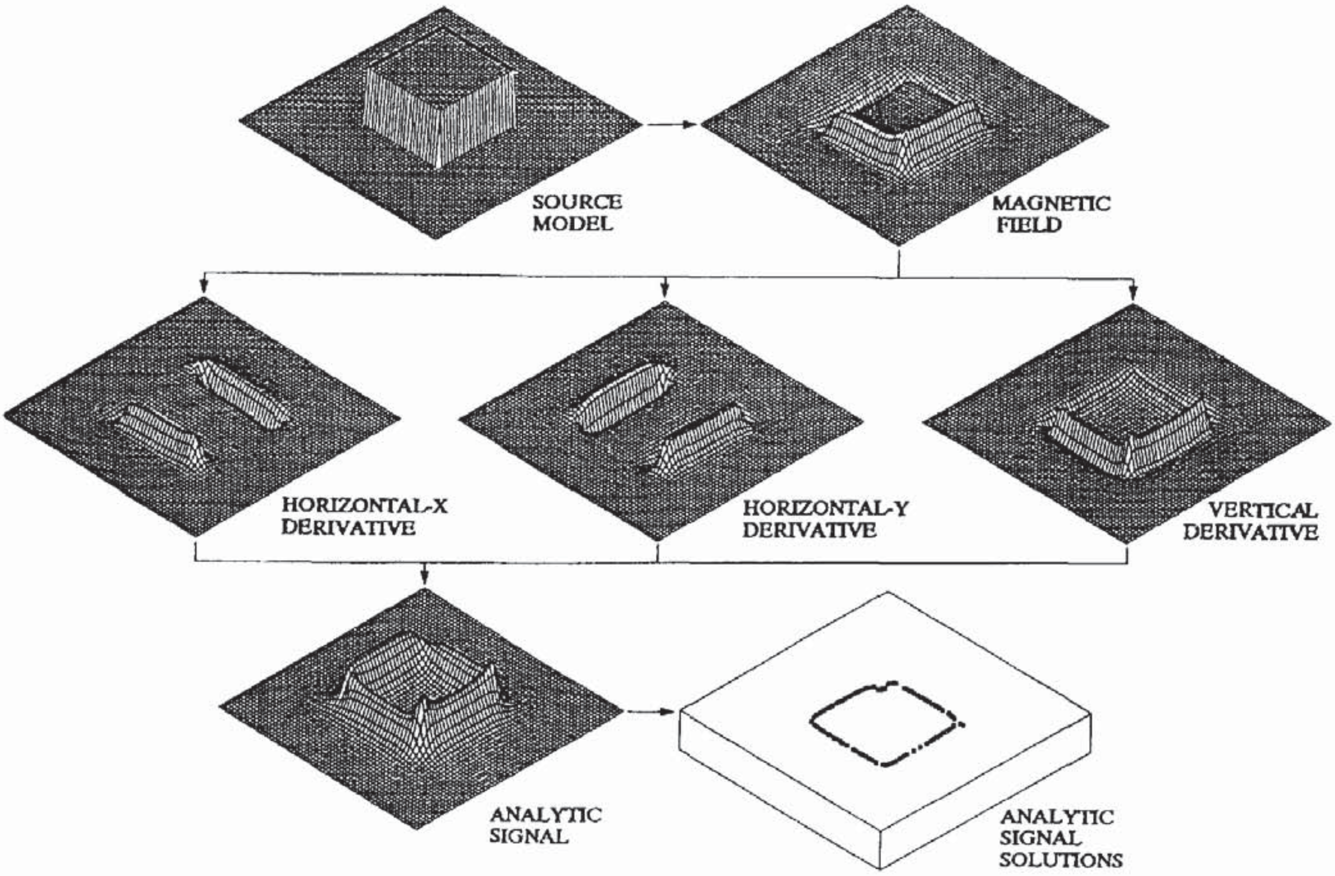


Figure 3.52 Schematic outline of the analytic signal method. Horizontal and vertical derivatives are calculated from the total field anomaly over a square prism and combined to yield the absolute value of the analytic signal. The locations of the maxima and the shape of this signal can be used to find body edges and corresponding depth estimates. From Roest *et al.* (1992), by permission

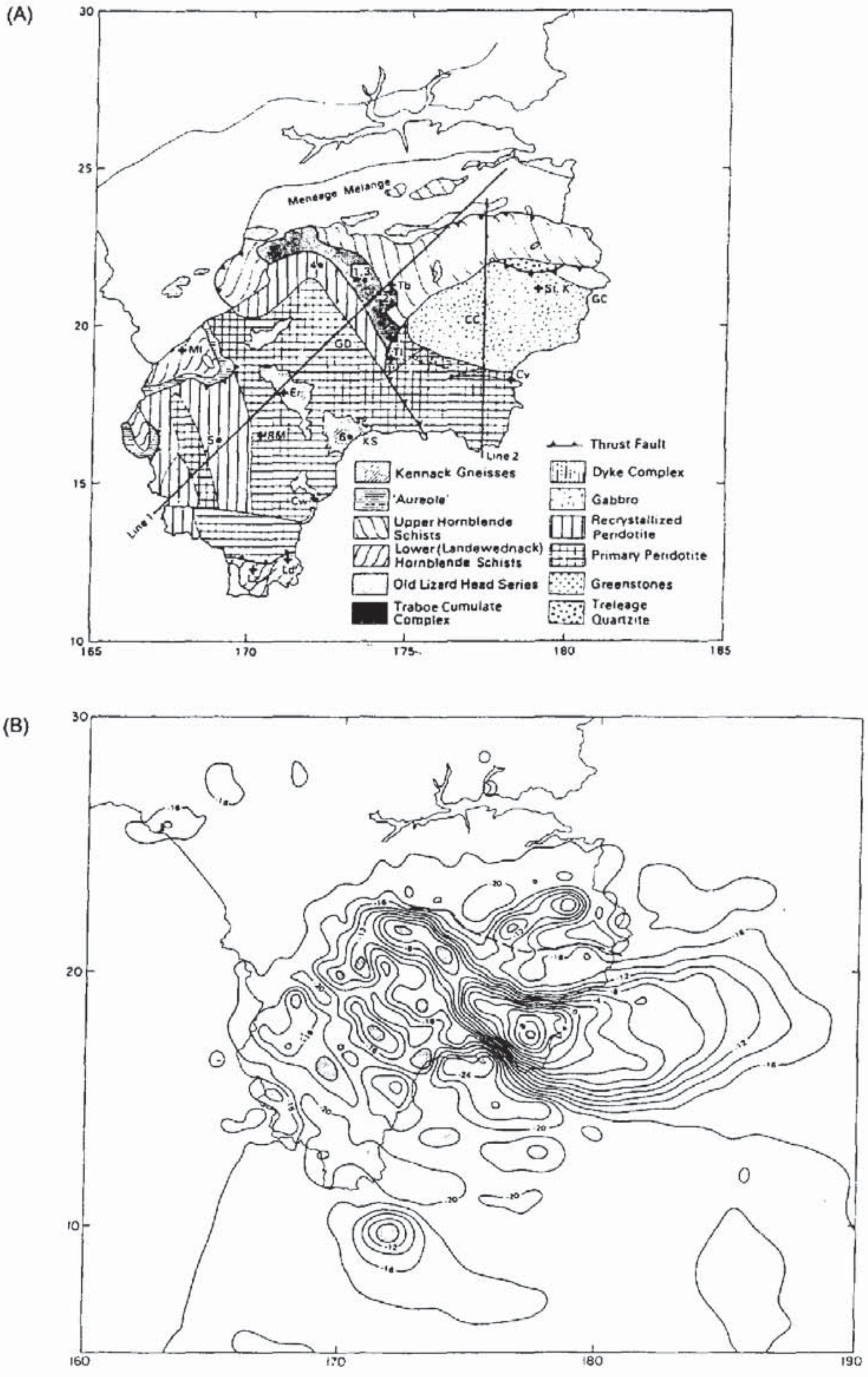
In shallow environmental applications, sources at very shallow depth (< 1 m) give rise to extremely high frequency signals which are difficult to resolve using these techniques. It is probably more cost-effective to dig with a shovel on the position of magnetic anomalies to locate the target source than to go through the analytic procedures outlined above. However, as soon as the depth is beyond easy excavatability, the value in the use of analytic solutions increases. Accuracies in depth determination are of the order of 30% of the target depth. This figure is one that may be improved upon in time with future developments and experience.

3.9 APPLICATIONS AND CASE HISTORIES

3.9.1 Regional aeromagnetic investigations

An aeromagnetic survey over the Lizard Peninsula in Cornwall, which was interpreted in conjunction with gravity data (Rollin 1986), provides an example of three-dimensional interpretation. The Lizard Complex comprises what is thought to be an ophiolite suite made up of a lower tectonic sheet of hornblende schists and metasediments and structurally overlain by peridotite and gabbro. This upper sheet shows lateral variation from harzburgite peridotite, gabbro and a dyke complex in the east to therzolite peridotite and cumulate complex to the west. Comparison of the simplified geological map with the corresponding aeromagnetic map (Figure 3.53) demon-

Figure 3.53 (A) Simplified geological map of the Lizard Peninsula, south Cornwall, and (B) the corresponding aeromagnetic map. From Rollin (1986), by permission



strates the correlation of the most prominent magnetic feature, a magnetic high which extends offshore to the east, onshore across the harzburgite peridotite south of Coverack north-westwards with diminishing amplitude over the Traboe Cumulate Complex. Western Lizard is characterised by small localised anomalies over the western peridotite. These features correlate with small outcrops of interlayered basic gneiss. A summary of the tectonic units and their respective schematic geophysical responses are shown in Figure 3.54. From this it can be seen that the lherzolite peridotite has a much smaller magnetic effect than the harzburgite peridotite while they both have comparable effects on the gravity field. It was found that the harzburgite peridotite was depleted particularly in TiO_2 compared with the lherzolite peridotite. Low concentrations of titanium in these rocks are indicative of complex geochemical processes which affected the formation of magnetite during serpentinisation.

