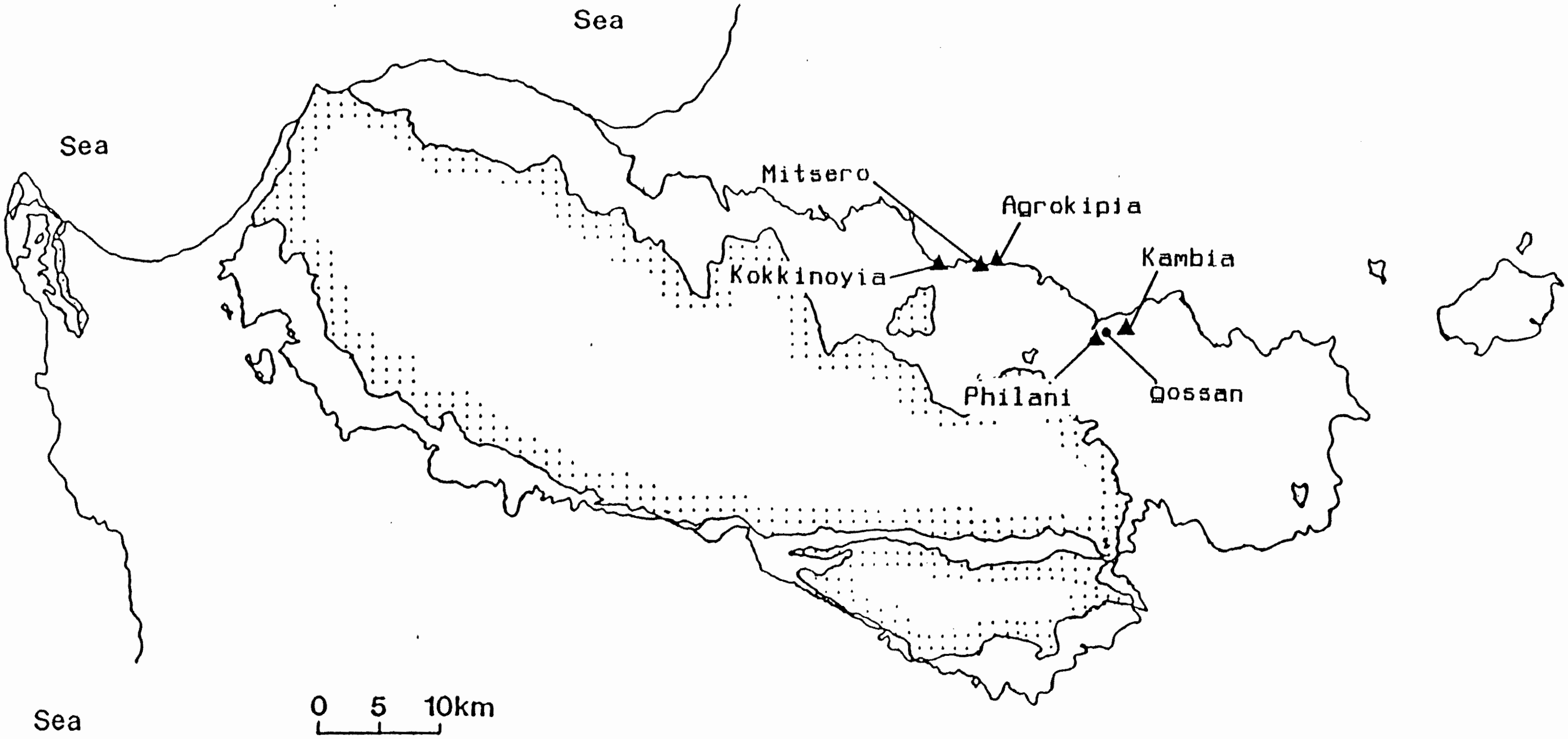


Figure 23. The location of aeromagnetic anomaly sites examined in the text.

Table 1

Area	Ground Anomaly	Aeromagnetic Anomaly
200 m square hole model	1000 gamma	100 gamma
Agrokipia	8000 gamma	0 gamma
Philani	10000 gamma	1000 gamma
Kambia	8000 gamma	2000 gamma
Mitsero	?	1000 gamma
Kokkinoiya	?	0 gamma
Kambia-Kaphedes gossan	10000 gamma	1500 gamma

The aeromagnetic anomalies associated with each of these sites are shown in figures 24 to 26. The Agrokipia mine site shows a high to the northeast and another to the northwest, but does not show the significant low present in the ground survey centred on the mine itself. This is assumed to be due to a measurement altitude effect as the plane rose to clear the hills to the north. A simplified illustration of this effect is shown in figure 27. The Kambia, Philani, and Mitsero mine results are straightforward in showing the anticipated northwest high and southeast low, assuming the data is positioned correctly. The Kokkinoiya mine (figure 26a) shows no anomaly whatsoever, which again we may speculate is due to an altitude variation in the flight path. However, there is no ground magnetic data for this mine so it is possible that no low is associated with it. As this is a possible contradiction, a ground survey must be a high priority in further work.

