Pergamon

Journal of Structural Geology, Vol. 18, Nos 2/3, pp. 349 to 358, 1996

0191-8141/96 $15.00+0.00

0191-8141(95)00083-6

Fractal geometries of vein systems and the variation of scaling relationships with mechanism

J. D. JOHNSTON* and K. J. W. McCAFFREY†

Department of Geology, Trinity College, Dublin 2, Ireland

(*Received* 9 *December* 1994; *accepted in revised form* 13 *July* 1995)

Abstract—Investigation of vein geometries has identified empirical relationships which allow extrapolation of outcrop-scale observation to larger scales. Measurements of vein shapes and aspect ratios in a number of different environments demonstrate that veins follow similar empirical scaling laws to those of faults. Geometries of veins are easier to characterise accurately than faults because their thickness is related to the variation in displacement from zero at their tips to a maximum at their thickest point.

Vein sizes obey the empirical relationship: $L = kT^a$ where L = length in mm, T = thickness in mm, $20 < k < 2000\ \mathrm{mm}^{1-a}$, for small veins $0.6 < a < 1.0$ (usually between 0.7 and 0.8) and for large veins $a > 1$. This suggests that veins amplify initially by inflation and subsequently by elongation.

INTRODUCTION

Some field techniques of structural geology are based on the premise that small-scale structures can be used to infer the occurrence of large-scale structures. Use of the general geometry of small-scale structures to predict precisely the large-scale geometries is, at best, an approximate procedure. Scale invariance in nature is familiar to geologists, but until recently, it was rarely quantified in a rigorous manner. Use of fractal statistics provides a ready way to deal with this problem. Faults have well established power law size distributions: cumulative frequencies of size, i.e. length, width or displacement (Watterson 1986, Walsh & Watterson 1988, Childs *et al.* 1990, Walsh *et al.* 1991, Jackson & Sanderson 1992), have been used to predict down-scale. Veins have analogous relationships (length, spacing and thickness, McCaffrey *et al.* 1993), and length and thickness vary in a power law relationship (Johnston 1992). In addition, veins which contain cements carry information about their fine-scale incremental growth history (Johnston 1993). This places constraints on the fracture mechanisms which are more difficult to infer for fault systems. When measured on a thin-section to outcrop scale, veins show the relationship $L \propto T^a$, where $a < 1$ (Johnston 1992). In most geological settings, $0.6 < a < 0.8$. Johnston (1992) has demonstrated that some mineralised vein systems have fractal characteristics. Here, the database of Johnston (1992) is expanded to include a wider range of geological environments, suggesting that many vein systems have a fractal distribution.

Measuring data over scale ranges of many orders of magnitude and with differing thresholds of resolution provides some constraints on possible growth mechanisms. However, these empirical observations need to be combined with textural information from the veins. Clearly, care needs to be used in extrapolation of these relationships, as individual strain processes may be confined to a particular length scale or range of length scales by layer thickness, grain size or some other geological constraint.

DATA COLLECTION AND PROCESSING

Five study areas with widely varying structural geometries (dextral, sinistral, thrust and pure extension) in a variety of host rock types were chosen for quality and area of exposure. Vein fills of both carbonate and quartz were investigated. Locations of study sites are indicated in Fig. 1.

The Lecanvey gold deposit at Croagh Patrick (250,000 t at gt^{-1}, Aherne *et al.* 1989, 1992) is hosted in quartz veins which occur in massively-bedded Silurian orthoquartzites metamorphosed to greenschist facies with a weak solution cleavage. Minor quartz and jasper pebble beds, and detrital chromite-rich beds occur. Regional geology has been described by Graham *et al.* (1986) and Johnston & Phillips (1995). Veins occur in three main sets: (1) NE-trending, moderately southerly-dipping sinistral sets, (2) WNW-trending, steeply east-dipping dextral sets, and (3) shallowly-dipping, southward-directed thrusts (Johnston 1992) which are probably Devonian in age. The three sets were all formed during one event and all show mutually cross-cutting relationships. The veins are typically en échelon, commonly sigmoidal, overlapping and their spacing is small compared with their lengths. Spacing between individual veins within arrays ranges up to fifteen times vein thickness.

Polydeformed Precambrian marbles exposed at Skelpoonagh Bay, Glencolumbkille, Co. Donegal are cross-cut by a set of quartz–pyrite–galena E-trending

*Deceased.

†Current address: School of Geological Sciences, Kingston University, Penrhyn Road, Kingston-upon-Thames, Surrey KT1 2EE, U.K.

extensional veins. The veins are lensoid and form a parallel array, with spacing ranging from five times to fifty times vein thickness. Overlap ranges from 50% to none. The regional geology was described by Howarth *et al.* (1966) and Pitcher & Berger (1972).

Quartz veins are particularly well developed in the vicinity of the Bridges of Ross, in a sequence of Namurian deltaic sandstones in West Clare. The geology is summarised by Gill (1979), Martinsen & Bakken (1990) and Fitzgerald *et al.* (1994). Continuous exposures of individual bedding planes for areas in excess of 500 m^2 afford excellent exposures of hundreds of N-trending dextral and E-trending sinistral vein arrays. Individual shear zones expose hundreds of quartz veins. The veins are typically en échelon, slightly sigmoidal, overlapping, and their spacing is small compared with their lengths. Spacing ranges from twice to 300 times vein thickness. Veins cross-cut folds but are deformed by a solution cleavage which parallels axial planes of regional open folds which trend east. Exposures allow the measurement not only of veins in the plane perpendicular to the shear zones, but also of the entire vein arrays themselves. Sections in the plane of the zones are rare and only a limited size range could be measured.