When modelling these aeromagnetic anomalies, Rollin found that it was necessary to investigate the remanent magnetisation which is

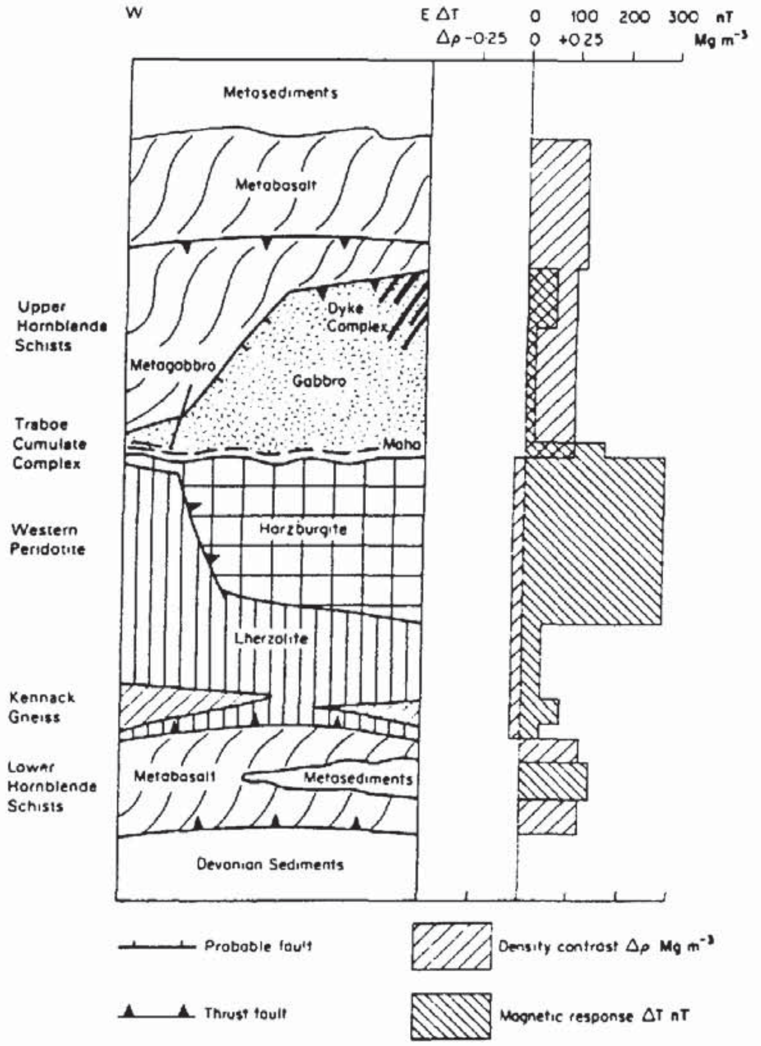
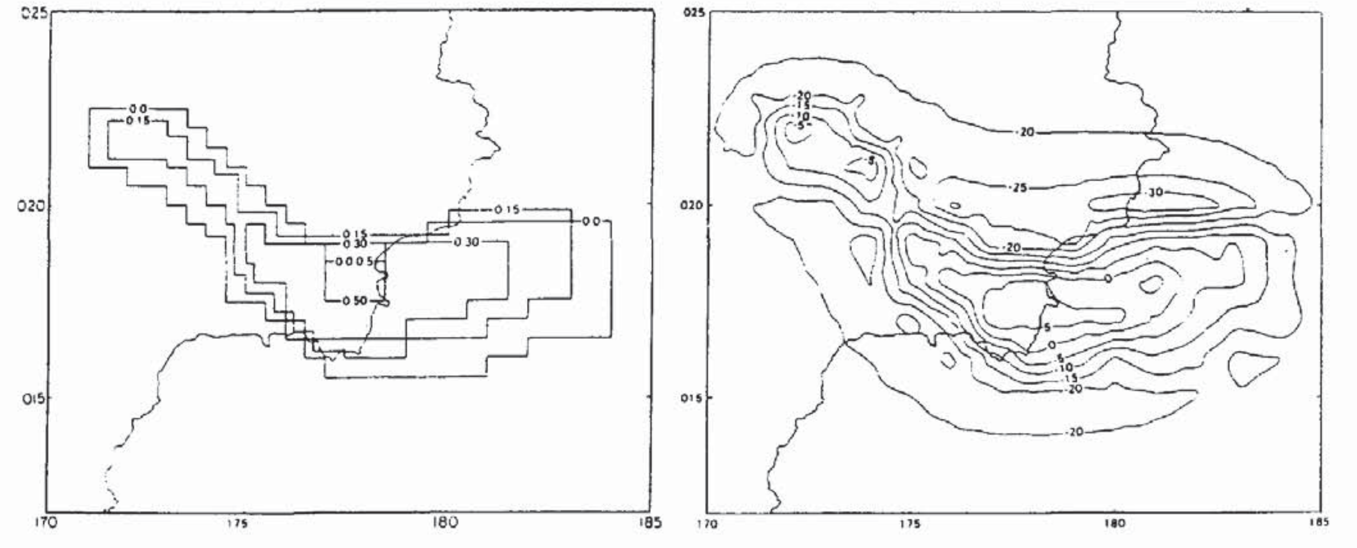


Figure 3.54 Tectonics units of the Lizard and a schematic representation of their geophysical responses. From Rollin (1986), by permission



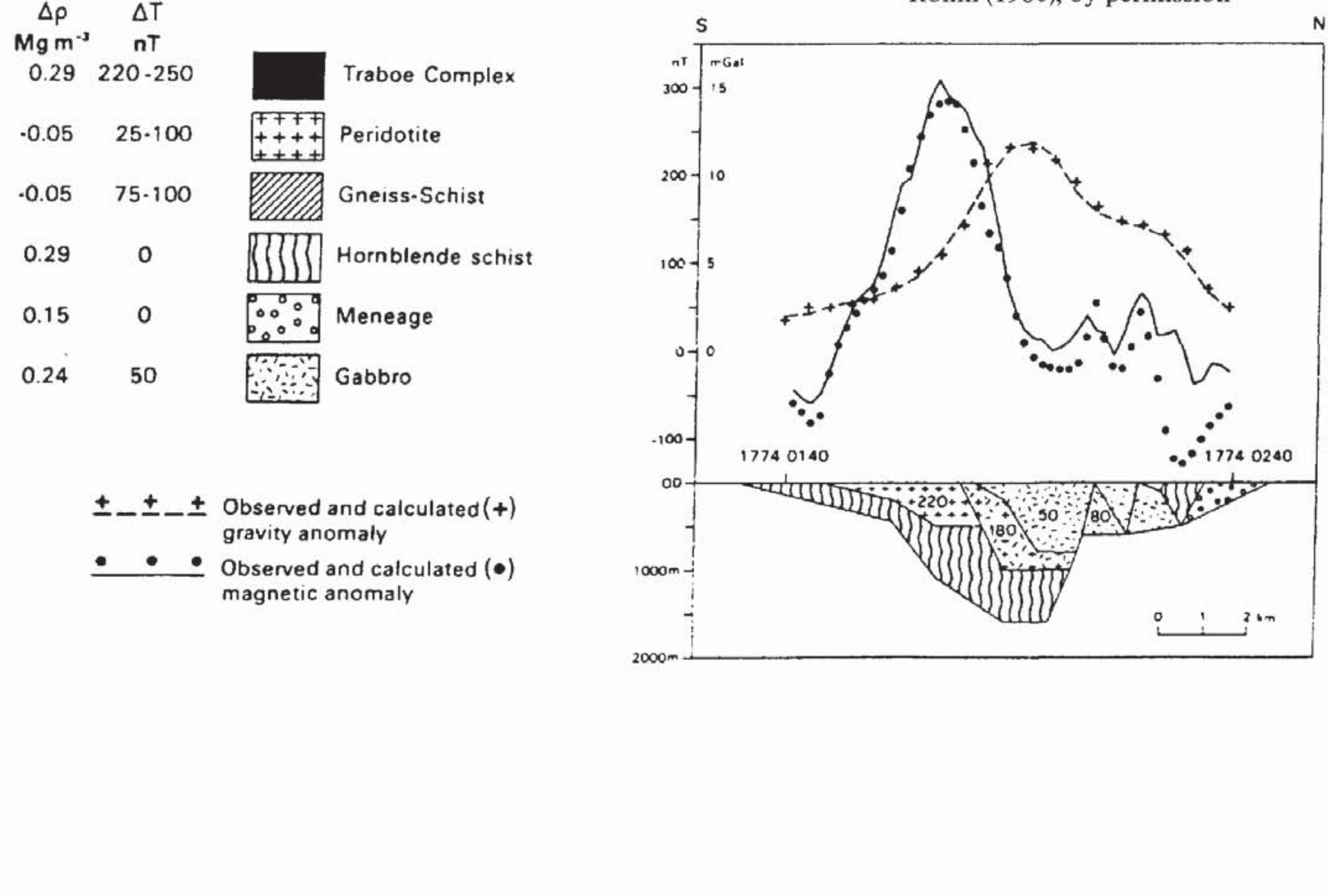
(A)

(B)

significant, as might be expected for such a suite of rocks. On the basis of field and laboratory measurements, the overall Königsberger ratio (remanent:induced magnetisation) was taken to be 0.43 with a declination and inclination of the remanent magnetisation of 286° and 75° respectively, with a resultant magnetisation up to 220 nT and a mean susceptibility of 0.0774 (SI). A simple three-dimensional model comprising stacked horizontal polygons was then constructed for the eastern area, which produced a calculated anomaly (Figure 3.55)

Figure 3.55 Three-dimensional modelling of the south-east part of the Lizard. (A) Stacked horizontal polygons, and (B) the resulting calculated magnetic anomaly. From Rollin (1986), by permission

Figure 3.56 Aeromagnetic and gravity anomaly profiles along Line 2 (Figure 3.53A) across the south-eastern part of the Lizard. From Rollin (1986), by permission



comparable to the observed aeromagnetic anomaly. The magnetic interpretation indicated that the Traboe Complex has a thickness of only 150 m while the eastern harzburgite peridotite is about 500 m thick (Figure 3.56). Independent gravity modelling gave the thickness of the eastern peridotite as 560 m, which is in reasonable accord with the magnetic interpretation.

