

RELATIONS OF JOINTING TO ORIENTATION OF SOLUTION CAVITIES IN LIMESTONES OF CENTRAL PENNSYLVANIA*

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ABSTRACT. Twenty-six caves located in anticlinal, limestone-floored valleys of the Central Pennsylvania Valley and Ridge were divided into passage segments inferred to have formed along the strike of fracture planes. These segments were cumulated by footage to determine statistically preferred orientations. For each cave passage, bearings weighted by footage were used to calculate an average passage orientation. Fractures measured at outcrops near the caves were classed by the strike of subparallel sets which were cumulated by frequency to determine their preferred orientations. The average passage orientation compared with the orientation of fracture frequency was significant to the 95 percent level, and a plot of the relationship proved to be broadly linear. Thus the caves develop more footage parallel to the strike of the more abundant fractures.

These most abundant fractures are mainly vertical strike joints and steeply dipping bedding planes, and they lie parallel both to the anticlinal axes and down-valley water flow. This evidence tends to support increased solution activity along vertical joints of possible tensional origin.

Individual cave patterns were found to reflect local fracture systems where: (1) linear caves develop along more steeply dipping and probably more closely spaced bedding planes; (2) several caves, particularly along flanks of folds, develop major passage along a set of the same subparallel fractures; (3) as the local structure changes the fracture orientation, the cave passages parallel the local fractures even though they are developed at a large angle to fracture-oriented passages in other caves; (4) widely-spaced cave passages develop where intersecting fracture sets are also widely spaced. Similarly, closely-spaced passages appear to develop in zones of fracture concentration.

Solution passages therefore can be used as one determinant of the local fracture system, and a selective solution process may be related to the mechanical origin of the fractures as well as their frequency.

INTRODUCTION

For many years it has been recognized that caverns formed by solution in carbonate rocks are opened along selected fractures through which water moves more effectively than elsewhere (for example, Davies, 1960). The distribution of these caverns in a body of soluble rock reflects an interaction between the orientation of gross bedrock structures and thus the fractures used as conduits, the general flow directions in the system, and the geochemical processes involved in dissolving the bedrock.

The general problem of the effects of a preexisting fracture system on the distribution of solution activity can be approached from the following three interacting components. The fracture system is approximated from the frequency of bearing measurements which are related to local and regional deformation. Directions of maximum water flow, along which there will be greater solution activity, are determined from maps of water-level gradients in the ground-water body. And, the average physical orientation of the caverns are derived from maps surveyed with compass and tape.

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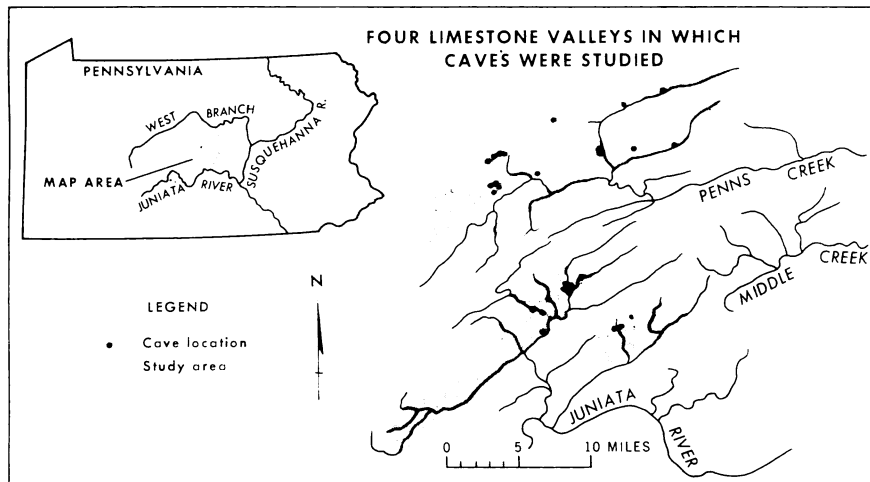


Fig. 1. Index maps showing location in central Pennsylvania of the four valleys studied. Shaded areas also show roughly the extent of carbonate sediments.

In this study an area was chosen in which water flow directions are reasonably well-known in order to test a quantitative method that directly relates the orientation of specific solution passages with associated local fracture systems.

GEOLOGICAL SETTING OF THE STUDY AREA

Twenty-six caves in Central Pennsylvania (see loc. map, fig. 1, and selected cave maps, fig. 10) were used for this study. The caves are in four valleys floored with Ordovician limestones (see geol. map, fig. 2). The three northern valleys, Brush, Penns, and Kishocoquillas Valleys, are breached anticlines. The valleys are nearly enclosed by long mountain ridges supported by synclinally folded sandstones and shales. Numerous small streams flow off the ridges and disappear into the limestones; surface flow of water on the valley floors is generally limited.

In 1938, S. W. Lohman noted that ground water here flows down-valley and thus along strike-oriented solution cavities. In order to intersect these conduits, he suggested locating new water wells some distance across the strike from existing low-yield wells. In general, this subsurface flow discharges at the nearest major gap in the southeastern ridges where springs emerge and large streams flow south through the gap into the next valley (see fig. 2).

In Pleasant Valley, to the south, the structures are more tightly folded and not so deeply eroded. The caves are on a ridge flank in a thin band of Devonian limestone between relatively impermeable beds. The limestone crops out along the northwestern side of the valley and dips southeast into a synclinal structure under the valley (see fig. 2). Streams rising on the mountain ridge north of the valley are captured within the limestone outcrop area, and the water is routed downdip and

