

Technical Report WK/90/5

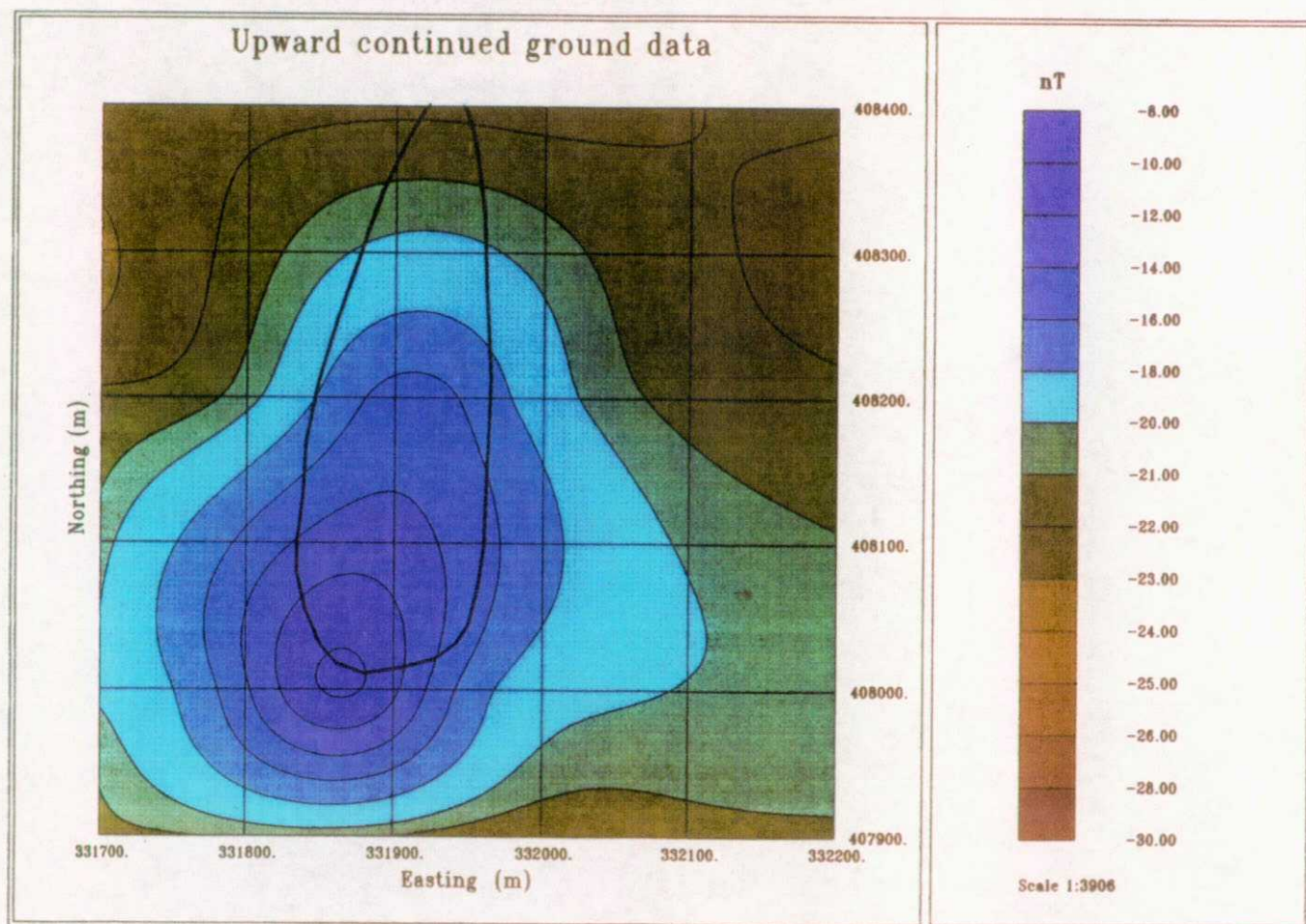
Regional Geophysics Series

Direct indication of hydrocarbons by airborne and ground magnetic survey

Contract No. EN3C. 0031.UK(RH)

SUMMARY REPORT

R D Ogilvy, J P Busby, R J Peart, C A Green, W J Rowley,
P H A Nancarrow, J P Williamson and A J Gibberd



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Optimization of the production and utilization of hydrocarbons

British Geological Survey
Natural Environment Research Council

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BRITISH GEOLOGICAL SURVEY

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Keyworth, Nottingham NG12 5GG

☎ Plumtree (060 77) 6111 Telex 378173 BGSKEY G
Fax ☎ 060 77-6602

Murchison House, West Mains Road, Edinburgh EH9 3LA

☎ 031-667 1000 Telex 727343 SEISED G
Fax ☎ 031-668 2683

London Information Office at the Geological Museum,
Exhibition Road, South Kensington, London SW7 2DE