Mace Head (Max & Talbot 1986, Derham & Feely 1988, McCaffrey *et al.* 1993) exposes a NNW-trending swarm of steeply-dipping quartz veins that cross-cut the undeformed end-Silurian Carna Granite. The veins are

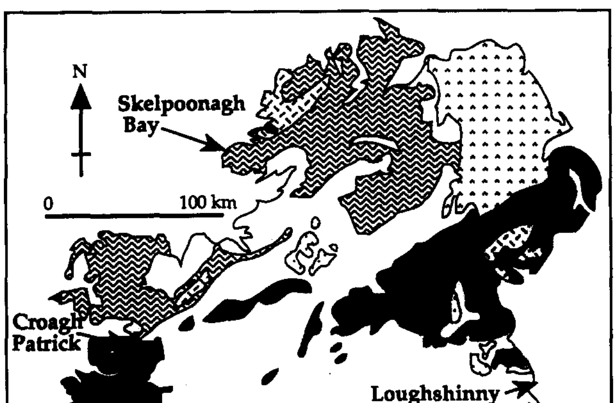


Fig. 1. Location map showing the sources of data: Quartz–pyrite–galena veins in polydeformed Dalradian marble in Skelpoonagh Bay, Glencolumbkille, Co. Donegal. Quartz–gold veins in Silurian quartzite, Croagh Patrick Range, Co. Mayo. Quartz–pyrite veins, Namurian sandstones, Bridges of Ross, Co. Clare. Quartz–molybdenite veins, Silurian granite, Mace Head, Co. Galway. Calcite veins, Dinantian calcarenites and calcisiltites, Loughshinny.

approximately tabular in geometry and are apparently the result of pure extension. The veins studied are well exposed on subhorizontal joint surfaces along the coast. Although the exposures provided abundant thickness and spacing data, most veins were longer than the exposures. Overlap of the veins is substantial, spacing ranges from 5 to 100 times vein thickness.

Interbedded Carboniferous calcarenites and calcisiltites of Brigantian age are exposed at Loughshinny. The geology has been described in detail by Nolan (1986) and the structural geometries by Johnston (1993). Calcite vein arrays are well exposed on bedding planes and perpendicular to bedding. Veins are generally en échelon and occur in both dextral and sinistral sets. The predominant set is dextral, NNW-trending, perpendicular and related to fold hinges (Johnston 1993).

Most of the veins investigated are made up of parallel arrays. In some of the arrays, the veins were distributed en échelon defining shear zones, while in others, purely extensional zones of parallel veins formed at 90° to the zone walls. Vein axial ratios and spacings were measured in sections parallel to the extension direction, both in the plane of the arrays and in sections perpendicular to the arrays. In sections containing the maximum and minimum extensions, the classic en échelon orientation, measurement of hundreds of veins, ranging in length up to about a metre was possible. However, continuous exposures of longer veins are extremely rare. Many veins can be traced for tens of metres, however, both terminations are rarely exposed. This problem is exacerbated in sections parallel to the zones where axial ratios are high. In many cases, trench and drill hole information were used. In measuring spacing of veins, it is difficult to find individual shear zones with hundreds of veins which are all exposed, so that their sequential spacing may be measured along entire sections of shear zones. Discrete en échelon arrays defining shear zones exposed in their entirety rarely contain more than 100 veins. This may reflect some underlying process.

Length–thickness data from vein sets are mutually dependent, so simple regression is an inappropriate way to fit a line to the data. Instead, the reduced major axis was calculated using the method of Imbrie (1956). While conventional regression assumes that there is a dependent and an independent variable, this situation is unusual in empirical geometrical data, Geologically, if one variable has an intrinsically larger error than another then it may be treated as the dependent variable. However, measurements of length and thickness have comparable errors and length is no more a function of thickness than the converse relationship. A reduced major axis is regressed perpendicular to the resultant line, rather than parallel to the dependent axis. Although there are only two variables, principal components were calculated, allowing an estimation of the percentage variance associated with the reduced major axis. The first principal component, which is the direction of maximum variance, is the same as the reduced major axis in all instances. Empirically, reliable results require at least three orders of magnitude of size range.

RESULTS

En échelon vein arrays were measured in Croagh Patrick (Bridges of Ross) and Loughshinny (Fig. 1). The results are illustrated in Fig. 2. Log of vein length (L) and log of vein thickness (T) show a systematic relationship. In all of the relationships presented here, both length and thickness are in mm, and hence the constant of proportionality is in units of mm^{1-a}, where a is the thickness exponent. A reduced major axis best fit to the Croagh Patrick data (Fig. 2a) yields a relationship $L = 25T^{0.83}$ ($n = 431$). The first principal component axis accounts for 93% of the variance. In perpendicular sections, L and T show a similar power relationship to the en échelon-oriented section, although the veins have a much higher axial ratio, $L = 172T^{0.68}$ ($n = 139$) (Fig. 2b). The first principal component accounts for 90% of the variance. Veins exposed on bedding planes at Loughshinny in sections perpendicular to the plane of the shear zone and the transport direction were measured, confirming the generality of the relationships observed. Samples from Loughshinny were thin-sectioned and examined under cathode luminescence. This enables resolution of veins down to 2 μm thickness (Fig. 2c). Vein shapes at Loughshinny and Bridges of Ross appear to have been influenced by bed thickness. In sections perpendicular to bedding the scatter is much greater than from sections in the bedding plane (Fig. 2d). In many cases, veins thin to below hand-lens resolution or disappear across arenite/siltite contacts. At Loughshinny, $L = 33T^{0.93}$ perpendicular to bedding and the shear zone ($n = 180$) (Fig. 2d) and $L = 57T^{1.01}$ ($n = 158$) in en échelon exposures on bedding planes (Fig. 2c). The first principal component accounts for 78% of the variance of the data collected perpendicular to bedding. At Bridges of Ross on bedding planes (Fig. 2e) $L = 149T^{0.83}$ ($n = 300$) and the slope of the first principal component accounts for 91% of the variance. Perpendicular to bedding, $L = 76T^{1.05}$ ($n = 96$) (Fig. 2f), and the first principal component in this case accounts for 75% of the variance.

Similar relationships were derived from pure extension vein arrays at Skelpoonagh Bay (Fig. 2g) and Mace Head (Fig. 2h), although the axial ratios of the veins in granite are higher. Veins could only be measured in the horizontal plane, perpendicular to the veins and parallel to the extension direction. At Skelpoonagh, $L = 57T^{0.87}$ ($n = 96$, Fig. 2g) and the first principal component contains 83% of the variance. At Mace Head (McCaffrey *et al.* 1993), $L = 1231T^{0.67}$ ($n = 16$), and here the first principal component contains 91% of the variance. The exponents in these pure extensional arrays are similar to those of the en échelon examples.

