1986-12-01

Structural, Remote Sensing and Multivariate Correlation Methods as Aids to Mineral Exploration, Central Ireland

D.W. Coller
University of Dublin, Trinity College

M.F. Critchley
University of Dublin, Trinity College

J.M. Dolan
Queen's University - Belfast

See next page for additional authors

Recommended Citation

Coller, D., Critchley, M., Dolan, J, McDonnell, C., Murphy, C, Phillips, W, Sanderson, D.: Structural, remote sensing and multivariate correlation methods as aids to mineral exploration, Central Ireland. Remote sensing in mineral exploration (Commission of the European Communities (Resources, 2) pp 1 - 41. Editors: G. Castaing, Ph Chevremont, D. W. Coller, K. Conradsen Publisher: European Communities, December 1986 ISBN 92-825-5808-8

Funder: European Union

Authors

D.W. Coller, M.F. Critchley, J.M. Dolan, Ciaran McDonnell, C.J. Murphy, W.E.A. Phillips, and D.J. Sanderson

Commission of the European Communities

resources

Remote sensing in mineral exploration

Report
EUR 10334 EN

Structural, remote sensing and multivariate correlation methods as aids to mineral exploration, Central Ireland

D.W. Coller[1], M.F. Critchley[1], J.M. Dolan[2], C. MacDonaill[3],
C.J. Murphy[4], W.E.A. Phillips[1], D.J. Sanderson[2]

[1] Geology Department,
Trinity College,
Dublin 2,
Ireland

[2] Geology Department,
Queen's University,
Belfast BT7 1NN,
N. Ireland

[3] Computer Sci. Dept.,
Trinity College
Dublin 2
Ireland

[4] Statistics Dept.,
Trinity College
Dublin 2
Ireland

ABSTRACT

Central Ireland contains some of the largest PB-Zn in Europe. The area is poorly exposed, with thick glacial and post-glacial deposits and extensive agriculture. The known base metal deposits are hosted in Lower Carboniferous carbonates and are stratiform in nature. All the major deposits are adjacent to faults and there is preferential developement near to the Courceyan/Chadian boundary. Further deposits are likely to exist beneath a cover of younger Carboniferous rocks and/or beneath thick Quaternary deposits. Such deposits are likely to be blind to conventional exploration methods.

The Carboniferous rocks of Central Ireland overlie the zone of the Caledonian collision suture (Iapetus suture). The structure within the Carboniferous cover consists of a series of E-W to ENE-WSW trending dextral shear zones. More stable blocks lie between these transcurrent shear zones. Surface and sub-surface mapping at the Silvermines ore deposit showed that the ore bodies were generated in the termination zone of an E-W dextral shear zone. The termination occurs against an inferred granitoid pluton in the basement . The epigenetic Ballyvergin vein deposits lie in a dilation zone at the intersection of major dextral and sinistral shear zones.

New methods of analysing the patterns of lineaments interpreted from aerial photographs and enhanced Landsat imagery have defined the known transcurrent shear zones. These methods have also located new shear zones within previously unmapped areas. The zones predicted by this analysis are supported by independent ground structural and geophysical data. Structural models derived from these analyses allow the prediction of possible exploration targets.

The geochemical, geophysical, remote sensing and structural data have been statistically combined using computer classification. By introducing geochimical data, this procedure provides, to some extent, an independent test of the previous predictions based on the structural models. Box classification has located new target areas based on the combination of data from known mineral deposits. Discriminant analysis for a set of unmineralised and mineralised 1Km2 sites shows that the ground structural data alone was capable of distinguishing between unmineralised and mineralised sites. With multivariate discriminant analysis (excluding the structural data), the geochemical and derivative aeromagnetic data proved to be best discriminators. The main problems which arose from the discrimant analysis were concerned with the interpolation of data.

CONTENTS

1 INTRODUCTION 7

2 CALEDONIAN STRUCTURE 7

3 VARISCAN STRUCTURE 9

4 DEXTRAL WRENCH TECTONIC MODEL 11
  4.1 Structural Pattern in Wrench/Transpression Zones
  4.2 Dilation and Compression Zones in Wrench Fault Systems

5 DETECTION OF FAULTS AND SHEAR ZONES 14

6 INTERPRETATION OF SILVERMINES PB-ZN OREBODY 22

7 INTERPRETATION OF THE BALLYVERGIN GROUP OF ORE DEPOSITS. 25

8 DIGITAL TREATMENT OF GEOLOGICAL DATA 26

9 CORRELATION OF GEOPHYSICAL AND GEOCHEMICAL DATA WITH REMOTE SENSING DATA 27
  9.1 Remote Sensing Data
  9.2 Gravity Data
  9.3 Geochemical Data

10 COMPUTER CLASSIFICATION OF MULTIVARIATE GEOLOGICAL DATA 32

11 DISCRIMINANT ANALYSIS APPLIED TO MULTIVARIATE GEOLOGICAL DATA 33
  11.1 Statistical Methodology
  11.2 Results of Geochemical Analysis
  11.3 Results of Structural Analysis
  11.4 Resultsof Geophysical Analysis
  11.5 Results of Multivariate Analysis
  11.6 Discussion of Discriminant Analysis

12 CONCLUSIONS 37

13 ACKNOWLEDGEMENTS 38

14 REFERENCES 39

1. INTRODUCTION

Central Ireland consists of an extensive area of Upper Palaeozoic rocks covering a Caledonian basement. Four major Pb/Zn/Cu ore bodies (Fig. 1) and many smaller prospects occur, hosted mainly in Lower Carboniferous limestones. Although the deposits at Tynagh, Silvermines and Gortdrum are no longer actively mined, that at Navan is still in production and the search for further orebodies is being actively pursued. Most of these bodies are relatively shallow and surface traces of their mineralisation are apparent. Stream sediment sampling and shallow geophysical prospecting methods further localised the deposits. As the search for deeper orebodies developed in this heavily glaciated terrain, the need for expensive soil and rock geochemistry has greatly increased exploration costs.

All the known orebodies lie near major faults, and where these intersect Lower Carboniferous limestones they present possible exploration targets. Though there is a well established spatial association between mineralisation and faulting in Central Ireland, the majority of faults are unmineralised. In fact mineralisation occurs at a few favoured places on otherwise barren faults. In the absence of detailed structural analysis of known deposits, apart from the pioneering work of Rhoden (1958) at Silvermines and Moore (1975) at Tynagh, it has not been possible to explain this localisation of mineralisation, let alone predict which faults are likely to be mineralised and where. In view of the sparsity of detailed structural data from the Carboniferous rocks of Central Ireland, a study of the structural controls of mineralisation was funded by the National Board for Science and Technology between 1980 and 1983, which involved the Geology Departments at Trinity College Dublin, Queeen's University Belfast, University College Cork, University College Galway, and the Geological Survey of Ireland. In 1982, as a result of a 12 month research contract with the Commission of the European Economic Community, the study led on to an extensive correlation programme in which the new surface and subsurface structural data for a 5,000 km area of west-central Ireland were integrated with remotely sensed, geological, geophysical and geochemical data in an attempt to improve mineral exploration methods within the Community.

In view of the poorly exposed nature of the bedrock, remote sensing methods (mainly Landsat and aerial photography) have been developed to aid structural analysis. The thick glacial sediment soil,and vegetation cover preclude the use of remote sensing to map bedrock by spectral reflectance characteristics (Siegal & Gillespie 1980). Instead, both Landsat and aerial photograph data were used to identify lineaments and lineament patterns. This paper presents a brief introduction to these methods and also shows how they can be enhanced by correlation with other ground data sets. The correlation should provide a significant aid to exploration in the future.

2. CALEDONIAN STRUCTURE

Caledonian basement crops out in a number of inliers (Fig. 1) which can be assigned into northern and southern groups separated by the Iapetus suture zone (Phillips et al. 1976).

The Northern inliers include the Slieve Aughty, Slieve Bernagh and Arra mountains. The succession starts with Caradoc basalts, cherts and graptolitic shales; the pelagic oceanic facies being replaced by northerly derived turbidites in the late Llandovery and Wenlock. The structure consists of a series of strike faults bounding blocks in which the

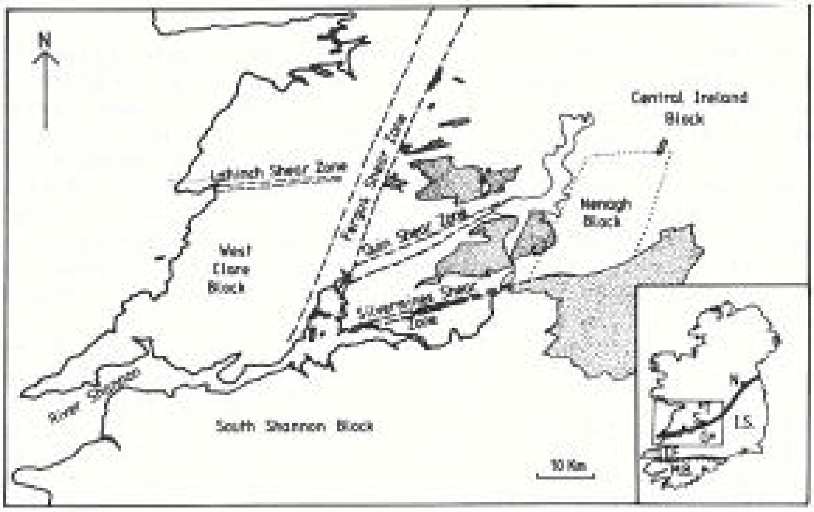


Fig. 1. Structural subdivisions of West Central Ireland Insert shows Iapetus suture (I.S.), Variscan Front (V.F.), Munster Basin (M.B.) and location of major ore deposits; Navan (N), Tynagh (T), Silvermines (S) and Gortdrum (G).

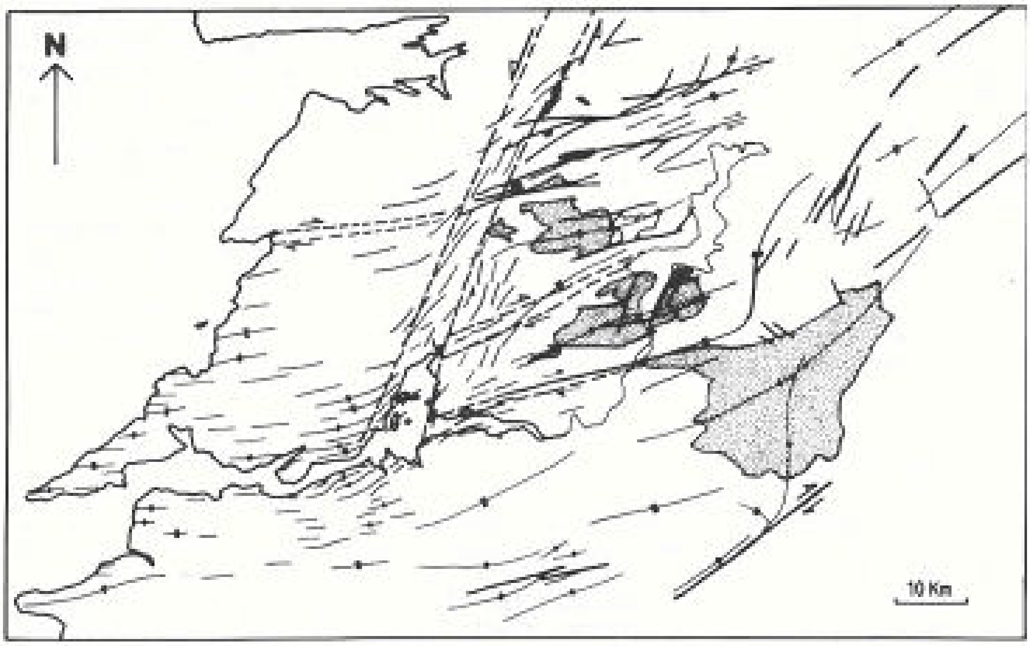


Fig. 2. Major gravity (m.gall) and magnetic (gamma) anomalies and major ore deposits of West Central Ireland. Barbs indicate decrease in anomaly value. T: Tynagh, S: Silvermines, B: Ballyvergin, C: Courtbrown, G: Gortdrum.

succession generally youngs northwards. Cleavage is steep in the south with a stretching lineation sub-parallel to strike, it becomes locally flat-lying in the northern part of the Slieve Bernagh and Arra Mountains. In the Slieve Aughty Inlier the cleavage dips moderately to the south and facing is downwards. The stratigraphy, sedimentology, faunas and structure indicate that these inliers belong to an accretionary prism marking the southern margin of the American Plate (Phillips et al. 1976, Leggett et al. 1980).