The gossan located between Kambia and Kaphedes, located in the Lower Pillow Lavas as are all of the mines mentioned above, gives an anomaly of significant magnitude. It is not, however, of the expected shape. A look at the ground data (figure 15) shows that while the anomaly is of significant magnitude, and thus must be seen in some manner at the higher altitude, it is of limited spatial extent. Accordingly, the line spacing as shown on the aeromagnetic map (figure 26b) is too wide to resolve the shape of the anomaly.

Even the most cursory glance at the aeromagnetic map shows that all magnetic lows do not correspond to mineralized areas or mines. Other explanations are required for most of the observed anomalies.

Outliers of sediment or weakly magnetized volcanic units in more strongly magnetized units are in principle capable of causing aeromagnetic lows. An example of this situation is shown

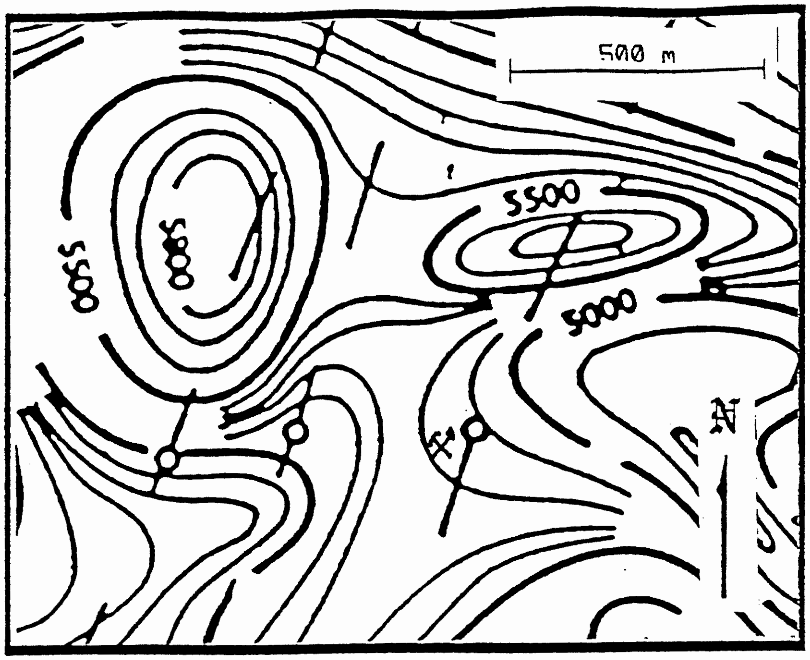
Aeromagnetic data

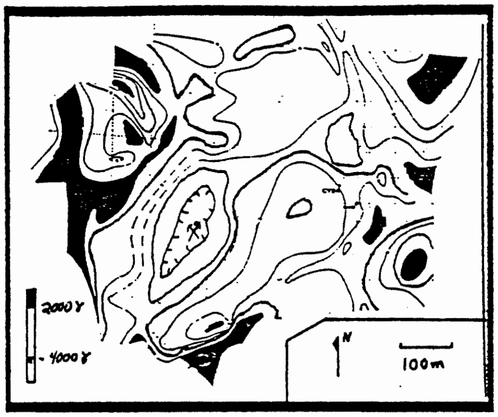
from the

Agrokipia mine are

(from Hunting Geology

and Geophysics Ltd., 1969)





Ground magnetic data from the

Agrokipia mine area.

(from Smith and Vine, 1987)

Topography of the

Agrokipia mine area.

