Using Knowledge-Base Rules to Map the Three-Dimensional Nature of Geological Features*

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ABSTRACT: Accurate measurements of three-dimensional geological structural parameters, such as dip and strike measurements, can be extracted from remotely sensed imagery and digital elevation models. This involves finding edges in both data sets and, by using a least-squares approach, fitting a planar surface through the resulting three-dimensional points. A knowledge-based system is required to assess the accuracy of the results and to combine the mass of structural data produced by these techniques into a realistic model of the geology.

STRUCTURAL GEOLOGY IN REMOTE SENSING

REMOTELY SENSED DATA HAVE BEEN USED SUCCESSFULLY to aid the mapping of various structural geological features, such as lithological contact (Drury, 1987), faulting (Stefouli and Osmaston, 1984), and folding (Dekker, 1989) at both local and tectonic scales (Trevett, 1986). To date, most of this work has been qualitative in nature. Although this may be adequate in some applications, others require the accurate extraction of structural parameters, such as dip and strike of folding and faulting (Morris, 1990b), in quantitative terms. This lack of quantitative measurements may be attributed to the use of traditional methods which are based on the analysis of a three-dimensional (3D) scene within the confines of a two-dimensional image. This means that structural mapping is restricted to the identification of the surficial extent of rock units rather than their subsurface structure. Similarly, the assessment of faults is constrained to their surface expression rather than their extension in 3D. Skilled photointerpreters may overcome these problems in part by using both textural and contextual information held within the image, combined with previous knowledge of the area and each workers' experience and accumulated knowledge. However, it is not always possible to determine accurate measurements in this way, and such methods are both subjective and time consuming. Considerable benefit may therefore be derived by developing automatic or semi-automatic techniques which perform these tasks more precisely and cost effectively.

There are two ways in which structural parameters may be automatically measured from remotely-sensed imagery. These include

- the use of shape-from-shading techniques (Wadge *et al.*, 1990), and
- the integration of digital elevation data with the imagery (McGuffie *et al.*, 1989; Chorowicz *et al.*, 1989; Sauter *et al.*, 1989; Morris, 1990a,b).

Shape-from-shading uses the natural shading in the scene combined with a knowledge of the sun's position at the time of imaging to determine estimates of local slope, which may in some geological environments be approximations to the local dip and strike of the geology. This method has the advantage of enabling measurements to be made directly from the imagery. However, it makes a number of restrictive assumptions, namely, that the irradiance on the target is due to direct solar illumination only, that the surface cover has a homogeneous reflectance, and that the target is a Lambertian reflector. In addition, some information must be supplied to constrain the multiple solution of the shape-from-shading technique (Wadge *et al.*, 1990). It is possible to solve many of these problems given enough *a priori* knowledge of the scene, but the techniques will probably never be used on a routine basis within the diverse range of geological environments.

One method which is more widely applicable is to incorporate digital elevation data into the analysis of the imagery. This provides a third dimension to the data and permits a quantitative analysis of 3D features described in the remotely sensed imagery. For instance, the 3D nature of these features may describe a planar or curved surface (Figure 1), directly related to the geology, from which dip and strike measurements may be derived. The feature may be identified manually using an interactive system (McGuffie *et al.*, 1989) or automatically using pattern recognition (Chorowicz *et al.*, 1989), edge detection routines, or texture analysis (Morris, 1990b).

Elevation data not only extends the applicability of remotely sensed imagery, but is also, in itself, a valuable source of useful geological information (Sauter *et al.*, 1989; Morris, 1991a). A digital elevation model (DEM) offers a description of the geomorphology of the surface which can be, in turn, strongly related to the surface and subsurface geology (Hobbs, 1903). For instance, a strike-ridge morphology is indicative of a gently dipping sedimentary sequence, while a break of slope may indicate a lithological contact, and a ring-like or dome feature may indicate an igneous intrusion (Figure 2). This information may be extracted in a number of ways, including

- simulation of Lambertian shading of the DEM to enhance certain directional components of the geomorphology (Sauter *et al.*, 1989); Figure 3a shows a simulated shading for the acquisition time of the imagery (*c.f.* Figure 7–the remotely sensed image used in this study). Figure 3b shows a shaded scene with the illumination positioned to the northeast which of course would never happen in a natural image of this area. Additional features are highlighted, particularly on the southeast facing slopes.
- using the DEM data to generate a perspective view of the terrain and "draping" the image on top. This increases the interpretability of both the image and the DEM (Figure 4) (Muller, 1988).
- using pattern recognition techniques to identify significant geomorphological features (Chorowicz *et al.*, 1989). For example, a pattern may be defined to describe a strike-ridge morphology and then used to search the DEM for such features.
- using edge detection and texture analysis techniques to identify primitive features rather than patterns (Morris, 1990b).

