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En échelon vein array development in extension and shear

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Abstract—A subdivision of en échelon vein arrays is proposed, based on the geometry of sets of transcurrent arrays from the Lower Carboniferous rocks in the SE midlands of Ireland. The parameter δ (vein-zone angle) is proportional to the array orientation (ϕ) for arrays developed through secondary failure in shear zones (shear arrays). For arrays developed during propagation of an extension vein (extension arrays) δ is proportional to the overlap of veins in the array P(o). Criteria for field distinction, together with the different methods of kinematic interpretation that are required for the two types of arrays, are described. For shear arrays, the average trends of the two members of the conjugate set are calculated and the axis of principal shortening strain (Z) bisects these. The average trend of extension arrays is parallel to that of extension veins and is therefore normal to the maximum extensional strain axis (X).

INTRODUCTION

THE determination of stress or strain trajectories using mesofracture analysis has recently been comprehensively treated by Hancock (1985). Among the kinematic indicators quoted were conjugate arrays of en échelon cracks and Hancock's summary (Hancock 1985, p. 443) highlights the controversy surrounding these shear zones centring on whether the veins contained in the zone are Riedel shears, hybrid fractures or extension fractures. Conveniently, this controversy has had little bearing on the determination of strain axial directions from these structures, as most authors are agreed that conjugate zones enclose an acute bisector parallel to Z (where Z is the maximum incremental shortening strain direction), many equating this direction with that of σ_1 (where σ_1 is the maximum effective compressive stress direction) in coaxial deformation. However, many en échelon arrays do not occur in conjugate sets, and some workers (Pollard *et al.* 1982, Nicholson & Pollard 1985) have proposed that en échelon arrays may form during propagation of an extension fracture. These workers view the above method of inferring stress orientations with scepticism (Nicholson & Pollard 1985, p. 589). This paper presents data from sets of natural arrays which may resolve both points at issue: the nature of veins within an array and the correct method for determination of regional strain trajectories from such arrays.

Of the many geometrical parameters that may be measured on arrays (Fig. 1) most attention has focused on the vein-zone angle, δ. The often quoted genetic classification of Beach (1975) relies on this angle: type 1 arrays have veins parallel to the conjugate zone (δ = dihedral angle), while type 2 arrays have veins in both arrays parallel to one another (δ = half the dihedral angle). Veins of type 1 arrays were interpreted as shear fractures and veins in type 2 arrays were interpreted as being extension fractures by Beach (1975). Ramsay & Huber (1983, pp. 48–49) use the variation in the angle δ to infer that the shear zone represented by the en échelon array has either a positive (δ less than 45°) or negative (δ more than 45°) dilation.

Two localities are described from the southeastern Irish midlands (Fig. 2) where large areas of rock are exposed, with many en échelon arrays. One method of determining the regional maximum (Z) and minimum (X) strain directions was to assume that all vertical en échelon arrays represented transcurrent sinistral and dextral shear zones, to map these, to calculate the

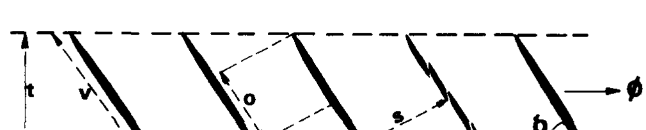

Fig. 1. Mesoscopic vein array parameters. o—overlap, s—spacing, t—zone width, v—vein length, δ—angle between vein and zone trend, ϕ—zone trend. Shows typical 'third-order vein'—extension array as one of the veins.

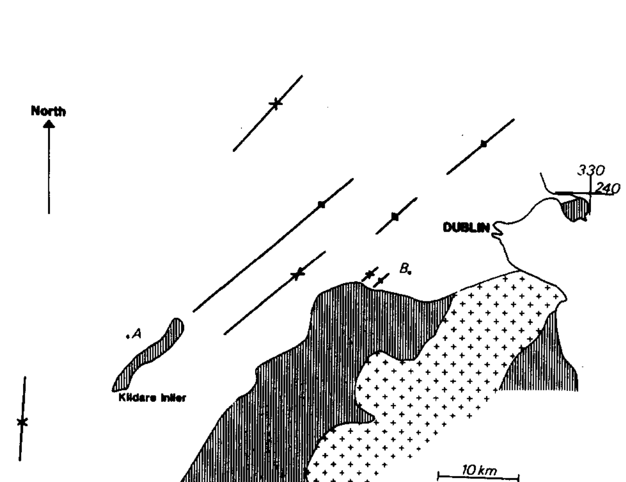

Fig. 2. Location map. A—Boston Hill, B—Belgard Quarry. Coordinates refer to Irish National Grid. Lower Palaeozoic—ruled, Leinster Granite—crosses, Carboniferous Limestone—blank, regional folds in Carboniferous shown with diamond (anticline) and cross (syncline).

average sinistral and dextral trends, and to bisect these directions. However, in order to be confident in this method it was necessary to show that these arrays could be classified as type 1 (Beach 1975) and therefore it was decided to investigate the variation in the angle δ and its relationship with the azimuth (in the horizontal plane) of the zone (ϕ). The same angular relationship was used to look at the apparent dilation (Ramsay & Huber 1983). In general, arrays closer in trend to the calculated Z direction should exhibit more positive dilation characteristics (lower δ).