3.9.2 Mineral exploration

In Finland, in regions of Pre-Cambrian basement comprising black graphite-schists, the location of sulphide ores is becoming increasingly difficult. The easy-to-find ores have already been identified. The more difficult ones, such as pyrrhotite-rich black schists and associated mineralisation, have been more easily eroded by glacial ice than the surrounding rocks and have become buried beneath a veneer of overburden, commonly up to 30 m thick. The overburden is characterised by high resistivities so the relatively conductive ore zones can be located using electrical methods. However, this is not always practicable so magnetic methods have also been used in conjunction with geochemical surveys. Furthermore, it is difficult to discriminate between the geophysical anomalies produced by economic sulphide mineralisation and those caused by the black schists and other rocks. Consequently, the identification of copper ores is particularly difficult.

The Saramäki orebody, located about 370 km north-east of Helsinki, forms a compact copper mass with some cobalt, and occurs in geological complexes comprising serpentinites, dolomites, skarns, quartzites and black schists, in a country rock of mica schist. The exploration strategy has been discussed in detail by Ketola (1979). The whole mineralised complex can be traced using aerogeophysical methods for over 240 km. The specific orebody, which was located in 1910 by drilling, is 4 km long, 200–400 m wide and extends down to about 150 m. Average copper content is 3.8% with 0.2% cobalt.

Problems with identification of the orebody can be seen by reference to Figure 3.57. The electrical resistivity (SLINGRAM) anomalies are caused by the black schists. The whole skarn zone forms a denser block (0.23 Mg/m^3 higher) compared with the country rock and so the sub-units within the mineralised zone cannot be differentiated using gravity. Susceptibility measurements made using the boreholes suggested that the mineralised zone was magnetised heterogeneously and that its upper part influenced the magnetic anomaly. In addition it was found by two-dimensional modelling that the main magnetised zones had significant remanent magnetisation. If remanence is ignored, the dip of the two main zones is inconsistent with the known dips, derived from drilling, even though the computed anomaly fits the observed one very well (Figure 3.58A). By incorporating remanence, with inclination 45° and declination 90° (compared

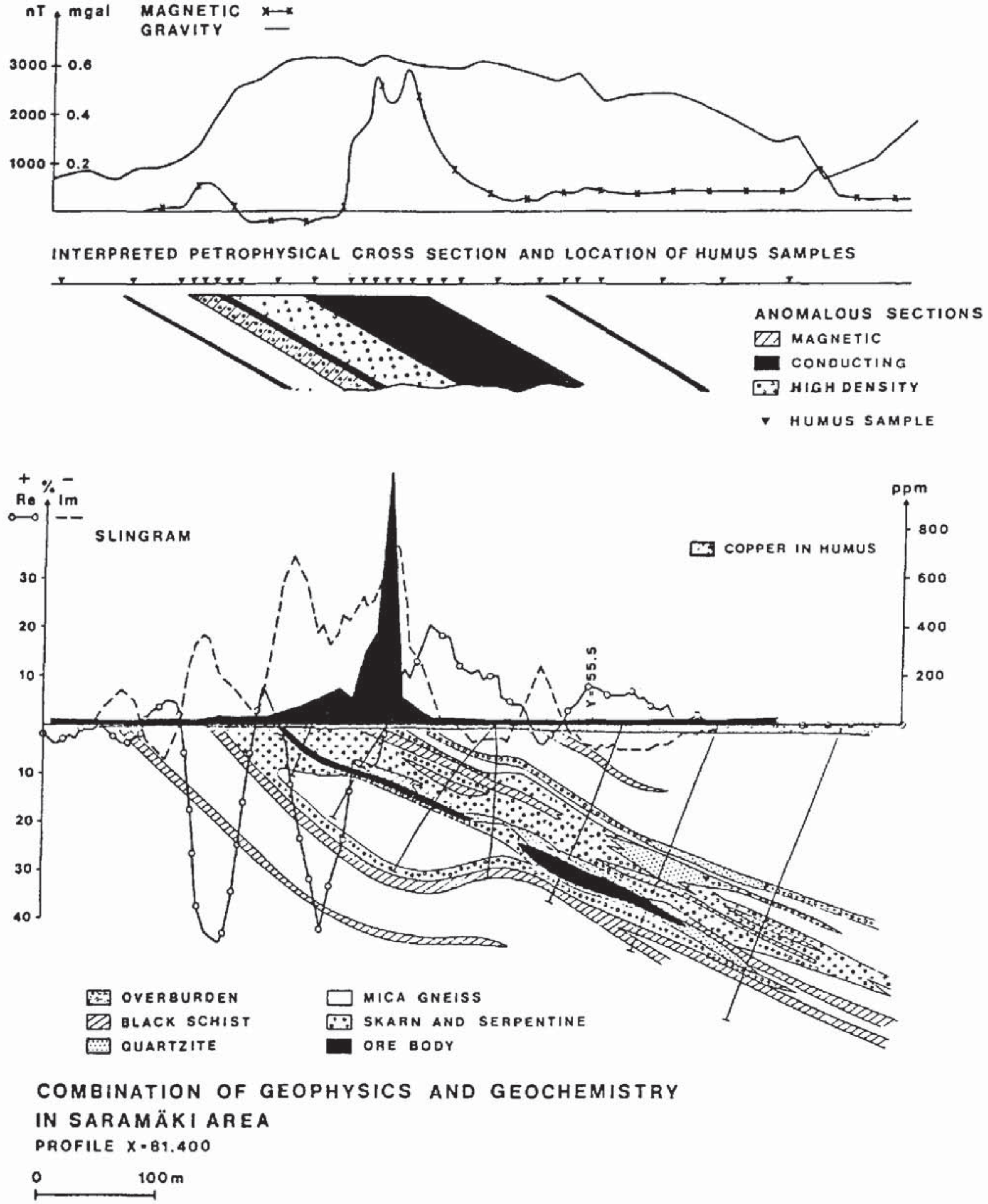


Figure 3.57 Magnetic, gravity and SLINGRAM electrical data with a geological cross-section for the Saramäki orebody, Finland. From Ketola (1979), by permission