Textural relationships

In field exposures, small arrays of small veins sometimes show simple geometries, with smooth, lensoid outlines (Fig. 3a). The larger veins and shears almost always show highly complicated geometries (Fig. 3b) with en échelon pinnate "half-vein" fracture creating serrated margins. Generally, the axial regions of such veins are highly deformed, while crack seal fibres may be preserved in the tips of the pinnate veins. In thin section under cathode luminescence, similarly complex geometries can be observed in crack-seal veins (Figs. 4a & b).

GROWTH OF VEINS

From the data presented above, a number of general empirical relationships for vein systems may be inferred. Measurements of vein shapes and aspect ratios in a number of different environments demonstrate that veins follow empirical laws similar to those of faults as originally recognised by Watterson (1986). Veins appear to have consistent axial ratios in parallel sections and therefore approximate to ellipsoids in shape. In general, for small veins $L = kT^a$, where L = length, T = thickness, $20 < k < 2000$ where L and T are in mm, and $0.6 < a < 1$. Similar relationships for widths and displacements of faults and shear zones have been noted by Watterson (1986), Hull (1988, 1989), Blenkinsop (1989) and Walsh & Watterson (1988). As the exponent, a, is less than 1, veins grow thicker faster than they lengthen. This means that large veins have higher axial ratios than small veins. Geometries which change exponentially as a function of the scale at which they are viewed are termed self-affine (Mandelbrot 1982, 1985). Therefore veins have self-affine geometry. (If the exponent was equal to 1, then vein axial ratios would stay constant, independent of scale, and veins would be self-similar.) If the relationship, where the exponent is less than 1 ($a < 1$, Fig. 5), is extrapolated, it would suggest that large veins should be almost circular in profile (along the x-axis to the right of Fig. 5). Yet, typically, the very largest veins and vein systems (larger than outcrop scale) have larger axial ratios than small veins.

This paradox can be explained when the nature of the larger-scale veins is investigated. This is possible at Croagh Patrick where the data set ranges over more than four orders of magnitude (Fig. 6). Although the data can be loosely fitted to a single power law distribution, at thicknesses of approximately 200 mm there is a discernible bend in the distribution. If the data set is divided at this kink, for veins less than 200 mm thick, the first principal component axis slopes 0.7 and accounts for 89% of the variance. In contrast, for veins greater than 200 mm thick, the slope of the first principal component is 1.36. This axis accounts for almost all of the variance (98%). In other words, the largest veins describe almost a straight line distribution.

The spacing of fractures is best described by log-normal distributions (e.g. Johnston 1992, Johnston *et al.* 1994). It is suggested, therefore, that fractures initiate in a pattern along arrays. Local stress and strain variations may affect the amount of clustering or anticlustering around large veins. However, a log-normal distribution is most likely to reflect an optimum spacing with noise