☎ 01-589 4090 Fax ☎ 01-584 8270
☎ 01-938 9056/57

64 Gray's Inn Road, London WC1X 8NG

☎ 01-242 4531 Telex 262199 BGSCLR G
Fax ☎ 01-242 0835

19 Grange Terrace, Edinburgh EH9 2LF

☎ 031-667 1000 Telex 727343 SEISED G

St Just, 30 Pennsylvania Road, Exeter EX4 6BX

☎ Exeter (0392) 78312

Bryn Eithyn Hall, Llanfarian, Aberystwyth, Dyfed SY23 4BY

☎ Aberystwyth (0970) 611038 Fax ☎ 0970-624822

Windsor Court, Windsor Terrace, Newcastle upon Tyne
NE2 4HB

☎ 091-281 7088 Fax ☎ 091-281 9016

Geological Survey of Northern Ireland, 20 College Gardens,
Belfast BT9 6BS

☎ Belfast (0232) 666595 and 666752

Maclean Building, Crowmarsh Gifford, Wallingford,
Oxfordshire OX10 8BB

☎ Wallingford (0491) 38800 Telex 849365 HYDROL G
Fax ☎ (0491) 25338

Parent Body

Natural Environment Research Council

Polaris House, North Star Avenue, Swindon, Wiltshire
SN2 1EU

☎ Swindon (0793) 411500 Telex 444293 ENVRE G
Fax ☎ 0793-411501

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**DIRECT INDICATION OF HYDROCARBONS BY AIRBORNE
AND GROUND MAGNETIC SURVEY**

R.D.Ogilvy, J.P.Busby, R.J.Peart, C.A.Green
P.H.A.Nancarrow, W.J.Rowley, J.P.Williamson and A.J.Gibberd

Contractor: British Geological Survey
Keyworth
Nottingham NG12 5GG UK

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1. INTRODUCTION

Reports from N.America (Donovan et al, 1984) and elsewhere (Henderson et al, 1984) have suggested that epigenetic magnetic mineral enrichment may occur over hydrocarbon deposits as a direct result of long term microseepage and diagenesis. The current research was undertaken to investigate this possibility since near-surface magnetite could give rise to low amplitude, high spatial frequency magnetic anomalies, and thereby permit the direct detection of hydrocarbons using aeromagnetic surveys.

The research objectives were:

- 1) to undertake special-purpose airborne and ground magnetic surveys over known UK hydrocarbon fields with a view to identifying high frequency anomalies that might be hydrocarbon indicators
- 2) to develop new computer-based processing, analysis and display schemes to selectively enhance high wavenumber, small amplitude magnetic anomalies
- 3) to study the magnetic/mineralogic characteristics of sedimentary roof rocks, both on and off known on-shore UK hydrocarbon fields

Low altitude, high resolution airborne surveys were flown over the Formby oilfield and a hydrocarbon prospect in the Fylde region, Lancashire. High resolution gradiometer data flown over a producing oilfield in the Welton area of Lincolnshire was supplied to BGS by BP Petroleum Development Ltd. This data set was also analysed for micromagnetic signatures. Although not part of the original research objectives, ancillary radiometric data was also examined for characteristic spectrometric signatures.

Magnetic minerals found in borehole chipping material from the Formby and Welton wells were subjected to detailed mineralogic analysis to determine the genesis of any magnetic phases (i.e. whether diagenetic and hydrocarbon induced or detrital and hence related to nearby volcanic or granitic terrain).

2. THEORETICAL STUDIES

As is well known, traditional magnetic data processing algorithms mitigate against the identification of small amplitude, high spatial frequency anomalies. If the micromagnetic survey technique was to be a viable exploration tool, particularly in developed countries, new and improved techniques would be needed to assist anomaly recognition, to separate out near-surface anomalies from regional variations and to suppress or remove magnetic cultural noise. Considerable time and effort was devoted to this problem and a significant amount of new software was developed.

2.1 Data manipulation

The commercial software package Interactive Surface Modelling (IVM) was used to calculate all 2D gridded surfaces, but to carry out grid operations a program SGPM was written with options to:

- analyse a grid (origin, size, sampling interval, minimum, maximum and mean values)
- examine grid values
- shift grid datum
- scale grid values
- interpolate a grid to a finer mesh (using a cubic spline on rows and columns)
- subsample a grid
- extract a subgrid
- add two grids together
- subtract one grid from another

For profile analysis (eg filtering, Fourier analysis etc.) two programs were developed to convert unequally-spaced profile data into equally-spaced data. A surface-to-surface continuation program LVL2LVL was used with very small continuation heights and program P_PROJ was written for cases where flight lines deviated from N-S or E-W directions. Although such deviations are often ignored in traditional processing, they could cause processing artefacts comparable to the features of interest. P_PROJ projects data onto a least-squares best-fit straight line and uses Lagrangian interpolation to give equi-spaced data.

2.3 High frequency anomaly enhancement

A package REGRES2D was developed to perform regional/residual field separation by fitting 2-D polynomial trend surfaces.

For frequency specific high frequency anomaly enhancement, a package FILTER2D was written to operate on gridded data. Directional and non-directional filters were designed as well as low/high-pass and band-pass/stop filters. To assist spectral analysis, a program ASPEC2D was written to calculate 2D power spectra by the Fast Fourier Transform method.

Given that short wavelength micromagnetic anomalies would probably only be recoverable from high density profile data, new techniques for the analysis and display of profile data were developed. A program PROFILE was written with options for:

- smoothing using a 7-point moving average triangular filter in the space domain (end effects minimised by linear extrapolation)
- first horizontal derivative calculation in the space domain
- upward and downward analytical continuation
- low-pass, high-pass and band-pass filters (Gibbs phenomenon distortions minimised by cosine bell tapering)
- vertical derivative calculation (any order)
- power spectrum calculation (Hanning window tapering)

Apart from low-pass, high-pass and band-pass filters, the derivative calculations are a traditional way of emphasising short wavelength anomalies. Derivative calculations for gridded data were performed in the program SGUPCONT. This also contained options for reduction-to-pole and analytical continuation.

