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STRUCTURAL TRENDS IN THE CONCEALED BASEMENT OF EASTERN ENGLAND FROM IMAGES OF REGIONAL POTENTIAL FIELD DATA

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(10 figures)

ABSTRACT.- New colour and grey-tone shaded-relief images of the gravity and aeromagnetic fields in eastern England are presented. These define the lineaments and correlations between anomalies in somewhat more detail than previous broad-scale images and have been used to update the analysis of structural trends and basement geology. The dominant trends in eastern England, on both the gravity and magnetic images, are SE and ESE. Structures which appeared to have an arcuate form on previous images have been resolved into separate SE- and ESE-trending segments. Likewise, the broad magnetic ridge extending from northern England to East Anglia has been resolved into separate SE- and ESE-trending components which are observed to intersect in the region of the postulated concealed granites at Market Weighton and around The Wash. The pattern of SE-trending lineaments associated with the northeastern margin of the Midlands Microcraton suggests that this boundary may be more irregular than previously supposed. The presence of the SE and ESE trends where the Upper Palaeozoic cover is relatively thin suggests that the lineaments correspond to structures within the concealed Precambrian to Lower Palaeozoic basement. The occurrence of the same trends in the northeast Midlands where the Upper Palaeozoic cover is thicker, strongly supports the widely held view that Lower Carboniferous sedimentation was controlled by reactivation of SE- and ESE-trending structural discontinuities in the underlying basement as a result of crustal extension during the Dinantian. The origin of the basement trends remains unclear. Both SE- and ESE-trending structures are seen in the Precambrian but it is also possible that major discontinuities in either, or both, of these directions originated during closure of the Tornquist Sea during the Ordovician or during end-Caledonian (Acadian) transpression.

INTRODUCTION

The Precambrian and Lower Palaeozoic basement of eastern England is almost entirely concealed beneath a cover of Upper Palaeozoic and Mesozoic sedimentary rocks (Figure 1). Reflection seismic data provide detailed structural information on the cover rocks in certain areas and a limited number of boreholes penetrate the basement (Pharaoh *et al.*, this volume, Molyneux, this volume). Over much of the region, however, knowledge of the deep structure relies heavily on the interpretation of regional gravity and aeromagnetic data. This applies especially to the concealed basement rocks where modelling of the gravity and magnetic anomalies has helped define the extent and form of postulated granitic and granodioritic intrusions around The Wash and in the East Midlands (Allsop, 1987).

The potential fields also contain valuable information on structural trends and lineaments within the basement which can be identified using image-based processing techniques. Lee *et al.* (1990) produced images of the gravity and magnetic fields covering a large part of Britain (south of the Highland Boundary Fault) and identified the major lieaments and broad-scale trends, including those in eastern England. In this paper new colour shaded-relief images of the gravity and aeromagnetic fields in eastern England are presented which define the lineaments and correlations between anomalies in somewhat more detail. These are used to update the analysis of structural trends and basement geology in the area. The paper is intended to provide background information for studies of the tectonic evolution of the eastern England Caledonides and their possible continuation towards the Brabant Massif.

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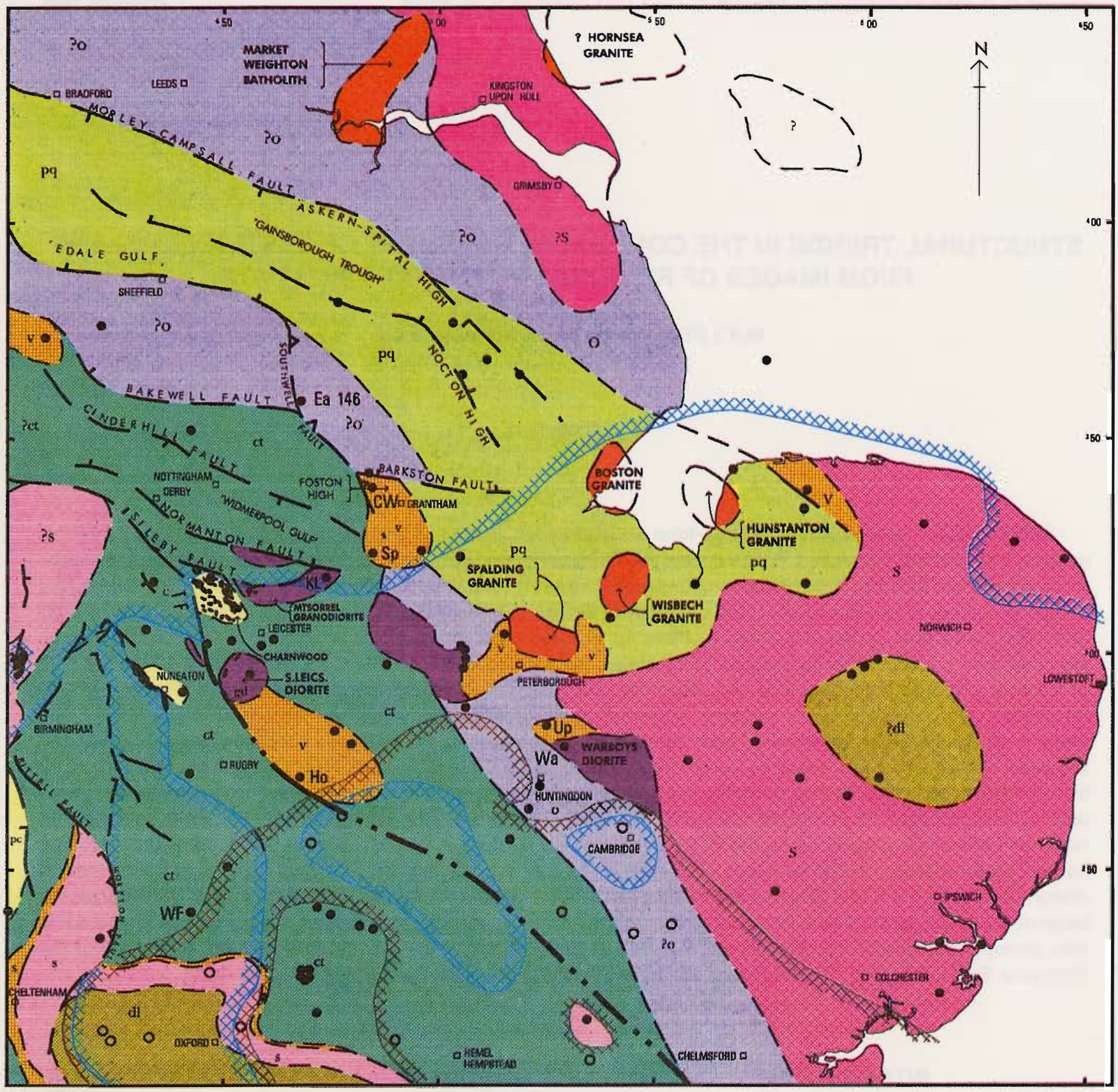

KEY

POST–ACADIAN UPPER PALAEOZOIC COVER

- Carboniferous(undivided)
- Late Middle and Upper Devonian (Upper Old Red Sandstone)

POST–ORDOVICIAN PLATFORM COVER OF MICROCRATON

- dl — Lower Devonian (Lower Old Red Sandstone)
- s — Silurian shelf facies

PRECAMBRIAN, CAMBRIAN–TREMADOC OF MIDLANDS MICROCRATON AND MARGINS

- ct — Cambrian–Tremadoc
- pc — Precambrian

EAST ANGLIAN CALEDONIDES

- dl — Lower Devonian (Lower Old Red Sandstone)
- s — Silurian basinal facies
- o — Ordovician(post–Tremadoc)
- pq — Green phyllite–quartzite association

ROCKS

- g — Granite(postulated) (? Devonian)
- gd — Diorite and granodiorite (proved and postulated)
- v — Volcanic rocks ? Precambrian, Ordovician and Silurian

OTHER SYMBOLS

- Outcrop of Precambrian and Lower Palaeozoic strata
- Normal fault
- Reverse fault or thrust
- Inferred limit of Midlands Platform in Silurian
- ● Borehole proving Acadian basement
- ○ Borehole proving Upper Palaeozoic cover

Figure 1. Overview of basement geology of eastern England. Modified from Smith (Fig. 7.8) in Plant & Jones (1989) with additional information from Smith (1985) and Allsop & Smith (1988). Key to boreholes: CW, Cox's Walk; EA-146, Eakring-146; Ho, Hollowell; KL, Kirby Lane; Sp, Sproxton; Up, Upwood; Wa, Warboys; WF, Withycombe Farm. NB numerous boreholes proving Upper Palaeozoic strata in the northern part of the area not shown for simplicity. TF indicates the Thringstone Fault.