The first two items can be used to extract geological information

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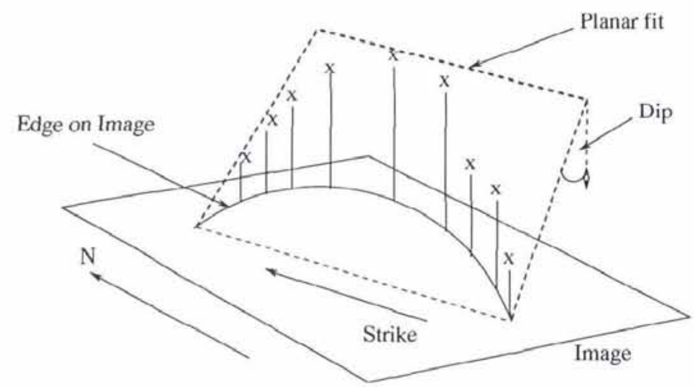


FIG. 1. Planar surface fit to 3D edges.

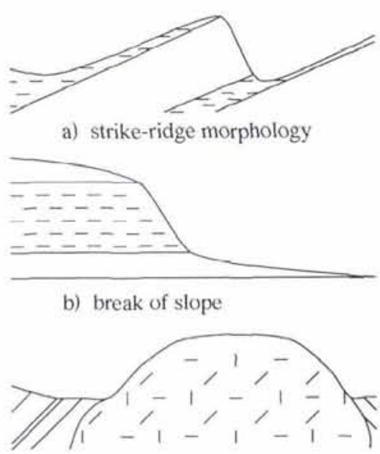


FIG. 2. Relationship between topography and geology.

with a great deal of success, but they require manual interpretation of the resultant images and are therefore subject to the same limitations as the manual interpretation of remotely-sensed imagery. The third and fourth items describe automated or semiautomated techniques designed to provide objective and accurate assessments of the geological structures in the scene and to assist in its final interpretation. Pattern recognition techniques have proved successful for simple geological structures well described by the topography (Chorowicz *et al.*, 1989). However, these are less likely to succeed in areas of more complex geology with much folding, faulting, and jointing or in areas where the geomorphology has been modified by processes such as glaciation. As an alternative, the identification of more primitive information, such as local dip and strike measurements, provides a much more flexible approach to the problem of mapping the structural geology of an area. Such techniques provide a mass of structural information (Morris, 1990b) which may either aid or confuse the final interpretation carried out by the geologist.

To improve the more traditional interpretations, only those measurements which are most likely to be accurate or those which are most relevant to the geology of a particular region of the scene could be used. However, if full use is to be made of all the information provided, an intelligent way of combining the data is required. This can be achieved using a knowledge-based system designed to combine the information within a model of the geological structure. Various rules can be defined to create and modify the model as each new piece of information is added. Similar rules may also be incorporated to segment the most geologically significant measurement and to enable an assessment of the confidence attributed to the accuracy and relevance of each measurement. The final output of such a system can be presented in a number of ways, such as a planimetric map, a block diagram of the geology, or a series of inferences relating to the structure of the geology.

The remainder of this paper describes the research carried out to develop tools for the extraction of structural data and to assess the role of a knowledge-based system in the understanding of the geology. The tools used to derive the primitive information from both the remotely sensed imagery and the elevation data are described, and a discussion of some preliminary results is included. Methods of incorporating knowledge-based rules and the creation of a structural model are then discussed.

STUDY AREA AND DATA ACQUISITION

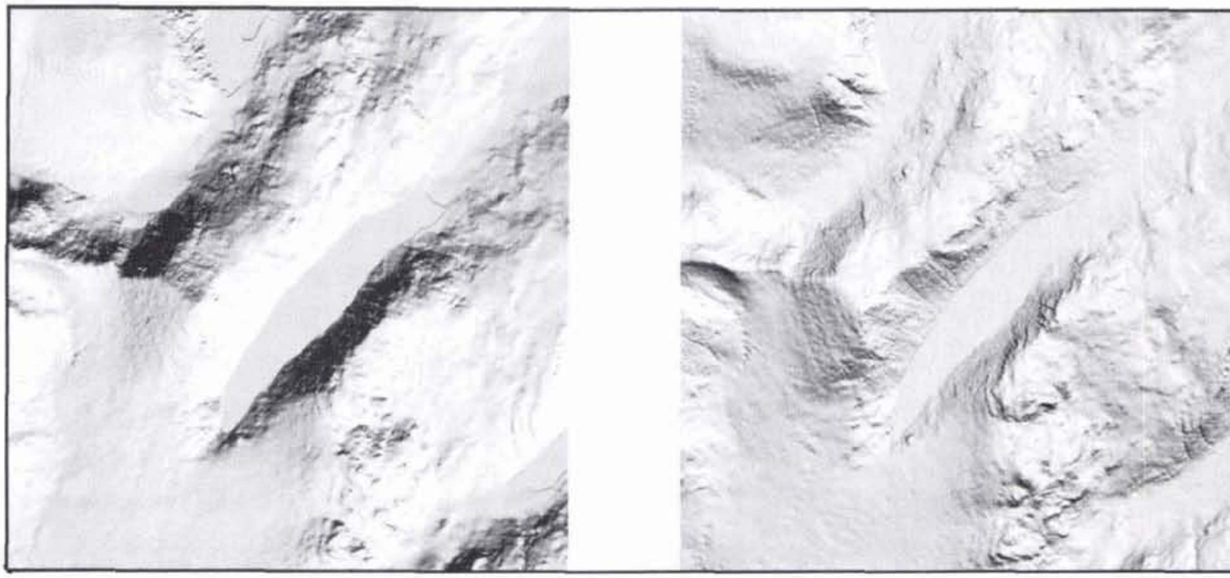
The study area for this investigation is an area of mountainous terrain, near Capel Curig, Snowdonia National Park, U.K. (Figure 5). Although the area is perhaps not ideal for an initial testing of the proposed methods, because of the complex structural geology, there is a pronounced relationship between the topography of the area and its geology. Moreover, suitably high spatial resolution remotely sensed imagery obtained by an airborne multispectral scanner was available.