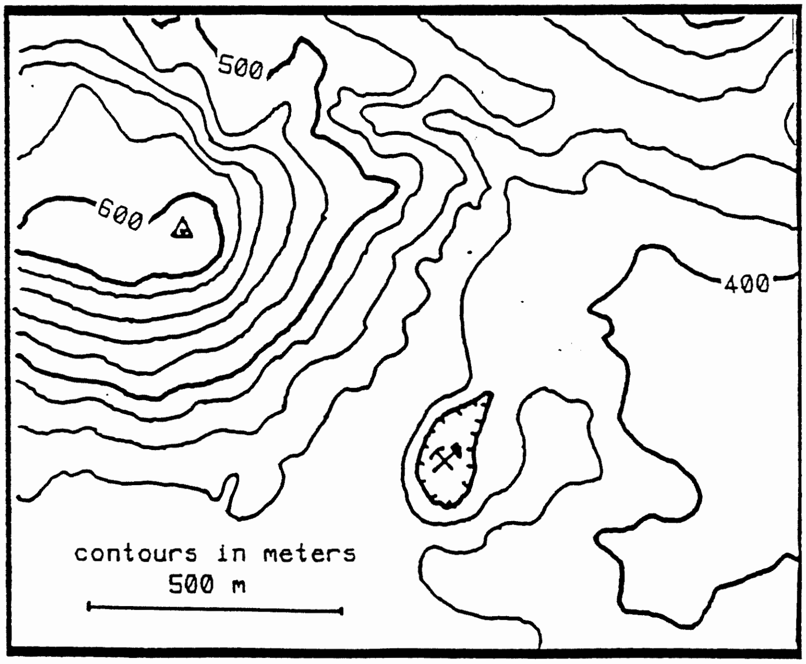
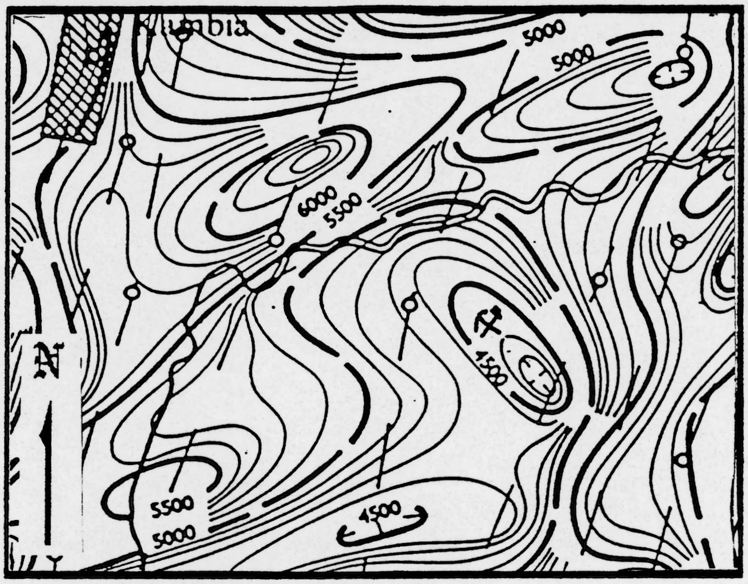


Figure 24. Agrokipia mine - Aeromagnetic, ground magnetic, and topographic comparison.