CREATION OF IMAGES AND ANALYSIS TECHNIQUES

Shaded-relief presentations are one of the simplest, and most effective, techniques for conveying structural information from gravity and magnetic data. These treat the fields as topographic surfaces illuminated from a certain direction and are particularly effective for conveying information on anomaly gradients. They also have the property of enhancing features which trend roughly perpendicular to the direction of illumination. This has the effect of enhancing subtle, but structurally important lineaments which are often not apparent on standard contour maps. Colour-shaded images have the added advantage of showing both anomaly amplitude (as colour) as well as anomaly gradients (as relief).

The distribution of regional gravity data in lowland areas of Britain is approximately 1 observation per 1 km^2. The aeromagnetic data were collected along flight lines 2 km apart. Both datasets are held in digital form by the British Geological Survey (BGS). In order to produce shaded images, the scattered data must first be interpolated onto a square grid. The quality of the final images is dependent on the choice of gridding interval and its relationship to the data spacing. Grid intervals of between 0.5 km and 1 km have been found to be the most appropriate for the UK regional data, depending on the size of area covered. In the present case two sets of images have been produced. Broad-scale features are shown on grey, north-illuminated, shaded-relief images of the gravity and magnetic data generated from 1 km grids over an area covering England, Wales and southern Scotland (Figures 2 and 3). Details in eastern England are shown in the set of six images given in Figures 4 to 9, which are based on 0.5 km grids. Figures 4 and 5 show grey shaded-relief images of the gravity field illuminated from the north and west respectively. Figure 6 and 7 show the equivalent images of the magnetic field.

Figures 8 and 9 show north-illuminated colour, shaded-relief images of the gravity and magnetic fields respectively, which provide information on both anomaly amplitude and gradient. The grids were generated using the Interactive Surface Modelling (ISM) package (Dynamic Graphics Inc. 1986) and the shaded-relief images were produced from the gridded data using the COLMAP software package (Green 1989).

A further point to note regarding the gravity data is that there may be a degree of correlation between Bouguer anomaly values and topography where a single rock density value has been adopted for the Bouguer corrections at all stations (Nettleton 1939). In areas of high topographic relief this effect can be quite significant, especially when enhanced by subsequent image processing techniques, and may obscure gravity variations due to geological structure. Density values vary widely across Britain, from less than 2.0 Mg/m^3 for some Tertiary sedimentary rocks to over 2.80 Mg/m^3 for some basic igneous and Lower Palaeozoic metasedimentary rocks. A value of 2.70 Mg/m^3 has been adopted as a reasonable compromise for the image shown in Figure 2 and a value of 2.55 Mg/m^3 has been used for eastern England (Figures 4, 5 and 8) where lower density rocks predominate. However, in parts of East Anglia, where a value of 2.1 Mg/m^3 is more applicable (J.D. Cornwell, BGS pers. comm.), a degree of topographic correlation is still apparent in the images. Some of the short SE-trending lineaments, for example, may be related to topographic features in the chalk. The reader should also be aware that false lineaments can occur along survey boundaries where the distribution of observations on each side is different. The E-W feature centred at [550,280] may be an example of this.

As pointed out by Lee *et al.* (1990), the most striking feature of the shaded images of southern Britain (Figures 2 and 3) is the way in which they highlight the two contrasting trends to the south of the Solway line. To the west of the Midlands Microcraton southwesterly (Appalachian) trends predominate, whilst to the east, southeasterly and east-southeasterly (Tornquist?) trends are apparent. The magnetic images in particular give the impression of structures moulded around the flanks of the Midlands Microcraton which Soper *et al.* (1987) suggest acted as a rigid indenter during the final (early Devonian) closure of Iapetus, moving northwards into an embayment formed by the earlier suturing of Laurentia and Baltica. The eastern England region, which is the subject of the present study, lies on the north-east margin of the Midlands Microcraton. The detailed images (Figures 4 to 9) are, therefore, dominated by the SE- and ESE-trending features, although other less prominent trends are also apparent.

The major gravity and magnetic lineaments in eastern England have been identified from Figures 4 to 9. These have been plotted on a composite image (Figure 10) which shows the gravity field (in colour) overlain by areas of positive magnetic anomaly (hatch patterns). Figure 10, therefore, correlates all the most important structural information contained in the potential field data (i.e. the anomalies and lineaments from both fields). A degree of subjectivity is involved in defining the exact trace of some of the lineaments. In a simple case, such as a linear vertical contact between two lithologies of contrasting density, the line of maximum gradient highlighted on the gravity shaded-relief images marks the contact. However, it is often

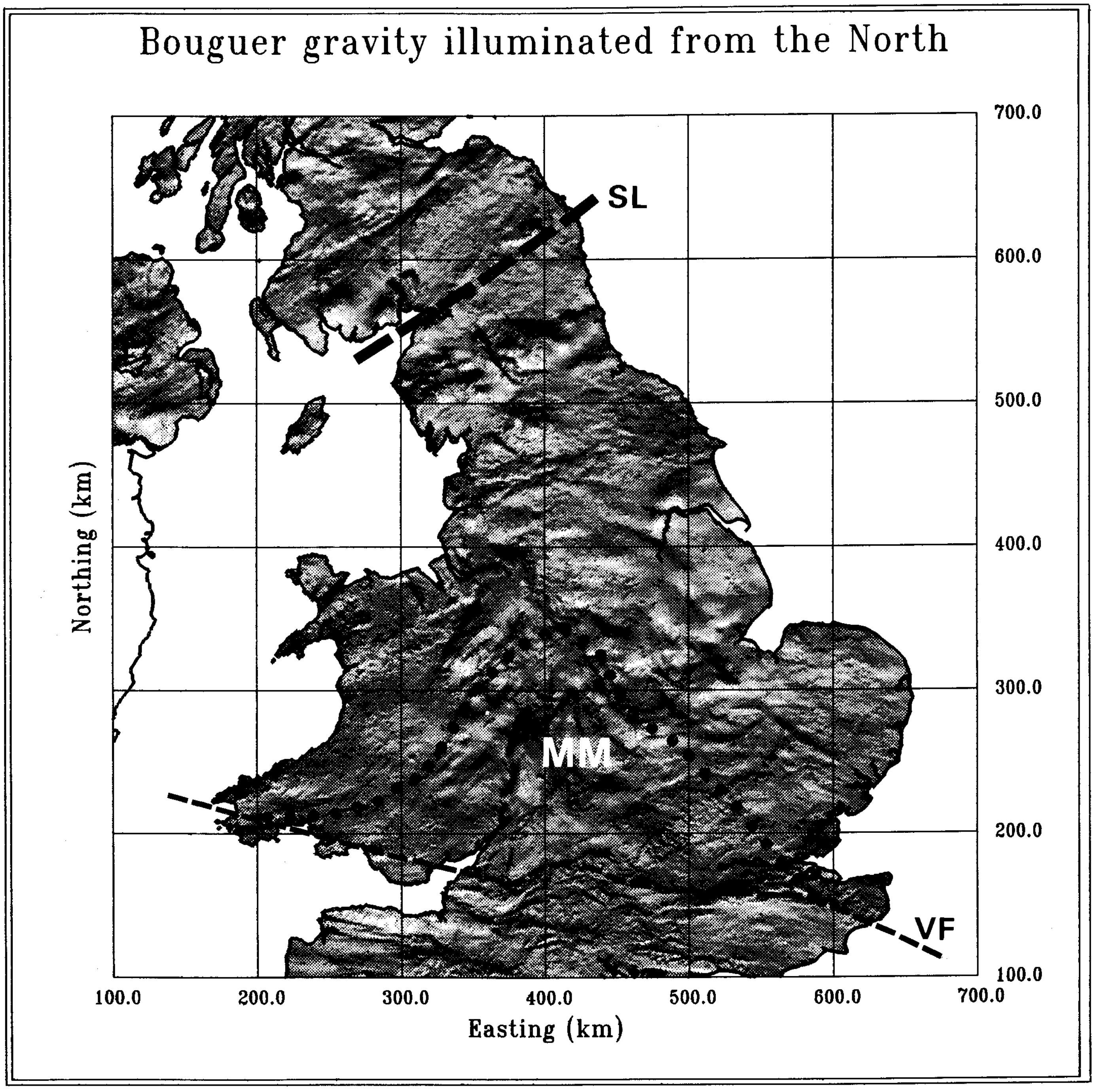

Figure 2. Shaded-relief image of the gravity field over central Britain illuminated from the north. Dotted line indicates the margin of the Midlands Microcraton (MM) inferred from previous studies (see text). Thin dashed line indicates the Variscan Front (VF). Thick dashed line indicates the Solway Line (SL).