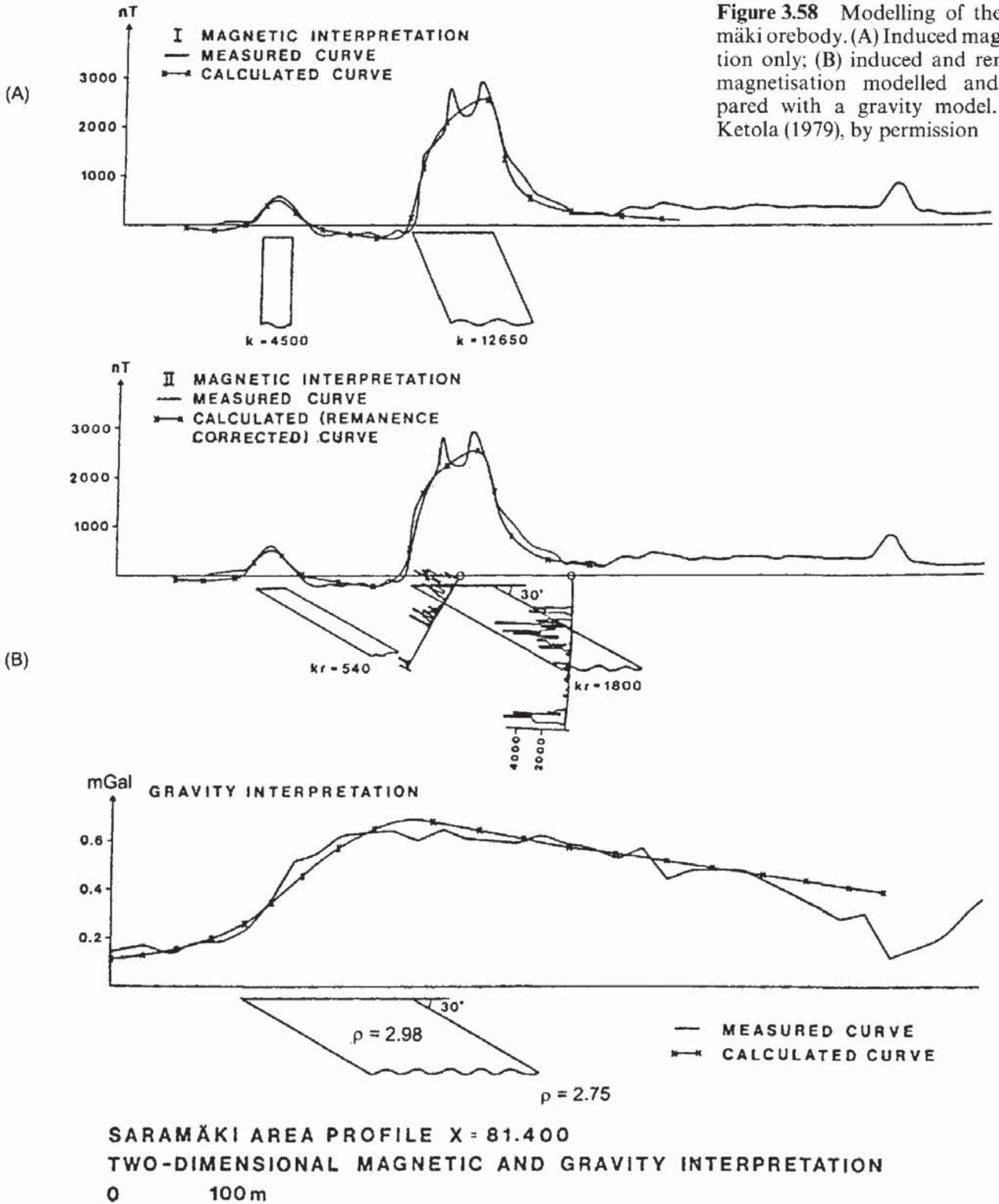


Figure 3.58 Modelling of the Saramäki orebody. (A) Induced magnetisation only; (B) induced and remanent magnetisation modelled and compared with a gravity model. From Ketola (1979), by permission

with 75° and 7°, respectively for the Earth's field), geologically compatible models were then produced which were also in accord with those used in the gravity modelling (Figure 3.58B).

Ketola concluded from this and other similar examples in Finland that geophysical or geochemical methods alone were insufficient to resolve these complex orebodies. It was necessary to use a wide variety of geophysical and geochemical techniques together, in conjunction with drilling, to provide a successful differentiation of the sub-surface geology.

Other illustrations of magnetic anomalies over mineralised bodies have been shown in Figure 1.9D, for a lode at Wheel Fanny, north-west Devon, where the course of the lode is picked out clearly by the linear magnetic anomalies. Figure 3.32 illustrates a ground magnetometer profile over sulphide mineralisation at Sourton Tors, north-west Dartmoor, Devon.

3.9.3 Engineering applications

3.9.3.1 Detection of underground pipes

Sowerbutts (1988) has provided a clear example of how high-resolution magnetic gradient surveys can identify not only the location of underground metal pipes but also the position of joints between individual sections of pipe. If joints can be located remotely, the amount of excavation required to examine and repair a pipe can be minimised, saving time, money and inconvenience.

The magnetic anomaly along a pipe consists of a series of smaller anomalies each of which corresponds to an individually cast segment of pipe which behaves like a magnetic dipole. For a pipe buried close to the surface and away from extraneous magnetic sources, a clear repetition of anomalies can be identified (Figure 3.59A). In the case illustrated, the pipe had a diameter of 0.5 m and was made of ductile iron in 6.3 m long sections and buried at a depth of 0.5 m. Magnetic highs, with gradients up to 4000 nT/m, are centred between 0.5 m and 1.0 m along from the socket end. For a pipe orientated east–west, a typical negative (north) and positive (south) anomaly doublet is produced along a profile aligned north–south in the northern hemisphere (cf. Figure 3.37A). A magnetised body orientated north–south produces a more symmetric positive-only or negative-only anomaly, and this is also seen in pipes orientated north–south (Figure 3.59B). For a smaller 76 mm diameter pipe (Figure 3.59C) this anomaly doublet effect is clearly repeated along the line of this north–south orientated pipe. In an urban environment, identifying the anomalies associated specifically with the buried pipe can be very difficult. Other magnetic materials are likely to be nearby and this can obscure or defocus the pipeline anomaly (Figure 3.59D). In the last case, the pipe was 0.15 m diameter and buried about 1.5 m down. Local metal grids

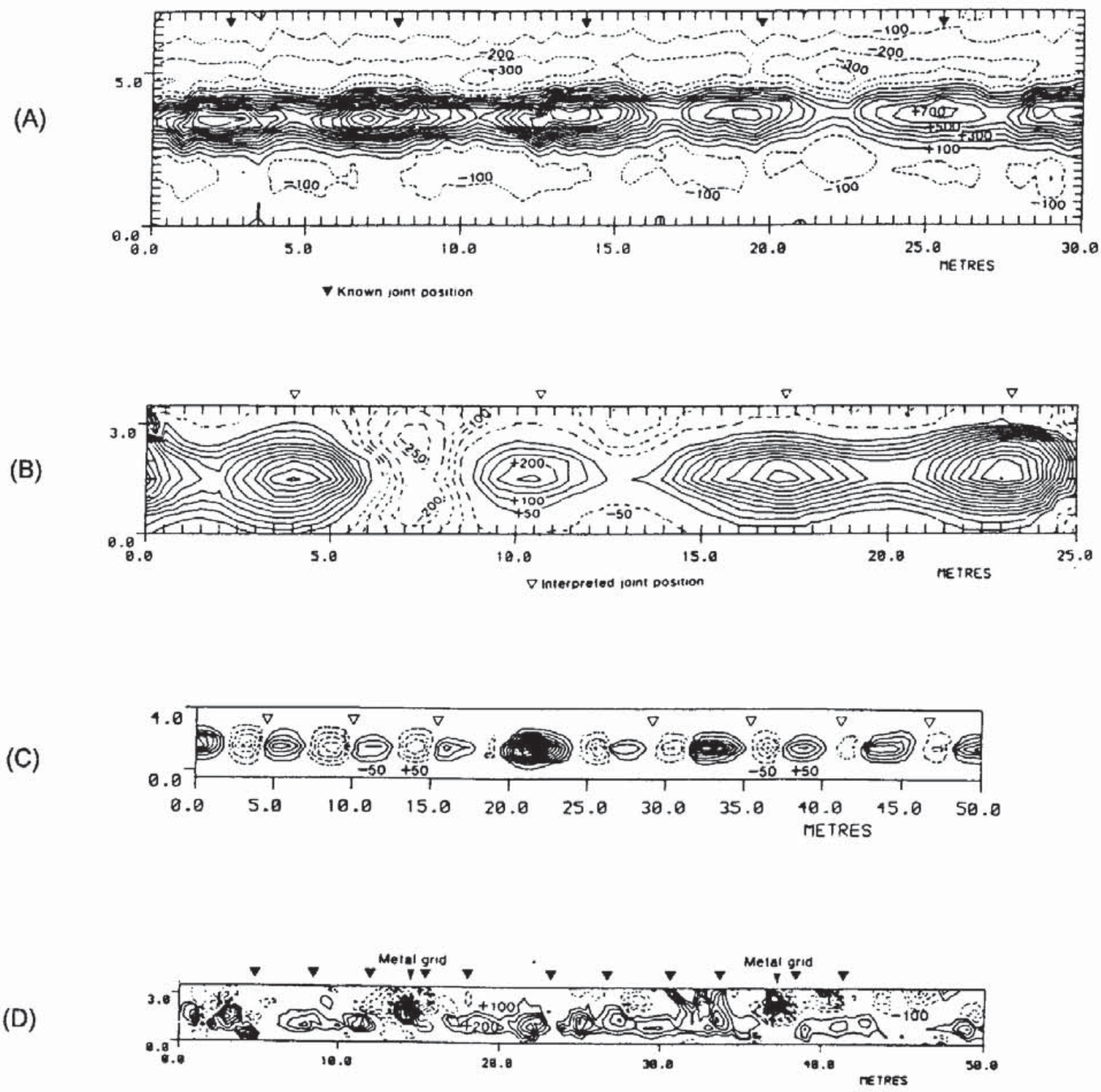
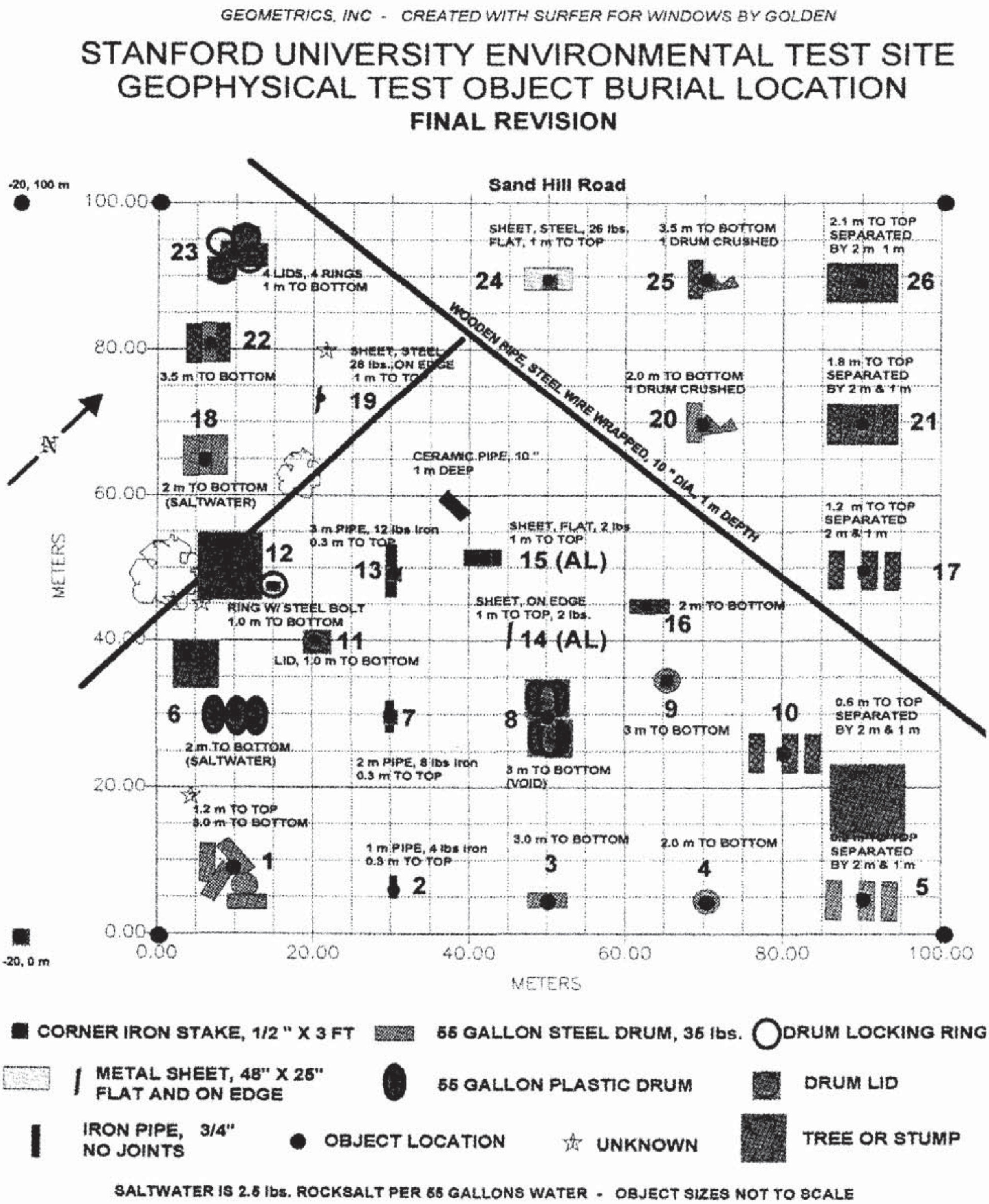