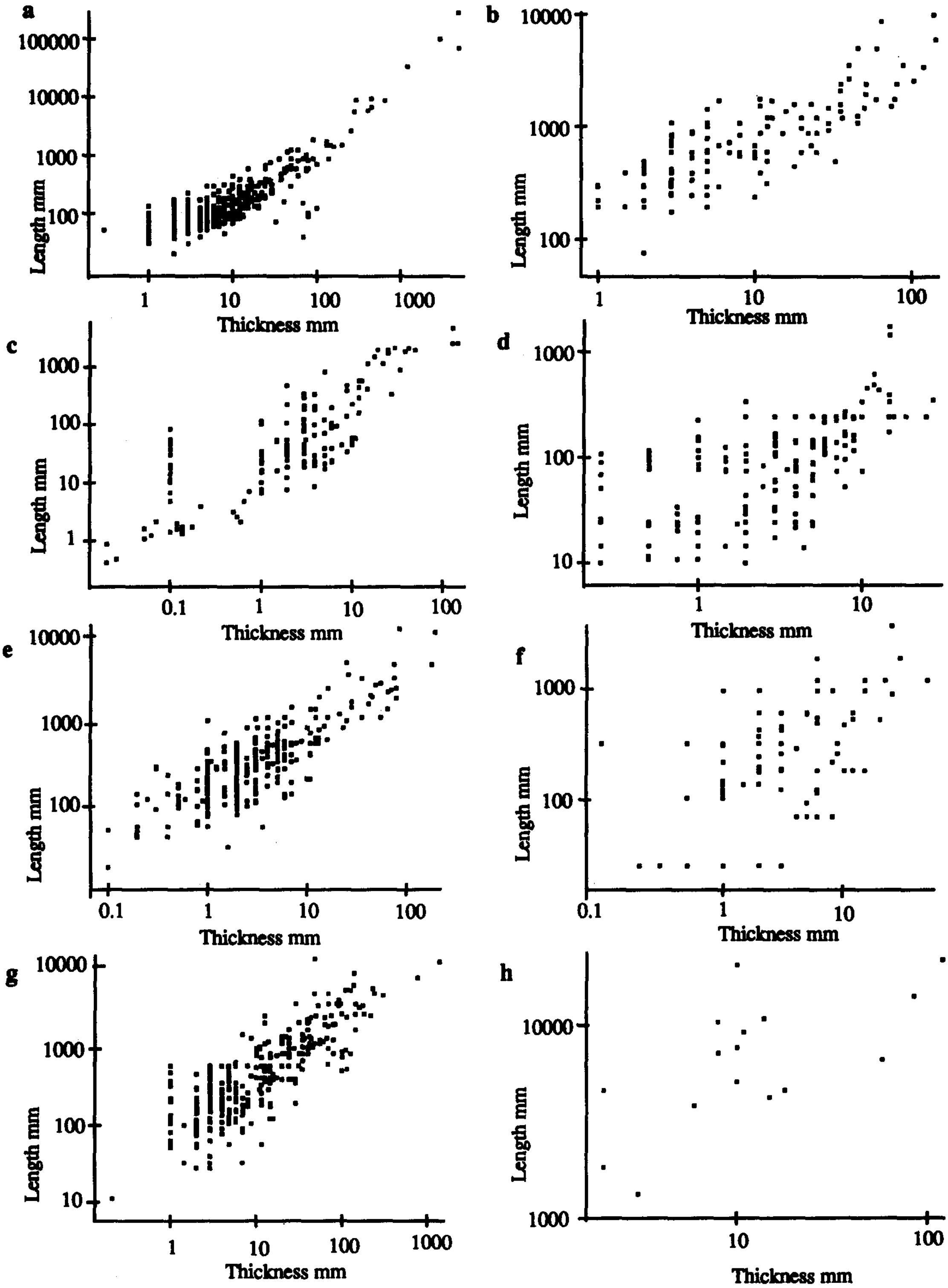


Fig. 2. Plot of apparent log length vs log thickness of veins from en échelon arrays in mm. (a) Croagh Patrick quartz veins in quartzite, $n = 431$. Veins, measured parallel to the transport direction and perpendicular to the zone, i.e. the *ac* kinematic plane. A reduced major axis best fit line indicates that $L = 25T^{0.83}$, $r^2 = 73\%$. (b) Section parallel to the vein array, Croagh Patrick, $n = 139$. A reduced major axis best fit line indicates that $L = 172T^{0.68}$, $r^2 = 64\%$. (c) Loughshinny, $n = 158$. Reduced major axis best fit line indicates that $L = 57T^{1.01}$, $r^2 = 64\%$. (d) Loughshinny, section perpendicular to shear zone and transport direction, the *bc* kinematic plane, ($n = 180$, $L = 33T^{0.93}$, $r^2 = 32\%$). (3) Bridges of Ross quartz veins in sandstone, $n = 300$. Veins measured parallel to the transport direction and perpendicular to the zone, i.e. the *ac* kinematic plane. A reduced major axis best fit line indicates that $L = 149T^{0.77}$, $r^2 = 68\%$. (f) Bridges of Ross, section parallel to zone, $n = 96$. A reduced major axis best fit line indicates that $L = 76T^{1.05}$, $r^2 = 26\%$. (g) Skelpoonagh Bay. Extensional array measured perpendicular to array and parallel to extension direction. $n = 305$ $L = 57T^{0.93}$. (h) Quartz veins in granite, Mace Head, $n = 16$. $L = 1231T^{0.67}$, $r^2 = 44\%$.

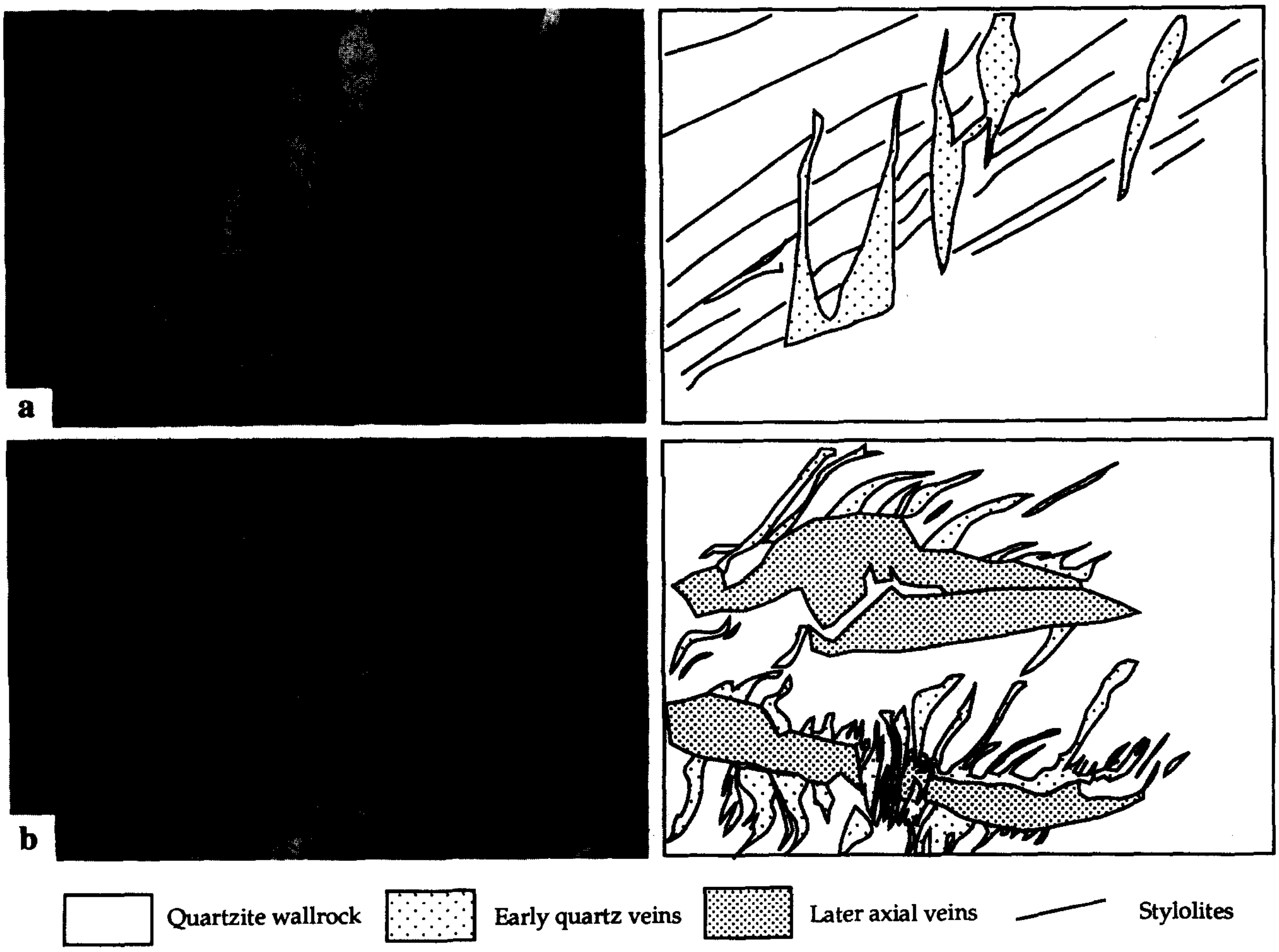


Fig. 3. (a) Field photograph. En échelon veins, Croagh Patrick. Simple vein array with lensoid veins. (b) Field photograph, large complex vein array, Croagh Patrick. Axial vein with en échelon pinnate 'half-veins' serrating its margins. Width of field of view is 3 m.

