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Structural remote sensing of south-west England

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Landsat Thematic Mapper data (30m resolution) provide a synoptic perspective of SW England on which structurally significant linear features can be identified, after edge enhancement and edge detection. Directional filters were applied in all orientations. The north and west orientated filters of mask sizes 3x3 and 5x5 are the most effective. Although the South West is a vegetated terrain with little rock exposure, there is significant correlation between linear physiographic features and the known structural pattern. The main features enhanced are the NW-SE trending strike-slip faults throughout the region; E-W fold trends in N Devon and NE to NNE faults with associated mineralization in S Cornwall. Poorly exposed stratigraphical boundaries and faults, such as those in the Culm Basin, are clearly seen on the images. Images suggest previously unsuspected structural zones that may be new areas of economic interest.

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Introduction

Geological remote sensing in temperate agricultural terrains, such as the South West, presents many problems. This paper demonstrates some means of reducing these problems and presents some results. The synoptic view provided by the satellite data is very effective for the interpretation of structural features over a large area. Faults, being lines of weakness, often control low lying features that are difficult to trace on the ground and also changes in vegetation and surface texture. Such trends can be readily identified on the imagery. Previous geological remote sensing studies in the South West (Moore and Camm 1982; James and Moore 1985) used Landsat Multispectral Scanner (MSS) data which had 79m resolution compared to the 30m resolution of TM data. They concentrated mainly on the evaluation of remote sensing techniques for mineralogical mapping, and did not consider in any detail image processing for structural enhancement.

Landsat TM data cover 7 wavebands from visible to thermal infra-red. All bands and enhancement methods were evaluated semi-objectively to assess the most favourable band or bands to use for structural assessment. Specific textural image enhancement techniques were used to obtain improved imagery for structural mapping and those found most favourable will be discussed.

The study area encompassed most of the South West peninsula as far east as Exeter and to Barnstaple on the north coast (Fig. 1). This area comprises a single scene of TM imagery (path/row 205/024) recorded on 11th September 1985. The image processing was carried out on a NERC International Imaging System (I^2S) Model 75. It is run on System 600 software supported by a Vax 11/750 mini-computer at Polytechnic South West. The techniques employed were standard methods, commonly used throughout geological remote sensing, but were developed mostly for studies in arid and semi-arid terrains.

Problems of geological remote sensing in temperate agricultural terrains

Most geological remote sensing studies have been applied to arid and semi-arid areas where vegetation and superficial cover is at a minimum, hence enabling a far better discrimination of lithologies and structure. Enhancement of structures in a temperate agricultural area such as south-west England faces several problems, such as:

1. The lack of exposed rock on the scale of individual pixels.

2. Slope degradation produces subdued topography and superficial cover can hide structural features. Fortunately in the South West superficial deposits consist mainly of alluvium and head and the terrain is moderately rugged so that such effects are reduced.

3. Soil and vegetation often bear a direct relationship to the underlying bedrock in humid areas, but in highly cultivated regions soil features will have been blurred by agricultural activity and could produce spurious results in the imagery.

4. 'Camouflage' produced by the patchwork-quilt pattern of fields with different crops tends to hide geological trends.

5. The time of the year will have a considerable effect on the condition of soil and vegetation; the stage of growth of the vegetation and the water content will result in varying spectral signatures. Therefore mid-winter is best when these signatures are going to be similar to each other (Drury 1986). 6: Solar azimuth is a general problem of terrain analysis and is not specific to temperature regions. A low sun-angle is best as the shadows will enhance the relief. Local capture time for Landsat TM over the South West is 0930hrs, therefore the sun is still reasonably low in the sky resulting in a preferential enhancement of features normal to the solar azimuth, i.e. NE-SW oriented features are enhanced in the northern hemisphere. One of the main structural trends in the South West is NW-SE and is therefore suppressed. However, as Drury (1986) explains, features parallel to the solar azimuth contain minor irregularities which cast shadows and have associated tonal features related to erosion, making them more visible than would be expected.

Image Processing

Band Combination

The imagery was examined with the above constraints in mind to identify the band, or combination of bands, that would be of most use for structural interpretation. Various band combinations were evaluated, but none were found to be successful for lineament identification. However they were used as an aid for the interpretation of texturally enhanced images.