The center of the area is dominated by a large reservoir, Llyn Cowlyd, situated at the base of a large glaciated valley. Although the topographic expression of the geology is to some degree masked by the effects of glaciation, the surface morphology can be used extensively, in some areas, to map the geology. This is particularly so in areas where there is an interlayering of hard and softer rocks, at the tops of mountains, and in areas of steeper slopes.

GEOLOGY OF THE STUDY AREA

The district around Capel Curig forms part of the Welsh Basin, in which thousands of metres of sediment accumulated during Ordovician (Howells, 1979). The sediments of the area comprise mudstones, siltstones, and sandstones, indicating a continuous fairly shallow marine environment in which sedimentation kept pace with the subsidence of the basin. These sediments were interspersed with tuffs, and the entire sedimentary sequence is intruded by dolerite sills. The topographic expression of the geology is manifested as quite distinct geomorphological features caused by the interlayering of hard and soft rocks. The harder and more resistant rocks include dolerite, ash-flow tuff, and sandstone, and are generally located along ridges or prominent features such as cliffs; while the soft rocks comprise slate, mudstone, siltstone, and tuff and are found in more low-lying areas, which are more likely to be covered by vegetation.

The main deformation phase occurred during the early stages of the Caledonian orogeny and resulted in major folding and faulting along a northeasterly orientation. The folds are gentle to isoclinal, have a gentle plunge to the northeast, and have axial planes which dip steeply to the northwest. A second, less pronounced deformation occurred along a southeasterly direction. A simplified geological map of the area is shown in Figure 6.



(a) (b)

FIG. 3. Lambertian shaded DEM. (a) Simulated natural shading. (b) Illumination source to the northeast.

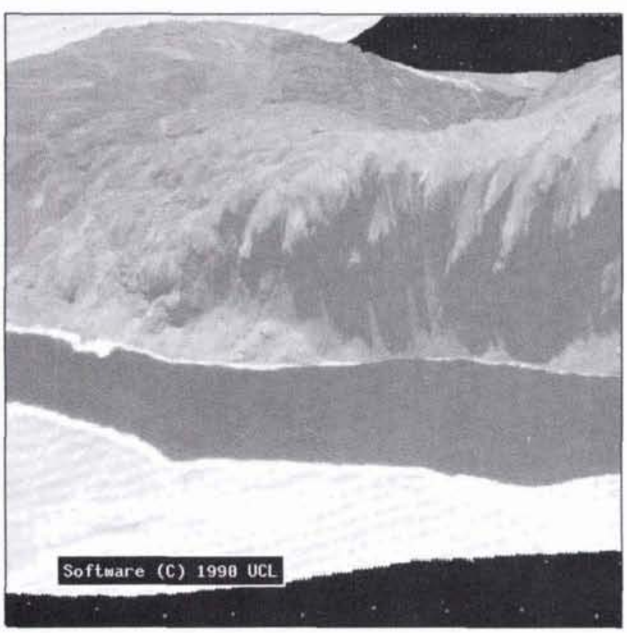


FIG. 4. Perspective view of Llyn Cowlyd area.

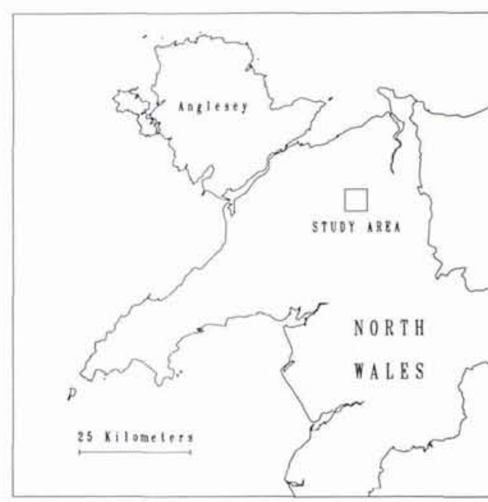


FIG. 5. Location of the study area.

DATA ACQUISITION

Remotely Sensed Imagery

The image data used (Figure 7) in this investigation were acquired by the U.K. Natural Environment Research Council (NERC) funded Daedalus Airborne Thematic Mapper (ATM) scanner (AADS-1268) which records data in 11 separate wavebands from the visible to the thermal infrared wavelengths. The altitude of the aircraft was approximately 2000 m, giving a nominal spatial resolution of 5 m in the nadir viewing position, although the rugged terrain and the wide scan angle of the ATM (86 degrees) results in extremely variable spatial resolution throughout an image. This made the geometric correction of the data to ground coordinates extremely difficult and resulted in a slight misregistration of the imagery with the DEM (root mean square error = 1.4 pixels).