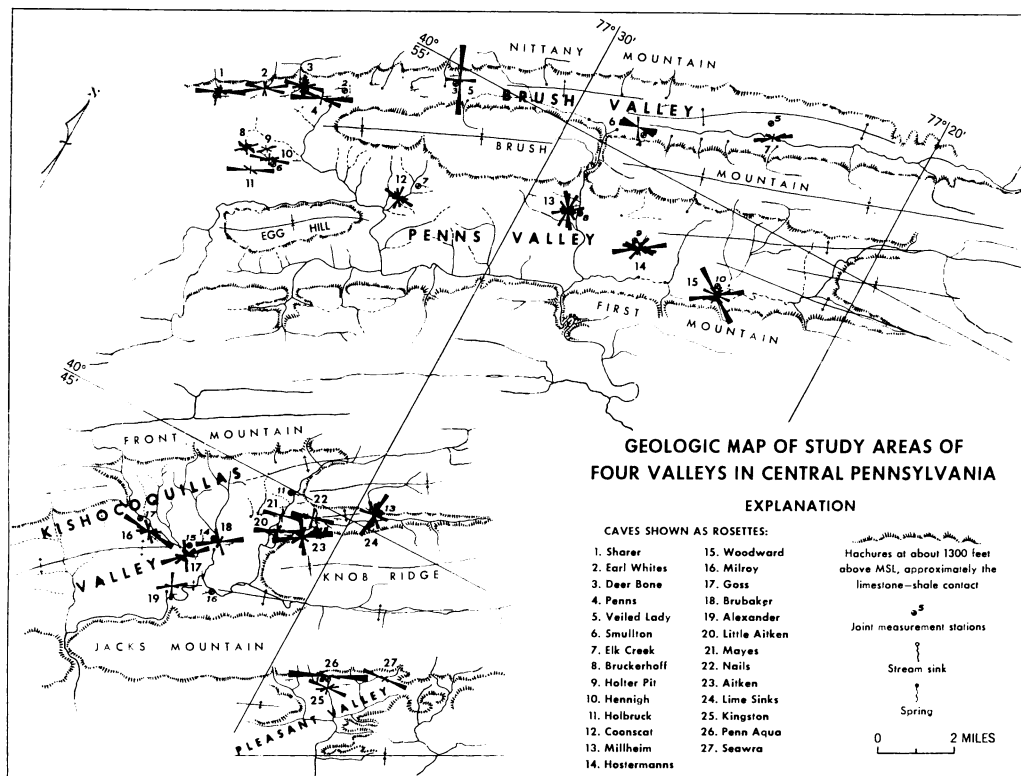


Fig. 2. Map of the four valleys studied showing general geology and rosettes of caves. The valleys and associated ridges are outlined by hachures at roughly the 1300-foot contour. Major fold axes are shown as are some scattered strike-dip measurements. Locations where fractures were measured are indicated.

deep underground. The limestone in the area of the cave is thin-bedded, jointed, and thus transmissible. The caves (see for example, the map of Penn Aqua, fig. 10) are long bedding plane tubes extending along the strike and were apparently developed where CO_2 -charged surface waters from the mountain stream had quick access to the groundwater body which lies at considerable depth below the surface.

REGIONAL AND LOCAL FRACTURE CONTROL OF GROUND-WATER FLOW

In the two histograms on figure 3, regional cave and joint trends are shown. In the lower histogram cumulative percent of cave footage plotted against bearing is shown for the 26 caves. In the upper histogram, roughly 400 joints measured at the locations shown on figure 2 are plotted cumulatively from each outcrop, where the joints in each set represent a percentage of the total for the outcrop, and each set possesses an average strike. These average strikes for all the outcrops are classed in 10° sectors along the x axis, and the percentage of the total for each set in a class are cumulated along the y axis.

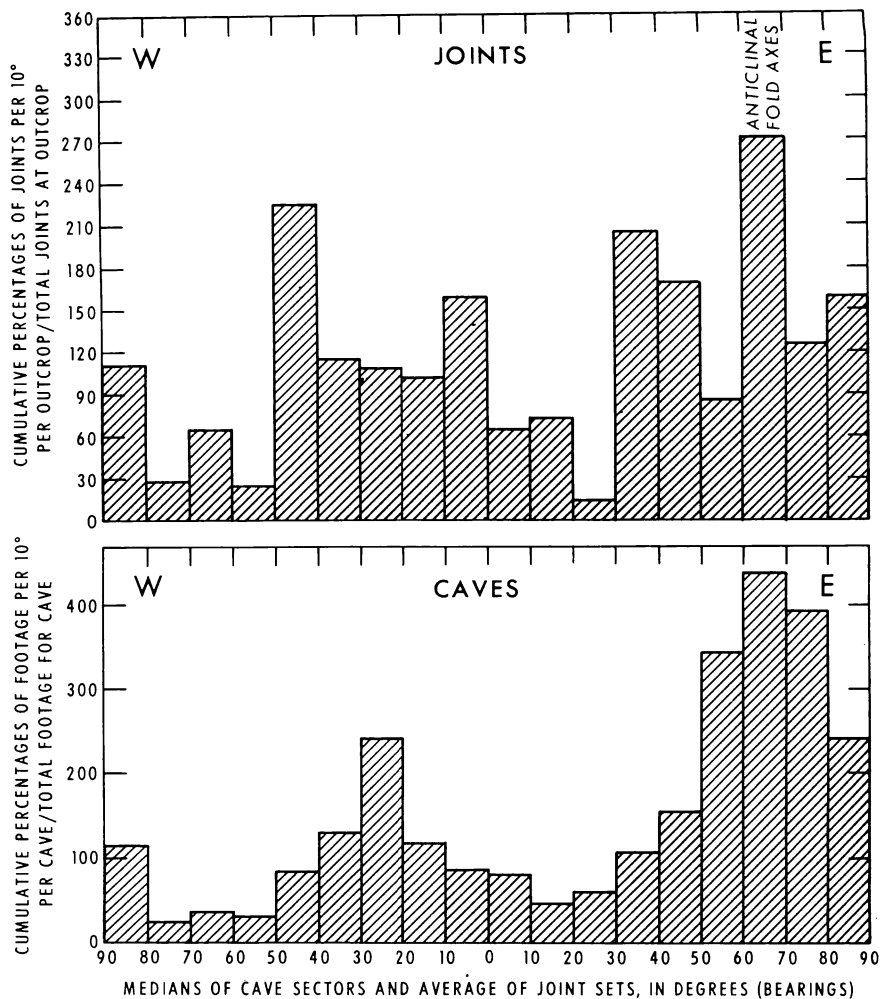
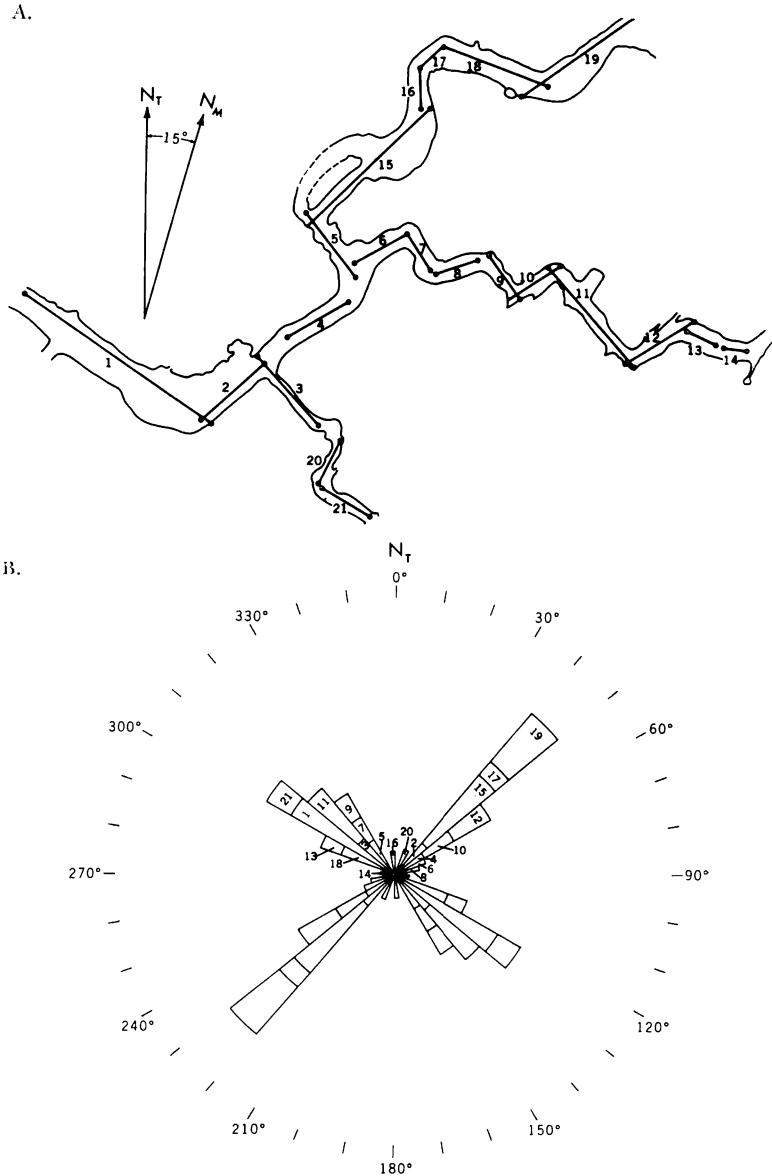