Choice of optimum band

Bands 1, 2 and 3, in the visible range, have high atmospheric attenuation and low signal-to-noise ratio while variations in vegetation reflectance in band 4 were very high, accentuating agricultural features. Band 6, in the thermal infra-red, showed the properties of the emitted rather than reflected wavelengths, which is not ideal for rock type discrimination. It also has 120m resolution compared with the 30m of the other bands. Bands 5 and 7 show similar responses but preference was given to band 5 because it covers the range where most rocks have their maximum reflectance and has a better signalto-noise ratio. Furthermore, band 5 includes the prominent water-absorption feature centred at 1.4μm and provides most information on variations in plant and soil moisture content. This feature is useful in humid terrains in mid-winter scenes because pasture and winter cereals seem to have roughly the same reflectances, thereby reducing 'patchwork' field patterns. Consequently any variations are likely to represent solar irradiance, which varies according to slope angle and azimuth and would thus correlate with topography and structural features (Drury 1986).

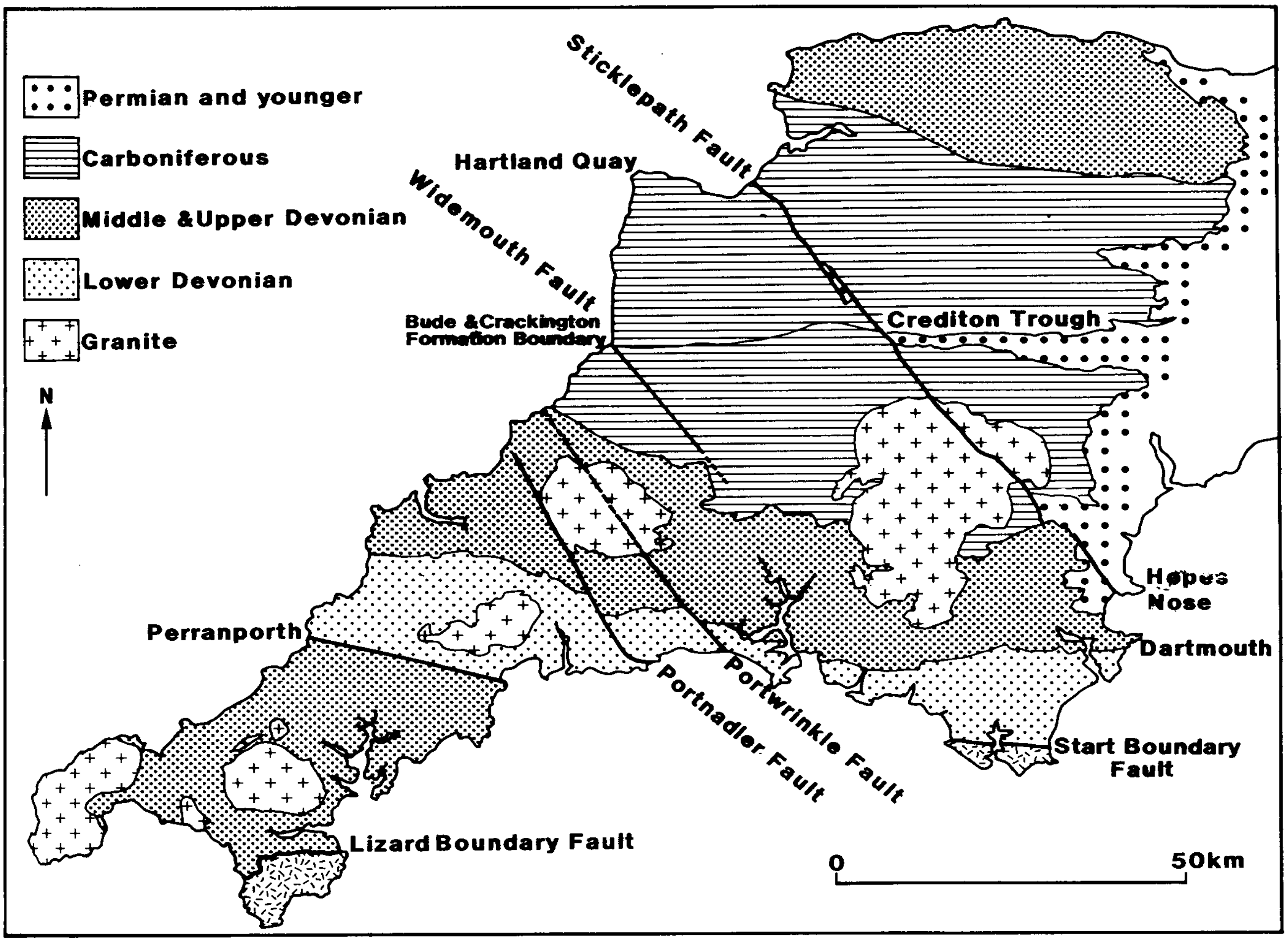

Figure l. Simplified geological sketch map of South West England.