Digital Elevation Data

A DEM of the area has been created by interpolating digitized contours onto a regular grid. The contours were manually digitized from a 1:10,000-scale Ordnance Survey topographic base map (© Ordnance Survey, 1976) at 10-m contour intervals. The DEM covers a 5 km^2 area centered on Llyn Cowlyd at a spatial resolution of 5 m (Figure 8), in order to correspond with that of the ATM imagery.

A number of different interpolation routines have been assessed, with accuracies being tested both in terms of absolute spot height accuracy and in terms of contextual geomorphological accuracy (Morris, 1990a). It is extremely important to retain all of the contextual information held within the original map if useful geological information is to be extracted (e.g., ridge lines and drainage channels). It has been shown that krig-

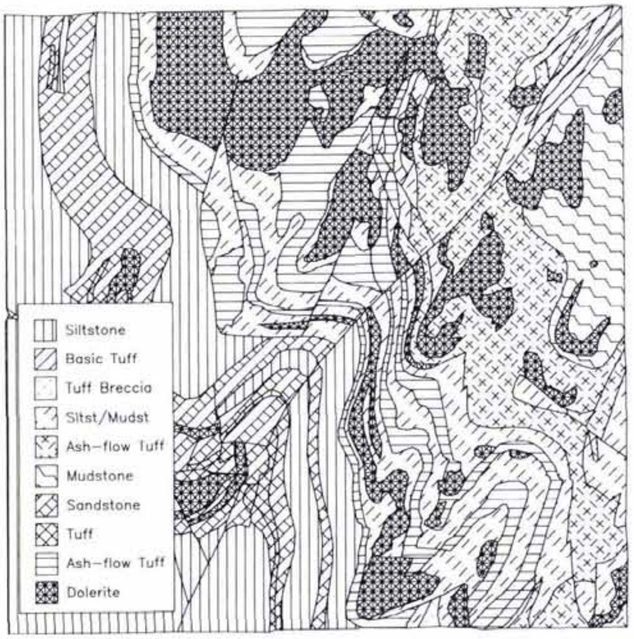


FIG. 6. Geological map of the study area.

FIG. 8. Digital elevation model of the study area.

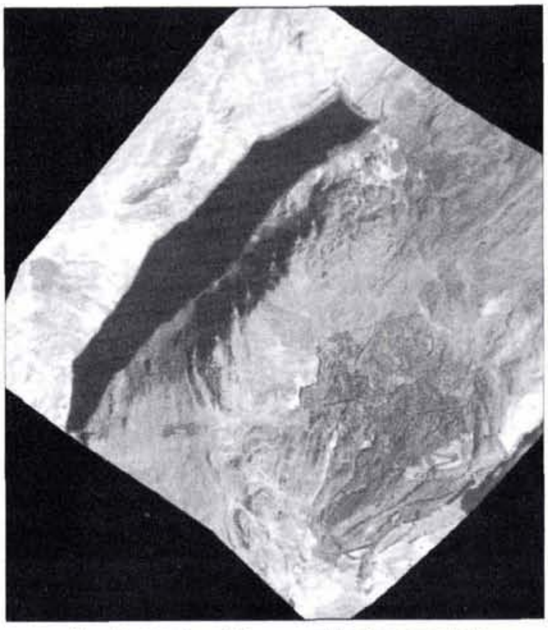


FIG. 7. ATM band 7, geometrically corrected.

ing, a geostatistical interpolation routine (Davis, 1973), and a weighted interpolation based on the creation of Theissen polygons around each of the digitized points (Mapics Ltd, 1986) proved to be the most accurate methods of creating a DEM (Morris, 1990a).

In the context of creating a fully automated knowledge-based system, this method of DEM creation is both labor intensive and time consuming. A more appropriate method would be to use stereo-matching techniques (Day and Muller, 1988), which measures automatically the disparity between patches identified in two stereo images, to generate the DEM. Unfortunately, it is not possible, at present, to perform these techniques successfully on imagery acquired from unstable platforms such as the aircraft used for this study.

To date, most of the research carried out for this study has concentrated on using the DEM to extract useful geological information. Future studies will focus on a more rigorous analysis of the remotely sensed imagery.

TOOLS FOR DERIVING THREE-DIMENSIONAL STRUCTURAL INFORMATION

A number of tools have been developed for extracting local 3D structural information from remotely sensed imagery and digital elevation data (Morris, 1990b). This information can then be input into a knowledge-based system to help fully understand the structural geology of the scene.

IMAGE SEGMENTATION

Many of the techniques, described later, produce results even in areas which almost certainly do not contain geological information, such as areas that are flat or have a fairly uniform slope. Results from these areas are redundant and tend to hinder further processing. The additional time taken to process the results is also wasteful and costly. It is therefore beneficial to segment the image into those regions which are geologically significant and those which are not. In this study area, where the surface is heavily vegetated and therefore little spectral information can be used to map the geology, the most geologically significant areas can be defined as being those areas which display the most texture within the topography. A simple texture measure applied directly to the DEM will segment some of the most textured areas but will also include some areas with fairly steep, but uniform, slope which may not contain any useful information.

