



Scaling relationships of joint and vein arrays from The Burren, Co. Clare, Ireland

P.A. Gillespie¹, J.J. Walsh^{2,*}, J. Watterson³, C.G. Bonson², T. Manzocchi²

Fault Analysis Group, Department of Earth Sciences, 4 Brownlow Street, University of Liverpool, Liverpool L69 7GP, UK

Received 10 January 2000; accepted 29 June 2000

Abstract

We present a study of the systematics of veins and joints in Carboniferous limestones of The Burren, Ireland. Scaling relationships were established for fracture arrays mapped from low elevation aerial photographs that image fractures on numerous limestone pavements for areas up to ca 1 km². The veins and joints occur in the same sequence, but have contrasting scaling properties. The veins strike north-south and cut many beds to form vertically persistent, non-stratabound arrays. They are strongly clustered and have scale invariant geometric properties. Vein geometries suggest they grew sub-critically under relatively high differential stresses, during north-south directed Variscan compression. The joints form stratabound arrays, with regular spacings that scale with bed thickness. They show greater strike variation than the veins and have lognormal length distributions. The joints formed during uplift, under low-differential stress conditions. The contrasting scaling properties of the joints and veins are attributed to different overburden stresses at the time of formation. The veins formed at greater depths than the joints, in conditions that favoured fracture propagation across mechanical discontinuities, resulting in the development of non-stratabound scaling properties. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

Subvertical fractures such as joints or veins are a common feature of rocks in both highly deformed areas and in regions that are otherwise undeformed. The spatial distribution and scaling of such fractures are highly variable and range from fractures with a small range of sizes and a very regular spacing (e.g. Mastella, 1972; Ladeira and Price, 1981; Huang and Angelier, 1989; Narr and Suppe, 1991) to fractures with very broad size distributions showing a high degree of clustering (Segall and Pollard, 1983; Odling, 1997; Gillespie et al., 1999). The underlying controls on the fracture scaling are likely to be related to both the nature of the host rocks and the conditions of deformation. This article describes the fractures in The Burren, County Clare, Ireland and attempts to provide an explanation for the scaling systematics of the different fracture types.

* Corresponding author.

E-mail address: fault@fag.ucd.ie (J.J. Walsh).

¹ Present address: Norsk Hydro ASA, Sandsliveien 90, N-5020 Bergen, Norway.

² Present address: Fault Analysis Group, Department of Geology, University College Dublin, Belfield, Dublin 4, Ireland.

³ Present address: Liverpool University Marine Laboratory, Port Erin, Isle of Man IM9 6AJ, British Isles.

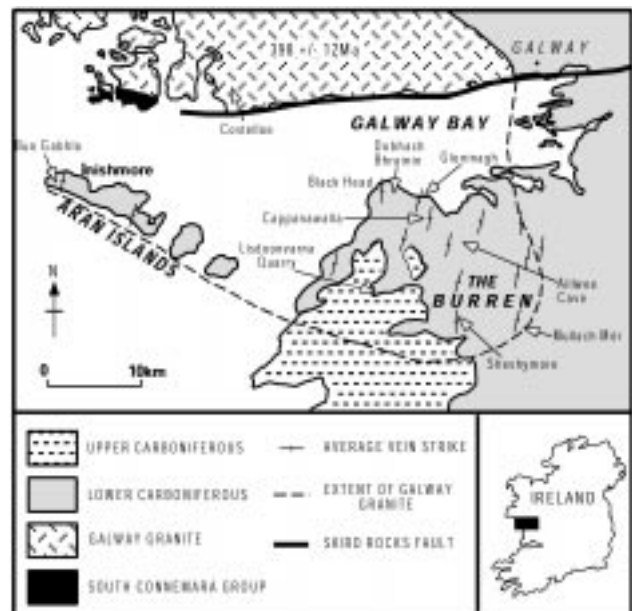


Fig. 1. Simplified geological map of The Burren and Aran Islands showing the average vein strike at selected localities.



Fig. 2. Pavement at Sheshymore, viewed northwards from point P in Fig. 5, showing the excellent development of clints and grykes. The hammer in the central foreground (circled) is 38 cm long.

Although the fracture outcrop is of exceptional quality, the area has been left undescribed by structural geologists since the work of King (1875) and Kinahan (1875).

The Burren is a barren area of Carboniferous limestone in the west of County Clare, Ireland (Figs. 1–3). Limestone pavements on the upper parts of hills and along the coast provide superb exposures (Figs. 1 and 3) where two prominent types of fracture occur: barren joints and mineralised veins. This article aims to show that these two fracture sets have contrasting size and spacing characteristics. The veins

are clustered and have power-law size distributions, whereas the joints are non-clustered and do not exhibit power-law size distributions. In this respect, The Burren provides a rare opportunity to characterise the systematics of two contrasting mode I fracture sets. Furthermore, in The Burren investigation of the causes of their differences can exclude lithological variation, often considered to be a crucial variable. Primarily, the fracture system mapping was carried out from low level aerial photographs. This facilitated acquisition of high-quality fracture maps and allowed relatively easy recognition and characterisation of the fracture patterns.

2. Background geology

A sequence of relatively undeformed Asbian to Brigantian age limestones, comprising mostly platform carbonates (Gallagher, 1996), crop out in The Burren (Figs. 1 and 4a). Below we present brief descriptions of the stratigraphic intervals where veins and joints have been studied. The Late Asbian Terraced Member of the Burren Formation forms the well-developed terraces on the upper parts of several of The Burren hills (Figs. 1, 3 and 4a), such as Capanawalla (described below). The Terraced Member consists of cyclic units of algal packstones/grainstones, 2–20 m thick, topped by palaeokarst surfaces (Fig. 4a). These are separated by clay layers,



Fig. 3. View, looking southwest, of the hill scarp at Black Head (Fig. 1), showing The Burren Formation cut by subvertical clusters of veins (dark lineaments). Many clusters are continuous across a thick shale bed (0.5m) at the contact between the Maumcaha Member and Terraced Member. Dashed lines represent the approximate upper and lower boundaries of the Maumcaha Member. The summit of Dobhach Bhraínín, in the distant right of the photograph is at 337m.

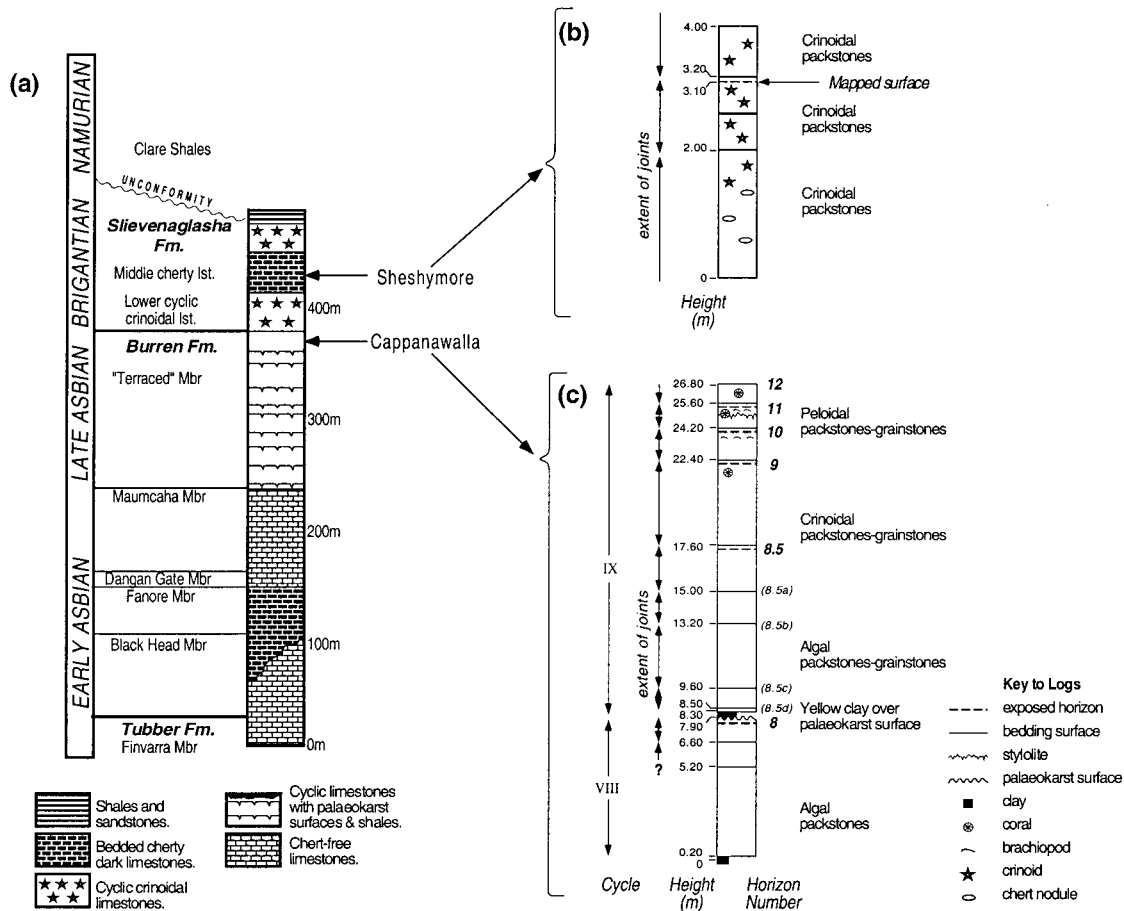


Fig. 4. (a) Stratigraphic log of The Burren showing the position of Cappanawalla and Sheshymore. Modified from Gallagher (1996). (b) Schematic log of the Slievenaglasa Formation exposed at Sheshymore, with the level of mapped surface indicated. (c) Schematic log of the Terraced Member of The Burren Formation exposed at Cappanawalla. The cycle numbers refer to the stratigraphic cycles of the Terraced Member (Gallagher, 1996). Horizon numbers refer to the exposed surfaces shown on Figs. 6 and 7. For both Sheshymore and Cappanawalla, the mechanical layering, which vertically confines the joints to a large extent, is indicated to the left of the lithological logs.

termed clay wayboards (Walkden, 1972), which are usually less than 0.2 m thick. The clay wayboards are rarely seen at outcrop because they are either weathered-out or covered by vegetation. However, they can be seen in the Aillwee Cave and particularly well in the cliffs of the Aran Islands (Fig. 1), where they tend to be thickest, up to 1.4 m. The tiered topography of The Burren (Fig. 3) results from the erosion of the limestone units which have been stripped by glaciation along the easily erodable clay wayboards (Vincent, 1995).