Figure 3.59 Magnetic gradiometer anomalies over buried pipelines: (A) Ductile iron pipe, diameter 0.5 m buried at 0.5 m depth, E–W trend of pipe; contour interval 200 nT/m. (B) Cast iron pipe, N–S trend of pipe; contour interval 50 nT/m. (C) 76 mm diameter cast iron gas pipe trending N–S. (D) 0.15 m diameter pipe, buried about 1.5 m down, in an urban environment with extraneous magnetic anomalies caused by adjacent metal grids. From Sowerbutts (1988), by permission

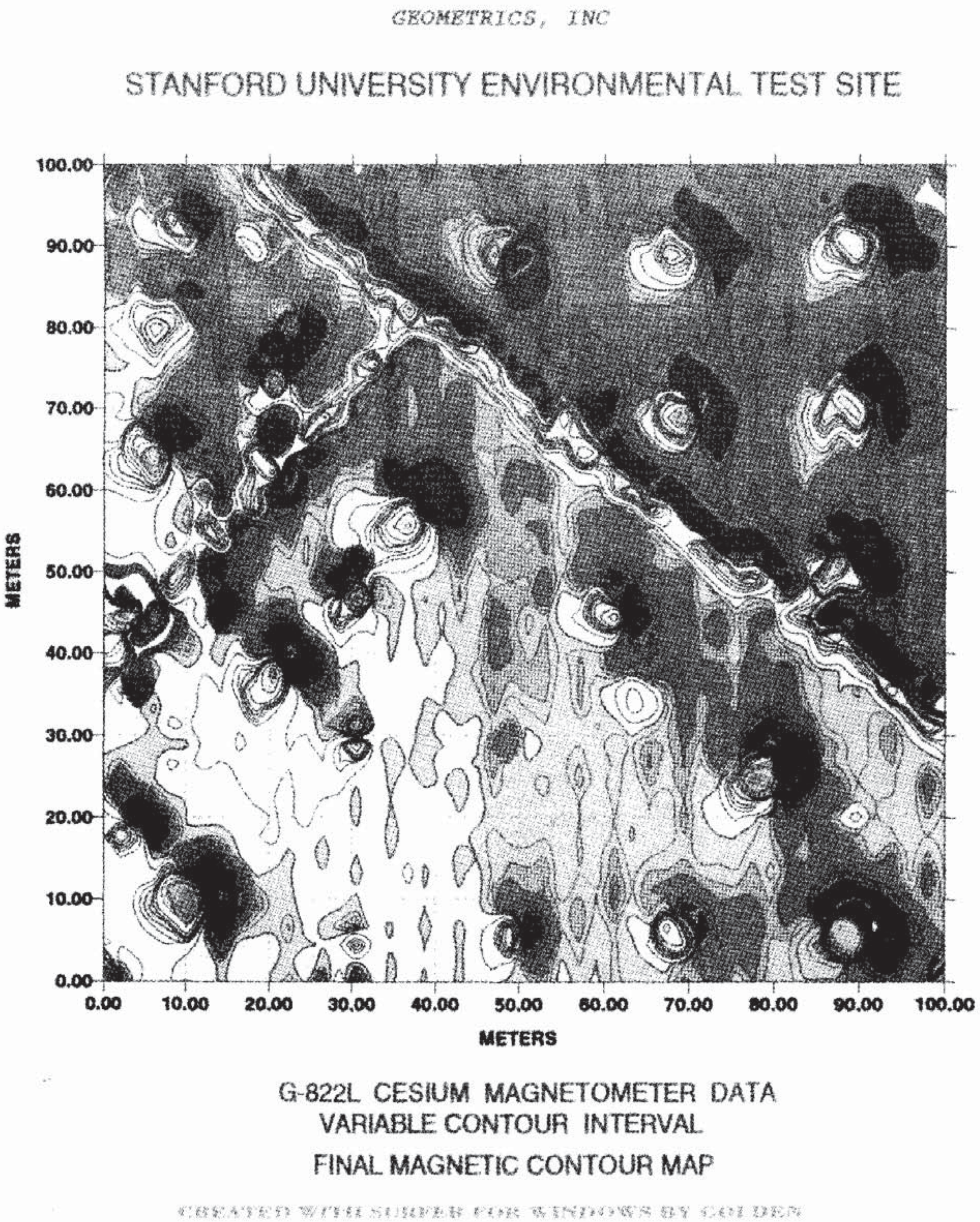
produce large magnetic anomalies. The anomaly pattern associated with this pipe is now irregular and complex, and it is not possible to identify pipe joints. Even seamless steel pipes with welded joints can be identified in areas with a quiet magnetic background.

A further example of the use of magnetometry to locate near-surface pipes has been given by Geometrics Inc., who acquired data over a test site at Stanford University, USA, using a caesium magnetometer. The data were contoured and displayed as both a map and an isometric projection which are shown with a map of the utilities in Figure 3.60. The correlation between buried objects and the corresponding magnetic anomalies is obvious.

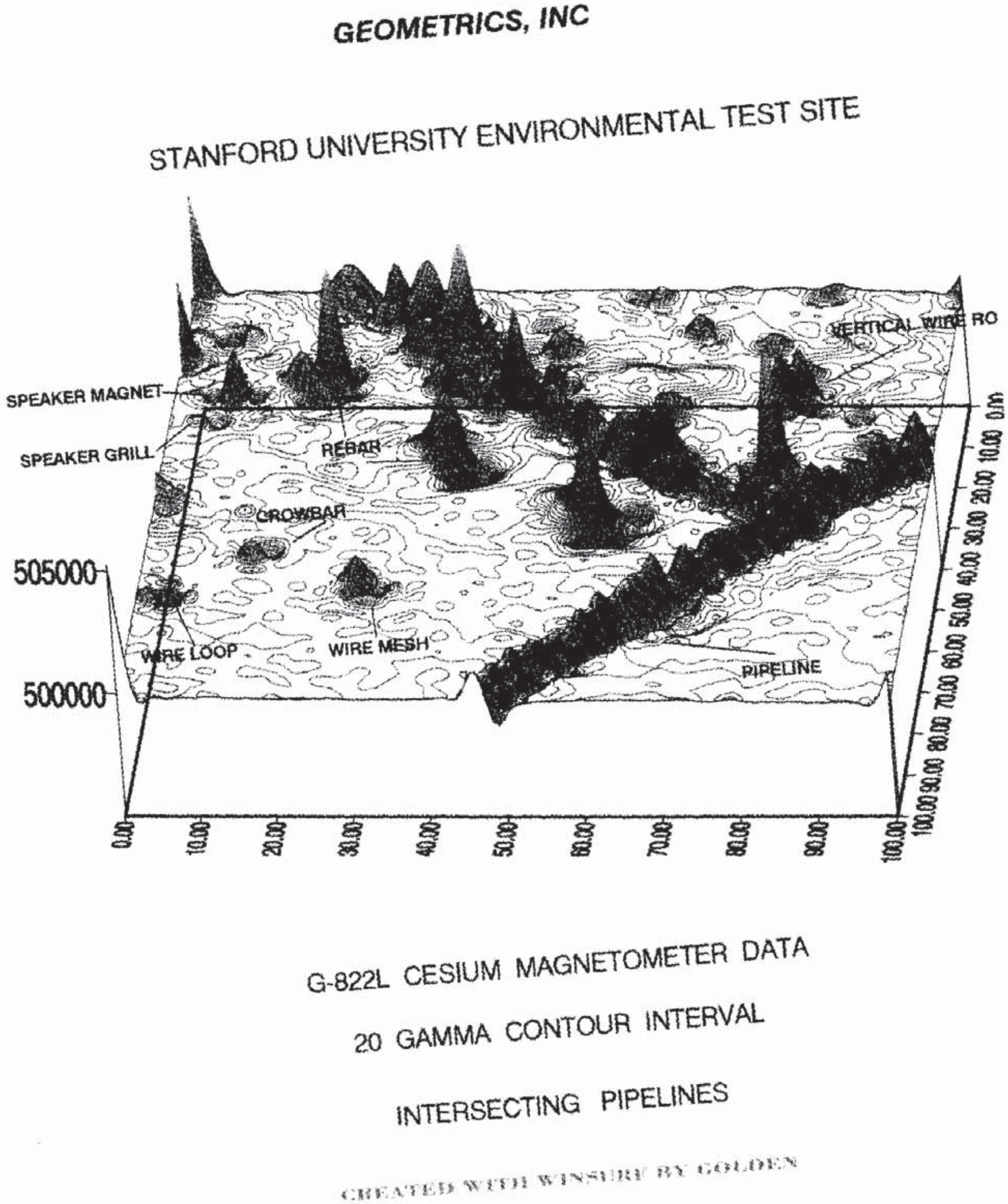
(A)