A more successful method is to apply the texture measure to Lambertian shaded images (Figure 3) of the terrain. The Lambertian shaded image is by definition directional in nature, being dependent on the position of the sun, and therefore a segmentation based on such an image would be biased towards that direction. This can be overcome by performing a logical OR operation on two thresholded texture images of Lambertian shaded images which have their illumination azimuths perpendicular to each other. Figure 9 shows the resultant segmentation overlain on a Lambertian shaded image and indicates how well the operation works, both in terms of successfully identifying geologically significant areas and in terms of pruning out the more irrelevant areas (*cf*. Figures 3a and 3b).

Edge Detection

To determine a complete picture of the geological structure of an area, it is important to locate as many lithological boundaries and faults as possible. These may occur as spectral changes or shading differences in the remotely sensed imagery, or, more importantly, as breaks of slope, ridges, or valley lines in the DEM. The simplest way of detecting all of these features is to apply an edge detection filter to both the imagery and the DEM. In this study a simple Sobel gradient filter has been employed to detect the edges required. The Sobel filter was chosen as an initial method simply to test subsequent procedures (other more sophisticated edge detection algorithms will be assessed at a future stage). Two orthogonal Sobel filters can be applied to the imagery and combined to produce edge strength and edge orientation images. The resulting "edge strength" images can be "thresholded" and "thinned," using standard image processing techniques, to produce definite edges one pixel in width. These "lines" can then be used further to calculate dip and strike measurements (see next section).

Lineament Orientation

The data points derived from the edge detection techniques represent lines which lie on a 3D surface. If this line represents a lithological boundary or a fault, the points may be used to calculate the dip and strike of the bed or fault. A least-squares approach has been used to fit the data to a planar surface (Figure 1), producing an equation of the form

$$z = ax + by + c$$

where x, y, and z are the 3D coordinates and a, b and c are the coefficients derived from the fit. A minimum of three points are required to solve the simultaneous equations. In practice, lines are only tested for dip and strike if they are at least 10 pixels in length (i.e., 50 m).

A major difficulty with this technique is that, if all of the data

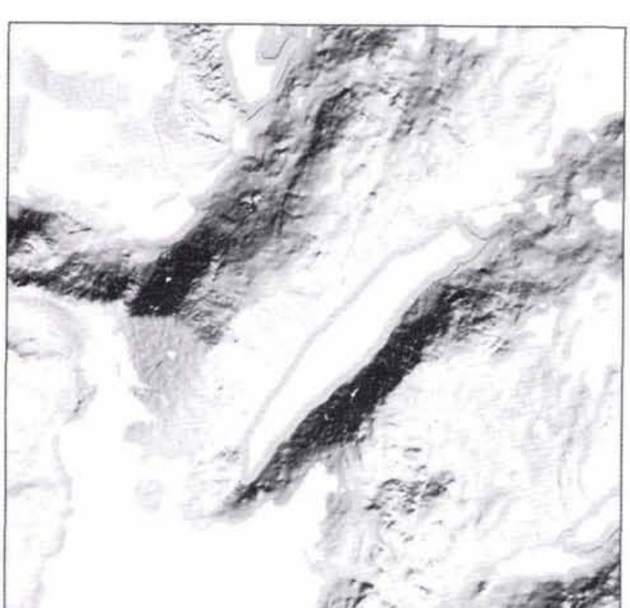


FIG. 9. Segmentation mask overlain on top of a Lambertian shaded DEM.

points lie along a straight line in 3D space, then any number of planes could also be fitted through the data where the line belongs to the plane (Figure 10). One test to determine whether or not this is happening is to investigate and compare the coefficient of determination (R^2) derived from the planar fit with that derived from a linear fit of the data in a new coordinate system defined by the planar surface. If the linear R^2 is $\geq$ the planar R^2, then the edge should not be used for the calculation of dip and strike, as it is more likely to define a line than a plane. In this study lines have been rejected if the R^2 for the planar fit is below a 0.6 threshold and if the linear R^2 is greater than the planar R^2 or greater than 0.9. These threshold limits have been set somewhat arbitrarily, but include two provisos. First, to give lenience to the planar fit, as the edge may delineate a slightly curved surface, and second, to be strict on the linear fit because of the gross inaccuracies caused by calculating dip and strike for a straight line.

In many cases it is possible that an edge may represent a lithological boundary which is folded. In such cases a curved surface may need to be fitted to the data, again using a least-squares method and producing an equation of the form

$$z = ax^2 + by^2 + cxy + dx + ey + f$$

where a, b, c, d, e, and f are the derived coefficients.

Once the equations have been determined, it is an elementary process to calculate dip and strike measurements for each edge.

Simulation of Drainage Networks

Drainage patterns are often indicative of geological environments and structures (Figure 11). A trellis pattern, for example, may signify a sedimentary sequence while a radial pattern may indicate an igneous intrusion. Some 50 drainage patterns have been classified (Howard, 1967), each of which are related to the underlying geology in some way or another.