Fig. 3. Histograms showing: 1. (lower) the percent of cave passage at each bearing per cave, accumulated for all caves studied; 2 (upper) the percentage of joints at each bearing per total measured at the outcrop, accumulated for all the outcrops measured.

The high frequency of joints between 60 and 70° E parallel the anticlinal fold axes. As a group, the caves develop maximum passages in two orientations, N 65° E and N 25° W. These are also the azimuths of strike and dip of the strata in this part of the Valley and Ridge province. Note that more cave passage develops in a strike direction and thus parallel to the high joint frequency than along the dip. This reflects the hydraulic gradient parallel to the valley and along the strike; it also suggests that more fractures may be available in this direction to carry water flow.

To determine quantitatively the extent of fracture control on cave passages, individual caves showing typically angular patterns (see the example in fig. 4A) are divided into segments of straight passage, each inferred to have formed along a fracture plane. Since many segments of



passage are subparallel, the further inference is made that they may have formed along a set of subparallel fractures. Therefore, the length cumulated for all solution cavities formed along the planes in each of the sets of fractures is assumed to be a measure of the influence of that set upon ground-water flow and subsequent solution.

To show the relative amounts of cave passage developed along different bearings, the pieces of straight cave passage are accumulated by length into a rosette or histogram based on azimuth. Line segments measured carefully along straight cave walls and through the center of straight passages are classed in 10° sectors within a half-circle. Within each sector the lengths of the segments are added to give a cumulative total footage for the sector.

To illustrate this, a part of a cave map (fig. 4A) has been divided into numbered line segments. The cumulative footage of these line segments is plotted (fig. 4B) in the northern 180° of the compass rose and then expanded into the southern quadrants by rotating the diagram 180° and replotting it, forming a 360° rosette.

In the rosette, figure 4B, the numbered straight segments from the cave map are shown as they are plotted cumulatively within the appropriate 10° sectors. For example, segments 2, 15, 17, and 19 make up the large sector between 40 and 50° . This implies that a set of fractures bearing between 40 and 50° was utilized preferentially in the flow of ground water. Note the stepwise configuration of the passage divided into segments 6 to 14. The bearings of alternate segments 6, 8, 10, and 12 on the cave map fall close to the bearing of the major rosette sector between 40 and 50° . From this it can be further inferred that these segments all formed along subparallel planes in this set of fractures.

A statistical analysis can be applied to evaluate apparent preferred orientations (in the example these extend about $N 50^\circ E$ and $N 45^\circ W$) of the total cave footage, cumulated in this way. The same statistical analysis can be further applied to evaluate the preferred orientation and frequency of sets of fracture planes, and, in turn, the influence of these sets upon the preferential orientation of the total cave footage.

DETERMINATION OF PREFERRED ORIENTATION OF CENTRAL PENNSYLVANIA CAVES

On the lower histogram in figure 3, the cave passages in this region fall into two maxima ($N 25^\circ W$ and $N 65^\circ E$). It can be assumed then, that for each cave, two averages, or one for each of the two northern quadrants, will be more sensitive than a single average for all the passages. Thus in each cave the total footage is separated into two groups bearing from $N 0$ to $89^\circ E$, and $N 1$ to $90^\circ W$, and an average bearing is obtained for each group.

Each individual rosette sector in a quadrant is characterized by its median bearing and by its percent of the total footage of passage in the quadrant. When these two quantities are multiplied, the weighted average bearing is obtained for that sector. The sum of all the weighted

average bearings in one quadrant is proportional to the average passage orientation in that quadrant by the following relationship:

If

x_e = percent of total footage in the
east quadrant per *sector*,

and

x_w = percent of total footage in the
west quadrant per *sector*,

and

and

y_e, y_w = median angle for each *sector*, east
and west quadrant respectively,

then the cumulative weighted average passage orientation per quadrant may be defined as:

$$C_e = \sum x_{e_i} y_{e_i}$$

$$C_w = \sum x_{w_i} y_{w_i}$$

Where,

$$i = 1, 2, 3, \dots, n$$

$$n = \text{number of sectors,}$$

$$C_e, C_w = \text{cumulative weighted average passage orientation for all sectors in the east and west quadrants, respectively.}$$

For each cave, the two cumulative weighted averages (C_e and C_w) can each be plotted against weighted averages for joints striking in these same quadrants. Weighted averages computed for the 26 caves studied are shown in table 1. Note that values for the eastern quadrants, C_e , are larger than those for the western quadrants, C_w , reflecting greater amounts of passage in a northeast direction. This is also shown on the lower histogram, figure 3.

DETERMINATION OF AVERAGE ORIENTATION OF FRACTURES

Having now obtained a quantity in each quadrant representing the average orientation of footage for each cave, it is necessary to express data on local fractures in terms of frequency and orientation which can be related meaningfully to cave footage. The relative abundance and orientation of joint sets and bedding planes were measured at 18 locations throughout the four valleys. On the average, each station is 0.27 mile from a cave entrance. The fractures were measured in outcrops at the cave entrance in seven cases, and the other 11 were outcrops of limestones stratigraphically near the level of the caves.