The Brigantian Slievenaglasa Formation crops out on the hills in the southern part of The Burren, such as Sheshymore (Fig. 1). The Slievenaglasa Formation comprises 3–20 m thick cyclic units of crinoidal grainstones with coral thickets and cherty limestones (Fig. 4a). These units lack palaeokarst surfaces in The Burren and are not separated by clay wayboards. Unconformably overlying the Slievenaglasa Formation are the Namurian Clare Shales (Fig. 4a), a thick sequence of phosphorites and shales (Hodson, 1952).

Throughout The Burren, the strata dip ca 2° to the south-

southeast and are not folded except at Mullach Mór (Fig. 1), where a series of northeast-southwest trending open folds have a wavelength of ca 1 km. In general faults are rare. However, minor normal faults (throws <10 m) do occur near Black Head and at Bun Gabhla (Fig. 1).

The uplift history of the Carboniferous rocks in western Ireland is poorly constrained as post Carboniferous sequences are largely absent. Uplift episodes in the Permo-Triassic, the late Jurassic (Cimmerian uplift) and the early Tertiary (Laramide uplift) have been proposed on the basis of stratigraphic evidence (Naylor, 1992). Fission track data (McCulloch, 1993) suggests between 1 and 3 km of uplift occurred in the Middle Jurassic and between 0.8 and 2 km occurred in the late Cretaceous-early Tertiary.

Denudation of the extensive limestone pavements in the Burren results from glaciation and subsequent solution erosion (Williams, 1966; Vincent, 1995). Pedestals under glacial erratics, up to 35 cm in height, require solution rates of 0.035 mm/year since the last glaciation 10 000 years ago (Drew, 1994). The solution was greatly enhanced

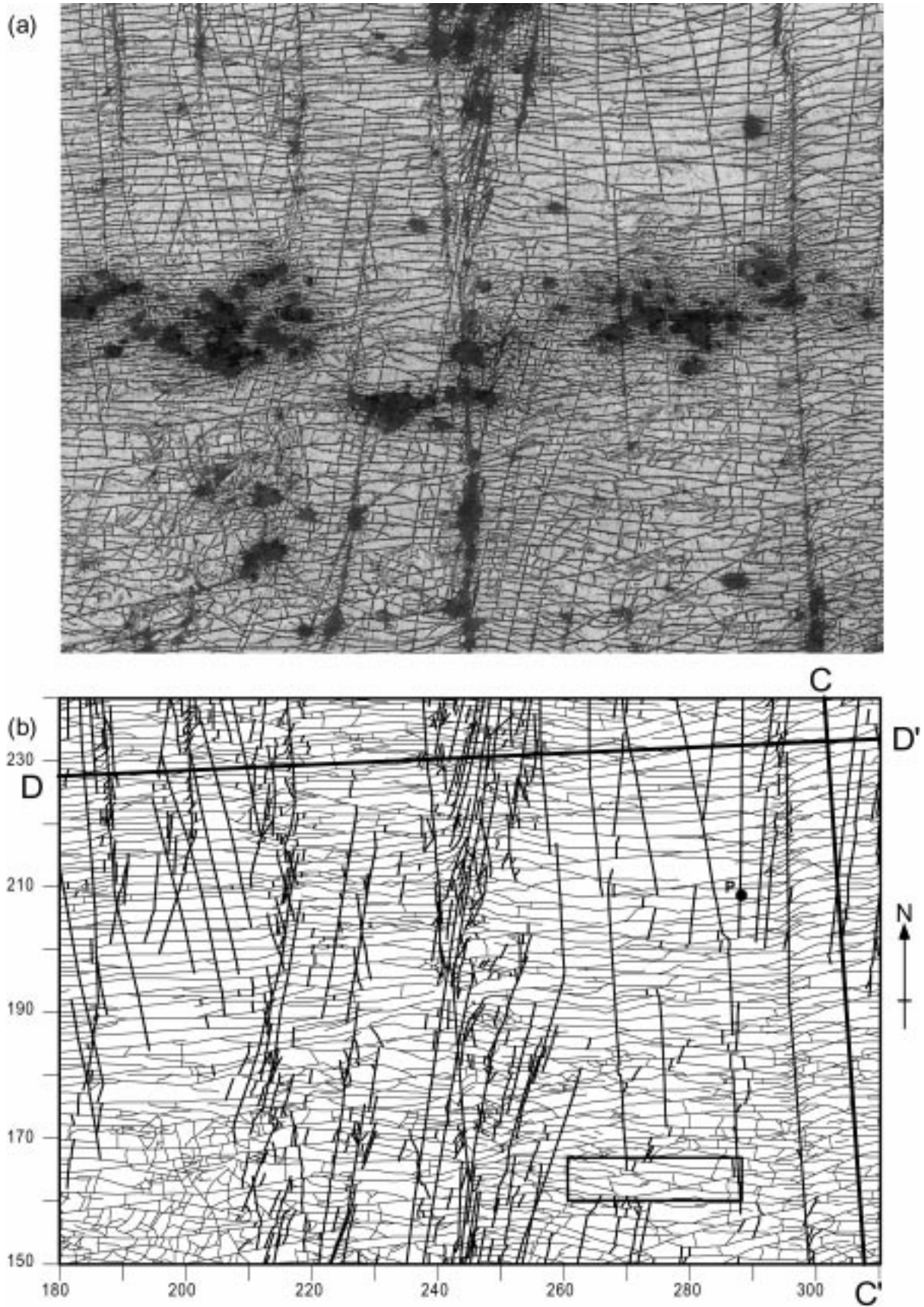


Fig. 5. (a) Aerial photograph of part of the pavement at Sheshymore. The grykes are the dark lineaments, which follow the veins (north-south) and the joints (west-east). Younger veins strike in a clockwise direction to the older veins. Vegetation locally obscures the pavement. (b) Digital map of same area showing veins (thick lines) and joints (thin lines). Sample lines C-C' and D-D' were used to measure the spacing of the joints and veins (Fig. 9; Table 3). Coordinates in metres.

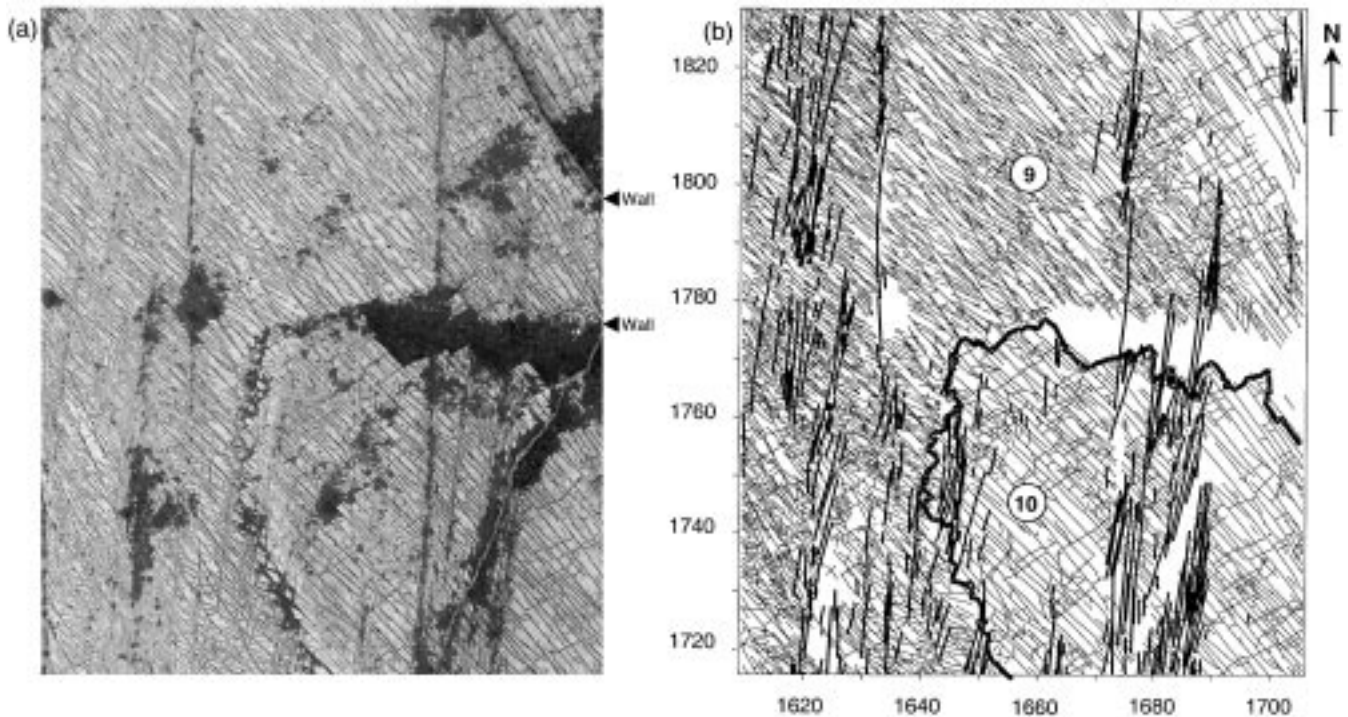


Fig. 6. (a) Aerial photograph of part of the pavement at Cappanawalla. (b) Digital map of the same area. The thick line separates pavement 9 from the overlying pavement 10. The pavements have a vertical separation of 1.8 m. The north-south lines of intermediate thickness are veins, and the thin lines are joints. Two walls are pictured in the right of the photograph (a) and coincide with areas of no data on the fracture map (b). Coordinates in metres.

along fractures and produced vertical slots, termed grykes which are typically 10 cm wide and up to 2 m deep, separated by blocks of intact limestone, termed clints (Fig. 2).

3. Data collection and analysis

3.1. Aerial photography

Aerial photographs were commissioned over the areas where fracture-related grykes are best developed. These areas are Sheshymore (Fig. 1), which exposes the Middle Cherty Limestone of the Slievenaglasha Formation (Fig. 4b and Fig. 5), and Cappanawalla, where the Terraced Member of The Burren Formation is exposed (Fig. 4c, Fig. 6 and Fig. 7). Monochrome photographs were taken from a height of 760 m above ground surface, providing a contact scale of 1:3000 and a ground resolution of about 5 cm. The grykes enhance the visual signature of the veins and joints, allowing both to be imaged clearly on the photographs.