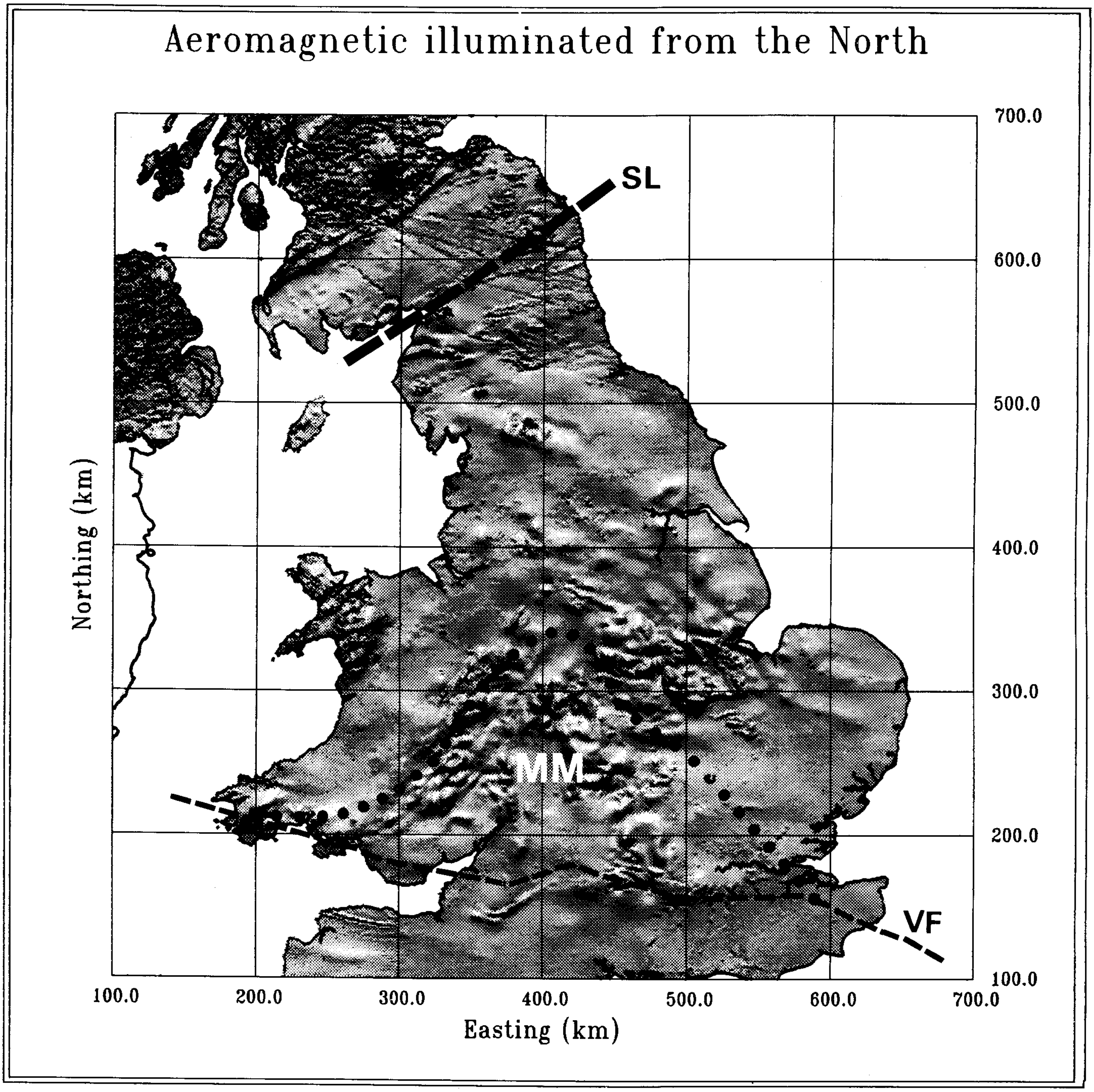

Figure 3. Shaded-relief image of the magnetic field over central Britain illuminated from the north. Dotted line indicates the margin of the Midlands Microcraton (MM) inferred from previous studies (see text). Thin dashed line indicates the Variscan Front (VF). Thick dashed line indicates the Solway Line (SL).

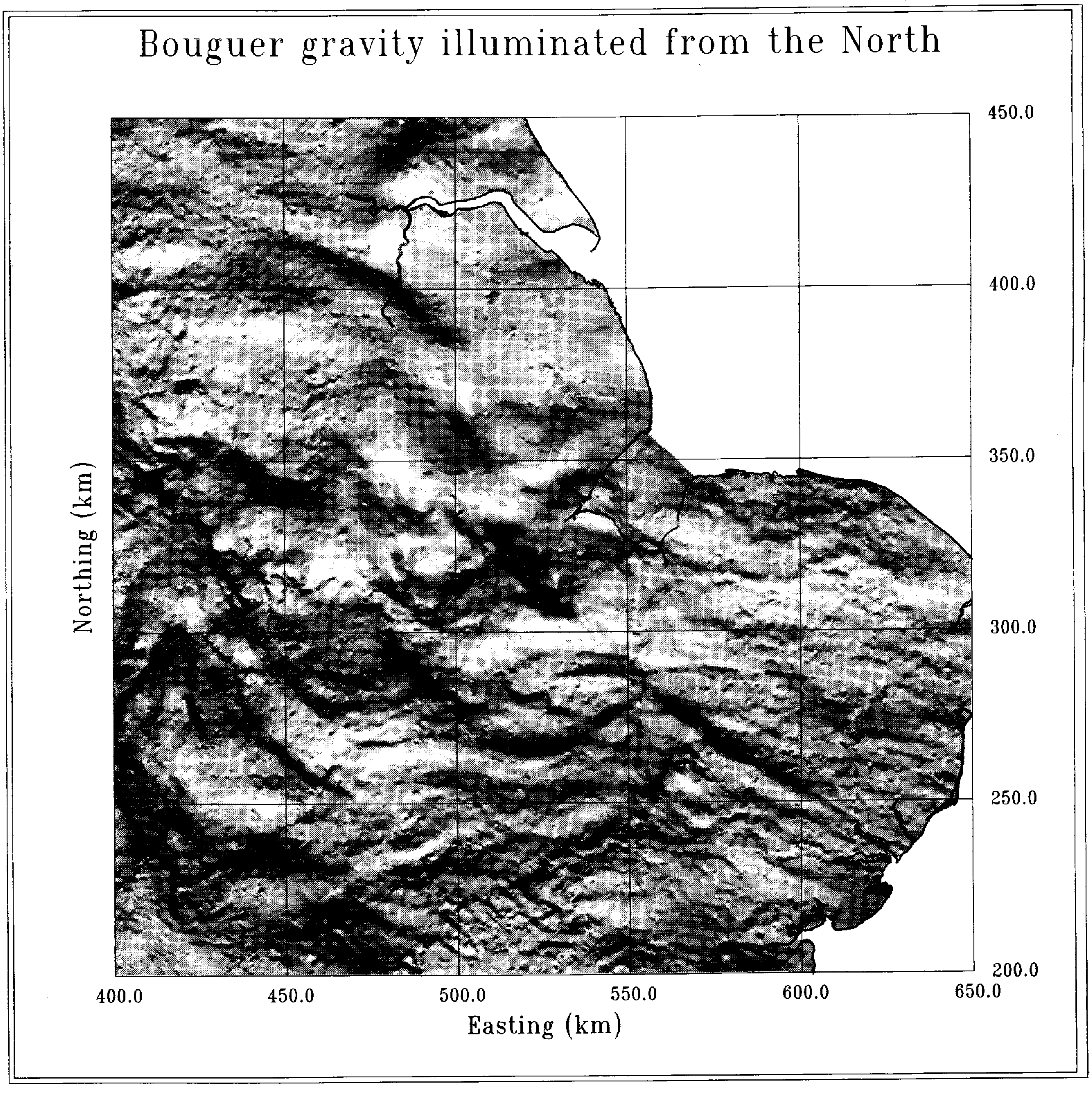

Figure 4. Shaded-relief image of the gravity field over eastern England illuminated from the north.

the case that lineaments are related to a series of structures developed along the same line due to the influence of an underlying basement feature. The lines shown on Figure 10, therefore, do not necessarily coincide with specific (single) density or magnetisation contrasts at the surface or within the basement. Rather, each defines the most 'representative' trace of a lineament as discerned from the complete set of images.