SETTING AND MORPHOLOGY OF THE ARRAYS

En échelon calcite vein arrays are common features of the Variscan deformation of the Lower Carboniferous limestones of the Irish midlands. Two working quarries afforded an opportunity to examine some en échelon arrays in detail over wide areas (Fig. 2). At Boston Hill, 3 km east of Rathangan, Co. Kildare, a 180 × 100 m surface was exposed prior to excavation in the adjacent quarry workings. The surface sloped 10° N, revealing beds of Courceyan argillaceous bioclastic limestones dipping between 15 and 20° N. Exposed on the surface were the traces of a set of en échelon arrays, which maintained a sub-vertical attitude (Fig. 3). At Belgard, 1 mile south of Clondalkin, Co. Dublin, a total area of 900 × 900 m of gently folded, Asbian limestones was exposed comprising a working quarry, with cliff sections, and cleared surfaces as described above. Here, four systems of en échelon arrays are developed, of which the two vertical array sets are described, these being the most accessible (Fig. 4).

At both localities the arrays are rarely seen in conjugate relationship (i.e. cross-cutting or adjoining an array of opposite apparent shear sense: the two arrays enclosing an acute angle), usually occurring singly or in multiple parallel sets (Fig. 3), in large poorly defined domains (Hoeppener *et al.* 1969). At Boston Hill 12 of 99 arrays were found in conjugate relationship, while at Belgard only six of 209 arrays were so associated. Zone orientations are quite variable resulting in up to 45° arc of overlap between apparent sinistral and apparent dextral zone trends. Where seen, dihedral angles between conjugate sets are low (20–40°). Veins within the arrays are mostly planar, generally 2–20 cm long, 1–5 cm wide and are filled with crystalline calcite, which may be fibrous or drusy in habit. Some arrays showed sigmoidal veins and a pressure-solution cleavage of dark planes at high angles to the vein centres, while others are of the pinnate vein variety (Cloos 1932, Hancock 1972).

In all, 47 timing relationships were observed at Belgard Quarry between N–S- and ESE–WNW-trending arrays or planar extension veins—later veins or arrays cross-cutting or terminating at older structures. However, none of these structures is seen to be consistently older or younger. The N–S arrays post-date the other types of structures 14 times and pre-date them 10 times,

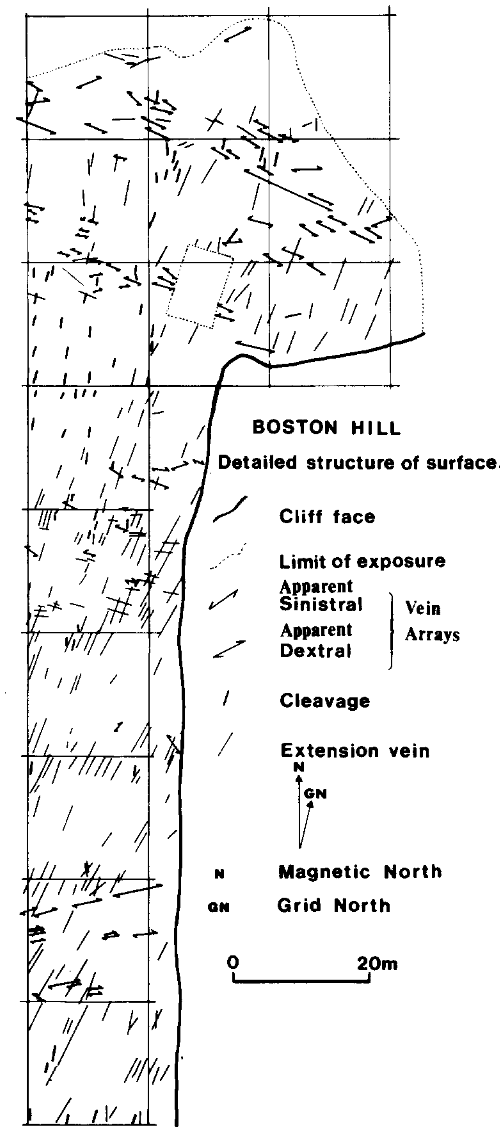

Fig. 3. Map of vein arrays and other mesoscopic structural features developed on a sub-horizontal surface at Boston Hill, Co. Kildare.

while the corresponding figures for the other structures are: ESE–WNW arrays 7–8 times, N–S veins 12–10 times and ESE veins 14–19 times. Extension and array veins are generally filled with pure fine granular to coarsely crystalline calcite, with dolomite and fluorite being recorded (not in the same veins) from veins of both trends of arrays and from N–S extension veins. At Boston Hill a strong set of N–S extension veins are developed (Fig. 3) and are seen to post-date E–W veins 39 times and pre-date them 8 times; so while largely coeval, the N–S veins may have had an extended development history relative to the other structures. The vein fill material, in all trends of veins, is most commonly crystalline calcite, with rare occurrences of dolomite, fluorite and galena. No evidence for any set of structures which either systematically pre-date or post-date these veins and arrays was found at either locality and it is therefore assumed that all the structures described in this paper belong to a single structural event—the Variscan deformation.