Textural enhancement

Most structural features have high spatial frequencies and will be identified as `edges' on the imagery. An edge can be defined as the intensity difference between neighbouring pixels; the boundary between the two being the edge. High-pass filtering accentuates the difference between adjacent pixels, thereby enhancing the edge. The edge enhancement operation was implemented by square, two-dimensional convolution masks. The size of the mask is varied from 2x2 to 101x101 depending on the application. The size is chosen according to the spatial wavelengths in the image that are of interest. A high-pass filter will normally enhance features that are approximately half the size of the mask (Chavez 1982). In this study masks of 2x2, 3x3, 5x5 and 7x7 were used with various weightings assigned to their component cells. The filter sizes found to be of most use were 3x3 and 5x5 (Table 1). The convolution operation is explained in Fig. 2.

Table l. Summary of directional edge-detection filters

NORTH

1	2	1
0	0	0
-1	-2	-1

WEST

1	0	-1
2	0	-2
1	0	-1

1	2	3	2	1
0	1	2	1	0
0	0	0	0	0
0	-1	-2	-1	0
-1	-2	-3	-2	-1

1	0	0	0	-1
2	1	0	-1	-2
3	2	0	-2	-3
2	1	0	-1	-2
1	0	0	0	-1

A directional filter will enhance edges in one direction and those up to 45° in the direction perpendicular to the filter direction (Drury 1987), whereas all other edges will be suppressed, particularly those normal to the filter direction. Not only do these filters suppress data but they can also introduce artifacts - some filters investigated were found to do this; hence were rejected. The weightings found most successful were all directional filters. Those used for the interpretation are known as Sobel filters (Table 1).

As the dominant NW-SE and E-W structural trends of south-west England would probably be most apparent on the imagery, the appropriate directional filters were first tested on these features. Other, less probable, orientations were also investigated. Adding each filtered image to the original image of band 5 combines the tonal information with the enhanced textural detail. This added image was used in conjunction with the filtered image thereby helping to eliminate the confusion of identifying features such as roads, railway lines etc., during analysis of geologically significant lineaments. It was also a help in identifying drainage patterns and other physiographic features.

Interpretation

The full scene of SW England was examined initially for structural trends from which four sub-areas were identified for further investigation at an approximate scale of 1:250000. All the following interpretations were produced from the analysis of four filtered images - i.e. Sobel north and west using mask sizes 3x3 and 5x5. Figs 3b to 5b show composites of the individual interpretations. For simplicity only one example of a filtered image is shown for the South West, plus two of sub-areas (Figs 3a-5a).

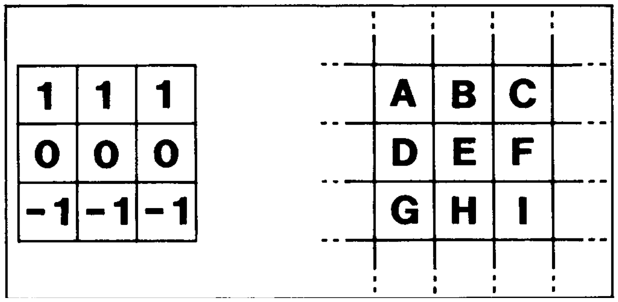

Figure 2. The DN (A etc) for each pixel is overlain by the convolution matrix and is multiplied by the corresponding weighting factor - Ax1, Bx1, Cx1 etc. The products are then summed to compute the value to be used in place of the DN of the pixel beneath the centre of the convolution matrix. E. The operation is performed on all the pixels in the image.

SW England

There are no continuous lineaments apparent on the images, but series of shorter lineaments can be extrapolated to form continuous trends which are consistent with known geological structures. The faults are represented largely by changes in the physiography on the image, which result in rather discontinuous trends. Large scale faults in this region are often fault zones rather than single faults which would also give rise to a series of smaller lineaments. Thus it is the general trends and the frequency of lineaments of a similar orientation that may be interpreted as structurally significant features. There are two general lineament trends at 310°±10° and 060°±10° (Fig. 6A). The first set represent the general NW-SE trending strike-slip faults and the second set appear to correlate with the ENE-WSW trending fold axes and lithologies.

Landsat MSS imagery has been used as part of a study of fractures in S England and N France (Bevan and Hancock 1986; Hancock and Bevan 1987). This study found that NW-trending lineaments were well developed in northern France but were only feebly developed in southern England where E-W trending lineaments were more dominant. In SW England the NW trending lineaments reported here appear to be dominant over the E-W trending features. In southern England, Alpine compression formed the dominant E-W structures. At this time SW England, due to the buoyancy of the granites, formed a positive land mass and the Alpine stresses reactivated structures already present, such as the NW-SE strike-slip faults (Holloway and Chadwick 1986).