Many of the lineaments shown on Figure 10 are the same as those identified by Lee *et al.* (1990), but the increased resolution of the new images has enabled some features to be defined more accurately than on the broad scale images used in the previous study. In particular, some of the lineaments defined previously have been resolved into two or more separate features and additional lineaments have been identified in some areas. In the following sections the structural information from the small areas of exposed basement is first briefly reviewed and then the images are discussed in relation to possible structures within the concealed basement.

STRUCTURES IN THE EXPOSED BASEMENT

Precambrian basement is exposed in two comparatively small areas in Charnwood Forest and at Nuneaton (Figure 1). Both of these areas represent Palaeozoic structural highs adjacent to fault lineaments with long geological histories (Lee *et al.* 1990), and the Charnwood area in particular may have suffered rotation with respect to the Midlands Microcraton. However, the limited basement exposures provide us with the only detailed information on the history and trend of Precambrian structures in the basement.

The Charnwood Anticline is a major ESE-plunging fold structure affecting a thick pile of volcanoclastic sediments deposited in an arc marginal-basin of late Proterozoic age. Emplacement of the diorite suites of Charnwood at about 600 Ma (Tucker & Pharaoh in press) appears to have been structurally controlled, but predated development of the penetrative greenschist facies cleavage (Boulter & Yates 1987, Pharaoh *et al.* 1987a) which transects the axial plane of the anticline (Evans 1963). The ESE trend of the fold axis and cleavage define what has long been referred to as the 'Charnoid' trend (Watson 1975). Subsequent, brittle faults on a WSW and SW trend, some of which indicate sinistral transpression, severely affect the outcrop pattern in Charnwood Forest (Worssam & Old 1988). Faults with a similar trend cutting the Precambrian basement at Nuneaton demonstrably predate the early Cambrian sequence there (T.C.P. personal observation).

A small ESE-trending linear magnetic high (lineament 23, Figure 10) corresponds to the outcrop of the intrusive diorites at Charnwood. These rocks have moderately high magnetic susceptibility values (0.005 to 0.079 SI, Cornwell & Walker in Plant & Jones 1989) and contrast with the majority of Charnian volcanoclastic rocks which are of broadly felsic composition, have low magnetic susceptibilities and are not associated with magnetic anomalies.

MIDLANDS MICROCRATON AND ITS NE MARGIN

The area of the map lying within the presently inferred boundary of the Midlands Microcraton is dominated by a SE-trending magnetic high some 190 km long by 30 km wide (anomaly MH1, Figure 10). This feature extends from Birmingham in the northwest to the southern margin of the microcraton and was referred to by Lee *et al.* (1990) as anomaly MH3 and Wills (1978) as magnetic ridge 3. The Withycombe Farm borehole (WF, Figure 1), which is located over one of the individual magnetic highs along this ridge, penetrated intermediate volcanic rocks with a moderately high susceptibility value of 0.063 SI (Cornwell 1978). These volcanic rocks are now known to be of Precambrian age, following the recognition that they are unconformably overlain by Early Cambrian strata (Rushton & Molyneux 1990). They are similar in geochemical composition to the diorites of Charnwood (Pharaoh, unpublished data), which form part of the late Precambrian volcanic arc complex (Pharaoh *et al.* 1987b) and which also have moderately high susceptibility values (see previous section). The susceptibility value of 0.063 SI from Withycombe Farm is sufficiently high to account for the magnetic anomalies, provided that the rocks are widespread within the basement. This raises the possibility that the magnetic ridge represents the plutonic core of a Charnian volcanic arc embedded within the microcraton.

The Moreton and Bittell faults, which are characterised by a set of gravity lineaments (1a, 1b & 1c), mark the western edge of the magnetic ridge. The northeastern edge of the magnetic domain coincides with the northeastern margin of the Warwickshire Coalfield, where the Polesworth Fault is characterised by a sharp gravity lineament (2) and parallel magnetic lineament (3). Likewise, the Western Boundary Fault of the coalfield and the Birmingham Fault are also characterised sharp gravity anomalies (4 and 5 respectively). The broad magnetic domain is also segmented by a pair of WSW-trending magnetic and gravity lineaments, one of which (22) passes close to Withycombe Farm.

Many authors have speculated on the position of the margin of the Microcraton since Turner (1949)

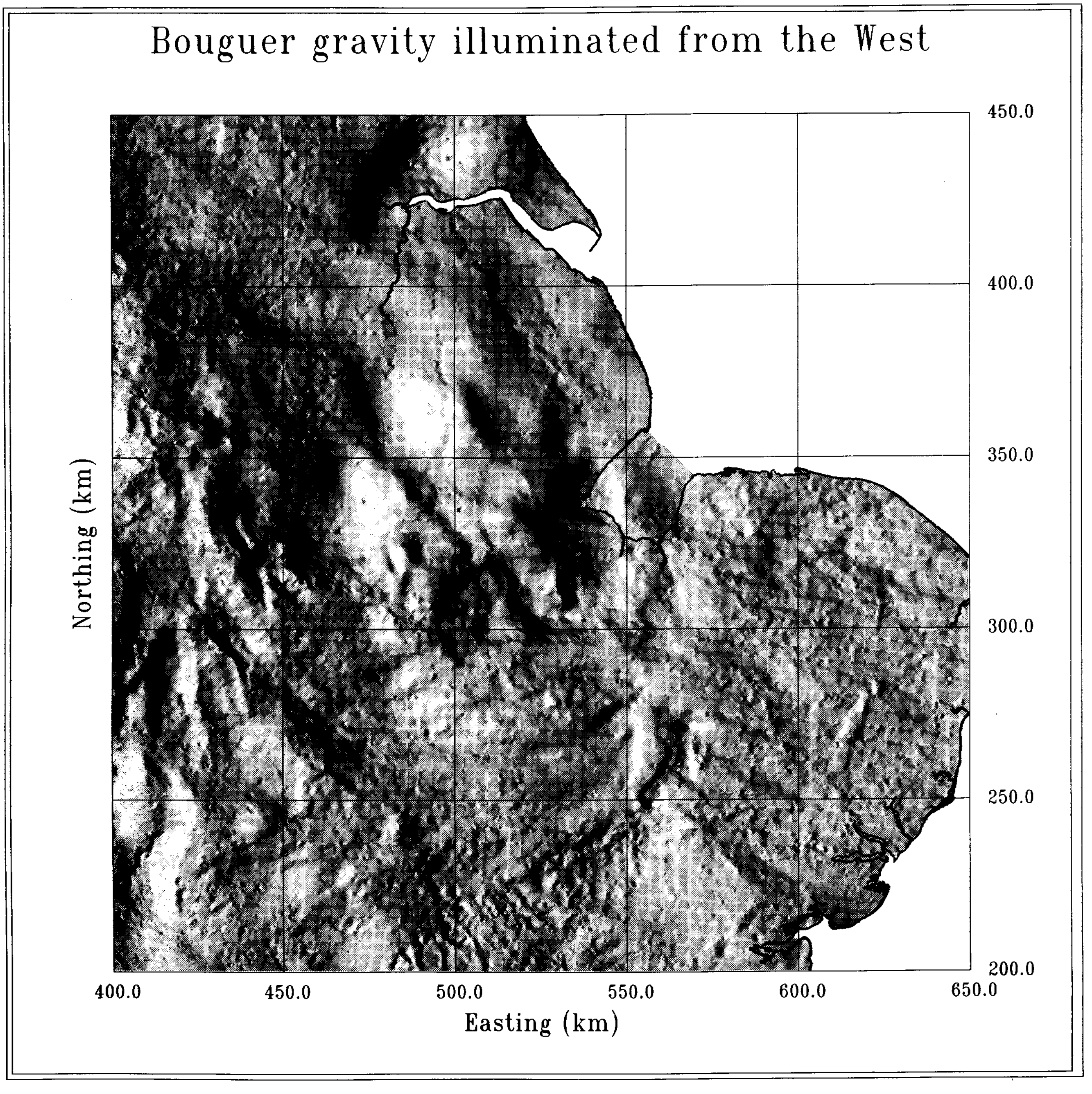

Figure 5. Shaded-relief image of the gravity field over eastern England illuminated from the west.