2.4 Data display

Conventional contour maps of aeromagnetic data often distort or fail to depict those features that have high spatial frequencies or small amplitudes. These components could be highly significant in the search for hydrocarbon-induced magnetic anomalies. The accurate recovery and display of this information was therefore a prime objective.

A colour graphics package COLMAP was developed with options for:

- for colour posting of random data
- for colour filled contours of gridded data
- for pseudo-relief plots of gridded data

As gridding can effectively remove high frequency anomalies an alternative display scheme was developed in the program WIGGLE. Each profile is displayed as a stacked 'wiggle' trace with options to colour fill either or both of the negative and positive lobes of the trace. High frequency anomalies and their spatial coherence are more readily established by this presentation. A square root amplitude scale was also found to be useful for suppressing large anomalies and enhancing smaller ones.

2.5 Cultural noise studies

It was anticipated that any micromagnetic anomalies due to shallow diagenetic magnetite would, if present, be within the amplitude noise envelope of culturally induced magnetic anomalies and to exhibit significant spectral overlap with such anomalies.

Three methods were investigated for suppressing cultural contamination of the data:

- frequency domain filtering and spectral analysis
- space domain filtering and data manipulation
- cultural noise modelling

Fourier domain filters are attractive because they are simple to design and apply. However, the severe spectral overlap between the cultural noise and the sought after anomalies results in comparable attenuation of

both, and is therefore self-defeating. An unacceptable amount of 'ringing' was also observed. Various filters were studied (continuation, vertical derivative, high-, low- and band-pass filters) and the results were observed in the frequency domain using power spectra and the Burg Maximum Entropy spectral estimation technique. None of the filters tried proved particularly effective.

Space domain filtering and data manipulation was examined as a more promising method for rejecting cultural noise. An interactive graphical program DESPIKE was written for manually eliminating noise "spikes" while retaining data trends. This approach worked well for individual data points but long sections of contaminated data tended to produce artefacts (boundaries of enhanced short wavelength activity) which might be mistaken for natural effects.

The quantitative modelling of cultural features was investigated to determine whether major sources of urban noise (eg metal pipes, well casing etc.) could be separated out of the observed data by simple subtraction. This approach however proved to be of only limited value because of the uncertainty associated with assigning magnetic properties.

None of the above methods proved universally applicable or successful. In general the most effective approach was often to display the data without editing, and to visually correlate any anomalies with known cultural sources. Remaining anomalies were then targeted for ground follow-up.

2.6 Magnetic source modelling and depth estimation

Several 2D and 3D magnetic modelling programs were acquired from the USGS and implemented on BGS computers, in some cases after extensive modification:

- SAKI for magnetic profile interpretation by generalised 2-D linear inversion.
- PF3MAG to compute the magnetic effect of a variably magnetised body bounded by irregular upper and lower gridded surfaces.
- MAGPOLY to model the magnetic effect of an assemblage of vertical prisms with polygonal cross-sections. This program was ideally suited for modelling intra-sedimentary diagenetic sources which can be expected to have the form of lamellae (50 - 100 m thick) of irregular plan view. An interactive graphical program (M_P04) was written to simplify input and editing of the plan location of the prism vertices.

To assist in the identification of zones of magnetic mineral enrichment, a program MAGSUS was implemented to transform total magnetic intensity data into apparent susceptibility maps. This technique also proved useful for automatic source depth estimation.

In view of the uncertainty relating to the probable spatial distribution of any diagenetic magnetite, frequency domain depth estimates were

considered preferable to estimates based on spatial modelling. One distinct advantage of power-spectral analysis and autocorrelation techniques is that they make no assumptions about the magnetic properties of the source. Two programs were implemented; DEPTH2D to calculate the depth from the power spectrum, and ADEPT which computes the depth to source from the spatially varying autocorrelation function.

Examples of the use of the above programs will be found in the Final Report of this contract.

3. MAGNETIC SURVEYS

3.1 The Formby oilfield, Lancashire

The Formby oilfield ceased production in 1965 and was considered to be an ideal test site for several reasons: a) there is a history of microseepage, b) earlier mineralogical analysis of oil well cuttings had confirmed the presence of magnetite and c) the overlying Permo-Triassic sediments are rich in ferric oxides - an essential prerequisite for the formation of diagenetic magnetite.

3.1.1 The aeromagnetic and radiometric survey

Aeromagnetic coverage of the Formby oilfield prior to the present investigation comprised only one profile, recorded some 25 years ago and flown at a height of 305m. Clearly more detailed coverage was required and a purpose-designed, low altitude/high resolution airborne survey was carried out using the modified Piper Chieftain aircraft owned by NERC Scientific Services.

The surveyed area covered a 10 km by 10 km block bounded by eastings 330000 m to 340000 m and northings 403000 m to 413000 m. It was flown at an altitude of 100m with 200m line spacing, using a high sensitivity (0.01 nT) proton precession magnetometer (Overhauser-effect). Data was recorded every 0.5 s, yielding a measurement approximately every 33m.

A Geometrics GR800D 256-channel spectrometer was used to record total count, and the radioelements potassium, uranium, and thorium.

