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GEOLOGIC STRUCTURE AND A NEW EXPLANATION OF LIMESTONE CAVERN GENESIS

by Derek C. Ford

INTRODUCTION

The purpose of this paper is to present a new explanation for the genesis of the kinds of limestone caves which speleologists most frequently encounter. As a theory it contains few new elements. Rather, it reconciles the conflict between older theories by indicating that each will be true where the controlling circumstances are right for it. The most important of these controlling circumstances are the structural attitude of the rock beds and the geographical relationship between structural trends and the location of sink and springs, the frequency of penetrable bedding planes, joints and faults and the frequency and geometry of their interconnection. As with the older theories, cave systems are analysed in the dimensions of length and depth, though reference is made also to length and breadth; i.e. to plan patterns.

It is pertinent to review features of the older theories. Until 1941 most authors assumed that a watertable or piezometric surface precedes cavern development in a limestone mass and, further, that it survives that development with little alteration in its vertical position or gradient or extent. The watertable was treated as a fixed entity and speculation was concerned with the locus of major cave development about it.

Early writing in America, Britain and France argued that major cave development would occur above the watertable because here, the input end of the system, solutional competence would be greatest and stream velocities highest, favouring an additional contribution from corrosive processes. These remain powerful arguments – the type of cave that expands most rapidly probably is the vadose vertical shaft Many caves possess substantial sections where vadose conditions of enlargement have been quantitatively predominant, (e.g. G.B. Cave in the central Mendips – Ford 1964). However, it is rarely apparent that the earliest parts of such sections were vadose.

In 1930 W. M. Davis argued for major cave development at random depth below a watertable. This is commonly called the deep phreatic theory. It was supported by Bretz (1942) who cited abundant field evidence.

In 1932 A. C. Swinnerton presented a probabilistic model in which groundwater streams may disperse through a number of alternative routes beneath a watertable but that route which is shortest (in most cases, closest to the watertable) wins in a competition. The Swinnerton watertable master cave is generated from the head (or input end), downstream. In 1941 Rhoades and Sinacori presented an alternative watertable model in which a flat master passage is generated retrogressively from the spring. Their views differ from earlier ideas because there is a substantial modification of the pre-cave watertable, which does not locate the cave passage at all, merely providing the head to push early water through it.

During the past 25 years local studies of caves have predominated. One must agree with G. W. Moore, introducing the N.S.S. Symposium on Cave Hydrology (1966), when he said that the majority favoured a watertable hypothesis of cavern genesis.

M. S. Bedinger (1966) investigated this by a two-dimensional electrical analogue model, Figure 1. A rectangular grid of resistors was used; it is equivalent to a horizontal and vertical orientation of flowlines. Horizontal segments may be taken to represent bedding planes and vertical ones, joints. The ratio of segment length of bedding plane passage to joint passage is 1:1. With this geometry and an assumed Darcy flow, Bedinger was able to show that power flow concentration was similar to Swinnerton's watertable model.

Note that with such an arrangement, the power (or water) intakes can only be the vertical elements or joints. If the grid is tilted to simulate steeply dipping rocks, bedding planes can also be direct intakes. At a glance, power flow concentrations then will not be as simple as in the horizontal case.

In 1968, J. V. Thrailkill presented calculations for the case where the segment length ratio, bedding plane:joint is 100:1 and showed that the enhancement of solubility in the shallowest passage (which may be taken to represent the watertable case), does not exceed 0.8%, a negligible advantage. Amongst those papers which present arguments for a general case of limestone cavern development, these two of Bedinger and Thrailkill are almost the first to pay any significant attention to geometrical characteristics of the host network of fissures. In my field experience, the ratio of bedding plane:joint passage commonly ranges 10-100:1 in those cave systems where bedding planes are of any importance at all. Bedinger's 1:1 ratio is only approached in rocks of very high frequency of penetrable fissuration i.e. very high groundwater transmissivity. The latter are quite exceptional.

From this review some major points should be emphasized.

1. The vadose, deep phreatic and watertable theories were all advanced as arguments for **a general case**, i.e. one which will encompass a majority of limestone caves. There is, therefore, an unspoken presumption that there should be **one** general case when cave passage patterns are considered in the dimensions of length and depth.
2. The general case models either disregard geologica structure altogether or assume flat bedding. Davis definitely draws for the horizontal case. Swinnerton presumed structure and structural attitudes to be irrelevant except in the rare, obvious instances of massive, simple control, e.g., a cave developed entirely in a single fault. Rhoades and Sinacori also disregarded structure but without some structural assumptions it is difficult to see why their master passage should develop as a flat or gently graded feature.

To avoid detailed argument here, their model is best applied where the bedding is flat. Both Bedinger and Thrailkill use flat cases. Most review diagrams illustrating these various hypotheses and the vadose one, indicate horizontal bedding or no structure at all.

There is, therefore, a second presumption that the general case applies to flat bedding and, seemingly, that most caves develop in flat-lying rocks. Very few limestones are truly horizontal: most possess some degree of dip. If it can be shown that different rules of genesis apply in steeply dipping rocks, the question if raised, "Where is the lower limit for the steep case or the upper limit for the flat one?" Do a majority of caves obey steeper or flatter rules? This calls into question the notion of one general case.

3. In the terms in which it has chanced to develop historically, a critical point in the genesis debate is the distinction of watertable, (or shallow), phreatic caves from random, (or deep), phreatic caves. In practice both types may display identical morphology. Discussion becomes a matter of comparative scale. This is a difficult, little-considered area of the debate in which the author's own thinking is anything but clear. But to illustrate the point Swinnerton allowed for his model of cave development a vertical zone of 200 feet of development about a watertable. Most of this was below the pre-cave level of that watertable. Thus, any passage that is only 200 feet down in a phreatic zone can be classed as shallow phreatic. But suppose that the total thickness of a limestone mass hosting such a vertical range of phreatic development is only 250 feet? In scale terms, passages at 200 feet depth are very deep and it is unlikely that it can be demonstrated that they are not random in the context. Swinnerton's is one of the few absolute dimensional indicators published. Applied to the famous cave regions of Indiana and Kentucky where the accessible limestone mass is about 250 feet, it poses considerable conceptual problems of scale.

AN ANALYSIS OF SOME DIFFERENT CASES OF STRUCTURAL FORM OR GRADIENT AND GROUNDWATER TREND

The new explanation is now offered in a series of analyses of different structural and groundwater trend situations. The rocks are presumed to be regularly bedded, with penetrable bedding planes spaced feet or tens of feet apart in the lithologic column. There is no significant primary permeability. These are the conditions which apply in the great majority of the limestone cave regions of Europe and North America.

1. Conditions of Cave Origin and Early Development : The Genesis of Antastomoses and Dip Tubes.

In the literature, there is a common assumption that the early development of cave voids in bedding planes takes the form of anastomoses of visible dimensions which are spread over the total two-dimensional area of the plane – as in Figure 2a. In my observation, (which includes some of the famous anastomoses sites of Mammoth Cave and the Flint Ridge system, Ewers 1966), this is often incorrect. Anastomoses are only common where the dip is very gentle. They occur as narrow bands oriented down the local dip. Tubes are largest in the central parts of the band and quickly diminish laterally to tiny sizes: here water is discharged into or out of the band from a broad but discontinuous planar void which is less than one millimetre in height. Bands of anastomoses occur in sub-parallel array in a bedding plane, as in Figure 2b, and are spaced tens to hundreds of feet apart laterally. They develop simultaneously in many penetrable planes. Therefore, there will be many families of anastomotic bands stacked one above another in a limestone mass.

Anastomoses are rare in steeply dipping rocks. Where they do occur, it can often be shown that they developed during or after the expansion of the major passage in whose walls they are observed: this is sometimes true of anastomoses in nearly flat-lying rocks as well. In the steeply dipping case, anastomoses are replaced by simple, linear tubes oriented down the dip – "dip tubes". Their dimensions range from the scarcely visible to the readily walkable. Like anastomoses, they are phreatic. Their distribution within a plane and in successively higher planes is the same as that of anastomotic bands.

