Joints in Carbonate Rocks in South-Central Indiana

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Abstract

Detailed maps of joints for about 40 sites in carbonate rocks of Mississippian age in south-central Indiana indicate that joint orientation data, as displayed by conventional rose histograms, are by themselves inadequate for engineering and geologic applications. The maps show joint spacing and other details of pattern as well as orientation.

Sets of parallel joints are classified initially as either vertical or inclined with respect to bedding. Vertical joints are classified either as master or cross joint sets in plan. Master joints are longer than cross joints. Several stratigraphically superjacent beds, each of which has a unique set of cross joints, are commonly disrupted by one set of master joints. A master joint consists of a series of segments *en echelon* with a preferred orientation (predominantly east-west in the study area). Most master joint segments are essentially straight, but some are sinuous. The segments may terminate, curve into abutting joints, diverge, or cross other master joints.

Cross joints terminate laterally at master joints and transect only one bed vertically. They are generally very straight and planar and are nearly normal to master joints.

Blasting operations for highways and quarries, prevention of rockfalls in road cuts, and grouting of foundations may be facilitated by detailed knowledge of jointing.

Introduction

This paper is a part of a study to describe the character of joints in the carbonate rocks of Mississippian age in south-central Indiana and to determine the relative importance of joints as 1) a control of ground water movement and the development of solution channels and caverns, and 2) to provide some data pertaining to jointing related to site selection, bedrock foundation construction, and bedrock excavation problems. This paper primarily presents a general description of the types of joints found, but some specific examples related to pattern, orientation, and spacing of joints are included.

Joints in bedrock have been mentioned by most authors of standard introductory and structural geology textbooks, but very few definitive papers that relate the pattern or intensity of joints to specific sedimentary lithologies have been written (5). Most articles related to joints or papers that briefly describe jointing in an areas discuss only the orientation of joints as if they are similar within all types of bedrock in an area. The data for this study, consisting primarily of more than 1,500 joint orientation measurements gathered from more than 40 mapped sites in carbonate rocks at various stratigraphic horizons, indicate that joints are not simple rectilinear fractures that divide the bedrock into joint blocks of uniform size and shape.

Joints have been mentioned by numerous authors of papers on karst topography and cavern development as the most important form of porosity and permeability in limestone; along them water or ground water flows and develops solution-enlarged joints, called grikes, or solution channels and caverns (6). Cavern passages have commonly been recognized as having either a linear or a random pattern, particularly on maps, and have been considered as joint controlled and bedding plane controlled, respectively (8).

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Significance of Joints in Carbonate Rocks

Most carbonate lithologies in the Mississipian rocks of south-central Indiana have a low primary porosity and permeability, but they have a high secondary permeability (6) owing to joints, and in places possess extremely high transmissivity owing to solutionally enlarged conduits. Because jointing is regarded as a form of secondary porosity, solutionally enlarged conduits and cavern passages that follow joints must be a tertiary form of porosity postdating the joint development. Numerous caverns with straight passage segments have commonly been considered to be joint controlled in that they exhibit obvious solutional enlargement by ground water flowing along a joint. Cavern passages that exhibit obvious linear trends or alignment with joints must have been formed by corrosion by ground water flowing along the joints. The joints thus allowed the ground water to flow freely, in contrast to the relatively impermeable rocks.

Some cavern passages are considered to have a random pattern because they do not exhibit joint orientation or because those joints which are observed, commonly within the ceiling of the passage, do not have orientations or a pattern that correlates with the trend or shape of the cave passage. The joints exposed in the ceiling or floor of a cave, however, may have no direct relationship to the orientation of the cave passage. In fact, they may not be a direct continuation of joints within the unit in which the passage developed. A cavern passage has obviously developed within the beds or strata that have been removed by solution; therefore, a basic assumption is that strata above or below those removed by solution are physically different. They may be less soluble, or they may lack some other characteristic of the more soluble unit, such as similar jointing.

Cavern passages that have been designated as having a random or no joint-controlled pattern usually have been considered to have developed along bedding planes. As jointing has not apparently controlled the flow path of the ground water, the assumption has been made that it was free to seek a random route along bedding planes (8), and that bedding planes are a counterpart to joints so far as ground water transmissivity is concerned (3). Bedding planes in general have not been proved to have a significant degree of porosity or permeability within bedrock *in situ*, although some bedding plane separations modified by weathering appear to have become more permeable.