3.2. Fracture mapping

The grykes can be divided into a clearly distinguishable straight parallel set, and a set of more sinuous, well connected grykes (Figs. 5 and 6). Where the straight parallel grykes run under erratics, they are less eroded and can be identified as calcite veins. However, where sinuous grykes

run under erratics, there is no evidence of mineralisation, implying that these grykes are eroded joints. Therefore, on aerial photographs, vein arrays are easily distinguished from joints by their geometry and orientation. In some cases, erosional channels unrelated to fracturing, known as solution runnels, occur in the top of the clints which drain into the grykes (Williams, 1966). These features can be distinguished from grykes as they are shallower, more sinuous and sometimes dendritic.

Scanned aerial photographs were used to identify and map individual fractures using the ERMMapper remote sensing software. The 0.0413 km² Sheshymore map contains 7526 mapped fractures and the 0.1144 km² Cappanawalla area 63068 individual fractures. Ground-truthing in the field confirmed that, except where obscured by isolated patches of vegetation, or where glacial cover is present, all fractures greater than 1 m in length have been detected and mapped on the photographs. The resulting digital maps were analysed using in-house software.

The Sheshymore map is of the exposed erosion surface of a crinoidal packstone bed, 1.2 m thick, which is approximately 10 cm below the original bedding surface due to solution (Fig. 4b). The map area occupies a very open east-west striking syncline, with limb dips of <3°. At Sheshymore, the fracture pattern is too intense to be shown here in its entirety: individual fractures would be indistinguishable. Therefore, 28% of the mapped area (Fig. 5b) is shown to illustrate the key geometric characteristics

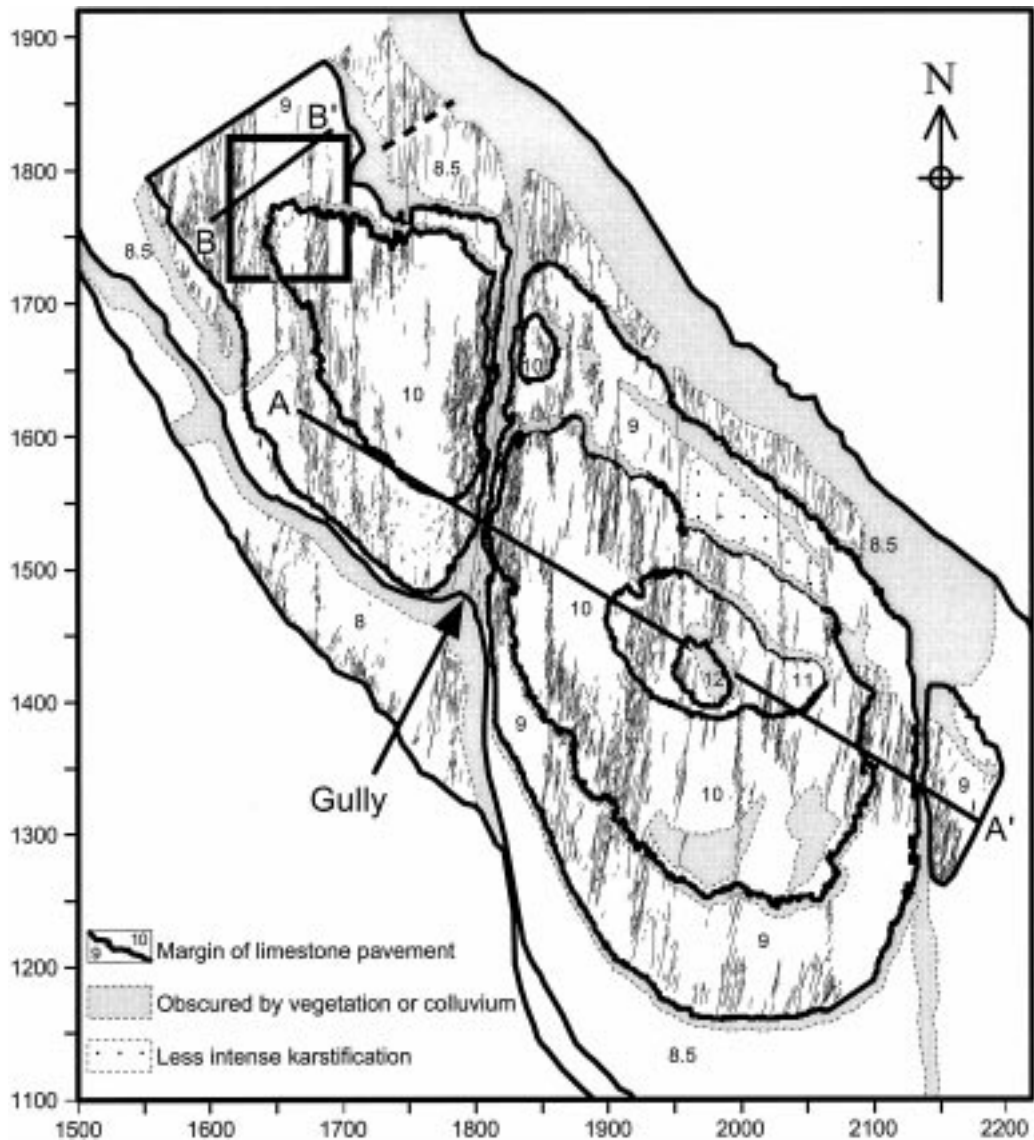


Fig. 7. Map of veins from southeast end of the plateau at the top of Cappanawalla. Numbers refer to different horizontal limestone pavements in ascending order of height. Horizons 9 and 10 are more than 90% exposed. Other horizons have more restricted exposure, due to the presence of vegetation and/or colluvium. The boxed area shows location of Fig. 6. Vein and joint spacing were measured along sample lines A-A' and B-B' respectively (Fig. 9; Table 3). Sample line A-A' crosses a grassy gully that coincides with the position of highest vein density. The region of no exposure is 6m wide. Thick dashed line (north of map) is an area of no data recovery, at the join between two aerial photographs.

of the fractures and also to show the detail of the aerial photographs (Fig. 5a).

The Cappanawalla vein map (Fig. 7) incorporates tiered surfaces from six different beds. The bed dip within the map area is 0.5° South. A notable feature of the map is the lateral continuity of vein traces, from one bed to another, indicating vertical continuity of veins across bedding discontinuities. Vertical persistence of the veins can clearly be seen in the Terraced and Maumcaha Members of the The Burren Formation on the northern flanks of Dobhach Bhraínín, at Black Head, ca 5 km to the northwest of Cappanawalla (Figs. 1 and 3). In contrast, at Cappanawalla (Fig. 6), joint patterns on two exposed surfaces differ in both density and

geometry. This difference indicates that, unlike the veins, joints generally do not continue across bedding discontinuities.

3.3. Vertical persistence

A measure of the persistence of the fractures across a bedding interface is the Persistence Ratio (see Petit et al., 1994). The Persistence Ratio, ${}_A P_B$, is the proportion of fractures that cross from bed A to bed B relative to the total number in A, and the ratio ${}_B P_A$ the opposite. For example, a Persistence Ratio ${}_A P_B = 0.5$ indicates that 50% of fractures from bed A cross to bed B. However, ${}_B P_A = 1$

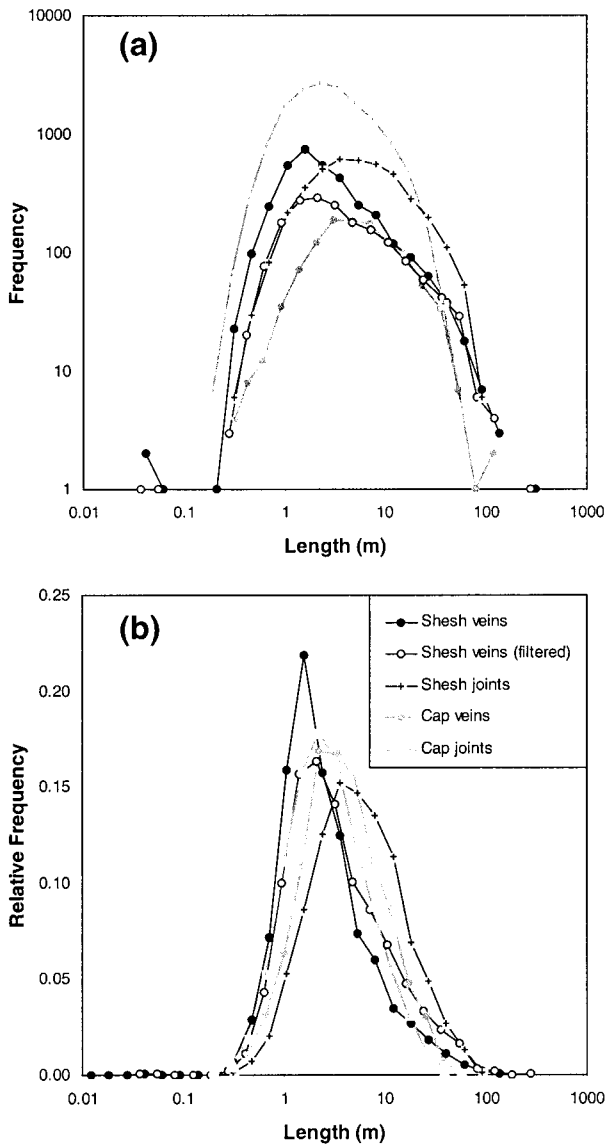


Fig. 8. Fracture length distributions from The Burren. (a) Log-log histogram produced using the log-interval method. (b) Log-linear histogram of the same data with the frequency normalised to relative frequency and shown on a linear axis.

indicates that all fractures in bed B persist into bed A. This measurement was applied to veins and joints separately at Cappanawalla.

3.4. Analysis of fracture scaling

Characteristics of a fracture array, such as the distributions of length, spacing and thickness or aperture, may be analysed at different scales of sampling domain to determine whether the distribution characteristics systematically vary with scale. These measures would ideally be based on 3D data, which are rarely available. Here we base the array characterisation on the available 2D maps. A discussion of the relationships between 1D, 2D and 3D scaling systema-

tics of fractures is given in Gillespie et al. (1993, 1999). Vein thickness data could not be obtained from the aerial photographs, and have only been obtained for veins at Gleninagh (Fig. 1). Also, original joint apertures have been greatly increased by erosion. Hence, the analyses concentrate principally on fracture density, and length and spacing distributions.

