The Use of Satellite Data for Improved Structural Interpretation in the Leicestershire Coalfield Area

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Abstract: Comparison of the results of interactive digital processing of Landsat multispectral scanner (MSS) and Thematic Mapper (TM) images with regional geophysical data and known geological faults has led to an improved understanding of the geological structure in and around the Leicestershire Coalfield in the East Midlands. Spatial filtering of the digital Landsat data enhanced the images for structural interpretation despite superimposed landuse patterns. A high correlation between Landsat lineaments and known geological fault patterns suggests that Landsat images will enable high confidence structural analyses to be made of areas that have significant cultural effects.

The distribution of sediments in various depositional environments is believed to be influenced by structures in the underlying basement, which also affect outcrop patterns. The purpose of this study is to establish the relationships between known structures, such as faults and fold axes, and structures inferred from geophysical anomalies and Landsat lineaments in the Leicestershire coalfield region (Fig. 1). The aim is a greater understanding of the relationship between the regional structural setting and structure found within the coalfield. Also, the structural setting of the Carboniferous rocks of the Leicestershire coalfield needs to be examined in some detail before conclusions can be drawn about the effects of structure on sediment distribution.

Only limited structural data are available from the basement and cover rocks in the area. This information has been supplemented with data inferred from Landsat images and geophysical maps. Known geological faults were digitized from published 1:250 000 (Institute of Geological Sciences, 1983), 1:50 000 (Institute of Geological Sciences, 1974, 1982) and 1:10 000 geological maps of the area. Other lineaments were interpreted and digitized from the regional gravity and aeromagnetic maps, available at scales of 1:625 000 and 1:250 000 (Geological Survey of Great Britain, 1956, 1964). Lineaments were also digitized off annotated overlays of Landsat multispectral scanner (MSS) and thematic mapper (TM) satellite images.

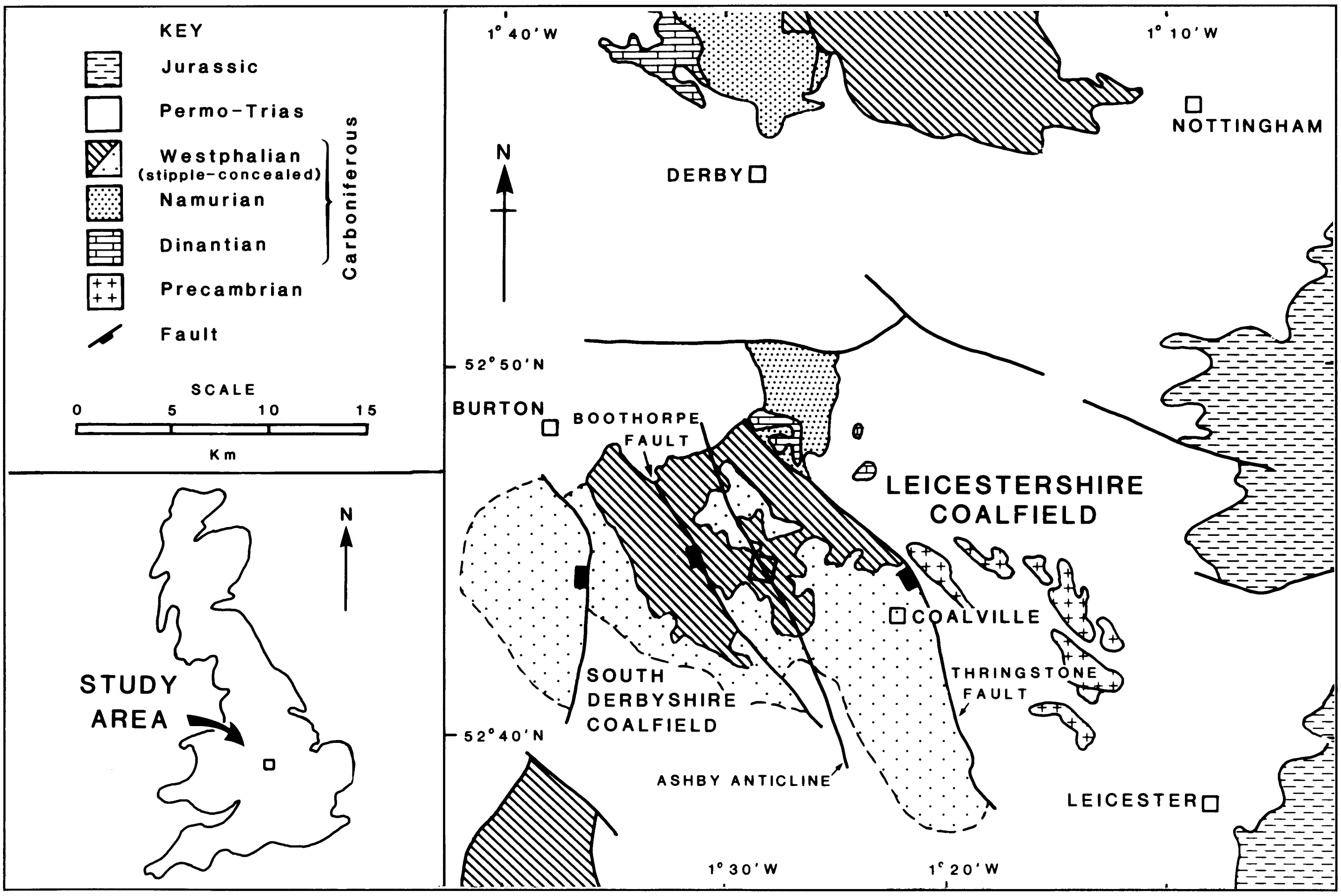


Fig. 1. Location of the study area, with simplified geology and structure.

Geological Setting

The basement rocks in the study area consist of Precambrian (Charnian) and Lower Palaeozoic rocks (Soper *et al.*, 1987; Pharaoh *et al.*, 1987). Charnian rocks crop out to the east of the Leicestershire coalfield (Fig. 1) and are thought to extend, in the subsurface, as far west as the Boothorpe fault (Whitcombe and Maguire, 1981b; Fulton and Williams, 1988). In outcrop the Charnian rocks are folded into an anticline (Watts, 1947) with a NW-SE trend. The rocks display both fracture and slaty cleavage with a strike of 280° (Evans, 1968, 1979). The NW or WNW trend is commonly referred to as the Charnoid trend.

Cambrian rocks have been identified adjacent to the Thringstone Fault to the east of the coalfield where they are folded, fractured, and cleaved with an E-W strike (Butterley and Mitchell, 1946; Evans, 1979). To the east of the Precambrian outcrops the Upper Palaeozoic and Mesozoic sediments are underlain by volcanic rocks associated with cleaved greenschist facies Lower Palaeozoic sediments (Pharaoh *et al.*, 1987). The boundary between the Precambrian and Lower Palaeozoic rocks trends NW-SE (Fig. 2).

To the west of the Boothorpe fault, subsurface data indicate that Lower Palaeozoic rocks form the basement of the South Derbyshire coalfield (Fulton and Williams, 1988). The Leicestershire coalfield itself has a complex pattern of faults and folds, dominated by NNW-SSE trending structures, e.g. the Thringstone and Boothorpe faults (Fig. 1).