The definition of joints, as intended here, excludes all fractures or separations along bedding planes and fractures parallel to bedding planes, such as low-angle fractures called sheet joints that are considered to be caused by unloading.

Joint Definitions

A joint is defined, in part, as "a surface of actual . . . parting in a rock, without displacement; the surface is usually plane and often occurs with parallel joints to form part of a joint set" (4). This definition must be modified to the extent that separation or parting normal to the fracture surface is recognized, although there has been neither lateral slip nor horizontal heave of the rock adjacent to the fracture surface sufficient to define a fault. Joints may, so far as degree of separation is concerned, be described as potential joints (9) along which stress has caused some form of strain that may eventually fracture, latent joints that have extremely thin separation or hair-line width and generally are not visible but appear as the rock is broken up, closed joints that are visible but have no noticeable separation, open joints that have obvious separation (2), and, in the carbonate rocks, joints that have been enlarged by solution or weathering.

The concept of joints as planar features may be somewhat misleading, unless the planar surface may in some places be accepted as rough, uneven, or irregular. A repetitive series of somewhat planar (straight) fractures that have a rough surface may be designated as joints in one lithologic unit, whereas in another rock type, extremely smooth but sinuous or wiggly fracture planes are a part of a joint pattern. The concept that some joints may be adequately identified or differentiated only by mapping their extent and shape is important, but modifying the definition of joints to specify that they are mappable fractures with a somewhat repetitive pattern is not practical.

Joint Types in South-Central Indiana

Joints in the carbonate strata of south-central Indiana are initially classified here as to their relationship with the bedding planes that bound the rock units within which they occur. Three major types were identified: vertical joints, inclined or slanting joints, and joints normal to bedding planes of cross-stratified beds (figure 1).

Vertical Joints

Vertical joints are the most common type observed in the field within the study area, and they were easier to map so far as their orientation and spacing were concerned. Vertical joints do not require a dip measurement, and thus they do not require projection to a mapping plane to establish their true orthogonal position. The only criterion for distinguishing vertical from inclined joints is the angle at which they intersect the bedding planes. Those joints that appear to be vertical commonly are within a few degrees of vertical, whereas

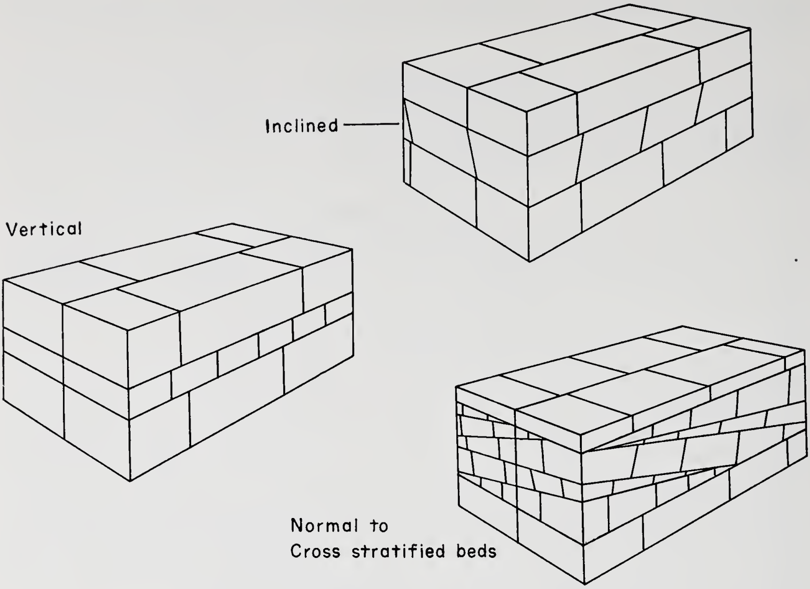


FIGURE 1. *Block diagram showing three basic types of jointing.*

most joints that appear to be inclined to bedding are more than three degrees from vertical.

Vertical joints were commonly found to consist of two joint sets, here called master joints and cross joints, somewhat as described by R. A. Hodgson (5), and perhaps the same as the systematic and nonsystematic joint types of N. J. Price (9) and others. Variations from their described types may be related to different local lithology and structural geology.