The Southern inliers comprise the Slieve Bloom, Devilsbit, Slieve Felim, Silvermines and Cratloe hills, where the succession consists of a monotonous series of sandstones and siltstones of Wenlock age. In contrast to the Northern inliers, these contain a mixed shelly and graptolitic fauna and derivation, where known, is from the east. The structure is dominated by upright folds and strike faults which repeat the Wenlock strata over at least 30 km across strike. The structural style and palaeogeography is comparable to that seen farther to the east in the Leinster inliers and they are interpreted as part of the European Plate.

Thus, the major structural element of the Caledonides in west-central Ireland is the collision suture (Iapetus suture) marking the boundary between the Iapetus Ocean during the Cambrian and Ordovician. This plate collision, together with accretion at the southern margin of the American Plate, produced Caledonian folding and cleavage with variable trends about the overall NE-SW to ENE-WSW trend of the suture. The Silvermines-Navan fault system is thought to coincide with the trace of the suture.

Around the Nenagh area there is a marked bend in the trace of the suture (Fig. 1) and this is associated with a complex pattern of strike variation in the Caledonian cleavage. The western end of this bend corresponds to a large negative Bouguer anomaly (Fig. 2) which gravity modelling suggests represents a granitic pluton in the basement. The effect of these features on the later Variscan tectonism is of considerable importance in understanding the structural controls of mineralisation.

3. VARISCAN STRUCTURE

Most of central Ireland is underlain by a thin (c. 2 km) sequence of Devonian and Carboniferous rocks, chiefly Lower Carboniferous. Both Dinantian and Namurian rocks thicken westward into the Shannon Basin to attain a total thickness of over 3 km. The Upper Palaeozoic rocks also thicken farther to the south into the Munster Basin.

The Upper Palaeozoic rocks show a very heterogeneous pattern of deformation, comprising blocks of varying degrees and styles of deformation separated by major faults and shear zones (Fig. 1). The area is traditionally considered as part of the Variscan foreland (Sanderson 1984). Structural synthesis of this large, and generally poorly exposed region is based on recent detailed structural studies by Coller (1984) and Dolan (1984a,b). These, together with further ground maping, have been used as a basis for a regional interpretation based extensively on Landsat imagery and aerial photography.

The overall trend of folds is E-W to ENE-WSW but these become modified within and adjacent to major faults and shear zones (Fig. 3). The fold style varies with stratigraphic level, mainly in response to differing lithologies, but there is little overall variation in strain at different structural levels. Argillaceous units, such as the Clare Shales and Lower Limestone Shales act as decollement zones, but deformation is not confined to the overlying strata and there is little displacement and thrust overlap of strata. Cleavage is heterogeneously developed and intensifies and

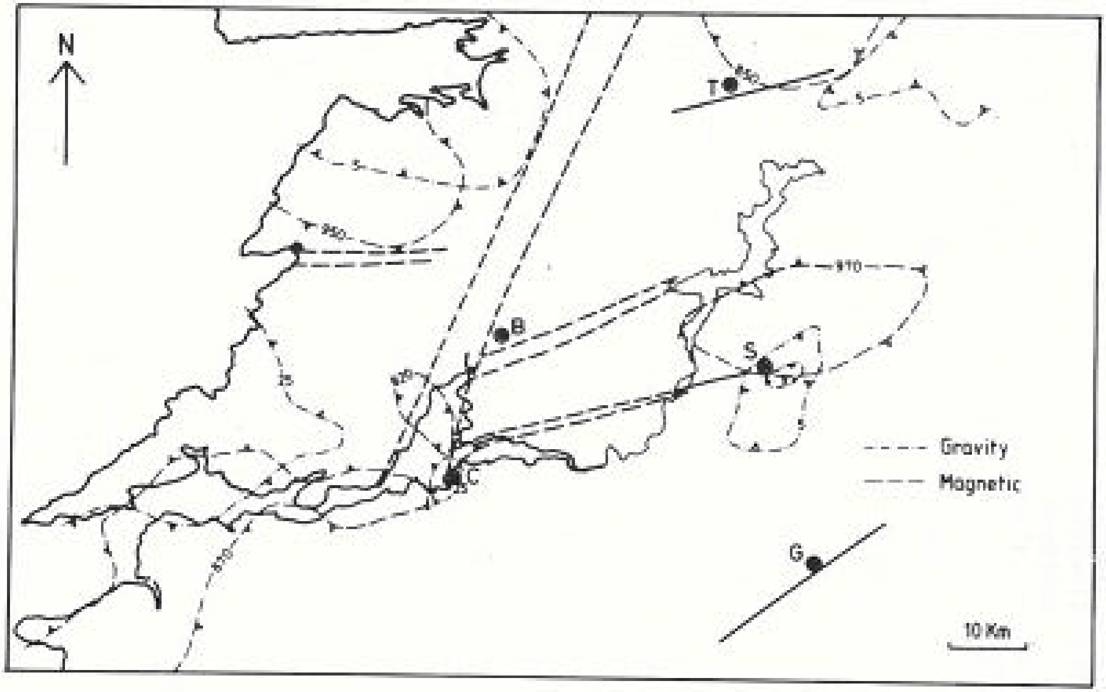


Fig. 3. Structural trends (folds and cleavage), major faults and shear zones of West Central Ireland.

swings into the shear zones. In the less deformed blocks cleavage may be generally absent or manifest as widely spaced solution seams.

The West Clare and South Shannon blocks, west and south of the Fergus Shear Zone, represent relatively unsheared domains within which there is a general southerly increase in intensity of deformation, indicated by the tightening of ENE-WSW and E-W trending upright folds and intensification of axial planar cleavage. This is in contrast to the more heterogenously deformed Central Ireland Block, east of the Fergus Shear Zone, where cleavage and fractures vary in orientation and intensity across a series of ENE-WSW shear zones (Fig. 1). The West Clare Block is however dissected by at least one low strain ENE-WSW trending dextral shear, the Lahinch Shear Zone (Fig. 1), which has been interpreted from statistical analysis of Landsat lineaments. In the two western blocks both aerial photo lineament analysis and field fracture patterns indicate a consistent pattern and southward increase in the development of conjugate NNE (sinistral) and NNW (dextral) wrench faults and minor shears which overlap in time with cleavage formation. This structural pattern suggests the main deformation west of the Fergus Shear Zone is one of simple N-S compression with little shear or rotational strain component.

The Fergus Shear Zone is a broad, dominantly ductile, sinistral shear zone which varies in width from 5 to 15 km. It extends from the Shannon Estuary northwards for at least 70 km. At its southern termination, the margins of the zone appear to diverge, possibly against the large positive gravity anomaly (>100 g.u.) which may represent more basic material in the underlying Caledonian basement. Within the shear zone, the regional ENE trending folds are tightened and rotated anticlockwise developing numerous higher order folds. Similarly cleavage, which remains axial planar, is rotated and enhanced. Fault patterns within the Fergus Shear Zone can be interpreted in terms of conjugate Riedal shears within a sinistral simple shear zone, producing NNE trending wrench faults (R shears) parallel to the zone, and shorter ESE-SSW dextral wrenches (R' shears) of smaller displacements. Approaching the southern termination of the zone, south of the River Shannon, local NNE-SSW synthetic, smaller scale shear zones rotate E-W cleavage and folds.

Within the sheared Central Ireland Block is a relatively low strain, unsheared region, the Nenagh Block (Fig. 1), which is broadly coincident with a large negative Bouguer anomaly which probably represents a granitic intrusion at 3 to 4 km depth in the basement (Fig. 2). The structure of this block comprises a large open NNE trending syncline of Lower Carboniferous limestone with no associated cleavage and little vein development. Minor structures typical of the surrounding shear zone regime, in particular en echelon folds, are absent. Riedel shears and heterogenous cleavage are not developed. Thus, it appears that this low strain, unsheared block is probably related to rigid behaviour of the buried granitic intrusion. The Silvermines Shear Zone terminates at the margin of this block.

4. DEXTRAL WRENCH TECTONIC MODEL

Central Ireland represents a foreland shelf, lying to the north of the main Variscan belt. Arguments exists as to the location and significance of the Variscan Front in Western Europe. Within Ireland the front is generally placed between the Munster Basin, with its thick Upper Palaeozoic sedimentary fill and strong cleavage, folding and faulting, and central Ireland, with its thinner cover and generally weaker, but more heterogeneous deformation (Fig. 1). It is becoming more widely recognised that the northern part of the Variscan belt represents a complex series of basins deformed at varying times by combinations of thrusting and dextral shear.

Badham (1982) has suggested an overall strike-slip or wrench model to explain the lack of structural continuity along the belt, the indistinct nature of any suture, the low degree of crustal thickening, the presence of long-lived wrench faults and to accord with the sparse palaeomagnetic evidence available. One of the most important, although not necessarily diagnostic, features of strike-slip belts is the complex and localised style and timing of deformation. Thus, rifting and basin development may occur in one place, contemporaneous with thrusting and folding in another. The transient nature of the deformation in both space and time is achieved by the interchange or transfer of compression and extension along wrench faults. In this respect, wrench faults play a somewhat similar role to transform faults between lithospheric plates. The tectonic transport direction within the northern parts of the Variscan of Western Europe is generally to the NNW or NW (Sanderson 1984, Coward & Smallwood 1984) and is thus oblique to the general ESE-WNW trend of the belt. The result of this oblique closure is to generate an overall dextral transpressive regime, which Sanderson (1984) and Max and Lefort (1984) have discussed with respect to Ireland. Such E-W belts of dextral transpression extend into the foreland, for example, the Ribblesdale foldbelt of N. England (Arthurton 1983) and the West Midlands of Ireland (Coller 1984).

Under this dextral transpression, the Iapetus suture in the Caledonian basement is suitably orientated to be reactivated as a zone of dextral shear, but if simple N-S compression operated then sinistral movement would result. The localisation of Variscan shear along the suture is manifest in the Silvermines-Navan fault system, which was active during the Carboniferous and controls mineralisation.

4.1 Structural Pattern In Wrench/Transpression Zones

Within a wrench system a wide variety of structures may develop. Using simple shear Wilcox et al. (1978) have outlined the general en echelon arrangement of structures (Fig. 4b). Many departures from this simple pattern can occur in response to modification of the boundary conditions, stress field and pore-fluid pressure in and around fault zones. One of the simplest modifications involves the introduction of a component of compression or extension across the zone, this is termed transpression (Harland 1971, Sanderson & Marchini 1984). Basically, compression causes a reorientation of the maximum compressive principal stress, producing folds and thrusts at a lower angle to the zone and extension and Riedel shears at a higher angle (Fig. 4a). The opposite is true for extension across the zone (Fig. 4c). The increased development of cleavage and folding, and their low angle to the zone, suggest that compression is general in the shear zones of West Central Ireland.

4.2 Dilation and Compression Zones in Wrench Fault Systems

The individual faults developed in a regional shear system are often discontinuous, and displacement along them must be transferred into compression and dilation at their terminations (Fig. 5a). The termination zones need not be symmetrically arranged. The wrench faults themselves may develop in order to transfer extension and/or compression from one place to another. The termination of the Silvermines Shear Zone illustrates the features of such dilation zones (see below) and many similar features have been described from wrench fault systems elsewhere, for example, Najd Fault (Moore 1979), Hope Fault (Clayton 1966), Dash-e-Bayes Fault (Tchalenko & Ambraseys 1970).

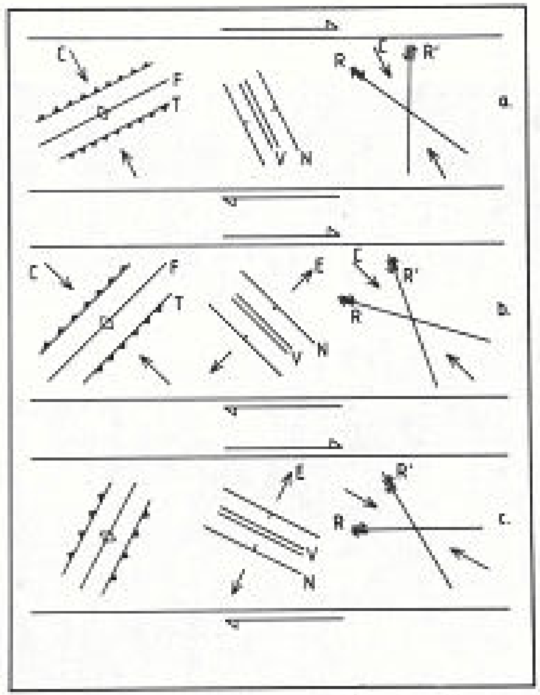


Fig. 4. Arrangement of structures in Transpression zones (after Sanderson & Marchini 1984); a) compression across zone, b) simple shear, c) extension across zone. C: compression E: extension, V: vein, N: normal fault, F: fold, T: thrust, R & R': Riedel shears.