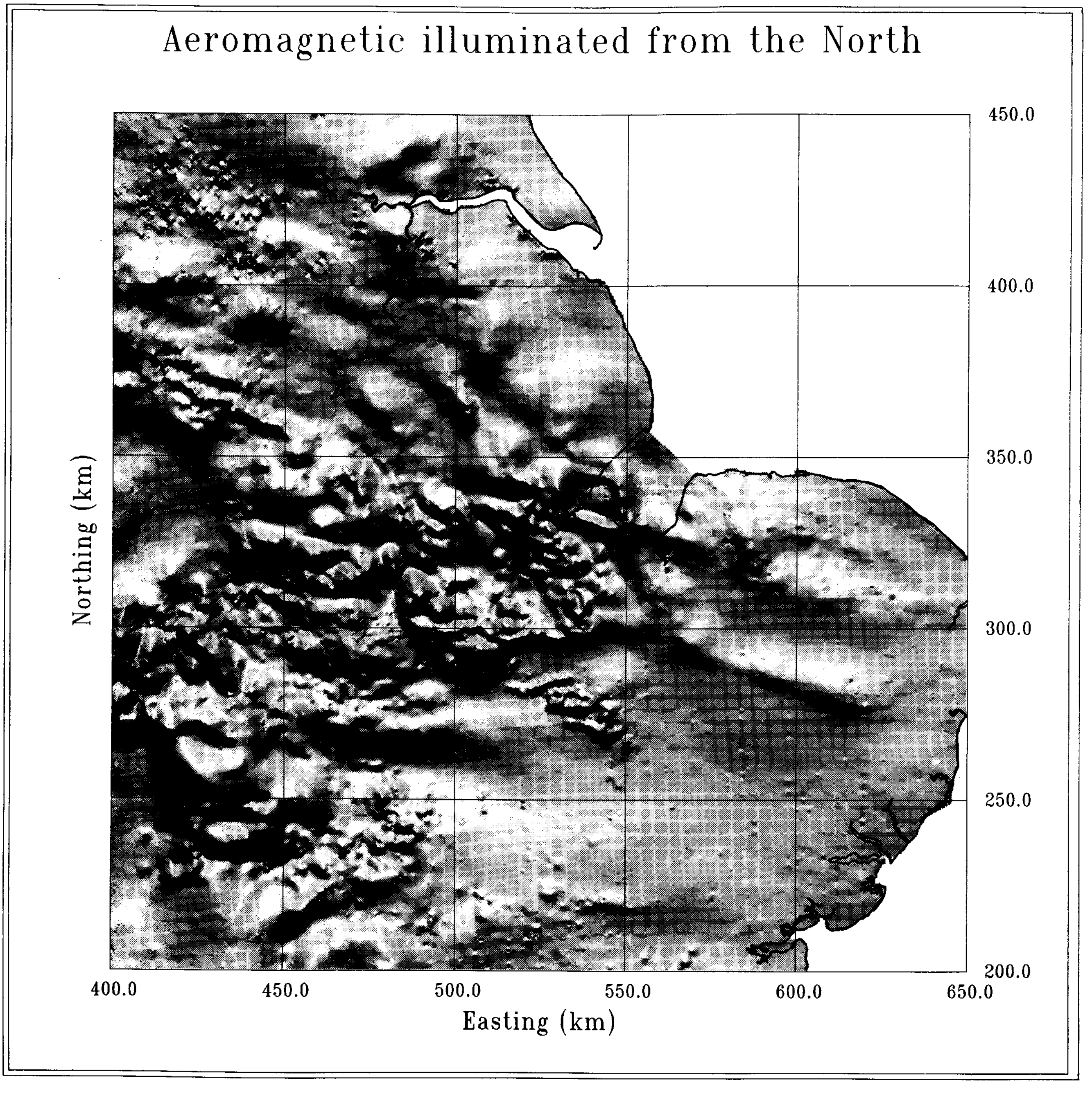

Figure 6. Shaded-relief image of the magnetic field over eastern England illuminated from the north.

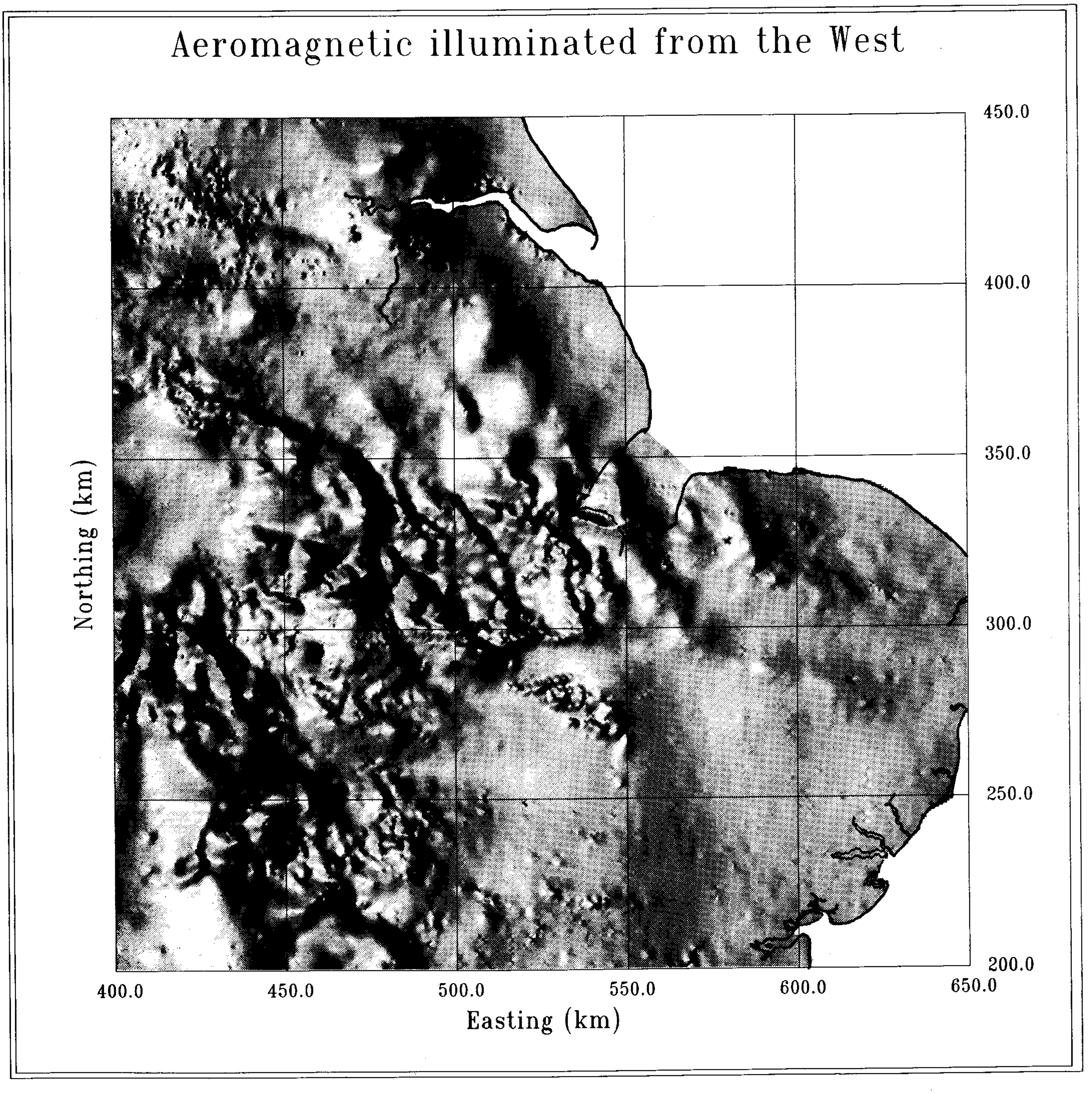

Figure 7. Shaded-relief image of the magnetic field over eastern England illuminated from the west.

pointed out the ESE trend of Caledonian structures in northern England. Turner (1949) inferred the along-strike continuation of the Caledonides of northern England with those of Belgium, central Europe and Poland. On the basis of petrographical similarities between volcanic rocks recovered from boreholes in East Anglia and Precambrian volcanic rocks exposed at Charnwood, Kent (1966) and Wills (1978) proposed that a massif of Precambrian rocks extended in the subcrop from the south Pennines to Charnwood and The Wash. However, Pharaoh *et al.* (1987a, and this volume) have shown that these volcanic suites are chemically and isotopically distinct, the isotopic data indicating an early Palaeozoic, probably Ordovician, age for many (if not all) the volcanics proven in the boreholes. Furthermore, the presence beneath East Anglia of steeply dipping Silurian sediments, the latter forming a thick basinal succession metamorphosed in the greenschist facies, indicate the presence of a concealed Caledonide deformation belt (Bullard *et al.* 1940, Pharaoh *et al.* 1987a).