3.1.2 Interpretation

A high frequency, low amplitude aeromagnetic anomaly was found over the main producing zone of the oilfield, which in the absence of any surface oil installations, was initially considered to be strong supporting evidence for the diagenetic theory (see Figure 1). However, subsequent theoretical modelling and detailed ground surveys demonstrated that the cumulative effect of steel casing from many closely spaced wells, when combined with aliased sampling, could result in apparent wavelengths greater than those calculated for single wells. The resulting aeromagnetic anomaly could suggest an extended, relatively shallow, authigenic source as shown in Figure 1. Figure 2 shows the detailed ground data when continued up to an elevation of 100m and then resampled along the aeromagnetic flight lines. The anomaly is very similar in both

shape and amplitude. Similarly, if the modelled response of all known well casing is upward continued to 100m (Figure 3) the combined effect is as seen in the aeromagnetic survey. Small differences are attributed to uncertainties in the exact flight path position; the uncertainty in estimating the magnetic properties of the well casing, and the effect of other unknown metallic relics from the former oilfield.

It seems highly probable that this effect may explain the anomalies observed over other oilfields and ascribed by other workers to diagenetic magnetite.

The remaining aeromagnetic data was analysed but of 267 positive closures appearing on the contour maps, only 21 (comprising 12 discrete zones) could not be correlated directly with cultural noise. None of these remaining anomalies could be identified in follow-up ground magnetic profiles. It was concluded that these residual aeromagnetic anomalies were data processing artefacts (e.g. caused by editing), or resulting from errors in navigation, the variable height of the airborne magnetometer, and the inaccuracy of the diurnal correction. Detailed ground magnetic profiles were carried out over known faults (i.e. potential seepage pathways) but again no anomalies were found.

Mineralogical analyses on borehole samples with high magnetic susceptibilities showed the magnetism to be due mainly to contaminant material from the drilling. The magnetite found in the samples was invariably detrital and of igneous or metamorphic origin as shown in the scanning electron micrograph (Figure 4). Although the presence of epigenetic magnetite could not be totally discounted the abundance of detrital magnetite was such that any diagenetic grains would have had a negligible effect on the magnetic properties of the sediments. Hence if diagenetic magnetite is present it would not produce a measureable magnetic anomaly.

The radiometric data were found to correlate with the drift geology and known cultural features. A search for classic 'halo' anomalies in association with the oilfield proved unsuccessful.

3.2 The Fylde area, Lancashire

The Fylde area of Lancashire, being an adjacent marginal basin to the Permo-Triassic Irish Sea basin, is considered to be a geologically favourable prospect for the accumulation of hydrocarbons. In addition, the overlying red-bed lithology provides a suitable environment for the potential formation of epigenetic magnetite.

The BGS special-purpose aeromagnetic survey, flown immediately after the Formby survey, is dominated by the effects of cultural disturbances. After extensive processing and selective editing, two residual anomalous areas were identified, one of which occurs over the faulted flank of the Weeton anticline - a favourable structure for oil/gas accumulation. The structural position of the second anomaly is not favourable for an oil or gas trap.

Detailed ground magnetic profiles over the first aeromagnetic anomaly, however, did not find a surface expression of this feature. Reprocessing and re-examination of aeromagnetic data indicated that during the

despiking process small residuals from the edges of culturally-induced anomalies may have been left in the data, together with a residual from a misplaced power line. It is concluded that the gridding process, used in the display of the airborne data, effectively smoothed these residuals into one coherent anomaly. This example clearly illustrates the importance of processing artefacts, and the danger in attaching geological significance to weak, short wavelength anomalies in developed countries.

It was concluded that if any magnetic anomalies caused by diagenetic magnetite occurred in the Fylde area, such anomalies would be effectively masked by cultural noise. This finding seriously detracts from the viability of the micromagnetic technique even assuming that diagenesis may take place over hydrocarbon reduction plumes.

All radiometric anomalies could be explained in terms of drift deposits, drainage patterns, and cultural features.

3.3 The Welton area, Lincolnshire

The scope of the research was considerably enhanced by the provision of aerogeophysical data from the Welton and neighbouring oilfields, one of British Petroleum's most recent producing areas. The Welton area comprises 300 km² bounded by eastings 495000 m to 515000 m and northings 370000 m to 385000 m. It contains the Welton oilfield and related fields at Nettleham, Scampton and Stainton.

3.3.1 The Welton Oilfield

The presence of numerous oil seepages in both lead and coal mines in the shallow Carboniferous strata of the East Midlands prompted the exploration for hydrocarbons towards the end of the First World War. Several exposed anticlines affecting Carboniferous rocks were tested, resulting in the discovery in 1919 of the United Kingdom's first commercial oilfield at Hardstoft in east Derbyshire.

The Welton field, the most easterly in this region, was discovered in 1981 following the testing of a north-west trending pre-Permian anticline that had been identified by reflection seismics. The field, operated by BP Petroleum Development Limited on behalf of the BPPD/Gas Council (Exploration) Limited Joint Venture, came on stream officially in 1986 with an approved plateau production rate of 2,500 bbl/day. The principal reservoir of the Welton field has been extensively faulted and is overlain by considerable thicknesses of red beds; the area is thus prospective for the formation of diagenetic magnetite. Discouraging features include the depth of oil accumulations (1400 m), the presence of numerous overlying horizons (clays, shales and evaporites) and the sparsity of near surface faulting.