Dip tubes and anastomotic bands should thus be considered to be a continuum of linear entities, which become more sinuous and braid the flatter is the gradient, just as river channels at the surface are observed to be more sinuous (and sometimes braided) where their gradients are gentler. Initial conditions in bedding planes are thus of a diffused flow which is probably laminar and does not generate distinct erosional features. Tiny dip tubes and anastomotic bands are the first features to develop through this diffused pattern and improve its hydrodynamic efficiency. They are closely analogous to the early rills of surface channel pattern formation, (R. E. Horton 1945), and their spacing is possibly governed by similar laws. It is important to emphasise that these features are oriented down the structural gradients, which are the only real gradients that exist in a limestone mass at an early stage of cave development.

2. Development of Caves in steeply dipping limestones where groundwater drainage is in the direction of the dip.

The author has published two accounts of the genesis of the central Mendip caves, (1965 and 1968). The limestones dip at 15°-40°. Groundwaters passing from sinks to springs are oriented generally in the direction of the dip. Because the dips are steep, waters sinking in one particular bedding plane must pass through many hundreds of feet of rocks that are stratigraphically higher before attaining the springs. This is the case in almost all regions of steeply dipping rocks. It is a consequence of the fact that the structural gradients are much higher than the topographic or hydrologic gradients. The case where a single dipping bedding plane hosts both the sink and the spring is comparatively rare though there are instances in Co. Clare and elsewhere.

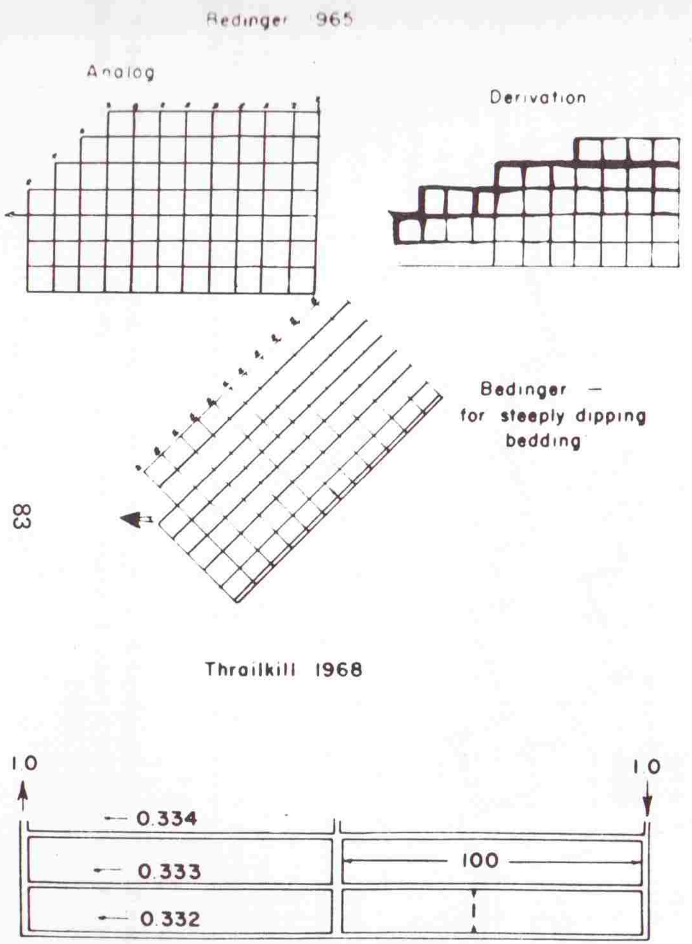

FIGURE 1. M.S. Bedinger's electrical analogue model of limestone groundwater circulation. J.V. Thrailkill's computation for the solubility of a vertical array of phreatic passages where the bedding plane:joint ratio = 100:1.

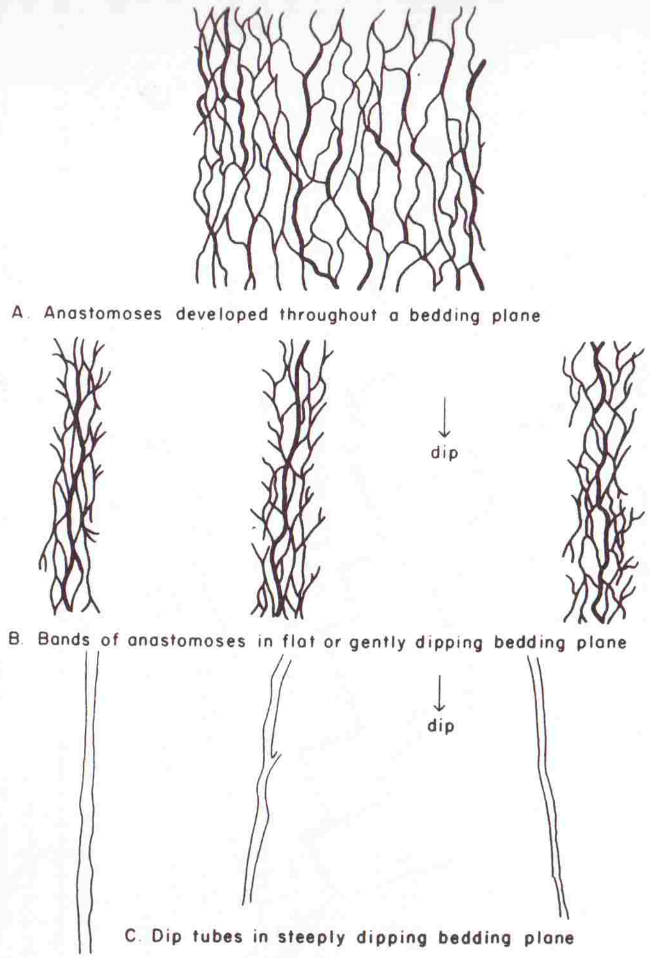

FIGURE 2. Distribution of anastomoses and dip tubes in a bedding plane.

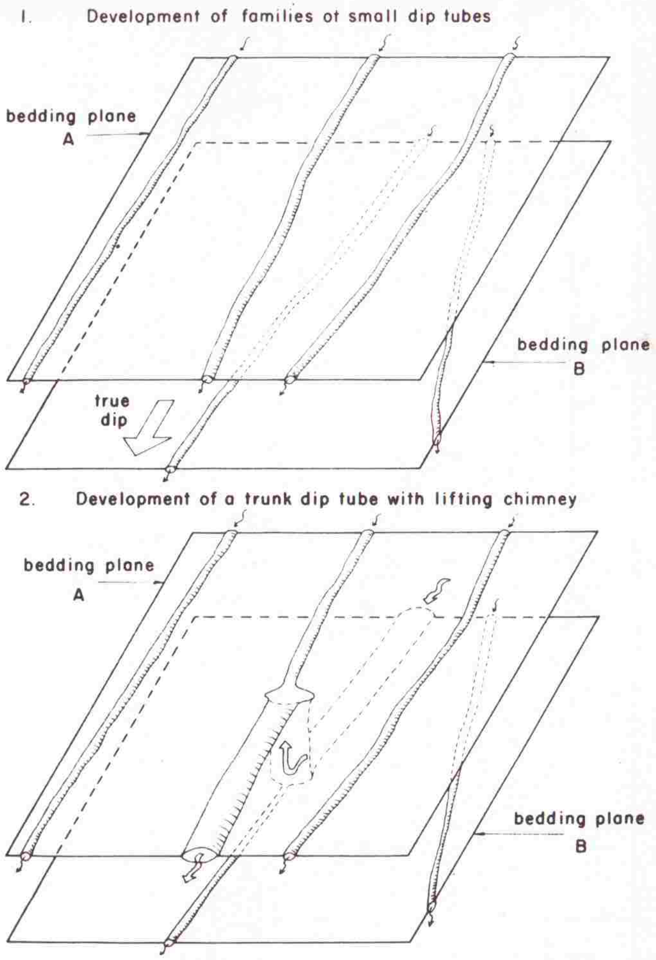

FIGURE 3. The nature and distribution of dip tubes, trunk dip tubes and lifting chimneys in steeply dipping bedding planes.