The boundary between the Midlands Microcraton and the concealed Caledonides has been shown in most recent work as running NW-SE from the vicinity of Charnwood towards the Thames Estuary (Figures 1, 2 and 3). This position has been inferred from several lines of evidence, including the analysis of sedimentary facies and dip of bedding in cored boreholes (Smith 1987), biostratigraphic data (summarised by Molyneux, this volume), low grade metamorphic zonation and borehole dipmeter information (Pharaoh *et al.* 1987a), and seismic reflection data (Chadwick *et al.* 1989). Lee *et al.* (1990) associated the margin of the microcraton with the Thringstone Fault which they correlated with an extensive NW-SE trending gravity lineament extending well to the NW and SE of the mapped fault. The detailed images show that this is an oversimplification. Two short gravity lineaments (6a & 6b) can be correlated with the Thringstone Fault, which defines the western limit of the Charnwood Massif, but these are separate from a series of more extensive SE-trending lineaments (7 and fainter parallel lines).

Similar SE-trending lineaments, running parallel to the inferred margin of the microcraton, are apparent throughout eastern England (e.g. 8, 9, 10, 11). It is possible that these may derive from original structures such as Caledonian thrust or strike-slip faults within the concealed basement. However, it is worth noting that those lineaments which lie close to the inferred boundary of the microcraton (7 and associated features) fade out to the southeast and run into magnetic high MH2. This anomaly is part of the extensive London Platform magnetic high which Cornwell *et al.* (1990) have interpreted as a distinctive block of relatively magnetic basement, lying essentially within the Midlands Microcraton. The SE-trending lineaments in East Anglia (e.g. 9), which lie farther outboard (northeast) of the London Platform anomaly, extend farther to the southeast, possibly indicating that the microcraton has a more irregular (sliced?) northeast margin than previously envisaged.

EASTERN ENGLAND

Throughout Eastern England three main structural trends are observed on the images. The most prominent are the SE-trending set of lineaments, referred to briefly above, and an ESE-trending set, both of which in some cases extend for many tens of kilometres. A third set of shorter lineaments, with trends varying between E-W and NE, is also observed in the central part of the map (Figure 10) and appear to be transected by the longer SE-trending lineaments.

In East Anglia two parallel ESE-trending magnetic lineaments (12 and 13) cross-cut the SE trend. The northernmost of these lines (13), referred to as the Grantham lineament by Cornwell & Walker (1989), also has a subtle gravity expression. The present images show that it comprises a series of separate segments (13a, 13b & 13c), the westernmost of which (13a) correlates with the Barkston Fault. Both lineaments 12 and 13 decrease in prominence and die out eastwards before reaching the coast of Norfolk, possibly reflecting the superimposition of a Silurian turbidite-filled basin upon the more magnetic, earlier Palaeozoic basement (c.f. the blanketing effect of the Silurian turbidites on the magnetic signature in Wales, Figure 3). Lineament 13 is also significant for two other reasons. It corresponds roughly to the postulated northern margin of the Midlands Massif of some earlier authors (e.g. Kent 1966) and, from The Wash westwards, seems to mark the junction of two areas of contrasting magnetic character. To the south lies a zone of relatively high frequency magnetic anomalies indicating relatively near surface magnetic sources, while to the north longer wavelength anomalies indicate slightly deeper magnetic basement.

In the southern zone, where the Upper Palaeozoic cover is mostly thin (see Figure 1), several different magnetic sources can be identified. A narrow belt of magnetic highs (MH3) lies just to the south of the Widmerpool Gulf. The exposed Mountsorrel Granodiorite, attributed an Ordovician age by Le Bas (1982) corresponds to one of the peaks in this zone and comparable plutonic rocks have been proven in the Kirby Lane borehole farther east (Maguire *et al.* 1982), indicating that the belt of magnetic highs marks a series of similar intrusions (Evans & Maroof 1976, Allsop 1987). Intermediate volcanic and hypabyssal rocks, proven by boreholes at Cox's Walk, Eakring,

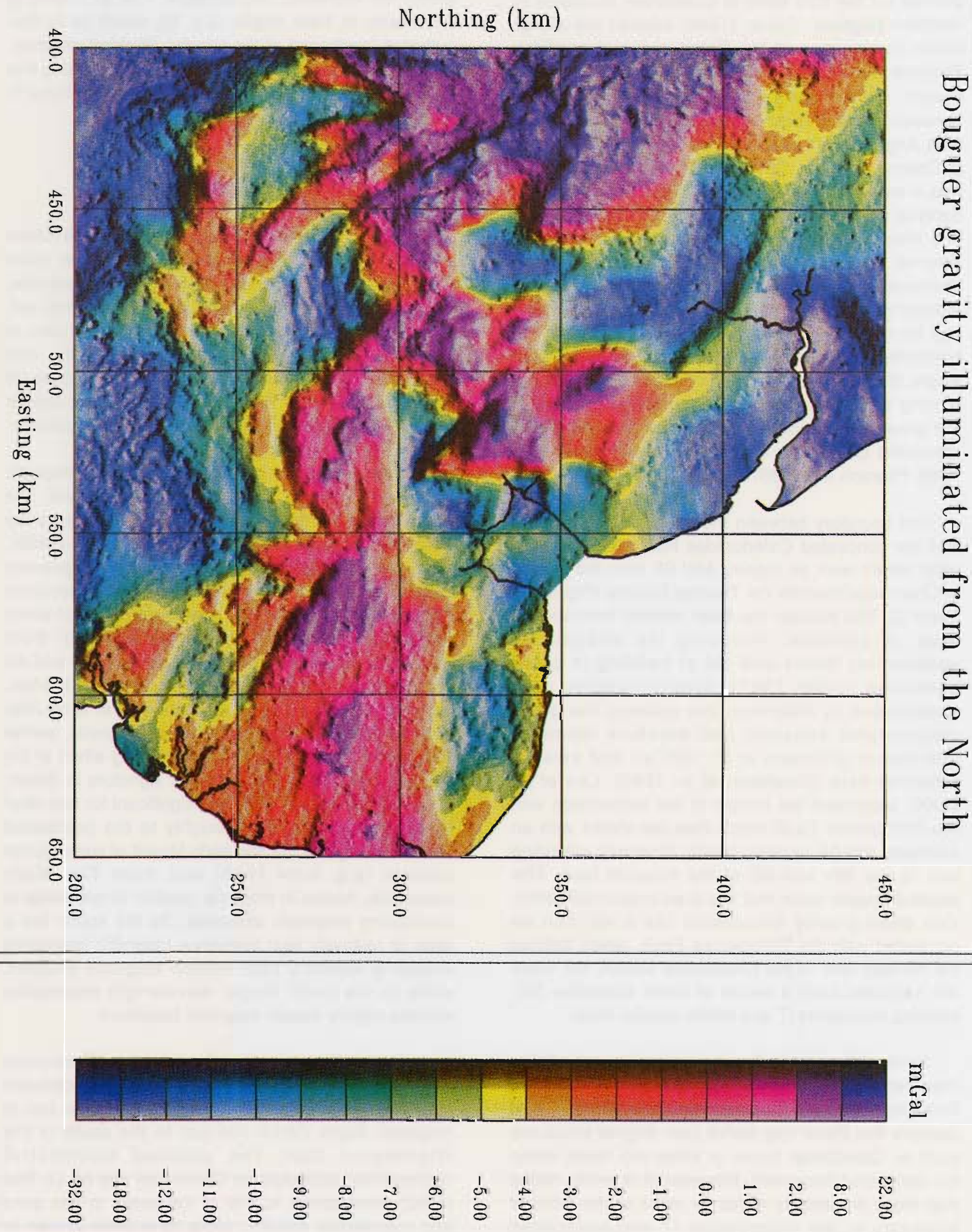

Figure 8. Colour shaded-relief image of the gravity field over eastern England illuminated from the north.

Sproxton, Upwood and Warboys are associated with the plutonic rocks. They form a calc-alkaline arc-magmatic association (Pharaoh *et al.*, this volume) and probably also contribute to the high frequency magnetic signature in this region. The magnetic anomalies around The Wash apparently have a different origin and are probably associated with upwarping, punching through and contact metamorphism of magnetic basement rocks by relatively non-magnetic Caledonian granites (e.g. Allsop 1987).

In those parts of the region where the Upper Palaeozoic and Mesozoic cover is relatively thin (i.e. the above mentioned zone of magnetic anomalies and in East Anglia) it might be expected that the gravity anomalies would correlate with structures within the concealed basement. Several of the prominent gravity lows have been ascribed to concealed granites, including those around The Wash (GL1, GL2 and GL3, Allsop 1987), in north Norfolk (GL4, Cox *et al.* 1989) and Spalding (GL5), but none has been proved positively. The Hollowell borehole was drilled by British Coal on anomaly GL6 to investigate the possibility of a concealed Carboniferous basin. In the event, the hole proved Lower Jurassic and Triassic sediments resting unconformably on tuffs and agglomerates and, as with the other negative gravity anomalies, a granite source is now proposed (Allsop *et al.* 1987). In East Anglia, apart from the suggestion by Cornwell *et al.* (1990) that gravity lineament 9 might be associated with a strip of less dense material near to (or at) the top of the concealed basement, the relationship between the gravity field and basement structure is still poorly understood.