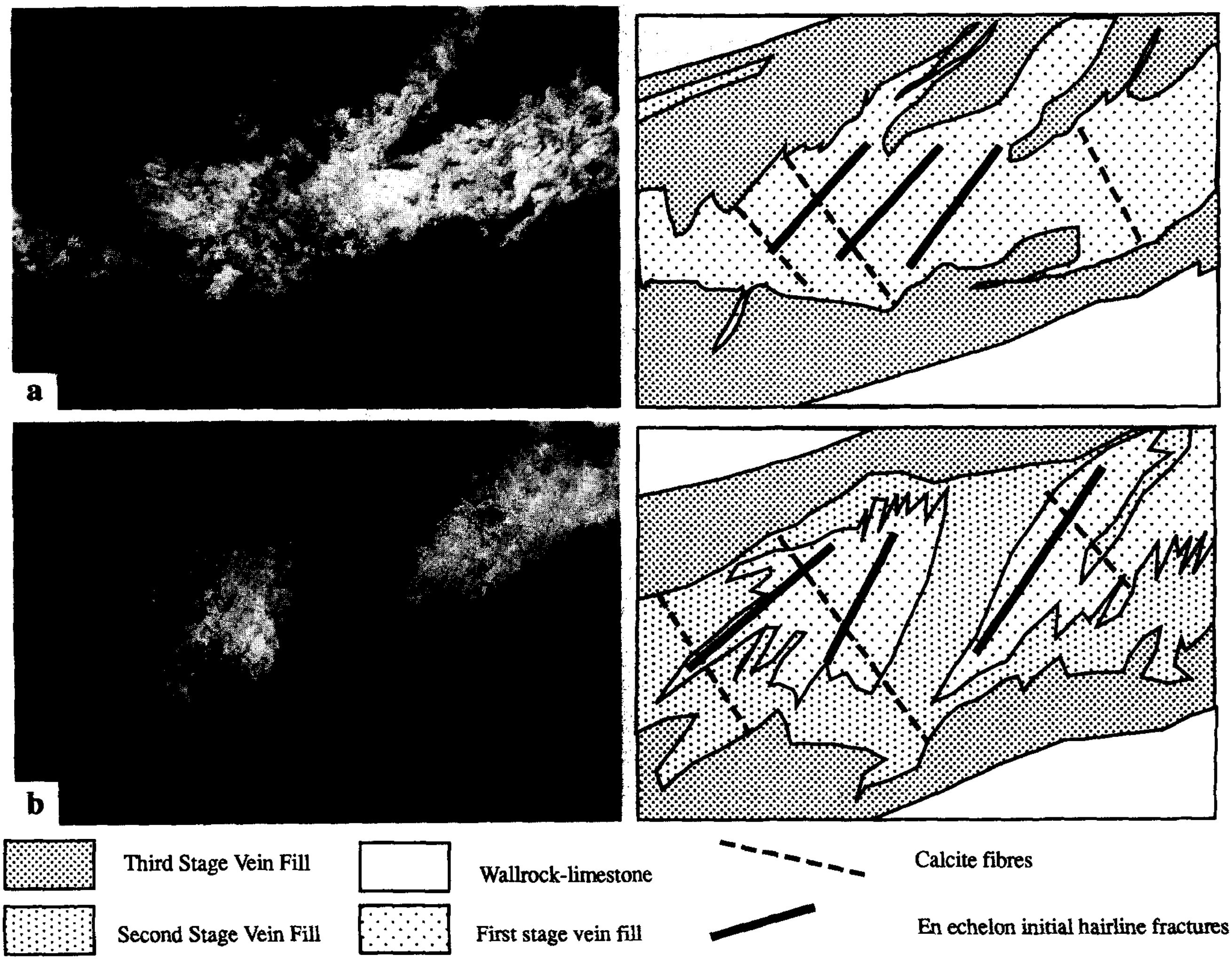


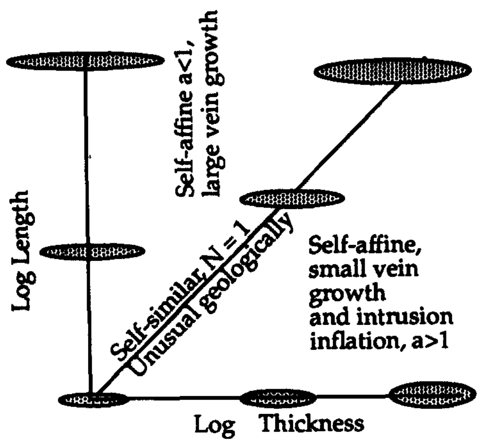
Fig. 4. (a) Cathodoluminescence photomicrograph of a calcite vein in the Loughshinny limestone. Field of view is 2 mm. The early en échelon increments (brightly to slightly later mid-luminescent) have inflated and linked and been enveloped by a later phase of vein growth (duller luminescence). Line diagram shows interpretation. (b) Cathodoluminescence photomicrograph of a calcite vein in the Loughshinny limestone. Field of view is 2 mm. Fibrous structures preserved within a vein with a complex incremental history. Line diagram shows interpretation.

which is multiplicative, rather than additive (which would produce a normal distribution).

Initial fractures develop with $a < 1$. At a critical threshold density, individual fractures link to form through-going fractures at and above this scale. This linkage occurs at a scale dependent on the effective mechanical thickness of the veined unit.

While the material deforms as a continuous medium, the veins behave as isolated flaws in that material, $a < 1$. When the fractures link and the material deforms as a series of blocks, then $a > 1$. The geometry of the blocks will typically reduce to three subparallel sets of faces. This changeover of mechanism is accompanied by a change in the power law of cumulative size frequency. While the spacing of the faces is commonly log-normal, the blocks themselves appear to have power law cumulative maximum size frequencies.

Petrographic studies of individual veins in en échelon arrays confirm that early increments of opening are in the shear-tensile field, often initiating with an original sigmoidal shape. As the veins grow they thicken by addition of crack–seal increments, which thicken the vein faster than it lengthens (Fig. 7a). In an en échelon array, the thickened veins eventually start to interact. At this point, an axial structure links the veins. This growth history results in a common macroscopic geometry in which large veins have fringe zones of oblique en échelon 'fins'. In pure tensile environments, random linkage



$$L = kT^{a}$$

Fig. 5. Sketch to show the difference between self-affine and self-similar veins on a log–log plot of length vs thickness.