DEMs may also be used to automatically simulate drainage networks of the area (Raizanoff *et al*., 1988). An algorithm, RAINDROP, developed as part of this project to derive a drainage network from the DEM, simulates the progress of a raindrop, falling on each pixel, as it flows down the steepest slopes through the DEM (Morris, 1990b). If the raindrop arrives at a sinkhole, then a lake-filling algorithm is invoked until a negative slope is again found. The grey levels in the resultant image (Figure 12) indicate the number of raindrops that have passed through each point and therefore describe the size of each stream.

In this study area, many of the smaller streams, towards the

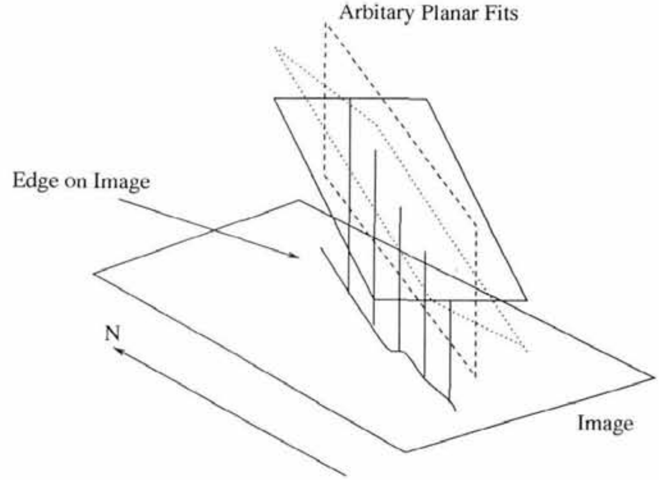


FIG. 10. Arbitrary solution to fitting a surface to linear data.

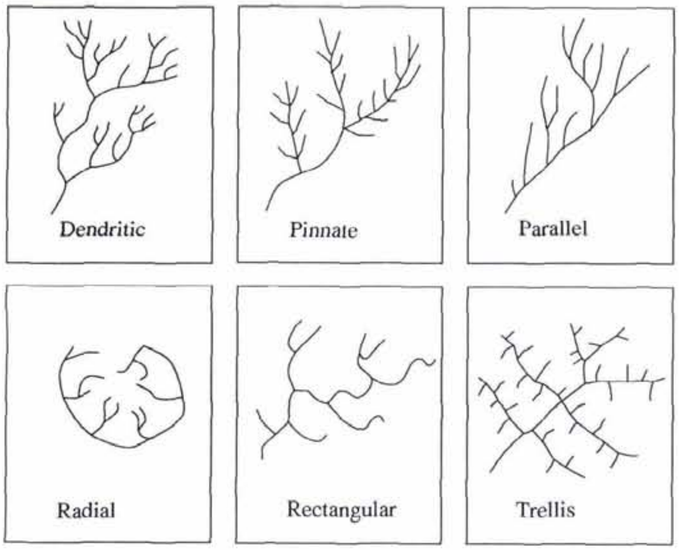


FIG. 11. Various drainage patterns which are related to different geology.

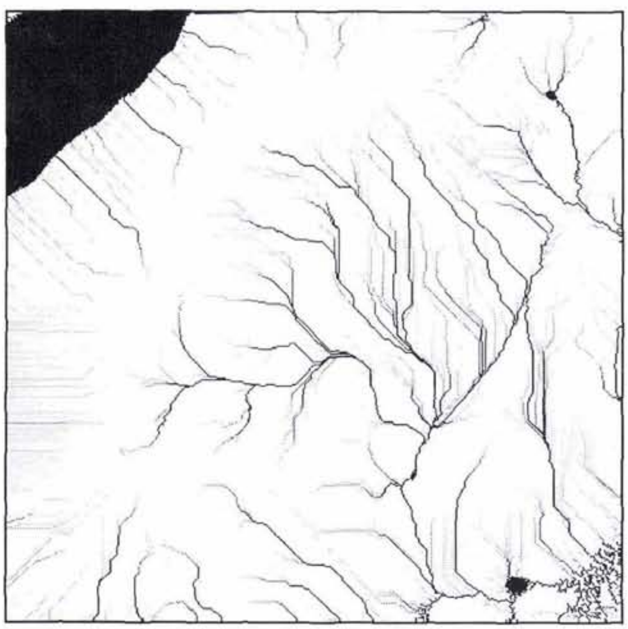


FIG. 12. Example of the RAINDROP image for a sub-area to the southeast of Llyn Cowlyd.

tops of the mountains, follow lithological boundaries, while some of the larger streams on the steeper slopes tend to follow fault lines. The RAINDROP image can be thresholded at different levels so that these features can be extracted from the drainage network and then used to derive dip and strike measurements.

RESULTS AND DISCUSSION

The application of the Sobel filters to the DEM results in two images which represent the slope and aspect of the terrain. These images may be combined with the DEM, the drainage network, and the remotely sensed imagery to provide an abundant source of useful information. Edges have been derived from each of these data sets and the resulting dip and strike measurements are often accurate and complimentary (Morris, 1990b). Results have been compared with British Geological Survey map data and data collected in the field, but are occasionally unreliable as they do not always relate to geological features.