The linear features in some areas are associated mainly with drainage patterns which generally have a strong structural control. In area C, South Devon (Fig. 3), the drainage pattern suggests a strong structural influence on the control of the channels so it was decided to trace out more of the drainage patterns than in other interpretations. Two main lineament trends are apparent, NW-SE and E-W to ENE-WSW, the latter trend being the most dominant at 070°±10° (Fig. 6B). The main drainage channels generally trend NW-SE with a few deviations, while the tributaries generally flow a more consistent E-W to ENE-WSW orientation which can be extrapolated across the imagery. The tributaries appear to have been influenced by the structure of the area. Bevan and Hancock (1986) suggested there is a direct correlation between the fracture sets and the lineaments. They observed that many of the lineaments in northern France are coincident with major rectilinear drainage channels but that this pattern is not found in southern England. In South Devon however, this rectilinear pattern of drainage can be traced on the imagery, though not as strongly as Hancock and Bevan (1987) found in northern France.

Coward and McClay (1983) measured fold axes and bedding cleavage intersections, trending at 080°±20°, between Start Point and Hopes Nose (Fig. 1). This trend correlates well with the lineaments detected on the image of this area (Fig. 6B). South of Dartmouth, Zone 8 of the Sanderson and Dearman (1973) divisions, the structure comprises NNW facing ENE-WSW trending folds and shows a change in structure from relatively flat-lying recumbent folds in the north to upright folds, becoming overturned towards the south (Shackleton *et al.* 1982). In this area the imagery exhibits a denser set of lineaments than in the north perhaps representing a better definition of the structures which are in a more upright position. The southern boundary for Zone 8 is the Start Boundary Fault (Fig. 1) which is distinct on the imagery. There are also a few linear features that are parallel to this zone which may be the expression of faults. g

Durrance and Laming (1982) state that there are a series of parallel shear zones to the north of the Start Boundary Fault giving the effect of a series of step faults of which the Start Boundary Fault is the highest. Coward and McClay (1983) are uncertain about the nature r of this boundary.

For area E, South Cornwall (Figs 3b and 6c), the dominant lineament direction is also ENE but with a greater spread. The northern edge of the Lizard Complex is quite obvious on the imagery as a zone of ENE trending lineaments (though is not apparent on the smaller scale image shown here - Fig. 3a). The N to NNE trending lineaments observed are, as yet, unidentified on the ground. There is a series of NW to WNW trending lineaments between Perranporth and Portreath on the north coast. The northern-most set of lineaments may represent part of the Perranporth-Start Line as suggested by Holdsworth (1989). In contrast Sanderson and Dearman (1973) have interpreted this as a southward trending thrust zone forming the southern boundary of their Zone 8. Lineaments with similar trends in this area may well be associated with this major structure.

There is a significant number of discontinuous lineaments trending ENE-WSW to NE-SW in this area. They are relatively short in length compared to the other lineaments in South Cornwall. Sanderson and Dearman (1973) and Rattey (1979) describe this as the main structural trend due to the orientation of fold axes.

The NE-SW features may well be due to the intrusive rocks of the Devonian to late Permian. The ENE lineament trends may be associated with tin/copper lodes (Dearman 1963) that are usually found infilling post-granite normal faults. He also noted that this lode system is intersected by faults, that may be mineralized, and were thought to form as tension joints at right angles to the fold axes. These faults may also account for the few lineaments with a NNW trend which lie normal to the general trend of the area. the mineral lodes become more dominant due to the proximity of the granite and may well be the reason for the increase of linear features in this area of the imagery.

The Carnmenellis Granite is not as clear as the Bodmin and Dartmoor granites on these images. The textural information is more subdued and not many lineaments can be identified. This may be due to the Carnmenellis Granite being significantly lower in elevation than Bodmin and Dartmoor, resulting in a change of the textural properties due to differences in the soil cover and vegetation.

