SOME ASPECTS OF THE ORIGINS AND DEVELOPMENT OF THE GAPING GILL - INGLEBOROUGH CAVE SYSTEM

Part 1 The science

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Introduction

Just over two kms to the south-east of the summit plateau of Ingleborough, a 723m high mountain in the western part of the Yorkshire Dales National Park, a lively mountain stream, known as Fell Beck, plunges abruptly over the lip of an oval hole, 20m by 5m occupying the full width of the bed of the stream. This 110m deep shaft is Gaping Gill, the greatest of all British pot-holes. Beyond the shaft, the 10m deep valley cuts into boulder clay covered with peat and terminates in a steep semi-circular grass-covered slope.

Ingleborough rises in two great sweeps 550m above the surrounding valleys and it has long been known as the classic area for limestone scenery in Britain. The area is also so regarded as the "classic among classics" for Britain's cavers. Around the flank of Ingleborough itself over two hundred caves of all degrees of complexity and severity are known today. Within this relatively small area (Ingleborough map Fig. xx) there are as many, if not more, deep shafts as there are in the whole of the rest of the country (Brook et al. 1975).

Thirty or more caves and potholes are known to lie within a radius of 500m of Gaping Gill (see Gaping Gill area map, figure xx). Among this collection of caves the Gaping Gill - Ingleborough cave system holds pride of place. Although neither the longest nor the deepest known cave system in Britain, it contains the highest free fall water-fall (100m) and the largest underground chambers. Most British cavers visit it at least once in their caving career and many return year after year. Some fifteen hundred descents of the Main Shaft are made by winch each year during the course of the Spring and Summer Bank Holiday camps run by local caving clubs. Each weekend throughout the rest of the year caving clubs from all over Britain hold meets to descend one or more of the several entrances to the system.

Geology of the area

History of the geology

Many aspects of the geology of the Ingleborough area have been studied in great detail over the years, and the volume of published material is considerable. Garwood and Goodyear's (1924) detailed palaeolontological account is still almost the standard reference to the geological succession within the Great Scar limestones (Fig. xx). For the speleologist, Wilson's account (Wilson, 1974, Fig. 3) summarises the geological succession in the Ingleborough area in the more modern manner. It does rely heavily on the lithology of the limestones, and is of greater value, although, as will be shown later very little information from underground exposures is included in this account. More recently Ramsbottom (1973) and Ramsbottom in Raynor & Hemingway (1974) point the way toward a new understanding of the events effecting the deposition of carbonate sediments during the Lower Carboniferous Period (Fig. xx). Dunham et al (1953), is still the best general guide to the geology of the Ingleborough area itself (Fig xx), whilst Waltham's (1974) Regional Memoir on the Limestones and Caves of NW England covers the geomorphological and speleological aspects of the area in much greater detail, and is the best and most up-to-date account of the full range of karst land-forms in the area. Accordingly only the barest outline of the geology and geomorphology of the area will be given here, together with additional comments on those aspects which are of particular significance in the Gaping Gill area.

Summary of the geology

In many of the Yorkshire Dales and around the flanks of Ingleborough in particular, the Great Scar Limestone of lower Carboniferous fossil zones S2 and D1 ages (in Vaughan's scheme of 1901) is topograhically prominent. (Fig. xx, geological map of region). These give rise to the characteristic land-forms of the area; that is the scars and pavements (see Sweeting in Drury, 1966). They form a unit averaging 180m thick of considerable vertical but little lateral variation Resting unconformably on a substantially rigid platform of folded and faulted slates and grits of Ordovician to Silurian ages. This platform, known as the Askrigg Block (Marr, 1921) has remained relatively stable for a very long period; probably as a result of the intrusion of the Wensleydale granite (Dunham, 1974) prior to the onset of Lower Carboniferous sedimentation in the area.

The basal rigid block dips gently to the north-east and is bounded by the Craven Fault system to the south and the Dent Fault to the west. Where the deeper south-westerly trending valleys have cut across the Craven Faults, the main exposures of the Lower Palaeozoic basement occur in Chapel-le-Dale, near Ingleton, Crummack Dale, above Austwick, and in Ribblesdale around the village of Horton. The Askrigg Block has been uplifted relative to the surrounding regions, especially to the area to the south and it is this "perched" nature of the Great Scar Limestone plateaux, together with the impervious nature of the underlying basement, which gives rise to much of the characteristic landscape and hydrology of the area. In addition, carbonate deposition commenced unconformably during S2 times, upon a surface of some considerable relief and of widely differing lithologies and structures. The resulting Great Scar Limestones, therefore show some features such as joint patterns, fault trends, and depositional dip structures which are clearly inherited from the basement rocks (Moseley, 1973) Many of the major resurgences occur at these basal unconformities grouped around topographic lows in the basement.

The uneven topography of the pre-Carboniferous surfaces and the resultant differences in the times of submergence in the Lower Carboniferous sea, have important consequences; even in the relatively small area of that around Gaping Gill (Fig. xx, geological map of Gaping Gill area). For example, the transitional beds vary both in altitude and lithology, as can be seen in the vicinity of Cat Holes. Here the unconformity is some 10 to 20m higher than the unconformity at Moses Well (NGR 751702), which lies less than 250m to the North. In Crummack Dale the classic exposure of the unconformity between the underlying Austwick Grits and the Great Scar limestones was discussed by Wilcockson (1927). On the western side of Crummackdale itself, the unconformity rises from around 240m OD near the North Craven Fault, in the vicinity of the Norber Sike springs, to a height of nearly 365m above sea level, across the broad anticlinal outcrop of Austwick Grits. Further north again, the unconformity can be seen to fall (and may be down-faulted to the north near Crummack Head Farm) to around 282m above sea level at Austwick Beck Head, before rising yet again to over 300m above sea level at the head of Crummackdale itself. At Norber Sike springs the lowest limestone beds are some 5 to 10m thick and consist of fine pebble conglomerates of C2 age which pass slowly into purer limestones above. To the north over the ridge in the unconformity, the contact between the Austwick Grits and D1 limestones is very sharp, with the transition beds being only a few centimetres thick. A similar contact occurs at Austwick Beck Head between Silurian slates and limestones of S2 age (See Fig. xx and also Fig. xx; contour map of basal surface in Gaping Gill area.) Thus it is clear that the earliest phases of the deposition of carbonate sediments in the Gaping Gill area was restricted to bays located in valleys or depressions in the pre-Carboniferous rocks. Consequently, there is considerable variation in the thickness of the Great Scar limestones in the area, and around Ingleborough it can be seen to vary between 100 and 250m.

The Great Scar Limestones are overlain by a cyclic series of thinly bedded limestones, shales and sandstones, known as the Yoredale Series, and which belong to fossil zones D2 and above. Although best developed in their type area, Wensleydale, to the north, they are still 300m thick on Ingleborough. Here they form the summits of Ingleborough, Little Ingleborough and Simon Fell. Their primary significance in the context of cave formation in the surrounding Great Scar Limestones is that they serve (partly as a result of their elevation) as very efficient collectors of rain water on the surface. This is aided by the thick covering of vegetation, peat and boulder clay which covers much of the higher slopes of Ingleborough. The integrated drainage pattern which therefore originates on the Yoredale rocks feeds large volumes of aggressive water on to the upper surface of the Great Scar Limestone, and thus has greatly influenced the development of major stream sinks such as Gaping Gill.

Lithology of the Great Scar Limestones

Lithologically, the Great Scar Limestones of the Yorkshire Dales consist mainly of fine grained, bioclastic carbonate sediments. They are generally pale grey in colour, although the uppermost beds of the D1 zone and some of the lower beds of the S2 zones are appreciably darker. Chemically they are very pure calcium carbonate, which accounts for 95-99% by weight. A matrix of fine calcite mud or coarser sparry calcite makes up 50% of the volume with foraminifera, brachiopod shells, shell fragments and crinoid ossicles, accounting for the remainder. Fragment sizes range from microscopic to greater than 5 cm in diameter, while matrix grain sizes range from under 0.01 mm to I mm in diameter. Partial recrystallisation of some of the calcite is responsible for the mottled texture of the "pseudo- breccias", commonly found in the upper D1 zone. Around Gaping Gill the Great Scar Limestone is approximately 180m thick (See Stratigraphical Column, Fig. xx.) although it may be as much as 200m.

The lowest beds are visible in Clapdale at the side of the stream close to Moses Well, at a height of 200m above sea level. Garwood & Goodyear (1924) suggest that these beds probably belong to the C2 fossil sub-zone, but neither they, nor the author were able to find any index fossils to substantiate this. A few hundred metres further upstream the next exposure consists of thinner bedded, dark limestones with thick shale partings, similarly to the limestones found immediately above Thornton Falls near Ingleton. They can therefore be assigned to the S1 fossil sub-zone. Garwood refers to these as the Gastropod beds, and in more modern terminology they are referred to as the Dalton beds, from their type site at Dalton-in-Furness. These particular beds are probably no more than 20-30m thick, since at and above the point in the stream bed below the Clapdale Grotto, at the height of 220-230m OD, they appear to pass smoothly into more massive light grey limestones, assumed to be the S2 zone. This latter zone is some 100m thick in this area and contains large colonies of the basaltiform coral Nematophyllum minus (M'Coy). It is characterised by poorly bedded, well jointed, buff coloured limestones, with few shale partings. The whole of Ingleborough cave is developed within this (S2) zone.

Over much of the Yorkshire Dales area, from Ease Gill in the west, as far as Penyghent in the east, the base of the overlying D1 zone is marked by a twin band of calcite mudstone, often referred to as the Porcellanous Band. This has provided a good datum horizon for mapping purposes in the Ingleborough area, both on the surface and underground, but since both the thickness and separation of the twin beds are found to vary from exposure to exposure, it is clear that all previous workers have often confused the two horizons and in published maps of the area only one horizon is usually denoted. In addition, both can be seen, on the surface, to feather out against the northern side of the pronounced ridge in the basal unconformity along the west side of Crummackdale, referred to earlier and they do not re-appear to the south side of this ridge in the vicinity of Norber Sike.