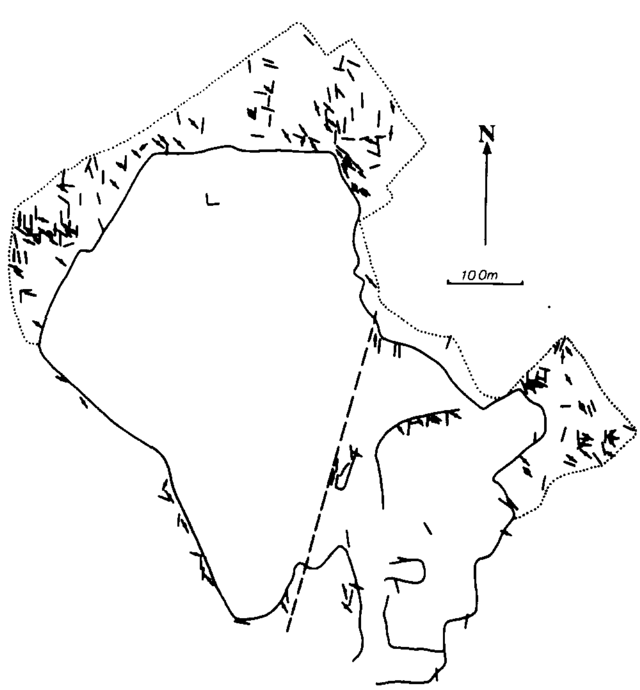

Fig. 4. Map of vein arrays and other structures at Belgard Quarry. Arrays shown with short dash, those with apparent sinistral sense having a central dot. Arrays showing 'double' sense have an open circle. Dotted line—area of exposure, solid line—cliff face, dashed line—fault.

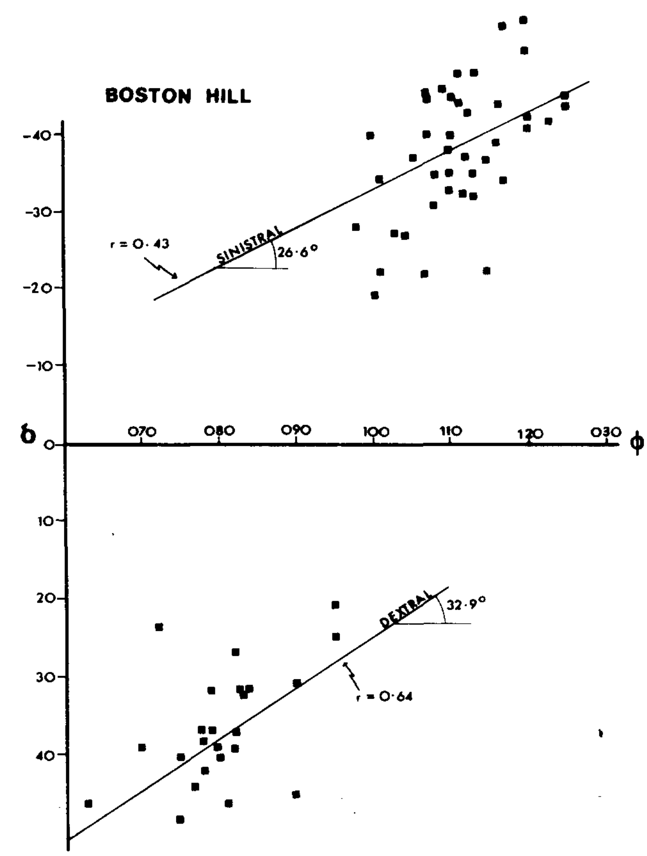

Fig. 5. Plot of ϕ (degrees) vs δ (degrees from north) for vein arrays at Boston Hill, Co. Kildare. Line is fitted by least squares method, r is the correlation coefficient of this line. Vein orientation for each array may be read by projecting a line from the data point to the δ axis at an angle of 45°, to the left for apparent sinistral arrays and to the right for apparent dextral arrays.

ARRAY GEOMETRY

The first investigation was carried out at Boston Hill (Fig. 3) and the δ vs ϕ data are presented in Fig. 5. The angle ϕ is measured in degrees from North, while δ is measured in degrees from the azimuth of the array to the azimuth of the veins, which results in δ being negative for apparently sinistral arrays and positive for apparently dextral arrays. The data points therefore plot as two clusters, but both display a similar range of absolute δ values (20–50°). Vein orientations may be read directly off the graph for each data point by projecting a line from the data point, at a slope of 45°, to the horizontal axis (to the right for apparent dextral arrays and to the left for apparent sinistral arrays). Within the data point clusters there are no preferred orientations for δ, ϕ or vein azimuth. It is also clear that vein azimuths for veins in apparent sinistral and apparent dextral arrays differ considerably. As far as δ and ϕ are concerned there is a clear linear relationship, which has been quantified here by fitting lines using the least squares method. The computed slopes of these lines are 26.6° for the apparent sinistral arrays and 32.9° for the apparent dextral arrays, with associated correlation coefficients of $r = 0.43$ and 0.64, respectively. There is no overlap of apparent sinistral and dextral directions at Boston Hill, although some arrays exhibit similar values (095° for an apparent dextral array, 097° for an apparent sinistral).