Kambia mine

Aeromagnetic data

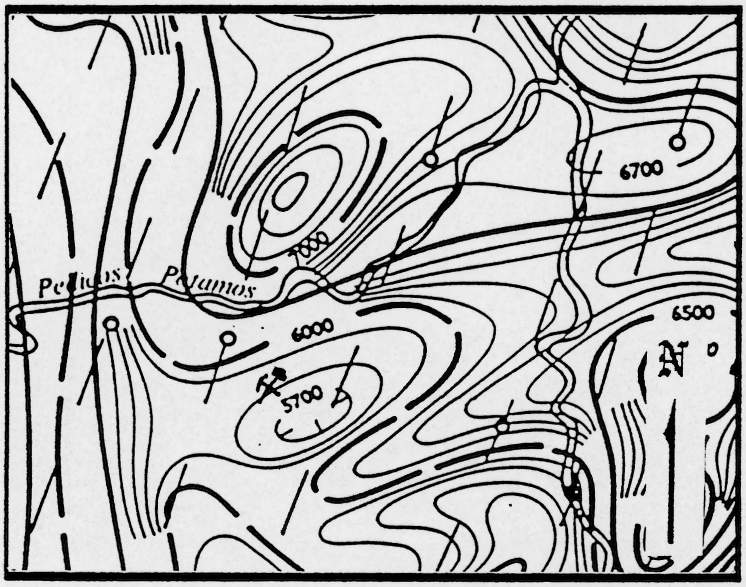
1000 meters



Philani mine

Aeromagnetic data

1000 meters



Mitsero mine

Aeromagnetic data

1000 meters

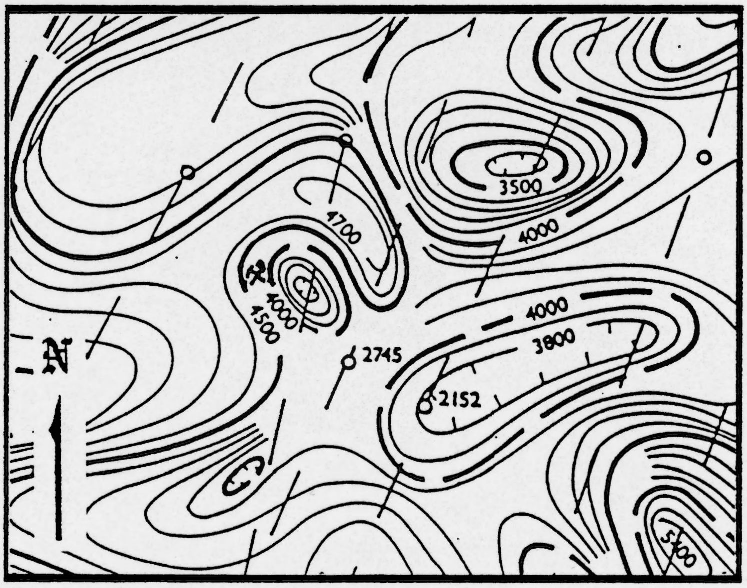
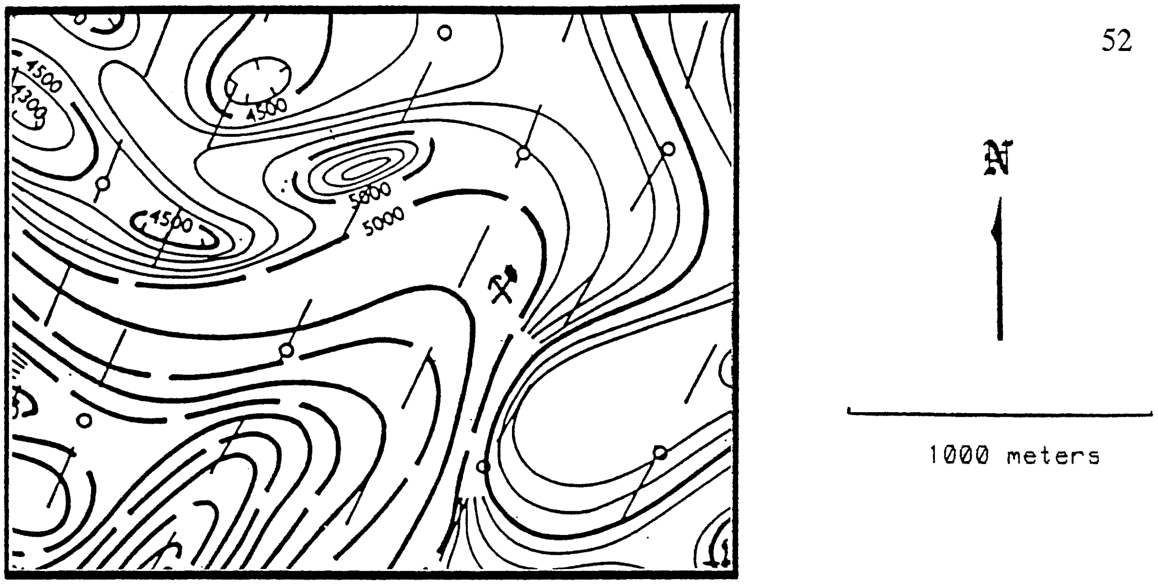


Figure 25. Aeromagnetic data from 3 sites. Modified from Hunting Geology and Geophysics Ltd., 1969.



Kokkinoiya mine - Aeromagnetic data

Kambia-Kaphedes gossan - Aeromagnetic data

Figure 26. Aeromagnetic data for two sites. Modified from Hunting Geology and Geophysics Ltd., 1969.

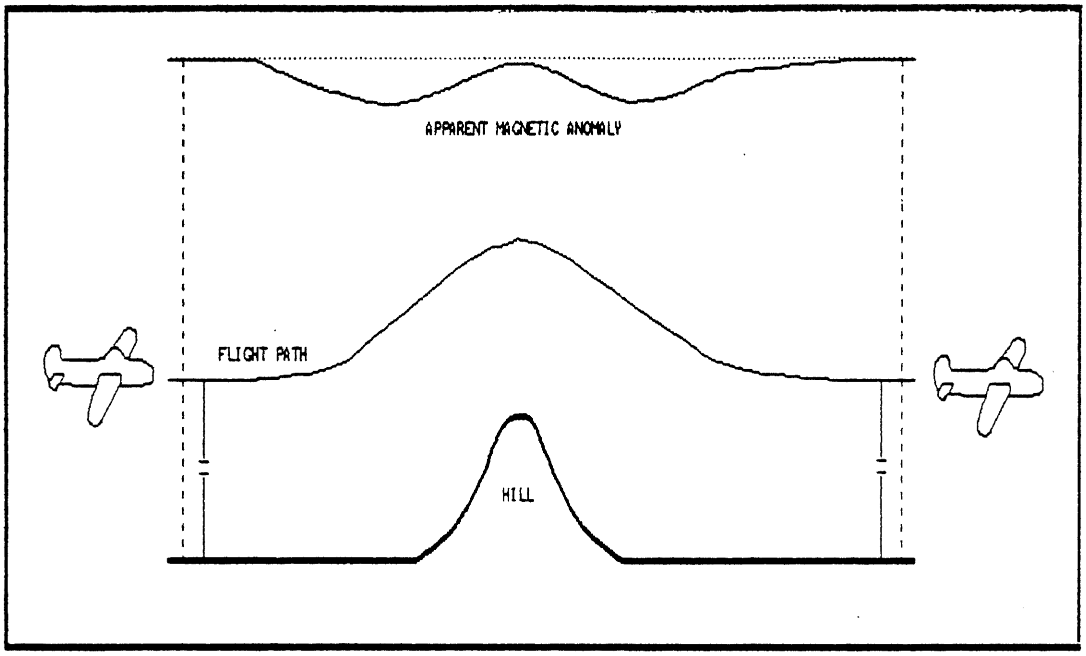


Figure 27. The effect of altitude variations on aeromagnetic measurements when crossing a small hill.

in figure 28.