About 20 fractures were recorded at each outcrop. Working from one end of the outcrop face, each continuous plane was measured. Joint planes were measured only if they extended through several beds, and to avoid slumped beds, bedding plane measurements were restricted to planes consistently repeated throughout the outcrop. Bedding planes were included since they seem to fulfill the function of joints (Billings, 1954; F. W. Trainer, personal commun.) and are of primary importance as

TABLE 1
Cumulative weighted averages of orientation for caves and joints

Area	Caves	C _w	C _e	Joint	J _w	J _e
		NW quad	NE quad	station	NW quad	NE quad
Brush Valley	Sharer	31.0	63.9	1	32.2	66.5
	Earl White	25.8	64.5	1	32.2	66.5
	Deerbone	29.4	57.1	1	32.2	66.5
	Penns Cave	45.0	73.3	2	47.0	62.8
	Veiled Lady	25.0	65.0	3	20.0	57.5
	Smullton	42.5	72.5	4	16.9	83.3
Penns Valley	Elk Creek	27.8	53.4	5	49.8	36.7
	Hennigh	25.0	66.1	6	38.5	74.6
	Bruckerhoff	46.9	48.0	6	38.5	74.6
	Holter Pit	31.9	49.6	6	38.5	74.6
	Coonscat	47.7	54.7	7	38.7	64.7
	Millheim	43.4	35.0	8	59.7	37.9
	Hostermans	43.7	54.1	9	28.6	45.4
Kishocoquillas Valley	Woodward	45.3	54.3	10	53.6	50.0
	Mayes	23.3	67.3	11	33.6	65.2
	Nails	15.0	72.2	12	28.4	68.4
	Aitken	38.7	50.0	12	28.4	68.4
	Little Aitken	21.1	55.5	12	28.4	68.4
	Lime Sinks	34.2	27.2	13	60.9	24.5
	Brubaker	46.5	55.0	14	42.4	48.0
	Goss	34.7	42.4	15	36.7	44.3
	Alexander	25.0	59.3	16	45.4	56.0
	Milroy	59.8	64.7	17	50.4	52.2
Pleasant Valley	Kingston	39.4	66.4	18	28.5	69.4
	Penn Aqua	25.0	64.5	18	28.5	69.4
	Seawra	52.7	67.5	18	28.5	69.4

fractures along which water may flow. The fractures were all grouped as sets of subparallel planes so the distinction between joints and bedding planes was not necessary for the statistical analysis.

Faults were not mapped for this study, mainly because field time was limited. However, Davies (1958) notes that in West Virginia, cave passages generally cross faults without enlarging along them. The entrance to Veiled Lady Cave in Brush Valley is in a fault zone, but the extent to which the fault has influenced the rest of the cave was not investigated. Faults are less common than joints, and most faults in this area are probably less permeable than joints. However, faults deserve investigation to determine more carefully the extent of their control on ground-water flow. For example, Bennett and Sayre (1962) describe the interesting case of water flowing in the cavernous Edwards Limestones along faults oriented in such a way as to carry local flow nearly parallel to the trend of regional contours in the piezometric surface.

In figures 5 to 8, the distribution of strike and dip of the fractures measured in the four valleys are plotted using a Schmidt stereo-net on which each point represents the pole of a fracture plane. So that individual caves can be compared with fractures from the closest outcrop, the

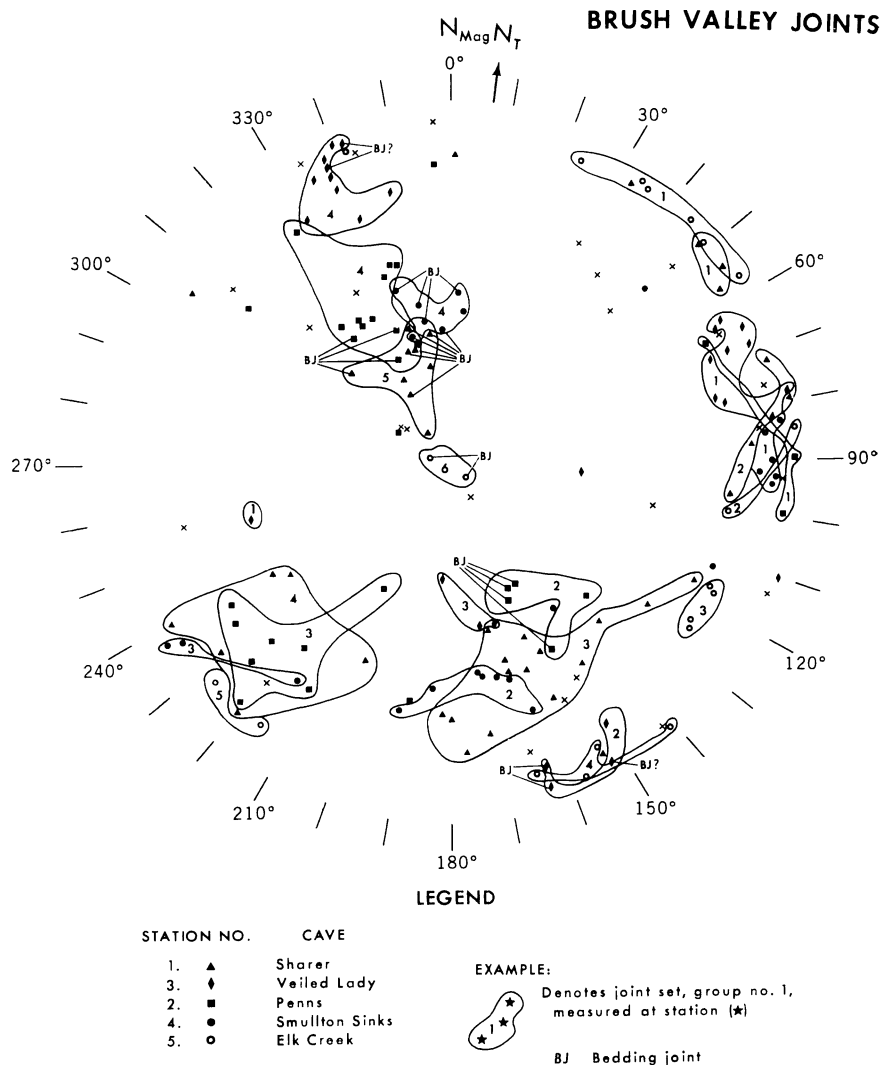


Fig. 5. Poles of joints measured in Brush Valley plotted on a Schmidt stereo-net. Poles labelled BJ are bedding joints. Sets of joints at each outcrop are outlined and numbered clockwise from north; station numbers shown in the legend are not related to joint-set group numbers shown on the diagram. The stations are located on the geologic map, figure 2. Joints measured at each outcrop are shown by different symbols.

points for each outcrop are kept separate and are indicated by different keyed symbols.