In the Main Chamber of Gaping Gill both beds can be observed in section, around the walls at 5m and 8m above floor level (Glover 1974). The lower bed is only partly developed in this locality, varying in thickness from zero to 50 cm., but the upper bed is particularly prominent. (See Fig. xx) This Upper Porcellanous Band consists of a dense, blue-white micrite, showing conchoidal fractures and lacks joints in comparison with be coarser grained micrites and sparites above and below this horizon. The Lower Porcellanous Bed, where present, possess similar characteristics. Garwood comments that "in addition to its Porcellanous texture, it is characterised by the infilling of the shrinkage cracks and cavities with a slightly darker crystalline calcite" (Garwood & Goodyear, 1924, page 196).

The massive beds of limestone exposed around the steep flanks of Clapham Bottoms and Crummackdale lie above the Upper Porcellanous Band and represents the higher part of the Great Scar limestone, belonging to the lower division (D1) of the Dibunophyllun coral fossil zone. These beds are 100m thick, and in contrast with the underlying S2 beds, they are well-bedded, forming massive posts which weather to prominent scars. These limestones maintain their identity over a very large area of the Craven Highlands, and are particularly well-exposed in Kingsdale, Chapel-le-Dale and Ribblesdale, where they give rise to the characteristic alternating scar and pavement topography. Possibly as a result of this, they have been studied in far greater detail than the rest of the Great Scar Limestones. Schwarzacher (1958) suggested that beds are dominated by micrite and sparite components alternating through the D1 zone in rhythmic succession, and that these rhythms were primary depositional features resulting from cyclic climatic changes occurring at the time of deposition. Each cycle includes a sparite and a micrite horizon and commenced and ended at a "Master Bedding Plane". He identifies nine such cycles, each about 10m thick. (See Fig. xx). More recently, Doughty (1968) has examined the density of jointing, exhibited in each bed exposed in the faces of the D1 scars. He showed that over much of the area cyclic variations in joint density occur through the thickness of the D1 zone, He also identified nine main units on this basis; each cycle commencing with a well-jointed bed at the bottom and finishing with a poorly jointed bed at the top. Doughty's cycles approximate to Schwarzacher's in both thickness and vertical position.

Waltham (1971) has drawn attention to the existence of the numerous shale partings which occur between beds in the D1 zone (Fig. xx). Throughout the thickness of the zone, wherever it can be observed in clean washed section in many of the cave passages and shafts in the area, there appear to be about twenty significant shale beds. Being easily weathered, the shale beds are rarely exposed at the surface, but correlation, across the area, between the underground sections shows that many of the shale horizons are of very great lateral extent. Some of the shale horizons take the form of paper thin partings, but some range in thickness between 1 and 50 cms. The thickest shale bed so far discovered underground is approximately two metres thick! Unfortunately, there does not appear to be any correlation between these shale bed sequences and the Schwarzacher/Doughty rhythms. Examination of the clean underground sections reveal lithological variations of the limestones of the D1 zone of far greater complexity and irregularity than the simple 10m cyclic alteration of micrite and sparite suggested by the Schwarzacher/-Doughty rhythms. Thus the significance of the Schwarzacher/Doughty cyclic interpretation of the conditions of deposition must be questioned, since neither author makes reference to the shale units which are much more important indicators of environmental variation during deposition. Johnson (1966) suggested that the basement exerted a profound tectonic control on sedimentation throughout the Carboniferous period, and that this mechanism (i.e. tectonic control) was responsible for the cyclic sedimentation of Yoredale and to some extent Coal Measure facies. He makes no mention of any cyclic depositional features in the Great Scar Limestone succession, but there seems no reason why the same mechanism should not apply.

Ramsbottom (1973) and Ramsbottom in Raynor & Hemingway (1974) suggested that the whole of the British Lower Carboniferous limestone succession shows clear signs of having been deposited under conditions of cyclic rises and falls of sea level (Fig. xx). The differences in the nature, i.e. joint density and fossil content, between the S2 and D1 limestones is thought to be largely due to a such widespread and long-lasting sea level regression. Thus in the West Craven area the Porcellanous Bands, lying between the S2 and D1 limestones are thought to have originated as sediments laid down in partially isolated lagoons in a gradually shallowing sea. These sediments were subsequently exposed to sub-aerial weathering, desiccation and shrinkage, and chemical alteration in the hypersaline conditions created by evaporation. This resulted in the co-precipitation of magnesium carbonate with the calcium carbonate and thus this horizon is often found to be partly dolomitised. In those places where the Porcellanous Bands are absent, the topmost beds of the S2 limestones are often affected in like manner. It would appear that the Porcellanous Bands are best developed in localities which allowed the development of clear water lagoons, isolated from the main sea by the topographic ridges of the underlying basement, which formed a series of off-shore island ridges (Fig. xx & xx).

On the pavement surrounding Ingleborough and in the bed of Fell Beck above Gaping Gill, a thin, dark blue/grey limestone forms the highest bed of the D1 zone. This bed of limestone, and the thick bed of shale which immediately overlies it, contain what McKenny Hughes called “almond- shaped concretions" (McKenny Hughes 1906). This is the Girvanella Algae Bed of Garwood and Goodyear (1924), and has been traced by Garwood (1912) over much of the north of England, marking a great change in the depositional environment, and thus in lithology and fauna both in this area and through the north-west of England generally. The Girvanella Band varies in thickness from 30 cm to 1m and contains the almond- shaped and almond-sized nodular concretions referred to above, around shell and coral fragments and crinoid ossicles etc. One of the best exposures of the Girvanella Band is to be found in Kingsdale, near Turbary Pot, just upstream of the point where the Swinsto overflow stream crosses the Turbary Track. Here the Girvanella Band forms small steps in the bed of the stream: the nodular concretions, being more resistant to solution, stand out very clearly. Above the Girvanella Band, a repetitive cyclic series of limestones, shales and sandstones, known as the Yoredale series, form the upper slopes of some of the hills of the area. As mentioned earlier, many of the streams flowing over the upper slopes of Gragareth, Whernside, Ingleborough and Penyghent finally sink underground at or just below the Girvanella Band. Although the Yoredale beds are best developed in the type area of Wensleydale to the north, they are some 300m thick on Ingleborough, forming the upper slopes of Ingleborough, Little Ingleborough and Simon Fell. In the Gaping Gill area, the drainage basin which provides Fell Beck with most of its water is formed in the Yoredale series, and the horizon of the Girvanella Band marks the level below which Fell Beck begins to loose water through the many cracks and joints in its bed.

(Note: in 1986 the girvanella limestone was discovered in the floor of Jub Tunnel by S E Warren)

Geological Structures

Situated on the southern edge of the relatively stable Askrigg Block, the Lower Carboniferous rocks of the Ingleborough area have a relatively simple structure, with beds generally dipping gently N/NNE at angles of 1-5 degrees. They are sharply truncated to the south-west by the Craven Fault System which downthrows to the south, with a total vertical development of the order of l.5 kms. Over much of the area gentle folds with a NW/SE axis, parallel to the Craven Faults, are super-imposed on this regional dip. These folds can be clearly seen in section in Kingsdale, Chapel-le-Dale, Crummack Dale and Ribblesdale, where vadose cave systems in the upper beds tend to collect water along the axis of the synclines and give rise to groupings of springs at the basal unconformity. In some exposures, particularly those in Crummackdale, what appears to be folding may be in part depositional or compaction dip features around the flanks of ridges in the underlying slates and grits. In addition, an overall synclinal structure is postulated from the upper beds of Ingleborough, as can be seen when viewing the outcrop of the Hardraw Scar Limestone (an upper limestone member of the Yoredale series), from across the Chapel-le-Dale valley. Strachan (1910) suggested that the survival of the outlier of the Yoredales, forming the upper slopes of Ingleborough, is likely to have been due particularly to the existence of this gentle folding.

Around Gaping Gill the irregular, patchy, cover of boulder clay, moraine and outwash till, together with the highly dissected and weathered nature of such small exposures of pavement as can be found, make accurate determination of the very shallow dip of the beds difficult. Equally, the good underground exposures of bedding planes afforded by the flat roof sections in Ingleborough cave do sot provide any more accurate information on local dip. This is partly due to the fact that cave survey techniques concentrate on measuring floor levels rather than bedding plane roof levels. In addition, over much of the area the dip angles are so low that they fall within the inherent inaccuracies of the instruments used for cave survey. In one area only is it possible to measure an anomalous dip angle in a particular block of limestones This is in the region of Trow Gill. It would appear that between the NW/SE line of Giant's Hall/Lake Avernus, and a similar trending line along Terminal Lake, at the far end of Ingleborough Cave, this block of limestone shows an anomalous dip of some 8-10^0 to the NW. This is best demonstrated in Trow Gill itself by the marked bedding-plane which forms a low cave in the south-west wall.

The anomalous dip of this particular block is, in part, responsible for the preservation of the gorge walls of Trow Gill itself, since here the dip runs back into the hillside, rendering the vertical walls of Trow Gill inherently stable. Further up Trow Gill, halfway to Bar Pot, a tributary valley enters from the NW. This marks the line of the Hurnel Moss Fault. A few hundred meters up this tributary valley a small region of pavement, lying immediately to the south of the valley, shows an anomalous dip feature, in as much as the pavement surface dips towards the valley at an angle of up to 10^0 as it approaches the line of the fault. At the top end of Clapham Bottoms, in the vicinity of Body Pot, a small outcrop of limestone exhibits an anomalous dip of 35^0 to the south-west, but less than a few hundred metres to the north-east, the scars and pavements along the edge of the Allotment snow no signs of this feature, but have the regional NNE dip. This implies the existence of a NS trending fault running down into Clapham Bottoms from P5.