At Belgard Quarry a later study revealed four groups of sub-vertical vein arrays which are plotted here in apparent conjugate sets: 76 approximately N–S (Fig. 6)

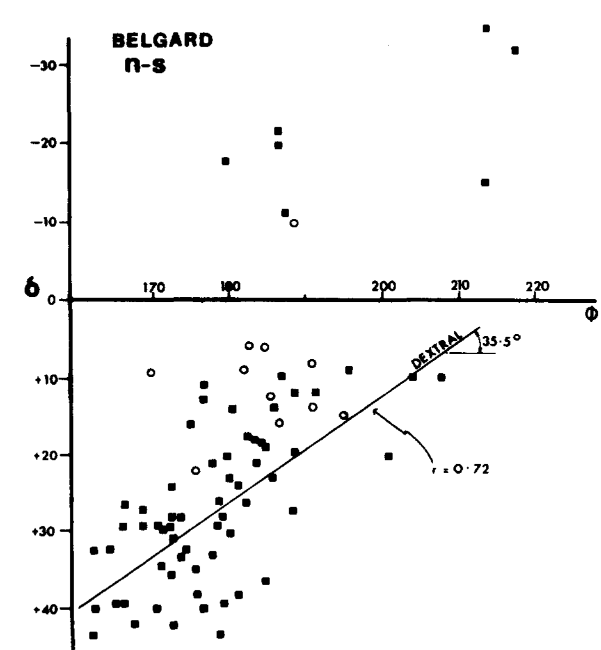

Fig. 6. Plot of ϕ vs δ for N–S arrays at Belgard. See Fig. 5 for explanation. Open circles are arrays which were identified in the field as 'third-order'.

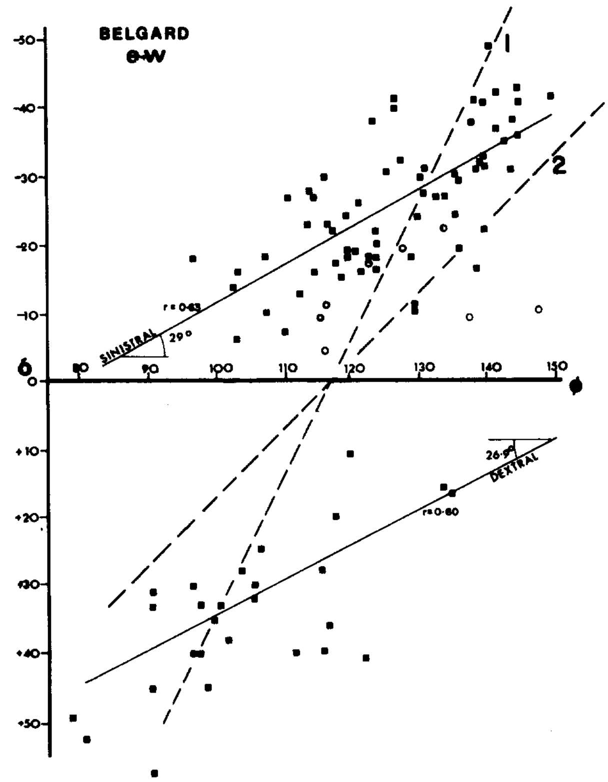

Fig. 7. Plot of trend of zones (ϕ) vs vein-zone angle (δ) for E–W arrays at Belgard, Co. Dublin. See Figs. 5 and 6 for explanation. Dashed lines marked 1 and 2 are derived from the definitions of type 1 and type 2 arrays (Beach 1975).

and 102 approximately E–W (Fig. 7). A wider range of δ, ϕ values is encountered, leading to considerable overlap in the orientations of apparent sinistral and dextral arrays. Again, no preferred orientation is observed within each cluster of δ, ϕ or vein azimuth values. As at Boston Hill, distinct linear trends are recognized in three of the four sets and have been quantified with best-fit lines of slope 35.5° (N–S apparent dextral), 26.9° (E–W apparent dextral) and 29° (E–W apparent sinistral), with corresponding correlation coefficients of r = 0.72, 0.60 and 0.63. These correlations were statistically tested using the Student t-test method and were found to be significant at the 99% confidence level.

When constructing these best-fit lines it became clear that a particular type of array did not give data points which shared this linear tendency. Those arrays marked with open circles on the graphs (Figs. 6 and 7) had been recorded in the field as 'third-order arrays', characteristically displaying one or more of four features. The first three features, generally associated, were a low vein-zone angle, a low overlap of veins in the array and an asymmetric vein-tip geometry. The last feature was whether or not the array was contained within a larger array: this kind of structure was described as a 'third-order vein' by Hancock (1972). However, at Belgard, not all arrays which displayed these characteristics were seen to occur within larger arrays and it was therefore decided to record them separately. On calculating the best-fit lines for the majority of arrays (which may be referred to as 'second-order') these 'third-order arrays' were eliminated. If included they reduced the correlation considerably and when they were analysed separately no linear relationship between δ, ϕ was found.