Master joints are those joints that 1) commonly are longer than joints in other joint sets and 2) commonly disrupt more than one distinct stratigraphic or lithologic unit (figure 2). Cross joints, in addition to generally trending at right angles to master joints, 1) commonly are shorter than master joints, 2) generally are restricted to one bed or stratum, and 3) commonly terminate laterally at the master joints to which they are approximately normal.

Contrary to the work of Hodgson, Price, and several previous authors, master joints were not found everywhere to be essentially planar or straight in plan, but sinuous joints do occur within sets that contain mostly straight segments (figure 3). Cross joints were found to be more planar or straight in plan. The amount of surface roughness of joint faces, considered as a distinct separate feature from overall planar characteristics, was not readily measured owing to the few unweathered extensive joint faces seen during the fieldwork, but general observation suggests that master joints are smoother than cross joints.

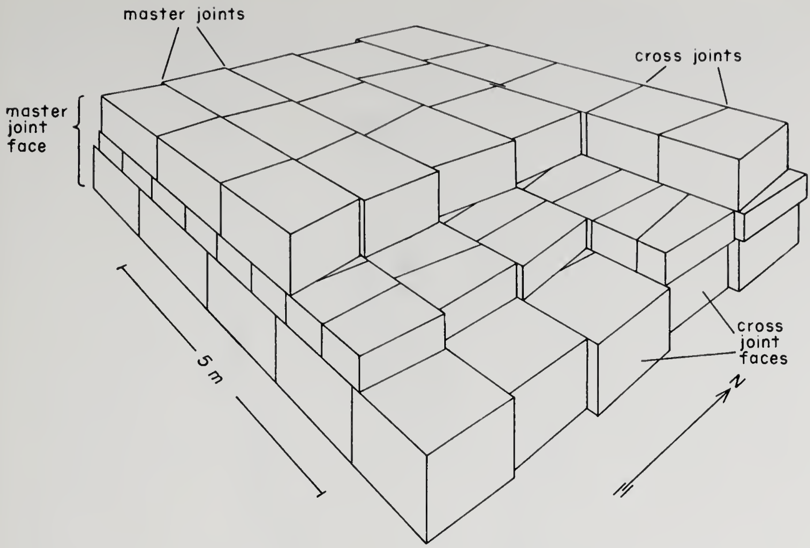


FIGURE 2. *Block diagram showing idealized sets of master and cross joints in three beds of rock.*

Various types of master joints have been mapped to date, but there is little doubt that additional types will be found. Segments of master joints are either straight or curved, arced, and sinuous (figure 3-B). The ends of master joint segments are known to: 1) end abruptly, commonly as one of a series of segments *en echelon*; 2) curve or arc towards a segment *en echelon* with which it terminates at an acute or obtuse angle (figure 3-A and C); 3) be connected to segments *en echelon* by short fractures between the master joint distal ends or by cross joints which extend through one of the master joints; 4) contain a series of parallel, short fractures or joints, some or all of which may be transected by cross features within the narrow space between the ends of master joint segments; 5) bifurcate, most commonly with other master joint segments, rarely with cross joints. Additional closely spaced joints parallel to master joints, but restricted to one bed of rock, are present in section view at some localities.

Cross joints apparently have less variation. Cross joints that extend essentially straight through one or more master joints have been mapped, but they are not common. Cross joints are not known to cross, but they are known to join other cross joints (figure 3-D). The master joints measured at any particular locality in the study area were found to be subparallel and to have either a single or acutely bimodal distribution of orientation trends as compared with cross joints, which commonly appear to have an obvious bimodal distribution that is more obtuse than that of the master joints.

An impressive site for determining various relationships of vertical joint types is Herron Cave, east of Alton in Crawford County. The cave, which consists mostly of a maze or network of passages, is within

FIGURE 3. *Maps showing the relationship of joints (heavy lines) to portions of cavern passages in various stratigraphic units.*