Local topography can have a significant effect. River valleys and hills sometimes show related anomalies, where the shape is loosely related to the topography. Reasonably, the survey aircraft was unable to follow the steeper slopes and maintain an exact altitude in these conditions. This was probably one of the problems in the area of the Agrokipia mine, as discussed earlier. Such effects are often obvious by their shape (eg. linear anomalies over river valleys). Figure 29 shows the effect of a topographic feature in the aeromagnetic data contours. Note that the relationship between the aeromagnetic anomaly shape and the topographic shape is not exact.

Similarly, all gossans do not correspond to clearly defined magnetic lows. Problems such as line spacing and overwhelming topographic effects apply here as well.

Discussion

The aeromagnetic data must be viewed with some suspicion. Positioning errors are known to occur in the maps, but their extent and magnitude are not known. Consideration of individual anomalies indicates that the line spacing has caused important features of expected or known anomalies to be missed. Indeed, considering that the width of the expected anomaly of an ore body two hundred meters across is approximately seven hundred meters (see figure 12), one might expect that they are very poorly defined and that the contouring may be quite misleading. The very critical factor of measurement height is suspected to be poorly controlled in some important areas, and is obviously impossible to control in others.

Nevertheless, the geology of an area is without doubt reflected in the aeromagnetic maps.

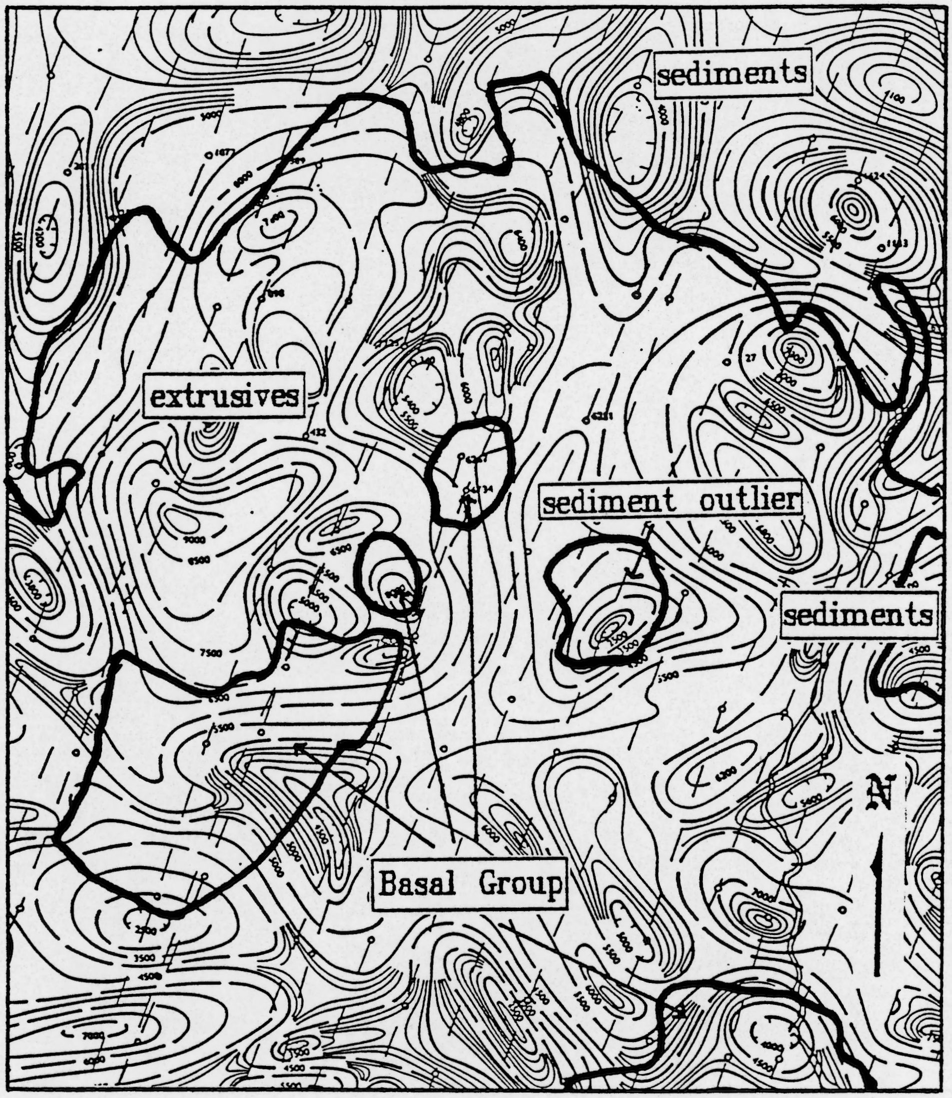
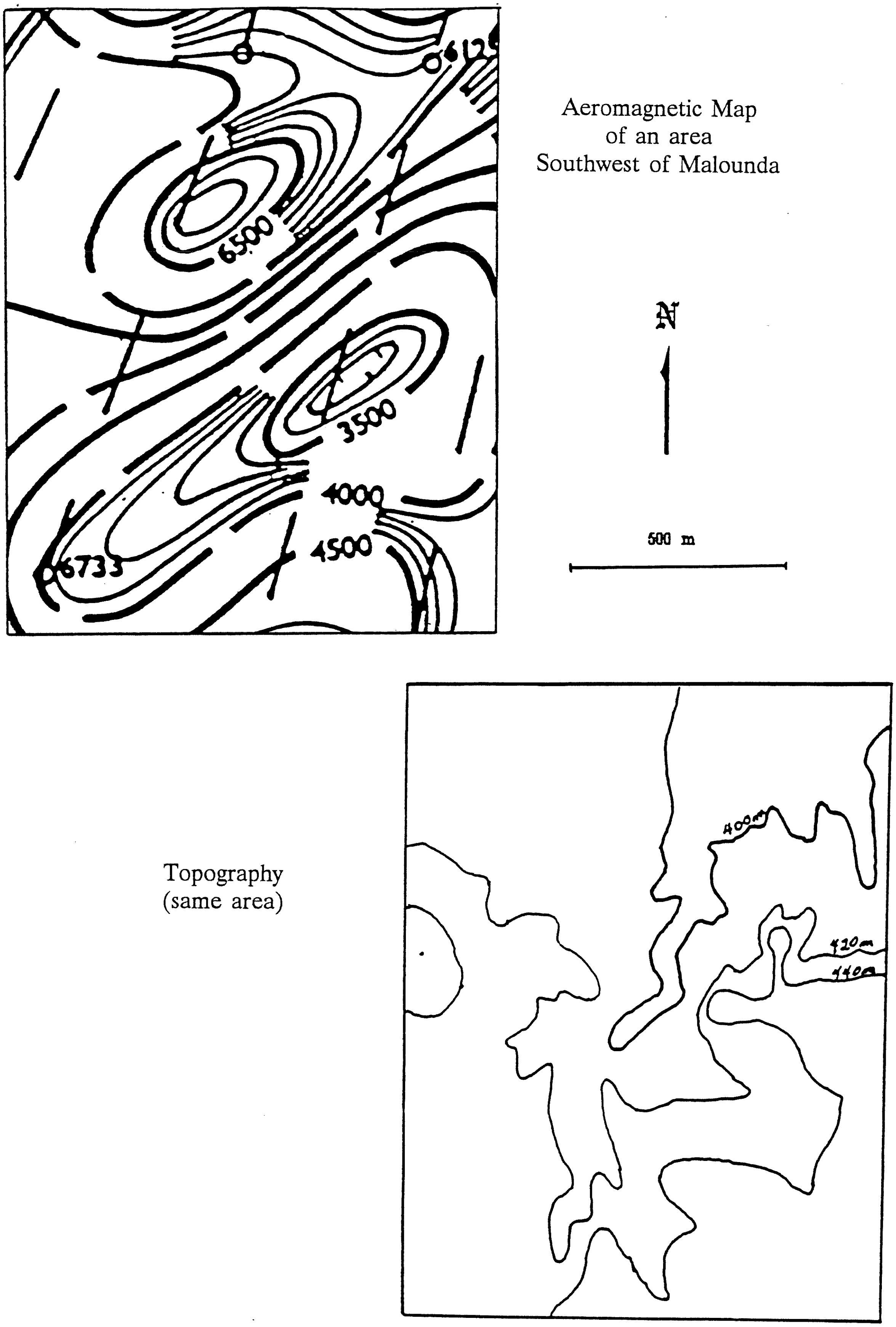