GEOMETRICS, INC - CREATED WITH SURFER FOR WINDOWS BY GOLDEN
STANFORD UNIVERSITY ENVIRONMENTAL TEST SITE
GEOPHYSICAL TEST OBJECT BURIAL LOCATION
FINAL REVISION
Sand Hill Road
-20, 100 m
-20, 0 m
N
METERS
METERS
0.00
20.00
40.00
60.00
80.00
100.00
0.00
20.00
40.00
60.00
80.00
100.00
WOODEN PIPE, STEEL WIRE WRAPPED, 10 " DIA., 1 m DEPTH
23
4 LIDS, 4 RINGS
1 m TO BOTTOM
SHEET, STEEL, 26 lbs.
FLAT, 1 m TO TOP
24
3.5 m TO BOTTOM
1 DRUM CRUSHED
25
2.1 m TO TOP
SEPARATED
BY 2 m 1 m
26
22
3.5 m TO BOTTOM
SHEET, STEEL
26 lbs., ON EDGE
1 m TO TOP
19
2.0 m TO BOTTOM
1 DRUM CRUSHED
20
1.8 m TO TOP
SEPARATED
BY 2 m & 1 m
21
18
2 m TO BOTTOM
(SALTWATER)
CERAMIC PIPE, 10 "
1 m DEEP
1.2 m TO TOP
SEPARATED
2 m & 1 m
17
3 m PIPE, 12 lbs iron
0.3 m TO TOP
12
13
SHEET, FLAT, 2 lbs
1 m TO TOP
15 (AL)
RING W/ STEEL BOLT
1.0 m TO BOTTOM
SHEET, ON EDGE
1 m TO TOP, 2 lbs.
14 (AL)
2 m TO BOTTOM
16
11
LID, 1.0 m TO BOTTOM
6
2 m TO BOTTOM
(SALTWATER)
7
2 m PIPE, 8 lbs iron
0.3 m TO TOP
8
3 m TO BOTTOM
(VOID)
9
3 m TO BOTTOM
10
0.6 m TO TOP
SEPARATED
BY 2 m & 1 m
1.2 m TO TOP
3.0 m TO BOTTOM
1
1 m PIPE, 4 lbs iron
0.3 m TO TOP
2
3.0 m TO BOTTOM
3
2.0 m TO BOTTOM
4
TOP
SEPARATED
BY 2 m & 1 m
5
CORNER IRON STAKE, 1/2 " X 3 FT
55 GALLON STEEL DRUM, 35 lbs.
DRUM LOCKING RING
METAL SHEET, 48" X 25"
FLAT AND ON EDGE
55 GALLON PLASTIC DRUM
DRUM LID
IRON PIPE, 3/4"
NO JOINTS
OBJECT LOCATION
UNKNOWN
TREE OR STUMP
SALTWATER IS 2.5 lbs. ROCKSALT PER 55 GALLONS WATER - OBJECT SIZES NOT TO SCALE

(B)


GEOMETRICS, INC
STANFORD UNIVERSITY ENVIRONMENTAL TEST SITE
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
METERS
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
METERS
G-822L CESIUM MAGNETOMETER DATA
VARIABLE CONTOUR INTERVAL
FINAL MAGNETIC CONTOUR MAP
CREATED WITH SURFER FOR WINDOWS BY GOLDEN

(C)



GEOMETRICS, INC
STANFORD UNIVERSITY ENVIRONMENTAL TEST SITE
SPEAKER MAGNET
SPEAKER GRILL
REBAR
CROWBAR
VERTICAL WIRE RO
WIRE LOOP
WIRE MESH
PIPELINE
505000
500000
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
G-822L CESIUM MAGNETOMETER DATA
20 GAMMA CONTOUR INTERVAL
INTERSECTING PIPELINES
CREATED WITH WINSURF BY GOLDEN

Anomalies have been produced which have been characteristic of induced magnetisation in many cases, but what has not been considered is that pipes acquire a permanent magnetisation on cooling during manufacture. It may be necessary to examine the orientation of the pipes as they cool at their respective foundries (hence determine the inclination and declination of permanent magnetisation). Having ascertained the permanent magnetisation, and knowing where these pipes have been buried, it should then be possible to determine more accurately the magnetic anomaly due to each segment of pipe.

Figure 3.60 (*previous pages*) (A) Map of the Stanford University, USA, environmental test site showing the details of the various buried targets. (B) Magnetic anomaly map produced using a caesium magnetometer sampling at 10 readings per metre along survey lines at 2 m spacings. (C) Isometric projection of the data in (B). Courtesy of Geometrics Inc.

3.9.3.2 Detection of buried infill

In areas where clay infills hollows in bedrock such as chalk, the slight contrast in magnetic susceptibility can still be sufficient for magnetic survey methods to be useful.

In many engineering investigations, an arbitrary spacing or grid of boreholes is used that in all too many cases is inadequate to indicate the actual variation on ground conditions. To drill holes at small enough separations may be prohibitively expensive as well as being unnecessarily intrusive. In such cases, geophysical methods can be used to image the ground variability.

McDowell (1975) has provided an example of how magnetic mapping of magnetic anomalies with only 15 nT amplitudes provided a clearer picture of a clay with flints cover over chalk in Upper Enham, Hampshire. A magnetic anomaly map (Figure 3.61A) of the site shows the possible clay infill and clearly demonstrates that the inter-borehole separation was far too large to provide a representative impression of ground conditions. Should a contractor have started excavations on the basis of ground conditions predicted by the borehole data, a claim for compensation could have justifiably been made to recompense the additional work required to cope with the unexpected variations in ground conditions. The cost of the claim probably would have exceeded that of the geophysical survey in the first place! The magnetic profile across the clay pipe, which is orientated north–south, shows a form similar to that illustrated in Figure 3.41 but with opposite polarity, as the clay with flints has the slightly higher magnetic susceptibility than the chalk.

3.9.4 Detection of buried containers

There are many situations where it is imperative that potentially harmful objects, such as bombs or drums of toxic waste, be located passively. Drilling holes to locate drums of poisonous waste, or using electromagnetic signals to detect hidden bombs, could have devastating consequences. As both types of object will produce a magnetic anomaly, it is possible to use magnetic methods to locate them without risk. The amplitudes of magnetic anomalies detectable for