A. Lehigh Quarry Spring Cave, Lawrence County, in the Salem Limestone.

B. Taylor Cave, Orange County, in the Beech Creek Limestone.

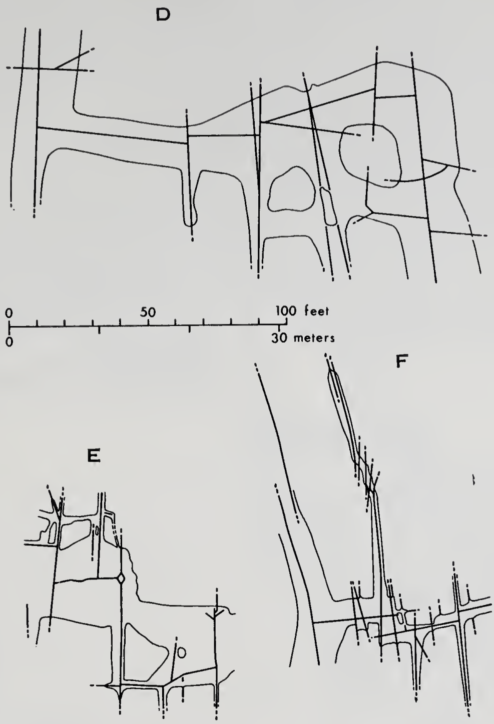
C. Waggoner Spring Cave, Lawrence County, in the Ste. Genevieve Limestone.

fine to coarsely crystalline biosparitic Glen Dean Limestone. More than 2,000 feet of joint-oriented passages were surveyed, and 136 measurements of joint trends were made (figure 4). Although the extensive cavern network at Herron Cave is not typical of caverns in this region, the joint pattern is somewhat similar to that seen in numerous other caverns in the Glen Dean, Haney (Golconda), and Beech Creek Limestones of the Chesterian Series.

The hydrologic origin of the network type of cavern development at Herron Cave is unknown at present, except that the passages show typical evidence of solutional enlargement of joint planes.

Inclined or Slanting Joints

Joints that are inclined or slanting with respect to bounding bedding planes were found at numerous localities. Inclined joints are most common within the upper part of the St. Louis Limestone and the lower part of the Ste. Genevieve Limestone, where they occur in part in conjunction with vertical joint sets. Inclined joints were also found within particular beds (primarily dolostones, dolomitic limestones, and argillaceous and silty limestones) within the Ste. Genevieve Limestone, bounded by other carbonate lithologies containing vertical joints.



D. Zinc Cave, Washington County, in the Salem Limestone.
E. Vowell Cave, Dubois County, in the Glen Dean Limestone.
F. May Cave, Monroe County, in the Salem Limestone.

A good exposure of inclined joints is along new State Highway 37, just south of Gullets Creek in Lawrence County, within the lower part of the St. Louis Limestone. Solutional enlargement and cavern development along inclined joints are most obvious in the lower level of Wyandotte Cave in the general vicinity of the Isles of Confusion, where the passage has formed in the lower part of the Ste. Genevieve Limestone and the upper part of the St. Louis Limestone.

Joints in Cross-Stratified Strata

Joints in cross-stratified carbonate rocks, specifically the Spar Mountain Member of the Ste. Genevieve Limestone, present a type distinct from vertical or inclined joints. The joints in an individual cross-stratified unit appear to have an inclined attitude, but are essentially normal to the inclined bedding planes, and the number of joints commonly increases towards the direction of wedging out (figure 5).