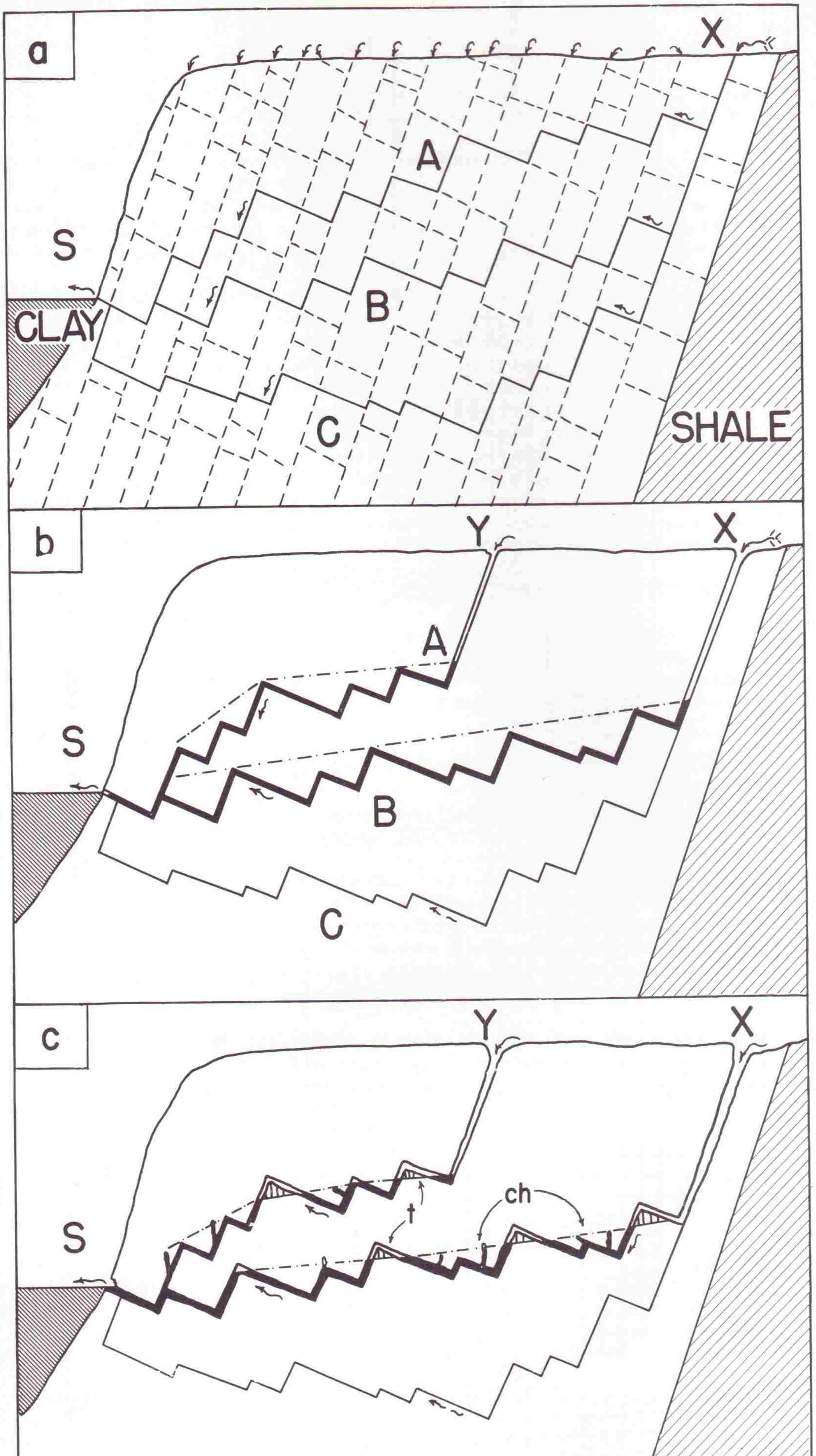

Figure 4. In steeply dipping limestones, caves of explorable dimensions, (Route B, part of Route A) develop after a route competition, (A - B - C), which favours the centrally located route B. (From Ford 1968).

The central Mendip caves are constructed from two basic elements. First, and quantitatively much the more important, are dip tubes. Most of the tubes remain of inaccessible dimensions throughout their active lifetimes. This suggests that they have only very small catchments at the surface. Some progressively capture the waters of larger surface streams and become expanded into trunk passages. Trunk tubes are observed to make the stratigraphic ascents necessary to attain spring points by way of the second basic building element – joint chimneys up which the water is lifted, (Figure 3). These are much shorter than the dip tubes. The length-ratio, dip tube: joint chimney, ranges 10-60:1.

The combination of one or more dip tubes and joint chimneys between successive piezometric surfaces along a trunk course constitutes a 'phreatic loop'. This is most readily defined by the amount of vertical lifting of water that is required. In the case of Swildon's Hole this was shown to be greater than 100 feet at an early stage, reducing to 15-30 feet at the latest stage. The reduction was a consequence of the increasing frequency of penetrated fissures as time passed, and the reduction of the bedding plane: joint length ratio. Increasing fissuration requires that significant quantities of water circulate about and below trunk passages during the active lifetime of the latter. This contention receives considerable support from hydrological test drilling in Greece, (Burdon and Papakis 1963).

In central Mendip many families of dip tubes existed in separate bedding planes. Selection of a major cave route from these alternatives was probabilistic. Higher or lower planes might be utilised but, in general, those centrally located tended to win, (Figure 4). Discussion of watertable control is irrelevant where the amplitude of the phreatic loop was greater than c 25 feet. Water was driven up the lifting segments by local piezometric heads which fell as the systems expanded in volume and were probably at the surface of the land at the beginning of dip tube genesis. The fall of head during the route competition left an uppermost zone of drained dip tubes that were still of small dimensions. Where fed by major streams these were entrenched to form major vadose caverns in which the early phreatic element constitutes only a few percent of the void space. Big vadose caves can always be expected where large streams are able to collect above the sinkholes, (very often they collect only on non-karst rocks), and where there is sufficient relief above the spring.

It is possible to define four 'states', (to use a less implicit term than 'phase'), of cave development in central Mendip. State 1 is of very deep phreatic looping. It is exemplified by St. Cuthbert's Swallet where there was more than 300 feet of loop penetration below the piezometric surface in a system which, in toto, extended only some 400 feet down into the rock. On any scale consideration of the type indicated in the Introduction, this must be considered 'deep' phreatic development. Swildon's Hole and the effluent caves at Cheddar illustrate the three other states culminating in the modern lower streamway of Swildon's where the active cave (descending and lifting portions), is restricted to a zone 25 feet in depth within a total descent of more than 500 feet – in scale terms, this is a watertable system as in Swinnerton's formulation.

Figure 5 illustrates three successive states in a hypothetical Mendip cave. The first two yield a deep phreatic cave though it is obviously improper to call it 'random - depth cave' per Davis. The third is a watertable cave, susceptible to further flattening of profile by the operation of gradational processes which work down the system from the head, (Ford 1965).

These different states led to the development of markedly different proportions of vadose, watertable and deep phreatic passage in the various caves. To some extent, different states may have coexisted in different parts of the rock mass. More certainly, within a given part of the rock mass the states developed successively 1-4. This again is probabilistic. **Thus it is most important to appreciate that in other regions of comparable dip, caves need not necessarily develop first with the State 1 phreatic amplitudes of the central Mendip example.** Fissuration density may be lower, creating deep phreatic systems of much greater amplitude. Or it may be greater, so that even the earliest caves are the smoothed, watertable type of Figure 5. This is to say that where fissure density is high and the geometric proportionality approaches that of Bedinger's experiment, the cave that develops approximates Bedinger's result. Initial fissure density is related to lithology and tectonic history, which varies from place to place.