3.5. Fracture lengths

The vein and joint lengths were measured separately from the digitised maps. Individual joint datasets were subdivided according to their orientation. These data were then plotted as histograms with the lengths divided into logarithmic class intervals (Fig. 8), termed the log-interval method (Pickering et al. 1995). This method has the advantage over the more frequently used cumulative frequency plot in that each point is independent so that any bias or censoring at one end of the distribution will not affect the other points.

3.6. Fracture spacing

Line samples were taken across individual limestone surfaces on the digital maps and the spaces between the adjacent fractures of the individual sets were calculated. The frequency distribution of the spaces was then plotted in the same way as the length populations (Fig. 9). A power-law distribution of spaces is characteristic of fractal geometry, and the exponent for a line sample should theoretically be in the range 0 to 1.0 (Gillespie et al., 1999).

Another measure for characterising spacing is the coefficient of variation (C_v), defined as the ratio of the standard deviation to the mean value of the spaces. The C_v expresses the degree of clustering along line samples (Cox and Lewis, 1966; Gillespie et al., 1999). For fractures with a Poisson distribution, the mean and standard deviation are equal, therefore $C_v = 1$ (Cox and Lewis, 1966). If fractures are clustered $C_v > 1$, while if they are anti-clustered (i.e. regularly spaced) $C_v < 1$ (Gillespie et al., 1999).

4. Veins

4.1. General features

The sub-vertical veins are characteristically planar and parallel-sided. Vein fill is preserved only where grykes are not well-developed, under glacial erratics and on the coast at Gleninagh (Fig. 1). The veins usually form simple parallel arrays but left-stepping en-echelon arrays occur locally, suggesting an element of dextral shear (Figs. 6 and 7). Sigmoidal veins are rare exceptions. Usually, individual veins are relatively regular, planar fractures, which show no signs of forking. In thin-section, small carbonate grains are offset in a simple extensional sense across the veins, with no visible shear displacement and therefore indicate that the veins are mode I fractures.

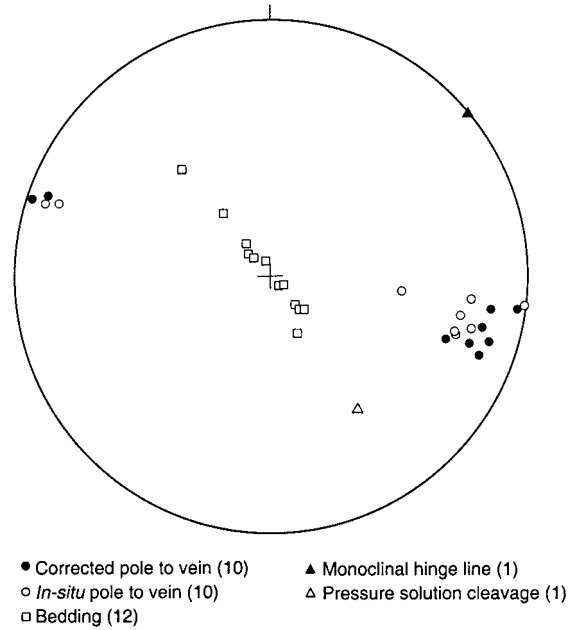
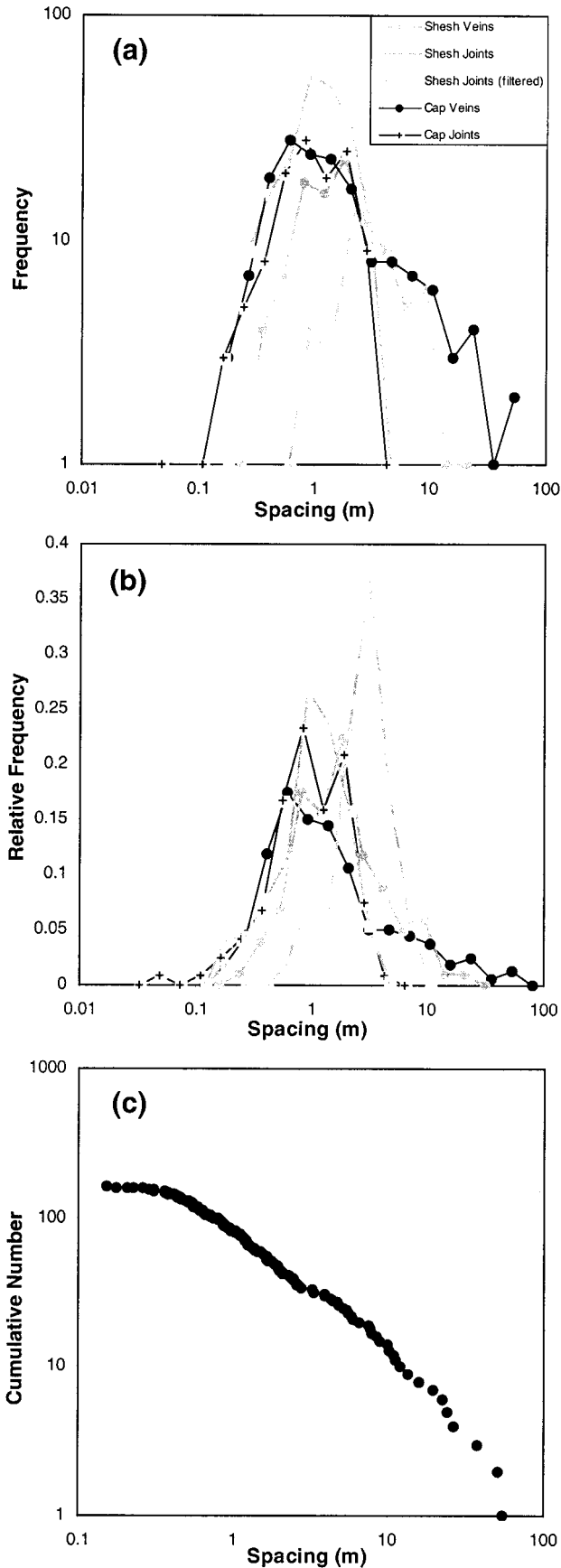


Fig. 10. Stereonet of vein data from a monoclinial fold at Mullach Mór. When bedding dip (i.e. the fold) is removed, poles to veins show a tighter grouping.

The vein thickness varies from a few microns to 0.5m. The fill is typically a sparry white calcite but, locally, thick veins (>5 cm thick) contain hydrothermal fluorite and galena (O'Connor et al., 1993). Fluid inclusions in the vein fluorite yield homogenisation temperatures in the range of 80 to 200°C (O'Connor et al., 1993). However, the depth of their formation has not been constrained from these studies.

The veins have a consistent north-south strike over the whole of The Burren (Fig. 1). At Cappanawalla, the vein clusters have a regular strike direction, slightly east of north, but the strike of individual veins is less regular and varies between 000° and 010° with the veins frequently arranged in left-stepping arrays (Figs. 6 and 7). At Sheshymore, the veins have a more variable strike from 350° to 010°. Here, cross-cutting relationships show a consistent clockwise change of vein orientation with decrease in age (Fig. 5).

At Mullach Mór (Fig. 1), the veins occur within the limbs of a monocline, which contains a pressure solution cleavage (Fig. 10). When plotted on a stereonet the poles to veins corrected for bedding tilt fall in a tighter group than the in-situ vein orientations (Fig. 10). Although based on relatively few data, the observations suggest that the veins pre-date or

Fig. 9. Joint and vein spacing distributions from The Burren. (a) Histogram produced using the log-interval method with both axes logged. (b) Histogram of the same data but with the frequencies normalised to relative frequency and shown on a linear axis. (c) Cumulative frequency vs spacing plot for veins from Cappanawalla (line sample A-A' on Fig. 7) showing an approximately power-law distribution with an exponent of -0.74.

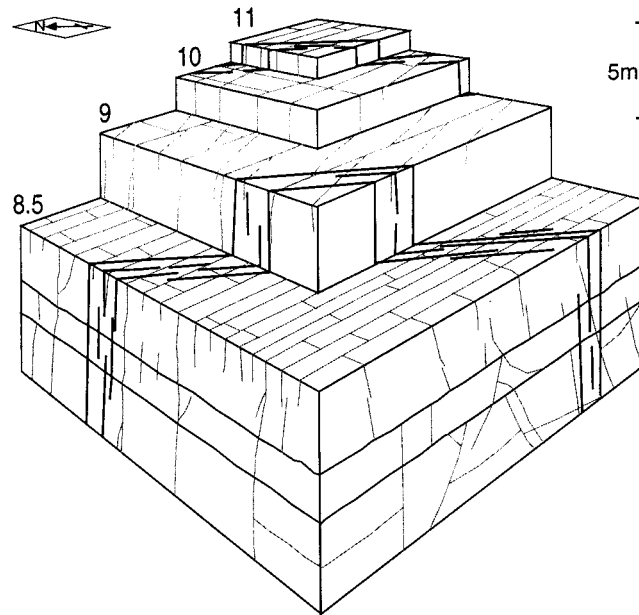


Fig. 11. Block diagram of the 3-D relationship between veins (thick lines) and joints (thin lines) at Cappanawalla. The numbers refer to pavement numbers.

were synchronous with folding. Since folding of Carboniferous rocks within County Clare is attributed to Variscan contractional deformation (Fitzgerald et al., 1994), the veins in The Burren are therefore interpreted to have formed during the north-south directed compression of the Variscan orogeny, prior to folding. A minimum burial depth of ca 1.25 km at the time of vein formation can be established from the estimated thicknesses of Upper Carboniferous rocks. A ca 1.8 km thick Namurian sequence in the south (Rider, 1969) thins to an estimated 500 m above The Burren (personal communication, Trevor Elliott). An overlying Westphalian sequence is now entirely eroded but, by analogy with other areas in the British Isles, would have had a thickness in excess of ca 750 m. A contrary view on the age of the veins has been advanced by O'Connor et al. (1993), who suggest a formation age coinciding with mid-Triassic continental rifting of the Atlantic margin, on the basis of fluorite-bearing veins on the north coast of Galway Bay at Costelloe that cut a dolerite dyke dated at 231 ± 4 Ma (Fig. 1). From our own field observations, the veins at Costelloe have a more exotic mineralogy (fluorite-galena-chalcopryrite-quartz-barite-calcite) and have a much wider spread in strike orientation (001° – 127°) than those of The Burren. Although these features suggest that the vein systems could be unrelated, we cannot rule out a mid-Triassic age for The Burren veins.