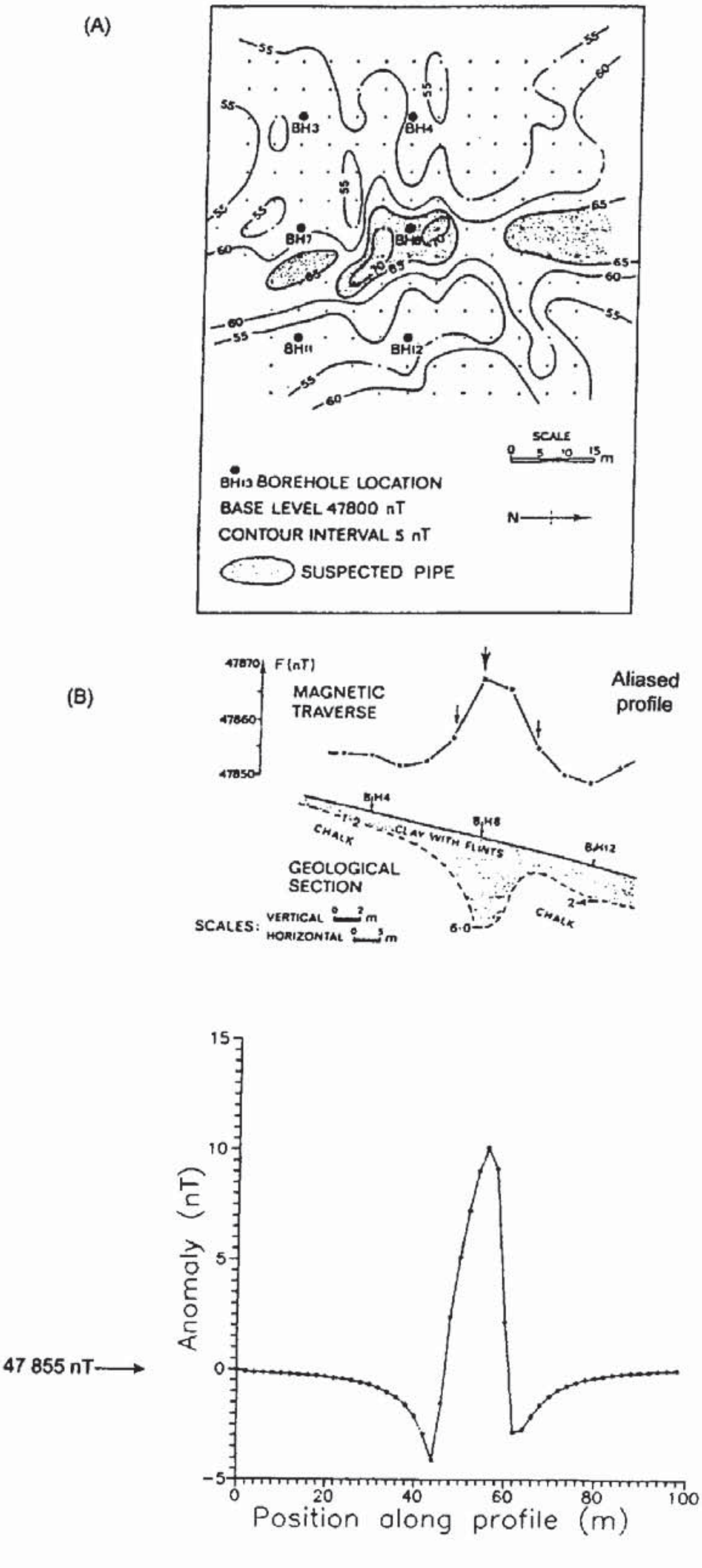


Figure 3.61 Megnetic anomalies over a clay-with-flints infill over chalk at Upper Enham, Hampshire, showing (A) how the magnetic survey resolved the variable ground conditions far better than the inadequately spaced boreholes, and (B) the shape of the profile across the clay pipe infill, which trends N–S, compared with a modelled anomaly (cf. Figure 3.41). (A) and (B) from McDowell (1975), by permission

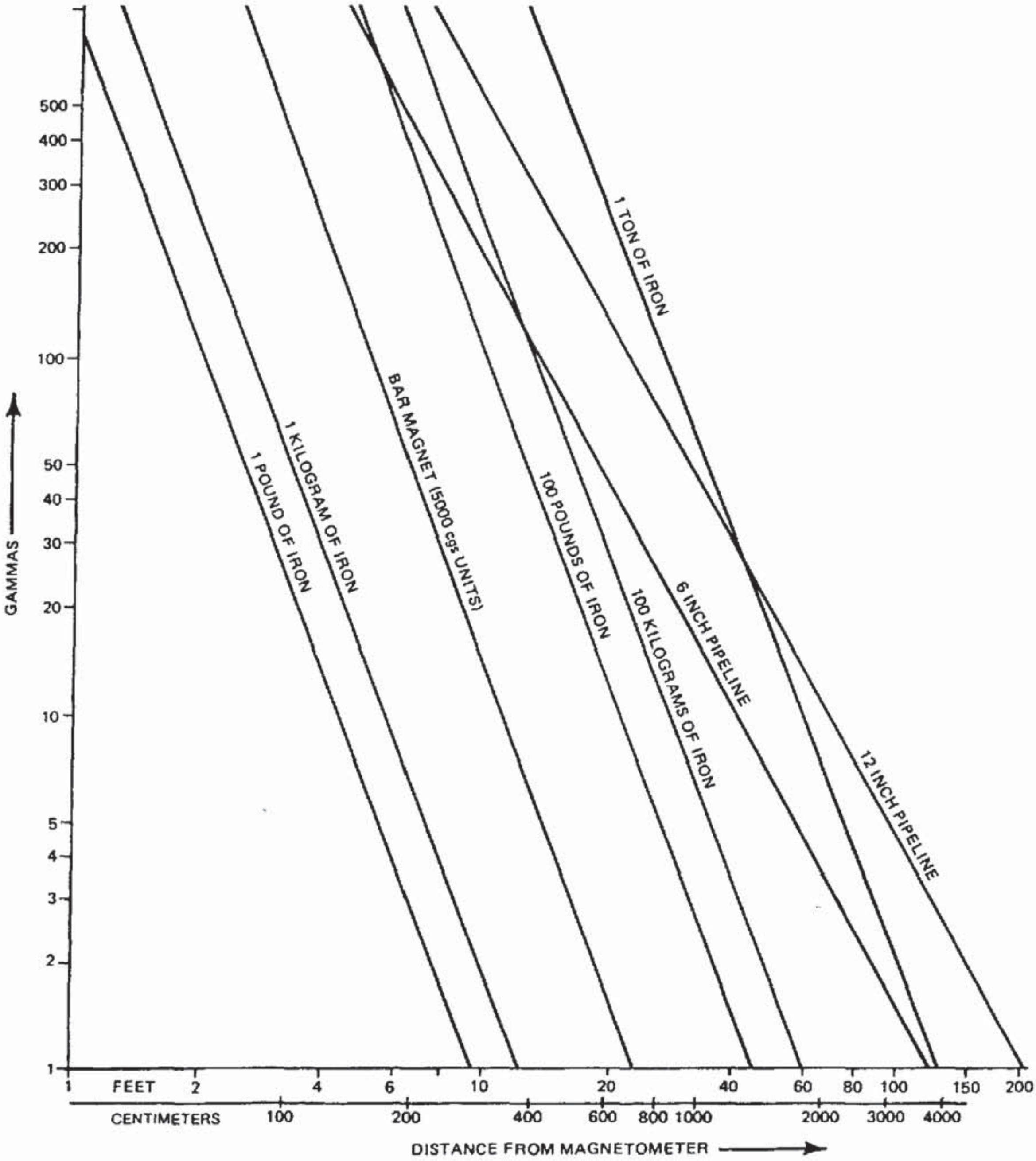


Figure 3.62 Minimum detectable anomaly amplitudes for different types of ordnance at various depths of burial. Note that the distances cited are those between the sensor and the target, not the depth below ground of the target. From Breiner (1981), by permission

various types of ordnance of different size and depth of burial are illustrated in Figure 3.62, assuming a maximum detectability of 0.1 nT. However, in practice, the smallest anomaly likely to be discernible above background noise is likely to be around 1 nT. This means that it would technically be possible to detect a 1000 lb bomb buried at a depth of 22 m.

Metal drums also give rise to strong magnetic anomalies and, if dumped together in a random way, will produce large-amplitude but highly variable anomalies that will stand out from background noise. An example of the kind of anomaly produced is shown in Figure 3.63.

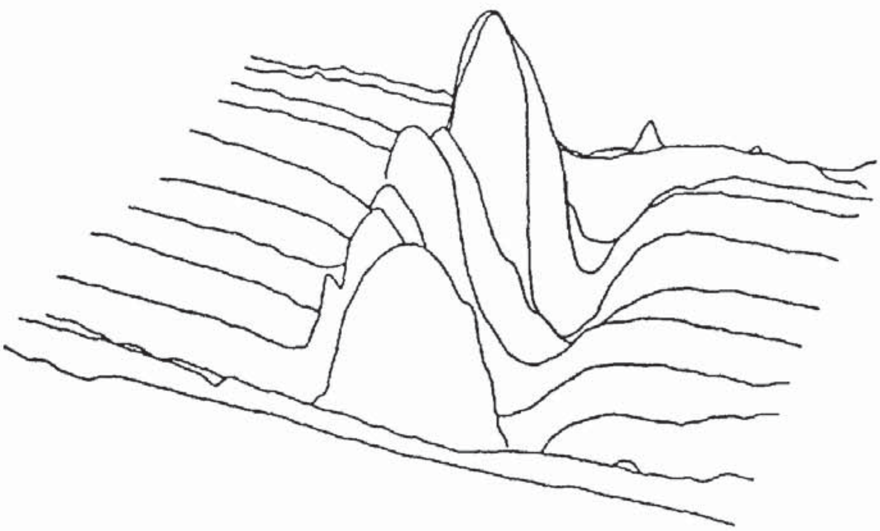


Figure 3.63 Magnetic anomaly over a trench containing metal drums of waste. From Evans (1982), by permission