3.3.2 The airborne survey

The low-level high resolution survey was conducted by helicopter at a nominal height of 200 m. Flight lines were in a north-south direction

with 500 m separation. In total about 520 line km were flown. Data samples were taken at 0.5 s intervals, giving a typical data point spatial separation of about 15 m along the lines. Thus, in profile form, there is sufficient resolution to detect any authigenic sources.

The magnetic measuring instrumentation consisted of a vertical gradiometer configuration of two total field sensors. The upper sensor was mounted 50 m below the helicopter and the lower sensor 100 m below, giving nominal sensor altitudes of 150 m and 100 m respectively. The magnetic vertical gradient data were particularly useful, since the gradient changes more rapidly for shallow sources than for deeper sources, and hence could be expected to be more sensitive to weak magnetic sources at shallow depth.

The gross disparity between along-track and inter-track measuring intervals required the analysis of both contour and profile data maps. The total field map is dominated by the Market Rasen anomaly, an extensive positive feature, the source of which is believed to lie some 3 - 4 km deep. Attention was focussed on the second horizontal derivative and vertical gradiometer 1:10,000 presentations; both of which accentuated the high frequency anomalies. Once again the data was severely contaminated by cultural noise and no high frequency anomalies were found that could not be correlated with man-made features.

Borehole cuttings from this area were generally of lower susceptibility than those from the Formby area, with the majority of samples displaying values well below 0.01 SI units. Infrequent peak measurements, not exceeding 0.03 SI units, were recorded but no extended sections of such elevated values were found. In common with the Formby results, the dominant magnetic component is contamination from the drilling process. Identifiable natural magnetic material was exclusively detrital in origin.

No characteristic spectrometric signature was observed over any of the oilfields.

4. CONCLUSIONS

We have investigated the theory that diagenetic magnetite may form above certain hydrocarbon accumulations in sufficient concentrations to be detectable by high resolution aeromagnetic survey. Aerogeophysical data sets over two known, and one prospective hydrocarbon field have been examined. An extensive library of innovative software has been developed to facilitate the selective enhancement and display of high frequency, low amplitude aeromagnetic anomalies. Surface magnetometer traverses were carried out to investigate potential anomalies seen in the aeromagnetic data and laboratory work was undertaken to identify magnetic material found in the cuttings of boreholes drilled in the two known oil fields.

No hydrocarbon induced magnetic anomalies have been detected. The vast majority of the high frequency events occurring in the airborne magnetic data have a cultural source while the remainder were shown to be artefacts of data processing or caused by inherent operational inaccuracies.

None of the oilfields investigated possess a characteristic 'halo' spectrometric signature.

A low amplitude aeromagnetic anomaly centred over the former Formby oilfield was shown by computer modelling to be due to the combined effects of well casings, while high amplitude features at the Welton site are related to surface installations. The airborne data is plagued with such cultural noise and a satisfactory routine for either eliminating this or for extracting potentially useful anomalies has not been found.

Ground follow-up traverses failed to substantiate several low amplitude aeromagnetic "anomalies" that did not appear to have a cultural source and, which due to their character, were considered prospective. It was shown that these spurious features arise from various factors including loop-closure errors (i.e. navigational inaccuracies); attempts to suppress the influence of cultural noise, variable sensor height and inadequate corrections for diurnal variations.

A further problem arose from gridding high density profile data from widely spaced lines, resulting in the suppression of localised high frequency anomalies. New schemes were developed for the analysis and display of fine detail in aeromagnetic surveys which effectively combined areal and profile information.

Detailed surface traverses at sites relatively free of cultural interference over the former Formby oilfield and the faults associated with this have shown these features to be without magnetic expression and it is concluded that measurable concentrations of diagenetic magnetite have not developed here.

No significant amounts of diagenetic magnetite were found in borehole samples from the Formby and Welton areas. Magnetic susceptibility measurements on cuttings from both productive and dry boreholes in these areas yielded occasional peak readings but no extended sections of elevated values were recorded. The principal magnetic component of the samples displaying increased susceptibility could be attributed to drilling contaminants. The preponderant natural magnetic material of the Formby samples was detrital, consisting of magnetite and ilmenite that had been derived from igneous and metamorphic rocks. Possible ultra-fine particles of diagenetic magnetite in scarce, unidentified magnetic material from the Formby area would have no measurable magnetic effect. Identifiable natural magnetic material from the Welton area was exclusively detrital.

These negative findings do not conclusively invalidate the diagenetic magnetite theory. Nevertheless, it should be noted that while the presence of characteristic high frequency anomalies over oil fields in the United States, is well documented, there is as yet no direct evidence that these anomalies are due to hydrocarbon-induced diagenetic magnetite. In fact, there is a growing body of evidence that other factors and mechanisms may be responsible for these anomalies as shown by the present research. Also for diagenetic magnetite to produce measurable aeromagnetic anomalies it would have to form in considerable quantities. No direct or indirect evidence has been found to support this proposition. However cultural contamination proved to be an intractable problem which severely inhibited the present study.

The theory could be tested further by magnetic surveys over known seepage zones and prospective oilfields in areas relatively free of cultural noise (e.g. off-shore areas, or undeveloped localities overseas), preferably in areas remote from igneous or metamorphic terrain, and hence detrital sources. Clearly any prospective anomalies should be followed up by core drilling; detailed mineralogic analysis of any diagenetic magnetite to determine its origin, and quantitative modelling of any distributions found, to determine if it is responsible for the observed aeromagnetic anomalies.