North Devon (Figs 4, 6D)

Two equally dominant lineament directions can be identified (Fig. 6D), 47% lie within 30° of NW and 51% with a more equal spread around ENE, again within 30°. The Sticklepath Fault Zone (Fig. 1) can be identified as a prominent zone of lineaments trending at approximately 150°. To the west of the Sticklepath Fault Zone another zone of lineaments trend 155° from Hartland Quay which also correlate with known geological structures. It is perhaps significant that the lineament density decreases between these Hartland Quay features and the Sticklepath Fault Zone. The geological map also shows a decrease in density of faults in the same area. The rose diagram (Fig. 6D) shows the dominant lineament direction as 325°±5° which confirms the distinct NW-SE fault trend in this area. The Cambeak Fault Zone is not as obvious as expected, though a definite trend of approximately 140° inland is apparent. The two NW-SE Widemouth lineaments are even less obvious though a trend can vaguely be discerned. The Cambeak Fault and the Widemouth Fault Zones are exposed on the coast, but inland the fault zones cannot be traced on the geological map.

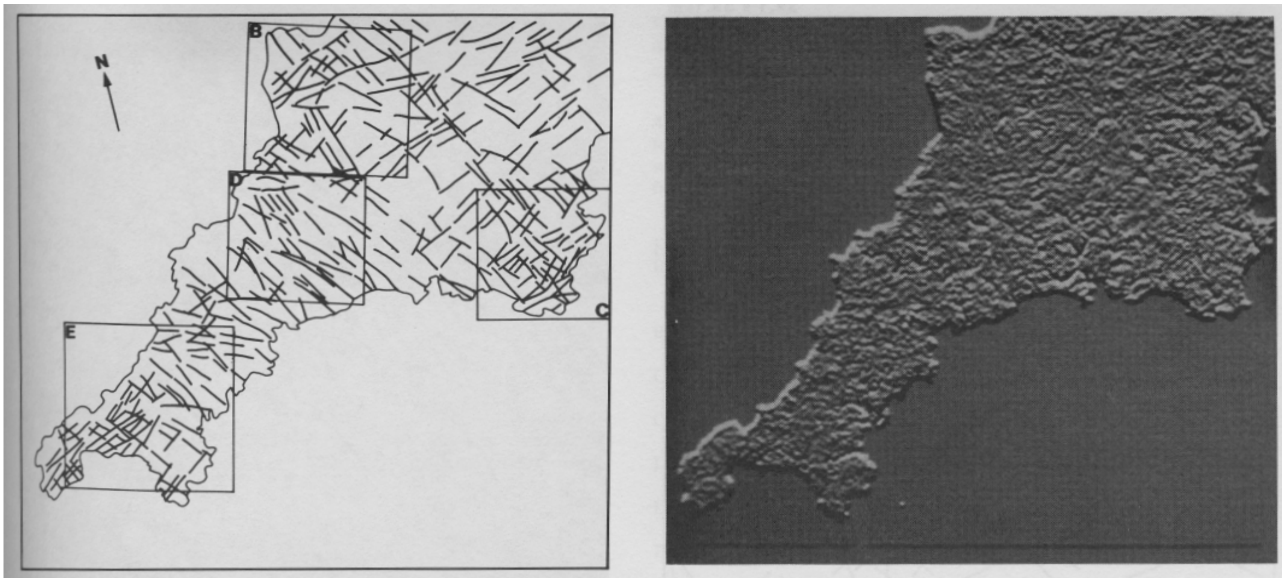

Figure 3. South-West England. (a) Sorbel north filter, 5x5 matrix image. (b) Composite interpretation from Sobel north and west, 5x5 and3x3 filtered images.