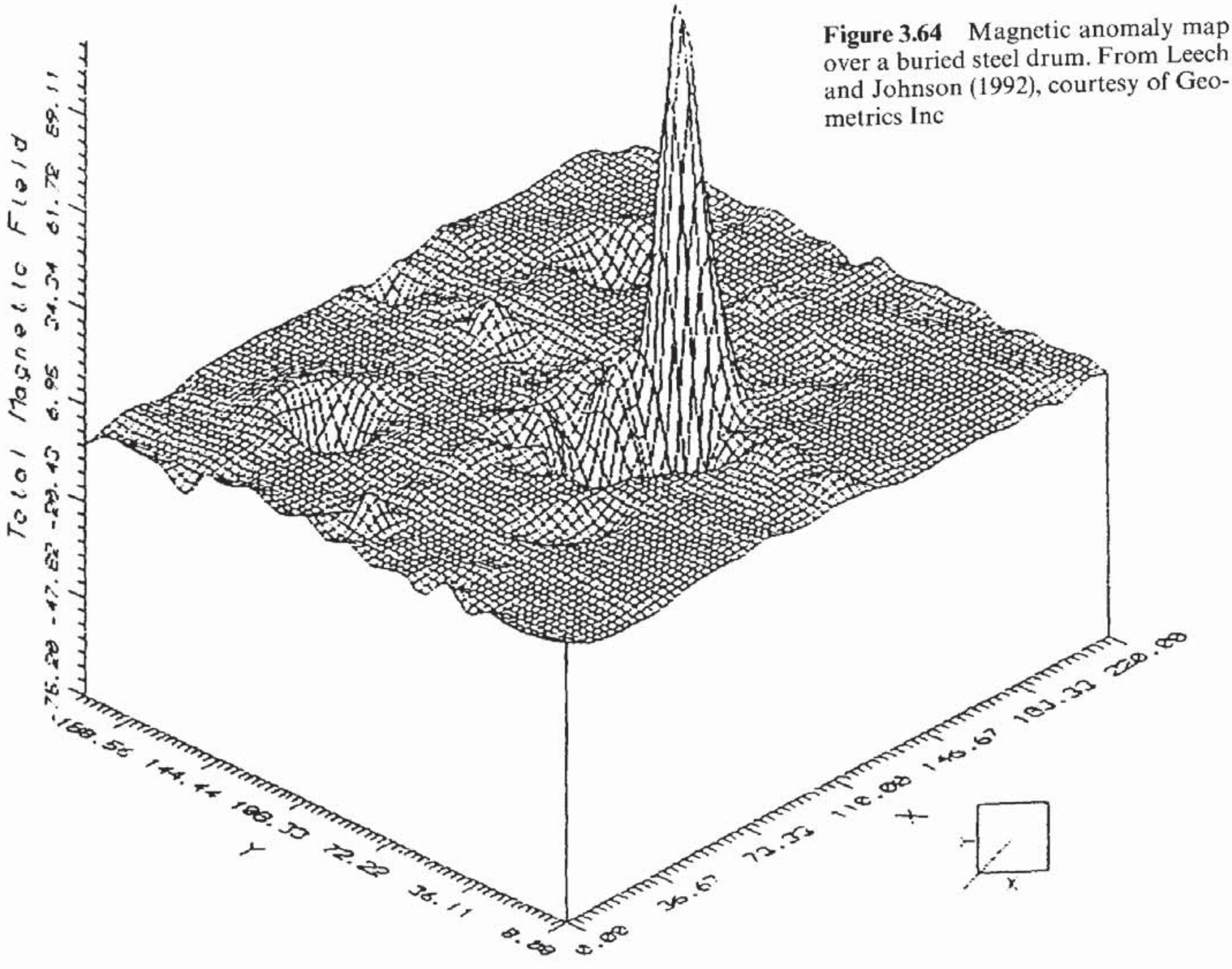


Figure 3.64 Magnetic anomaly map over a buried steel drum. From Leech and Johnson (1992), courtesy of Geometrics Inc

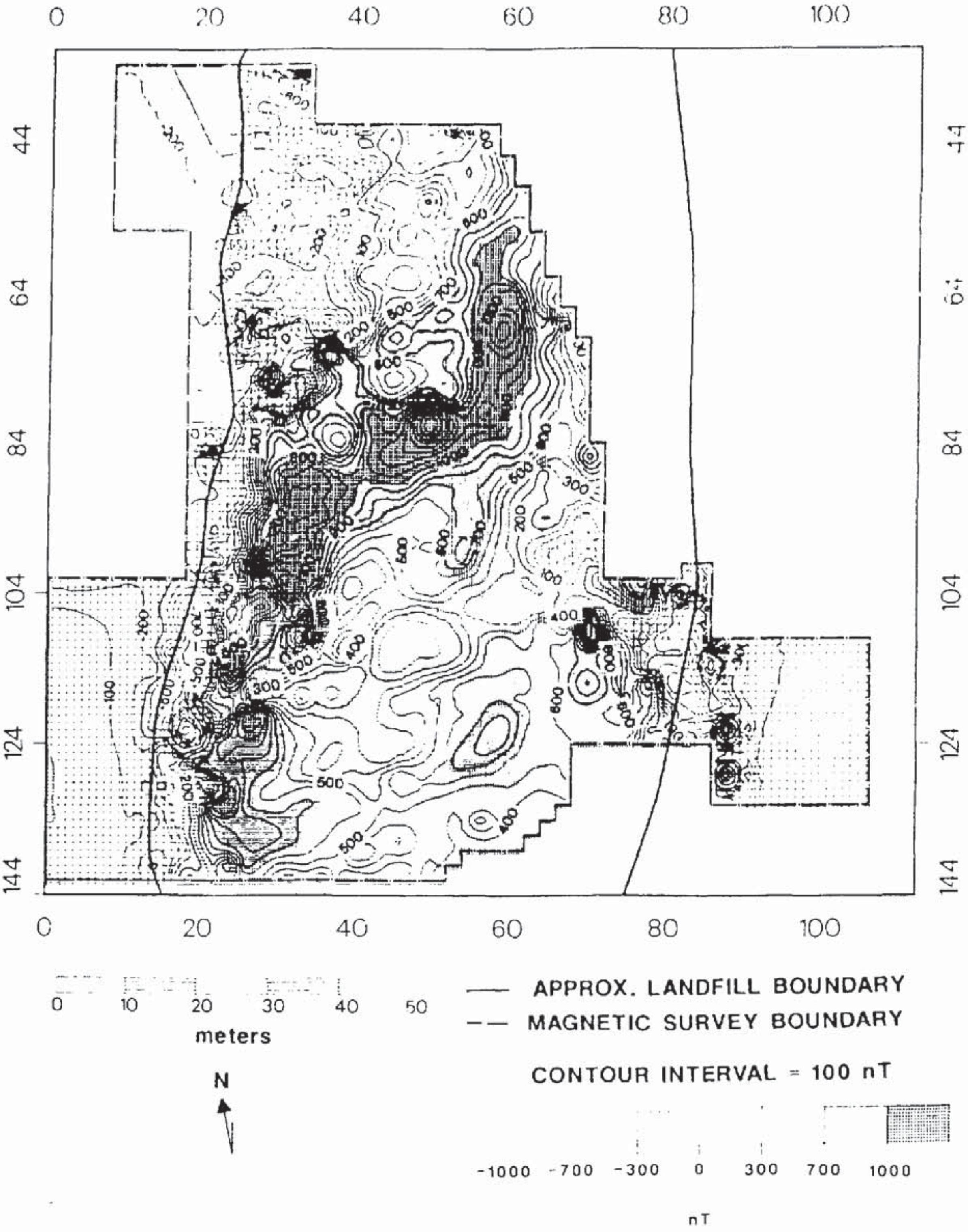


Figure 3.65 Contour map of total field magnetic intensity data measured at 1 m height, at the Thomas Farm landfill site, USA. From Roberts *et al.* (1990), by permission

To resolve the number of drums and their possible size, it may be preferable to use a gradiometer survey and datalogger so that the anomalies can be imaged with greater resolution. The magnetic anomaly over a buried steel drum is shown in Figure 3.64, from which it can be seen that local anomaly amplitudes are as high as several thousand nanoteslas, and field gradients several thousand nanoteslas per metre (Leech and Johnson 1992). The main difficulty with locating illegally buried drums of toxic waste is that they are usually dumped in ground with other rubbish which would help to mask their anomalies. However, by careful analysis of the anomaly shapes, amplitudes, orientations and overall characteristics, it should be possible to differentiate between various buried objects, if not actually identify them.

3.9.5 Landfill investigations

One of the aspects of landfills is that they are likely to contain large amounts of ferrometallic debris deposited at irregular angles. Consequently, a magnetic anomaly map produced over a former landfill will show a considerable amount of high-frequency noise from near-surface ferrometallic objects. There is perhaps a tendency to think that such noise is likely to dominate the magnetic anomaly map to produce a highly chaotic and largely unhelpful anomaly map.

One aspect of old closed landfills is that their previous tipping history may have been lost, or was never recorded. It might be useful to be able to obtain some idea as to whether a site has had different tipping sequences, such as periods of waste of a similar character being tipped and then having another type of waste with different magnetic properties. Consequently, the magnetic method lends itself to the rapid surveying of closed landfills in order to assess previous tipping histories and the zonation of waste types within a site.

An example of a magnetic survey over the Thomas Farm landfill in the USA has been given by Roberts *et al.* (1990). The site was surveyed on a 2×2 m grid with a sensor height at 1 m above the ground. Roberts and co-workers demonstrated that, by careful data processing, the high-frequency noise could be filtered out to reveal longer-wavelength anomalies more closely associated with broad types of waste. An example of one of their maps is given in Figure 3.65. In this case, the lateral extent of the landfill was already known. The magnetic anomaly map reveals several zones with quite distinctive magnetic anomaly characters. For example, note the band of strong magnetic anomalies (> 1000 nT) orientated NE–SW. To the south-east of this the magnetic anomalies are broader in wavelength and have low positive amplitudes, whereas those anomalies found north-west of this band are slightly higher frequency but predominantly negative. The actual wastes were domestic refuse in the north-west and brush, wood-cuttings and construction debris in the southern part.