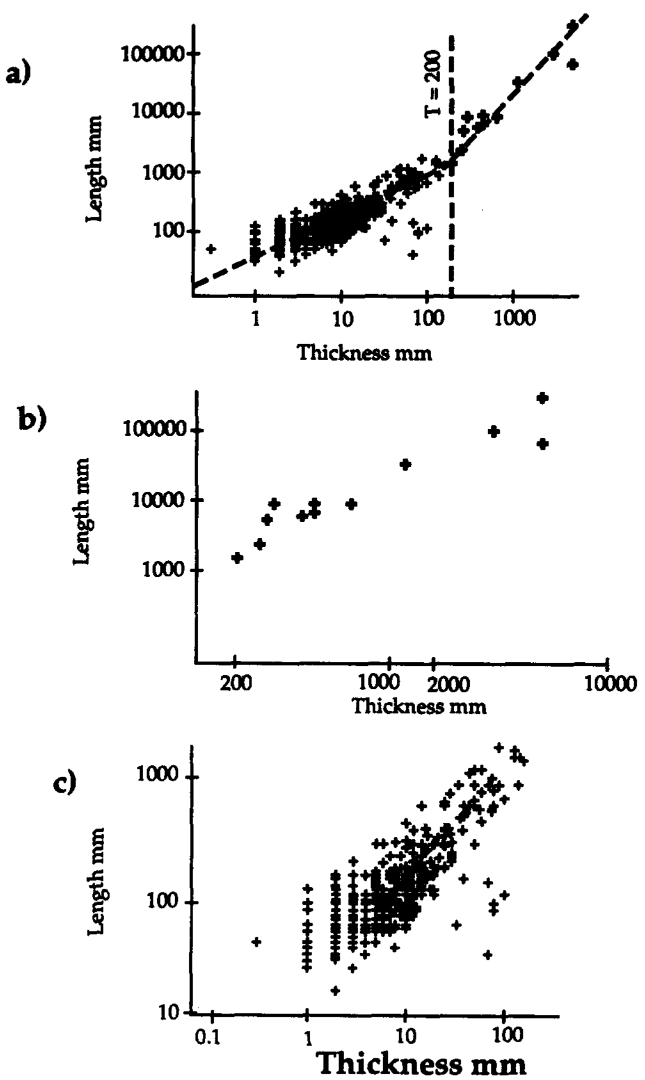


Fig. 6. Croagh Patrick data. (a) The data can be divided into two subsets. (b) Set with thickness T greater than 200 mm. (c) Set with T less than 200 mm.

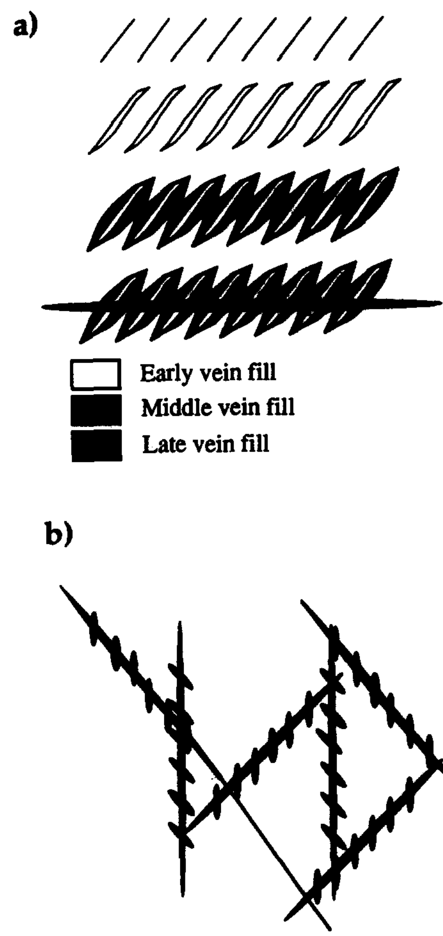


Fig. 7. (a) Growth model for the veins and vein arrays. Initially, en échelon fractures initiate in arrays. These then inflate incrementally, with relatively small amounts of lengthening. Eventually they interact and an axial vein links the veins together. (b) When the axial veins link individual veins together, the rock ceases to behave as a continuous medium with a series of flaws in it and changes to a series of blocks separated by shear zones.

of fractures produces a similar change in growth mechanism with scale (Sanderson *et al.* 1994). At that point, the rock starts to behave as a series of blocks (Fig. 7b) with high effective permeabilities for mineralising fluids rather than a medium with individual flaws. The large amount of scatter on length–thickness plots (Fig. 2) may reflect linkage of small en échelon fractures by axial veins. Some small-scale linked veins have been observed in outcrop, and these could contribute to the scatter in much the same way as fault displacement–length geometries are scattered by segment linkage (Cartwright *et al.* 1994).

A practical implication of this non-linear scaling is that typically maps should plot large veins as relatively more elongate than individual small veins appear in exposures. The evolution of vein aspect ratios with increasing size can be seen in Fig. 8. Initially high axial ratios progressively decrease as the veins inflate. Subsequently the vein aspect ratios increase rapidly.

If the specific geometries of the vein systems at Croagh Patrick are considered in three dimensions (Fig. 9), the first motions of seismic events (Sibson 1989) in each of the shears can be considered. The schematic in Fig. 9 illustrates a block, looking northwards. The upper surface is the footwall of a thrust. The near face is a sinistral shear and the side faces are dextral shears. The base is the hangingwall of a thrust. The areas of maximum dilation are coloured white. This suggests that when the interconnectivity of veins was increased by growth of axial veins, the zones of greatest dilatancy were at the intersections of the dextral and sinistral shear zones. This would be accentuated by differential strains and block mismatches at shear zone intersections. This hypothesis is confirmed by the observation that in this region there are great concentrations of coarse gold, suggesting that the pressure drop has been important in destabilising the gold. This is consistent with fluid inclusion data described elsewhere (Wilkinson & Johnston unpubl. abstract).