In addition to the vertical veins, high quality exposures within the Aillwee Cave expose a set of subhorizontal veins with thicknesses of up to 0.5 m within shales between the massive limestones of the Terraced Member and close to the boundary with the Maumcaha Member (Fig. 1). Bedding surfaces in the Aillwee Cave, bear slickensides with a mean trend of 156° ($n = 7$), and are interpreted to indicate fold-related bed-parallel slip. We interpret this occurrence

to mean that subhorizontal veins and bed-parallel slip indicators occur within the poorly exposed shale beds of The Burren, particularly the thicker beds.

4.2. Vertical persistence

Individual veins typically extend vertically through limestone beds, cross bedding surfaces, thin shale layers and pressure solution surfaces without change in thickness or being offset by bedparallel slip (Fig. 11). This vertical persistence is best observed at Cappanawalla, where individual veins cross several beds of the Terraced Member. Surveys of vein persistence between limestone units at Cappanawalla (Fig. 7) yield persistence ratios ranging from 0.55 to 1 (Table 1).

The high persistence ratio values are consistent with the through-going nature of the veins. Despite their general persistence, however, veins can terminate upwards where they encounter a thick shale layer (>0.5 m). This is best observed on the Aran Islands where shales tend to be

Table 1

Persistence ratios of veins and systematic joints crossing the limestone unit interfaces 9, 10 and interfaces within terrace 8.5 (8.5a and 8.5b) at Cappanawalla (Fig. 4c and Fig. 7). Persistence ratio ${}_U P_L$ signifies joints crossing from the unit above the interface (upper) to the unit below the interface (lower). ${}_L P_U$ is the converse

Horizon number	Systematic joints		Veins	
	${}_U P_L$	${}_L P_U$	${}_U P_L$	${}_L P_U$
10	0.60–0.70	0.60	0.67	1
9	0.06–0.37	0.08–0.25	0.92	1
8.5a	0.48	0.38	0.63	0.55
8.5b	0.30	0.38	0.93	0.63

Table 2

Summary of the fracture length distributions from analysis of digital maps. LN = lognormal, PL = power-law. SD(*s*) is the standard deviation and \bar{s} the mean of the log values that define the normal distributions. K is the coefficient and $-D$ is the exponent of the power-law distributions

Fracture type	Locality	Sample area (m ²)	No. in sample	Distribution
Vein	Capp.	3.60×10^4	1117	LN $\bar{s} = 0.706$, SD(<i>s</i>) = 0.416
Vein	Shesh.	1.144×10^5	3439	PL $K = 1487$, $D = -1.007$
Vein (filtered)	Shesh.	1.144×10^5	1770	PL $K = 630.3$, $D = -0.749$
Joint	Capp.	2.708×10^6	15254	LN $\bar{s} = 0.437$, SD(<i>s</i>) = 0.442
Joint (filtered)	Shesh.	1.144×10^5	4087	LN $\bar{s} = 0.722$, SD(<i>s</i>) = 0.392

thickest (i.e. up to 1.4 m) and both veins and clusters sometimes terminate upwards at shales. In The Burren, however, shales are markedly thinner. Shales are absent from the Slievenaglasha Formation (Gallagher, 1996) and tend to be less than 0.2 m thick in the Terraced Member. The thickest shale was observed in the Aillwee Cave, having a thickness of 0.5 m. Stratigraphically this shale occurs at the boundary of the Maumcaha and Terraced Members of The Burren Formation (Figs. 1 and 4a). In the cave, individual veins were observed to terminate vertically at the shale. However, our field observations, combined with detailed examination of aerial photographs of the Burren (e.g. Fig. 3), suggests that co-planar clusters of veins occur above and below even the thicker shales and that shale beds were not barriers to the vertical propagation of vein clusters.

4.3. Length distribution

Measured vein lengths represent traces on sub-horizontal outcrop and, therefore, are unlikely to represent the maximum bed-parallel dimensions of each vein. We have only limited data concerning the 31 shapes of these veins and their vertical dimensions.

The length distributions of the veins measured from each map area are shown in a frequency distribution plot (Fig. 8a) and summarised in Table 2. At Sheshymore some of the smaller north-south grykes may represent joints rather than veins. Therefore, the data was filtered to exclude all north-south fractures which abut against joints, i.e. those with an ambiguous origin. Both filtered ($n = 1770$) and unfiltered ($n = 3439$) Sheshymore vein datasets are shown on Fig. 8a. The filtered data are believed to provide a better indication of the vein length distribution. Frequency-length curves for both Sheshymore vein samples have a relatively straight portion over the length range 2–70 m (Fig. 8a), indicating an approximately power-law distribution over this length scale (Yielding et al., 1992; Gillespie et al., 1993; Pickering et al., 1995). Veins below 2 m in length are probably undersampled. Veins with a trace length of 70 m are approaching the size of the map and so their length is censored. Regression between lengths of 2 and 70 m, yields the exponent of -1.01 for the unfiltered sample and an exponent of -0.75 for the filtered sample.

At Cappanawalla, veins have a consistent strike that is oblique to the joints and are therefore easily distinguishable (Fig. 6). The fracture map from Cappanawalla includes

Table 3

Summary of the spacing distributions from line samples A-A', B-B' (Fig. 7), C-C' and D-D' (Fig. 5). LN = lognormal, PL = power-law, N = Normal. SD(*s*) is the standard deviation, and \bar{s} is the mean of the spacing or log spacing values that define the normal or lognormal distributions. K is the coefficient and $-D$ is the exponent of the power-law distributions

Fracture type	Locality	Line length (m)	No. in sample	Distribution	C_v
Vein	Capp.	599.08	160	PL $K = 23.68$, $D = -0.69$	2.19
Vein	Shesh.	282.89	103	?PL $K = 33.17$, $D = -0.88$	1.14
Joint	Capp.	139.30	120	LN $\bar{s} = -0.037$, SD(<i>s</i>) = 0.334	0.63
Joint	Shesh.	241.10	202	LN $\bar{s} = -0.001$, SD(<i>s</i>) = 0.299	0.59
Joint (filtered)	Shesh.	149.38	52	N $\bar{s} = 3.020$, SD(<i>s</i>) = 1.562	0.48

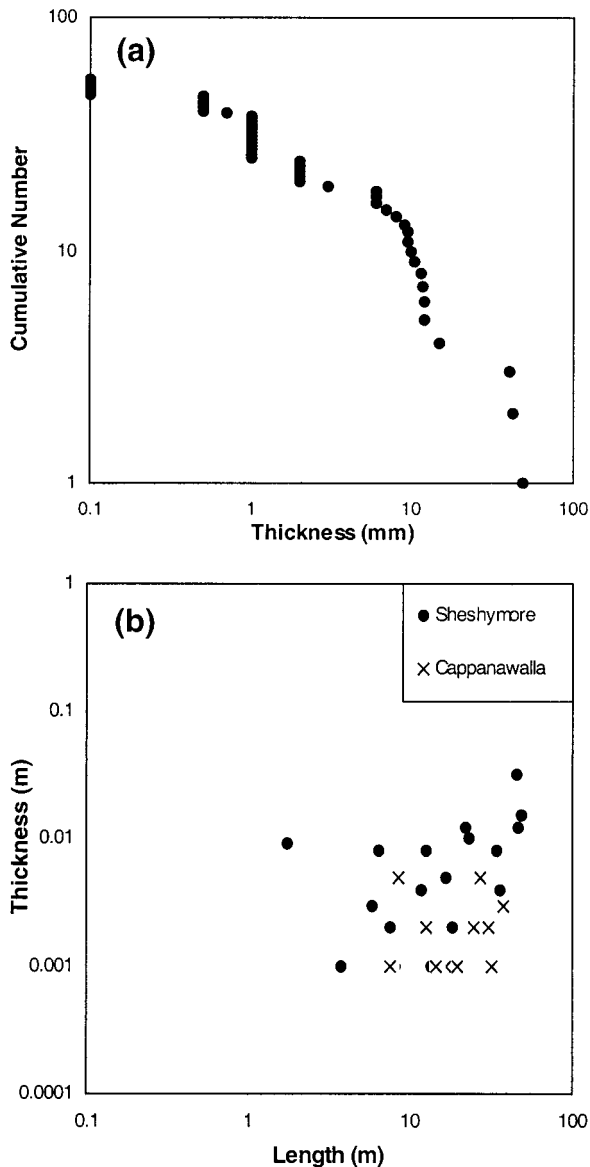


Fig. 12. (a) Cumulative frequency plotted against thickness for veins from a line sample taken at Gleninagh foreshore (Fig. 1). Line length = 156.58 m. (b) Vein length plotted against thickness for data from Sheshymore ($n = 18$) and Cappanawalla ($n = 12$).

small areas with poorly developed grykes and grassy patches of limited exposure. If included in analysis, these areas of limited exposure can introduce errors into the measured length populations. Therefore, the veins were sampled from a subarea in which the exposure is almost 100% (Fig. 6). Veins from Cappanawalla have an approximately lognormal distribution, which produces a bell shaped distribution on log-linear axes (Fig. 8b). It is not clear whether this lognormal distribution is representative of the vein length population or whether the sampling method, boundary effects and outcrop conditions have caused degradation of an underlying power-law distribution to a lognormal distribution, as suggested for joints in the Hornelen sandstone by Odling (1997).

4.4. Spacing

The spatial distributions are represented by vein spacings along single sample lines normal to the strikes of the vein clusters (Table 3). The Sheshymore filtered veins were sampled along a single east-west sample line 283 m long, part of which is shown in Fig. 5b (Line D-D'). On the log-log frequency plot (Fig. 9a), the Sheshymore veins, although not defining a clear power-law, do have a straight line segment which closely parallels that of the Cappanawalla map over the scale range ca 2–10 m.