Figure 28. An example of the aeromagnetic anomaly over a sediment outlier.



Aeromagnetic Map
of an area
Southwest of Malounda

Topography
(same area)

Figure 29. The effect of a topographic feature in the aeromagnetic data.

Sizeable anomalies measured on the ground usually appear in the aeromagnetic data. Indeed, it is physically impossible that they do not occur at the altitude of the data and special circumstances must be imagined to explain any absence. Large scale variations in geology, with associated variations in rock magnetism, are clearly seen in the aeromagnetic data.

While it is possible in many, if not most, cases to account for the aeromagnetic anomaly by the surface geology, the reverse is not true. Individual aeromagnetic anomalies or perturbations in the shape of these anomalies do not provide a good basis for estimating the local geology. There are too many uncertainties involved. The value of the aeromagnetic maps must lie in the forward instance: using known geology to account for as many anomalies as possible, and targeting the remaining anomalies in the most promising areas for further, more conclusive study, such as ground magnetic surveys. In many cases ground anomalies may be completely missed in the aeromagnetic data, and likely areas must be selected by other methods, such as promising geological structures.

Examples of promising areas are not in short supply. A large proportion of the area underlain by strongly magnetized extrusives is covered by overburden, often to only shallow depths. This is commonly the case in the Agrokipia-Mitsero area where much of the exposure is limited to road cuts and river valleys. The edges of the volcanics which are covered by marine sedimentary rocks are other possible target areas, although depth of burial will become an important factor here.

Summary, Conclusions and Recommendations for Further Work

It is useful at this time to summarize the results of the previous chapters, to draw any further conclusions that are warranted, and to consider how they may be applied. In addition, it is important to consider where, as well as how, these results may be used.