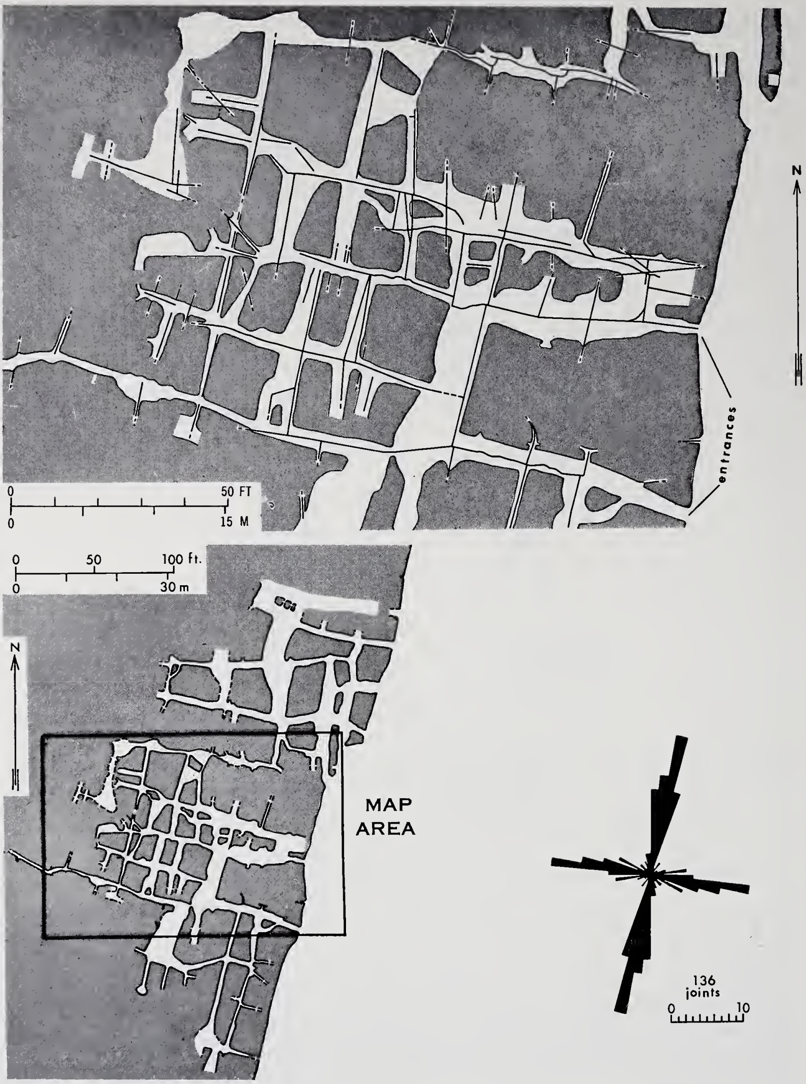


FIGURE 4. *Map of a portion of Herron Cave, Crawford County, in the Glen Dean Limestone, showing the pattern of master and cross joints in relation to cavern passages. The rose histogram was compiled from 136 joint measurements and represents the entire cavern.*

Whether or not the joints follow an isoheyt related to bed thickness or are linear regardless of crossbed orientation is not known. This type of jointing is inadequately described because fieldwork was insufficient to map and describe the type accurately. Field sites conducive to detailed mapping were not found. The entire unit of crossbedded layers may be dissected by an overall set of vertical master joints and cross joints.

FIGURE 5. *Solution-widened joints normal to cross stratified beds in the Spar Mountain Member of the Ste. Genevieve Limestone along State Highway 135 about 3.5 miles south of U.S. Highway 460, Harrison County. Rod is marked in foot intervals.*

Spacing of Joints

The strata of Mississippian age in south-central Indiana consist of a heterogeneous sequence of carbonate and noncarbonate lithologic types, ranging from noncalcareous shales and sandstones to an extensive suite of limestones, dolostones, calcareous sandstones, and shales. There is also a great range in thickness of these different strata. The spacing of jointing is obviously different from one major stratigraphic or lithologic unit to another, and it may be apparent even where the difference between beds or units of a general lithologic type is only minor. The contrast in brittleness, cohesiveness, or plasticity between major sedimentary lithologies, such as limestone, dolostone, shale, and sandstone, is sufficient basis for a generalized explanation of differences in joint spacing which are attributed to differences in bed thickness. The variation in specific lithology and bed thickness in a single bedrock exposure is usually sufficient to account for differences of competency between units which exhibit differences in joint spacing, and perhaps even differences in joint type and pattern.

An example which demonstrates differences in joint spacing related to bed thickness and the effect on cavern development is the road cut on new State Highway 37 immediately south of Gullet's Creek in Lawrence County. The strata exposed in the road cut include shale, limestone, and dolomitic limestone of varying thickness (figure 6). A bed of limestone about .5 meter thick (A, figure 6), broken by joints averaging .25 meter apart, is a zone of intense solutional enlargement, ranging from minor solution along joint faces to complete removal of the bed for an approximate width of 15 meters. An overlying bed of similar rock is about 1 meter thick (B, figure 6) and is broken by joints with an average separation of 2.3 meters, but it contains solution channels only in the basal portion of a few joints above the intensely

FIGURE 6. *Rock cut on west side of new State Highway 37, just south of Gulletts Creek, Lawrence County, showing differences in joint spacing and development of solution channels. Bed A, 1.5 m thick, has joints averaging .25 m apart, whereas joints in bed B, which is about 1.5 m thick, average 2.3 m apart. A filled solution channel at C has developed in the closely jointed bed. Rod is marked in feet.*

dissolved underlying bed. The underlying strata are shale and shaly limestone. The intensive solution in the closely jointed dolomitic unit is attributed to three major factors: 1) the underlying shale served as an aquatard, confining water to the overlying rocks and forming a perched water body, 2) ground water body was greatest in the intensely fractured bed, and 3) the increased surface area rendered to that bed by jointing provided a greater surface area exposed for solution.