The best-fit lines of these distributions are considerably different from the hypothetical lines (shown on Fig. 7) derived from Beach's (1975) classification and therefore these arrays cannot be classified under Beach's scheme. The two lines shown (Fig. 7) have been drawn to intersect the horizontal axis at an arbitrary, geologically reasonable, value of ϕ close to an inferred Z strain axial direction, which should offer the best chance to fit the observed distribution. It is clear that the data points lie neither on these lines nor on 'Beach lines' with any other possible intercept on the horizontal axis. Similar data have been presented by Dolan (1984), but in this case classification of the arrays as 'Beach type 1' is invalid, as Dolan demonstrates a linear δ/ϕ relationship with a slope of 45° (the slope defined for type 2 arrays).

To investigate further array geometry, a smaller set of data was collected, including data on vein overlap and vein length (Fig. 1, Table 2). Of these 39 sub-vertical vein arrays 18 were apparent dextral and trended approximately N–S, half displaying 'third-order' characteristics. For this sub-sample of 18 arrays Fig. 8(a) shows δ plotted against P(o) and shows the same relationship obtained by Beach (1975, fig. 7) for 12 arrays: i.e. a strong linear relationship (r = 0.8, significant at 99% confidence level). However, Fig. 8(b) shows that there is another factor present controlling the geometry of some of the arrays. In this plot, which is the equivalent of Figs. 5, 6 and 7 for these data, the 'second-order' arrays again show a distinct linear relationship between δ and ϕ (line slope 23.6°, r = 0.68, significant at a 95% confidence level), while the 'third-order' arrays do not. Looking back at Fig. 8(a), we find that when the 'second-order' arrays are analysed on their own, no significant relationship is present. The nine 'third-order' arrays on Fig. 8(a) give a significant line with r = 0.5.

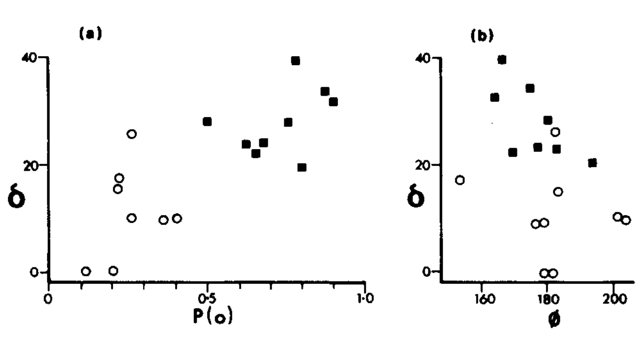

Fig. 8. Plots of vein-zone angle (δ) vs two parameters for nine shear arrays (black squares) and nine extension arrays (open circles). (a) δ vs P(o), proportion of vein overlapped by neighbour. (b) δ vs ϕ, zone trend. Arrays are all of apparent dextral sense. Vein orientation may be read by projecting a line at 45° to the right to intersect the ϕ axis. Shows similar linear relationship for shear arrays (black squares) as seen in Figs. 5, 6 and 7.

Table 1. Proposed en échelon vein array classification

	Shear arrays	Extension arrays
Mechanism of development	Secondary extension failure in shear zone	Propagation from extension vein
Vein tips	Symmetric	Asymmetric
Vein-zone angle δ (°)	High, 27–45+	Low, 0–27
Vein overlap P(o)	High, 0.4–1.0	Low, 0–0.4
Geometry	δ dependent on ϕ	δ dependent on P(o)
Mode of occurrence	Conjugate sets or domains	Some in domains, may change sense of vein rotation along array
Z direction in regional analysis	Bisects average dextral and average sinistral array trends (transcurrent arrays)	*Z–Y* plane parallel to average array orientation

ARRAY CLASSIFICATION

The examination of the geometry of δ for the natural arrays described has shown that the data do not fall into either of the two categories proposed by Beach (1975) and so therefore other criteria for estimating regional strain directions from the data are required. A difference in morphology and geometry has been encountered in the arrays described and it is now appropriate to examine the theoretical background to this situation in order to suggest how regional strain information may be obtained from these arrays.

A propagating crack in a deforming zone may initiate and grow under different stress regimes. Pollard *et al.* (1982) have described the mechanics of a propagating dilatant crack which breaks down into en échelon segments due to a spatial or temporal rotation of the remote stress. In this case, the vein-zone angle δ will tend to have a direct relationship with P(o), the vein overlap. Low overlap and asymmetric vein tips were noted as being associated by Beach (1975) and in analysis of vein arrays limited to "échelon cracks oriented at small angles to the trend of their array", Pollard *et al.* (1982, p. 1292) found that overlap tended to be low and that vein-tip asymmetry arose as a consequence of crack interaction.

Alternatively, if the horizontal stresses are large enough to allow shear failure, such an initiated or propagating crack may provide the locus for a failure plane in the formation of a shear zone. With the ensuing stress re-orientation en échelon extension veins may form (Lajtai 1969), but in this case the amount of stress re-orientation, and therefore the vein-zone angle δ, will be governed in part by the dilatancy of the shear zone and its orientation relative to the stress axes. A shear zone that lies closer to the σ_1/σ_2 plane will tend to be more dilatant. Ramsay & Huber (1983) have demonstrated the relationship between δ and dilatancy in shear zones.