The overriding aspect of the aeromagnetic data must be its unreliability on the scale of individual ore bodies and alteration zones. Uncertainty as to the position of the data, the measurement altitude inconsistency, and the finer details not resolved by the one-quarter mile line spacing colour any interpretation that may be made.

This being taken into account, it is seen that the observed aeromagnetic anomalies on a larger scale do reflect the ground geology in areas where it is possible to make certain comparisons. This is required by the physics involved; the upwards extrapolation calculations indicate that sizeable anomalies present on the ground must be present in some way in the aeromagnetic data.

Thus a limited amount of interpretation may be conducted from the aeromagnetic maps. Anomalies may be examined individually and some judgement made as to their source (sediment outliers, topographic feature, etc.). Examination of the actual area will be necessary to eliminate all possibilities other than zones of alteration and mineralization. Even then, the identifications will not be unique, as anomalies may also be caused by features that cannot be seen on the ground such as buried, non-magnetic bodies of rock, and some anomalies may not be resolvable in the aeromagnetics.

The ground surveys show more promise of success. In all areas surveyed, the mineralized zones are characterized by pronounced magnetic lows, with associated peaks on their peripheries. The uniqueness of these anomalies is not well established in the absence of control surveys of similar quality over known non-mineralized areas. However in all of the present surveys, the magnetic low over the mineralized zone was a predominant feature in the data.

One situation in which a negative anomaly may not occur is at the Kokkinoiya mine. In all other cases, all mines surveyed are associated with some form of aeromagnetic anomaly, however distorted it may be. No hint of such is visible at Kokkinoiya. This may be due to inaccuracies in the aeromagnetic data (as discussed earlier) or to a different geological situation. The explanation of this situation is definitely of further interest. Clearly, a ground profile should be a high priority.

Application of the Results

The analysis of actual data from the Troodos leads us to ask several questions about the results.

Firstly, where is the best location to apply these results? The most obvious restriction is that of rock type. Most of the economic sulfide bodies in Cyprus are found in the extrusives. This limits the area of interest to the lower elevations of the complex and excludes the intrusive rocks at higher topographic elevations. It does not exclude the surrounding sedimentary sequences beneath which the extrusives are buried to varying depths. In all of the sites surveyed, the anomaly from the mineralized zone was the most significant feature in the profile. However, the magnitude of the anomaly will be less, by direct proportion, over less strongly magnetized units. This factor may be of importance when the rocks are overlain by overburden or a sedimentary sequence.

Measurements made over flat terrain have a distinct advantage when analyzing magnetic data of this type. Happily, much of the extrusives are found under flat farmland and this may be used to advantage. Furthermore, when small topographic features are encountered, such as river gullies and small hills, they may be considered by weighting the data acquired. Anomalies caused by variations in magnetization may still be significant and resolvable by considering the shape and anticipated anomaly of the topographic feature.

Depth of burial is another important factor. More deeply buried features may be obscured by surface effects. In ground surveys, features close to the surface predominate. Again happily, this is coincidental with economic interest; deeply buried bodies are less likely to be commercially viable.

The depth of burial criterion restricts the area of application of the method in the sediments. On the northern flank of the ophiolite, assuming a dip of twenty degrees (taken from the geological maps - Bear, 1960), the volcanics will be buried under the sediment cover to a depth of two hundred meters at a distance of only 550 meters from the volcanic-sedimentary contact. On the north-eastern tip of the ophiolite, where dips are shallower, the coverage may become more practical. Assuming a dip of five degrees in this area (Gass, 1960), the two hundred meter sediment burial contour lies over two kilometers from the contact. Indeed the presence of a volcanic inlier north-east of the main body of the ophiolite indicates that the volcanics may, in places, lie even closer to the surface than this simple calculation indicates.

To summarize, the most promising areas for further exploration of this type are the topographically flatter lying areas underlain by the extrusive sequence and the extensions of the ophiolite under the sediments, particularly to the east where the sediment dips are small. This is, of course, still a sizeable area. The temptation exists to use the aeromagnetic data to further restrict the possibilities. While this has been shown to be unreliable in some instances, some general correlation with the ground geology is evident. In the absence of other data, and with careful consideration of each anomaly and its several possible causes, the aeromagnetic maps may be used with caution in selecting among possible sites for ground surveys. Any pertinent geological information should be given preference, and additional information, such as airborne electromagnetic data (Hunting Geology and Geophysics Ltd., 1969 - flown in conjunction with the magnetics, and hence subject to many of the same uncertainties) may also be considered.

As mentioned in the introduction, Hall et al. (in press -a) described the mineralized zones as being organized into strips cutting across the ophiolite and postulated that this distribution corresponds to cyclicity in the formation of the ophiolite. This cyclicity was seen to coincide to some degree with the locations of massive sulfide bodies and their associated features. Exclusion of areas not falling within these strips will help to further limit the number of possible targets.

A further criterion which may be applied to limiting prospective areas is that of dike percentage. As noted in the introduction, the twenty five per cent dike contour seems to have some correlation with the occurrence of ore deposits (Yang, personal communication). Careful consideration of this feature may also limit the potential areas.