Conjugate Joint Systems

Joints are a prominent feature of the Great Scar Limestone throughout the region. The majority of the joints fall into two sets which form a conjugate (i.e. perpendicular) system. These were first shown by Wager (1931) to exhibit a regional swing: the NW/SE set found in the western part of the Craven area swing to NS in the eastern part, and their conjugate set swings from NE/SW in the western part of the area to EW in the east. Earlier workers have also been interested in the join patterns. Philips (1836) investigated the relationship between joints and faults and concluded that the joint systems were unrelated to minor faults. Tiddeman (1901) noticed that in the western part of the area the south Craven Fault was parallel to one set of joints, but further east, between Austwick and Settle, this fault changed direction to become parallel with another joint set. The Yorkshire Geological Society, in the course of their investigation into the flow of underground water in the area (Carter, Dwerryhouse et al, 1900), attempted to relate the direction of flow of underground water to that of the major joints. More recently, joint pattern studies have been made by Mosely and Ahmed (1967) and Mosely (1973) and also Goldie (1973). Moseley in particular implies that in some areas the directions of the major joint set appear to be inherited from structures underlying the basal unconformity.

There are three types of joints discernible in the Gaping Gill area, and they can be distinguished in the field comparatively easily. There are (a) conjugate joint sets: these are the commonest type and are described by Wager as shear joints. They occur in two parallel sets, usually it right angles to each other and are perpendicular to the bedding. The vertical extent of these joints is variable, ranging from under 3m to over 50m, but most of them commonly cut though a few beds and some are restricted to one bed only. They commonly terminate at bedding planes. It is clear from air photographs of the pavements around Ingleborough, and in particular the Long Scar area on the edge of the Allotment, that there is considerable variation in the orientation of the conjugate sets with stratigraphic level. On Long Scar, for example, the joint sets appear to swing to vary by more than 10^0 over a stratigraphic range of less than 50m. (See Plate xx and Fig. xx.)

The origin of conjugate joint systems of this kind has been the subject of controversy over the second half of the last century. Three main theories have been proposed. Wager (1931) concluded that the paired joint sets were due to shearing fracture caused by a maximum horizontal pressure acting in a NW/SE direction. The swing of the set of joints close to the Craven and Dent Fault systems was explained by Wager in terms of rotation of the stress field and by drag along parts of the Craven Faults themselves. Drawbacks of this theory included failure to account for the orthogonality of the conjugate joint set, also the lack of slickensides on the joint faces. Price (1959 & 1966) has provided a more widely accepted interpretation based on lateral expansion and the release of "built-in" stresses which occurs as a result of uplift.

More recently, Moseley and Ahmed (1967) have proposed that the fractures (i.e. joints) are primarily NW and NE shear structures, formed in an EW stress field probably during the development of the Irish sea and North sea basins during Tertiary times, but are subject to later tensional modifications. Over the stable blocks such as the Askrigg Blocks these important trends, including the NS trend, are possibly inherited from parallel fractures or "lineaments" in the basement. However, in the Craven area, and in the Gaping Gill area in particular, few structures appear to cross the basal unconformity and those that do, appear to be faults and not joints. For example, in Crummackdale there are considerable differences between the direction of structures in the Lower Palaeozoic basement and the joint patterns exhibited on Thwaite Scar and overlying basement rocks. Only the Clapdale Fault appears to be related to a basement feature. In addition, on Thwaite Scar at least, one if not two further sets of joints in the limestones have no equivalent in the basement.

None of these theories takes account of shrinkage effects in a horizontal plane which would be expected to occur as a result of vertical expansion of beds which have undergone lithification under considerable vertical pressure (from later, overlying beds) and which have been subsequently "unloaded" by erosional stripping of the superincumbent strata. This mechanism has been proposed to account for the lamellar weathering which can be seen to occur along 'pseudo' bedding planes, particularly in the uppermost bed of the Great Scar Limestone. As yet it has not been suggested as a possible cause or controlling feature in the origin of the major conjugate joint sets. It would appear to this author that a possible mechanism for the development of these major conjugate joint sets would be tension fracture following shrinkage, resulting from unloading. In view of the fact that erosional stripping first exposed limestone in the close vicinity to the Craven Faults, the faults could be expected to act as nuclei or foci from which joint sets could propagate. This would explain the observed parallelism of the conjugate joint sets close to the Craven Faults with the faults, and the subsequent rotation to a more NS trend away from the faults.

It is not possible here to go into greater detail of the mechanism and origins of the conjugate joint sets on this basis. it is offered purely as an alternative theory which, in the author’s opinion, is equally capable of explaining the observed facts.

Tension Joints

Tension joint sets approximately bisect the angle between the major conjugate sets and differ from them in several ways. Their lateral persistence is much less and they often occur in "gash" form, that is "in echelon", and are frequently calcite filled. They appear throughout the full thickness of the limestone and the interpretation of this structure as tension joints is based on the original description by Wager (1931, pages 397/8).

Low Angle Joints

These are rare in the Craven area and they cut through the limestone at angles varying from a few degrees up to 60^0 to the horizontal They are short, rarely exceeding 3m in length and some are straight but the occasional curved joint can be found. The majority of this class of joint appear to be associated with faults.

The distribution, although not the direction, of the density of conjugate joints in bedding exposed in scars, has been examined by Doughty (1968 & xxxx). The results of Doughty's work show that: (a) spacing in a given bed is regular within narrow limits, except where disturbed by joints carrying through either a higher or a lower bed: (b) there is little variation in joint density from bed to bed in the limestones of the 'S' zone but a nine-fold rhythmic repetition was found in the beds of the D1 zone and as mentioned earlier, this sequence appears to match the Schwarzacher cyclic sequence of micrite and sparite, (c) the thickness of the bed is unrelated to the joint density, (d) joint density is related to lithology. A higher joint density is found in the more coarser grained calcarenites (sparites) than in the fine grained calcite mudstones or micrites. This is possible due to the presence of larger cleavage surfaces in the sparite limestones. (e) surprisingly, in view of the observations above regarding the joint orientation observed in air photographs on Long Scar, Doughty found no evidence of relationships between joint density and orientation of joints. however, none of these observations were made in the Gaping Gill or Allotment areas.

The author has made a number of joint direction observations in the Gaping Gill area, some of which are made underground. As a control feature some measurements were made in the field, on the surface, and from air photographs, These are summarised in Fig. xx. They confirm Wager's observations, but the major joint directions vary with distance from the North Craven Fault. Running parallel to and at right angles to the fault (127/307° and 37° to 217°). Above Clapdale Farm, they swing gradually to orientations of 139°/319° and 49°/229° in the vicinity of Long Scar, on the Allotment. Along Thwaite Scar and Long Scar, as far as Sulber Nick the same pattern can be observed, although on this flank of Ingleborough the large areas of exposed pavement permit the observation of intermediate sets at 42 , 52 , 102 , 122 , 162 and 177^0 .

The above measurements can be compared with major joint controlled development in Gaping Gill. Glennie (1952) analysed passage direction in Gaping Gill, based on Butcher and Gemmel's Key Plan of Gaping Gill (1952) and showed two major joint sets controlling passage direction at 15 /105 and 60°/150°. By comparison joint directions controlling the Whitsun Series appear as two pairs of complementary sets at 20/110° and 55/145°. This latter pair appear to be much the more important, with the 145^0 direction predominating.

Faults in the Gaping Gill area

All discussion of faults in the Gaping Gill area is naturally dominated by discussion of the existence and implications of the Craven Faults. These terminate the Lower Carboniferous rocks in a south-westerly direction with down-throw to the south-west in excess of 1.5 kms. Between Ingleton and Skirwith and also at the head of Ingleborough Lake, the North Craven Faults bring the basal Ingletonian and Lower Ordovician (Coniston) limestones into contact with down-faulted D1 limestones to the south-west. The Craven Faults have a long and complex history and have attracted the attention of geologists since the late 1800's. Both Tiddeman (1890) and Marr (1899/1910) concluded that in some places the Craven Faults acted as shear faults and that faulting was contemporaneous with deposition of Lower Carboniferous sediments both north and south of the fault line. The fault system appears to have acted as a contemporaneous hinge zone during Lower Carboniferous times, and form the boundary between the shallow water limestone facies of the Askrigg Block and the more varied deep water sediments to the south.

Furthermore, the fault zone has been active in more recent tines. In particular the South Craven Fault appears to have moved in post-Permian (possibly Tertiary) times, either under Alpine fold pressures or more likely as a result of Tertiary subsidence of basin structures to the west. The various earthquakes which have occurred in Yorkshire (e.g. Settle, 1944 etc.) appear to have originated close to, or are associated with, the South Craven Fault. More recently the Dent Fault has shown signs of renewed activity both in 1970 and 1976, with minor earthquakes occurring, whose foci appear to have been along the line of the Dent Fault some 16 kms deep, in the vicinity of Dent.

Within the area bounded by the Craven and Dent Faults to the west, there are a number of other small faults which appear to have penetrated the Great Scar Limestone over its full thickness. Many are marked by the development of large and deep shafts or "potholes", for example Death's Head Hole on Leck Fell, Growling and Spectacle Holes on the east flank of Kingsdale, Meregill and Tatham Wife Hole in Chapel-le-Dale, Rift Pot, Juniper Gulf and Nick and Sulber Pots on the Allotment, Hull Pot on the west flank of Pen-y-Ghent and Birks Fell cave in Wharfedale, are but a few of the fault-guided cave systems of the area. The orientation of these minor faults is variable, although many are close to and are sub-parallel to the North Craven Fault. One interesting feature exhibited in some of these fault-guided cave systems is that the fault appears to exhibit two phases of movement. For example. in Rumbling Hole on Leck Fell, a displacement of shale beds clearly shows a degree of vertical movement, but the presence of horizontal slickensides possibly indicate a later phase of shear movement. It is possible, however, that this effect can be explained by the fact that horizontal movement in gently dipping beds can have a pseudo-vertical displacement effect.