The natural arrays described show many of the characteristics described for both types of vein formation and propagation. Yet, the majority of arrays sampled provide no clear evidence of having developed from a parent extensional crack or from a zone of localized shear strain. The quandary for a field geologist is clear—how are they to be interpreted kinematically? The conflicting current hypotheses for array development, together with the field evidence, suggest that the vein arrays described should be divided into two classes for kinematic analysis. However, the term 'third-order' array or vein is inappropriate for those arrays which have developed from extension cracks, because it is clear that not all such arrays occur within other arrays. The name 'extension array' will be used here for such an array, while the name 'shear array' will be employed for vein arrays which owe their development to a localized shear zone. It should be possible to assign the majority of arrays to one class or the other (in the absence of direct morphological evidence) depending on their geometry, using the relationships described. Such a division is proposed at δ = 27°, P(o) = 0.4 (Tables 1 and 2), with lower values defining a field for extension

Table 2. Values of vein array geometrical parameters at Belgard Quarry. P(o)—overlap of vein in array by its neighbour expressed as a proportion of vein overlapped (o) to vein length (v). δ—vein-zone angle. ϕ—zone trend in horizontal plane. T—field identification as 'third-order'. A–H see text

P(o)	δ (°)	ϕ (°)	v (mm)		
0.11	0	2	180	T	
0.14	43	144	70		A
0.19	0	2	180	T	
0.20	15	36	50	T	
0.22	17	153	45	T	
0.22	15	3	225	T	
0.25	11	110	40	T	
0.25	9	179	40	T	
0.26	26	3	15	T	
0.30	36	39	130		B
0.31	28	123	160	T	C
0.33	23	113	60	T	
0.35	9	179	40	T	
0.35	10	24	70	T	
0.38	23	113	60	T	D
0.40	10	24	150	T	E
0.40	30	99	100		F
0.40	40	121	100		
0.45	24	114	33	T	G
0.46	36	39	130		
0.47	30	99	190		
0.50	36	39	100		
0.50	28	2	80		
0.50	40	121	200		
0.55	36	39	100		
0.55	28	118	180		
0.62	23	4	80		H
0.65	43	144	170		
0.66	22	171	90		H
0.67	43	144	280		
0.68	23	179	150		H
0.74	52	95	50		
0.75	28	2	60		
0.77	39	166	250		
0.80	20	15	50		H
0.80	40	155	55		
0.88	34	175	63		
0.90	32	163	20		
0.90	33	97	150		

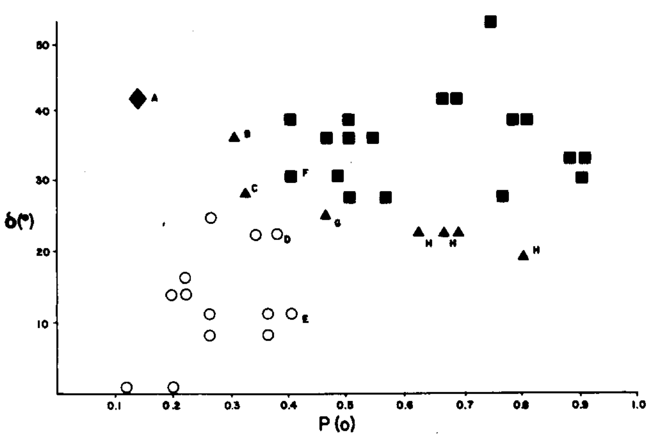

Fig. 9. Plot of δ vs P(o) for 39 arrays from Belgard, Co. Dublin. Black squares—shear arrays, open circles—extension arrays, triangles—intermediate arrays, diamond—reactivated, 'double-sense' array. Letters as Table 2 and as discussed in text.

arrays (Fig. 9). The value of δ is taken in part from the work of Garnett (1974), who found that the mechanical theory of vein development in shear zones breaks down where δ is less than 27°. Ramsay & Huber (1983) envisaged considerably lower values for δ in shear zones, but took no account of vein overlap or crack interaction. Hancock (1972) estimated the average δ of 'third-order veins' as being 13°.

Some points that may arise in analysis of a natural data set are illustrated (Fig. 9) for the smaller sample of 39 arrays. Reading A is one of two readings from an array that showed two phases of vein development. The later set plots at A and is one of a number of such 'double-sense shear zones' that have this orientation at this locality (Fig. 10c). Six suitably trending (azimuths 127°/307°–153°/333°) sinistral shear zones showed evidence of being reactivated later in a dextral sense. Arrays marked B, C, F, G and H have values close to the definition boundary but may be regarded as shear arrays, one of the two variables being relatively high. Arrays D and E are more likely to be extension arrays.