Each valley has its own structural setting, and fractures vary accordingly. Note the straightforward assemblage of just four sets of planes in two neighboring locations measured in Pleasant Valley. In groups 2 and 4 are the poles of northeast trending bedding joints and vertical

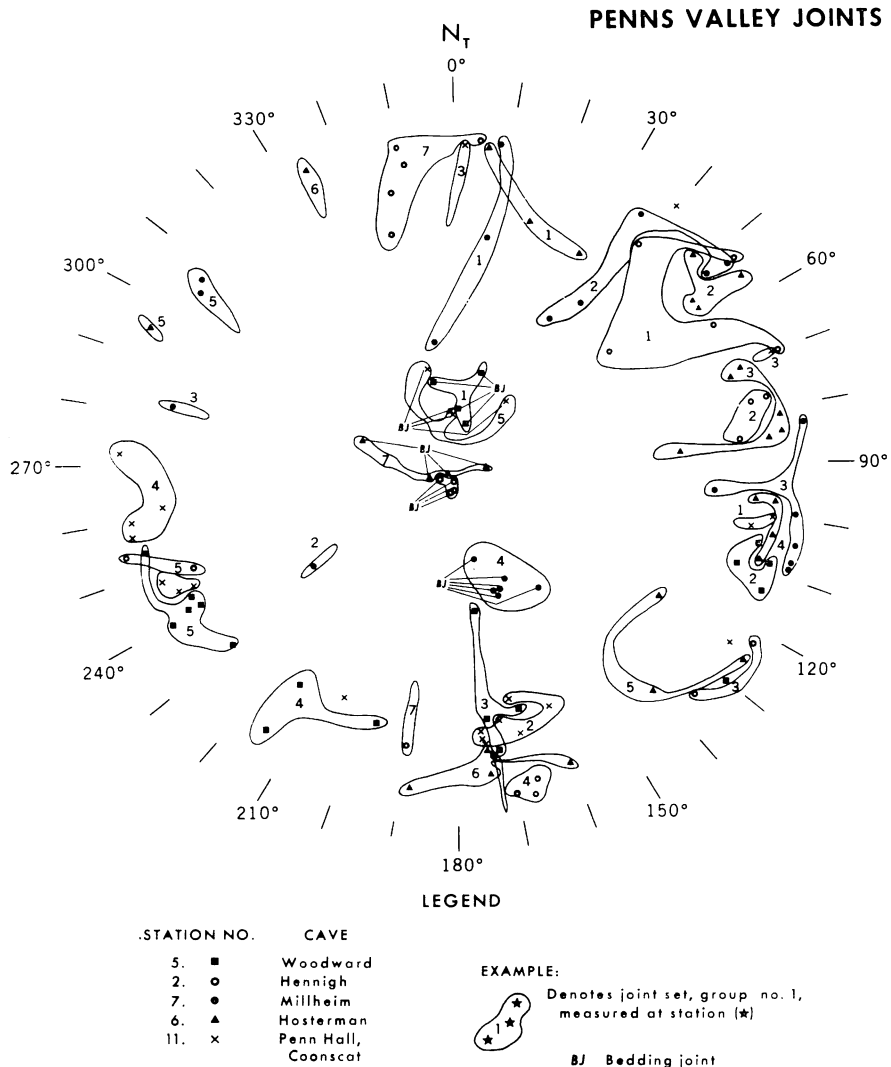


Fig. 6. Poles of joints measured in Penns Valley.

strike joints along which nearly all the cave footage is developed. These fractures are probably most nearly parallel the regional hydraulic gradient. The other two sets provide cross-flow interconnections. The lines of intersection between these four sets of planes are very likely the most active areas for initial solution.

By contrast, fracture sets measured at six or more widely separated locations in the other valleys show the variations in local structure throughout the valley. Bedding, however, and strike joints are predominantly northeast in all outcrops. And these sets again are those with

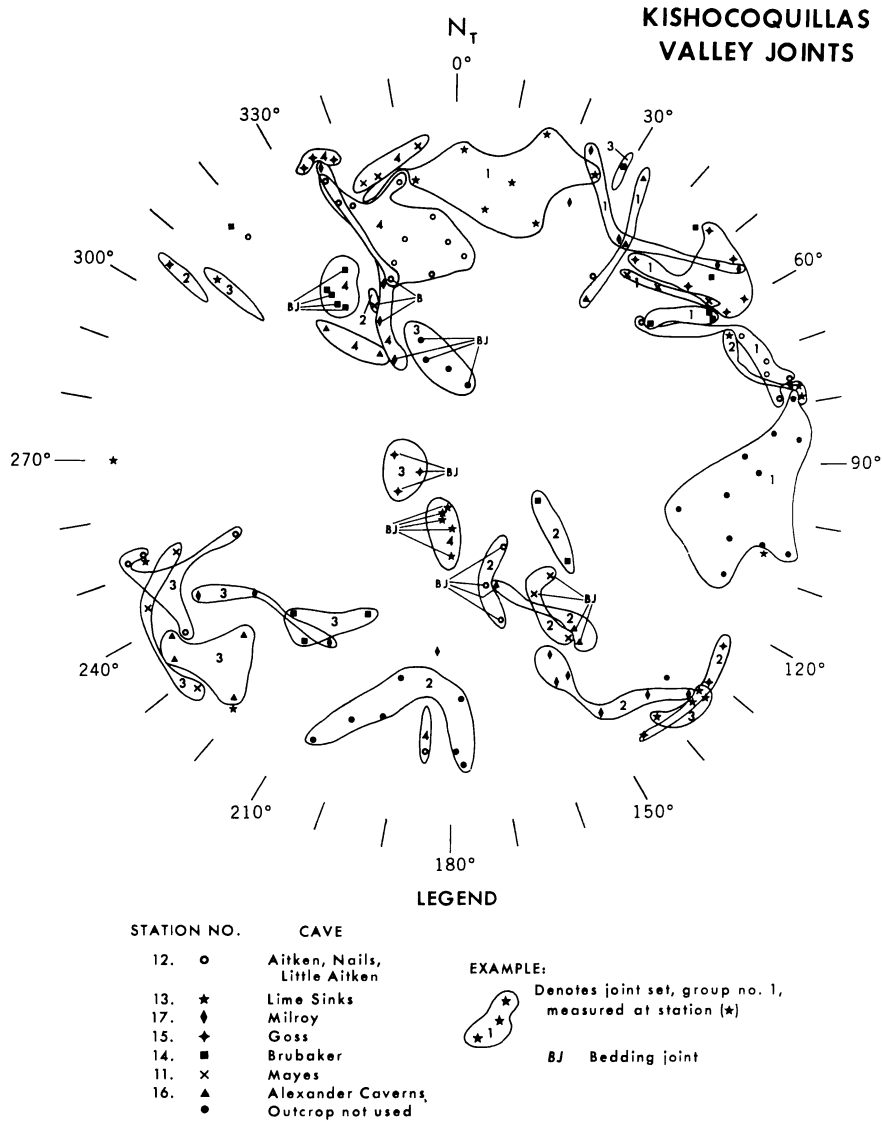


Fig. 7. Poles of joints measured in Kishocoquillas Valley.

the highest joint frequency. The majority of joints are steeply dipping or vertical providing easy access for recharge water.