In close proximity to these minor fault lines joint density increases markedly and the joints themselves become parallel to the fault itself. Where this happens in areas of pavement the resultant pavement exhibits narrow vertical blades of rock instead of the usual block and crack topography. Where two such joint sets intersect the fault, the result is a spectacular display of residual spikes or "dragons teeth" (see Photo x). Sub-aerial erosion has in many places reduced such zones to shallow grassy gullies which clearly stand out in aerial photographs as dark straight or gentle curved lines running for long distances across the pavement areas, often intersecting the major joint sets at angles of up to 20°. Several such fault lines can be traced from one limestone spur to another across the intervening valleys of Kingsdale, Chapel-le-Dale and Crummack Dale. (Waltham 1974, page 41)

In the Gaping Gill area just such one feature can be traced from Newby Moss eastwards, just to the north of Clapdale Scar and Clapdale Farm, across Clapdale itself and across the end of Thwaite Scar. Garwood and Goodyear, and Wager, map this fault continuing on to the Lower Palaeozoic basement rocks in Crummackdale. An examination of the detailed geological map of the Crummack Dale inkier (shown in Dunham et al, 1953) suggests that the same fault separates the Ordovician (Ashgillian) from the Austwick Grits of Silurian age. If this is correct, it supports, in part, Moseley's contention previously referred to, that some of the structures in the Lower Carboniferous rocks are inherited from the 'rigid block' basement. McKenny Hughes also was of that opinion, he wrote in 1908 “there are some small faults on Ingleborough.... Some appear to be cracks in the

Carboniferous rocks, recurring over pre-existing lines of disturbance in the underlying Silurian and Bala beds". (McKenny Hughes, 1908, p. 289)

The Clapdale Fault is of interest in several other ways, in as much as there appears to be a conflict of views as to the direction and magnitude of the throw of the fault. In the first instance, the earliest geological map of the area which accompanied the Geological Survey Memoir on the Ingleborough area (Dakyns et al, 1890), fails to record the existence of a fault along this line. Indeed, the field slips of the officer of the Geological Survey who mapped this particular area (believed to be William Gunn), show the words "no sign of a fault" along a line north-west of Clapdale Farm to the north of Clapdale Scar.

As previously mentioned, Garwood and Goodyear, and Wager, map the fault. but make no reference to it in their texts. Garwood's map implies, by virtue of showing discontinuities, both in Cyrtina Septosa band, and the junction between the S2 and D1 zones, that the fault down-throws to the north. This view is supported by the fact that Dunham (1953) shows the continuation of the fault in the underlying basement in Crummack Dale, also down-throwing to the north. This interpretation has been incorporated in the latest Geological Survey 1 inch to 1 mile (Revision Geological Map of the Hawes District - sheet 50, 1971).

However, Sweeting, (unpublished PhD thesis, 1948) maps the Cyrtina Septosa band along the flanks of the limestone ridge west of Clapdale, and claims that the Clapdale Fault downthrows some 40 feet to the south, just west of Clapdale Farm. This view is supported by Waltham (1974, page 31), commenting upon the relationship between the thickness of the Great Scar Limestone of the Ingleborough area and the depth attained by cave systems within it. He states: "the Long Kin West - Moses Well connection has the exceptional range (depth) of 250 meters but this is due to the water passing through a number of limestone fault blocks stepping down towards the Craven Faults, i.e. down-throwing to the south-west".

The only other fault previously mapped in the Gaping Gill area is the Sulber Fault which runs a few degrees south of east from Nick Pot, lying at the inner edge of the pavements of Long Scar on the Allotment, across the head of Crummack Dale to Horton-in-Ribblesdale. This fault downthrows some 1-3m to the north and forms a small north-facing step on the otherwise featureless pavement overlooking the Ribble Valley. Also on the Allotment, the morphology of the deep potholes of Jockey Hole, Rift Pot and Juniper Gulf, suggests that these systems owe their origin to stream invasion of small local faults aligned with the major joint set, but which penetrate the full depth of the limestone. The planes of all these small local faults are vertical, and this tends to support the view that they are largely the result of lateral movement rather than tensional 'normal' faults. Aerial photographs of the limestone ridge between Clapdale and Crummockdale show that the limestone in this vicinity is traversed by several small faults (see Fig. xx and Phot xx), particularly immediately to the west of Crummack Head Farm where one small section of pavement has an anomalous dip in excess of over 10^0 in a west-north-westerly direction.

The continuations of these faults across Clapham Bottoms towards Gaping Gill cannot be traced since they are buried beneath superficial deposits which blanket the valley floor. However, at least one of this group is clearly visible, both on aerial photographs and on the ground. This is the Hurnel Moss Fault which runs east-west from Clapham Bottoms to Hurnel Moss. The line of the fault is marked on the west flank of Clapham Bottoms by a line of three large collapse, or subsidence, dolines. This fault appears to truncate the northern edge of three small areas of pavement which appear from below superficial deposits on the ridge to the north of Trow Gill. (see Photo xx). The fault crosses the upper section of Trow Gill where it swings to the north-east. Further west, the fault line is marked by a shallow tributary valley which hangs above Trow Gill and which contains a line of small dolines. In one of these fault breccia and secondary calcite vein material is visible. Immediately to the south of this shallow valley a small section of pavement shows monoclinal folding, the dip increasing from one to two degrees to nearly ten degrees as the fault line is reached. (Photo xx and Fig. xx.)

At the north-western end of this shallow valley a small stream flows down a blind valley, and disappears underground. This is Hurnel Moss Pot where the water drops straight down a 10m shaft followed by a 55m shaft into a very large old phreatic tunnel which runs back to the south-east along the line of the fault.

The Hurnel Moss Fault is the first of three minor faults which appear to have played a very important role in controlling the development and morphology of the Gaping Gill system itself. The other two faults, the Southeast Passage fault and the Main Chamber Fault, are nowhere visible on the surface and the evidence for their existence is derived entirely from underground observations. In consequence they will be discussed later.

GEOMORPHOLOGICAL AND GLACIAL FEATURES OF THE AREA

Introduction

As mentioned earlier, the high karst plateaux of the Ingleborough area are developed in Carboniferous Limestones which show marked vertical variations, but little lateral change, over the area. These limestones lie on a rigid block basement bounded by the Craven Fault System to the south and the Dent Fault to the west. This whole rigid block has been uplifted relative to the surrounding areas, and the effects of the resulting rejuvenation are most marked in the south-west corner between Ingleton and Kirkby Lonsdale, since this corner of the rigid block is much nearer the Irish Sea than the rest of the area. Here the limestones are almost completely free draining, since the major valleys of Ease Gill, Kingsdale, Chapel-le-Dale and Ribblesdale have cut down into the impermeable basement beds. One further important consequence of this rejuvenation on subsequent drainage of the limestones has been the preservation, on the limestone plateaux themselves, of the relief forms of "many erosion cycles of 'fluvial denudation". (Sweeting 1950).

The whole area was greatly modified by the Pleistocene glacial sequence which carved out much of the present relief. During this period many of the older pre-Pleistocene landforms were removed or buried by glacial deposits. Thus the three major controls over the relief of the area are lithological, tectonic, and glacial. Although the Ingleborough area is now a fine example of glacial karst, Tertiary erosion, prior to the onset of the glacial period, was almost certainly important in the evolution of the relief of the district. In the literature there has been much discussion about the Tertiary dissection of North-west Yorkshire, relating in particular to the summit surfaces of the Askrigg Block. First mentioned by McKenny Hughes (1901) and later discussed by Trotter (1929) and Hudson (1933), a recent trend surface analysis by King (1969) has confirmed the earlier suggestions that this summit surface consisted of an eastward trending peneplane which was warped early in its history probably as a result of Tertiary crustal adjustments which accompanied subsidence in the North Sea and Irish Sea basins. Thus the easterly draining valley sections of Upper Wharfedale would appear to be the oldest remnants of the original drainage pattern. The south-easterly trend of the lower section of Wharfedale and of the River Skirfare, the southerly trend of the River Ribble and the south-westerly trend of the River Greta are a result of this Tertiary warping.

One result of this early erosion was that, in places, particularly in the Malham area, and on the eastern and south-eastern slopes of Ingleborough, between Moughton and Giggleswick Sears, a considerable area of Great Scar Limestone was exposed to sub-aerial erosion prior to the onset of the glacial period. It is in these areas that the oldest relief forms on the limestones are to be found. Despite some local modification by ice, some, if not a great deal of the relief of these districts must be of pre-glacial origin. Thus the Tertiary and Pleistocene dissection of the summit surface was accomplished by river and glacial erosion and seas influenced by the sub-horizontally bedded rocks and the contrast in lithology between the limestones and underlying basal rocks.

Headward erosion of those rivers draining into Morecambe Bay was more rapid than those draining east into the North sea since the gradient of the former is much steeper. Subsequently the majority of the present day rivers flow south or south-west, despite an overall regional dip to the north-east. Many of the present limestone plateaux are now regarded as stratimorphs; that is bedding plane surfaces stripped by glacial erosion (Waltham 1970), and not erosion surfaces such as was proposed by Sweeting in 1950. However, some erosion surfaces do truncate the bedding of the rocks, particularly in the Malham Tarn area, where dipping beds of limestone and of the lower Palaeozoic basement rocks are truncated sub-horizontally. Sweeting also claims that an erosion surface cuts across step faults in the vicinity of Clapdale Scar (Sweeting 1914 and Waltham 1974). Whether any definite erosion surfaces can be ascertained in these areas needs much more field work in the light of modern geomorphological thought.

The major relief forms

There are three major relief forms in the Gaping Gill area. They are the limestone plateaux, the valleys and dry valleys, and the deposits of glacial erosion. They will be dealt with in that order.

The plateaux

In the Gaping Gill area the major relief form consists of a wide sub-horizontal plateau, lying at a height of 375-425m above sea level. This extends for over 4 kms around the south-east flank of the summit pyramid of Ingleborough, from Newby Moss in the west to Fell Close in the east. Over much of the area the plateau is more than 1 km wide and its surface corresponds to the topmost beds of the Great Scar Limestone. Where it is not covered by deposits of glacial and peri-glacial erosion, classic pavements have been developed (Fig. xx). Along the inner edge of the plateau a marked break may correlate with the outcrop of the Lower Yoredale beds. The outer edge of the plateau, although much dissected by valleys, marks the scarp of the North Craven Fault from Newby Moss as far east as Norber Brow. Crummackdale effectively terminates the plateau to the east, although strictly speaking the limestone spur of Moughton forms an easterly extension overlooking the Ribble Valley.