The veins in the Cappanawalla map were sampled along a single 599 m line sample (line A-A'; Fig. 7). The resulting spacing distribution shows a clear straight line on log-log axes, indicating a power-law with an estimated exponent of -0.69 for values greater than 0.5 m (Fig. 9a). A cumulative frequency plot of vein spacings for the same sample line shows the power-law extending clearly between 0.4 and 60 m; the exponent of the power-law is -0.74, which is close to the value for the frequency distribution (Fig. 9c). The flat portion of the cumulative frequency curve below 0.4 m is probably the result of undersampling below this level (Yielding et al., 1992; Gillespie et al., 1993).

The Cappanawalla veins have a $C_v = 2.19$, which quantifies the high degree of clustering (Gillespie et al., 1999) evident from visual inspection of the map (Table 3, Fig. 7). The Sheshymore veins yield a $C_v = 1.14$, which, although indicating a significant degree of clustering, is considerably less than that at Cappanawalla (Table 3). The difference is at least partly due to the greater strike dispersion of the Sheshymore veins (Fig. 5), which tends to make the clustering appear more random within the sample line.

4.5. Vein thickness

A wave-cut platform at Gleninagh (Fig. 1) affords good exposure of the north-south striking vein set and allows the thickness of the veins to be recorded. Vein thicknesses were measured along a line sample on the wave-cut platform (Fig. 12a) where the extension accounted for by the veins is 0.21%. A log-log cumulative number vs thickness curve for the line sample is rather irregular and subject to rounding errors, but is consistent with a power-law distribution, with an exponent of -0.62 for values in the range 0.5–10 mm (Fig. 12a).

At Sheshymore and Cappanawalla rare outcrops of uneroded veins allow some vein thicknesses to be measured. The length to thickness ratio ranges between 1000 and 10 000 (Fig. 12b). The ratio follows a lognormal distribution with a geometric mean of 3.66 and a standard deviation of 0.48. This value is consistent with values measured for veins formed of non-relaying veins (multi-segment veins) measured by Vermilye and Scholz (1995).

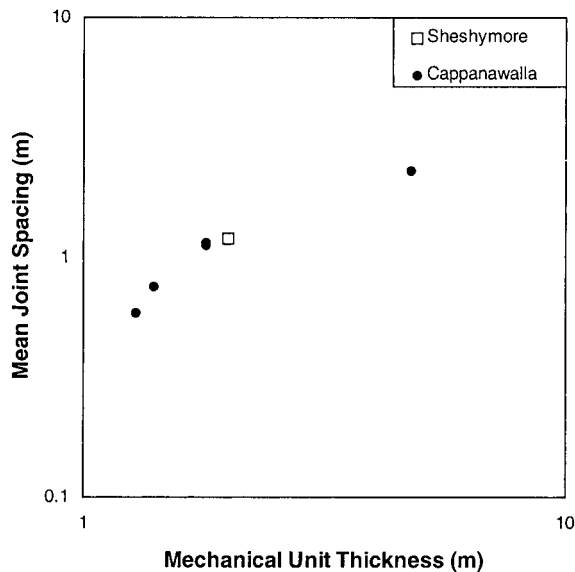


Fig. 13. Plot of mechanical unit thickness against mean spacing for systematic joints in The Burren (Sheshymore and Cappanawalla).

4.6. Conditions of vein development

The subvertical veins form a single set with limited strike variation. At the few localities where observation is possible, the veins can be shown to have opened in a direction normal to their walls. These veins, therefore, are a relatively simple set of mode I fractures, sometimes accompanied by the development of the bed-parallel veins which may be of the same age.

Where the subvertical veins pass each other, in plan view, they are not deflected. This feature indicates that the veins may have formed under relatively high differential stress (Olson and Pollard, 1989). It is probable that such high differential stresses occurred during Variscan deformation in response to north-south directed compression.

The subvertical veins are likely to have formed at a depth greater than that at which a tensile minimum principal stress would be expected. Therefore, the fractures required the presence of an overpressured pore fluid for their formation as mode I fractures (Secor, 1965; Narr and Currie, 1982; Engelder, 1985; Olson, 1993). The existence of the bed-parallel veins indicates that pressures within the overpressured pore fluids may locally have exceeded the lithostatic pressure. Although the overlying Namurian shales (Fig. 4a) could have provided a top-seal to the overpressured fluids, thicker shale interbeds between the limestones of The Burren may, to some extent, have compartmentalised the pore fluid system.

The geometry of the veins, in particular their regular, planar nature and their lack of forking, is consistent with sub-critical vein growth. In addition, the presence of C-type plumes (Bahat and Engelder, 1984; Engelder, 1985) with a lack of rib marks or coarse hackles found along preserved vein walls at Lisdoonvarna Council quarry (Fig. 1) further

suggests sub-critical crack growth (Engelder and Fischer, 1996).

5. Joints

5.1. General features

The joints are typically subvertical and form organised connected networks in plan view. In most areas of The Burren a dominant systematic set of subparallel joints can be identified with individual joint traces up to 100 m long (Figs. 5 and 6). The systematic joints show no evidence for shear displacements and have no tendency to form *en échelon* alignments. The joints have smooth trajectories and do not bifurcate.

Other joint sets abut against the systematic joints and, therefore, the systematic joints formed earlier (Dunne and Hancock, 1994). The later joints that are perpendicular to the systematic joints are termed perpendicular cross joints (Gross, 1993; e.g. southeast part of Fig. 6), while later joints which are oblique to the systematic joints are termed oblique cross joints (e.g. northeast part of Fig. 6). Perpendicular cross joints or oblique cross joints are typically no more than 4 m long, and have lengths and spacings that are controlled by the spacing of the earlier systematic joint sets. Details of the relationships between systematic and cross joints are, however, beyond the scope of this article. Curvilinear and subhorizontal joints also occur in the more massive limestone units.

The orientation of the systematic joints is generally consistent on the scale of a few kilometers. Joint orientation however is not consistent over the whole of The Burren. For example, the systematic joints at Cappanawalla strike consistently northwest-southeast (Fig. 6), while the systematic joints at Sheshymore strike east-west (Fig. 5). The orientation of the later cross joints varies over a few tens of metres. For instance, at Cappanawalla (Fig. 6) the later joints are oblique in the centre of the map, but in the southwest and northeast portions of the map only perpendicular cross joints occur.

At Sheshymore the systematic joints generally strike west-east, parallel to the synclinal axis (Fig. 5). Where one joint has a strike that is clockwise of another, the clockwise joint is consistently found to abut against the other (e.g. Fig. 5, boxed area). This feature suggests that during joint formation there was a progressive clockwise rotation of ca 10–30° of the minimum principal stress direction. At Cappanawalla, the abutting relationships of the systematic joints and the relative orientations of systematic and oblique cross joints both suggest a progressive anticlockwise rotation of ca 15–25° (Fig. 6). These small rotations, together with the difference in the rotational sense between Cappanawalla and Sheshymore, can be reconciled with the work of Rives and Petit (1990) which demonstrates that slight rotations of joint sets occur during the

development of noncylindrical folds in analogue models. Although joints in The Burren post-date folding, progressive rotation of joint orientations may reflect the small changes in local stress orientations arising from the uplift of weakly folded beds. These rotations were important in determining the lengths and the connectivity of the joints (Odling et al., 1999).

5.2. Vertical persistence

The Burren joint patterns vary markedly between beds in terms of overall density and spacing of the systematic joints (e.g. surface 9 vs 10, Fig. 6). These variations reflect an important difference between joints and veins in The Burren. Unlike veins, individual joints are mostly confined to a single limestone bedding unit. Here, the term limestone unit refers to a mechanically distinct layer in which the joints are largely vertically contained, bounded either by bedding-parallel pressure solution surfaces, or by thin shales. Commonly, individual limestone units coincide with distinct terraces at Cappanawalla, although occasionally a single terrace may include several mechanical layers (e.g. Fig. 4c, terrace 8.5). Furthermore, where the unit is more than a few metres thick, the joints commonly do not extend throughout the full vertical extent of that individual unit (Fig. 11). Together, these features are reflected in joint persistence ratios as low as 0.06 (Cappanawalla horizon 9, Table 1). The difference in joint pattern characteristics between units cannot be easily explained in terms of lithology, because the units are grainstones/packstones which are very similar in thin section.

Although not commonplace, some units have joint persistence ratios of as high as 0.7 (Table 1), indicating that they are not as mechanically distinct as others. It is suggested therefore that some joints may have been controlled by a larger mechanical layer thickness than the limestone units in which they were measured (Becker and Gross, 1996), providing a fracture system geometry that is, to some extent, hierarchical (Fig. 11). Lower persistence ratios are nevertheless the norm, and joints seldom tend to cross more than two mechanically significant interfaces. The generally low vertical joint persistence contrasts with the veins and vein clusters at Cappanawalla, which tend to persist from one unit to another (Figs. 6 and 11). The joints generally cut straight across the veins. Unimpeded joint propagation is to be expected because the veins were calcite-cemented prior to joint formation.

5.3. Length

Length populations of the systematic joints from the two areas are shown in Fig. 8 and summarised in Table 2. The Sheshymore data were recorded over the entire digitised map area and are of high quality. The Cappanawalla data are from unit 9 (Fig. 7) and are more affected by areas of indifferent exposure, which tends to truncate the lengths of the joints.

The results (Fig. 8) show clear lognormal length distributions for both samples, with no indication of power-law behaviour. It is thought that the lognormal distribution arises from the process of rotation and abutment described above. At both Cappanawalla and Sheshymore, a high proportion of joint terminations are abutments with other joints, so joint lengths are largely constrained by the relative orientation and spacing of pre-existing joints. This geometry explains why joint lengths are restricted to a relatively narrow range of scales.

5.4. Spacing

The systematic joints of the Sheshymore map were sampled along line C-C' in Fig. 4. A subsample was also produced along this line including only the earliest systematic joints. These were chosen on the basis of systematic abutting relationships and are essentially those that strike north of 090° (Fig. 5). The systematic joints of unit 9 at Cappanawalla were sampled along line B-B' in Fig. 7.

Visual inspection of the maps (Figs. 5 and 6) suggests that systematic joints are much more regularly spaced than veins and this impression is confirmed by C_v values of 0.63 and 0.59 for Cappanawalla and Sheshymore, respectively (Table 3). The Sheshymore sub-sample gives a C_v of 0.48 (Table 3), which indicates that the earliest set of systematic joints has a more regular spacing than the fully developed set of systematic joints. The frequency distributions of the spacing of the systematic joints for Cappanawalla and Sheshymore are approximately lognormal (Fig. 9b). The filtered Sheshymore joints, however, have an approximately normal distribution, which is consistent with their more regular spacing and the limited scale range of the spaces.