KINEMATIC INTERPRETATION OF SHEAR ARRAYS

Most previous kinematic analyses of en échelon vein arrays have assumed that all arrays have similar development histories, and most assume what would be termed here 'shear array' geometry. The exception is Beach (1975), but the arrays of the SE Irish midlands cannot be classified in this scheme (see above). It is proposed here that arrays are of two categories which differ considerably in development, in geometry and therefore in kinematic interpretation (Table 1). Classical kinematic interpretation assumes that the acute bisectrix of conjugate shear arrays is parallel to Z (Shainin 1950, Wilson 1961, Ramsay & Graham 1970), but this approach is inadequate in the SE Irish midlands since conjugate sets are rarely developed, arrays occurring largely in domains of one sense of rotation (Figs. 3 and 4), with largely varying trends (Figs. 5, 6 and 7). From the latter plots it may be seen that ϕ (zone trend) has a qualitative Gaussian distribution, but no sign of any preferred orientation within this which would imply the presence of a pre-existing fabric. Evidence has been quoted above that all these arrays belong to the same deformation: it is also important to emphasize that the available evidence, both from these veins and from other structures (partly described below), point to the deformation being coaxial in a broad sense. There is no evidence of a progressive rotation of incremental strain axes or of any large-scale simple shear zones. The present distribution of zone trends could have arisen as follows: the orientation of σ_1 (main compressive stress) may have varied regularly around a mean and for any given orientation of σ_1, local mechanical factors may have contributed to a range of ϕ trends. Differing σ_1 trends will therefore cause the recorded overlap of sinistral and dextral orientations (Figs. 6 and 7) and reactivation of suitably oriented zones in the opposite sense. The data presented show a maximum sinistral–dextral trend overlap of 40° (Fig. 7) which implies a minimum 20° variation in σ_1 trend around a mean. The mean trend of Z (which may be taken as being parallel to σ_1 orientation in coaxial deformation) may be estimated by bisection of the average dextral and sinistral zone orientations (a similar operation for vein trends gives similar results).

Estimates of Z calculated according to the above method agree well with conventional estimates from the few conjugate zones seen. For example, at Belgard only two conjugate sets occur and have acute bisectrices of 116 and 130°. These are compatible with the estimate of Z at 117° for 102 approximately E–W arrays (Fig. 7). In the case of the approximately N–S arrays (Fig. 6) no conjugate sets were recorded, but the method outlined here allows an estimate of Z as 010° (190°) from the 76 arrays that do occur. Sinistral arrays are poorly represented, probably due to domainal development, i.e. that a 'domain' in which arrays of a similar trend and sense commonly occur is not present in the area sampled for the N–S sinistral arrays (Fig. 4). Previously proposed methods of Z estimation such as bisecting the vein-zone orientations (Roering 1968) or taking Z as parallel to average vein orientation (Choukroune 1976) would be seriously in error for this system as a regional estimate.

Further confirmation of the validity of the method presented above may be found in the sub-parallelism of the estimated Z trends with other tectonic axial trends estimated from other structures (Rothery 1985). At Belgard, the approximately E–W Z (117° above) is close to an extension vein peak (125°) and is normal to a regional pressure-solution cleavage (028°), while the approximately N–S Z (010°) is close to the line of intersection of a conjugate set of normal shear zones (008°) and an extension vein peak at 012°. At Boston, the estimated Z (095°) is close to Y calculated from a set of normal shear zones (113°), the Z–Y plane trend from an extension vein peak (087°) and Z from cleavage (101°).