The valleys

The second major relief forms of the area are the valleys. The wide expanse of limestone plateau is cut into by three south/south-westerly trending valleys. Cote Gill to the west, cuts straight across the scarp of the North Craven Fault from Hurnel Moss to above Newby Cote, where it hangs above the Craven lowlands to the south. It is now dry and contains much till, outwash and solifluction deposits, and little solid rock is exposed. The flanks and floor of Cote Gill, however, are pitted with a large number of small dolines, some of which form linear arrays which appear to mark the lines of small step faults associated with the North Craven Fault (e.g. the Clapdale Fault etc.).

Further east, Clapdale contains Clapham Beck and in its lower section comprises a deep narrow ravine incised in the floor of a wider shallower valley, both of which hang over the Craven Lowlands to the south. The narrow gorge directly below the path near the Clapdale Grotto has been described by Sweeting as being either a nick point or a meltwater notch. Above this point the valley opens out with Clapham Beck flowing in a deep but wider trough cut into the floor of a wide shallow valley. Above Ingleborough Cave, and the resurgence of Clapham Beck Head, Clapdale continues to ran in a north-easterly direction along the same line (which is possibly joint controlled), for a distance of 500m. It takes the form of a dry valley with a narrow, flat floored trench, incised in the floor of the same wider valley mentioned earlier. The floor of Clapdale rises steadily for nearly 50m before swinging left towards its junction with the well-known, impressive, dry gorge known as Trow Gill. The narrow dry gully leading to Clapham Bottoms also enters from the right at this point, immediately beyond the gate at the foot of the Trow Gill path.

Trow Gill itself runs from over 300m in a north-westerly direction, at right angles to the preceding section of Clapdale, and in alignment with the major joint system of the area. It consists of a narrowing, steep, rock-walled gorge, cut into massively bedded limestones of D1 age which dip to the north-west at an angle of 8-10^0. The floor of Trow Gill rises some 50m. At the base of the final steep section a low shallow bedding cave has been developed along the line of a conspicuous bedding plane on the south wall of the gorge. This has given rise to the mistaken impression that Trow Gill itself originated as a cave whose roof has subsequently collapsed (Sweeting, 1972, p. 118). The wide mouth of Trow Gill, and the absence of any significant amount of collapse debris is inconsistent with an origin due to cavern collapse. It would seem that Trow Gill is probably a former meltwater notch incised into the limestone, aided by the strong joining of the area, and on a more spectacular scale than many other small gorges in the Ingleborough area. Many of these still contain streams and in these localities it can be seen that cave formation and collapse play a very minor role in the formation of the gorges.

Above the narrow slot at the head of Trow Gill, the dry valley continues to rise in a north-westerly direction for a further 500m.

Over this part it is a deep V-shape in cross-section, and would appear to be flanked and floored with grass covered clastic sands, gravels and scree of fluvio-glacial or peri-glacial origin. Bed rock is visible only occasionally in the form of small scars, although dissected pavement can be found along the top edge on both sides. After 500m, a tributary valley associated with the Hurnel Moss Fault, enters on the left, hanging some 10-20m above the floor of the main valley. The point of entry of the tributary is marked by a steep sided, grass-covered, mound, which may represent either the remains of an outwash fan associated with the tributary valley or, alternatively, a cone of fluvio-glacial deposit which has only partially been dissected by the streams which formerly flowed down both the main valley and its tributary. A number of small dolines occur in the floor of the main valley at this point, but solid rock is nowhere visible.

Above this point the main Trow Gill valley swings north, then north-east for a further 500m, becoming narrower and shallower with steep, well-jointed, scars rising some 10m on both sides. Some 10m before the Bar Pot stile is reached, the now shallow valley widens suddenly, becoming floored with a flat-lying grass-covered bog. Beyond, it terminates abruptly in a line of low rock scars in the form of a semicircle. It would appear that the whole of the upper part of the Trow Gill valley has been excavated in clastic material of fluvio-glacial origin, which formerly completely filled a deeper, wider gorge cut in solid limestone. Support for this supposition is given by the fact that the lowest section of Trow Gill, which still today exhibits its original gorge shape, is parallel, to the south, by an older, higher dry gorge continuing a large collapse doline, sometimes referred to as Owl Holes and which terminates in the sheer cliff directly above Fox Holes and which hangs above Clapdale by several metres. The upper end of this earlier Owl Holes valley has been beheaded by the last 50m of upper Trow Gills immediately before the notch at the start of Trow Gill gorge itself. The semi-circular cove of low scars at the head of Trow Gill appears to terminate the valley itself. No sign of surface flow of any size can be discerned on the undulating plateau surface in the vicinity of Bar Pot and Gaping Gill. It would appear therefore that Trow Gill, and presumably its predecessor, the Owl Hole Gorge, originated, in two stages, as a result of water rising to the surface from a series of major springs at the foot of the semi-circular cove at its head, and now occupied by the small patch of wet bog.

Clapham Bottoms comprises a wide, flat floored, dry valley, lying at an altitude of some 300-320m, surrounded by limestone scars and pavements end with several dry tributaries, some of which are formed in soft material of glacial origin and some in solid rock, and which enter from the north-west, the north, the north-east and from the east. in places bed-rock shows through the grass-covered valley floor in the form of small semi-circular limestone cliffs, two to three metres high, known locally as coves, each of which is backed by small areas of deeply dissected and overturned pavement. In the south-western corner three large dolines can be seen in a line which runs east-west down side of the valley. These lie on the easterly continuation of the Hurnel Moss Fault. It is clear that Clapham Bottoms once formed the upper end of the older, wider, valley in the floor of which Clapdale itself was later incised, fossil by water flowing down Trow Gill. It is now isolated from Clapdale by a high moraine barrier which formerly stretched east-west along the north flank of Trow Gill.

This moraine barrier rises some 20m above the flat floor of Clapham Bottoms on the inner side and is some 300m thick. (see Fig. xx and morphological map of Clapham Bottoms showing moraines, overflow channels etc.). The short, narrow gully entered by turning into the north immediately after passing through the gate at the bottom of Trow Gill, and which now gives access to Clapham Bottoms from Clapdale, almost certainly represents a glacial melt-water channel which breached the moraine barrier. It is incised partly in boulder clay and partly in solid rock. A recent 3m deep excavation in the floor of this meltwater channel revealed a section of laminated sands and clays overlying a coarse sand and cobble layer which rested directly on buried pavement. (See photo xx). This meltwater channel may pre-date the formation of Trow Gill gorge, since the latter has cut down the Clapdale valley floor below the level of the channel, which has thus been left hanging. At the right angled bend in Clapdale, where it turns from north-east to north-west, it is possible to trace the inner, incised, Clapdale valley disappearing under the moraine barrier, but the relationships between Trow Gill, Clapdale and the Clapham Bottoms melt-water channel cannot completely be determined for reasons which in part are due to the amount of outwash material brought down by the Trow Gill stream, and in part due to the obvious re-arrangement of valley floor levels which have accompanied the construction of the track up Clapdale and Trow Gill. However, a nine-fold sequence of development is suggested by the evidence available. This is summarised in the following table (Table 1). No attempt can as yet be made to correlate these stages of development in Clapdale with other valleys in the area.

Table 1 Sequence of development of the valleys of the area

Stage	Nature of Activity	Results
I	Erosional in a full glacial environment	Glacial stripping of Lower Yoredales, leaving large areas of bare proto-pavement at around 400m above sea-level
II	Erosional, predominantly sub-aerial. Possibly inter interglacial climate.	Slow development of outer wider portions, Clapham Bottoms and Clapdale with valley floors at 300m above sea level.
III	Erosional, possibly in interglacial environment	Incision of inner Clapdale by surface flow from Clapham Bottoms.
IV	Erosional	Formation of Owl Holes Valley as meltwater notch cutting back along major joint lines.
V	Depositional in glacial climate	Deposition of terminal moraine barrier aross lower end of Clapham Bottoms.
VI	Erosional, in peri-glacial climate	Incision of meltwater notch in Clapham Bottoms moraine.
VII	Erosional, in wet post-glacial	Flow down previous line of upper Trow Gill diverted to form present Trow Gill Gorge, beheading Owl Holes valley and leaving Clapham Bottoms meltwater gully hanging.
VIII	Erosional, in an interglacial climate	Surface flow disappears underground above Clapham Beck Head
IX	Erosional, as a result of rejuvenation	Incision of head-ward retreating nick point in floor of Lower Clapdale from Clapham village to Clapdale Grotto.

Superficial and glacial deposits

All over the Ingleborough area the solid rocks are in places covered by a wide variety of superficial deposits, among which glacial deposits predominate. The glacial history of this part of North-west England is far from being fully understood, since little local work has been done in the area since the classic account by Tiddeman (1872) and the officers of the Geological Survey (Dakins et al 1890). Over much of the area glacial deposits have been mapped under the all-embracing and overworked term of "drift". Largely this material consists of blankets or mounds of monotonous boulder clay containing coarse sub-angular and rounded detrital fragments of local rocks. In places, where sectioned by streams, this can be seen to be roughly stratified, but coarse sub-angular and rounded detrital fragments of local rocks. In places, where sectioned by streams, this can be seen to be roughly stratified, but more often it is heaped into long mounds of unsorted material, which are aligned, as is shown by such glacial striae that have been found, along the direction of ice movement. This usually corresponds with the alignment of the major valleys.

Boulder clay is also found as a blanket deposit in the valley bottoms and along the flanks of the lower valleys. It is particularly thick, up to 10-15m in depth, on the interfluves between the larger valleys. Medial, lateral and terminal moraine forms composed of boulders, pebbles, and sand/cobble mixtures have been described and the major drumlin field of Upper Ribblesdale is very well known but has been little studied. Perched erratic blocks are common, the best known examples being found in the Norber area, although some areas of pavement support erratics of limestone or gritstone boulders. Many valleys particularly to the south-east, are floored by outwash sediments derived from the boulder clay. These take the form of stratified and laminated sands, gravels and clays. Lacustrine deposits of relatively recent age floor part of Kingsdale, the Ribble valley, around Horton-in-Ribblesdale, and also further to the south beyond Settle, and the top end of Chapel-le-Dale in the vicinity of the Ribblehead Viaduct.