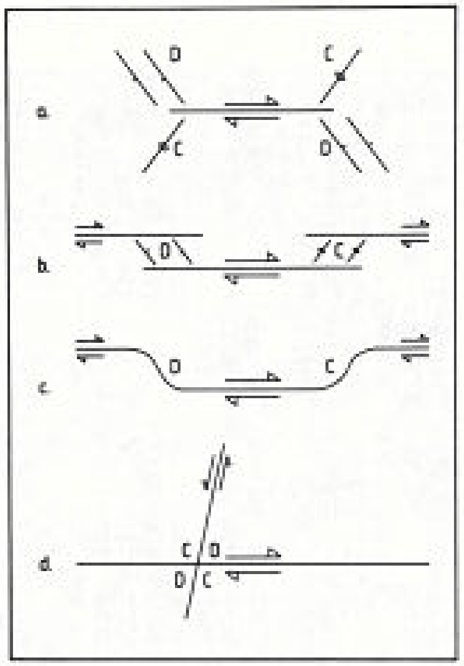


Fig. 5 . Generation of compression (C) and dilation (D) zones in wrench fault systems; a) at terminations, b) at overlaps, c) at bends, d) at intersections.

Overlap of faults (Fig. 5b) leads to a similar, but more symmetrical, pattern, producing pull-apart grabens (Crowell 1974) and block uplifts. Bends also generate compression and dilation zones (Fig. 5c) and are particularly important in braided fault systems. Transient compression or dilation zones may develop during periods of movement on the bent portions of faults, during the development of linking faults to transfer movement from one fault to another, or where bends are induced by faults propagating into or around obstructions.

Intersections of active wrench faults will give rise to compression and dilation zones (Fig. 5d); care must be taken to distinguish this from situations of a new fault crosscutting and displacing an older one. Slip, without dilation or compression, is only possible on two intersecting faults if it is parallel to the intersection. Wrench faults generally have steeply plunging intersections, which are at a high angle to the sub-horizontal slip, thus some compensatory deformation is necessary. At low strains, this may take the form of dilation, compression and rotation of the faults (arranged as in Fig. 5d). For large displacements, additional movement zones may develop producing a type of triple-junction (cf. oceanic triple-junctions, McKenzie & Morgan 1967). An exact analog with plate junctions is not implied as the blocks or 'plates' in this study are themselves deformable.

5. DETECTION OF FAULTS AND SHEAR ZONES

The importance of structurally generated dilation zones in the location of known mineral deposits has already been described. It is evident that the future discovery of similar potentially mineralised zones will depend greatly on the recognition of shear zones and the accurate delineation of their margins and terminations. It is also probable that potential discoveries in the Lower Carboniferous of the Irish Midlands will be in areas of extensive drift cover within which limited geological and structural information will be available. In these circumstances, it is suggested that the application of remote sensing studies will offer a significant and cost effective exploration tool to mineral prospecting in Ireland.

Two forms of remote sensing data are available for the Irish Midlands. Aerial photographs, at a scale of 1:30000, have been interpreted for tonal and topographic lineaments. Unenhanced Landsat imagery (Fig. 6a) shows a limited amount of structural information. Directional filtering of Landsat imagery (Fig. 6b) has proved to be a very useful technique for detecting lineaments.

Shear zones and faults in cover rock sequences generally occur as complex zones or systems of fractures. Some zones may be manifest as simple lineaments on remotely sensed imagery, but many occur as subtle, complex systems of lineaments reflecting the distribution, sense and amount of strain in the zone. In this section we will discuss some of the methods used to detect fault and shear zones, particularly using remotely sensed imagery, based on examples drawn mainly from the Fergus and Quin shear zones.

The mapping and direct display of structural features and lineaments allows the larger blocks and shear zones to be detected. The rotation of folds and cleavage (Fig. 7) into the Fergus Shear Zone is obvious where ground structural data is available; inland, however, the limits of the zone are less clear. Limited outcrop allowed the minor structures to be mapped in some detail. Folds progressively tighten and rotate slightly en echelon to the zone. Fault patterns within the zone are distinctive and

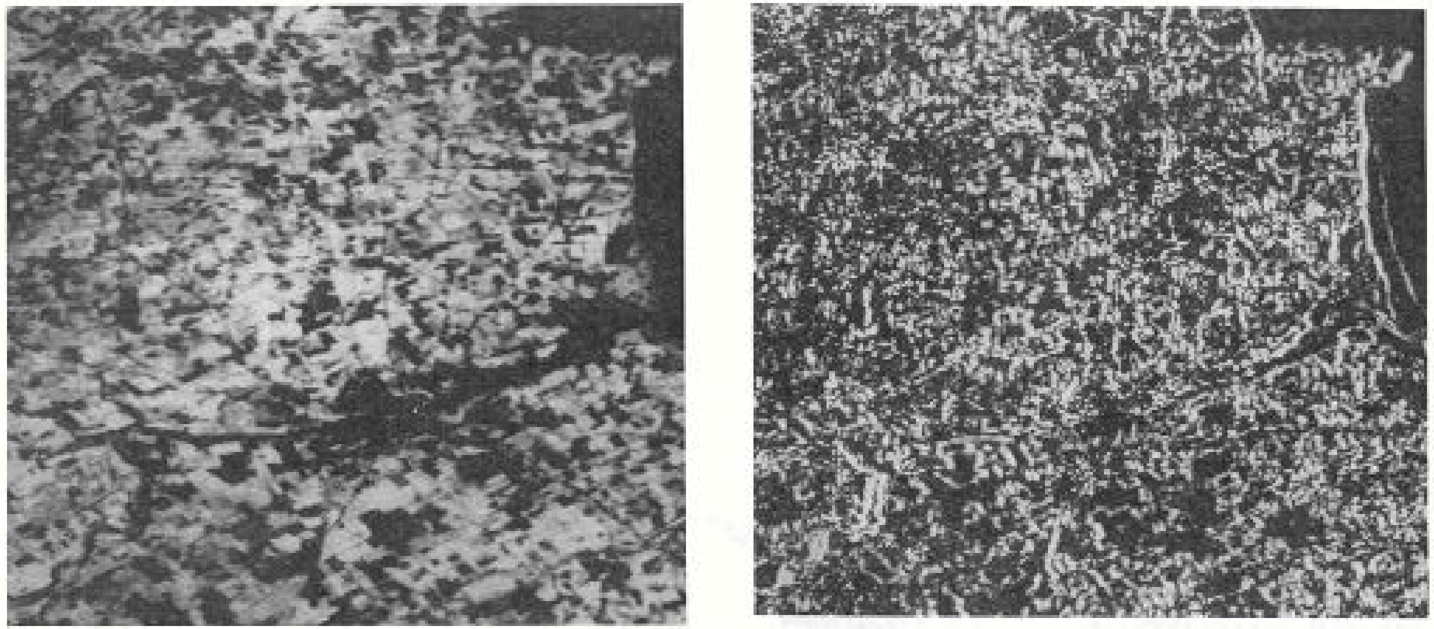


Fig. 6. Digital image processing of Landsat imagery to enhance structural interpretation; a) unprocessed band 7 image, b) E-W masked band 7 image, showing ENE and NW lineaments. [Photography by Comdt. Patrick Walshe (Retd.)]

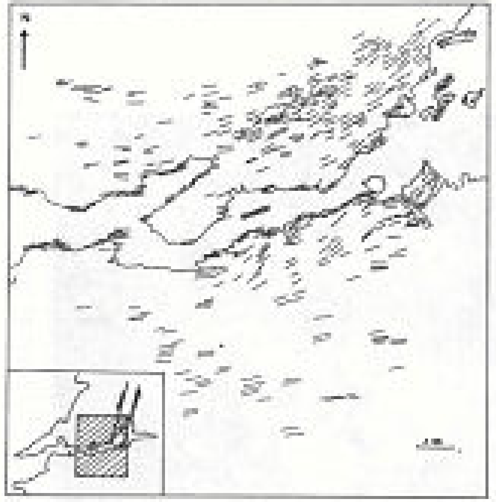


Fig. 7. Cleavage trends around the Shannon Estuary showing a swing from E-W to NE-SW into and within the Fergus Shear Zone.

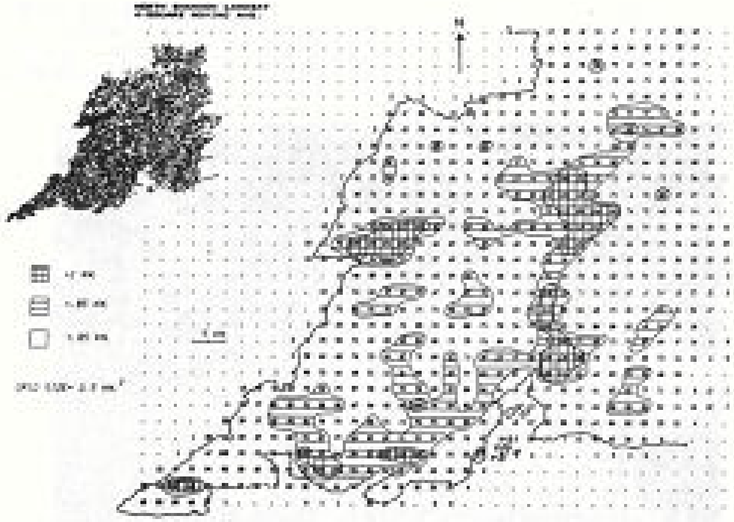


Fig. 8. Landsat lineament density showing a NNE trending zone of high lineament concentration coinciding with the Fergus Shear Zone and an ENE zone of high lineament density along the Lahinch Shear Zone.

can be interpreted in terms of conjugate Riedel shears with dominant NNE-SSW wrench faults (R-shears) and subordinate ESE-WSW antithetic faults (R'-shears). NW-SE extensional faults commonly occur.

The concentration of structures and lineaments in the Fergus Shear Zone can be expressed in terms of density (total length or frequency within a specified square grid). In the West Midlands most of the known shear zones show an increase in fracture and lineament density within the zone (Fig. 8). Many authors have recognised this increase in fracture density in fault zones (eg. Wheeler & Dixon 1980), but occasional studies show the inverse arrangement (eg. Pohn 1981). With remotely sensed lineaments, density is not simply related to degree of fracturing and much variation can be attributed to variation in thickness of drift cover etc. (see Babcock 1974).

The Fergus and Quin shear zones are not expressed as zones of high density of air photo lineaments, possibly because the mapped increased density of fractures and fracture arrays have allowed a deeper level of weathering within these zones. Both the Fergus and Quin shear zones have a strong negative topographic expression. The Landsat lineaments are fairly widely spaced and need grid sizes of 2-5 km to cover enough lineaments for statistical analysis, which limits the definition of the zones. However, Landsat lineament density is not as dependent on drift thickness and locates the Fergus Shear Zone as a broad density high (Fig. 8). Directional density, the percentage of lineaments or fractures within specified directional intervals, is a useful measure of the dominance of particular orientations. Many studies have shown the preferential development of certain fracture sets within fault zones (eg. Weaver 1974). Fig. 3 shows a low proportion of Landsat lineaments in the range 50 to 90 degrees within the Fergus Shear Zone, whereas there is a high proportion of lineaments in the range 90 to 125 degrees (Fig. 10). This pattern is due to the development of the Riedel shear system in the zone, which is not represented in the surrounding blocks. These maps, particularly those from aerial photograph lineaments, allow detailed definition of the edges of the shear zone (Fig. 10).

Angular atypicality (Pretorius & Partridge 1974) is a measure based on directional density which uses the total data in a large area to define orientations which occur relatively infrequently (ie. are atypical). The percentage of such orientations in individual grid cells is then a measure of the atypicality of the cell. We have found variations in angular atypicality associated with shear zones, but the nature of these depends strongly on the definition of the orientations of atypical regional orientations.

The development of complex fracture systems within fault zones is manifest as a change in the degree of preferred orientation or randomness in the zone. A useful measure of the randomness is Relative Entropy (RE):

$$RE = \frac{-100*(\Sigma_{i=1,N} P^i*(\log_2 P^i))}{\log_2 N}$$

Where N = number of classes (N = 18 for 10 degree class intervals) and P^i = proportion of lineaments in class i. RE = 100% for perfect randomness, RE = 0 for parallelism of lineaments.