In the northern half of the area gravity lows correlate more closely with known (Upper Palaeozoic) structures, such as the Widmerpool and Edale gulfs and the Gainsborough Trough (GL7, GL8 and GL9 respectively). Anomaly GL10, however, is thought to be related to the postulated concealed Market Weighton Granite (Bott *et al.* 1978). Previous studies (Cornwell & Walker 1989, Lee *et al.* 1990) have identified lineaments associated with known basement highs, such as the Nocton and Askern-Spital highs, and ESE-trending lineaments associated with faults which controlled Upper Palaeozoic sedimentation, such as the Normanton Fault on the southern margin of the Widmerpool Gulf (Figure 1). The regional structure has been interpreted in terms of series of SE- and ESE-trending Dinantian tilt blocks and half-grabens which developed as a result of syn-depositional, extensional reactivation of structural discontinuities in the underlying basement (Smith & Smith 1989, Evans *et al.* 1988, Fraser *et al.* 1990, Plant *et al.*, 1988, Plant & Jones, 1989).

Lee *et al.* (1990) commented on the apparent continuity of trends in the northeast Midlands which, on the broad scale images, appeared to form an arc curving from an ESE direction in the northwest corner of the present map to SE near The Wash. The present images show more clearly that there are two distinct and separate trends in this area (ESE and SE) as observed farther south. Thus the apparent arcuate form of the Askern-Spital High is resolved into ESE- and SE-trending components (14, 14b & 14c). SE-trending gravity and magnetic lineaments are associated with the Nocton High (15 & 16). The Normanton Fault is characterised by a strong ESE-trending magnetic lineament (17a & 17b), which is along strike from lineament 12 in East Anglia. Other broken or less prominent ESE-trending gravity and magnetic lineaments are associated with the Cinderhill Fault (18), postulated Bakewell Fault (19, Smith & Smith 1989) and the southern margin of the Edale Gulf (20). However, the Normanton and Cinderhill faults have SE-trending components at their northwestern ends (Figure 1) which appear to correlate with magnetic lineament 21. Thus the present images strongly support the suggestion that the pattern of Upper Palaeozoic sedimentation was controlled primarily by the interaction between the SE- and ESE-trending structures within the basement.

While individual lineaments (gravity and magnetic) may correlate with specific structural features (faults?) within the concealed basement, the trend of the broader magnetic highs is also worth noting. The most prominent of these in eastern England is the belt of magnetic anomalies running from the northwest corner of the map to East Anglia (MH4 to MH8), as described by Bullerwell (in Bott 1961). To the southeast of The Wash the belt has a predominantly ESE trend (associated with lineaments 12 and 13) which contrasts with a more southeasterly trend immediately north of The Wash. Farther north again (northwest of the postulated Market Weighton Granite, GL10) the trend swings back towards ESE. Thus the broad magnetic belt comprises a series of segments showing the same two trends as observed in the sharper lineaments.

The source of the magnetic anomalies has been the subject of considerable discussion. They originate in rocks older than the Upper Palaeozoic cover (Bott *et al.* 1978) and have been used to infer the northern extent of shallow Proterozoic rocks of the Midlands Microcraton (Wills 1978). However, as discussed above, the northern margin of the craton is defined mainly on other criteria and lies well to the southwest. The annular magnetic highs associated with the Wensleydale Granite (north of the present study area) and postulated Market Weighton and Wash granites have been ascribed to upwarping of the magnetic

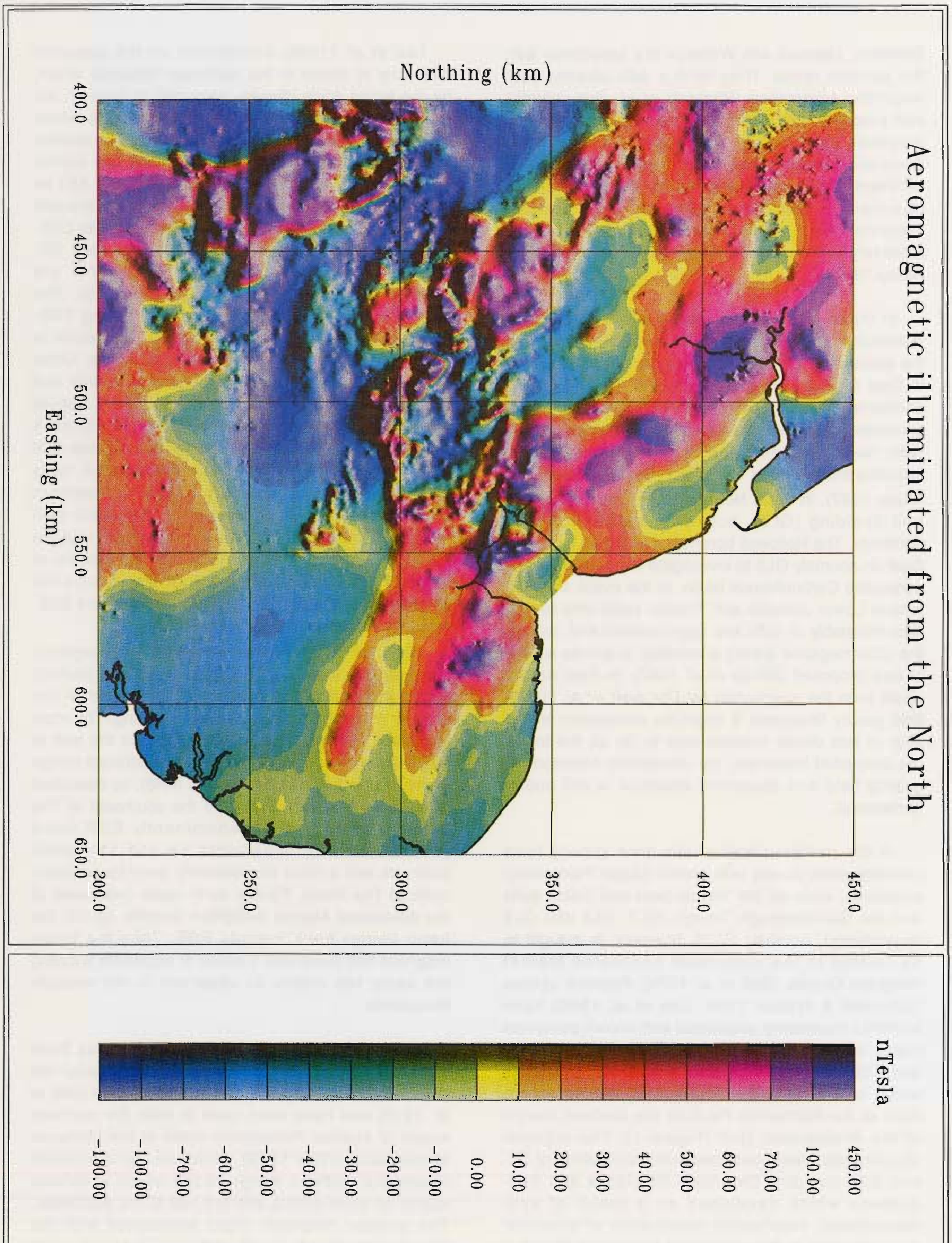

Figure 9. Colour shaded-relief image of the magnetic field over eastern England illuminated from the north.