In most of these areas these deposits take the form of great thickness of laminated or 'bible leaf' clays, which in the past have presented considerable engineering problems during road and railway construction. They would appear to be pro-glacial lake sediments; the lakes themselves forming behind terminal moraines deposited during successive retreat phases of the last valley glaciation of the area.

Around the flanks of Ingleborough, evidence in the form of striae and mounds of boulder clay, and/or lateral moraines, or kame terraces, which curve around the flanks of the upper slopes at around the 425m contour, suggest that ice of the last major glacial advance was of sufficient thickness to at least as high as this, but there is evidence in the form of boulder clay, erratics etc., occurring up to heights of 600m and higher of earlier, thicker, icesheets. In particular, on the south-eastern flank of Ingleborough, underlying the thick peat beds which cover much of the Main Limestone outcrop on Simon Fell, an unusual type of glacial deposit can be observed, which consists of angular blocks of sandstone embedded in clay. At White Stones south of Simon Fell, and overlooking Gaping Gill, a large mass or raft of white crinoidal limestone, probably forming a section of the Main Limestone outcrop, and measuring some 70m by 40m, appears to have been transported bodily southwards from the fell top. (Dakins et al, 1892)

In all these upland areas, where most of the karst landforms are to be found, and which undoubtedly originate from the series of glacial advances occurring during the Pleistocene successive glaciations have been dominantly erosive, so that each glacial advance has tended to remove both results and evidence of previous advances. The number and chronology of the Pleistocene glaciations in the area are therefore not completely understood, particularly by comparison with the very detailed glacial chronology which has been worked out for Southern England and for much of lowland Europe. For example, there is only one indication in the whole area of two types of till. In the Raven Ray gorge, immediately above Thornton Force at the southern end of Kingsdale, two types of till may be observed in section where the river has cut through the terminal moraine of Kingsdale. The lower till is sandy, orange/yellow in colour and is almost completely decalcified, in contrast with the over-lying, much darker brown boulder clay, which contains solid limestone fragments. It is therefore assumed that the lower deposits are highly weathered fragmentary remnants of a much older glacial till sheet.

Glacial deposits

Around Gaping Gill glacial deposits of three main types may be distinguished. The first type consists of a blanket of boulder clay covering much of the limestone plateau as described earlier. The thickness of this blanket varies markedly from place to place as can be established by the widely differing depths of the many small dolines which pit down to bed rock. This seemingly featureless stretch of peat covered moorland was formerly an area of considerable relief, with many hills and valleys cut in solid limestone, and which are now buried between the blanket of glacial deposits. Mapping the depth of boulder clay, exposed in section in the thousands of small dolines over the area, suggests that at least two former stream channels exist below this blanket.

Both former stream channels originate along the line of the present course of Fell Beck, but diverge south of Gaping Gill. They appear to consist of rock floored gorges cut into the top beds of the Great Scar Limestone (Fig. xx). The first channel swings to the east, away from Gaping Gill itself, but appears to terminate before reaching the top end of Trow Gill near the Bar Pot stile. The second channel swings to the south-west from Gaping Gill, through Disappointment Pot entrance, Stream Passage Pot entrance, probably as far as Hurnel Moss Pot, before swinging to the south-east then east, along the line of the Hurnel Moss fault, which as mentioned earlier, appears to hang above upper Trow Gill. Thus this second channel appears to pre-date channel one.

In addition, a number of the tributary valleys which run into the top end of Clapham Bottoms, leading from Grange Rigg Pot, P5, and the Slit Pot/Car Pot area, and which themselves appear to be deep gorges cut in limestone, and later completely filled by glacial deposits which have only partially been removed during subsequent periods of surface stream flow, that these are relict features, dating from a time when Fell Beck flowed much further to the east than at present.

The second major type of glacial deposit found in the Gaping Gill area take the form of mounds, hillocks or elongated, oval ridges, rising above the plateau level (Fig. xx). These would appear to be either a continuation of the lateral moraines which can be seen to swing around the east flank of Simon Fell or, more probably, they are a variation of drumlin. The location and approximate alignment of the most prominent mounds of this type of deposit, in the area surrounding Gaping Gill, are shown in Fig. xx, together with the former direction of ice movement deduced by the direction of glacial striae. It can be seen that the long axes of most of these mounds, which rise some 10-20m above the surrounding plateau, coincide with the direction of former ice movement. This confirms the concept that they are in effect a type of drumlin. However, around the flanks of some of them, particularly the two immediately to the north and south of Bar Pot, have many small dolines on their flanks. Bed rock is visible in many of these, indicating that many of the mounds are partially rock-cored. No clear sections exist of any of these mounds which has precluded observation of the nature of the deposits of which they are exposed. It is therefore not possible to determine the existence, within them, of any detailed structures such as stratification, stone orientation etc., which might provide more detailed clues as to their origin and mode of formation.

A third major type of superficial deposit includes those comprised of outwash sediments, i.e. sands, gravels and clays or variable mixtures of all three, which show some degree of transportation, sorting and stratification, by the action of water flowing on the surface or sub-glacially. Fluvio-glacial deposits of this type are visible along the sides and in the bottom of the now dry valleys of Trow Gill, Clapham Bottoms and Clapdale. It has not proved possible to map these in detail due to the extensive grass cover.

At the junction of the Hurnel Moss Fault valley with upper Trow Gill, a cone or outwash fan of sand and gravel projects into the latter from the former. At several places in upper Trow Gill, the valley floor appears to be composed of a white clay, containing a very high calcium carbonate content. Man-made erosion, in the form of paths leading down into Bar Pot and Gaping Gill, provides sections of the upper deposits around these potholes. Here it can be seen that the deposits in these vicinities consist of water-worn sandstone pebbles in a sandy matrix. This resembles, to a remarkable degree, sediments found in many parts of the Gaping Gill cave system and in Ingleborough Cave.

Over the whole of the Gaping Gill area all three types of glacial deposit are, in general, covered by a layer of peat, varying in thickness between 0.5 and 1.5m. In places this peat cover is still actively growing, particularly in the area immediately to the east of Gaping Gill, where a peat bog up to 5m thick may be found and which is permanently water-logged. Over much of the rest of the area, particularly on the Allotment, and wherever the slope of the land permits, extensive network of drainage ditches have been cut in the peat in attempts to drain boggy areas to improve the quality of the grassland which is now used exclusively for sheep grazing. These ditches are often dug in herring-bone pattern and convey water from the boggy areas to a convenient doline or sinkhole. In some places the digging process known as 'gripping', has resulted in a greatly increased rate of run-off and has initiated active erosion of the peat. On many summit plateaux in the area, for example, on Simon Fell, a former thick blanket of peat is being actively eroded.

The fourth type of deposit which almost certainly is of glacial origin is the large number of erratic blocks of limestone, sandstone, and gritstone which may be found lying on the surface all over the area.

These are particularly common on pavements which have been formed on inter-fluves. Many other large erratics can be found partly buried in the bottom of many of the small dolines. One of the largest erratic boulders of limestones, known as the Harry Horse Stone, lies south-west of Hurnel Moss, on the edge of Newby Moss, at a height of over 410m. However, the most spectacular example of erratics may be found on the pavements of Norber Brow. Here a wide train of boulders, many of them perched on low pedestals of limestones occur at heights of between 300 and 360m. They consist mainly of large blocks of Austwick Grit which have been plucked from the bare outcrops found on the floor of Crummack Dale, and which have been lifted some 25 to 100m uphill by the action of ice, which formerly overflowed out of Ribblesdale, into Crummackdale, across the corner of Norber Brow and into the Wenning valley beyond. All constituent rocks of the boulder clay, and all known erratics, are of local origin. This indicates that the area was a centre of ice dispersion.

HYDROLOGY

The climate of the Ingleborough area is basically mild and wet. It is usually described as a Marine West Coast climate, with the bulk of the precipitation arriving from the south-west to north-west quadrant, as Atlantic depressions track in over the Irish sea. No official climatic data are recorded nearer than Malham Tarn Field Centre. From these figures, however, it is clear that rainfall is generously and evenly divided throughout the year, with slight variation in the form of an early winter maximum and a late spring minimum. In recent years, a network of rain gauges in the area immediately to the west, have provided evidence of a marked increase of rainfall with altitude. although this effect is much modified by local topography (Lyon - personal communication). Rainfall records from the village of Clapham have been kept for many years (see Table xx) but no such information is available for the Gaping Gill catchment area in particular.

The 6 inch to I mile OS map of the south-east flank of Ingleborough records some twenty four springs between Newby Moss and the Allotment. These lie at altitudes of between 400 and 600m above sea-level and give rise to nine separate streams which flow part way down the slopes of Ingleborough before disappearing underground at the inner edge of the Great Scar Limestone plateau. Fell Beck, formed by the union of three principal and several smaller streams, is by far the largest. No continuous measurements of flow volume of Fell Beck have ever been made. However, in recent years several spot measurements have been made (by gulp dilution methods) in the course of dye tracing work. From these it would appear that the volume flow of Fell Beck, above the point where it begins to sink in its bed, as it approaches Gaping Gill, can vary from under 0.5 cusec (10-14 litres per second) to well over 200 cusec (4 x 10^3 litres per second) with a probable mean flow of the order of 2 cusec (40-50 litres per second). (Ashton 1966, Gascoyne - personal communication, Glover 1966.)

There are in fact six groups of streams on this flank of Ingleborough (see Figure xx). Firstly the Newby Moss group, including the stream entering Long Kin West Pot, as far round as Grey Wife Sike; Hurnel Moss Pot group including the stream entering Stream Passage Pot; the Know Gap Sike (an artificial contour channel, formerly providing a water supply to Clapdale Farm House); the Gaping Gill group, including Fell Beck and its tributaries, and the P5 stream. The sixth group includes the Allotment streams entering Marble Pot, Long Kin East, Juniper Gulf and Nick Pot. None of these streams succeeds in crossing the limestone, all sink at or near the inner edge of the Great Scar Limestone plateau.