The point is illustrated by caves of the eastern Mendip Hills. The limestones there dip at 60-80° beneath a plain bevelled across them and groundwaters drain in both dip and strike directions. The known caves (Stoke Lane Slocker and the caves of Fairy Cave Quarry), appear to comprise earlier systems looping at the amplitudes of States 2 or 3 of central Mendip, underlain by later, active passages equivalent to State 4 or even flatter. Thus, the central Mendip rules apply in these very steeply dipping rocks.

What happens where the stratal dips are less than those of central Mendip is more important, because the flat-lying state presumed for past general case hypotheses is approached. The lowest dip at which I have seen the Mendip rules operating incontravertibly is 5-5½°. The example is Castleguard Cave in the Canadian Rockies, (Figure 6). It has a trunk passage length of more than five miles. This is composed of three very long dip tubes which are entrenched in their headward parts and linked together by phreatic lifts of 40-100 feet. Length ratios, bedding plane:joint (or in this case, fault), exceed 100:1 in one instance. It must be stressed that the limestone beds at Castleguard Cave are exceptionally massive. Where bedding is thinner (and fissuration potentially more frequent as a result) the steep dip cave pattern might not occur until greater dips than 5° were encountered.

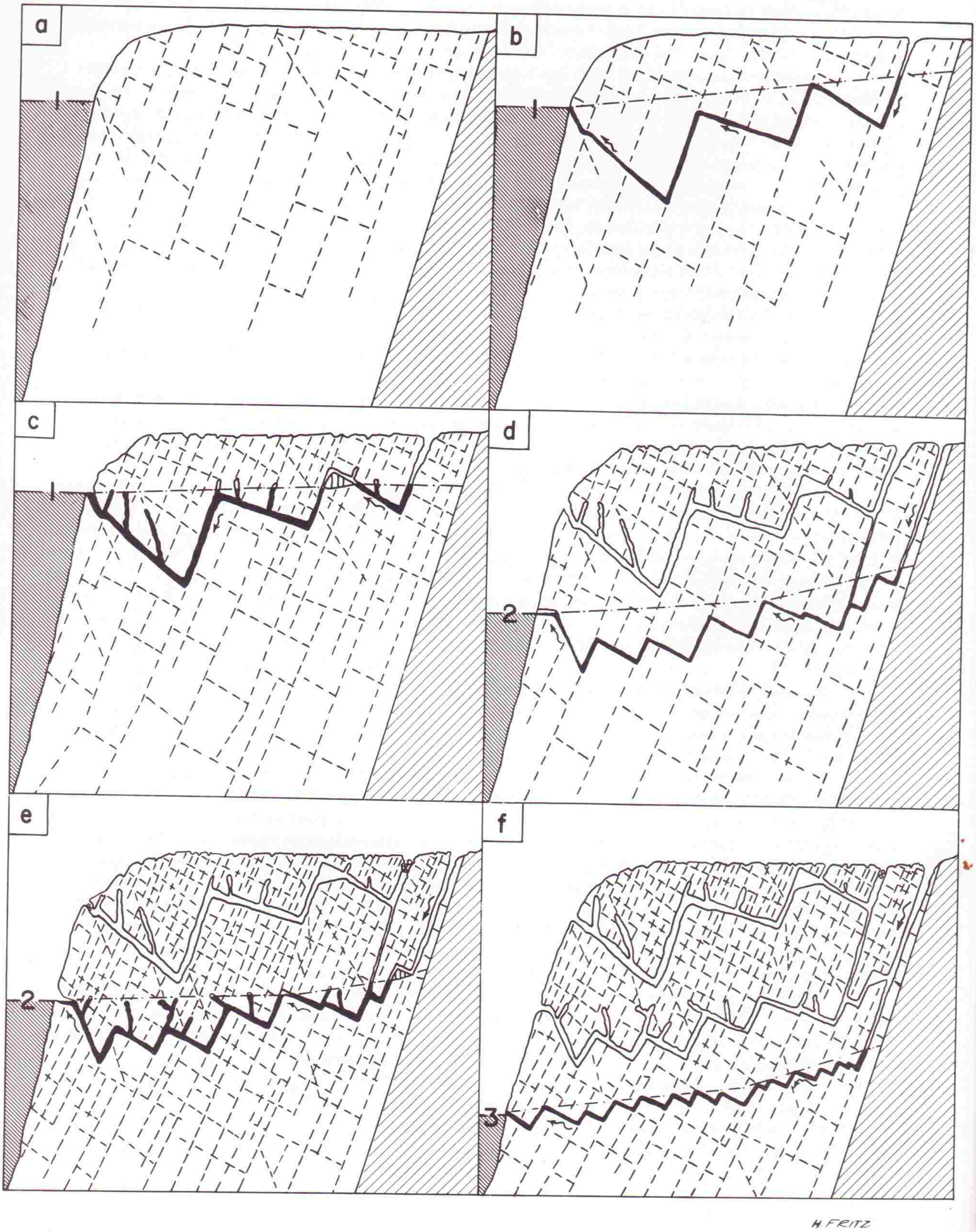

Figure 5. Successive states of phreatic looping in a hypothetical multi-phase cave in steeply dipping limestones. Loop amplitude is proportional to the frequency of penetrable fissuration. Caves 1 and 2 are 'deep phreatic'. Cave 3 is vulnerable to gradation processes operating from the head of the system and may appear to be a 'watertable' case. (From Ford 1968).

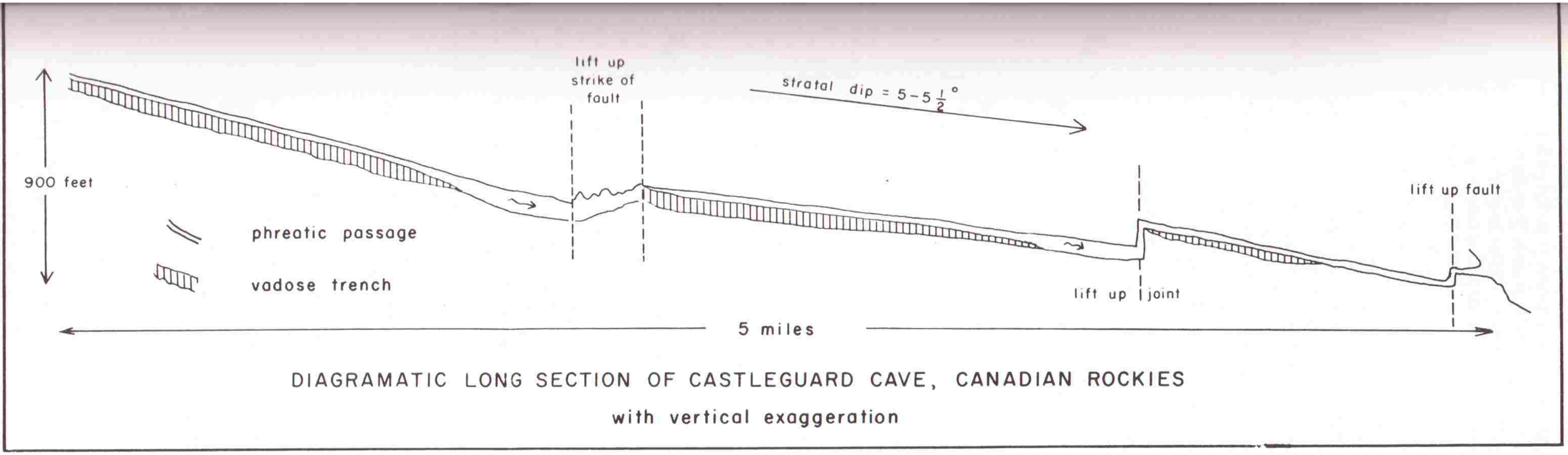

FIGURE 6. Castleguard Cave, Banff National Park, Alberta, Canada. This cave consists of three long dip tubes, entrenched in their upstream portions and linked by short lifting sections in joints or faults.