The Dinantian limestone, which unconformably overlies the Cambrian and Precambrian basement rocks, was strongly affected during deposition by active block faulting in the basement (Falcon and Kent, 1960; Collinson, 1988). A number of narrow basins, separated by more stable blocks, have been identified from geophysical exploration and borehole data (Fig. 2) (Anderton *et al.*, 1983). One such basin is the Widmerpool Gulf, which has an E-W alignment and lies immediately north of the Leicestershire coalfield (Fig. 2).

The Dinantian rocks in Derbyshire have been formed into a dome with an axis which strikes approximately SSE. Results of a 40km seismic survey (Whitcombe and Maguire, 1981b) between Ballidon Quarry in the north and Cloud Hill Quarry near Charnwood in the south (Fig. 2), indicate a positive structural feature which crosses the Widmerpool Gulf. This effectively creates an extension of the dome axis southwards, to link with the SSE trending Ashby anticline which lies between the Leicestershire and South Derbyshire coalfields.

The limestone is succeeded by relatively undeformed Namurian and Westphalian strata. These in turn are overlain unconformably by Triassic sediments and further east these are covered by Jurassic rocks.

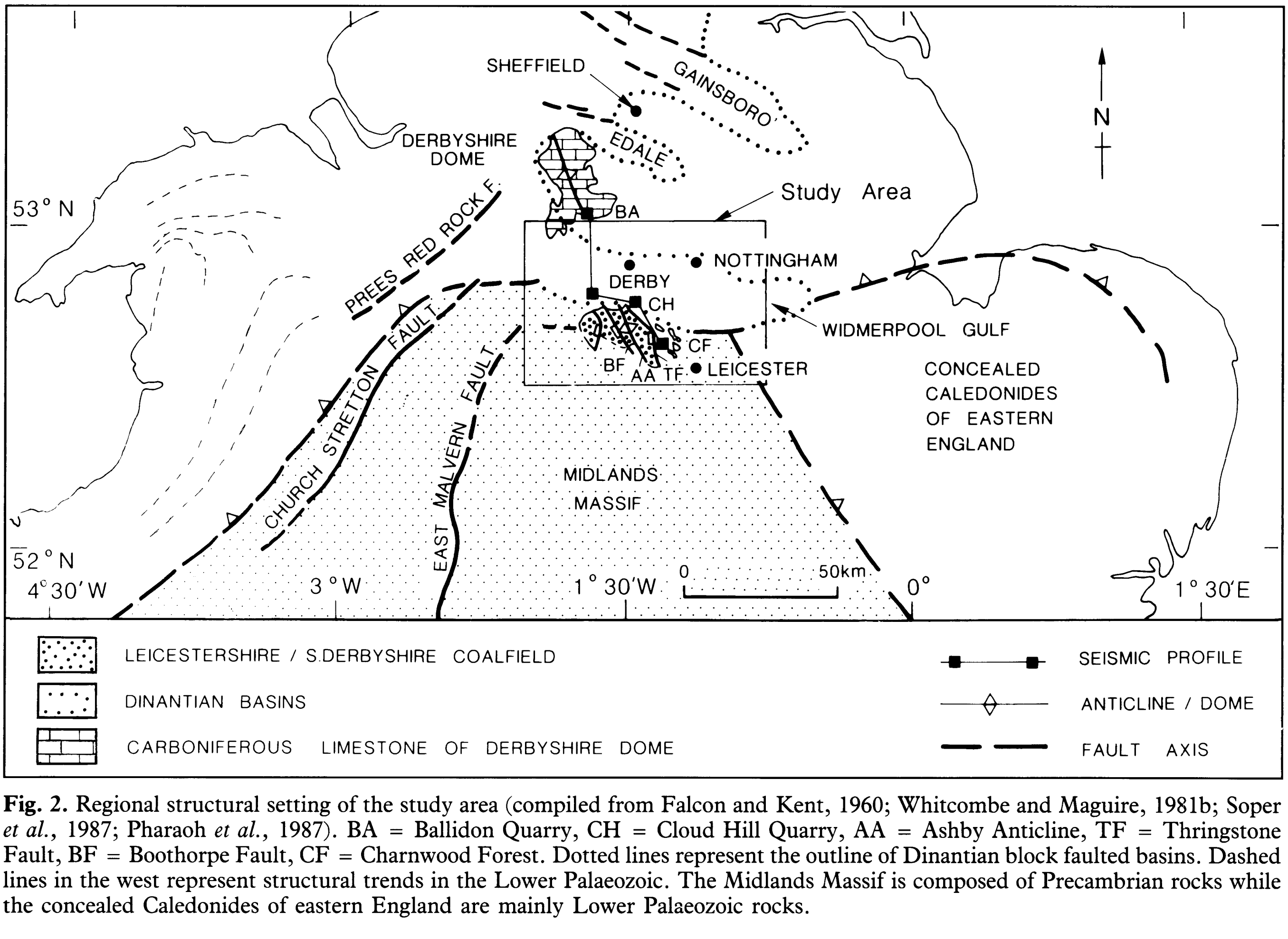


Fig. 2. Regional structural setting of the study area (compiled from Falcon and Kent, 1960; Whitcombe and Maguire, 1981b; Soper *et al.*, 1987; Pharaoh *et al.*, 1987). BA = Ballidon Quarry, CH = Cloud Hill Quarry, AA = Ashby Anticline, TF = Thringstone Fault, BF = Boothorpe Fault, CF = Charnwood Forest. Dotted lines represent the outline of Dinantian block faulted basins. Dashed lines in the west represent structural trends in the Lower Palaeozoic. The Midlands Massif is composed of Precambrian rocks while the concealed Caledonides of eastern England are mainly Lower Palaeozoic rocks.