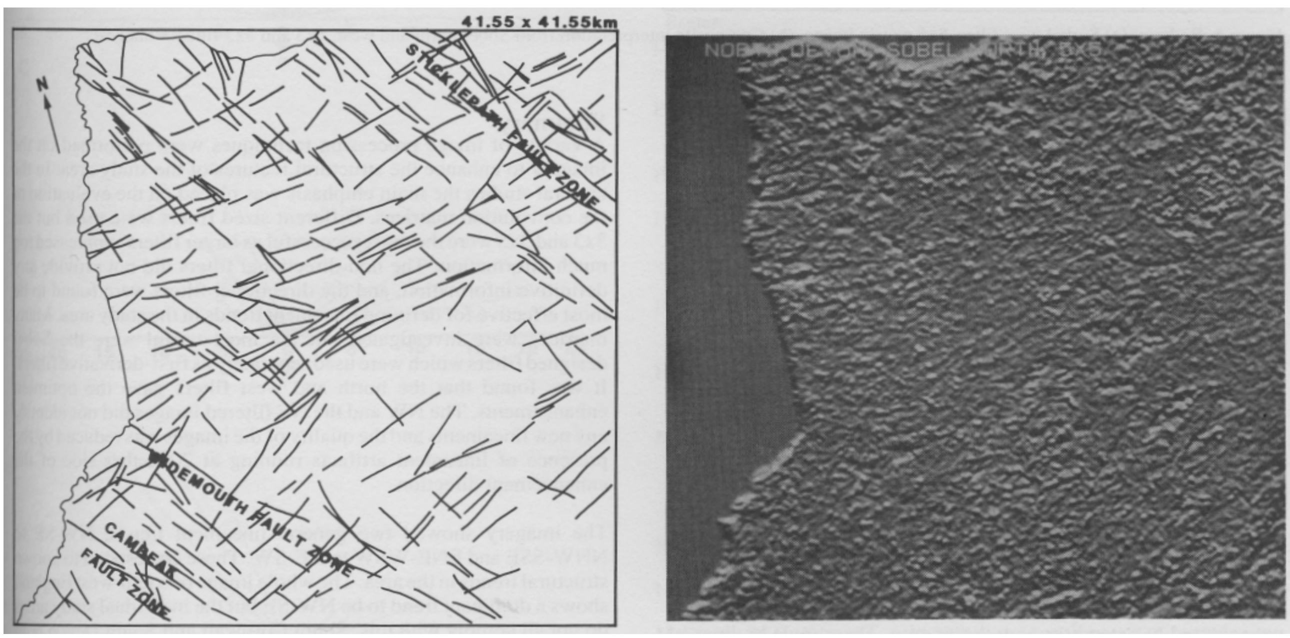

Figure 4. North Devon. (a) Sorbel north filter, 5x5 matrix image. (b) Composite interpretation from Sobel north and west, 5x5 and3x3 filtered images.

Across the centre of the image there is a broad band of lineaments from Duckpool to Cambeak trending approximately 080°±5° which correspond to the second main lineament direction (Fig. 6D). This is a region of interbedded sandstone and shale of the Bude Formation in upright E-W folds. The nature of the southern boundary of this area between the Bude and Crackington Formations has undergone much discussion (Sanderson and Dearman 1973; Edmonds *et al*. 1975; McKeown *et al*. 1973; King 1971; Holloway and Chadwick 1986; Durrance 1985). The change in texture and lineament pattern on the imagery marking this boundary is quite strong, perhaps indicating both lithological change and structural control. The lineaments on the imagery correlate with the features as described by Durrance (1985). The northern boundary of this E-W trending zone is coincident with the change from sandstone to shale dominant lithologies. There are a few lineaments trending 140°±10° that cross-cut this strong ENE direction and correlate with the slight faulting present in this area.

Thus the lineament analysis of images provide inland traces of major faults identified on coastal sections which might help resolve problematical boundaries and poorly exposed faults such as these.

Bodmin (Figs 5, 6E).

The Portwrinkle, Portnadler and Looe Valley Faults are all evident on this image as NW-SE trending zones of discontinuous lineaments. The Portwrinkle Fault is not as obvious as other structures on the imagery. It is described by Tanner (1985) as having an 8.5km dextral displacement, but it is not exposed and does not give rise to any obvious topographic feature. This is the main reason for the absence of a dominant lineament trend on the imagery although this zone can be extrapolated along strike through the Bodmin Granite (discussed later). The Looe Valley Fault is probably a normal fault with little displacement, but it does cause a prominent topographic feature (Tanner 1985) and is quite pronounced on the imagery.

The Portnadler Fault Zone is clear on the imagery and can be traced from the south to the north coast along a NW strike (Dearman 1963).