The strongest edges derived directly from the DEM occur where the slope of the terrain is steepest. These steepest slopes often follow lithological boundaries, but in some places they may cut across contacts where a fault dissects some of the harder rock units. Slope edges occur where the rate of change of slope is greatest and particularly at the tops and bottoms of cliffs. The results are therefore very similar to the DEM edges. Aspect edges appear where the rate of change of slope is largest and therefore occur mostly along ridges and valleys. These edges also occur surrounding rock exposures so, rather than representing lithological boundaries, many of the edges give false results. Edges extracted from the drainage network are reasonably accurate at the tops of the hills and mountains but erroneous in the valleys. On the mid-slopes the edges outline many of the faults very well, although the dip and strike of these features may be inaccurate due to the edges being more representative of a straight line than a surface.

Edges derived from the ATM imagery may follow any feature present in the scene, such as forest boundaries, roads, tracks, and lakes, as well as geological features (usually enhanced by the natural shading of the scene). Those edges related to the shading produce mostly accurate results, but those delineating anthropogenic features not surprisingly, give inaccurate dip and strike results. Knowledge-based rules may be applied to these results in order to eliminate the non-geological edges; for example, a simple set of rules to eliminate lake edges are based on the following assumptions:

- the edge has a constant elevation along its entire length,
- if the edge is complete it will form a closed shape, and
- one side of the edge will have the distinctive spectral signature of water.

Similar identification rules may be created for field boundaries, forest plantations, tracks, habitation, and any other man-made feature. Extreme care must be taken when designing and implementing rules of this kind. They should be general rules which may be applied to any imagery of any area, and should not be made specific to a particular scene.

DEVELOPMENT OF A KNOWLEDGE-BASED SYSTEM APPROACH

The development of a knowledge-based system is essential if the mass of structural data is to be used fully in the production of the final map or block diagram. The structural measurements produced in the previous section can be interpreted manually, but a knowledge-based system has several advantages, including

- speed of performing analysis and, in particular, the dull and mundane jobs;
- accuracy and repeatability;
- objectivity; if the system is properly configured, it should be perfectly objective, although in practice the system is set up by humans who, by nature, are subjective to some degree;
- the ability to carry out an extremely large number of processes, which may be directed towards any part of the image;
- the ability to recursively improve a model of the understanding of the scene; and
- the provision of a number of possible models as final output.

Some initial steps towards a knowledge-based system have been made in this research, whereby a library of specialized image processing routines exists, a C-shell script has been written to direct processing to any particular area of an image, and some rules have been defined to help in the interpretation of various features and to produce a structural model of the area. A preliminary plan of the knowledge-based system is shown in

Figure 13. The center or engine of the system is the structural model of the scene. All inputs find their way to the model. After initialization, the model guides further processing, and the model provides the final output. The dip and strike (D/S) database, image processing library, and knowledge database surround the system, and can always be used or queried at any time during the understanding process.

The initial work, which has been described in the previous sections, results in a list of D/S measurements which are stored in the D/S database. A simple linearly dipping structural model can then be made using the most frequently occurring D/S measurement in the database. The frequency of D/S measurements can be found using a contoured stereonet of all of the measurements. Figure 14 gives an example of a stereonet using the results derived from the elevation data. It can be seen from this plot that several peaks occur where the frequency of measurements are highest. To date these peaks are extracted manually, but this could easily be automated. The most common D/S are 32/295 and 39/148 and are dispersed roughly northwest and southeast, respectively, throughout the DEM on either side of a major fault running along a strike of 40 degrees through Llyn Cowlyd reservoir.

The DEM can then be used with the structural model to predict all other occurrences of a rock unit. This is achieved by solving the equation of a surface, representing the rock unit, for each coordinate in two-dimensional space, to determine a height value. If this height value corresponds with that of the DEM, then that rock unit is predicted to occur at this position. A set of rock unit thicknesses may be arranged using all the occurrences of one particular D/S and by calculating the perpendicular distance between each of the planes. Figure 15 shows an example of a prediction for a sequence of rock units at two D/S taken from the stereonet and which are separated by the major fault.

The next stages are controlled by the model in conjunction with the knowledge database. The flow of the system could return to the D/S database, to choose other structural measurements and incorporate these into the model, or go on to direct further processing in areas that may help to prove or disprove the current model. Once all the D/S measurements have been checked, the latter path will be taken by default. Further processing may include more sophisticated edge detection, different thresholding, line following, and spectral data enhancement, in a smaller, more focused subimage of the area. As more evidence is added recursively to the model, so the confidence of the model increases. Once a set confidence level has been attained, the model can be output in the desired format, for example, a geological map (Figure 15) or a 3D voxel model (Raper, 1989). Figure 16 shows an extension of the prediction techniques (mentioned above) into 3D. This model can be rotated