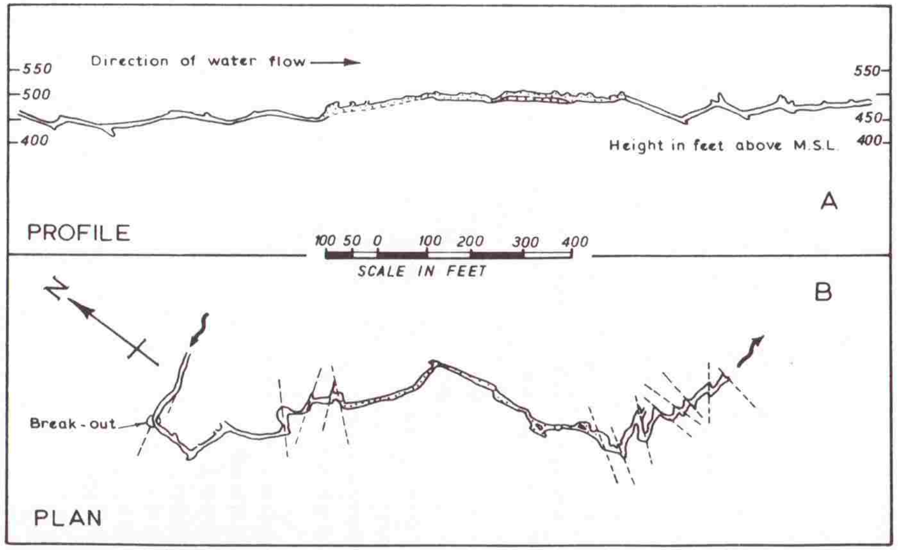

FIGURE 8. Long section and plan of part of "Paradise Regained", Swildon's Hole, Somerset. This is an excellent example of an irregular strike passage. Dashed lines are dip tubes.

3. Development of Caves in steeply dipping limestone where groundwater drainage is to the strike.

Groundwater drainage and cave development broadly along the strike in steeply dipping rocks is more common than the dip drainage considered above. This is to be expected. Rather special geomorphic conditions are required to expose the dip front of a limestone mass and thus attract groundwater drainage to it. In the case of the central Mendip Hills it is a complicated story of Triassic desert weathering and the selective stripping of a later marl cover, (Ford and Stanton 1968). Normal river entrenchment across a region of mixed strata, (e.g. sandstone, limestone, shale) will expose the limestone portions to predominantly strike drainage.

Information on strike-line cave genesis in steeply dipping rocks comes, initially, from central Mendip. In the early states of fissuration and groundwater transmissivity, (States 1-3), passage segments developed to connect independent dip tubes within a single bedding plane. These segments are oriented up or down aslant the dip and strike, changing their orientation at each dip tube junction, (Figure 7). This creates a cave profile of irregular looping, largely or entirely below the piezometric surface. Where the states of transmissivity were higher, (state 4), independent dip tubes were connected by the shortest possible passage segments. These follow the true line of strike. Quasi-horizontal passages result: if the piezometric surface is lowered into them as their dimensions expand, these passages become the ideal watertable caves.

Figure 8 illustrates some 2000 feet of the Vicarage Passage – Paradise Regained section of Swildon's Hole. It is a State 3 example. The trunk stream flowed from left to right. It is seen to be looping irregularly to depths of 70 feet beneath the contemporary piezometric surface which was attained only in a central, joint-guided segment of the passage. However, central Mendip is not a proper strike-line case. Strike passages there play a secondary, amalgamating role in systems directed to true dip. It was not at all apparent that dip tubes, (essential in this kind of strike cave development), should appear where the whole rock mass drained only to the strike.

I have had several opportunities to test the Mendip findings in proper strike-line situations. The first was at Crowsnest Pass in the Canadian Rockies. The Pass intersects a narrow range of mountains in medium-to-massive limestone which dip at 10°-40°. Modern groundwater drainage is to the strike and discharges at 4400-5000 feet above sea level. Accessible cave fragments are scattered all the way up to the mountain summits at 900 feet. These caves are fossil and frequently choked with debris. During my last visit, in 1969, no caves longer than 1500 feet were found. But almost all that I examined were composed of dip tubes, joint chimneys or aslant-strike phreatic passages climbing and descending irregularly in the Mendip fashion. In one instance it could be seen that a big groundwater stream had flowed steeply upwards aslant strike for some two hundred feet of vertical ascent. In 1970 two big, deep caves were discovered. From the explorers' accounts, they are composed of the same Mendip elements and hundreds of feet of looping flow down and up to the strike has occurred. One particular trunk dip tube is more than 100 feet wide.

Another example is the second longest cave in the world, Hölloch, in Switzerland. Thanks to Professor Alfred Bögli's kindness, I have seen some 15 kms. of passages there, representing a fair sample of the variety of morphology and scale in the system. Hölloch is comprised of a main cave in a lower thrust plate, overlain by smaller systems in an upper plate. In the main cave, the massive crystalline limestones dip in a northerly direction at 12°-20° in most places. Drainage is westerly, i.e. to the strike. In the broadest analysis, the main cave is an amalgam of dip and strike conduits generated by uniclinal shifting of spring points down dip. There is 1200 feet of relief, North-South. In detail, the main cave is a gigantic version of Paradise Regained, Swildon's Hole, being composed of the same basic elements. Dip tubes are comparatively small; aslant-strike conduits channelling water up and down may be very large (e.g. Titanengang). The amplitude of phreatic looping to the strike is hundreds of feet. During summer floods, the lowest 400 feet of the accessible system may be filled: the vertical amplitude of aslant-strike phreatic lifting must then be in excess of 600 feet in some loops. Figure 9 shows the form of some of these strike passages. The similarity to the example from Swildon's Hole is quite evident though the scale is much larger.

The famous Postojna Caves in Yugoslavia are an instance of strike orientation in steeply dipping limestones where the frequency of penetrable fissures is higher than in the above cases, approximately equivalent to Mendip State 4. The modern river passage and the most recently abandoned conduit, which is the main tourist route, have a gentle gradient which is well sustained. Significantly, joints play a more important part in guiding passages than they do in Hölloch, etc. But above the tourist level is an older strike passage, Lepe Jama, which undulates up and down regularly in association with minor changes of direction. Details are obscured by stalagmite deposits. The undulations suggest development shallowly aslant-strike, intermediate between Mendip States 3 and 4. Thus, with time, the trend in this system has been to increasing fissuration and flattening of trunk passage profiles as in the Mendip dip case.

4. Some other structural cases: The Artesian Special Case.

The karst of Greenbrier Co., West Virginia is little known on this side of the Atlantic. It contains many river caves with eight or more miles of mapped passages. The medium-to-massively-bedded limestones generally dip westwards at 5° but the groundwater drainage trends to easterly springs, i.e. this is an instance of flow **against** the dip where the dip gradient is intermediate between steep and flat cases. The bulk of cave passage development is to the strike. The caves appear to be a complex misture of