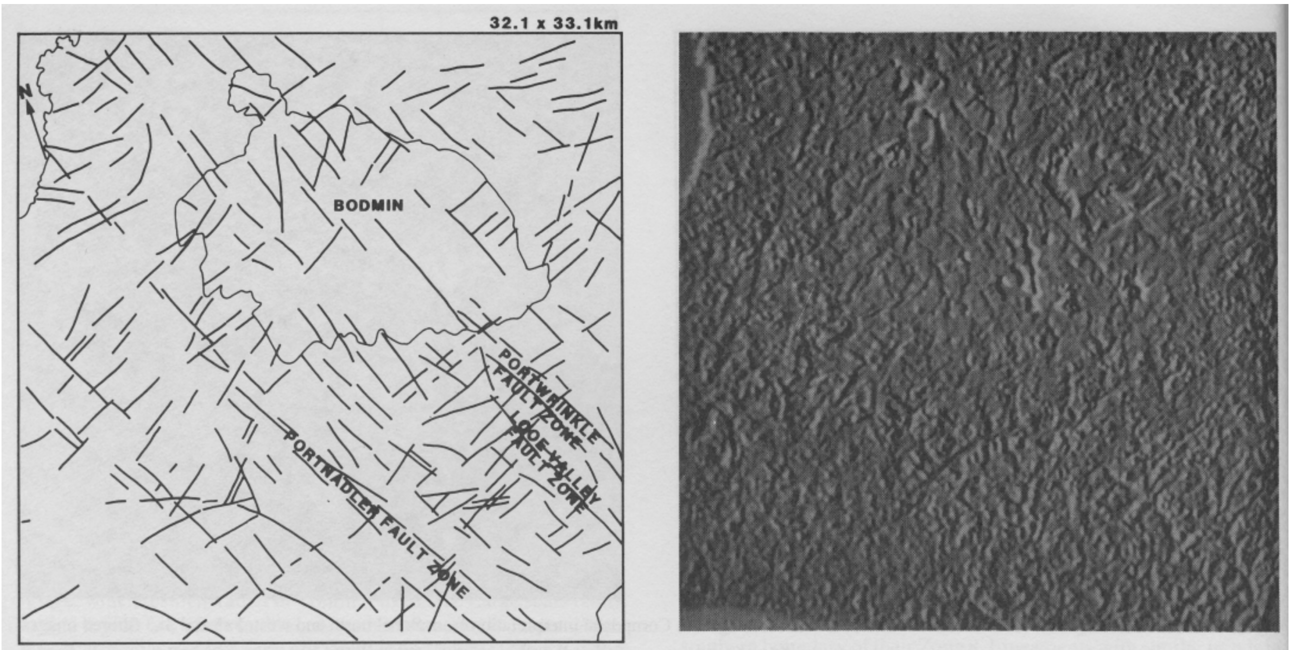

Figure 5. Bodmin. (a) Sorbel west filter, 5x5 matrix image. (b) Composite interpretation from Sobel north and west, 5x5 and 3x3 filtered images.

The fault is considered to have a c.2km dextral displacement (Dearman 1963; Lane 1970) which is far less than the displacement of the Portwrinkle Fault, yet it is more apparent on the imagery. This may be because the Portnadler Fault separates this area of south Cornwall into two zones of identical structural styles, but of different structural orientation (Lane 1970). There is a change in the lineament pattern across the fault which may represent this change in structural orientation.

To the NE of the Portnadler Fault Zone there are another series of lineaments that also have a NW-SE strike. These features can be traced from close to the south coast, through the granite, as far as the north coast. They are contiguous with the Warlaggen Fracture Belt (Exley 1965).

The lineaments through Bodmin Moor have a NW-SE trend which is consistent with the general structure. There is a feature through the centre of the moor following this trend marked by the River Fowey. The river changes direction off the granite but the SE trend of the linear feature can be extrapolated southwards where it is coincident with the Portwrinkle Fault Zone. However the Portwrinkle Fault is not reported to extend through the granite. There must be lines of weakness running through Bodmin Moor for the drainage to keep this trend. Exley (1965) found that the mean tension joints of Bodmin Moor have a strike of 073°, and the mean compression joints strike at 171° which correlate with the trends shown in the rose diagram (Fig. 6E). Exley (1965) also illustrated important NW-SE fracture belts crossing the granite, including the Warlaggen and Fowey Belts, that can be seen quite clearly on the imagery. The transverse fracture zones through the granite have a strike of ENE-WSW are not obvious on the imagery but can still be inferred. Other lineaments on the imagery which run through the granite may be identified with the less important fracture belts inferred by Exley (1965). He further noted that there is no evidence for displacement along any of these belts. This observation is surprising as some of these belts follow the same trend as the NW-SE strike slip faults which have known displacements, such as the near-by Portwrinkle and Portnadler Fault zones. On this basis Exley suggested that the fracture belts throughout the granite were due to Tertiary stresses reactivating Variscan trends. These belts are not widely discussed in the literature yet they appear clearly on the images. There has been economic interest shown in the area around Bodmin and these fracture belts should be sites for investigation. Blyth (1962) noted very similar features with similar trends in northeastern Dartmoor.

Summary

A variety of image processing techniques were performed on the imagery to enhance the structural features of the study area. In the textural studies the main emphasis was placed on the evaluation of the convolution matrices. Different sized filters were used but the 3x3 and 5x5 were the most successful as larger filters suppressed too much information. The non-directional filters did not provide any definitive information, and the directional filters were found to be most effective for defining lineament trends in the study area. Many matrices were investigated but the most useful were the Sobel designed filters which were used separately as first-derivative filters. It was found that the north and west filters gave the optimum enhancements. The NW and the NE filtered images did not identify any new lineaments and the quality of the images was reduced by the presence of lineament artifacts running at 20° either side of the enhancement direction.