At each outcrop, the joint sets (families of subparallel planes) are represented by groups of points which cluster together on the net. The clusters of points for each of the six outcrops measured in Brush Valley, for example, have been outlined and numbered clockwise as shown on figure 5. The bedding planes, labeled BJ, fall into closely spaced groups

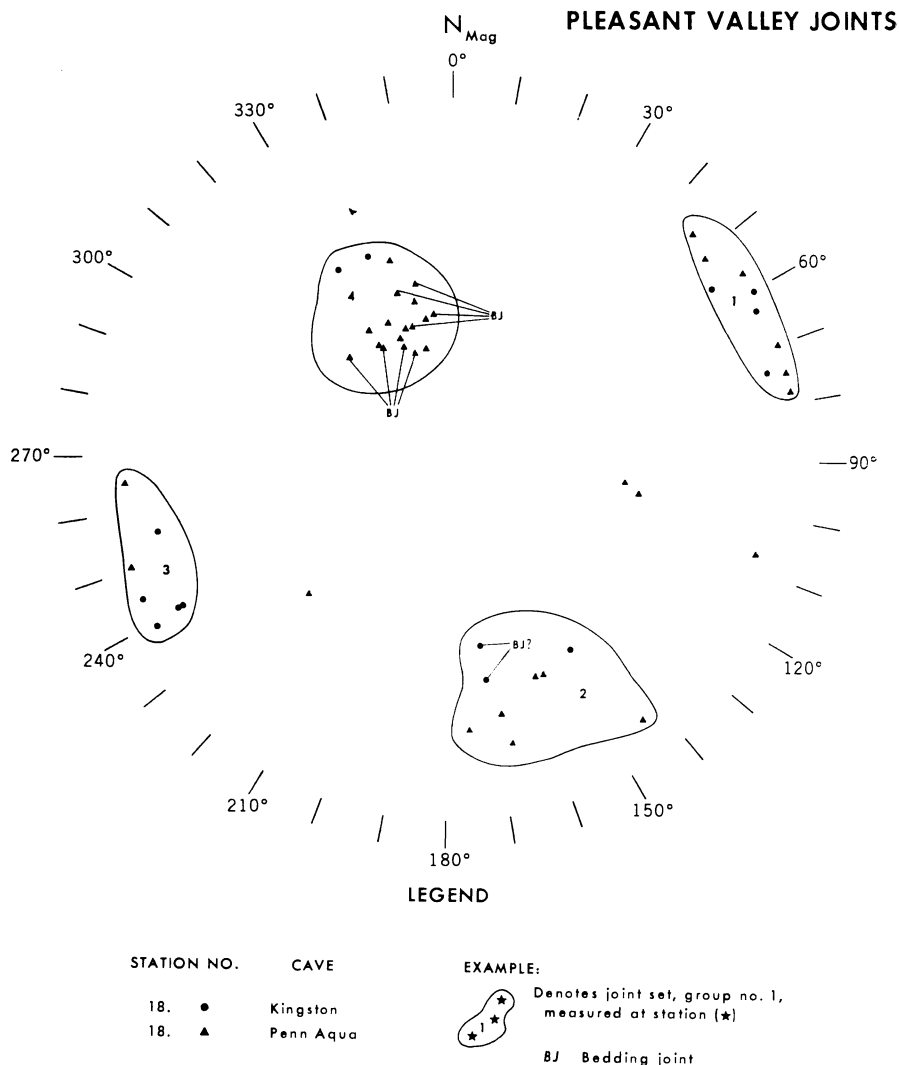


Fig. 8. Poles of joints measured in Pleasant Valley.

for each outcrop. Joint planes are less regular than bedding planes, and thus the individual points have a wider range of strike and dip on the net. The planes making up a set of joints are defined by points on the net falling within roughly 40° maximum range in strike and 45° maximum range in dip. Points falling outside these maxima are disregarded.

Sets of joints at each outcrop generally fall into four groups of points on the net, as noted in Pleasant Valley. Sets that strike in the east quadrant can thus be separated from those that strike in the west quadrant. Within each set of planes, the strikes are averaged. The aver-

age strikes of these sets are weighted according to the number of planes per set, against the total number of planes in the quadrant. The weighted average bearing of all the joints per quadrant is then defined:

If

$$a_e = \text{percent of total number of joints striking in the east quadrant per set of joints,}$$

and

$$a_w = \text{percent of total number of joints striking in the west quadrant per set of joints,}$$

and

$$b_e, b_w = \text{average bearing of a set of joints, in the east or west quadrant respectively,}$$

then

$$J_e = a_{e_i} b_{e_i}$$

$$J_w = a_{w_i} b_{w_i}$$

where

$$i = 1, 2, 3, \dots, n$$

$$n = \text{number of sets of joints,}$$

$$J_e, J_w = \text{cumulative weighted average bearing for all joint sets in the east and west quadrants respectively.}$$

Values for J_e and J_w for all outcrops are shown in table 1. Because a larger number of the fractures strike northeast than northwest and because they lie at a larger average angle from north, the values of J_e are higher than those of J_w .

If cave footage were solely dependent upon the abundance and orientation of fractures, then J_e/C_e and J_w/C_w would be 1. Plotting these values for all the caves and fractures results in the broadly linear distribution shown in figure 9.

Note that the values for J_w/C_w cluster at the lower end of the distribution, and J_e/C_e in the upper part. There are fewer fractures and shorter cave segments striking in the northwest quadrant relative to those in the northeast quadrant, thus the lower values for J_w/C_w .

Since caves develop in response to a number of factors in addition to fractures, the correlation evident in figure 9 was tested for statistical significance.

The values of r , shown in table 2, were determined by:

$$r(x,y) = \frac{\text{Cov}(x,y)}{\sqrt{\text{Var}(x)} \sqrt{\text{Var}(y)}}$$

where

$$x = J_e \text{ and } y = C_e \text{ for east-striking joints and caves,}$$

and

$$x = J_w \text{ and } y = C_w \text{ for west-striking joints and caves.}$$

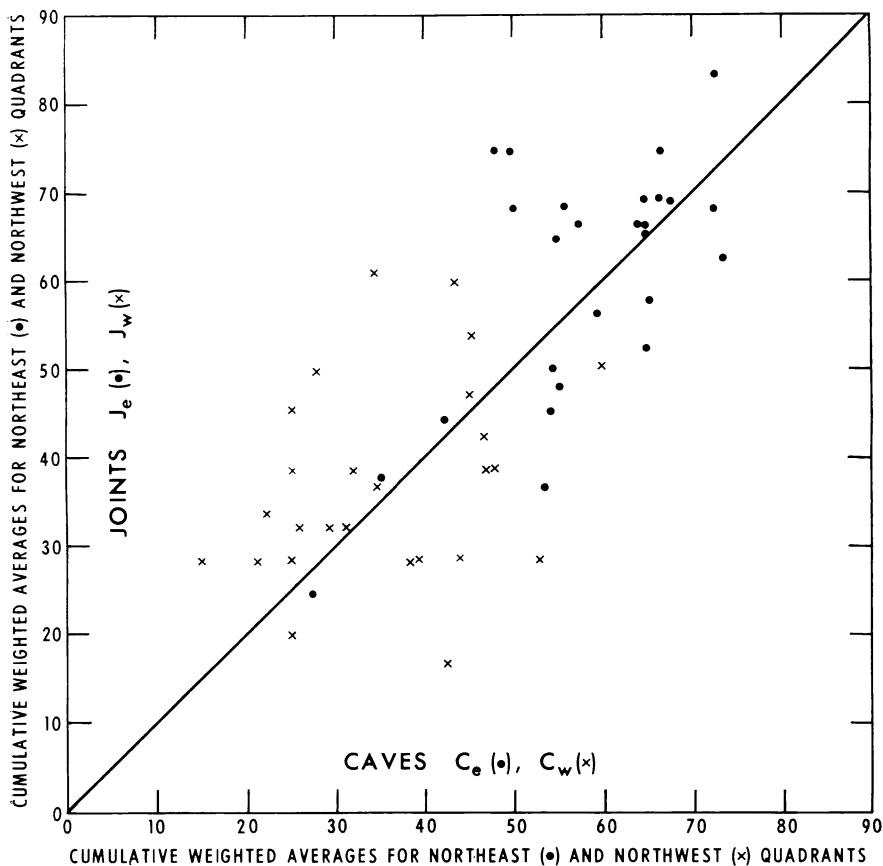


Fig. 9. The linear relationship between values of J_e and J_w , the cumulative average bearings for fractures weighted according to frequency; plotted against C_e and C_w , the cumulative average bearings of cave segments weighted according to footage. C_e and C_w computed for each of the 26 caves were plotted against corresponding values for J_e and J_w computed from the nearest outcrop at which fractures were measured.

The comparison of all cave and fracturing data was significant at the 95 percent level, and thus at this level of significance, the relation between caves and fractures cannot be attributed to chance. The values of r for east-bearing joints and caves were all larger than those for west-bearing joints and caves, indicating greater dependence between joints and caves in the easterly direction (see table 2).

RELATIONSHIP BETWEEN TYPE OF JOINT PLANES AND LENGTH OF CAVE PASSAGES

In the upper histogram on figure 3, the largest frequency of fractures falls between 60 and 70° NE. This is roughly parallel to the regional fold axis. These fractures are made up of sets of bedding planes and nearly vertical joints.

TABLE 2
Correlation coefficients

Area	n	Correlation coefficients		
Brush Valley	14	$r[(C_w + C_e), (J_w + J_e)]$	=	0.414
Penns Valley	14	$r[(C_w + C_e), (J_w + J_e)]$	=	0.451
Kishocoquillas Valley	18	$r[(C_w + C_e), (J_w + J_e)]$	=	0.593
Pleasant Valley	6	$r[(C_w + C_e), (J_w + J_e)]$	=	0.706
Four Valleys (combined)	52	$r[(C_w + C_e), (J_w + J_e)]$	=	0.814
Four Valleys (combined)	26	$r(C_w, J_w)$	=	0.482
Four Valleys (combined)	26	$r(C_e, J_e)$	=	0.735

C_e, C_w = Cumulative weighted average passage orientation for all sectors in the east and west quadrants respectively.

J_e, J_w = Cumulative weighted average bearing for all joint sets in the east and west quadrants respectively.

The joint sets can be grouped and then analyzed with regard to possible stress patterns during folding of the anticlinal valleys (DeSitter, 1956, p. 132). In this way the preferred orientation of cave passage segments can be related to various types of joints such as shear and tension sets. A larger sampling of joints will be required to evaluate such genetic relationships. The purpose of the present work is to establish the relationship between fracture planes, regardless of origin, and cave passages which are inferred to have developed along them. However, even using the small sample of joint sets, some relationships can be tentatively established between the types of joint planes and length of cave passage.

DeSitter (1956), using the theory of Mohr and Anderson relating stress directions to fracture orientation, suggests that in the general case of anticlinal folding, a set of tension joints will form parallel to the axis of the fold. DeSitter describes these tension joints as nearly vertical and sometimes curved and irregular. Because the joint surfaces have been separated by tension they are rough rather than smooth and planar as are joints releasing shear forces. The evidence here suggests that, in this area, these vertical joints along which cave passages dissolve are tension joints and probably favor the flow of ground water because of their vertical orientation and irregular surfaces.

That the vertical attitude of the fracture plane itself may affect longer solution cavities was shown by Trainer and Ellison (1967). They found that in the Shenandoah Valley, Virginia, the strikes of fracture traces mapped on carbonate rocks are strongly parallel to the strikes of near vertical joints in these rocks. Fracture traces are linear features distinct enough to be mapped on aerial photographs. Since they cut across both topography and structure, they must be the expressions of vertical fractures in the underlying bedrock, and Trainer and Ellison conclude that surface weathering and solution along vertical joints produce a mappable linear feature. They further note that there may be inherent differences in those fractures that weather to produce traces.

Caves develop nearly linear response to groundwater flow through local fractures. The maximum cave trends, however, are closely dependent upon regional hydraulics, which because of lithological control of erosion in these valleys is uniformly aligned with the regional strike. The fractures, however, do not remain uniform throughout the region since they are dependent upon local structure which varies considerably from the regional structural trend. Thus the caves express the regional hydraulic gradient as an integration of ground-water flow through varied local fracture systems.

DEVELOPMENT OF CAVE PATTERNS IN
RESPONSE TO LOCAL FRACTURE SYSTEMS

Rosettes constructed for the passages in four representative caves are shown with the cave maps in figure 10. Rosettes for all the caves studied are located on a geologic map of the four valleys, figure 2.

Linear caves along steeply-dipping planes.— It would be reasonable to expect that in anticlinal valleys of the Valley and Ridge province, caves preferentially develop more passage length parallel to the valley and along the strike where limestone dips are steep, and correspondingly larger numbers of bedding planes are available to carry down-valley ground-water flow. In 1960 W. B. White found that in central Pennsylvania what he defined as linear caves tend to develop more passage along the strike than across it. Of the caves studied for this work, roughly two-thirds are linear. They have simple elongate patterns with dominantly one or two, or less frequently up to five or six, single branches or arms. Penns, Veiled Lady, and Smullton Caves in Brush Valley; Hennigh and Bruckerhoff Caves in Penns Valley; and Penn Aqua (see map fig. 10) and Kingston in Pleasant Valley are typical examples of these linear caves. Roughly 50 percent of the passage in these caves is along the local strike, and the caves are developed in bedrock dipping approximately 30°.