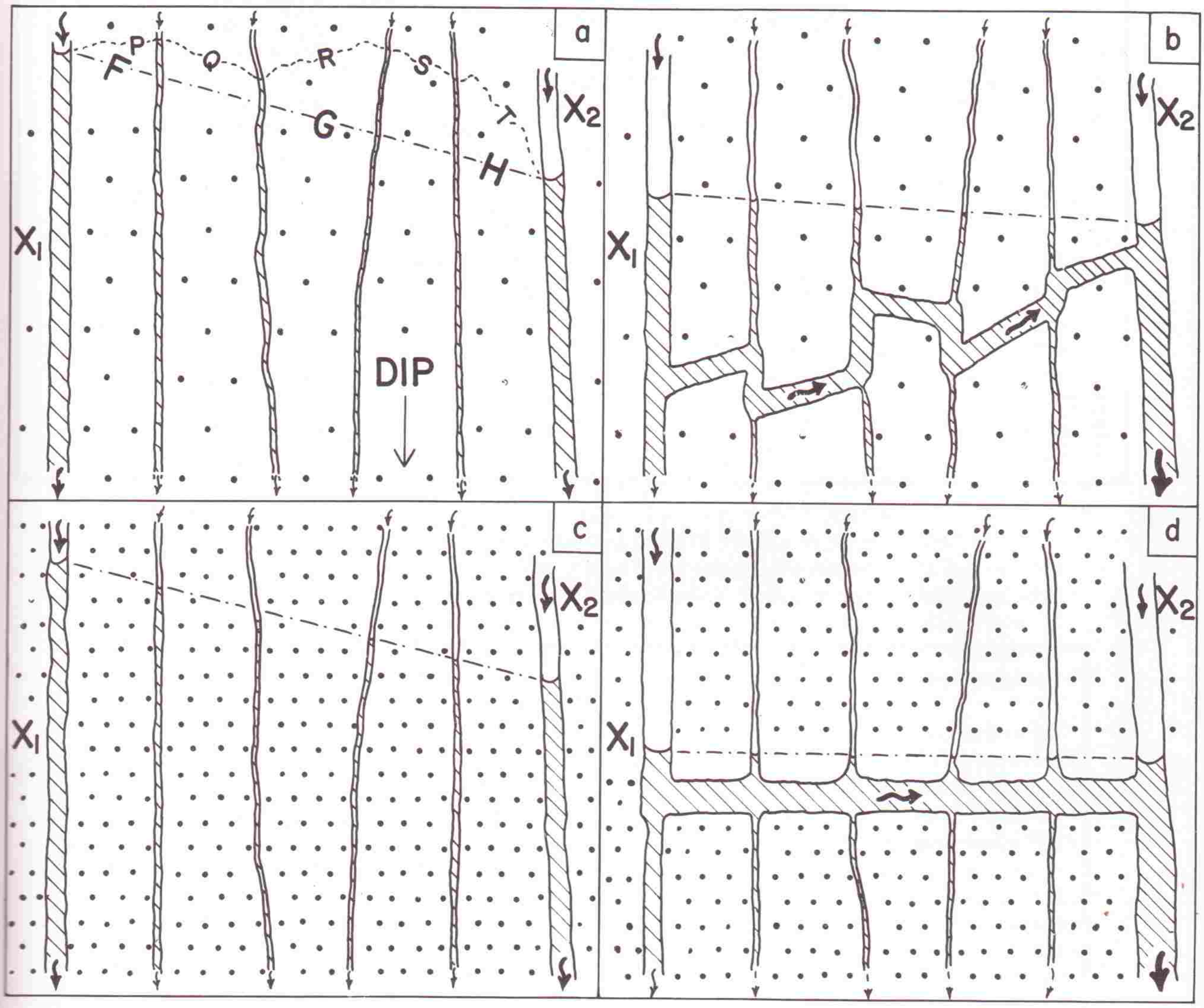

Figure 7. Development of strike passages to link trunk dip tubes in steeply dipping limestones. Diagrams are in the plane of the bedding plane. 7 a/b - hydraulic transmissivity across bedding plane is low, indicated by irregular piezometric surface, PQRST. An irregularly oriented strike passage results. 7 c/d - hydraulic transmissivity is high, piezometric surface is regular. A straight strike passage results. (From Ford 1968).

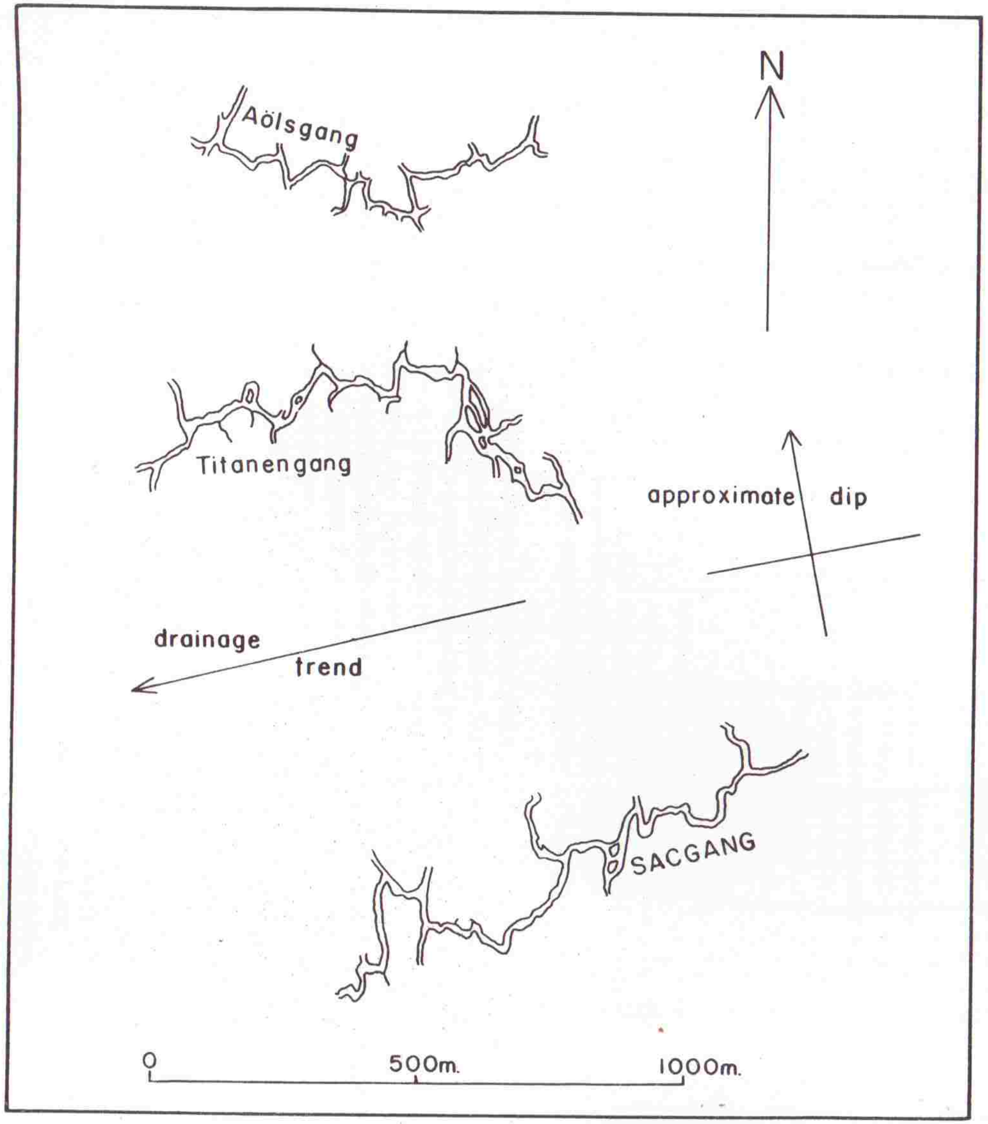

FIGURE 9. Irregular strike passages from the Hölloch, Switzerland. Most of this great system is composed of phreatic dip and strike passages switching direction with the frequencies illustrated.