Breaching of the thick roof stratum of the cavernous zone by road construction disrupted the lateral lithostatic pressure which held it in place and allowed the roof rock to unload in the direction of the road cut and to collapse into the cavern. Although the removal of the closely jointed bed by solution was followed by infilling of clastic sediments, the sediments are insufficiently consolidated and are being removed by erosion, so that the overlying strata collapse into the cavity and slump into the road cut.

Engineering Application of Joint Mapping

Essentially every large rock cut in carbonate strata in the study area has been examined in the field during the course of this study. Rock falling from the cuts following final construction appears to be attributable to one cause or a combination of causes, as follows: 1) failure to remove or secure either unstable joint blocks or portions of joint blocks fractured by blasting, which eventually results in the falling of a large rock or rocks, 2) failure to stabilize adequately the rock adjacent to either open, sediment filled, or partially collapsed cavernous openings or solutionally enlarged joints, which results in massive failure of rock either from above or next to the cavity into the cut, and 3) failure to control water flowing over or seeping through the rock, which results in an accelerated freeze-thaw process that usually produces small rock spalls. Many of the rock falls involving single blocks or massive failures occur several seasons or years following excavation owing to the effects of freeze-thaw or removal of supporting unconsolidated sediment by erosion and sapping.

The practice of pressure testing carbonate units during the preliminary test boring program could lead to discovery of troublesome and potentially hazardous cavernous zones. The pressure emplacement of grout to refusal in benches prior to presplitting might be an economical treatment of known cavernous zones, or known cavernous strata could be left on rock bench treads and not in rock faces.

If rock cut benches are aligned with joint sets in such a way that narrow pieces of joint blocks with greater height than depth normal to cut faces are left adjacent to master joints, the blocks may eventually topple into the cut, and therefore the situation should be avoided. Realignment of a rock cut parallel to master joints could use the joint faces as a terminal excavation line, provided the joint spacing was advantageous and the contractor and the highway engineer could reach and economical settlement. Proper blasting could essentially eliminate fracturing of rock across the joint plane (1 and 7). Rock cuts parallel or at an angle to cross joints can be benched bed by bed or cut to a gentle slope with benches to alleviate the necessity of maintenance caused by dislodgement of various joint blocks.

The location of vertical bore holes for pressure grouting to establish a grout curtain in a dam abutment commonly is a random process relative to joint locations. The assumption that one of a series of adequately spaced holes will encounter a vertical joint, a permeable bedding plane, or a solutionally enlarged conduit, cave, or mud seam, if present, is not valid unless the cavity has a significant width to be penetrated by one of a series of equally spaced adjacent holes. The subterranean conduits are commonly aligned along joint planes that served as the initial form of permeability which transmitted the ground water that caused solutional enlargement. There is a greater probability that the full height of a joint plane within a given bed has been modified by solution than that the solutional enlargement progressed laterally along a bedding plane. Therefore, theoretically at least, one horizontal bore hole pressure grouting in each rock unit which has a particular set of cross joints must encounter all joints along a line.

Conclusions

The mere compilation of joint data to draft a joint rose histogram for all the joints within several different carbonate lithologies at a site does not constitute the total significant data that are obtainable.

Joint patterns may be mapped if sufficient exposure is present, or joint spacing and orientation may be mapped along an outcrop of a rock unit or in a cavern passage. The increase in labor and time required to map a site accurately, as opposed to simply taking rapid compass readings of joint orientations, is clearly justified because the identification of joint types, trends, spacing, and patterns provides information that solves many problems.

The preparation of large-scale maps for selected sites in south-central Indiana has aided in identifying some types of joints and joint patterns and spacings in various carbonate lithologies. The mapped portions of caverns clearly indicate that essentially all solution conduits and cavern passages originate by ground water flowing along joints which become enlarged by solution. Even the so-called random type of cavern passage is actually oriented through a more closely spaced joint network than is the case with more easily recognized joint-controlled passages. Joints impart a high permeability to carbonate rocks and are related to lithology and bed thickness.

An understanding of jointing at any bedrock construction or excavation site is directly applicable to rock engineering problems, particularly those involving control of ground water and stability of final slopes.

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