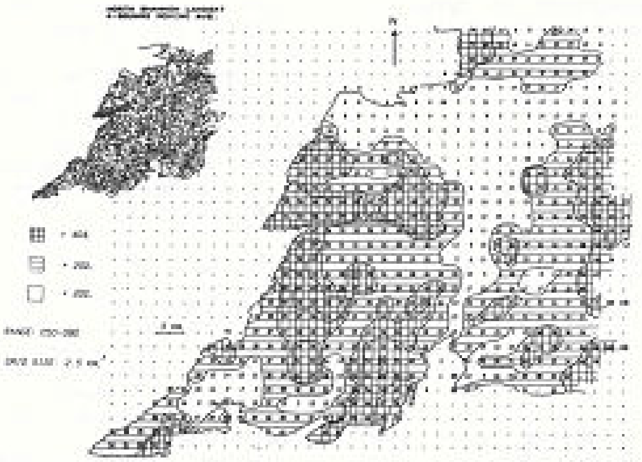


Fig. 9. Directional density map of Landsat lineaments in the range 50 to 90 degrees, showing a corridor of low concentration of lineaments of this orientation within the Fergus Shear Zone.

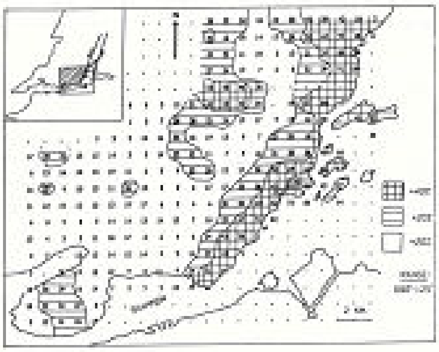


Fig. 10. Directional density map of aerial photograph lineaments in the range 90 to 125 degrees, showing a high concentration of lineaments of this orientation within the Fergus Shear Zone. This correlates with the high density of similar trending fractures (R' shears) observed within the zone. The boundary of this zone of high concentration coincides with the western margin of the Fergus Shear Zone.

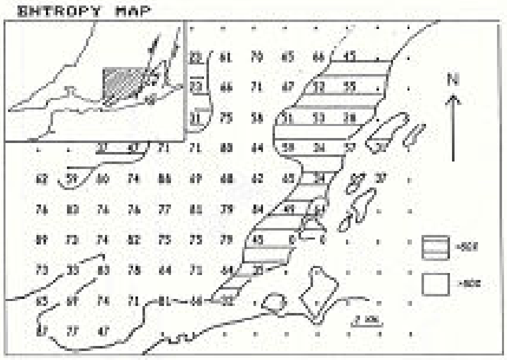


Fig. 11. Relative Entropy map of aerial photograph lineaments, showing a high degree of preferred orientation (i.e. low randomness)within the Fergus Shear Zone.

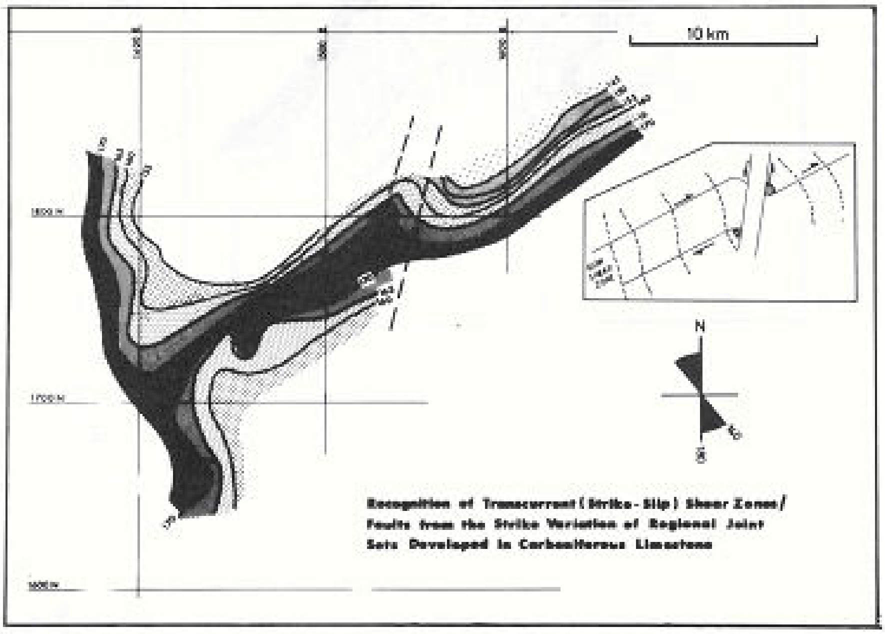


Fig. 12. Contoured Group Mean map, showing the clockwise rotation of cleavage into and within the Quin Shear Zone

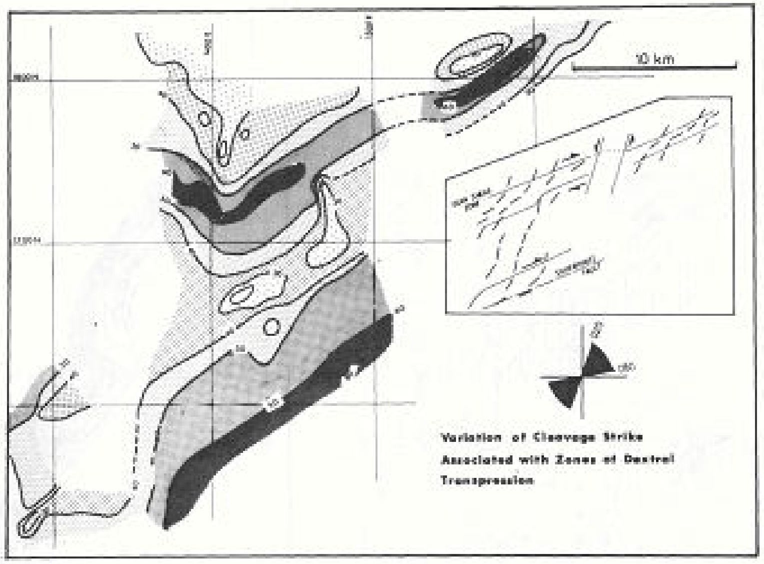


Fig. 13. Contoured Group Mean map, showing the clockwise rotation of the regional NNW-SSE fracture system within the Quin Shear Zone.

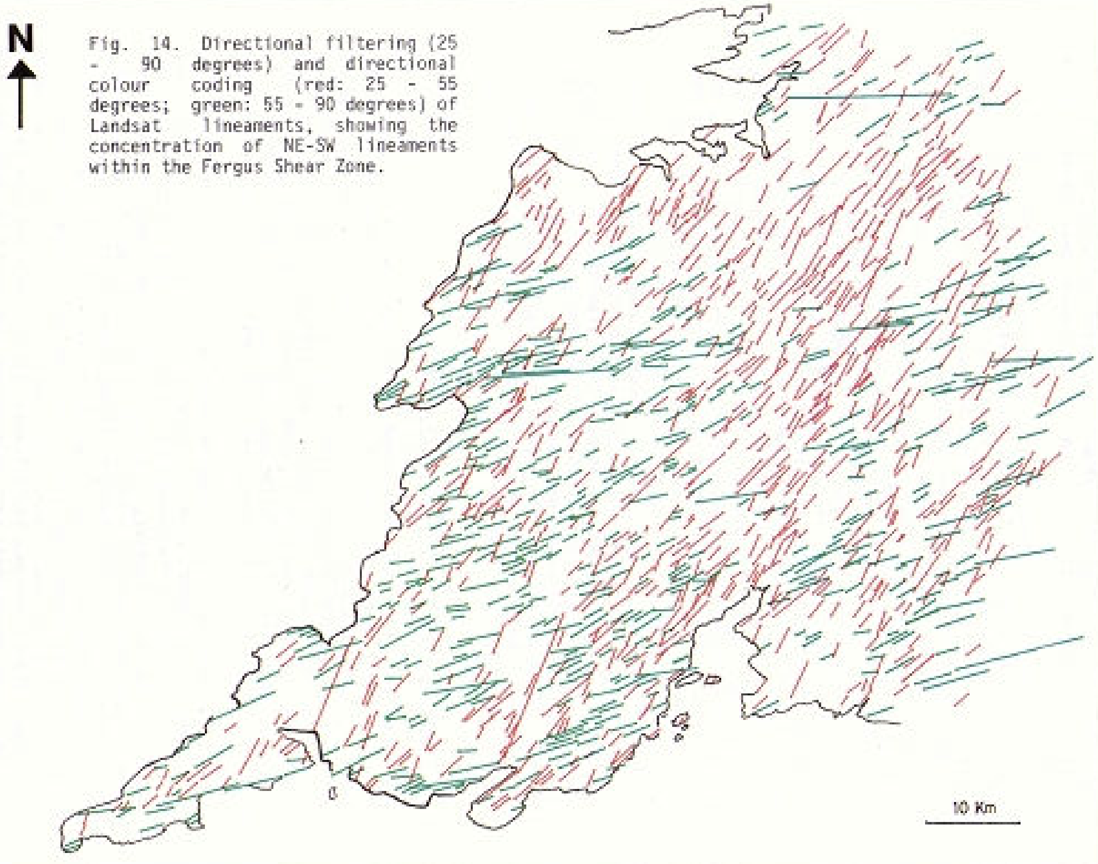


Fig. 14. Directional filtering (25 - 90 degrees) and directional colour coding (red: 25 - 55 degrees; green: 55 - 90 degrees) of Landsat lineaments, showing the concentration of NE-SW lineaments within the Fergus Shear Zone.

The RE of aerial photograph lineaments at the western edge of the Fergus Shear Zone (Fig. 11) shows a greater preferred orientation of fracture sets within the zone due to the regular development of Riedel shear pattern.

One feature which comes out clearly from most forms of data is the change in orientation of fracture and lineament sets on entering shear zones. This phenomenon has been recognised in many studies of fractures adjacent to faults (eg. Stearns 1968, Nelson 1979, Critchley 1981) and has been applied to regional fracture studies in the north Pennine orefield by Carter and Moore (1978). There is a clear clockwise swing in mean orientation of cleavage (Fig. 12) and a prominent N-S joint set (Fig. 13) into the Quin Shear Zone. This can be interpreted as a rotation due to dextral shear in this zone. Similar counter-clockwise swings occur in the sinistral Fergus Shear Zone. Due to the low density of Landsat lineaments, unless large grid cells are used, a very simple and effective way of displaying these strike swings is in the form of filtered and/or colour coded plots. In figure 14 the lineaments in the range 20 to 90 degrees display an obvious counter-clockwise rotation into the Fergus Shear Zone, which can be visually enhanced by colour coding. Other minor shear zones, such as the Quin and Lahinch shear zones, also become more obvious by these methods. With a dense pattern of aerial photograph or Landsat lineaments it is possible to produce a contoured Group Means Map by calculating the vector mean for data within a specified range of orientations.

The ability to reduce complex lineament patterns to scalar measures of a wide range of attributes has greatly facilitated the recognition and delimitation of faults and shear zones. Zones previously known from ground structural work can be mapped into poorly exposed ground and their margins and terminations delineated more accurately. By 'finger printing' the lineament characteristics of the known shear zones, computer aided searches may be used in an attempt to locate new shear zones and hence potentially mineralised sites.

6. INTERPRETATION OF SILVERMINES PB-ZN OREBODY

The Silvermines area has been mined discontinuously since the early 17th century. There are a number of stratabound Pb/Zn orebodies within the Upper Palaeozoic strata, particularly the Lower Carboniferous, together with economic barite mineralisation (the Ballynoe deposit). Extensive drilling in the 1960's and 1970's indicated ore reserves of about 20 M tons, grades varying from 1-5% Pb, 0-9% Zn, with up to 1% Ag (Taylor 1979). Production approaching 1 million tons was reached in the late 1970's. In addition 2.5 M tons of barite ore (at 85% barite) were indicated at Ballynoe.

For several tens of kilometres west of Silvermines, the Silvermines Shear Zone is a narrow zone of high strain and large displacement which for the most part is accommodated along a single major fault - the Silvermines Fault. However, just west of Silvermines the fault bends clockwise and terminates in a broad zone of deformation. Strain is largely accommodated by movement on newly initiated fractures (Fig. 15). Virtually all of these fractures strike clockwise of the trend of the main fault and hence lie in the extensional field of the dextral incremental shear. They form a major dilational zone, the overall structure being a stepped half-graben; the Silvermines Fault forming the southern boundary fault.