In considering the growth of veins, simple en échelon veins appear to grow incrementally in approximately equal increments of thickness (e.g. Cox & Etheridge 1983, Cox 1987). For simplicity, a vein can be modelled volumetrically as an ellipsoid. Strictly, the terminations are wedge-shaped and the sides are lens-shaped, but assumptions involving ellipsoidal shapes are a valid first approximation of the volume. Therefore, as the height and length are both proportional to the thickness (T) to an exponent of 0.7–0.8, the volume is proportional to the thickness to the power of 2.4–2.6 (Fig. 10). For N increments of opening t, the volume is proportional to $Nt^{2.5}$ and each incremental volume growth is proportional to $t^{2.75}$. In other words, at small T, pressure drops increase for each event. However, when the axial

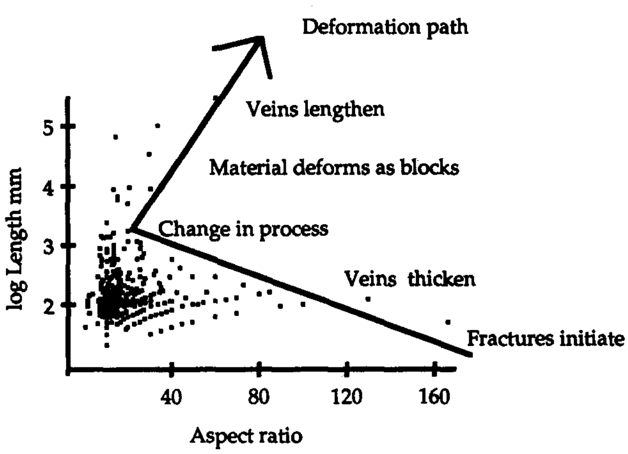


Fig. 8. A plot of length vs aspect ratio for veins from Croagh Patrick. The arrow represents the inferred strain path.

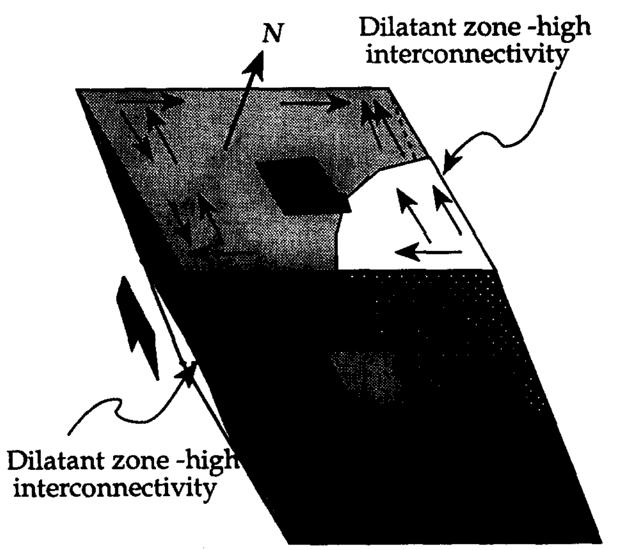
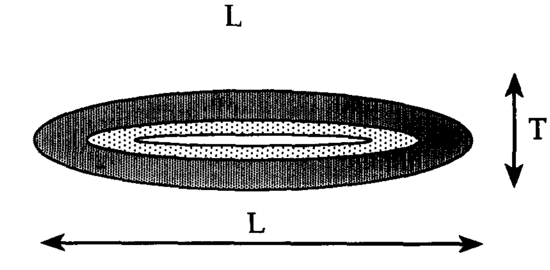


Fig. 9. Idealised three-dimensional sketch of the shear vein array systems at Croagh Patrick, looking north. Arrows indicate the first motion of seismic events on these systems. The white region is the region of maximum dilatancy.



$$L \;\alpha\; T^{0.76} \qquad H \;\alpha\; T^{0.76}$$

$$H \;\alpha L$$

$$V \approx \pi HLT/6 \qquad \Rightarrow V \;\alpha\; L^{2.76}$$

Fig. 10. Simplified geometry of incremental vein growth. For ease of calculation, the veins are approximated as ellipsoids, although they are really lens-shaped. The volume is approximately proportional to the thickness to the power of 2.5.

veins link the en échelon veins the volume increase, and hence the stress drop, is very much greater. Texturally, in axial veins, grain size and fibres, if present, are much coarser than in the en échelon veins, suggesting much larger increments of growth. Furthermore, these veins appear to grow longer faster than they thicken (Fig. 8). Therefore the stress drop is likely to evolve to larger and larger values.

Taking the Croagh Patrick example, the existence of three orientations of dilatant shear zones allied with fibrous quartz and occasionally vuggy quartz is strongly suggestive that the system was overpressured. This suggests that the differential stress must be less than four times the tensile strength of the rock (Etheridge 1983). Ultimately, this must place a constraint on how large the veins can grow.

CONCLUSIONS

Veins are approximately lenticular in shape. They may be described in terms of maximum, intermediate and minimum major axes L_1, L_2, L_3:

$$L_n = kL_m^a$$

where $n, m = 1, 2$ or 3; a and k = constants.

In general:

$$L = kT^a$$

where L = length, T = thickness, $0.6 < a < 1$. Where L and T are in mm, $20 < k < 2000$.

k is a function of wallrock strength and the strain field. Simple shear in soft rocks leads to low axial ratio veins (small k), while pure extension in hard rocks results in high axial ratio (large k).

These empirical relationships place constraints on possible mechanisms for vein growth. It appears that initially, veins are seeded with a log-normal distribution of spacing and normal distribution of lengths and thicknesses. Lengths of the thinnest veins scatter over an order of magnitude. Subsequently, the distribution amplifies in a non-linear manner. As $L = kT^a$ where a is generally less than 1, the largest veins have smaller axial ratios than largest veins. This means that vein geometries are self-affine (Mandelbrot 1982). Thus vein systems on a map should appear less elongate than on the outcrop.

Acknowledgements—The ideas presented here have benefited greatly from discussions with Dave Doff, Ide van der Molen, Juan Watterson, John Walsh, Paul Gillespie, Dave Sanderson, Steve Aherne and Neal Reynolds. The initial part of this study was funded by Burmin Exploration and Development PLC. The study has been funded by EC Raw Material Contract No. MA2M-CT90-0040 and EOLAS Contract SC90/143.

Note added in proof—Regrettably, Dave Johnston lost his life whilst on fieldwork in N.W. Mayo in October 1995. He will be sorely missed by his many friends and colleagues.

Ken McCaffrey.

REFERENCES

Aherne, S., Reynolds, N. A., Burke, D. J. Harrington, K., O'Keeffe, N. & Verbruggen, K. M. 1989. Gold mineralization in Silurian rocks south of Clew Bay, County Mayo, Ireland. *Trans. I. M. M.* **98B**, B60–B62.