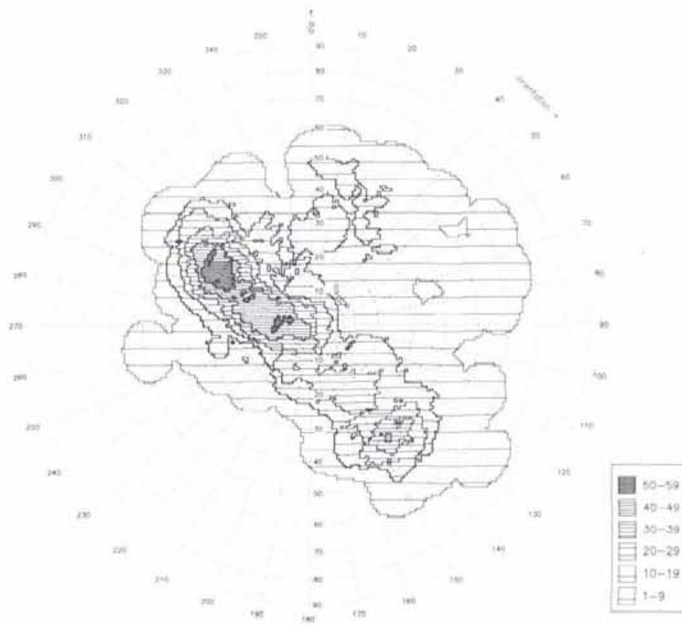


FIG. 14. Stereonet of dip and strike measurements derived from the elevation data.

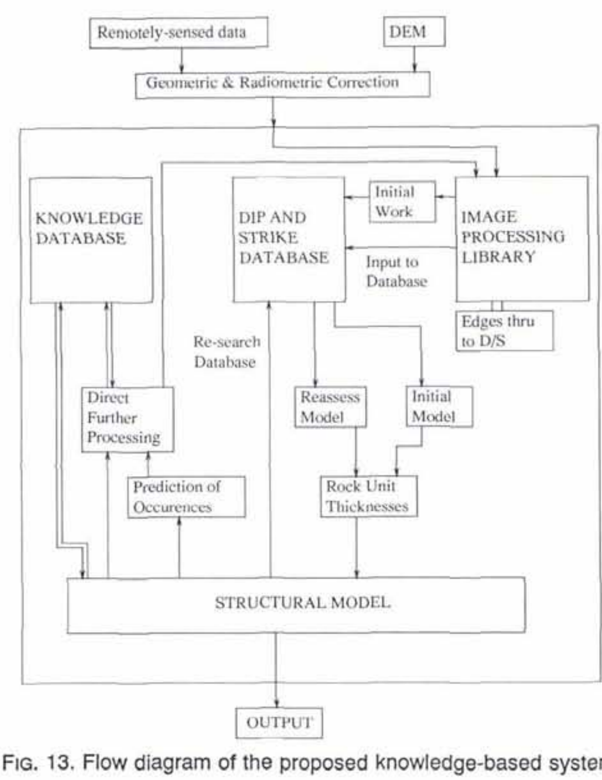


FIG. 13. Flow diagram of the proposed knowledge-based system.


FIG. 15. Prediction of rock outcrops using results derived from stereonet.

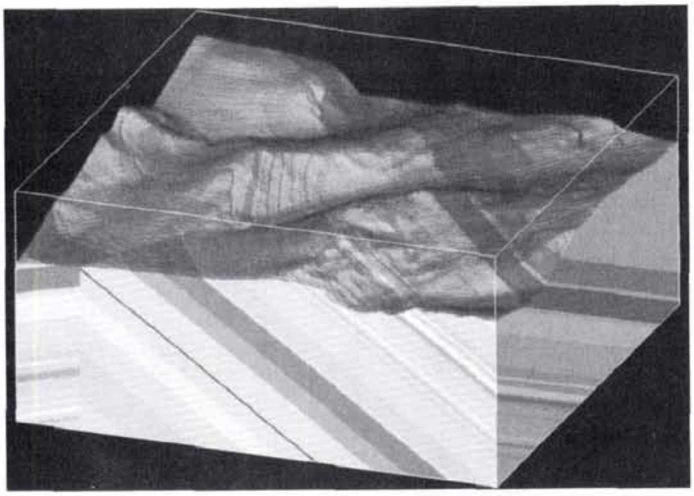


FIG. 16. Block diagram of the surface and subsurface geology, using the results derived from the stereonet.

to any view position, disected at any angle, and various layers can be made transparent according to the user's requirements.

CONCLUSIONS

A knowledge-based system is an essential requirement for the automatic mapping of 3D structural features from remotely sensed imagery and elevation data. A vast amount of primitive 3D structural information may be routinely extracted from these data sets, which can be extremely difficult to interpret. Furthermore, the accuracy of each result is not easy to assess. Knowledge-based rules may be used both to determine accuracies and to combine the mass of data within a structural model or understanding of the geology.

This paper presents tools which have been used successfully to extract 3D structural data from imagery and DEMs. A provisional knowledge-based system has been designed and developed which goes part of the way towards achieving a system aiming to fully understand the structural geology of a scene. Future work should expand the library of image processing tools and extend the knowledge-based system to cover all forms of geological structure and to fully automate the entire process.

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