At the base of the limestone there are four major resurgences and a number of minor springs (see Fig. xx). They either occur along the line of the basal unconformity or along the line of the North Craven Fault. The four major risings are Moses Well, Clapham Beck Head, Norber Sike and Austwick Beck Head which are all used as water supplies for local farms and villages. This has precluded any thorough investigation of the catchment areas, flow volumes and flow-through times for these major springs, but a number of individual dye tests have established the major features of each drainage system.

During the classic series of water tracing experiments carried out on Ingleborough at the beginning of this century (Carter, Dwerryhouse et al., 1904), a number of the streams sinking on Newby Moss and on the allotment were tested. In addition, a major series of experiments were carried out on the Fell Beck - Clapham Beck Head drainage route. These latter tests confirmed the age old belief that Fell Beck reappeared at Clapham Beck Head with a delay that varied from 5-14 days, depending on the level of the flow. These results were obtained under low flow conditions. Streams sinking on Newby Moss were shown to reappear at Moses Well and those sinking on the Allotment reappeared at Austwick Beck Head.

More recently a number of dye tests have been carried out in the area using fluorescein, rhodamine B and optical brighteners (Refs. xx). These have begun to fill in the gaps in the overall pattern of underground drainage, but many of the results are the overall pattern of underground drainage, but many of the results are questionable since they were based on tests carried out at the limits of detection (due to water supply problems). This requires to be confirmed as soon as the provision of an alternative, piped, water supply for the area is completed. Figure xx summarises the connections so far established, and indicates the actual catchment areas compared with the theoretical, topographic catchment areas.

It is interesting to note that although water appears to traverse the Gaping Gill/Clapham Beck Head route quite slowly in dry weather, taking between five and fourteen days to travel a straight line distance of over 1.5 km, the system responds to natural flood pulses in a matter of hours. Recent work by Pitty (1974) shows that the low calcium carbonate content of water emerging at Clapham Beck Head during peak floods suggests that it has not spent long underground. (See Table xx for summary of Pitty's results.) This observation is confirmed by the visual observation that reddish-brown peat-stained, and sediment laden water emerges from Clapham Beck Head within two to three hours following the onset of heavy rain falling on the slopes of Ingleborough.

Theories of cave origins and development

Of primary importance to the understanding of the origins of cave systems, and to their subsequent development, are the processes which give rise to the characteristic fissure permeability of massively bedded limestones. These may be classified into three categories (T.D. Ford, 1911):

a: Syngenetic features

This class of feature includes all those operating during the period of original deposition of the carbonate sediments. It includes such features as bedding planes, shale bands and the differing types of carbonate sediments laid down from place to place and from time to time, and which result from variations, both in time and place, in the depositional process.

b: Diagenetic Features

These relate to the processes operating within the body of the rock subsequent to the deposition of carbonate sediments Diagenetic processes are very largely chemical in nature and relate to the slow alteration of the chemical and crystalline microstructure of the sediments, often taking place over a very long period and often under great gravitational pressure resulting from the weight of superincumbent strata.

c: Tectonic Features

These are the result of internal processes and forces operating in and on the area and which occur subsequent to the original deposition and diagenetic alteration of the rock mass.

All three types of process give rise to horizontal and vertical variations and/or discontinuities in the body of the rock, and which result in the body of the rock containing a three-dimensional network of planes of weakness which are particularly susceptible to attack, by solution, by ground water when the latter first enters the rock mass. Bedding planes and shale bands are the most characteristic results of syngenetic processes, whilst joint systems and litbological variety are the most common results of diagenetic processes. Folds and faults are the most obvious types of tectonic feature, as are the tension joint systems developed along the axes of fold structures. A fourth minor category of pseudo-tectonic features are the gravity-slip fissures and lateral expansion joint systems which are frequently found close to the edge of valleys.

As a result of the action of the above processes nearly all massively bedded limestones, of all geological ages, possess bedding plane irregularities with relatively insoluble horizontal partings. In addition, they often contain one or more sets of joint systems, often forming conjugate sets, and which usually occur at right angles to the bedding planes. Some of the joints pass through more than one bed of rock.

The resultant three-dimensional network of planes of weakness is susceptible to solutional attack by groundwater, or by surface water entering the body of a rock through one or more of the planes of weakness. This is particularly the case with joints and faults, in horizontal bedded limestones, as soon as they appear at the surface as a result of uplift and erosional stripping of younger strata. Atkinson (1968) has recently claimed that the early stages of this process of solutional attack down joint planes may take a very long time, but once established, the development of this primary flow net from a three-dimensional network of micro-fissures into major drainage conduits (i.e. caves) may proceed very much faster. More recently, Palmer (1969) has shown, by comparing the flow regime and solution rates under conditions of laminar and turbulent flow, that in the first of a network of micro fissures to reach a diameter greater than approximately 1 cm, turbulent flow can become established and that the solution rate increases, in this tube alone, by as much as four times compared with all others. Thus the bulk of the flow is captured by this tube, and development of all others may cease.

Once the primary network of fissures is established along bedding planes, joints or in the plane of faults, within the body of the rock, major conduits can develop in one of three ways: they may develop above the regional water table, i.e. in the vadose zone; at the top surface of the regional water table (a zone of fluctuation); or at any level within the flooded or phreatic zone. The question as to which type of development takes precedence, or whether all conduits develop in all three zones simultaneously is still the subject of major controversy. Indeed, the very existence of a water table, in the classic sense, in limestone areas, is still disputed. It can be shown in many areas that water filled, phreatic, cave passages cross over lower, dry or vadose stream passages. In view of these difficulties, it is not surprising that a number of widely differing theories of cave development have been proposed.

Water table and phreatic zones

The many theories of cave origin may be divided broadly into groups based upon the division of ground water environment into vadose, water table, and phreatic zones. (Ref. Cvijic 1918). In 1907, Dwerryhouse suggested a vadose origin for the Yorkshire caves and this theory was generally popular in other parts of the world at that time. (Matson 1909). Gardner (1935), modified this vadose theory by proposing an early stage of phreatic opening by static water which was then subsequently drained, and the basically phreatic network underwent major vadose modification. Malott, 1937, suggested a modification of Gardner's theory whereby the main enlargement took place as a result of the invasion of the cave system by surface water, i.e. by vadose modification. Davis (1930) and Bretz (1943) proposed that all major cave development originated in the phreatic zone but that there were significant later vadose modifications. Theories of cave formation in the zone of fluctuation, at the surface of the water table, owe their origin to Swinnerton (1932), and Sweeting's paper on the Ingleborough caves, was a major contribution to this school of thought.

A detailed analysis of the various theories was made by Warwick (in Cullingford, 1962, Part I, Chapter 3). Warwick makes the very important point that care must be taken in distinguishing between cave *origin* and cave *development*. However, many of the above mentioned theories are based on observations in particular, often quite local, areas and major differences in lithology, structure, relief, etc. from area to area were not taken into account. Re-assessment of all these theories was made by Moore (1960-1966), who showed that the majority of local studies of caves in America, discovered in the preceding twenty-five years, favoured a water table hypothesis of cave genesis.

Chemistry

A further complication arose out of the results of a growing number of studies, both theoretical (Weyl, 1955; Atkinson, 1965) and those based on field measurement of the detailed chemical properties of streams entering cave systems. These results showed quite clearly that both percolation and stream water become saturated with respect to calcium carbonate within a very few metres of entering the body of a limestone rock mass. It appeared, in consequence, that the bulk of vadose trenching occurred as a result of mechanical erosion rather than solution. In addition, continued solution at or below the water table, in either a shallow or deep phreatic environment, appeared to be precluded on both theoretical and observational grounds. Thus all theories invoking any chemical, solutional development, at any stage in the life of a cave, either at the surface of or deep within the phreas, appeared to be rendered invalid; a conclusion in obvious contradiction with observed facts. Attempts were made to resolve these difficulties by invoking a number of disparate chemical processes, all of which could possibly result in renewed aggression of ground water at depth.

Prominent among these were the acquisition of additional carbon dioxide, in solution, either by absorption from cave air, or by the bacterial oxidation of in-washed organic material. In addition, the direct oxidation of sulphides, known to be present in shales, was proposed. None of these processes, however, appeared plausible to account for the active solution observed to have taken place deep within the flooded zone, where by definition, no cave air was present.

This major difficulty was largely overcome by the concept of “mixing corrosion", proposed by Alfred Bogli (1964a, 1964b, 1965. 1971) as a result of detailed study of deep phreatic development in the Holloch, in Switzerland. Bogli pointed out that the equilibrium graph of dissolved calcium carbonate versus original carbon dioxide in solution, first proposed by Trombe (1952), and subsequently verified on both theoretical (Weyl 1959) and experimental grounds (Picknett 1964), is a curve, not a straight line. Furthermore, the direction of curvature is such that if two samples of saturated water are mixed, each containing different amounts of carbonate in solution as a result of starting with different carbon dioxide content, the resultant mixture is always aggressive. Hence renewed solution can, and will, take place at any depth within the phreas, wherever and whenever two types of water, having different chemical histories, meet and mix. Of particular significance to the development of a primary network of micro-conduits deep within the phreas is the renewed aggression resulting from the mixing of the slow laminar flow of water down joints and faults with that of joint and fault-guided bedding tubes in three dimensions. In addition, Picknett (1971) has recently shown that the presence of small quantities of magnesium, in solution, is capable of significantly enhancing the mixing corrosion effect: thus the observed preferential development of major phreatic conduits in the vicinity of particular lithological horizons, i.e. those partially dolomitised, can be explained.