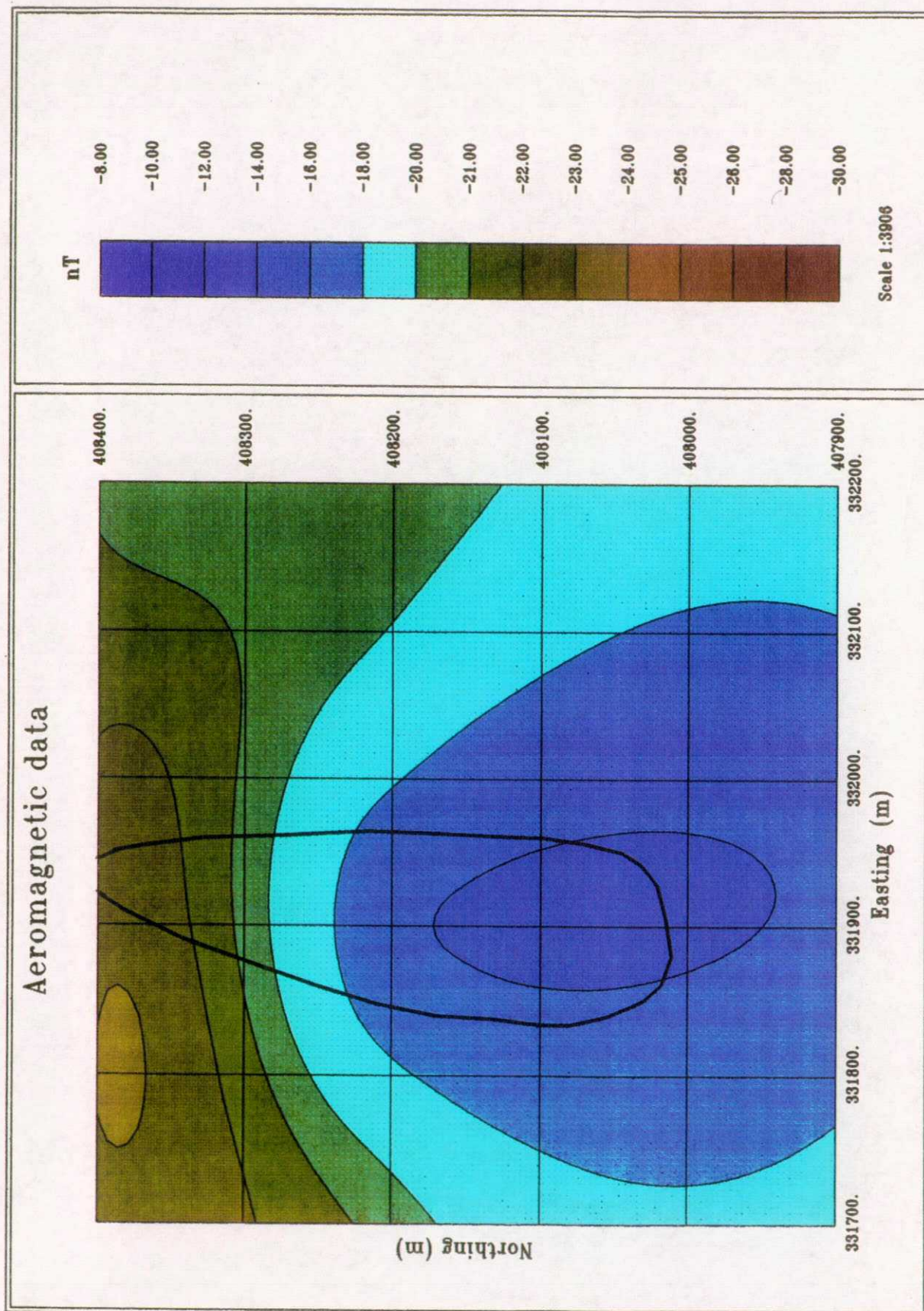


Figure 1 Aeromagnetic anomaly over the Formby oilfield, with the superimposed outline of the main producing zone