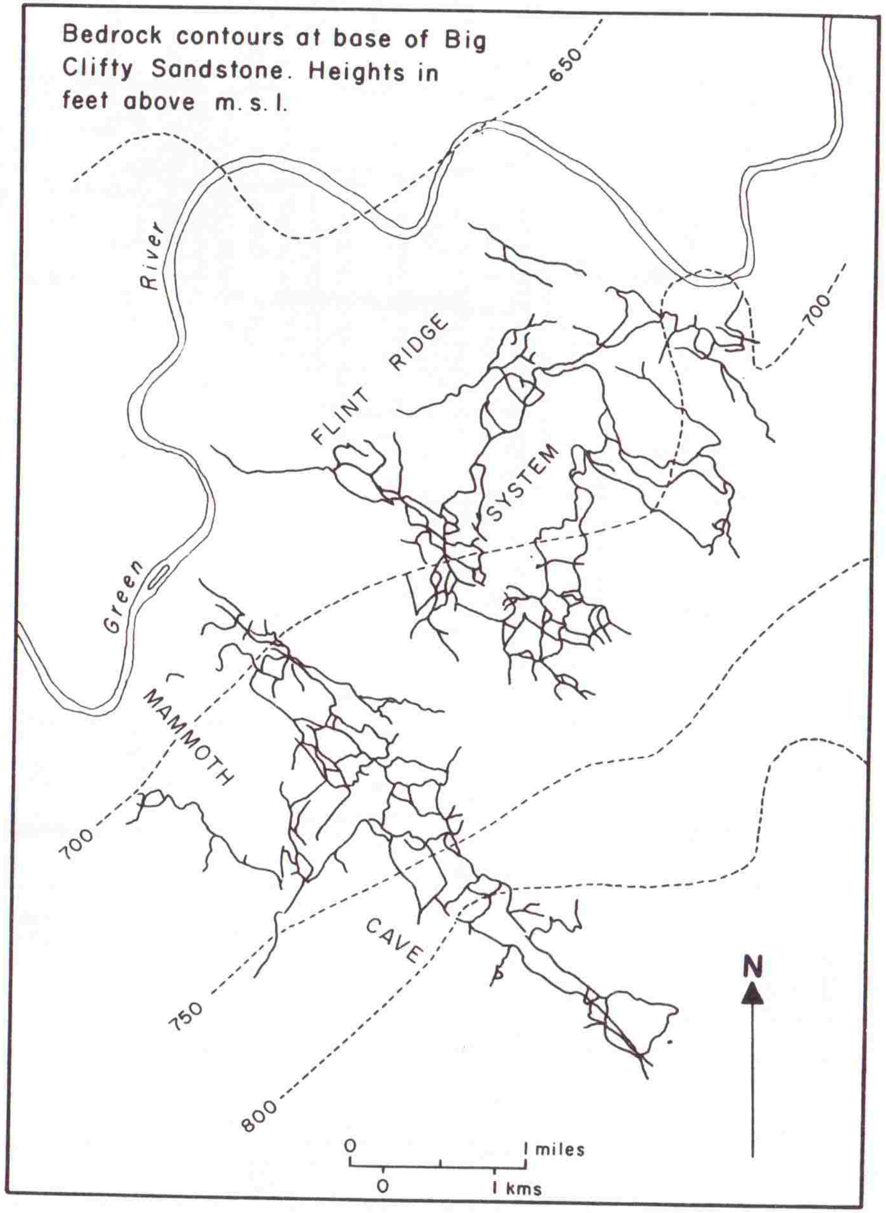

FIGURE 10. Mammoth Cave and the Flint Ridge System, Kentucky, an example of caverns in nearly flat-lying rocks. Bedrock contour information courtesy of Mr. J.F. Quinlan

Mendip dip tube and States 3-4 strike-line elements with passages associated with horizontal conditions. The caves penetrate 200-5000 feet underground; the amplitude of the active cave zone is generally less than 50 feet so that, in scale terms, they appear Swinnertonian.

There are many cave systems wherein stratal dips change radically in direction or gradient, i.e. the scale of the folding is smaller than the scale of the cave. For a number of good reasons, tight folding in intermediate to massive limestones is likely to yield very high frequencies of penetrable fissuration. Davies (1960) found that caves in tight folding in Virginia had profiles which were accordant to local river terraces, suggesting "watertables" or State 4 development.

Deike (1960) and Howard (1964) have described instances in the United States where caves have developed along or across synclines containing overlying impermeable rocks, i.e. artesian conditions. These true artesian caves are bedding plane and joint mazes apparently without any of the Mendip constructional elements (dip tubes, joint chimneys, etc.). But true artesian conditions should always be considered a special case of cavern development.

Greenbrier Caverns in West Virginia, (more than 20 miles mapped), are developed across several anticlines and synclines which are widely spaced but have steep flanks. There is not true artesian confinement. Trunk drainage follows the pitch of the synclines. The cave appears to be composed of a mixture of artesian maze forms and flat-bedded-type passages in the synclinal troughs linked by State 3-4 dip and strike passages across the anticlines.

5. Some characteristics of cavern development in flat-lying limestones.

As a first approximation, "flat-lying" is taken to mean limestones dipping at less than 5°. This is the situation adopted for the general case theories, in so far as structural attitudes were considered at all.

A preliminary point is that of the more than 500 caves I have seen in Europe and North America those developed in flat-lying limestones are the most alike, region to region. Predominant passage types are the phreatic ellipse or flat-roofed gallery which has been expanded from a particular bedding plane, or the taller rift following the junction of joints and a bedding plane. These passages, especially those guided only by bedding planes, maintain their form, dimensions and direction for greater distances than will be found in most steeply dipping rocks and also maintain very regular gradients.

The most important principle of cavern genesis in flat-lying rocks is again a matter of geometric analysis. The predominant water intake from the surface must be by way of joints, as in Bedinger's model. Joints are discrete features in a rock mass. There is not usually the potential for an individual joint to entrain a groundwater stream and guide it to great depth as there is in the case of an individual bedding plane in steeply dipping rocks. Joints intersect with one another and with bedding planes. Groundwater streams threading a course through systems of joints alone will make many turns at the joint intersections. These make the course one of high friction, vulnerable to capture by a straighter, more efficient course such as can develop in a bedding plane.

In contrast to joints, bedding planes in a flat-lying limestone mass must be considered to be continuous to the boundaries of that mass and thus to spring points at the boundaries. The flat-lying systems is characterised, therefore, by discrete intake fissures and continuous outlet fissures; which is the reverse of the case in steeply dipping rock where drainage is to the dip. Further, lateral streams utilising the continuous outlet fissures are more efficient than lateral streams utilising joint systems alone and so are more likely to be predominant. Thus, in conditions of equal fissure frequency and proportionality, it is always probable that caves in flat-lying rock will be shallower than caves in steeply dipping rock and so they will be more frequently representative of the watertable case. Deep phreatic caves may occur in flat-lying rocks: this depends upon absolute fissure frequencies and proportionalities as in the steep-dip analysis and is favoured by the presence of very deep joints or faults such as occur in Yorkshire[1]. Further, there is abundant evidence to show that significant groundwater circulation continues beneath developed trunk passages in flat-lying rocks, as it does in steeply dipping rocks. Once again, this increases fissure frequency in the context of later generations of cave galleries developing at lower elevations.

In flat-lying rocks, deep phreatic development will often be interpreted as the watertable case. Suppose that a conduit develops for a length of several miles at a depth of forty feet beneath a spring point. It is a deep phreatic cave in the extant piezometric circumstances. Whilst the conduit is expanding to explorable dimensions, allogenic processes lower the spring position forty feet. The entire cave is drained. Comparable fissuration in steeply dipping rocks might yield a system that loops to 300 feet below the original spring elevation. Lowering of the spring by forty feet will drain only a very small part of it.

It is contended, therefore, that shallow, watertable-type caves are more probable than deep phreatic caves in flat-lying rocks. Setting aside the case of the vertical shaft, unmistakably vadose enlargement is also inhibited in flat-lying rocks. The rate and competence of vadose entrenchment is roughly proportional to the gradient of a passage. Drained dip tubes in steeply dipping rocks may be uniformly and spectacularly entrenched for considerable distances e.g. Swildon's I. Flat or very gently

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[1] Dr. A. C. Waltham's recently published discussion of cave development in Ingleborough, Yorkshire, appears to uphold this analysis of the flat-lying case completely and emphasises the importance of perching on shale beds or other impermeable strata, (Waltham 1970).

descending galleries are not susceptible to uniform entrenchment along their lengths. Very often, entrenchment proceeds headwards from a drop at the downstream end and upstream portions may be phreatic in appearance, frequently sumped or wholly waterfilled during storms long after the introduction of permanent vadose conditions at the downstream end. This feature is common in Kentucky and Indiana. The Flood Entrance gallery of Gaping Ghyll and the Canal of Penyghent Pot are also examples.

To conclude analysis of the flat-lying case and point out some further features of it, it is interesting to consider the longest caverns in the world, Mammoth Cave and the Flint Ridge System in Kentucky. In the English-speaking world, I think that these caves have had a profound and undue influence upon speculation about cave genesis. The two systems occur side by side and currently aggregate more than 130 miles of mapped passageways. Before 1845 A.D., 21 miles of cave were sketch-mapped in the Mammoth portion. These caves have been the longest known in the world for a long while. It is not surprising that American authors should come to treat them as a norm to some extent, the principal test for the validity of theories and the central cave type against which all others must be compared. Misled by a map which was almost a fiction, W. M. Davis interpreted them as a deep phreatic complex. Later workers have looked upon them as the ideal watertable case.