The imagery showed two general lineament trends, NW-SE to NNW-SSE and ENE-WSW to NE-SW. These correspond to known structural trends in the area. The whole image of south-west England shows a dominant trend to be NW-SE but the individual study areas do not all comply with this. South Cornwall and South Devon both have a more dominant ENE-WSW trend which was attributed to mineralization features and drainage, respectively, that made the prevalent structures more obvious. North Devon has a dominant NW trend though the total percentage of lineaments in the ENE direction is greater due to more variation in orientation. These features are confined to distinct zones on the imagery, representing specific structures and lithologies. There are very strong indications of more NW-SE structures in this area than previously suggested in the literature. The Bodmin area also has a dominant NW trend related to the NW-SE strike-slip faults. The ENE lineaments in this area are more numerous with a greater variation in direction than those with a NW trend.

Drury (1986) advised caution when using directional filters in agricultural areas as these may spuriously suggest tectonically controlled linear features. Despite this, it is believed that the application of the image processing techniques used for the identification of geological structure throughout the South West can be of benefit to background analysis prior to, or synchronous with, field investigations. Various features have been identified on the imagery that are consistent with the known basic structure of the South West yet have so far been undetected on the ground. These features are potentially

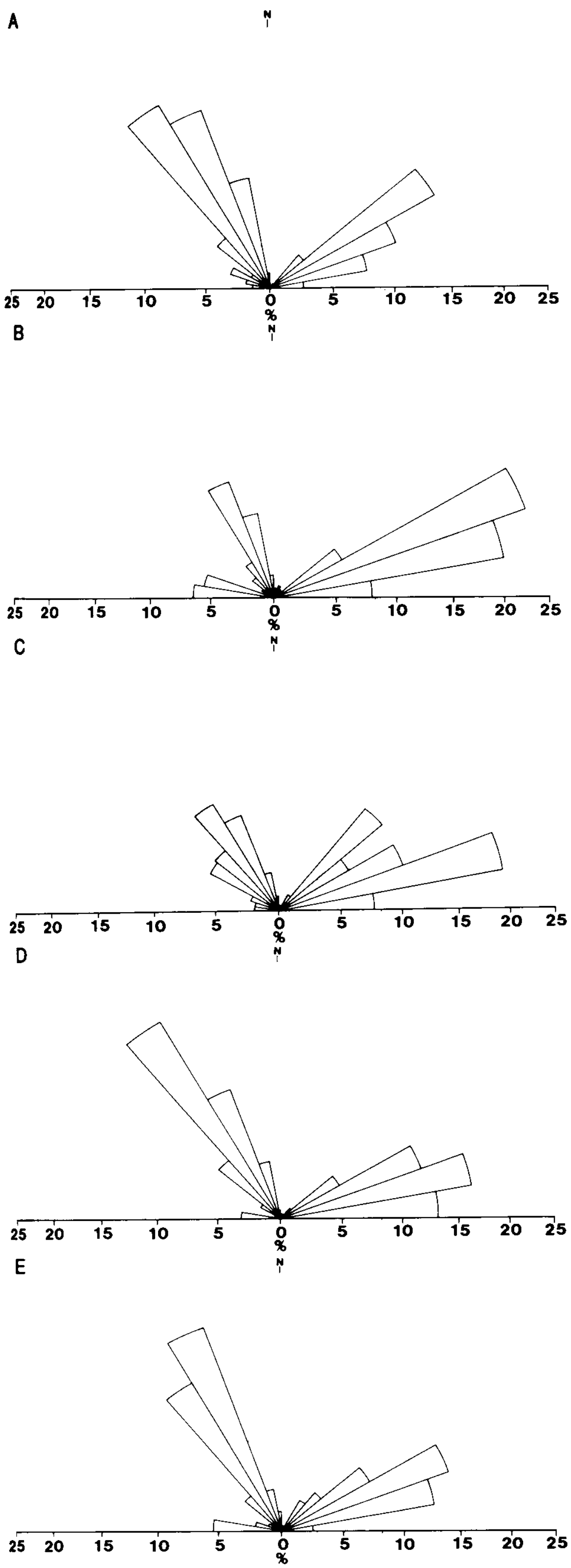

Figure 6. Percentage weighted rose diagrams for each area (percentage of lineaments within 10° arc). The total numbers of lineaments are given for each area below:
A South West England (311)
B South Devon (266)
C South Cornwall (260)
D North Devon (363)
E Bodmin (241)

very important, especially as new areas for economic interest. The images can also be used in areas of poor exposure to extrapolate coastal features inland that are hard to detect at ground level.

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