There are three important mineralised horizons. The Upper Devonian sandstones are hosts to breccia and vein style mineralisation, with a high initial porosity and fluid pressure possibly facilitating hydraulic

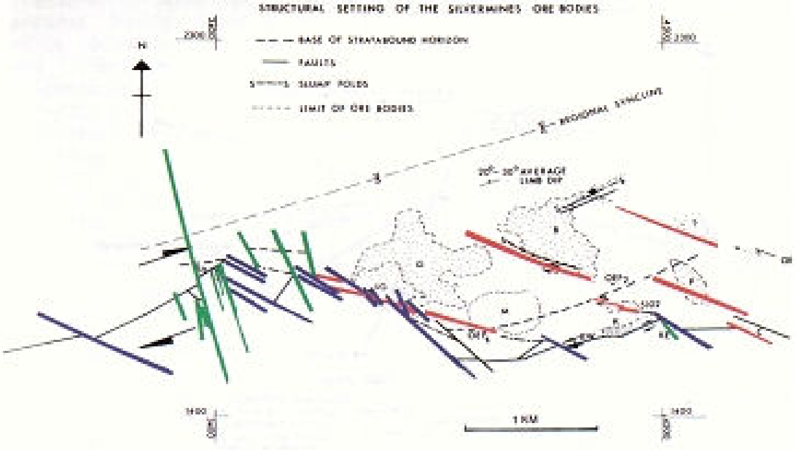


Fig. 15. Structural setting of the Silvermines orebodies. The three Pb-Zn stratabound orebodies (LG: Lower 'G' zone, G: 'G' zone, B: 'B' zone) were controlled by the development of oblique extension faults (OEF shown in red) at the termination zone of the Silvermines Fault. The feeder areas for 'G' and 'B' zone statiform orebodies are located at the foci of the oblique extension faults at the points of maximum dilation (see also Fig. 16a). The colour coding of the faults is explained in Fig. 16b.

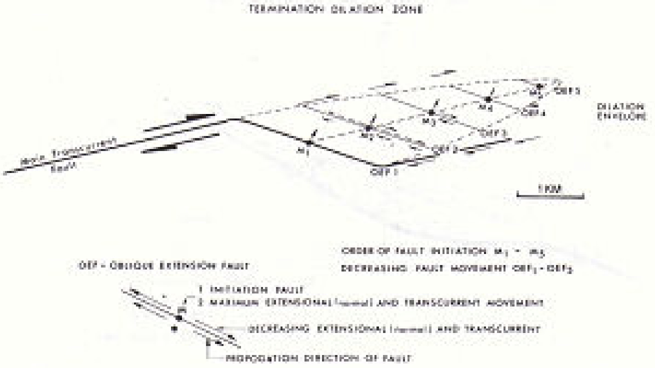


Fig. 16a. A schematic plan summarising the main fault orientations and movement histories in the Silvermines area. The initiation and early movement of the faults is compatible with dextral shear on the ENE trending principal shear - the Silvermines Fault.

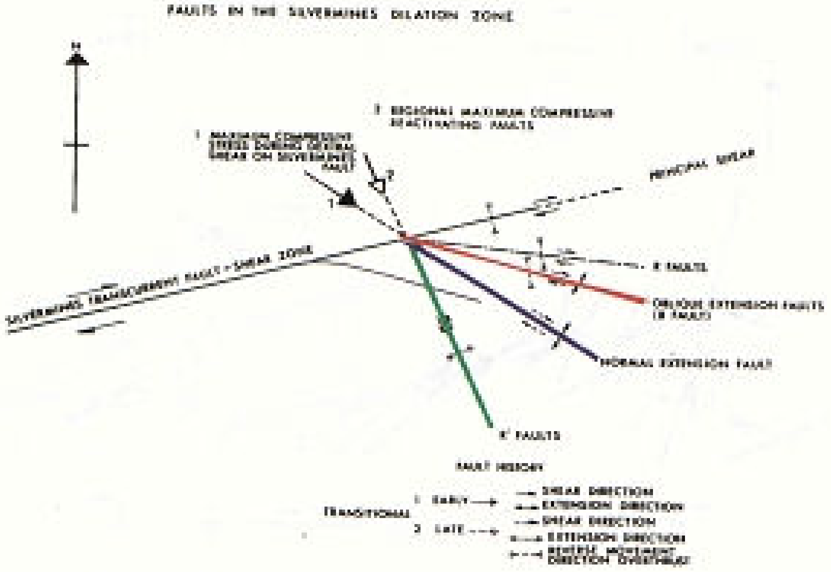


Fig. 16b. Reactivation of faults at Silvermines under regional compression.

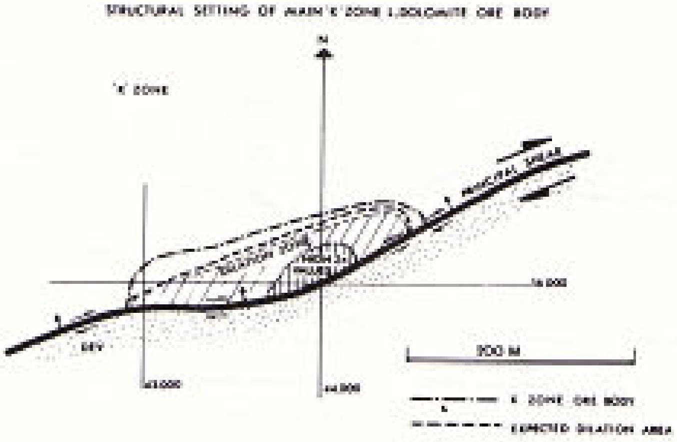


Fig. 17. Structural control of epigenetic 'K' zone mineralisation at a bend along a dextral wrench fault at Silvermines.

fracture. Secondly, vein and replacement mineralisation (Lower zone) is present in the Lower Dolomite (bioclastic Middle Ballysteen Limestone), in which dolomitization generated much secondary porosity. The most complex and important stratigraphic control of mineralisation is within dolomitized, in situ and transported breccias which overlie or interdigitate with Waulsortian, mud-bank, reef limestones. The two largest stratiform orebodies (the Upper 'G' and 'B' zones) are hosted in this lithology.

All the known mineralisation is within the limits of the dilation zone and is at least partially controlled by fault activity. A simplified model outlining the growth of the faulting and dilation zone at Silvermines is shown in Fig. 10. The Oblique Extension Faults (Fig. 15) were active during the Lower Carboniferous;metal zonation and textural studies suggest that they acted as feeders for mineral bearing fluids, with mineralisation decreasing away from the faults. This is the situation in the upper 'G' and 'B' zones where faults control the development of debris flows producing the mineralisated breccias. The maximum stratigraphic separation on the 'B' fault zone is near its centre where a large slump fold was generated. The breccias and slump fold suggest that the fault acted as a 'growth fault' during the early Visean.

Transcurrent movement on the oblique extension (OEF), principal shear (P), extension (E) and antithetic Riedel (R') faults (see Fig. 15) generated local dilation zones at overlaps, bends and terminations, and these areas are often the sites of mineral concentration. The 'K' Zone orebody is located on the Silvermines fault where dextral movement at a clockwise bend in the fault would have produced a local dilation zone (Fig. 17). Extensional faults generated the veins and brecciation in the Shallee area and contribute to mineralisation in many of the other orebodies.

Hydraulic fracturing associated with all the faulting is commonly localised along faults and results in fluid flow and seismic pumping which contribute to the remobilisation and concentration of ores. In addition to these direct controls of mineralisation, open NE-SW trending folds may have controlled the alignment and position of mud-banks which in turn strongly influence the distribution of stratiform ore. These folds are compatible with compression in a ENE dextral shear regime.

Thus, the Silvermines deposit is, as a whole, structurally controlled at a dilation zone at the termination of the Silvermines Shear Zone. Individual faults and resulting dilation zones control the individual orebodies within the area. The extension faults produced acted as feeders for the syngenetic stratiform mineralisation. Syn-sedimentary faulting produced a thick development of dolomitized limestones and breccias which act as hosts for the mineralisation. Later movements and fracturing produced epigenetic mineralisation in veins and breccias.

7. INTERPRETATION OF THE BALLYVERGIN GROUP OF ORE DEPOSITS

Six small sulphide and several associated calcite spar epigenetic deposits are clustered NE of the intersection of the Quin and Fergus Shear zones. The sulphide deposits, chiefly Pb-Ag-Cu, are hosted in a variety of limestones of Lower Carboniferous age and tend to occur as linear lodes associated with faults. The pattern of faults and mineralisation in this area, as interpreted from ground structures and remote sensing, indicates a complex of dextral, sinistral and extensional minor faults which locally control mineral lodes (Fig. 18). These faults and the complex basin and dome folds suggest an interference pattern resulting from transcurrent shear movements at the intersection of the two major shear zones. Thus, synchronous dextral and sinistral shear on the Quin and Fergus shear zones respectively has resulted in a structural dilation zone which appears to have controlled the generation and location of the Ballyvergin group of epigenetic deposits.

8. DIGITAL TREATMENT OF GEOLOGICAL DATA

We have described the structural framework of the West Midlands of Ireland and shown how the interpretation and statistical analysis of Landsat and aerial photograph lineaments can help in mineral exploration. But to fully understand the origin of lineaments, incorporate them in any structural model and develop a multivariate exploration method, it is necessary to integrate the remote sensing data with all other available geological data.

The storage of geological data in digital form allows the rapid comparison of different data sets, particularly if the data is in image format. In order to produce images from non-spectral data it is usually necessary to interpolate the irregularly distributed samples onto a regular geographical grid. In the case of the Vicom image processor at Trinity College, Dublin, the data are interpolated on to a 512 by 512 grid; with a grid spacing of 100m this results in a data set covering an area 51.2km by 51.2km. The grided data set can be turned into an image by scaling the range of sample values to cover the display range of 0 (black) to 255 (white) and transferring each grid point as a pixel to the image processor.

With geological data sets in image format it is very quick and easy to use standard image processing techniques to enhance and analyse these data. It is possible to rapidly overlay different data sets with the aid of an image processor to look for visual and statistical correlations. Geographical information can be obtained by overlaying a Landsat image registered to the geological image; alternatively map data may be input from a digitizer or video camera.

A series of computer programmes implemented on a VAX 11/780 computer in conjunction with the Vicom image processor, or on an Apple II microcomputer,. perform statistical processing of individual data sets. The statistical techniques used operate on either the image format or raw data sets, depending on the processing method, and have been developed for the following data sets: stream sediment and soil geochemistry; gravity and aeromagnetics; ground structure; lineaments. In treating the geological data with computer analysis the emphasis has been to firstly develop methods, based on geological reasoning, which will enhance the interpretation of individual data sets. Only then has multivariate correlation been undertaken. Multivariate analysis should not be followed blindly without any supporting geological knowledge or framework.

Integration of the various data sets has proceeded in three directions. Firstly, visual correlations of the processed data sets were aided by the overlaying facility of the Vicom image processor. Secondly, multivariate pattern recognition methods, such as classification and principal component analysis, have been used to investigate the statistical correlations between variables. Finally, discriminant analysis has been used for data from a test area to 'fingerprint' the geological characteristics of mineralisation. Aspects of each of these three procedures are described below.

9. CORRELATION OF GEOPHYSICAL AND GEOCHEMICAL DATA WITH REMOTE SENSING DATA

The correlation of geophysical, geochemical and remote sensing data is illustrated for an area within the Carboniferous terrain of Central Ireland.

9.1 Remote Sensing Data

The lineament data set from a typical aerial photograph interpretation (Fig. 19) consists of many hundreds of lines. Statistical analysis methods already described can be used to summarise the underlying patterns in such a lineament map. The group means map of lineament data is a good technique for detecting rotation zones of lineament orientation. Figure 20 is a grey-scale group mean image derived from those lineaments in figure 19 which strike between 60 degrees and 100 degrees (average orientation = 80 degrees). Light tones on the image show areaswhere lineaments strike near to 100 degrees (i.e. clockwise of average); tones are dark where the lineaments strike close to 60 degrees (i.e. anti-clockwise of average). Geological modelling, based on wrench fault patterns and ground structural observations, suggests that the NE trending light toned rotation zones could be the result of NE dextral wrench faults. Similarly, the NW trending dark toned rotation zones could result from NW sinistral wrench faults.

9.2 Gravity Data

The raw gravity image for the same region (Fig. 21) shows a NE trending line of gravity high (light-toned), flanked on the west by a gravity low (dark-toned). The gravity high is due to a ridge of dense Lower Palaeozoic rocks, whilst the gravity low may result from a local thickening in the Carboniferous cover.

Structural observations of the mineralisation in the Irish Carboniferous have emphasized the role of faults in locating mineral deposits. The boundaries between the bodies forming gravity anomalies may often be structurally controlled. Thus, in integrating gravity data with lineament and ground structural data the position of gravity anomalies is of lesser importance than the boundaries to these anomalies. In the gravity data these boundaries are manifest by steep gravity gradients or by changes in the gradient or curvature of the gravity field. The regions of high gravity gradient can be found by taking the first derivative of the raw gravity data (Henderson 1960). Figure 22 shows the first derivative gravity image; there is a good correlation between the Landsat rotation zones (Fig. 20) and the first derivative high (Fig. 22).