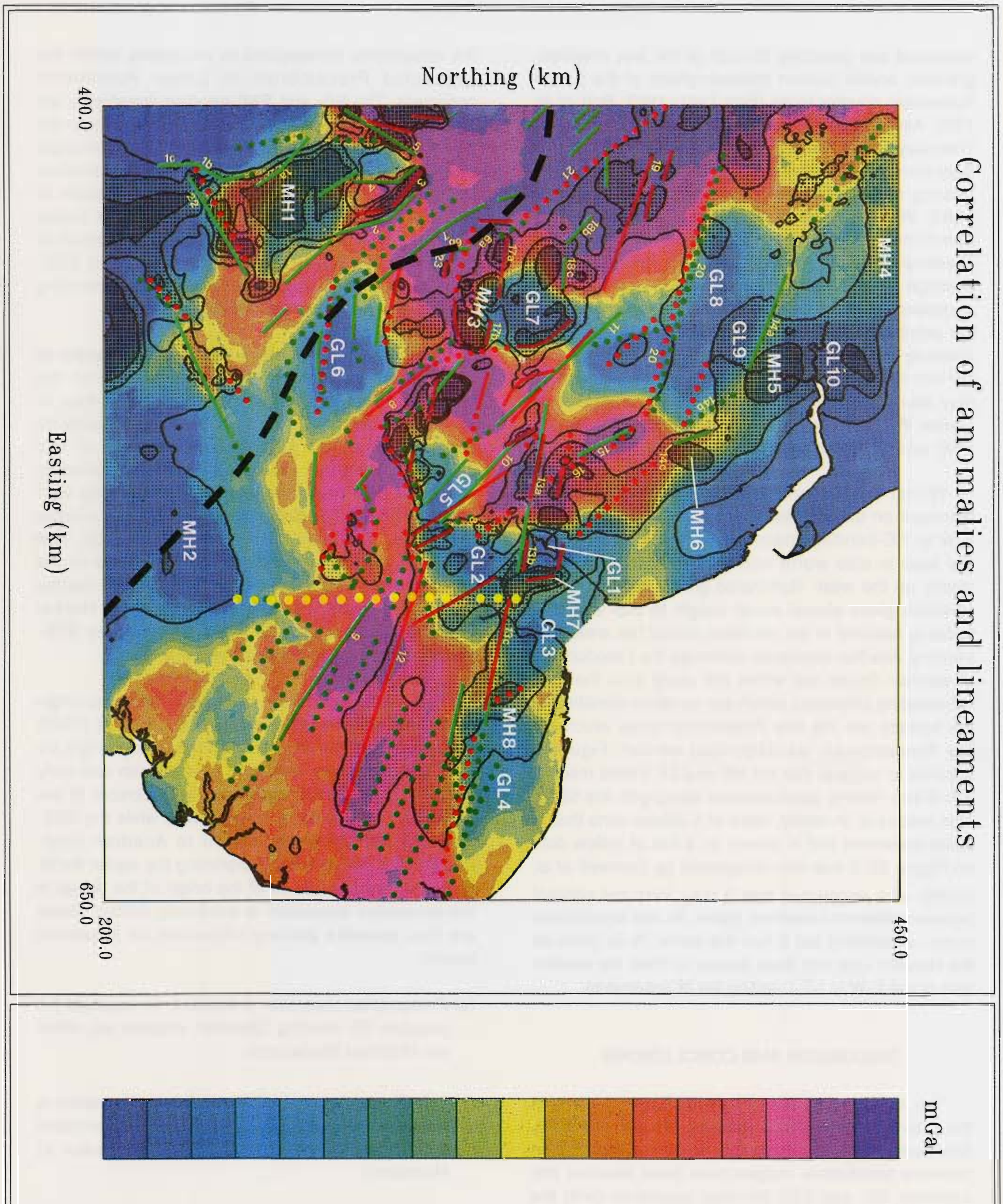

Figure 10. Compilation of information from the gravity and magnetic images. Colour fill indicates Bouguer gravity anomaly values (red = high, blue = low). Hatch pattern indicate positive aeromagnetic anomalies (light stipple = 0 to 50 nT, medium stipple = 50 to 100 nT, dark stipple = > 100 nT). Gravity lows discussed in the text are labelled GL1 to GL9, magnetic highs are labelled MH1 to MH8. Gravity and magnetic lineaments are shown as green and red lines respectively. Continuous lines indicate strong lineaments, broken lines indicate weak lineaments. The line of yellow dots indicates the diffuse N-S zone through East Anglia visible on Figure 5 which appears to mark the approximate eastern limit of the E- to NE-trending set of lineaments. The black dashed line indicates the northeastern margin of the Midlands Microcraton inferred from previous studies (see text).

basement and punching through of the less magnetic granites, and/or contact metamorphism of the Lower Palaeozoic country rocks (Bott 1961, 1967; Bott *et al.* 1978, Allsop 1987). The anomaly on the margin of the Wensleydale Granite was investigated by the Beckermonds Scar borehole which found magnetite bearing sedimentary rocks of Arenig age (Berridge 1982, Wilson & Cornwell 1982). Berridge (1982) concluded that the magnetite was of primary (sedimentary) origin but Cann (in discussion of Berridge 1982) thought that the evidence pointed to a secondary origin. The issue remains unresolved but the persistence of the magnetic belt as a deep-seated anomaly between the known granites suggests that contact metamorphism cannot be the only cause. It may also be significant that the postulated granites at Market Weighton and around The Wash occur where ESE- and SE-trending segments of the belt intersect.

Whilst the SE and ESE trends are the most dominant on the images, the presence of the shorter E-W to NE-trending lineaments in the central part of the area is also worth noting. These appear most clearly on the west- illuminated gravity image (Figure 5) which gives almost equal weight to NE- and SE-trending features in the southern part of the area. NE-trending Acadian structures dominate the Caledonides of western Britain but within the study area the only NE-trending structures which are certainly identified at the surface are the late Proterozoic faults which cut the Precambrian, as described earlier. Figure 5 appears to suggest that the NE and SE trends meet at a N-S line running approximately along grid line 555E. This feature is, in reality, more of a diffuse zone than a sharp lineament and is shown as a line of yellow dots on Figure 10. It was first recognised by Cornwell *et al.* (1990) who suggested that it may form the contact between different basement types. Its real significance is not understood but it has the same (N-S) trend as the Malvern Line and does appear to mark the eastern limit of the E-W to NE-trending set of lineaments.

DISCUSSION AND CONCLUSIONS

The dominant trends in eastern England, on both the gravity and magnetic images, are SE and ESE. Structures which appeared to have an arcuate form on previous broad-scale images have been resolved into separate SE- and ESE-trending segments (with the exception of some short arcuate anomalies associated with the margins of intrusions). A subordinate set of shorter E- to NE-trending lineaments is also observed in the central part of the area.

The presence of the dominant SE and ESE trends in the southeast Midlands and East Anglia, where the Upper Palaeozoic cover is relatively thin, suggests that the lineaments correspond to structures within the concealed Precambrian to Lower Palaeozoic basement. The SE- and ESE-trending lineaments are equally apparent in the northeast Midlands where the Upper Palaeozoic cover is thicker. This strongly supports the suggestion from previous studies (references cited above) that the complex pattern of SE- and ESE-trending Lower Carboniferous tilt blocks and half-grabens in this area developed as a result of the interaction between reactivated SE- and ESE-trending structural discontinuities in the underlying basement during Dinantian crustal extension.

The new images resolve SE-trending lineaments associated with the northeastern margin of the Midlands Microcraton in rather more detail than in previous studies. The pattern of these lineaments suggests that the northeastern margin of the microcraton may be more irregular than previously supposed. The broad magnetic ridge extending from northern England to East Anglia has, like the sharper lineaments, also been resolved into separate SE- and ESE-trending components. While the source of the anomaly remains unclear it may be significant that the postulated (early Devonian?) granites at Market Weighton and around The Wash occur where ESE- and SE-trending segments of the belt intersect.

There has been much speculation as to the origin of the basement trends. For example, Lee *et al.* (1990) suggested that the SE-trending lineaments might be related to structures within the Precambrian and early Palaeozoic basement associated with closure of the Tornquist Sea (Cocks & Fortey, 1982) while the ESE-trending set could be related to Acadian (end-Caledonian) deformation overprinting the earlier trend. However, direct evidence of the origin of the trends in the concealed basement is extremely limited. There are four possible primary influences on basement trends:

(a) Precambrian magmatic processes, for example the possible SE-trending Charnian volcanic arc within the Midlands Microcraton.

(b) Late Precambrian (Avalonian) deformation which is observed in Charnwood to have an ESE orientation with SW-trending cross-faulting (also seen at Nuneaton).

(c) Possible structures relating to closure of the Tornquist Sea in the Ordovician. A SE-trending arc has been inferred by Pharaoh *et al.* (this volume) but the vector of closure is not well constrained.

(d) Structures relating to Acadian (early Devonian) dextral transpression as inferred from the models of Soper *et al.* (1987).

Contrary to the view expressed by Lee *et al.* (see above), it is possible that the ESE-trending structures are related to the Avalonian deformation observed at Charnwood while the SE-trending structures originated during the Acadian (early Devonian) transpression, perhaps influenced by the massive bulwark of the Charnian volcanic arc complex within the microcraton. However, structures of Precambrian age exist with both SE and ESE trends (a and b above) so it is also possible that these represent the primary trends which were reactivated during Tornquist closure and/or Acadian transpression to form the set of discontinuities which were subsequently exploited during Upper Palaeozoic crustal extension. A degree of uncertainty in interpreting trends in Eastern England is not surprising when one considers the complexity of the Welsh Caledonides where Acadian folds and cleavage trend from N-S through NE-SW to E-W and are cut by faults which trend in particular NE-SW and ENE-WSW (N. Woodcock, pers. comm.).

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