Possible Areas for Further Study

As a final exercise, a detailed consideration of the geological and topographic maps of the Troodos was conducted to identify promising areas. The western section of the northern flank was rejected, as the topography is rugged and the present political situation makes access difficult. The southern half of the ophiolite is more complicated geologically due to the presence of the transform fault, and generally sparser in outcrop of extrusive units. Thus, the most promising general area seems to be the north-eastern section.

The topography in this area generally becomes flatter towards the east. The mines and mineralized zones are, from the geological maps and Hall et al. (in press -a), generally grouped into three major zones:

1. the Sha mining district and the extension of the ophiolite under the sediments to the north-east,
2. the Kambia mining district, and
3. the Mitsero-Agrokipia mining district.

Of these, the first is preferred for its flat topography. Several aeromagnetic lows occur, and would provide a starting point for ground surveys. The area, showing mines, gossans, geology, aeromagnetic anomalies and potential targets is illustrated in figure 30.

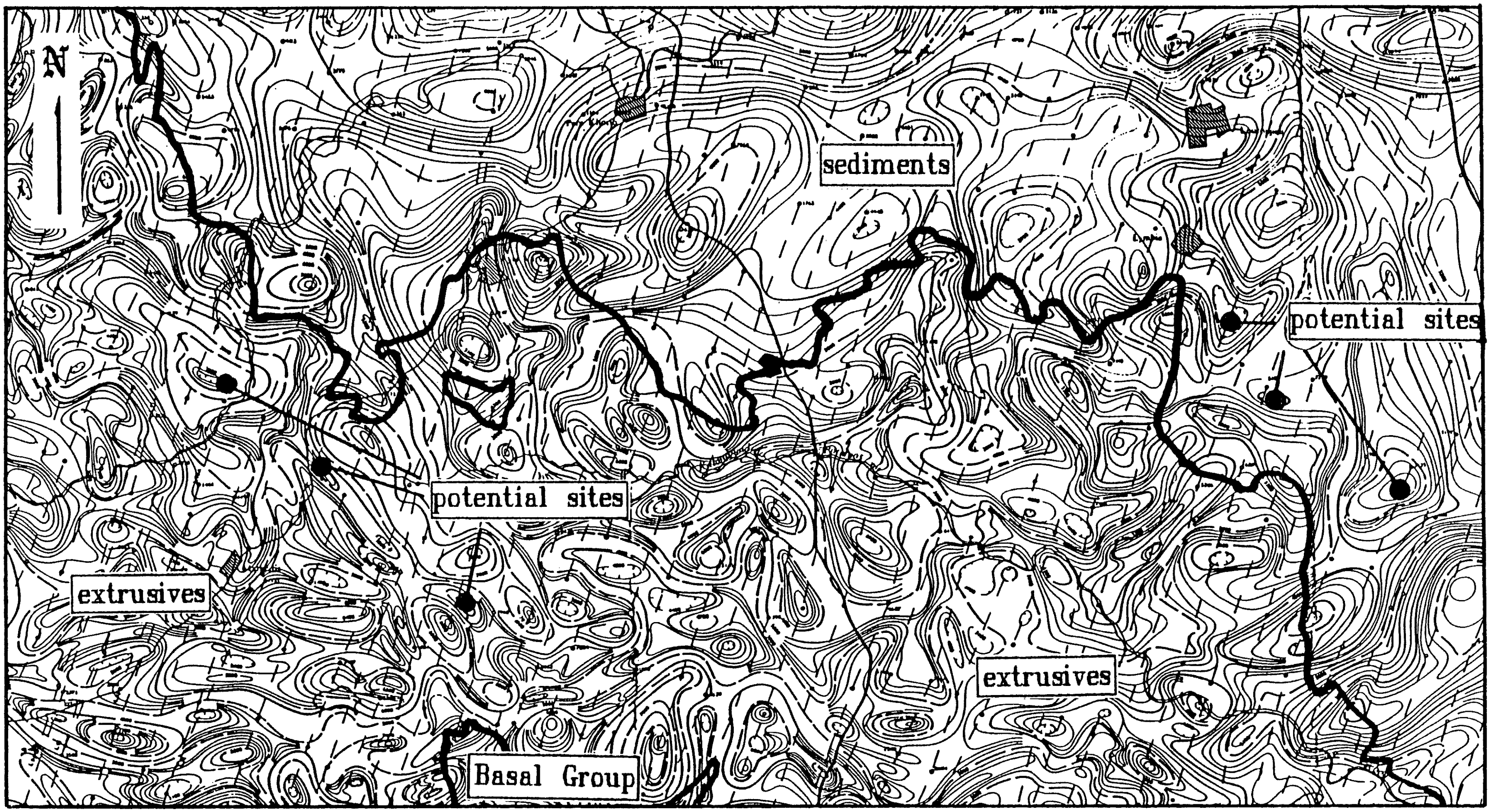


Figure 30. Potential sites for future exploration.

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