Mean spacings between systematic joints are plotted against mechanical unit thickness for different localities in The Burren (Fig. 4a, b and Fig. 13). The positive relationship between mechanical unit thickness and joint spacing for joints in The Burren, reflects the scale dependence of the joints and is a common feature of many other joint systems in layered sequences (Huang and Angelier, 1989; Narr and Suppe, 1991; Gross et al., 1995; Bai and Pollard, 2000).

5.5. Conditions of joint development

The joints post-date the veins and are therefore post Variscan; the only other age constraint is that the joints pre-date the formation of the >350 ka Aillwee cave (Drew, 1994). The joints and veins controlled the development of the cave system beneath The Burren. Maps of cave systems down to 300 m below the present topographic surface demonstrate the influence of both the vein and the joint systems on the cave geometry and so both veins and joints extend to at least this depth (Tratman, 1967).

The joints formed as simple mode I fractures, developed perpendicular to the minimum principal stress. Their smooth shape, lack of bifurcation and the absence of

evidence of shear displacements along them indicate that they most probably formed under subcritical conditions (Lawn and Wilshaw, 1975; Atkinson and Meredith, 1987; Olson, 1993).

The regionally variable orientation of the systematic joints is not compatible with their formation under a high differential tectonic stress and it is more likely that they were formed during regional uplift as “unloading joints” (Engelder, 1985). The absence of mineralisation is also consistent with formation at relatively shallow depths and not by hydraulic fracture. At Sheshymore, adjacent overlapping systematic joints typically curve towards one another and intersect at high angles or have perpendicular abutments (Fig. 5, coordinates (225, 235)). This is a characteristic of joints formed in a stress regime where the ratio between the regional horizontal principal stresses ranges between 1 and 3 (Dyer, 1988; Olson and Pollard, 1989).

6. Comparison between vein and joint characteristics

A summary of the principal geometric characteristics of the veins and the joints in The Burren is given in Table 4. The crucial difference between the veins and joint arrays is that the vertical propagation of veins was more or less unrestricted whereas most joints are restricted to single limestone mechanical units. The vein characteristics are consistent with a fracture array in a mechanically uniform host. The joints, on the other hand, are characteristic of fracturing in a multilayer, where each mechanically isolated layer fractures largely independently of the other layers. The two types of fracture systems are referred to as non-stratabound and stratabound, respectively (Gillespie et al. 1999). Non-stratabound systems may be scale-independent, whereas stratabound systems are typically scale-dependent, with fracture dimensions and spacing determined by the scale of the mechanical layering.

At Cappanawalla, the veins cut through the different units, but the joints are largely limited to individual units (Figs. 6 and 11). The description of the joints as a simple stratabound system is, however, a simplification. In the thicker units, the cross-sectional geometry of the joints can be quite complex and not all of the joints are continuous throughout an individual limestone unit (i.e. terminating at upper and lower interfaces). In addition, we cannot rule out the possibility that the geometry of the veins and vein

clusters are not influenced, to some extent, by larger scale mechanical units in excess of a few tens of metres thick. At this large scale, vein clusters may show some hierarchical scaling properties with, for example, the preferential development of characteristic spacings related to larger scale mechanical unit thicknesses (Huang and Angelier, 1989; Narr and Suppe, 1991; Gross et al., 1995; Bai and Pollard, 2000). Further studies are required to more rigorously test this hypothesis. From our detailed studies of Cappanawalla and Sheshymore, it is however clear that the vein system is non-stratabound within sequences in excess of a few decametres thick.

A possible reason for the difference between the vein and the joint systematics might be that the rock properties of the host limestones were different at the time of formation of the veins and of the joints. Given that the limestones had reached minimum burial depths of 1.25 km prior to vein formation, they would however have lost their porosity and had properties that were much the same as at the time of joint formation.

The size and spacing systematics of the scale-independent vein system are similar to those of other scale-independent systems, both geological and non-geological. The length distribution is power-law, as is the spacing distribution, which is clustered rather than periodic. A power-law length distribution has also been described for unidirectional and highly clustered joints within granite (Segall and Pollard, 1983). Joints in granite typify fractures in a non-stratabound system and are therefore very similar to The Burren veins. Although growth models for fractures have been previously devised to account for power-law length distributions (e.g. Clark et al., 1995), a mechanical model to account for the power-law spacing distributions and clustering of scale-independent fracture systems is briefly described below.

7. Mechanical rationale for spacing of veins and joints in The Burren

7.1. General

The spatial distribution of the joints and veins in The Burren can be understood in terms of the stresses around the fractures predicted by linear elastic fracture mechanics. Opening-mode fractures have complex stress distributions in their surrounding volumes. These comprise: (i) a zone of reduced tensile stress (i.e. stress shadow) in the volumes on either side of the fracture, in which fracture growth is inhibited; and (ii) a tip region of increased stress, in which the growth of new fractures is enhanced. The stress intensity at the crack-tip and the size of the stress shadow are proportional to the square-root of the length of the fracture (Ingraffea, 1987) when the fracture is not strongly affected by rock layering (Olson, 1993; Gross et al., 1995). The spatial distribution of fractures is the result of the balance

Table 4
Comparison of vein and joint systematics from The Burren

Veins	Joints
Non-stratabound	Stratabound
Regionally uniform strike	Regionally variable strike
Clustered (power-law)	Regularly spaced
Probable power-law lengths	Lognormal lengths
Disconnected (in plan view)	Highly connected (in plan view)

between these factors, arising from the mechanical interaction of fractures within the fracture system.

7.2. The Burren veins

From the vertically persistent nature of The Burren veins, it can be inferred that the stratigraphic layering of the host rocks was of little importance during their growth. As a consequence, mechanical unit thickness did not control the size of the stress shadow, and the stress intensity at the crack-tips scaled with the length of the fractures. This situation implies that longer fractures had higher stress intensities and grew at faster rates than smaller fractures. In front of the tip of a long propagating fracture, elevated driving stresses can promote the growth of smaller fractures (Olson, 1993; Renshaw and Pollard, 1994). As the smaller fractures are passed by a more rapidly propagating longer fracture, they will fall into the stress shadow of this larger fracture, and die. This process is known as crack-tip shielding (Weertman et al., 1983; Olson, 1993) and is probably responsible for a significant proportion of vein clustering in The Burren. The significance of crack-tip shielding and the degree of fracture clustering does however vary with the velocity exponent on the crack-tip intensity (Renshaw and Pollard 1994). The velocity exponent controls how strongly the propagation velocity of a fracture is related to the degree of stress concentration at the fracture tip. Our unpublished numerical modelling, using a scheme similar to that of Renshaw and Pollard (1994), suggests that the vein system geometries of Capanawalla and Sheshymore are compatible with relatively low velocity exponents (personal communication, George Tuckwell).

Clustering of fractures resulting in power-law or skewed distributions of spacing has also been reported for other non-stratabound systems, for example in the jointed Jabal Qutan granite in Saudi Arabia (Genter and Castaing, 1997) and is evident in the massive sandstones of the Navajo Formation, Utah (Olson, 1993). These results support the notion that non-stratabound systems, such as The Burren veins, have fractal geometries.

7.3. The Burren joints

In multilayered elastic materials, such as The Burren limestones, it is well established that the width of the stress shadow around fractures is controlled by the rock layering and specifically by the mechanical unit thickness (Hobbs, 1967; Narr and Suppe, 1991; Gross et al., 1995; Bai and Pollard, 2000). Therefore, as a fracture population develops, the fracture density increases towards a finite value until no more joints can develop due to the interaction of stress shadows, at which point the system is said to be saturated for the given stress conditions (Rives et al., 1992; Bai and Pollard, 2000). The magnitude of stress intensity at the crack-tip is also controlled by the unit thickness. Once fractures have lengths greater than the mechanical unit thickness, the stress intensity factor is largely independent

of length, and the absolute stress intensity factor is small compared to non-stratabound systems. These lower stress intensity factors do not promote the growth of small associated fractures at the crack-tip. This factor combined with the relatively uniform stress shadow widths, provides fracturing conditions in which clustering is inhibited and regular spacing is developed.

In stratabound systems, joints tend to be long, as the stress shadows around the fractures are relatively narrow. In such a system, joint lengths are determined by abutting relationships and small progressive rotations in the remote stress orientations will strongly control the joint length populations.

7.4. Depth control on fracture characteristics

In the preceding sections, we have argued that the scale of the operational mechanical layering in The Burren has played a fundamental role in determining the systematics of the veins and joints. The question then arises as to what are the critical controls on the vertical persistence of fractures. Some idea of the depths at which the transition occurs between the two types of system can be obtained by applying a model proposed by Renshaw and Pollard (1995). This model is based on the premise that vertical propagation of a fracture across a sub-horizontal discontinuity is determined by whether the dilation, or extension, across a fracture in one bed can be accommodated by sliding on the interface between that bed and the next. If sliding on the interface is not possible and the tensile strength of the rock on the far side of the interface is exceeded, then the fracture will propagate across the interface. In general, at greater depths and higher lithostatic pressures, the normal stress across the interface between two beds will be higher and so will tend to inhibit sliding and, therefore, to promote propagation of a fracture across the interface. Hence vertically persistent fractures will tend to form at greater depths than impersistent fractures. Though this factor provides a rationale for the different geometrical properties of the veins and joints in The Burren, we briefly consider some of the broader implications of this model below.

The condition for a fracture to propagate across a horizontal discontinuity between two beds of identical elastic properties is (Renshaw and Pollard 1995):

$$\frac{\sigma_v}{T_0 + \sigma_h} > \frac{0.35 + \frac{0.35}{\mu}}{1.06} \quad (1)$$

Where σ_v = vertical principal stress, σ_h = minimum horizontal principal stress, T_0 = tensile strength of the material, μ is the coefficient of friction on the interface and compressive stresses are positive. As the fractures are vertical it is assumed that $\sigma_v > \sigma_h$. To include the effects of pore fluid pressure, the principal stresses are replaced with effective stresses:

$$\frac{\sigma_v - P}{T_0 + (\sigma_h - P)} > k \quad (2)$$

Where P is the pore fluid pressure and k represents the frictional constant on the right-hand side of Eq. (1).