9.3 Geochemical Data

The soil geochemical data for copper, lead and zinc are shown as a colour composite in figure 23. This image was produced on the Vicom image processor by displaying copper as shades of blue, lead as green and zinc as red. The black regions are areas where no data were available. The colours in the image are dependent on the relative proportions of Cu, Pb and Zn; areas having similar hues of colours have similar values of all three elements. Coincident high values of Cu, Pb and Zn result in white in the image. The colour composite can be correlated with bedrock lithological or surface overburden data. It can also be used to find coincident anomalies in all three data sets.

Analysis of the frequency distribution of the geochemical data using the cumulative frequency plot method of Sinclair (1974, 1976) has shown that the data set for each element is composed of three populations. For the copper data, these populations have ranges of <11 ppm (pop.1), 12 ppm

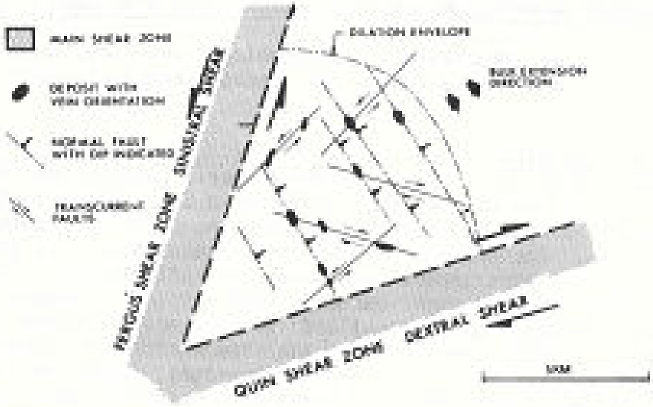


Fig. 18. The Ballyvergin group of deposits, showing structural control of calcite and sulphide vein-type mineralisation in a dilation zone at the intersection of the Fergus and Quin shear zones.

Fig. 19. Aerial photograph lineaments for an area in the Central Midlands of Ireland. Area shown is about25x25 Km.

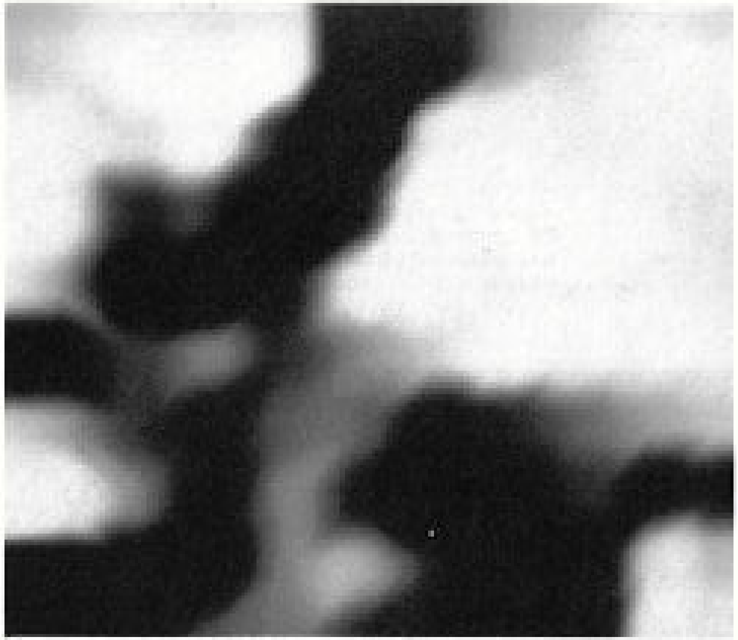


Fig. 20. Grey scale Group Mean image of aerial photograph lineaments between 60 and 100 degrees. In light toned regions, lineaments strike close to 100 degrees, in dark toned areas they strike near to 60 degress. NE trending light zones follow trend of dextral wrench faults. [Photography by Comdt. Patrick Walshe (Retd.)]

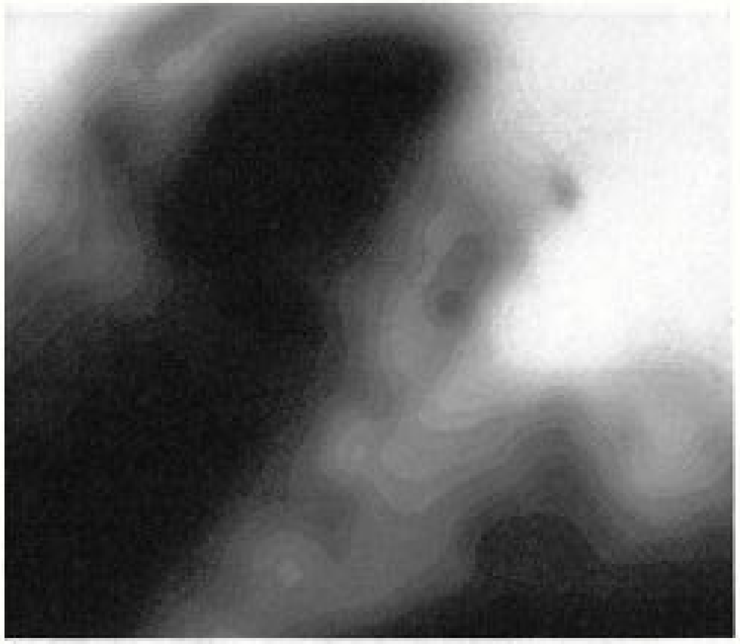


Fig. 21. Unprocessed gravity image, showing NE trending gravity high (light) due dense basement rocks and corresponding gravity low (dark) due to thick carbonate succession. [Photography by Comdt. Patrick Walshe (Retd.)]

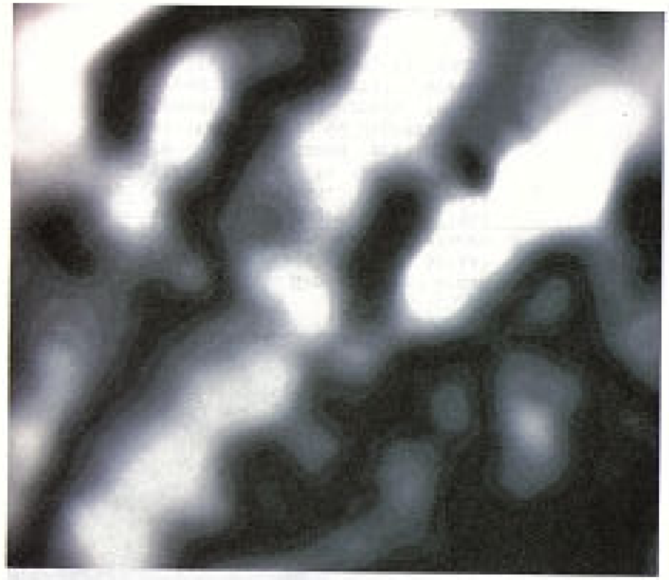


Fig. 22. First derivative gravity image (gradient), showing NE trending derivative highs which correspond to major NE faults. [Photography by Comdt. Patrick Walshe (Retd.)]

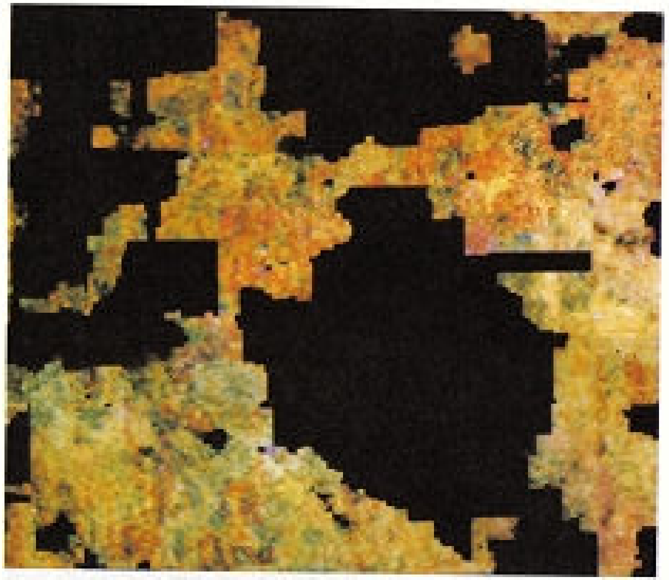


Fig. 23. Colour composite geochemical image, formed by displaying copper as blue, lead as green and zinc as red. Coincident elemental highs have light tones, areas of similar hue have similar combinations of all three elements. Areas where no samples were available are black. [Photography by Comdt. Patrick Walshe (Retd.)]

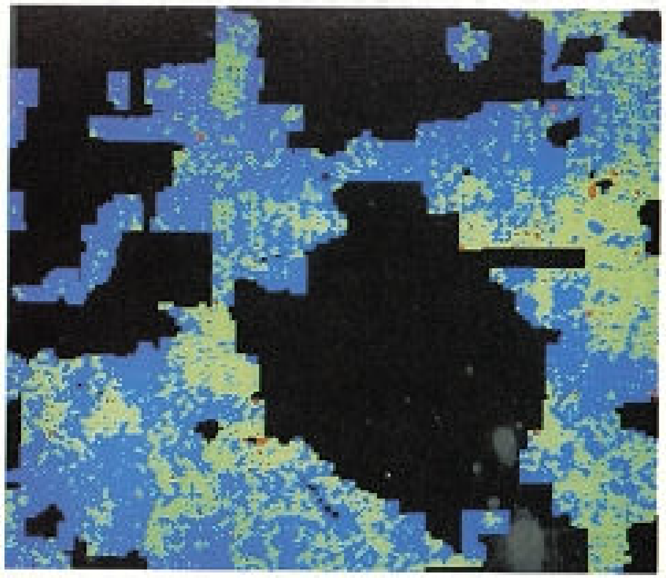


Fig. 24. Copper population image, showing population 1 (<11 ppm) as blue, population 2 (12-31 ppm) as green and population 3 (>32 ppm) as red. NE and NW trending lineations of population 2 may be structurally controlled. [Photography by Comdt. Patrick Walshe (Retd.)]

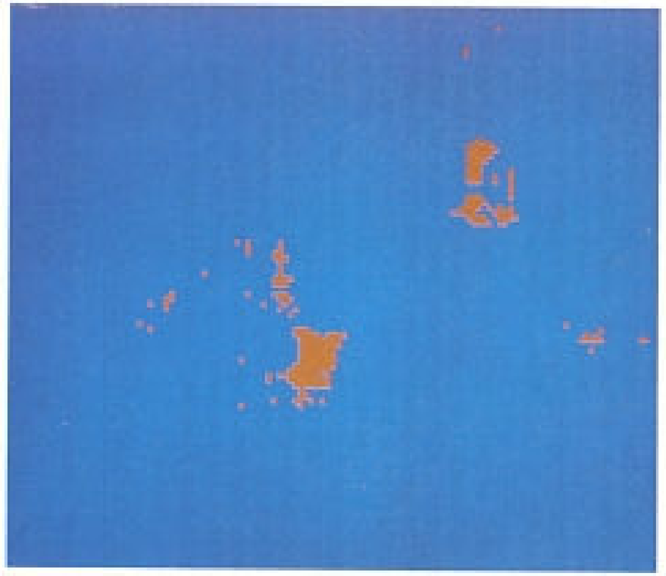


Fig. 25. Colour coded classified image showing areas of anomalous copper, lead, zinc, gravity first derivative and aerial photograph lineaments Group Means. Training samples were taken from an area of known mineralisation and the red parts of this image represent prospective target areas. The area shown in this image corresponds approximately to the upper right quadrant of figs. 19-24. [Photography by Comdt. Patrick Walshe (Retd.)]

to 31 ppm (pop. 2) and >32 ppm (pop. 3). Using these population ranges it is possible to assign each individual copper sample into one of the three population groups. This technique allows a statistical definition of cut-off values to anomalies. It is also a very useful method when combining data sets of different origin. The copper populations are shown in figure 24, where population 1 is blue, population 2 is green and population 3 is red.

On a regional scale the western part of the area is dominated by population 1, with pockets of population 2 and points of population 3. In the east population 2 predominates, with a greater occurrence of population 3 than in the west. Thus, in the west population 1 represents the dominate background Cu value, with population 2 anomalous. In the east population 2 is background and population 3 is anamolous. The strong cut-off between the region of background population 1 in the west and background population 2 in the east corresponds to the edge of a Lower Palaeozoic inlier. This feature also corresponds to the boundary between the NE trending gravity low and high (Fig. 21), suggesting some lithological and maybe structural control of the junction between the two background populations. Within the area of background population 1 to the west are several NW trending zones of anomalous population 2, which may also be structurally controlled.

10. COMPUTER CLASSIFICATION OF MULTIVARIATE GEOLOGICAL DATA

In the geochemical example given above it can be seen that it is very easy to look for visual combinations of geological variables using colour composites displayed with the aid of an image processor. However this technique is limited to the integration of no more than three different variables at a time. In many mineral exploration projects there are commonly a multitude of different data sets or different statistical measures of these data. The storage of geological data in digital form, especially image format, allows computer assisted pattern recognition with virtually any number of data sets.