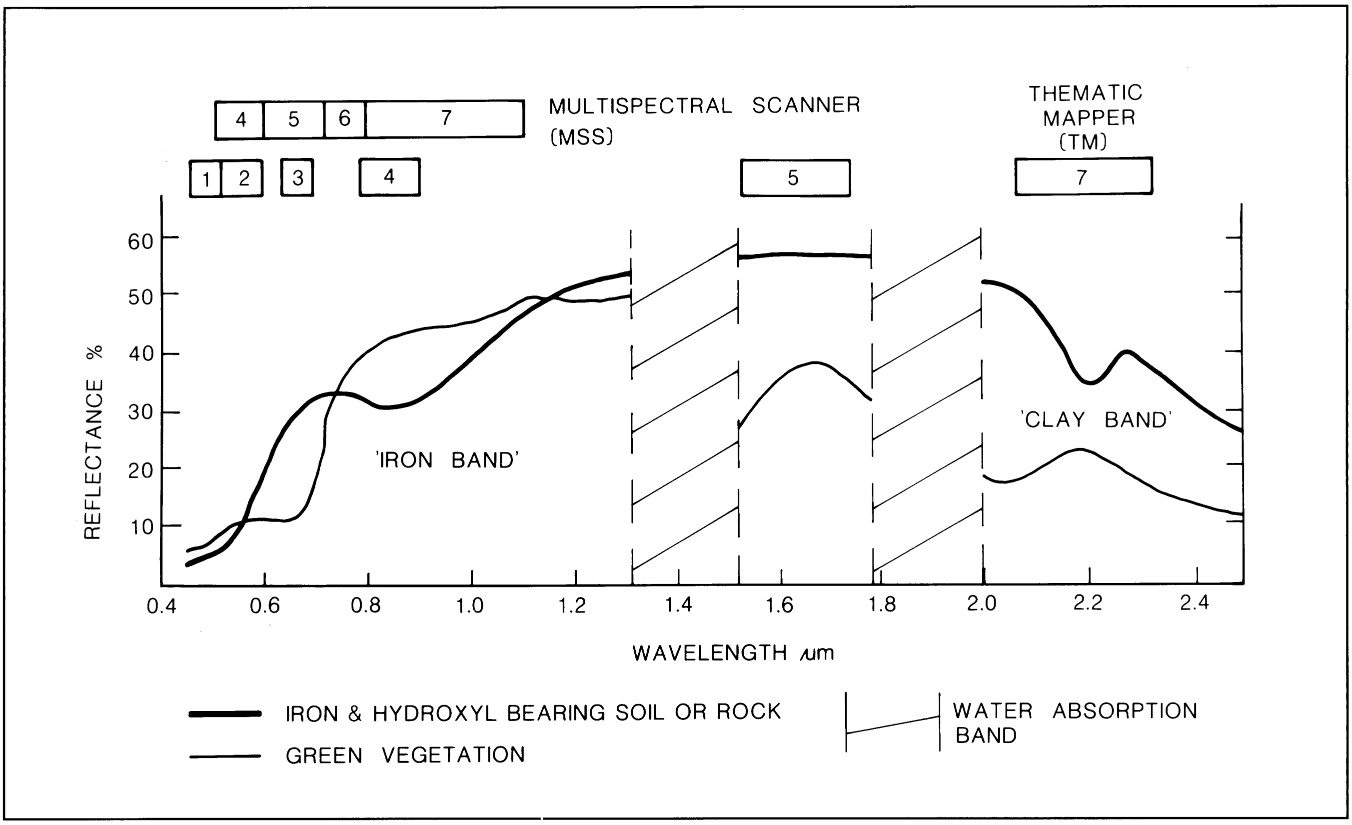


Fig. 3. Reflectance spectra of green vegetation and iron- and hydroxyl-bearing soil or rock in the visible to short wavelength infrared regions, illustrating the wavelengths for which data are recorded by the Landsat multispectral scanner and thematic mapper (modified after Abrams, 1984).

Remote Sensing

Remote sensing of geological structures has been used successfully in mineral exploration (Smith, 1977; Nash *et al.*, 1980; Peters, 1983; Guinness *et al.*, 1983), oil exploration (Bailey and Anderson, 1982; Peters, 1983, Lake *et al.*, 1984), exploration for water (Walters, pers. comm.) and geothermal energy. Satellite images provide a synoptic view of an area and allow the interpreter to see the regional structural/morphological patterns. Comparisons can then be made between the lineaments (inferred structures) observed from the synoptic view and those observed on the ground, and the relationship of the two sets of data rationalized (Drury, 1986).

Drury (1986) pointed out that there has been little success in structural analysis by remote sensing in areas with considerable cultural cover (housing, farms, roads, etc.) such as the East Midlands because of thick soils, modern sedimentological or geomorphological processes and the camouflaging effects of agricultural patterns and urbanization. Structural analysis has been most successful in semi-arid or arid terrains with a high percentage of rock exposure (Berhe and Rothery, 1986). Areas of natural vegetation are now also available for interpretation (Chang and Collins, 1983; Sabins, 1983), because residual soil reflects the underlying bedrock composition, and different rock types have differing mineral contents which may affect the vegetation cover. Extreme concentrations of minerals may induce stress in the natural vegetation, affecting reflectance properties.

It has been demonstrated that interactive processing of satellite images preserves fine detail and clarifies the position of lineaments. Various image processing techniques were adequately described by Lillesand and Kiefer (1979), Siegal and Gillespie (1980), Rothery (1985), Drury (1987) and Sabins (1987).

The Landsat multispectral scanner (MSS) bands 4, 5, 6 and 7 (Fig. 3) were designed for use by earth resources scientists studying vegetation and land-use. Hence they discriminate between soil and plants and between different plant species. Thematic mapper (TM) bands 1, 2, 3 and 4 are used in a similar way. The electromagnetic spectrum cannot be monitored in its continuous range because certain wavelengths are absorbed by water giving rise to areas through which energy is not transmitted. TM bands 5 and 7 record data in atmospheric windows between water absorption bands (Fig. 3). Band 5 was designed to monitor plant moisture content variations as well as maximum rock reflectance. As plant moisture content changes, so the depth and width of this window changes (Goetz *et al.*, 1983). Drury (1986) suggested that the variations between soil and plants are at a minimum between late January and late March in the northern hemisphere and that the cultural clutter is muted, so structural interpretation becomes possible. Here we examine the possibility of using data acquired during summer for structural interpretation. Empirical observations of TM bands 5 and 7 of a cloud-free June image showed that band 7 gave better enhancement of linear features. Therefore a portion of Landsat TM band 7 covering part of the East Midlands was used in this study as well as a portion of a cloud-free June Landsat MSS band 7 image of the same area (Fig. 4). The MSS image was used for comparative purposes. MSS band 7 has been shown by previous workers (Larson, 1982; Lake *et al.*, 1984) to respond well to enhancement techniques for structural interpretation.

Image Processing

Two data sets were available for this study, Landsat TM data with 7 bands and MSS data with 4 bands. The TM data from path 202, row 23, was flown in June 1984 and the MSS data from path 213, row 28, was acquired in June 1976. Only TM band 7 and MSS band 7 were used in this study. The MSS image was pre-corrected to fit the National Grid, while the TM image was geometrically corrected using control points recognized on Ordnance Survey topographic maps.

Image Enhancement

The area chosen was broken down into a series of adjacent 512 x 512 subsections (Fig. 5), and the same enhancement techniques were applied to both the MSS and TM subscenes. Each 512 x 512 subscene was subjected to a linear intensity (contrast) stretch.

Digital images consist of discrete picture elements called pixels. Associated with each pixel is a number that is the average radiance, or brightness, of that very small area within the scene. An image is built up of a series of rows and columns of pixels. The image intensity level histogram is a useful indicator of image quality (Fig. 6). The histogram describes the statistical distribution of intensity levels, or grey levels, in an image in terms of the number of pixels (or percentage of the total number of pixels) having each grey level. Figure 6 shows the general characteristics of histograms for a variety of images. A histogram of a typical untransformed image has low contast (Fig. 6a, b) and in this case the input grey level is equivalent to the transformed grey level (Schowengerdt, 1983). A simple linear transformation, commonly called a contrast stretch, is routinely used to increase the contrast of a displayed image by expanding the original grey level range to fill the dynamic range of the display device (Fig. 6c).