Yet there are many unusual features in the geological setting of the caves, features which would certainly not be warranted in an idealised model. I am indebted to Mr. J. F. Quinlan, who has studied the regional lithology and structure, for the following information. The known caves are developed in the upper 200-250 of a limestone which, below this limit, is increasingly dolomitic, cherty and silty. Amidst the cavernous limestone beds there are two major cherts of regional extent and a few thinner, local chert bands. Any of the cherts may terminate the tops and bases of domepits and control the levels of the vadose crawlways which drain the domepits. There are also three or four locally occurring dolomite beds in the section which control certain domepit levels in the same manner. Therefore, we are dealing with a comparatively thin limestone mass in which there is potential for an unusual amount of lithological perching of passageways. In the major passages, perching is difficult to trace because of clastic fill and ceiling breakdown.

Another unusual feature is that the caves are overlain by a thick caprock, the Big Clifty Sandstone and higher formations. This retards overhead infiltration of groundwater, reducing the solutional openings of joints, so causing excessive elongation of passages in bedding planes. Deike (1967) carefully investigated jointing in the Flint Ridge system and was surprised by its lack of effect.

The dip of the limestone in central Kentucky is generally less than ½° but in the vicinity of the Mammoth Cave and Flint Ridge systems it is steepened slightly by shallow anticlinal flexures. Figure 10 shows the caves with the structural contours for the base of the Big Clifty Sandstone superimposed. The flexures may have strongly influenced the development of these very great caves. It is seen that Mammoth Cave is oriented parallel to true dip whilst the Flint Ridge System has dip and strike components. Structural gradients are exerting an effect upon major passage orientation even in this very shallow dip case.

However, the gradient of most trunk passages is less than that of the dip. These passages must make a stratigraphic ascent to attain the springs, as in the steep dip case. Phreatic lifting, up joint chimneys, is difficult to observe because of subsequent expansion of passages through the lifting site and because of clastic fill and breakdown. It may not have occurred very often because of the minimal role of joints in the systems. But I have seen one unequivocal instance in the middle of a long trunk passage, Swinnerton Avenue in Flint Ridge. The steep-dip rules operate to some extent in these caves in gently dipping rock.

CONCLUSION

The principal contentions of this paper are as follows:

1. There is no one general case of limestone cavern development which can be so precisely defined as older theories would have it. Rather, there are three **common** cases: the predominantly vadose cave, the deep phreatic cave and the watertable-type cave. There is also one **special** case - the true artesian cave. Some caves in non-artesian settings display characteristics that are transitional to the artesian type, e.g. the two-dimensional joint maze.
2. The type or types of common cave which will develop in a system are governed by the frequency of fissures significantly penetrated by groundwater and the geometric proportionality of this fissure network, i.e. the bedding plane:joint ratio. These characteristics are combined in the hydrologist's conception of hydraulic conductivity. The higher the value of hydraulic conductivity, the more likely is the watertable-type of cave, (and, often, the vadose cave) to develop.
3. In a given limestone mass, hydraulic conductivity may vary from place to place, creating different proportions of the common cave types in different systems. In a given limestone mass, hydraulic conductivity will normally increase with the passage of time after onset of karstification. Hydraulic conductivity differs from region to region.
4. Predominantly vadose caves can develop where sufficient streams collect above sink points and where there is sufficient relief between sink and spring. The maximum extant hydraulic gradients that I have recorded in alpine, (very high relief) systems in limestone are around 1:12, (in interbedded limestones and dolomites gradients are steepened to as much as 1:8 in one instance). Therefore, where the straightline gradient between a sink point and a spring is steeper than about 1:12 it may be predicted that draw-down of the piezometric surface during the early phase of route competition will create a

vadose zone ready for expansion. Very often, this will be true where the gradient is gentler than 1:12. It depends upon the value of the hydraulic conductivity.

5. Deep phreatic caves attain their optimum development in steeply dipping rocks because continuous bedding planes may guide water to great depths. Watertable caves are particularly common in flat-lying rocks because deep penetration is inhibited by the presence of shallow, opened bedding planes which are continuous to spring positions. Lithologic perching of cave conduits is most effective in flat-lying rocks.

6. Before any caves have begun to develop, few limestones have such a high density of fissuration that all runoff can be absorbed at a time. Seasonally or permanently, the fissures are filled, i.e. the watertable is at the surface. This is recognised in the Sawicki/Cvijić formulation of a cycle of surface karst erosion and it is curious that many later speculations about cavern genesis did not adopt the point. Where a watertable or piezometric surface is established at depth in rock from the very inception of karstification it is predicted that fissure frequency will be so high that the watertable type of cavern will develop.

7. Where the ratio of penetrable bedding plane length to joint is large, the fundamental building blocks of caves are linear anastomotic bands in gently dipping or flat rocks and dip tubes in steeply dipping rocks, linked by ascending or descending chimneys following joints. Strike-oriented passages may develop subsequently. Caves which are guided predominantly by joints, (excluding the artesian special case) are associated with high values of hydraulic conductivity at inception.

This paper has not touched upon caves in the tropics. Many cavernous limestones there are younger than is common in Europe or North America. It appears that they may possess a significant measure of primary permeability. Other things being equal, this will increase the hydraulic conductivity, making the watertable type of cave more probable. It possibly explains the high frequency of shallow river caves described in the tropical literature. However, the Association for Mexican Cave Studies and the McMaster University group are exploring caverns in high relief in tropical rainforest around Huatla, Mexico and finding systems that have many features in common with those of alpine caves. It is doubted that difference of climate alone generates any fundamental difference in patterns of cave development.

The American and continental European writings about cavern genesis differ so much in character and emphasis because it just so happens that American examples have been drawn predominantly from a population of caves in nearly flat-lying rocks in regions of rather low relief. Per contra, European examples derive in the main from the very high relief of alpine and foreland settings, the optimum for substantial vadose development. British investigators are fortunate because they have at hand, explored and mapped in more detail than anywhere else in the world, examples of caves in flat-lying and steeply dipping rocks in settings of intermediate relief. These supply a sample range of a central kind wherein to investigate the basic principles of cave construction.

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DISCUSSION

G. T. Warwick (Birmingham): In addition to the other variables mentioned by Derek Ford, there is the relationship between the underground and external drainage. In the case of the Mendips, some caves are related to the external risings and others such as those in Cheddar Gorge are orientated towards the old "Gorge River". This orientation affects the relationship to geological structure.

The new concept of the "stratigraphical lift" is a very useful one and it can be applied in Ogof Ffynnon Ddu I, in the passages up-dip from the stream. This concept also applies to caves that fill up due to constricted lower passages as well as to flooded caves in the phreatic zone, but such caves only operate occasionally. In Italy, on the eastern side of Lake Como, I have seen a cave which backs up a dip passage and occasionally overflows from a horizontal cave. On the occasion of my visit the flood was falling at 1 cm. per minute. The steep slope was covered in gravel which decreased in size uphill. This flood was at least 100 feet in depth. Similarly some of the resurgences appear to be the upper end of a "lift". Others are the natural outlets of Ogof Ffynnon Ddu, Gaze Gill Cave etc. The Fontaine de Vaucluse appears to be a particularly large example of such a terminal "lift".

A. C. Waltham: referred Dr. Warwick to details which were in the paper but which he had been unable to speak about in the time available.

W. H. Little: What considerations should be given to climatic conditions different from those now prevailing, which were presumably operative at the time when some of the cave were being formed?

A. C. Waltham: Answering for myself, I feel that within a cave system climate has relatively little effect on the form and distribution of passages within a given structure. Climate may affect the rate of development, but not the features themselves. The apparently different features of many tropical caves are in fact due to their being in highly porous limestones, i.e. a structural influence. Glaciation and peri-glacial erosion too affect the underground parts of a system very little, but Dr. Warwick will deal with that later. On the other hand climate may affect surface features to a considerable degree given similar structural conditions.