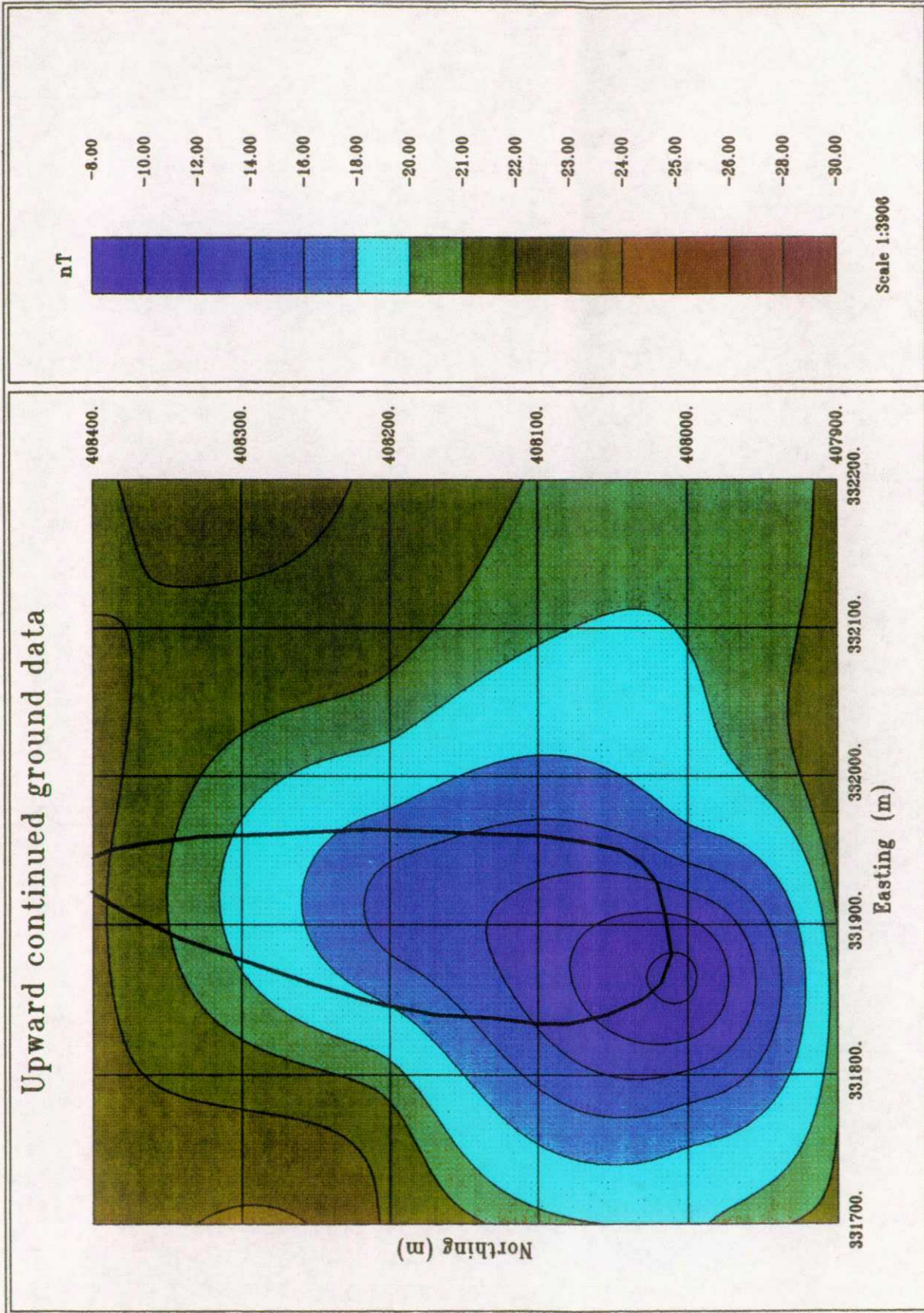


Figure 2 Upward continued and resampled detailed ground total field data with outline of main producing zone