In this study the histogram 'tails' were clipped manually for each scene because the subscenes around the edges of the study area incorporated large areas of constant illumination where no data were recorded, and other subscenes included large conurbations. A general contrast stretch did not necessarily give the best results in any given subscene.

Spatial Frequency Filtering

Spatial frequency filtering is used to enhance (or suppress) edges. An edge is determined by the gradient of brightness with distance. For example, a white line on a black background can be resolved digitally at a closer spacing than a light grey line on a dark grey background (Drury, 1987). High frequency, high amplitude features have steep brightness gradients and are known as edges. Descriptions of filtering techniques used to enhance edges, or linear features, were given by Sabins (1987) and Drury (1987) amongst others. By selection of an appropriate rectangular or square

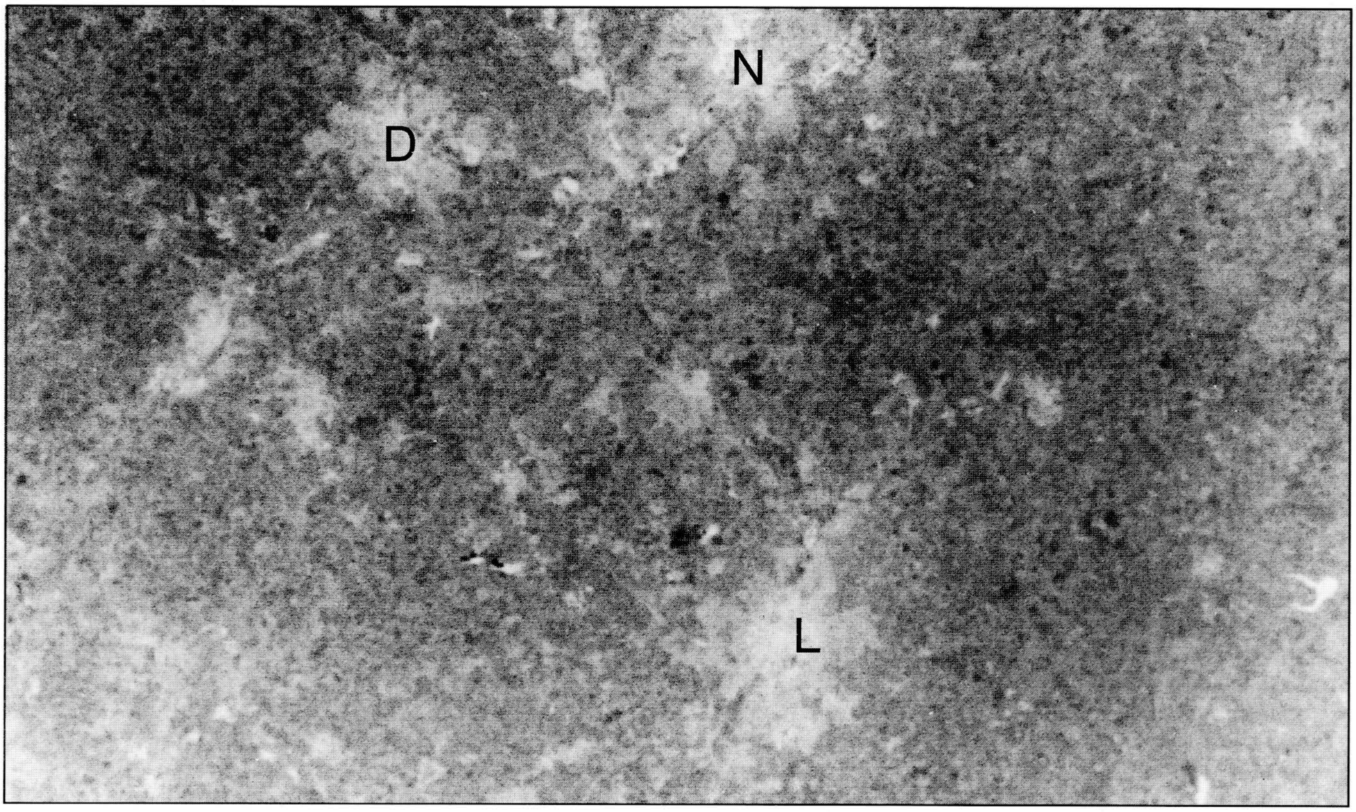


Fig. 4. A resampled Landsat MSS band 7 image of the study area. L = Leicester, N = Nottingham, D = Derby.

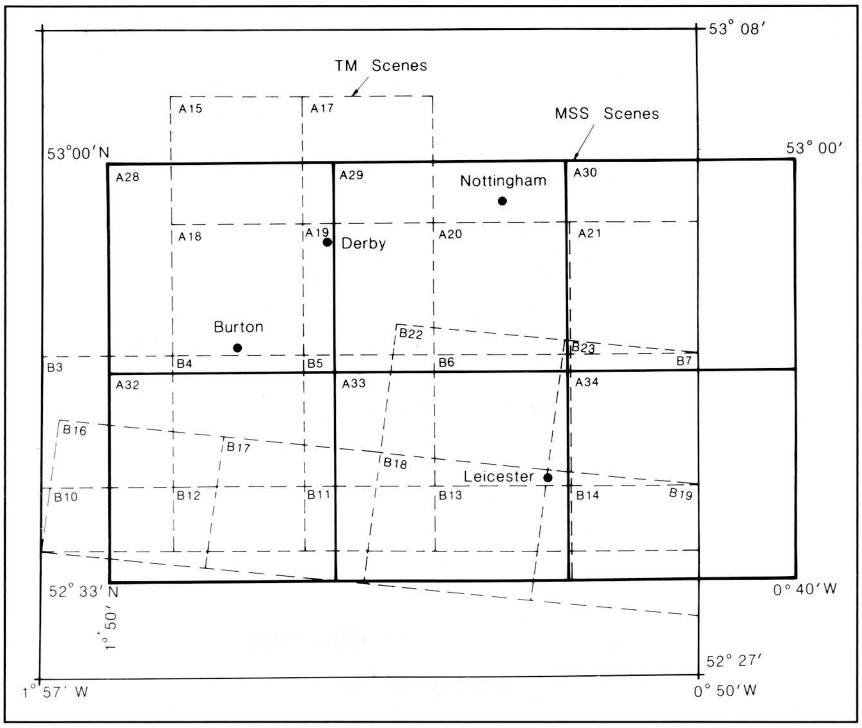
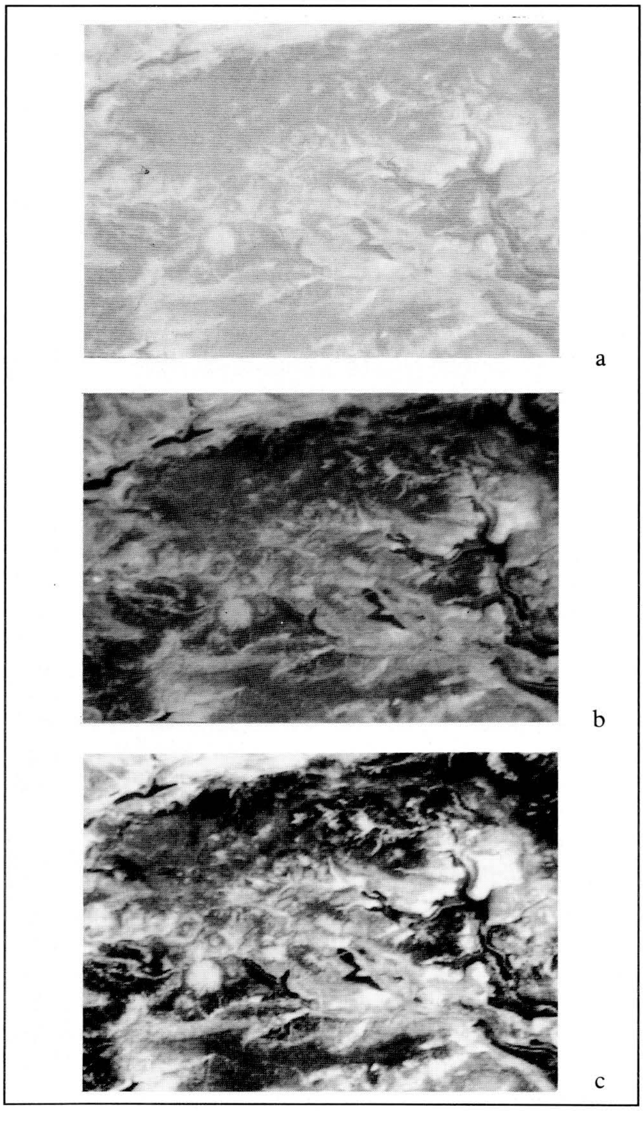