Caves developed along the same sub-parallel fractures.—Where several caves occur close together, they have developed much passage along the same subparallel fractures. Their orientation as a group is primarily dependent upon the uniform strike of bedding planes. The two groups of caves in the western ends of Brush Valley and Penns Valley (fig. 2) show major rosette sectors in nearly the same orientations. A striking parallelism is shown by passages in the caves along the length of Kishocoquillas Valley. These caves are all in moderate to steeply dipping limestone, and several are on the axes or flanks of anticlines.

Orientation of caves reflects local folding.—Exceptions to a uniform alignment of the rosettes occur (see for example Milroy and Lime Sinks Caves) where changes in local structure have affected the cave development. This is shown remarkably in Lime Sinks Cave (fig. 10) where 23 percent of the fractures measured are bedding planes which parallel 24 percent of the cave footage, and about half of the fractures measured are joints which parallel about half of the cave passages.

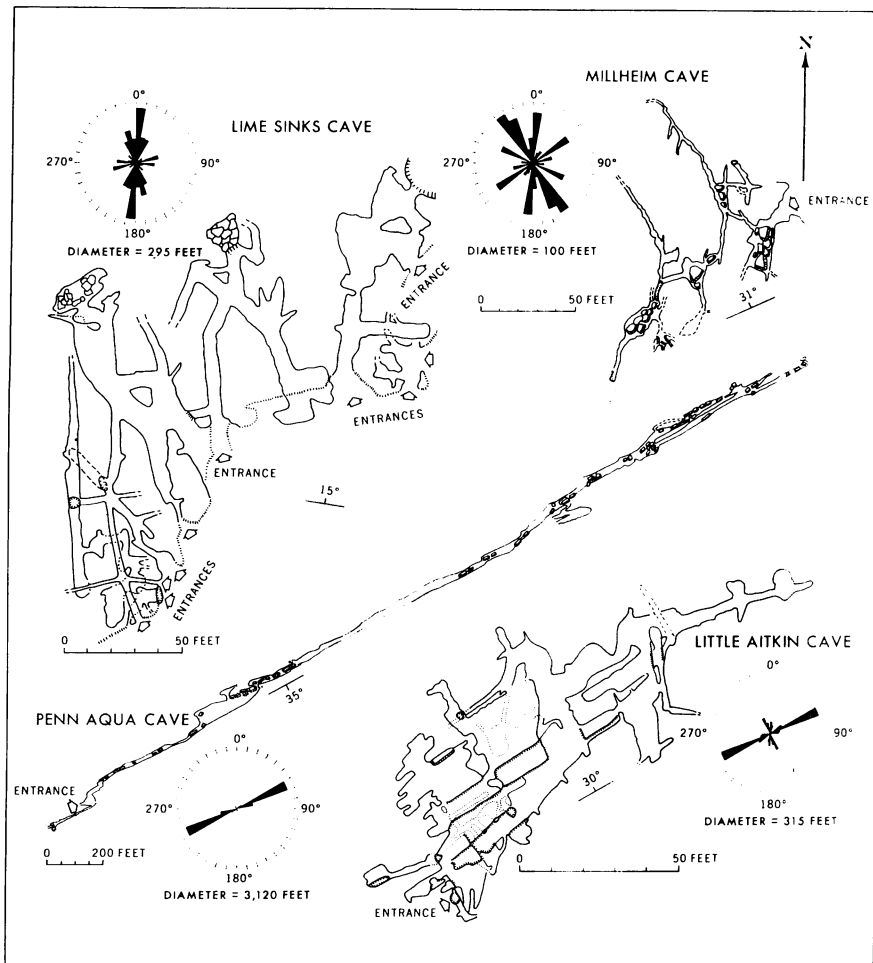


Fig. 10. Maps and corresponding rosettes of four caves showing various patterns of development. Penn Aqua Cave is linear and essentially parallel to 80 percent of the fractures measured at the entrance. Little Aitken Cave is a tight maze with 70 percent of the fractures parallel to predominant bearings shown in the rosette. Lime Sinks is a network with all of its footage bearing within 20° of 78 percent of the fractures measured at the entrance.

Rosettes for isolated caves in the center of Penns and Brush Valleys have several prominent sectors as a group but show little apparent parallelism of major sectors. These caves have each developed passages along at least two or three sets of fractures, but the sets vary greatly from cave to cave. For example, Millheim cave, (see fig. 10) in the center of Penns Valley, shows five prominent directions of passage development, which generally appear anomalous compared to Hostermans and Woodward. However, of the joints measured at the entrance to Millheim

Cave, 80 percent either parallel or are within 10° of 81 percent of the cave passage.

Cave patterns suggest spacing of local fractures.—In some caves, straight lengths of nearly parallel passages, spaced roughly equal distances apart, are intersected by a second set of parallel passages also spaced regularly, producing a pattern roughly resembling a grid. The spacing between subparallel passages varies a great deal from cave to cave. Some caves have developed widely-spaced passages and an overall plan that is roughly square. (The overall plan of a cave is the shape enclosed by a line connecting the ends of mapped passages.) Hosterman's and Woodward caves, for example, shown as rosettes on figure 2, both have square plans. In these caves the spaces between two sets of intersecting passages are wide, and thus the network pattern is open. In Millheim Cave (fig. 10) with a branching pattern, the passages are also widely separated.

However, Little Aitken (fig. 10), Mayes, and Milroy Caves, all in Kishocoquillas Valley, show a multitude of intersecting small passages. The caves have an overall elongate plan which suggests the possibility that they were developed in an elongate zone of fracture concentration.

Little Aitken Cave is developed in a highly joint-controlled maze pattern. The passages trend in two predominant directions. One group between 60 to 70° E has developed along a set of joints whose average strike is 71° E. This set probably provides half the available fractures. The second prominent group of cave passages trend between 20 to 30° W and have developed along a joint set whose average strike is 28° W. About a quarter of all the available fractures fall in this set. Thus the strikes of at least 70 percent of the fractures measured are within a few degrees of parallel to most of the cave passages. The passages in Sharer Cave (rosette, fig. 2) in Brush Valley are interconnected in an irregular pattern but are predominantly oriented 60 to 70° E. Sixty-five percent of the fractures measured near Sharer Cave strike 67° E. These caves are all highly dependent upon fracture planes, and since so many passages in the caves are opened in a relatively small volume of rock, it seems likely that they too could have developed in zones of fracture concentration.

CONCLUSIONS

In this area cave passages develop by length in approximately linear response to the frequency of the strike of available fractures even in cases where the fracture planes are not parallel to regional water flow directions. This establishes the importance of the local fracture system in the solution process. Thus the cave passage themselves can be used to infer the configuration of the fracture system. Because of differential solution along the strike of selected fractures the relative transmissibility differences between various fracture sets can probably be explained in terms of the tension and shear forces producing the fractures. Thus knowing the forces producing the fractures in a given structure, it may then be possible to predict local transmissibility.

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