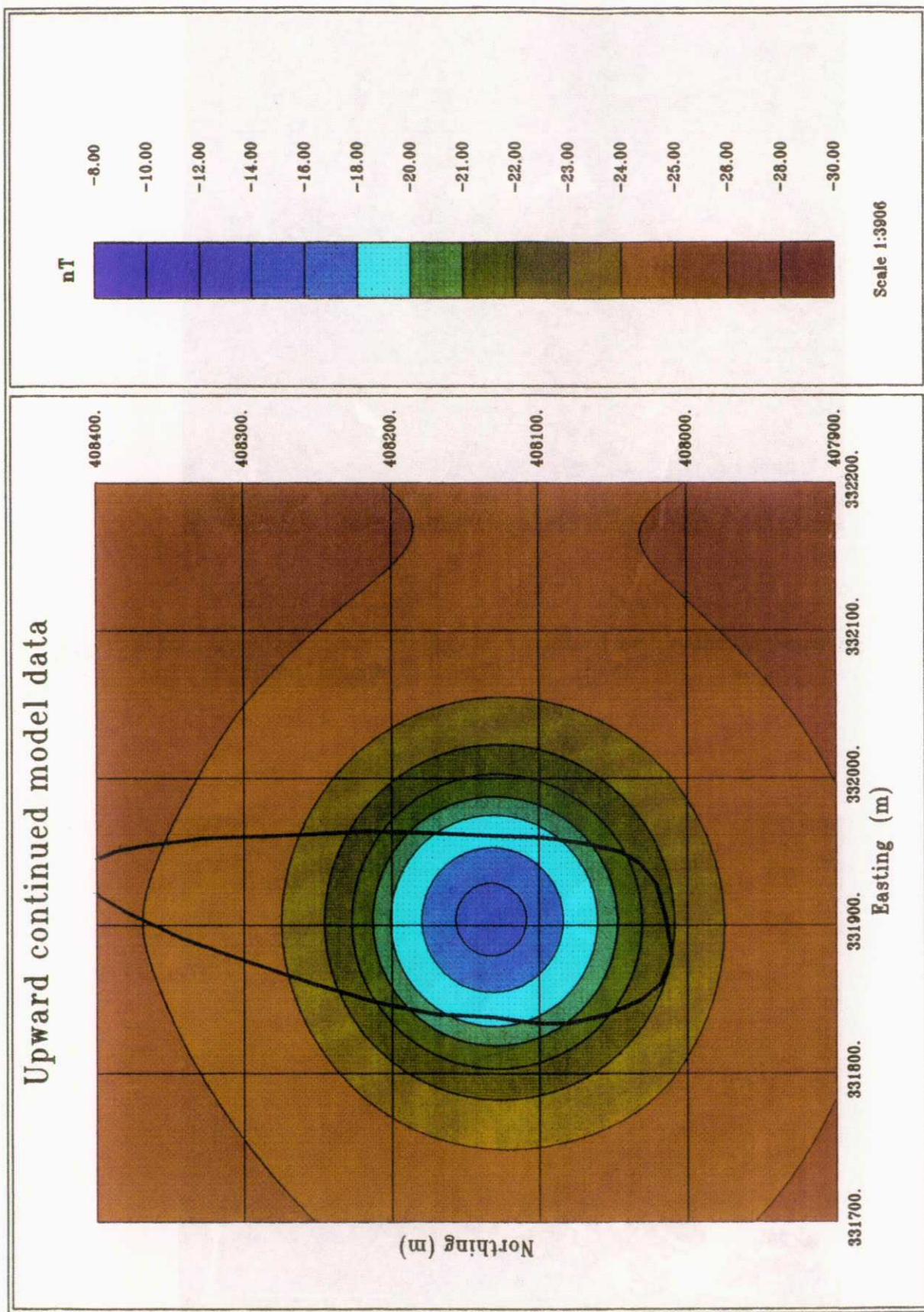


Figure 3 Upward continued total field response of the known cased boreholes, modelled as oppositely magnetized monopoles.

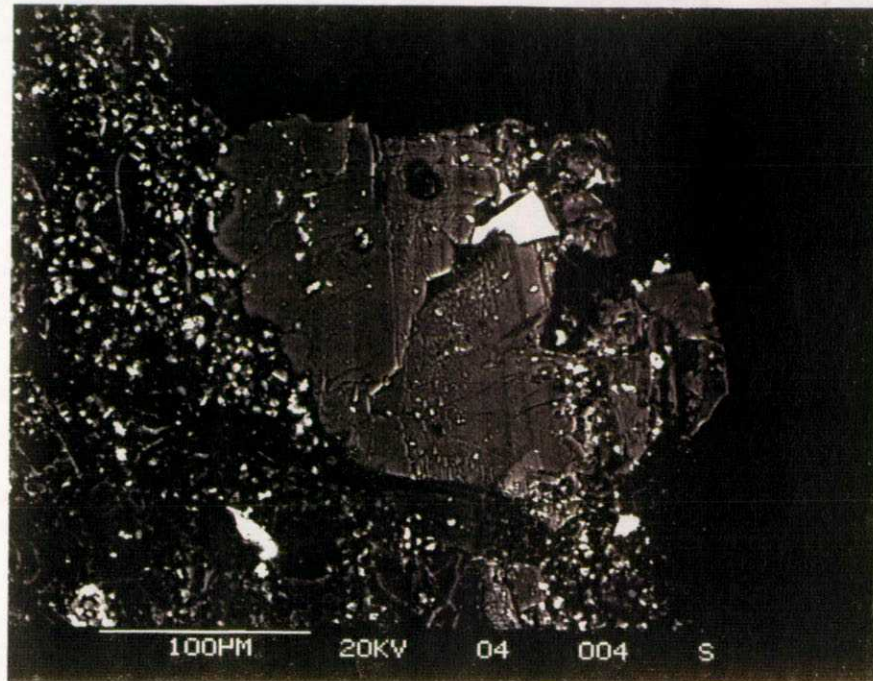


Figure 4(a) Micrograph of a typical igneous rock fragment showing detrital magnetite.

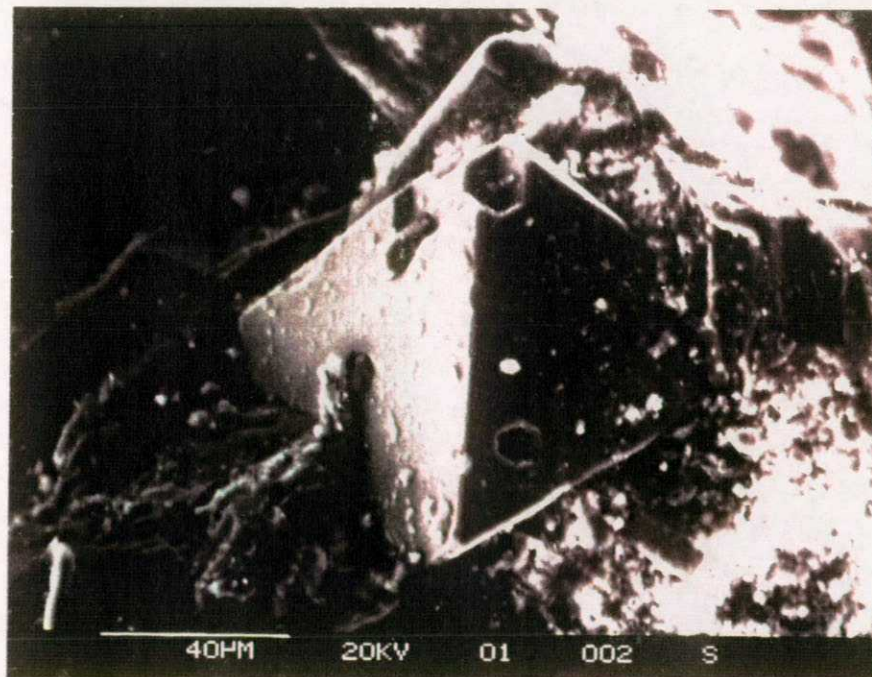


Figure 4(b) Octahedron of detrital magnetite in plagioclase feldspar.