Fig. 5. Location of Landsat MSS and TM subscenes in the study area.



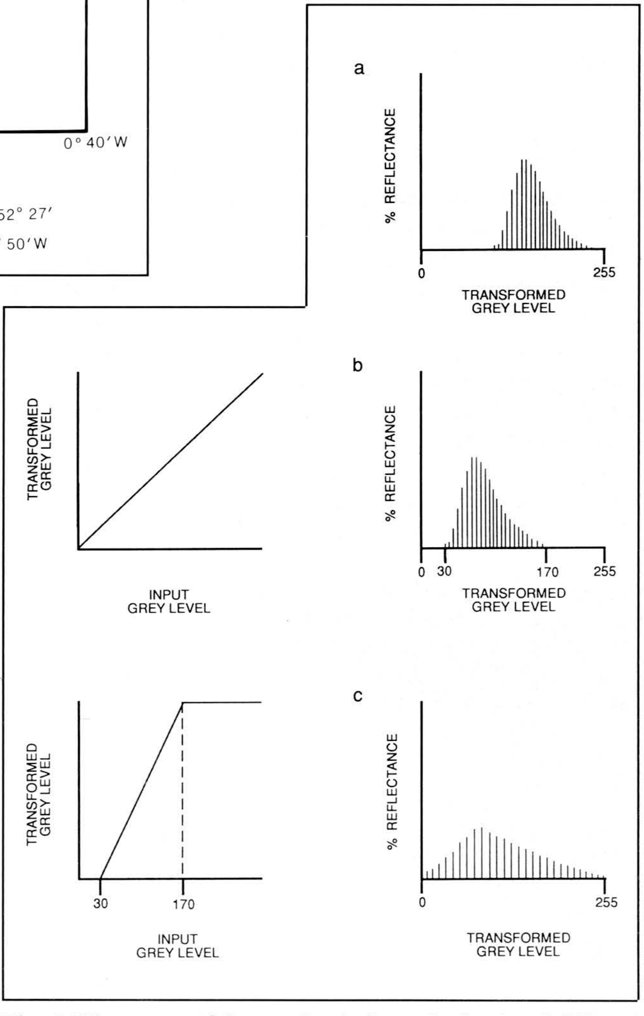


Fig. 6. Histograms of the grey levels (intensity levels) of different images. The image is part of Landsat 5, TM band 3 taken on 26 April 1984 of the High Peak District of northern England. The area is approximately 15 x 15 km. The dark areas are water bodies; those in the upper left corner are the Longdale reservoirs whilst those in the lower right are the Derwent Valley reservoirs. The two E-W trending bright areas in the lower right of the images are the lowland valleys of Edale and Castleton (Mather, 1987). (a) A bright (high radiance), low intensity image with low spectral resolution and its associated histogram. (b) A dark, low intensity, low contrast, low spectral resolution image with its associated histogram. (c) An image with high spectral resolution but low reflectance values. Increased spectral resolution has been achieved with a simple histogram transformation, also known as a histogram stretch. Modified after Schowengerdt (1983).

convolution matrix, different high spatial frequency features can be enhanced and/or other features suppressed.

Directional enhancement is achieved by using square convolution matrices with cell weightings arranged asymmetrically about an axis. For example:

$$\begin{matrix} -1 & 0 & 1 \\ -1 & 0 & 1 \\ -1 & 0 & 1 \end{matrix}$$

If an edge is orientated N-S, with the bright side of the edge on the east (right), as one would expect in summer imagery collected at 9.30 a.m. local time, then this filter produces maximum enhancement of N-S features.

Many different combinations of matrix type and size were applied to both data sets. For this particular area it was found empirically that the following matrices provided the greatest discrimination:

$$\text{TM images} \quad \begin{matrix} -2 & 0 & 0 & 2 \\ -2 & 0 & 0 & 2 \\ -2 & 0 & 0 & 2 \\ -2 & 0 & 0 & 2 \end{matrix} \qquad \text{MSS images} \quad \begin{matrix} -2 & 2 \\ -2 & 2 \end{matrix}$$

Ideally, two perpendicular directional filters are needed, but because of the time required to process each 512 x 512 subscene, and the limited time available on the image processing system, only one filter was used.

The major structures in the area trend NE-SW and SE-NW, and high pass directional filtering in either of these directions would enhance features perpendicular to it and subdue features parallel to it. The filters shown above fall midway and should highlight both structural trends. Lineaments trending SE-NW are generally suppressed on Landsat images because of the southeasterly illumination. It was felt that the chosen filter would maximise the potential for enhancing the expected structural features.

Image Interpretation

Black and white photographs of each enhanced subscene were made and used for structural interpretation (e.g. Fig. 7). Transparent overlays of each subscene were annotated, several times by different people, with lines indicating possible structural trends (Larson, 1982). The obviously spurious lineaments identified by, say, only one interpreter, were ignored as unreliable (cf. Wise, 1982). A compilation of reliable lineaments (compared with the local knowledge of the authors) was made and a field checking exercise undertaken. Prominent topographic and cultural features enabled lineaments to be located on the ground fairly accurately. Lineaments resulting from straight roads or field boundaries were identified and removed from the compilation.

It became evident that the majority of non-cultural lineaments resulted from the alignment of river or stream valleys and topographic ridges (see Saunders and Hicks, 1976). Some lineaments were caused by variation in surface texture, particularly on the TM images. These probably result from a variation in landuse or repetition of tonal change over a short distance giving the effect of texture. Upon compilation it became apparent that some of the lineaments extended over several images, although they were not necessarily continuous. For consistency, only the annotated lineaments were recorded while interpolations were omitted.