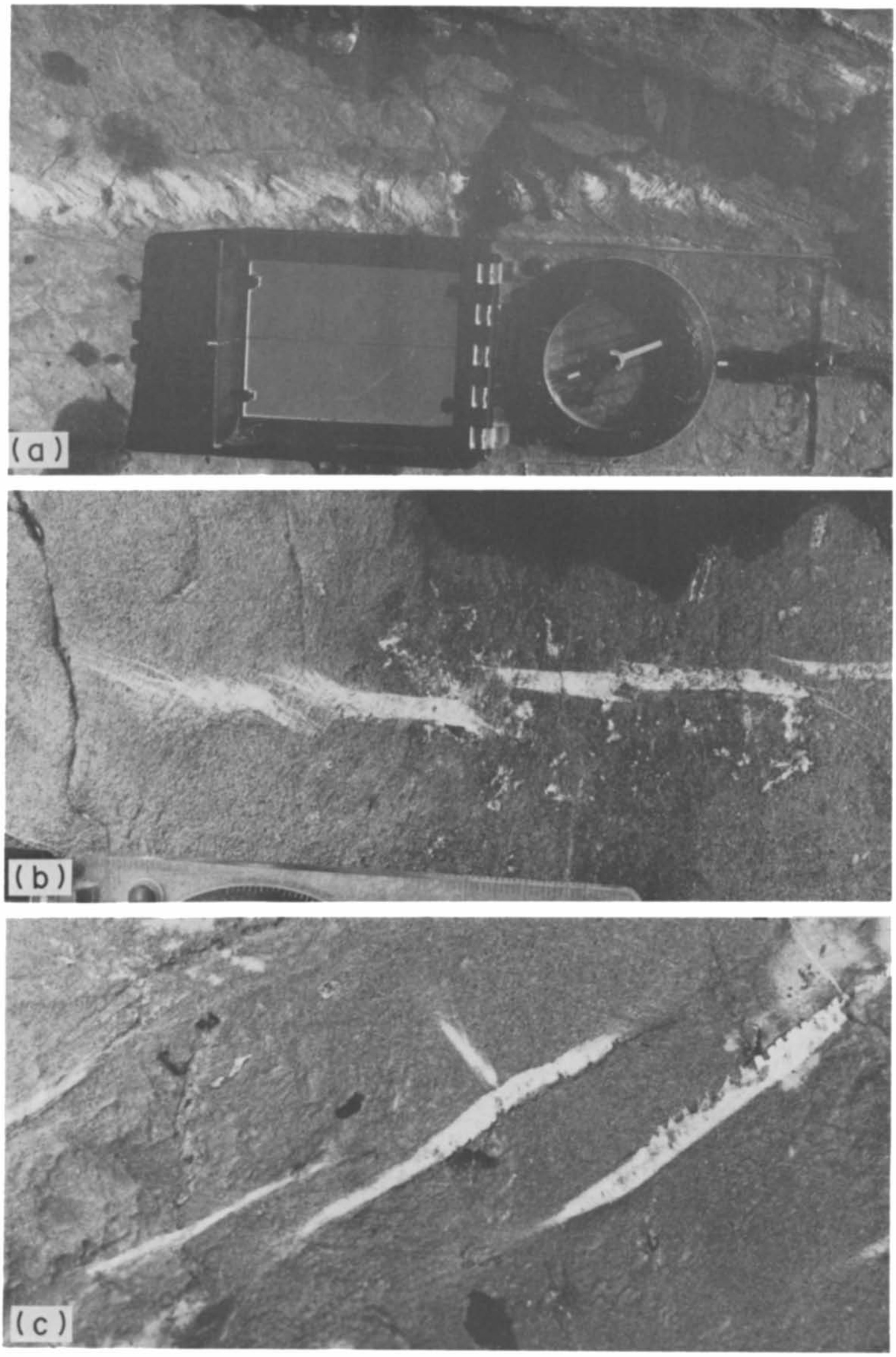

Fig. 10. Examples of vein arrays at Belgard Quarry, photographed on a sub-horizontal bedding surface of bioclastic limestone. (a) Shear array, showing veins at high angle to zone, sigmoidal veins and high vein overlap. (b) Extension array, showing veins at a low angle to the zone, asymmetric vein tips and low vein overlap. Termination towards the left of the photograph. (c) Shear array of apparent sinistral sense showing later reactivation in a dextral sense by development of small veins abutting the original veins and by stylolitic cleavage which affects the edges of the two central veins. Picture is 170 mm across.

KINEMATIC INTERPRETATION OF EXTENSION ARRAYS

From theoretical considerations Nicholson & Pollard (1985, p. 589) considered that the central part of en échelon cracks may be perpendicular to the 'remote least compressive stress'. However, Pollard *et al.* (1982, p. 1293), in defining the properties of the remote stress, stated that it may change orientation spatially along the propagation direction, or temporally as the parent crack interacts with adjacent structures. This is, clearly, a local variation in stress on the scale (1–10 m approx.) of propagation of an extension vein. Kinematic interpretation is concerned with a regional analysis (10–100 km). Regional strain trajectories may be arrived at by averaging trend information from many readings, such as are available in Belgard and Boston Hill. One should expect that the overall extension array trend should be close to the trend of extension veins and that this direction is a good estimate of the trend of the Z–Y plane, in coaxial deformation.

At Belgard, there are two sets of sub-vertical extension arrays. The N–S set of 18 arrays has a mean trend of 007.3°, while the E–W set of 21 arrays trends 121.9°. Kolmogorov–Smirnov statistical testing (Cheeney 1983) shows that these populations may not be separated from the extension vein sets which have mean trends of 012 and 125°, respectively (Rothery 1985, p. 27). These results also agree well with those from shear arrays, which give mean Z orientations of 010.4 and 116.5°.

We can now return to one of the initial considerations, the nature of veins within an array. Previous evidence for the shear nature of some veins within arrays included the development of 'third-order' arrays (Hancock 1972); definition of these as extension arrays removes the need to invoke primary shear in their development. Other evidence quoted included the offset of vein walls and the tilting of vein fibres in the direction of shear (Hancock 1972). Pollard *et al.* (1982, p. 1299) showed that vein wall offset may occur in en échelon crack growth without applied shear, while fibre tilt evidence from the arrays studied indicates a complicated vein growth history rather than a consistent shear development history. Of 23 fibre orientations in veins within arrays recorded, 16 tilt between 3 and 56° in the shear direction, five are curved and two tilt in the opposite direction (Rothery 1985, table 5). To summarize, 'shear' evidence such as development of en échelon arrays, offset across veins and tilting of vein fibres may arise during the development of an extension fracture as well. Most evidence now points to veins within arrays being extensional (see summary by Rickard & Rixon 1983).

CONCLUSIONS

A set of natural en échelon vein arrays has been described, whose geometry and morphology cannot be explained by any previously proposed hypothesis. A sub-division of these arrays into two types is proposed: shear arrays arise due to secondary failure in shear zones, while extension arrays develop during propagation of an extension vein.

Occurrence of shear arrays in domains of one sense of rotation renders previously proposed methods of kinematic analysis inappropriate, and new methods of kinematic interpretation for both shear and extension arrays are needed and described here. The regional principal shortening direction may be taken as bisecting the average orientations of the conjugate set of shear arrays, or as parallel to the overall trend of extension arrays.

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