Aherne, S., Reynolds, N. A. & Burke, D. 1992. Gold mineralization in the Silurian and Ordovician of South Mayo. In: *The Irish Minerals Industry* 1980–1990—*A Review of the Decade, Galway* 1990 (edited by Earls, G. V., Bowden, A., Pyne, J. & O'Connor, P.). Irish Association for Economic Geology, 39–50.

Blenkinsop, T. G. 1989. Thickness–displacement relationships for deformation zones: Discussion. *J. Struct. Geol*, **11**, 1053–1054.

Cartwright, J., Trudgill, B. & Mansfield, C. 1994. The growth of faults by segment linkage. *Tectonic Studies Group Abstr. & Prog. for Spec. Meet. Fault Populations*, 48–50.

Childs, C., Walsh, J. J. & Watterson, J. 1990. A method for estimation of the density of fault displacements below the limits of seismic resolution in reservoir formations. In: *North Sea Oil and Gas Reservoirs—II* (edited by Buller, A. T., Berg, E., Hjelmeland, O., Kleppe, J., Torsæter, O. & Aasen, J. O.). Graham and Trotman, London, 309–318.

Cox, S. F. & Etheridge, M. A. 1983. Crack–seal fibre growth mechanisms and their significance in the development of oriented layer silicate microstructures. *Tectonophysics* **92**, 147–170.

Cox, S. F. 1987. Antitaxial crack-seal vein microstructures and their relationship to displacement paths. *J. Struct. Geol.* **9**, 779–788.

Derham, J. M. & Feely, M. 1988. A K-feldspar breccia from the Mo–Cu stockwork deposit in the Galway Granite, west of Ireland. *J. geol. Soc. Lond.* **145**, 661–667.

Etheridge, M. A. 1983. Differential stress magnitudes during regional deformation and metamorphism: upper bound imposed by tensile fracturing. *Geology*, **11**, 231–234.

Fitzgerald, E., Feely, M., Johnston, J. D., Clayton, G., Fitzgerald, L. J. & Sevastopulo, G. D. 1994. The Variscan thermal history of West Clare, Ireland. *Geol. Mag.* **131**, 545–558.

Gill, W. D. 1979. Syndepositional sliding and slumping in the West Clare Namurian Basin, Ireland. *Spec. Pap., Geol. Surv. Irl.* **4**.

Graham, J. R., Leake, B. E. & Ryan, P. D. 1986. *The Geology of South Mayo: Map and Accompanying Notes*. Scottish Academic Press, Edinburgh.

Howarth, R. J., Kilburn, C. & Leake, B. E. 1966. The boulder Bed succession at Glencolumbkille, Co. Donegal. *Proc. R. Ir. Acad.* **65B**, 117–156.

Hull, J. 1988. Thickness–displacement relationships for deformation zones. *J. Struct. Geol.* **10**, 431–435.

Hull, J. 1989. Thickness–displacement relationships for deformation zones: Reply. *J. Struct. Geol.* **11**, 1053–1054.

Imbrie, J. 1956. Biometrical methods in the study of invertebrate fossils. *Bull. Am. Mus. Nat. Hist.* **108**, 211–252.

Jackson, P. & Sanderson, D. J. 1992. Scaling of fault displacements from the Badajoz–Córdoba shear zone, SW Spain. *Tectonophysics* **210**, 179–190.

Johnston, J. D. 1992. The fractal geometry of veins: potential for ore reserve calculation. In: *The Irish Minerals Industry* 1980–1990— *A Review of the Decade, Galway* 1990 (edited by Earls, G. V., Bowden, A., O'Connor, P. & Pyne, J.). Irish Association for Economic Geology, Dublin, 105–118.

Johnston, J. D. 1993. Three dimensional geometries of veins and folds: examples from the Carboniferous of Eastern Ireland. *Ir. J. Earth Sci.* **12**, 47–64.

Johnston, J. D. & Phillips, W. E. A. 1995. Terrane amalgamation in the Clew Bay Region, west of Ireland. *Geol. Mag.* **132**, 485–501.

McCaffrey, K., Johnston, J. D. & Feely, M. 1993. Use of fractal statistics in the analysis of Cu–Mo mineralisation at Mace Head, Co. Galway, *Ir. J. Earth Sci.* **12**, 139–148.

Mandelbrot, B. B. 1982. *The Fractal Geometry of Nature*. Freeman, San Francisco.

Mandelbrot, B. B. 1985. Self-affine fractals and fractal dimension. *Physica Scripta* **32**, 257–260.

Martinsen, O. & Bakken, B. 1990. Extensional and compressional zones in slumps and slides in the Namurian of County Clare, Ireland. *J. geol. Soc. Lond.* **147**, 153–164.

Max, M. D. & Talbot, V. 1986. Molybdenum concentrations in the western end of the Galway Granite and their structural setting. In: *Geology and Genesis of Mineral Deposits in Ireland* (edited by Andrews, C. J., Crowe, R. W. A., Finlay, S., Pennell, W. M. & Pyne, J. F.). Irish Association for Economic Geology, 177–185.

Nolan, S. C. 1989. The style and timing of Dinantian syn-sedimentary tectonics in the eastern part of the Dublin Basin, Ireland. In: *The Role of Tectonics in Devonian and Carboniferous Sedimentation in the British Isles* (edited by Arthurton, R. S., Gutteridge, P. & Nolan, S. C.). *Occ. Publ. Yorks. Geol. Soc.* **6**, 83–86.

Pitcher, W. S. & Berger, A. R. 1972. *The Geology of Donegal—A Study of Granite Emplacement and Unroofing*. Wiley Interscience, New York.

Sanderson, D. J., Roberts, S. & Gumiel, P. 1994. A fractal relationship between vein thickness and gold grade in drill core from LaCodosera, Spain. *Econ. Geol.* **89**, 168–173.

Sibson, R. H. 1989. Earthquake faulting as a structural process. *J. Struct. Geol.* **11**, 1–14.

Walsh, J. J. & Watterson, J. 1988. Analysis of the relationship between displacements and dimensions of faults. *J. Struct. Geol.* **10**, 239–247.

Walsh, J. J., Watterson, J. & Yielding, G. 1991. The importance of small-scale faulting and their effects on fault-related regional extension. *Nature* **351**, 391–393.

Watterson, J. 1986. Fault dimensions, displacements and growth. *Pageophys.* **124**, 365–373.