There are two forms of pattern recognition available for multivariate geological data on the Vicom/Vax image processing system. The first technique is termed 'unsupervised' classification. In this method the computer looks for statistical groupings between samples within the data. The geologist then has to relate these groupings to known geological factors. In the second method, termed 'supervised' classification, training samples are taken from restricted geographical sites within the whole data set. Such a site should be geologically homogeneous; an example might be an area of known mineralisation. The technique is not restricted to one category of site, but there may be several categories, for example sites of vein mineralisation or sites of stratiform mineralisation. The computer then compares each of the remaining data points in the data set with the training samples for each category, and classifies each point into the category which has the 'most similar' combination of all the geological variables. There are several decision criteria to assign a point to a category; the most commonly used are the box and maximum-likelihood classifiers.

The application of supervised classification to mineral exploration in the Irish Carboniferous can be illustrated using the geophysical, geochemical and remote sensing data described above. Training samples were taken from the copper, lead and zinc soil geochemistry data, first derivative gravity data and the group means aerial photograph lineament data for sites having known mineralisation. The training sites were characterised by moderate copper values, high lead and zinc values and high first derivative and group means values. Figure 25 is a colour-coded classified image in which points having a similar combination of all five geological variables are shown in red. These may be areas of higher mineral potential.

Computer assisted pattern recognition (classification) thus allows a rapid assessment of areas having similar values of geological variables and hence probably similar geology. The technique is, however, subject to two main sources of error. Firstly, errors of omission in which the training samples do not truly represent the full range of each variable for a given category. Secondly, errors of comission arise where training samples for a given category are taken from sites which are not geologically homogeneous.

11. DISCRIMINANT ANALYSIS APPLIED TO MULTIVARIATE GEOLOGICAL DATA

A major theme of our study in the Carboniferous of Ireland has been to develop statistical correlation models for the different data sets which might distinguish between mineralised and unmineralised areas. This goal of 'fingerprinting' mineralisation by statistical analysis depended upon acquiring in digital form a suitable set of data from an area containing a variety of types and scales of mineralisation. For the 5000 square kilometres of west Central Ireland the following data sets were obtained:

- Surface solid geology
- Mineral occurrence data
- Sub-surface geology
- Surface and sub-surface structure
- Gravity
- Magnetic
- Landsat and air photograph lineaments
- Stream sediment geochemistry

Each data set were digitized, using a 1km unit square, and stored in digital format. Some data were smoothed or more rigidly defined using the 1 square km cell.

A sub-set of 110 cells were selected from the total of 5,000 cells in order to investigate whether there is a statistical difference in the geology between mineralised and unmineralised areas. The sub-set of 110 cells were selected based on the criteria that they were known with confidence to be either mineralised or non-mineralised and were confined to areas of Tournasian bedrock (the age of the host rock for stratiform Pb-Zn deposits). The non-mineralised cells were designated by the absence of any recorded mineralization in the surface, and in some cases sub-surface rock. The selection of non-mineralised cells proved to be a difficult problem and the choice was restricted to areas which had been intensively investigated by mining companies. This, however, gave a bias in the data for unmineralised cells, as the companies had been attracted to these areas partly because of the economically promising geology. Thus, the sub-sample of un-mineralised cells may not truly have represented the total population of unmineralised sites. In addition, unless a cell designated as unmineralised had been intensively drilled, then we could not totally preclude the possibility of mineralization in these particular cells. Mineralized cells were those with a record of lead or zinc mineral occurrence without any classification of grade or style.

For each cell in the sub-set relevant measures or summaries of each data set were calculated. The Landsat lineament data were excluded from this study because the unit cell used in calculating lineament statistics

(10 by 10km) was considered incompatible with the sub-set cell size (1 by 1km). It was impossible to reduce the size of the Landsat cell as this would result in too few lineaments per cell. Aerial photograph lineament and sub-surface structural data were also excluded because of incompleteness of these data sets for the region as a whole. The partial coverage of the study area by the stream sediment geochemistry and the ground structural data has resulted in several of the selected cells having an incomplete set of variables, which reduced the population for some correlations.

11.1 Statistical Methodology

The study was approached from the point of view of discriminant analysis in which an attempt is made to allocate 1km cells to one of two categories - mineralised or non-mineralised - based on the geochemical, structural and geophysical data, taken individually or together. The method of logistic discrimination, or logistic regression, was adopted, which models the probability of mineralisation in a cell to a function of the data at, or near that cell. The model was fitted step wise so that the final discrimination only contains those variables which significantly contribute to the model. Cells were allocated to the mineralisation category if their calculated probability of mineralisation was greater than 0.5, otherwise they were allocated to the unmineralised class. The computer programme used in this study was the BMDP routine PLR (Dixon 1981), implemented on the DEC 20 at Trinity College. This study formed an M.Sc. thesis by one of the authors at Trinity College (Murphy 1982).

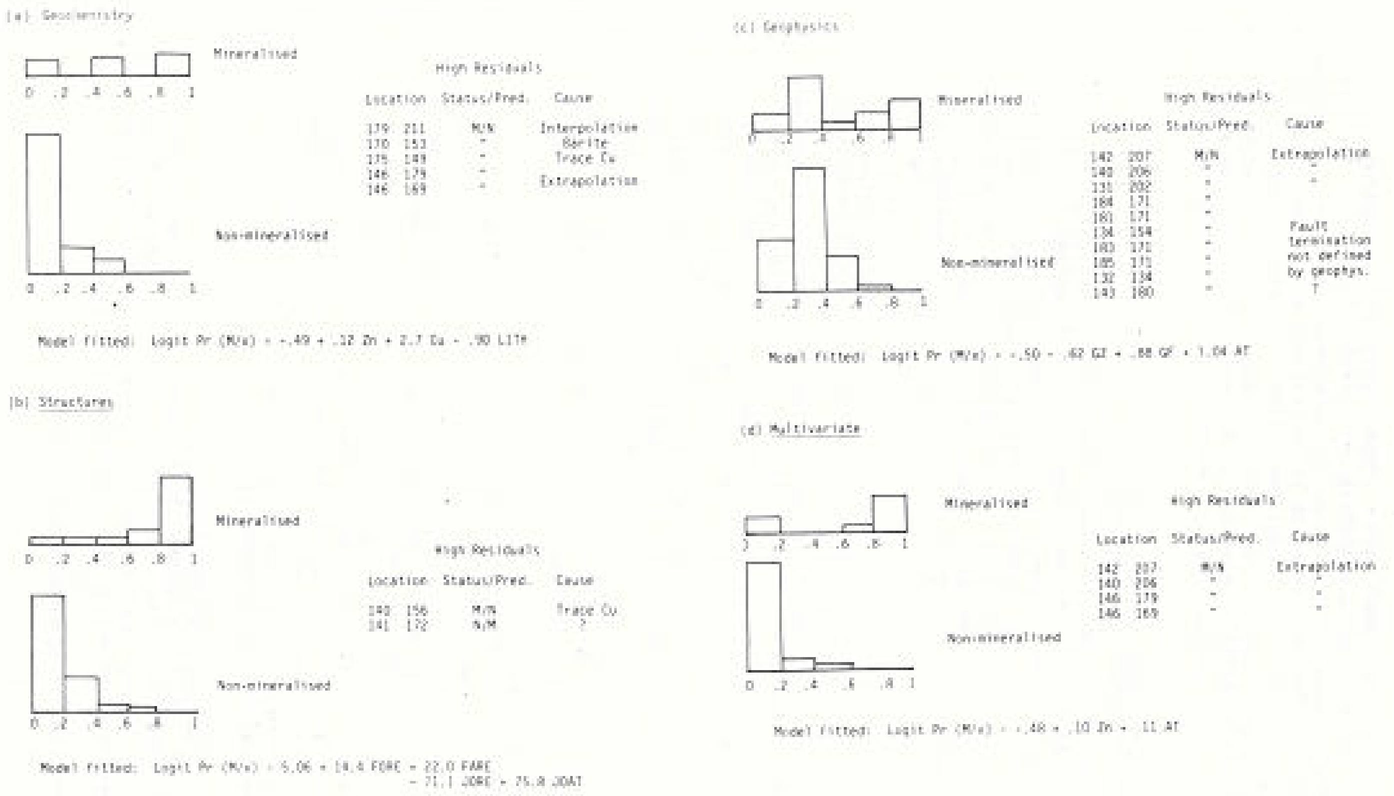
11.2 Results of Geochemical Analysis

The geochemical analysis was based on 18 mineralised and 59 un-mineralised cells, data being unavailable at the other locations. A significant number of these 77 cells had geochemical values that were interpolated or extrapolated from other areas. Lithologically corrected Cu, Pb and Zn stream sediment values, and a 0-1 variable indicating whether the cell has a mixed lithology, were used as variables for the geochemical analysis.

The multivariate model selected step wise does not include Pb, resulting from the high correlation between Pb and Zn values. Separation of the distribution of fitted probabilities is good, apart from five mineralised cells which were given low probabilities of mineralisation (Fig. 26a). An examination of these misclassified cells showed that one contained barium mineralisation and this would not be detected by the chemical elements used. Three of the cells involved interpolated or extrapolated geochemical values and thus contained suspect data. More seriously, the fourth cell contained the major Pb-Zn deposit at Tynagh. Stream drainage in the Tynagh area forms small internal basins and, thus, no uncontaminated stream sediment samples were available for the mine area. Again, the geochemical values for this fourth cell had been interpolated from the surrounding area. The fifth cell contained trace copper, which perhaps should not have been designated as a mineralised cell in the first instance.

11.3 Results of Structural Analysis

The structural discriminant analysis was based on 16 mineralised and 26 non-mineralised cells. This was the smallest data set examined, but it was also the most successful. The variables used were calculated values for relative entropy and atypicality of folds, faults, veins and joints. These data were obtained from the four types of structures in a 5 by 5km square centred on the cell in question.



(a) Geochemistry

High Residuals

Location	Status/Pred.	Cause
179 211	M/N	Interpolation
170 153	"	Barite
175 149	"	Trace Cu
146 179	"	Extrapolation
146 169	"	

Model fitted: Logit Pr (M/x) = -.49 + .12 Zn + 2.7 Cu - .90 LITH

(b) Structures

High Residuals

Location	Status/Pred.	Cause
140 156	M/N	Trace Cu
141 172	N/M	?

Model fitted: Logit Pr (M/x) = 5.06 + 14.4 FORE - 22.0 FARE
- 71.1 JORE + 75.8 JOAT

(c) Geophysics

High Residuals

Location	Status/Pred.	Cause
142 207	M/N	Extrapolation
140 206	"	"
131 202	"	"
184 171	"	
161 171	"	
134 154	"	Fault termination not defined by geophys.
183 171	"	
185 171	"	
132 134	"	
143 180	"	T

Model fitted: Logit Pr (M/x) = -.50 - .62 GZ + .88 GF + 1.04 AT

(d) Multivariate

High Residuals

Location	Status/Pred.	Cause
142 207	M/N	Extrapolation
140 206	"	"
146 179	"	"
146 169	"	"

Model fitted: Logit Pr (M/x) = -.48 + .10 Zn + .11 AT

Fig. 26. Summary of results from logit discriminant analysis of geological data from West Central Ireland. Histograms of predicted probabilty of mineralisation are shown for mineralised and non-mineralised cells. Details of mis-classified cells (high residuals) are recorded by grid reference, with known and predicted mineralisation status; M: mineralised, N: non-mineralised.

The multivariate model was fitted using relative entropy of folds, faults and joints, and atypicality of joints (Fig. 26b). There is an almost complete separation between the categories, however, two residuals were identified. One cell known to be mineralised had a low probability of mineralisation. This cell contained trace Cu mineralisation and was perhaps not significant in an area of mainly lead-zinc deposits. The second cell was originally allocated as non-mineralised, but the model gave this cell a high probability of mineralisation. There was no ready explanation for this cell.

11.4 Results of Geophysical Analysis

The geophysics analysis was based on 40 mineralised and 67 non-mineralised cells. The data were mostly interpolated. Of all the data sets examined, it was most difficult for the geophysical data to decide what features of the gravity or magnetic field would be most closely associated with mineralization. As the ground structural studies had shown the close relationship between faulting and mineralisation, it was decided that three derivatives might be the best measures for the geophysical data. These derivatives were (i) the gradient in the direction of maximum slope (1st derivative); (ii) the rate of change in gradient in the direction perpendicular to the maximum slope (2nd derivative); (iii) the rate of change of the 2nd derivative, again in the direction perpendicular to maximum slope (3rd derivative or curvature). These three measures were calculated from a 3 by 3km block surrounding each cell.