Fig. 7. Landsat MSS subscene A29, an example of the hardcopy black and white photograph used for annotation (see Fig. 5 for location).

Known, geologically controlled, lineaments were identified in a few instances, e.g. the Jurassic scarp and the Carboniferous Limestone inliers at Breedon on the Hill. Some previously mapped faults were also detected on the satellite images, such as the eastern boundary fault of the Leicestershire coalfield, the Thringstone Fault.

Topographic ridges of differing widths were detected by TM and MSS because of their ground resolution (30m and 80m respectively). Generally, ridges between 30-70m wide were detected on TM images, and 50-200m wide ridges on MSS images, although ridges at different scales were seen on both. Vegetation cover did not significantly affect a ridge's detection potential, and prominent ridges could be detected in urban areas by shadowing. Where there was a sharp change in slope, such as along stream and river banks, lineaments had good definition.

Correlation of Data Sets

In order to correlate data sets, the Landsat lineament data and known geophysical and geological data were digitized in stream mode, i.e. the digitizer collected data at a rate of 10 points per mm, so continuous, detailed definition of the lineaments was recorded. Each set of data points could then be plotted as a curvilinear feature (Figs 8-10).

For each data set, rose diagrams were plotted of lineament frequency and length (Figs 11-13). In length plotting mode, the program determines the midpoint of each lineament, and plots the direction on the rose, the radius of which corresponds to the lineament length. In frequency mode the program determines the maximum number of data points on a lineament which occur within a sector with a predetermined search angle. The smaller the search angle the greater the detail recorded. Rose diagrams for each data set were plotted for length (search angle 15°) and frequency with search angles set at 3°, 7° and 10°. The 3° search angle is used to illustrate the latter rose diagrams. Artifacts can be produced at angles away from the main directional filter, which may affect rose diagrams and hence interpretation.

The MSS lineaments (Fig. 8), although sparse, display two distinct trends, ENE-WSW and WNW-ESE. The lineament lengths are similar in both directions although there is a higher frequency of

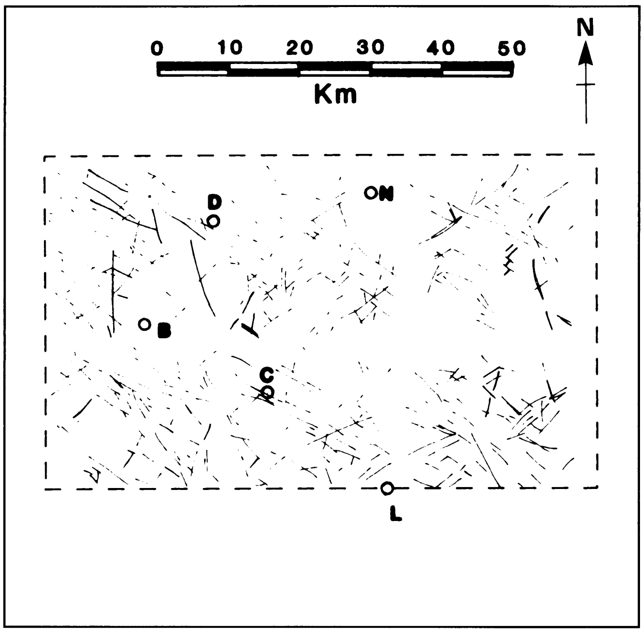


Fig. 8. A plot of the digitized lineaments annoted off Landsat MSS subscenes. D = Derby, N = Nottingham, B = Burton, C = Coalville, L = Leicester.

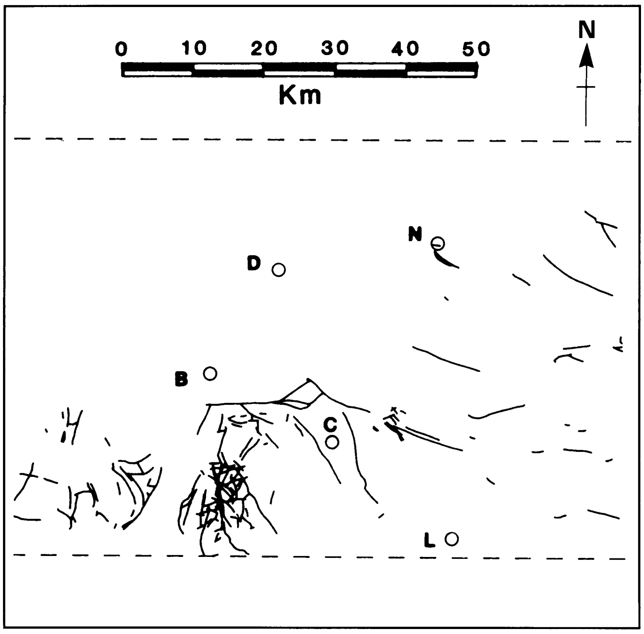


Fig. 10. A plot of the known faults in the study area, digitized off published geological maps (Geological Survey, 1964, 1982, 1983).

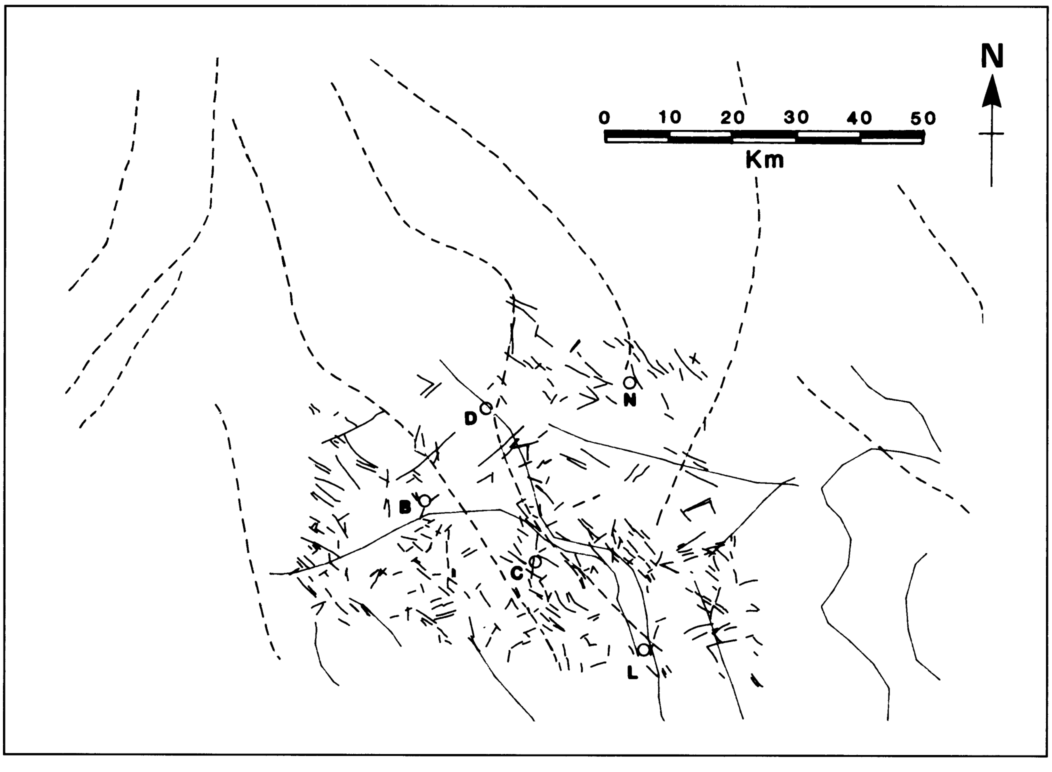


Fig. 9. A plot of the digitized lineaments annotated from Landsat TM subscenes. Dashed lines represent digitized linear gravity anomalies and long solid lines represent linear magnetic anomalies.