The ratio of pore fluid pressure to lithostatic pressure is defined as λ . The minimum horizontal principal stress is not known, but at constant λ , σ_h is proportional to σ_v , (McGarr and Gay, 1978; Brace and Kohlstedt, 1980), so if the stress ratio, R , of horizontal and vertical principal stresses is defined as:

$$R = \frac{\sigma_h}{\sigma_v} \quad (3)$$

then Eq. (2) can be reformulated to:

$$\frac{\sigma_v(1 - \lambda)}{T_0 + \sigma_v(R - \lambda)} > k \quad (4)$$

Substituting $\sigma_v = z\rho g$, (z = depth, ρ = density and g acceleration due to gravity) and rearranging, vertical propagation across a horizontal discontinuity will occur at $z > z_c$, where:

$$z_c > \frac{kT_0}{\rho g[(1 - \lambda) - k(R - \lambda)]} \quad (5)$$

Where Z_c , is the critical depth for the development of non-stratabound fractures.

Analysis of Eq. (5) shows that for realistic values of ρ , the critical depth (Z_c) is strongly dependent on R and only weakly dependent on λ (see Fig. 14), because any increase in fluid pressure, whilst lessening the effective normal stress on the discontinuity and promoting sliding, will also provide a greater increase in the tensile driving stress of the fracture. The critical control on vertical propagation is therefore the lithostatic pressure, although an increase in λ decreases the driving stress, thus inhibiting propagation and increasing the depth of transition from stratabound to non-stratabound fractures. This model applies to interfaces between rock units with elastic properties and is not applicable where there are clay or shale layers between the massive limestone units. Ductile layers can inhibit crack propagation by dramatically reducing the crack-tip stresses by ductile flow, and the presence of clay layers will tend to increase the critical depth z_c .

The tensile strength of Carboniferous limestone from Colwyn Bay, north Wales, which is similar to The Burren Formation limestone, is 13.72 MPa (Snowdon et al., 1982). Assuming a tensile strength of 14 MPa, $\mu = 0.6$ and a density of 2650 kg/MPa for The Burren limestones, the critical depth for vertical fracture propagation across bedding discontinuities is 0.6–2 km, for stress ratios of 0.25–0.75 (Fig. 14a). Our estimated depth of formation of veins in The Burren is in excess of 1.25 km (Section 4.1) and is therefore consistent with the calculated critical depths.

Improved definition of the likely depths of formation of The Burren veins can be derived from the model for mode I fracturing developed by Secor (1965) and further refined by Sibson (1996). Failure in mode I requires low differential stresses and high fluid pressures, and the criteria $(\sigma_1 - \sigma_3) < 4T_0$, and $P > (T_0 + \sigma_3)$ must be satisfied (e.g.

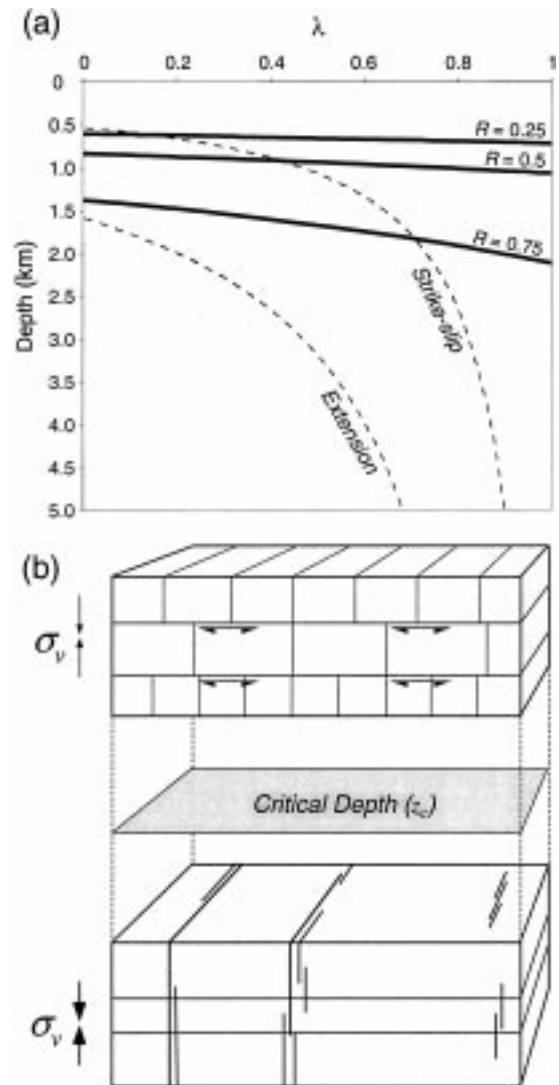


Fig. 14. (a) Calculated curves for critical depths for stress ratios, $R = 0.25$ – 0.75 , in rocks equivalent to The Burren limestones (solid lines). The solid curves represent z_c , the theoretical minimum depth at which non-stratabound fractures develop. Dashed lines represent the theoretical maximum depth of mode I fracture development under extensional and strike-slip stress regimes. From these curves, it can be deduced that The Burren veins are likely to have formed at depths of 0.6 km to in excess of 2.5 km. The estimated minimum depth of formation was 1.25 km (see text) and pore fluid pressures were in excess of, hydrostatic (i.e. $\lambda > 0.38$). (b) Schematic diagram to illustrate the dependency of the geometric characteristics of fracture systems upon the overburden stress (σ_v) at the time of their formation. At shallow depths, a regularly spaced, stratabound systematic joint set will tend to develop (The Burren joints). Below the critical depth (z_c), a non-stratabound fracture system will develop (e.g. The Burren veins).

Secor, 1965). Sibson (1996) used the procedure of Secor (1965) to determine the limiting depths for the formation of mode I cracks as a function of the pore-fluid factor. In an extensional regime, $\sigma_v = \sigma_1$ and the limiting depth is $h < 3T_0/(1 - \lambda)g\rho$. In a pure strike-slip regime, $\sigma_v = 0.5(\sigma_1 + \sigma_3)$, and the limiting depth is given by $h < T_0/(1 - \lambda)g\rho$. Curves generated from these expressions show the depths above which mode I fractures can develop

in these different regimes (Fig. 14). Combining these curves with the critical depth curves suggests that the non-stratabound fractures of The Burren must have formed between depths of 0.6 km and greater than 2.5 km for pore fluid pressures at, or in excess of, hydrostatic (Fig. 14a). These predictions are consistent with our estimate of the 1.25 km minimum depth of formation of the Burren veins and evidence suggesting that related pore fluid pressures were greater than hydrostatic. We have not presented curves for a thrust stress regime because the Burren veins are vertical and therefore did not grow under a Vertical least principal compressive stress (σ_3).

Evidence that open fractures similar to the veins of The Burren exist at depth comes from fractured reservoirs, where relatively undisturbed sub-horizontal bedding is cut by a single set of open subvertical mode I fractures of consistent strike direction (Table 5). All listed examples have mineral fill and, except for the Altamont reservoir, have fractures striking parallel to the present maximum horizontal principal stress, i.e. they are neotectonic rather than ancient fractures. These and numerous other examples provide unequivocal evidence of subvertical mode I fractures having formed at depths of 1–4 km in sedimentary sequences. In the Piceance Basin, Lorenz and Finley (1991) report that fracture spacing is not related to bed thickness and that the average fracture spacing tends to be small, possibly implying a non-stratabound system similar to The Burren veins.

The observations in The Burren suggest that at any one time there may be different kinds of fracturing occurring at different levels in the crust (Fig. 14b). At lower levels, non-stratabound fractures may occur which may be clustered and filled with mineralising fluids. Higher in the crust the fractures will be stratabound and scale-dependent. A similar concept was suggested by Hancock (1991) who suggested that fluid driven “wet” fractures occur deeper in the crust, while at shallower depths (less than 500 m) joints can develop by true tensile stresses, driven by uplift and erosion. In The Burren the “wet” fractures would represent the veins and the “dry” fractures the joints.

8. Conclusions

1. The Late Asbian to Brigantian age limestones of The Burren host two types of mode I fractures, veins and joints, with fundamentally different scaling properties.

2. The Burren veins are highly clustered, non-stratabound fractures formed in response to N-S directed compression during the Variscan Orogeny. The veins show probable power-law size and spatial distributions. They are poorly connected in plan view but may be linked by subhorizontal layer-parallel veins.
3. The Burren joints occur in stratabound fracture networks formed during uplift. Joints have regular spacings, the scale of which is related to the thickness of the mechanical units. They form well connected networks, with the lengths of the joints controlled by abutting relationships and providing a lognormal distribution.
4. The different scaling properties of joints and veins are attributed to different overburden stresses at the time of formation. The veins formed at greater depths than the uplift-related joints, under conditions that allowed the propagation of fractures across bedding discontinuities and the consequent development of non-stratabound scaling properties.
5. Mechanical modelling suggests the critical depth for vertical fracture propagation across bedding discontinuities in The Burren is 0.6 to >2.5 km, for stress ratios of 0.25–0.75, and for pore fluid pressures that are at, or in excess of, hydrostatic. These predictions are consistent with the estimated depths of vein formation (> 1.25 km) and with evidence suggesting pore fluid pressures in excess of hydrostatic.
6. The Burren study demonstrates that stratabound and non-stratabound fractures, characterised by very different scaling properties, can be developed within the same lithological sequence but at different formation conditions.

Acknowledgements

We acknowledge Conor MacDermot for much helpful information about the geology of The Burren. Thanks are also due to Paul Jackson and the late Dave Johnston for help in the field. Additionally, Marie Eales and Dan Ellis of the Fault Analysis Group are thanked for the excruciating task of digitising the fracture maps. BKS Ground Surveys carried out the aerial survey of The Burren. Discussions with George Tuckwell and thorough reviews by Tim Davis, Mark Fischer and Bill Dunne helped to significantly improve the manuscript. This work was funded by the Joule II program of the European Commission (CT93 0334).

Table 5
Depths of partially open fractures in flat lying oil reservoirs

Field	Lithology	Present depth of open fractures	Reference
Altamont Field, Utah	Quartz cemented sandstones	3.4–4.1 km	Narr and Currie, 1982
Little Knife Field, North Dakota	Limestones/dolomites	3.0–3.15 km	Narr and Burruss, 1984
Appleby Field East Texas Basin	Sandstones	1.79 to 3.6 km	Laubach, 1989
Piceance Basin, Colorado	Sandstones and siltstones	1.2 to 2.5 km	Lorenz and Finley, 1991

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