The discriminant model fitted included gravity and aeromagnetic curvature and gravity first derivative (Fig. 26c). The separation of the distributions of the resulting predicted probabilities was generally poor. Ten mineralised cells were calculated to have low probabilities of mineralisation. Three of these cells exhibited aspects of extrapolation and one cell could not be easily explained. The remaining six misclassified cells contained the large mineral deposits at Silvermines and Courtbrown. These mineral deposits are situated at fault terminations and in the local area surrounding these cells the geophysical fields were rather flat. Some better measure of the geophysical fields is therefore needed to identify fault terminations.

11.5 Results of Multivariate Analysis

A multivariate analysis, combining data sets, was performed on 30 mineralised and 59 non-mineralised cells. Since there were few cells with structural data, these were not included in the analysis, despite the successful results using this data set alone. This multivariate analysis, therefore, only involved geochemicaland geophysical data.

The model fitted used Cu and Zn geochemical and aero-magnetic curvature values (Fig. 26d). An excellent separation was achieved, except for four mineralised cells which were classified as non-mineralised. All of the misclassified cells contained extrapolated data values, and thus are suspect. Signifcantly, all the major mineral deposits were correctly classified, as was the barite mineralisation.

11.6 Discussion of Discriminant Analysis

The results of this study suggest that logistic discrimination can be used to help identify the multivariate patterns which 'fingerprint' mineralisation. Inspite of the initial difficulties in deciding whether a cell was mineralised or not it has been successful in:-

(i) Discriminating mineralised sites (using structural or multivariate data).

(ii) Helping to understand inadequacies in the data (interpolation and extrapolation problems with geochemical or geophysical data).

(iii) Helping to define more clearly what features of the geophysical data help to locate mineralisation.

The study has been particularly useful as a pointer to further research. Four areas of future research to mention are:

(i) Improved methods of interpolation and extrapolation; perhaps using geostatistics.

(ii) Exploration of interaction between variables; perhaps filling 'holes' in one data set by estimates from other variables.

(iii) Development of discriminant methods which are optimal for spatial data.

(iv) Development of new measures which characterize faults or nearness to fault terminations.

12. CONCLUSIONS AND DISCUSSION

This study is part of a continuing cooperative research programme aimed at understanding and predicting the siting of mineralisation. A dominant theme has been the attempt to explain why some fault systems are barren and others locally mineralised. We have found that image processing of Landsat tapes, using directional filtering of band 7 and textural analysis methods, has provided a useful basis upon which to identify large scale lineament patterns. Interpretation of aerial photographs provides additional lineament data on a more local scale.

A range of pattern analysis methods have been developed for the structural and lineament data, which allow detailed mapping of major structural zones separating relatively homogeneous blocks. Whilst this analysis is essentially 2-dimensional surface and sub-surface structural studies indicate the importance of a component of wrench tectonics, thus facilitating the interpretation of the lineament data. At Silvermines, underground structural mapping provided an ideal opportunity of correlating this data with sedimentology and stratigraphy, thus providing an integrated study of the controls of syngenetic Pb/Zn mineralisation. Ground structural mapping has established a chronology of deformation, which together with careful integration with other forms of geological information allows a 'basin analysis' approach, hence this study is not just a blind extension of the mapping of faults based on remotely sensed data.

In order to fully understand and use the structural data it has been necessary to develop new methods for processing and integrating remotely sensed data with all the available geological, geochemical and geophysical data. Although we are still at an early stage of developing multivariate methods suitable for exploration, we are convinced that each data set must first be processed separately, using a wide variety of methods, by geologists who are familiar with the nature of the data and the study area. It is only by a trial and error, 'tuning' approach that meaningful interpretations and summaries of the geophysical data and population splitting of the geochemical data have aided our geological interpretations. These unvariate summaries then allow multivariate correlations and 'fingerprinting' of mineralised sites to be attempted. Without this step-by-step geological interpretation of each data set, a mulivariate computer analysis is unlikely to produce meaningful results and may confuse and mislead the exploration process. Multivariate discriminant analysis highlighted the importance of the structural data in identifying mineralised sites and we predict that remote sensing data should be equally successful.

ACKNOWLEDGEMENTS

This study was funded by the National Board for Science and Technology and by the Commission of the EEC. In addition Dr. Michael Smith of McKinlay Smith International Limited and Barrick Petroleum Corporation provided very substantial support through generous help in purchasing hardware, and in many other ways. Studies at Silvermines were greatly assisted by Mr S. Taylor of Mogul of Ireland Limited and by Mr R. Crowe of Aquitaine Mining (Ireland) Limited. Dr. R. Holman gave invaluable assistance in providing access to stream sediment geochemical data and by assisting in the processing and interpretation of the data. We thank Mr B.S. Williams for guiding us in the use of aeromagnetic data and the gravity data which was made available to us by Professor T. Murphy of the Dublin Institute of Advanced Studies. We also thank the Director of the Geological Survey of Ireland for lending aerial photographs and for providing maps. Mr J. Haslett of the Department of Statistics at Trinity College devoted many hours to assisting us in statistical matters. Finally without the support of Mr D. Kelly, Mr N. Haughey and Mrs M.M. Critchley, the daunting amount of data preparation would never have been carried out.

REFERENCES

ARTHURTON, RS. 1983. The Skipton Rock Fault - an Hercynian wrench fault system associated with the Skipton Anticline, northwest England. *Geol. J.*, 18, 105-114.

BABCOCK, E.A. 1974. Photolineaments and regional joints: lineament density and terrain parameters, south-central Alberta. *Bull. Can. Petrol. Geol.*, 23 (4), 810-826.

BADHAM, J.P.N. 1982. Strike-slip orogens - an example from the Hercynides. *J. geol. Soc. London*, 139, 493-504.

CARTER, J.S. & MOORE, J.McM. 1978. Some major lineaments in the northern Pennine orefield. *Trans. Instn Ming Metall.* (Sect. B: Appl. Earth Sci.), 87, B90-93.

CLAYTON, L. 1966. Tectonic depressions along the Hope Fault, a transcurrent fault in North Canterbury, New Zealand. *N.Z. J. Geol. Geophys.*, 9, 95-104.

COLLER, D.W. 1984. Variscan structure in the Upper Palaeozoic rocks of Western Ireland. In: Hutton, D.W & Sanderson, D.J. (eds) *Variscan Tectonics of the North Atlantic Region.* 185-196. Blackwell, Oxford.

COWARD, M.P. & SMALLWOOD, S. 1984. An interpretation of the Variscan tectonics of SW Britain. In: Hutton, D.W. & Sanderson, D.J. (eds) *Variscan Tectonics of the North Atlantic Region.* 89-102. Blackwell, Oxford .

CROWELL, J.C. 1974. Origin of late Cenozoic basins in southern California. In: Dott, R.H. & Shaver, R.H. (eds) *Modern and Ancient geosynclinal sedimentation.* Soc. Econ. Paleontol. Mineral. Spec. Publ. 19, 292-303.

CRITCHLEY, M.F. 1981. Structure and formation mechanisms of vein-fracture systems in the north Pennine orefield. *Unpubl. Ph.D Thesis*, Univ. of London.

DIXON, W.J. (ed.) 1981. *BMDP Statistical Software.* Univ. California Press. 726pp.

DOLAN, J.M. 1984a. A structural cross-section through the Carboniferous of northwest Kerry. *Irish J. Earth Sci.*, 6, 95-108.

DOLAN, J.M. 1984b. Structural and remote sensing studies in the Shannon Basin, Western Ireland. *Unpubl. Ph.D. Thesis*, Univ. of Belfast.

GILL, W.D. 1962. The Variscan Fold Belt in Ireland. In: Coe, K (ed.) *Some aspects of the Variscan Fold Belt.*, 44-64, Manchester Univ. Press.

HARLAND, W.B. 1971. Tectonic transpression in Caledonian Spitsbergen. *Geol. Mag.*, 108, 27-42.

HENDERSON, R.G. 1960. A comprehensive system of automatic computation in magnetic and gravity interpretation. *Geophysics*, 15, 569-585.

LEGGAT, J.K., McKERROW, W.S. & EALES, M.H. 1979. The Southern Uplands of Scotland: A lower Palaeozoic accretionary prism. J. geol. Soc. London, 136, 755-770.

MAX, M.D. & LEFORT, J.P. 1984. Does the 'Hercynain Front' in Ireland follow a dextral shear?. In: Hutton, D.W. & Sanderson, D.J. (eds) Variscan Tectonics of the North Atlantic Region. 177-184. Blackwell, Oxford.

McKENZIE, D.P. & MORGAN, W.J. 1967. Evolution of triple junctions. Nature, 224, 125-133.

MOODY, J.D. & HILL, M.J. 1956. Wrench fault tectonics. Bull. geol. Soc. Am., 67, 1206-1246.

MOORE, J.McM. 1975. Fault tectonics at Tynagh Mine, Ireland. Trans. Instn Ming Metall. (Sect. B: Appl. Earth Sci.), 84, B141-145.

MOORE, J.McM. 1979. Tectonics of the Nadj Fault system, Saudi Arabia. J. geol. Soc. London, 136, 441-452.

MURPHY, C.J. 1982. The analysis of geological, geochemical and geophysical data from west-central Ireland with a view to applications of results. Unpubl. M.Sc. dissertation, Univ. of Dublin.

NELSON, R.A. 1979. Natural fracture systems: Description and classification. Bull. Am. Assoc. Petrl. Geol., 63 (12), 2214-2221.

PHILLIPS, W.E.A. 1977. Discussion of a plate tectonic model. J. geol. Soc. London, 133, 497-499.

PHILLIPS, W.E.A., STILLMAN, C.J. & MURPHY, T. 1976. A Caledonian plate tectonic model. J. geol. Soc. London, 132, 579-609.

POHN, H.A. 1981. Joint spacing as a method of locating faults. Geology, 9, 258-261.

PETORIUS, J.P.G. & PARTRIDGE, T.C. 1974. The analysis of angular atypicality of lineaments as an aid to mineral exploration. J. S. Afr. Instn Ming Metall., 74, 367-369.

RHODEN, H.N. 1958. Structure and economic mineralisation of the Silvermines District, Co. Tipperary, Eire. Trans. Instn Ming Metall., 68, 67-94.

SANDERSON, D.J. 1984. Structural variation across the northern margin of the Variscides in NW Europe. In: Hutton, D.W. & Sanderson, D.J. (eds) Variscan Tectonics of the North Atlantic Region., 149-165. Blackwell, Oxford.

SANDERSON, D.J. & MARCHINI, W.R.D. 1984. Transpression. J. Struct. Geol., 6, 449-458.

SIEGEL, B.S. & GILLESPIE, A.R. (eds) 1980. Remote Sensing in Geology. Wiley & sons, New York. 702pp.

SINCLAIR, A.J. 1974. Selection of threshold values in geochemical data using probability graphs. J. Geochem. Exp., 3, 129-149.

SINCLAIR, A.J. 1976. *Applications of probability graphs in mineral exploration*. Spec. Vol. 4, Assoc. Exp. Geochem., 95pp.

STEARNS, D.W. 1968. Certain aspects of fracture in naturally deformed rocks. in: Rieker, R.H. (ed.) *NSF Advanced Science Seminar in Rock Mechanics*. Spec. Rep. Air Force Cambridge Res. Labs, Bedford, Mass., AD6693751, 97-118.

TAYLOR, S. 1979. The Silvermines Deposit. In: Brown, A.G. (ed.) *Prospecting in areas of glaciated terrain*. Excursion Handbook, Irish Assoc. Econ. Geol., 47-65.

TAYLOR, S. & ANDREW, C.J. 1978. Silvermines orebodis, County Tipperary, Ireland. *Trans. Instn Ming Metall*. (Sect. B: Appl. Earth. Sci.), 87, B111-124.

TCHALENKO, J.S. & AMBRASEYS, N.W. 1970. Structural analysis of the Dasht-e-Bayaz (Iran) earthquake fractures. *Bull. geol. Soc. Am.*, 81, 41-60.

WEAVER, J. 1974. Jointing along the Swansea Valley Disturbance between Clydach and Hay-on-Wye, South Wales. *Geol. Mag.*, 111, 329-336.

WHEELER, R.L. & DIXON, J.M. 1980. Intensity of systematic joints: methods and applications. *Geology*, 8, 230-233.

WILCOX, R.E., HARDING, T.P. & SEELY, D.R. 1973. Basic wrench tectonics. *Bull. Am. Assoc. Petrol. Geol.*, 57, 74-96.

ISBN 92-825-5808-8

Price (excluding VAT) in Luxembourg
ECU 13.28 BFR 600 IRL 9.60 UKL 7.90 USD 12

OFFICE FOR OFFICIAL PUBLICATIONS
OF THE EUROPEAN COMMUNITIES

L - 2985 Luxembourg

9 789282 558089