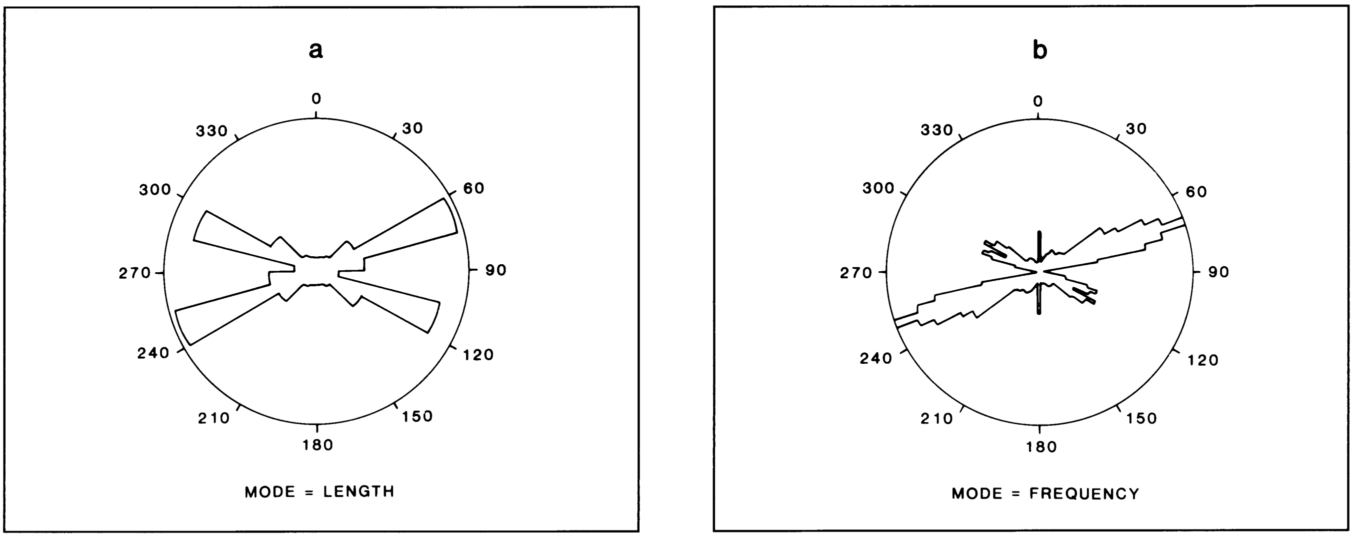


Fig. 11. Rose diagram of inferred structures derived from Landsat MSS imagery of the East Midlands. (a) Length mode with a 15° search angle. (b) Frequency mode with a 3° search angle.

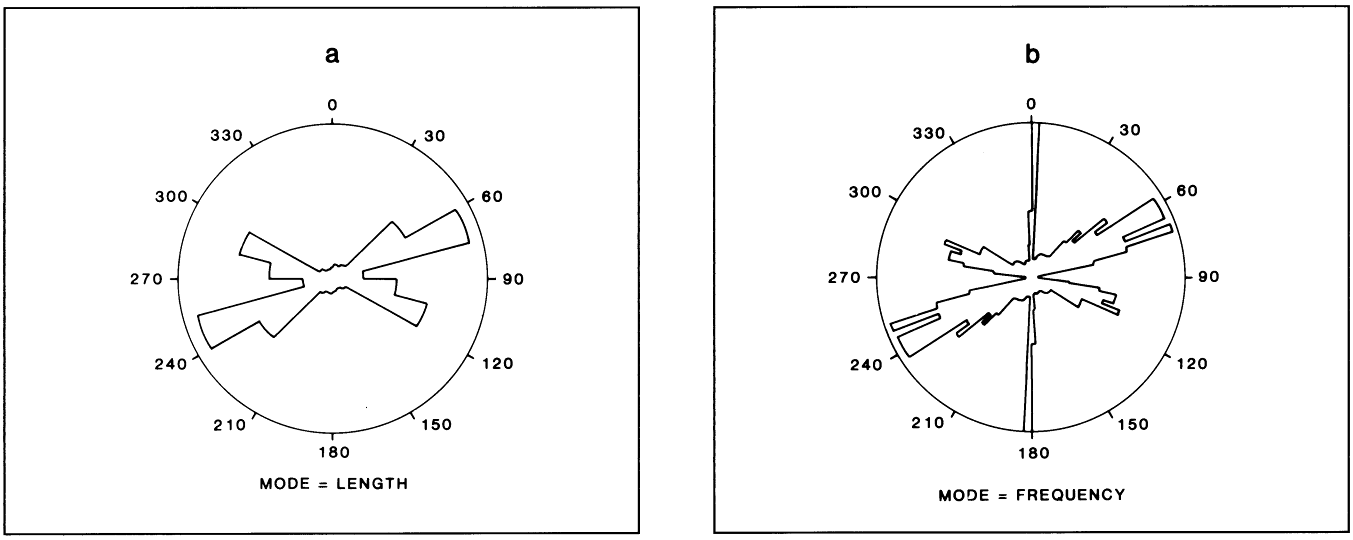


Fig. 12. Rose diagram of inferred structures derived from Landsat TM imagery of the East Midlands. (a) Length mode with a 15° search angle. (b) Frequency mode with a 3° search angle.

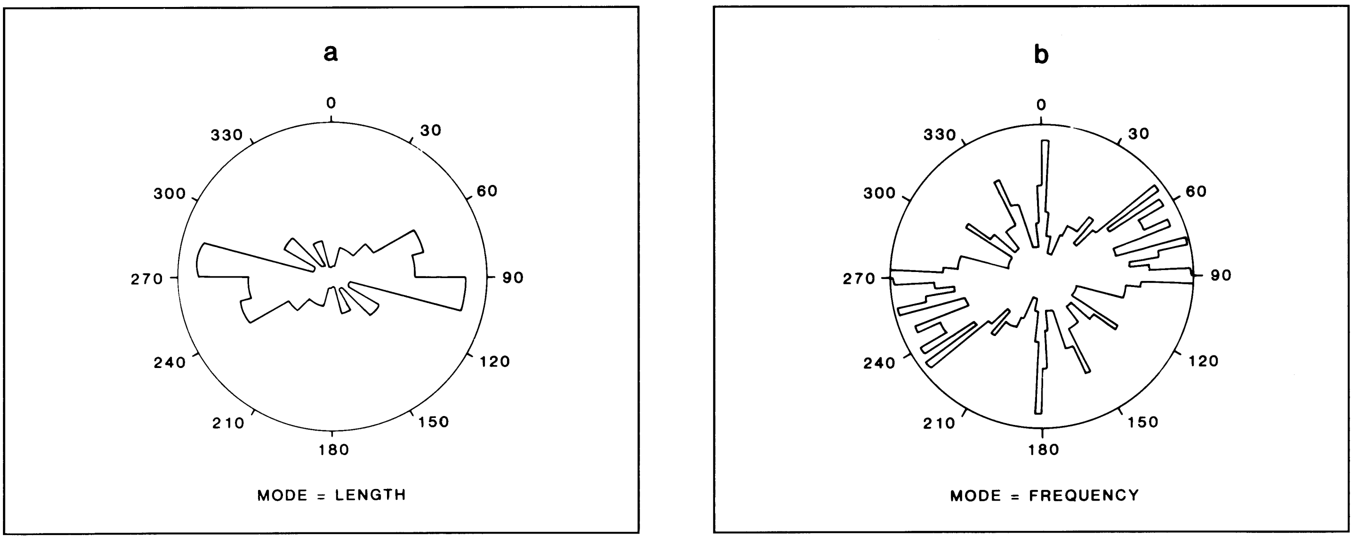


Fig. 13. Rose diagram of known structures derived from faults digitized off geological maps of the East Midlands. (a) Length mode with a 15° search angle. (b) Frequency mode with a 3° search angle.

lineaments in the ENE direction. A small number of lineaments with a N-S component occur in frequency mode (Fig. 11b). A similar pattern appears in the rose diagrams of TM data (Fig. 9). The ENE trend is composed of slightly longer lineaments (Fig. 12a). The N-S component is much more strongly developed (Fig. 12b).

The digitized faults show a greater variability (Fig. 10). In length mode the dominant trend is E-W (Fig. 13a), while in frequency mode there is a distinct pattern in the ENE direction (Fig. 13b). There is a well defined N-S trend as well.

These results suggest that there is a strong correlation between known (faults) and inferred (lineaments) structures. This positive correlation indicates that no artifacts were introduced into the rose diagrams. The dominant E-W trends are subparallel to the Widmerpool trend and the well defined N-S trend is parallel to the strike of Dinantian limestone bedding and faults (Ford, 1978) SE of Cloud Hill (Fig. 2). The length mode should provide a more representative result and implies that the lineaments show a stronger correlation to basement features such as the control on the Widmerpool Gulf (Saunders and Hicks, 1976).

A relationship between basement structures and inferred (geophysical) lineaments is also recognized. Interpretation of the Bouguer anomaly gravity map based on gravity survey overlay, sheet 11 (Geological Survey of Great Britain, 1956) and the aeromagnetic map (Geological Survey of Great Britain, 1964) provided the basis for the geophysical lineaments (Eardley, 1985). Whitcombe and Maguire (1981a, b) and Maguire (1987) have demonstrated with seismics the presence of a structural feature which runs ESE from Mountsorrel (near CF on Fig. 2) to Ticknall (near CH on Fig. 2). This coincides with both gravity and aeromagnetic lineaments (Fig. 9) and is closely aligned with the eastern margin of the Midlands Massif as depicted by Soper *et al.* (1987) (Fig. 2). These authors inferred that hidden Acadian (late Caledonian) basement structures beneath the East Midlands controlled the Dinantian block and basin topography. The controlling faults on these structures trend ESE. Folds in this area show interference between ESE and N-S sets, both trends which feature strongly in the pattern of inferred structures.

Discussion

The study area lies astride the northern margin of the Midlands Massif (Fig. 2). This massif has been described as a rigid indenter (Soper *et al.*, 1987). It acted as a cohesive unit which moved northwards, resulting in reactivation of existing faults, and deformation of the Lower Palaeozoic rocks. Soper *et al.* (1987) also speculated that the curvilinear patterns of faults and folds of the Upper Palaeozoic rocks in N England provide evidence of movement of the rigid indenter. As a result the indenter is flanked at depth by arcuate structures of Lower Palaeozoic age (Soper *et al.*, 1987). To the west of the massif in central Wales, the traditional NE-SW Caledonian (Acadian) trend has been used to describe the tectonic grain. However, in N England, including the NE Midlands there are significant departures from this trend (Fig. 2). In the NE Midlands, the block and basin topography of the pre-Dinantian (Collinson, 1988; Lee, 1988) can be used to infer hidden Acadian structures (Soper *et al.*, 1987). For example, the Gainsborough Trough and Edale Gulf appear to be controlled by ESE trending faults, which are presumed to reflect the Caledonian basement trend. Lee (1988) suggested that a number of faults which control this block and basin topography are orientated N-S, parallel to the N-S Malvernian trend, as extrapolated to other areas in Britain by Haszeldine (1988). The Widmerpool Gulf has a more E-W alignment (Falcon and Kent, 1960; Kent, 1966; Collinson, 1988). The Precambrian basement rocks exposed in Charnwood exhibit a NW-SE Charnian trend, as does the eastern margin of the massif.

Elements of all four structural trends are present in the study area, the NW-SE Charnian trend, the NE-SW Acadian (Caledonian) trend, the N-S Malvernian trend and the E-W Widmerpool trend. The structural patterns that appear on the rose diagrams are ESE, ENE and E-W. It is suggested here that these patterns result from modification at the apex of the rigid indenter of the NE and NW trends on the west and east sides of the Midlands Massif respectively. The northern end of the indenter would not have been a sharp point, but an area of gradual transition and interaction between the NE and NW trends. This would result in a 'rounding off' with the main trends merging to produce hybrid trends to the ESE and ENE.

This combined pattern is further modified in this area by the occurrence of the E-W Widmerpool trend. Soper *et al.* (1987) suggested that this appeared to be controlled by the northern margin of the Midlands Massif. As the Midlands Massif moved northwards, the Lower Palaeozoic rocks were deformed. The northern contact may have been a thrust fault, with the Lower Palaeozoic rocks thrust southwards up on to the Midlands Massif along a roughly E-W line. Reactivation of the 'thrust' fault in pre-Dinantian times, in an opposite sense as a listric normal fault (Quirk, 1988), would have resulted in the formation of a deeping basin, the Widmerpool Gulf, in which thick Dinantian sediments accumulated.

The analysis of known structures correlates with the structural pattern identified in the basement i.e. ESE, ENE and E-W. Further, there is a strong correlation between known structures and inferred lineaments. Despite the speculative origin of the Landsat lineaments in the East Midlands, this correlation lends weight to the theory that basement control is a major factor in their formation.

We suggest that, with care, lineament analysis can be used to infer the presence of structurally controlled geological features, despite cultural camouflage. This work was carried out some time ago, and although some of the software and hardware for image processing has improved, the basic principles applied are still sound. For example, image processing hardware is now capable of undertaking an edge enhancement over an entire MSS or TM scene, without the necessity of creating 512 x 512 pixel subscenes.

Acknowledgements

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