Picknett (1971, p.l48) also points out that the mixing corrosion effect is only one special case of a general effect which takes place whenever waters are mixed which differ in any property (i.e. dissolved material, pH, temperature etc.) Runnells (1969) has suggested that under these circumstances the state of saturation will always change: sometimes the mixed waters will be aggressive and sometimes they will become super-saturated. In general, however, in karst processes, such effects will be small, but Bogli's case is the major exception, where the mixing of strong and weak saturated solutions of calcium carbonate can result in the rejuvenation of aggression by as much as 35%.

A composite theory

Recently, D.C. Ford (1965, 1968, 1971, 1972) has presented a new, composite, theory for the origins and development of the sorts of caves in limestone most frequently encountered by cavers. Based upon the study of over five hundred caves in Europe and North America, Ford's principal suggestion is that there is no one general case of limestone cave development. There are, however, three very common types:

1) the predominantly vadose cave;
2) the deep phreatic cave, and
3) the water table cave.

There is also a fourth category which is a special case: a cave in a true artesian (or confined aquifer) setting. Ford has found that almost all, accessible, cave systems, between sink and rising, may be comprised wholly of one of the above types or alternatively, may consist of a combination of vadose cave types in the upper parts with deep phreatic and/or water-table types in the lower sections. In many cases, all three may be found in combination in a single system, although they may not all have been created at the same time. In essence, Ford proposes that the interaction of 5 classes of control features determine which type or combination of types of cave will develop in a given situations

These major control features are:

a: The fissure density, both in the horizontal and vertical planes, within the host limestone, penetrable by ground water, and the geometry of this fissure network. These factors may be combined to give an equivalent three-dimensional hydraulic conductivity. The higher the numerical value of the hydraulic conductivity, the higher the probability is that the water table type of cave, often fed by inlets of vadose type, will develop.

b: In a given mass of limestone this hydraulic conductivity may (and will) vary from place to place. This gives rise to differing proportions of the common types of cave passage in different cave systems. Hydraulic conductivity will, in general, increase with time, (but not always) subsequent to the initial onset of solution. Hence the type of cave formed will change with time. This hydraulic conductivity is also likely to differ from one region to another.

c: The type of cave formed is also strongly dependent upon the hydraulic gradient between the point at which water sinks, or enters the limestone and the springs or resurgences, where the water reappears. Areas with high hydraulic gradients contain predominantly vadose cave types.

d: The type of cave formed is also very strongly dependent upon the of structural attitude of the limestone mass. Four separate groups or types of structural attitude may be defined. These are: a) horizontally bedded limestones, b) gently dipping limestones, c) steeply dipping limestones d) folded limestones. Deep phreatic caves result when well-bedded, low jointed, steeply dipping limestones outcrop round the edge of an impermeable core, or surface cover. Streams reaching the limestone after flowing on the impermeable rocks enter the limestone mass via one of the many exposed bedding planes. Their lateral continuity over long distances can guide water to great depths, prior to it resurging at valley level. In contrast, shallow water table caves are particularly common in horizontal or gently dipping limestone areas since deep penetration is inhibited by the occurrence of shallow, open bedding planes, which are often continuous from sink to spring. Lithological control is important by insoluble shale beds and less soluble limestone horizons. These often perch the initial phreatic conduits which may only partially be drained by subsequent vadose trenching. In particular, in Yorkshire, where closely jointed well bedded limestones containing many relatively insoluble horizons, provide many good examples of down-dip trending cave passages, which originated as phreatic tube networks, perched on the more insoluble beds and which only subsequently have undergone vadose modification and enlargement as a result of valley deepening, and partial drainage of the phreatic network.

e) Finally, Ford claims that the concept that a water table (in the classic sense) exists within a mass of limestone, and that this precedes significant cave development, is wrong in most instances. It only occurs where the fissure frequency is exceptionally high, i.e. in the vicinity of faults. In all limestones masses the water table is, by definition, at the surface prior to cave development, but it falls as the primary conduit begins to develop. This fall may be substantial, from a few tens to many hundreds of metres, while the primary phreatic tubes are still of very small dimensions - (i.e. diameter). Their subsequent enlargement into enterable cave systems, may well then be by vadose action, but the original system skeleton is phreatic in origin.

There is a sixth control feature, not specially mentioned by Ford, but which should be included in his list and which is of particular relevance to the Yorkshire area. This is the control exerted by the presence, or absence, of impermeable rocks or deposits overlying the major limestone mass. These, when present, give rise to normal surface drainage patterns often integrated, to form a single, large stream, which then flows onto the limestone. This is of particular importance in controlling the location, size and type of secondary development which may occur, i.e. it is in effect adding Malott's "invasion theory" to the list of control features. Yet another major control found in Yorkshire, although of lesser importance elsewhere, is the presence of a major suite of impermeable rocks underlying the limestone, and which by their very nature divert all types of underground stream flow towards the nearest valley. This control feature may well operate throughout the whole history of origin and development of any given cave system, since it limits the depth to which ground water may penetrate. The presence of topographic irregularities in these underlying, impermeable, beds can give rise to the development of deep phreatic systems, which remain in existence and active development, subsequent to the limestone mass as a whole being drained as a result of valley deepening.

In conclusion, it may be stated that Ford’s ideas, taken in conjunction with Boglis mixing corrosion concept, are capable of explaining the origin and subsequent development of most caves so far explored and studied all over the world. Arguments still arise as to the relative importance of Ford's controlling factors, in particular when applied to any one cave or groups of caves in a given area. A case in point is the current debate over the origin of many of the recently discovered extensive cave systems in Yorkshire. Waltham (1970, 1974, Chapters 4 and 15) argues that many of these systems demonstrate the existence of large, mainly fossil, phreatic trunk routes, and that therefore deep phreatic developmental of ‘pre-glacial’ age, was a significant factor. On the other band, Brook (1971, 1974, Chapter 14), claims that it is not necessary to involve a deep phreatic environment for the origin and development of these types of cave, and that the bulk of major development has occurred, and still occurs, in the shallow, valley level controlled, zone of water table fluctuation. It is the writer's opinion that these particular differences of opinion and interpretation are largely fallacious and arise in part out of a failure to comprehend, in detail and in particular cases, the implications of Ford's and Bogli’s concepts, and in part are due to the almost complete absence of an established chronology for both landscape evolution in the Yorkshire area (Waltham 1974, chapter 24), and for the caves themselves. All attempts to correlate internal and external relative sequences of development are inevitably bound to lead to circular arguments (Waltham, ibid) of the chicken and the egg variety.

A conceptual model of cave development in a glaciated area

None of the above mentioned theories makes specific reference to the effects that major, cyclic, changes in climatic conditions are likely to have on a cave system already established, and of whatever type, in an upland limestone area. In order to interpret many of the features found in some of the major cave systems in Yorkshire, it is necessary to have an overall model of the conditions, processes and events, which may be expected to occur in such an area, during the onset, duration and retreat of a glacial ice sheet covering the area, and which may be expected in turn to greatly modify the nature, pattern and type of cave development.

Stage i)

It is more convenient to begin consideration of such a model at a point in time which may be said to mark the end of a major interglacial. At such a period, climatic conditions may be reasonably expected to parallel those found today in North-west England. In particular the climate would be temperate, and wet. Most major cave systems would contain active streams, either vadose trenching the higher parts of the system, or enlarging, by solution, passages at or below whatever water table may be said to exist. Very heavy flooding could be expected to occur only once every decade, or less frequently, (Hanwell, 1969; Hanwell & Newson, 1970). Much cavern enlargement would take place during peak flood periods by collapse and/or simple mechanical erosion of passage walls and floors (and roofs in flooded passages), in the manner described by Newson (1971). Thus the overall pattern of cave development during this stage is one of excavation and enlargement by both corrosion and corrasion, i.e. the hydraulic conductivity of the limestone will increase slowly and steadily with time, but with marked, discontinuous increases, which result from such infrequent high floods which may recur.

Stage ii)

For the purposes of this model, the onset of a glacial cycle in these latitudes is assumed to be marked by a slow increase in the amount of rain falling on the area, and by a slow, steady fall in mean winter temperatures (Manley 1959). High flood peaks may be expected to occur at more frequent intervals and the pace of cave enlargement will increase in consequence. There is one school of thought, however, which is of the opinion that for glaciation to occur, cold has to develop to such an intensity that allows the build up of ice sheets. Thus the land may have been subjected to very low temperatures in a pre-glaciation, peri-glacial, period, which may remain relatively dry throughout, due to the establishment, over the land, of a permanent cold, high pressures anticyclonic mass of air. Under these conditions, the onset of a glacial period would not result in cave development and enlargement to the degree suggested above. Nevertheless, the size and severity of spring melts, at these latitudes, would be considerably greater than the present. Winter flood peaks, and similar processes would be expected, although perhaps on a more restrained scale.

Eventually, the establishment of permanent (i.e. all year round) snow fields in the upper catchment areas results in greatly increased mean annual flow levels, with annual flood events of considerable magnitude accompanying each spring melt. Under these conditions some cave systems may not be able to transmit the total volume of water flowing into their entrances, and the whole system will flood up to the entrance. This results in two major changes, both in the pattern of drainage and the type of cave development taking place. Firstly, surface streams will continue to flow on the surface beyond their former point of sinking underground, and may cut new or may utilise existing dry valley systems in those direction of the highest hydraulic gradient. En route, they may re-occupy old abandoned stream sinks down valleys and/or may continue to flow on the surface across the limestone on to impermeable rocks in the major valleys below. The cave systems associated with the original stream sinks therefore, return to totally phreatic conditions and many high level, abandoned passages undergo a renewed phase of phreatic enlargement. Former, down valley, cave systems, associated with abandoned sinks, will undergo a temporary phase of vadose enlargement, but they in turn may return to a phase of totally phreatic development. Eventually, the shift in the average annual temperature, in particular the mean winter temperature, results in the establishment of ice sheets in the highest portions of existing valleys and on the top of extensive upland plateaux. These ice sheets give rise to valley glaciers, which extend down valley, eventually completely filling all major valleys surrounding the limestone area, at which point they will begin to spread across the top surface of the limestone itself. This is accompanied by major erosion of the valley floors and sides and by the stripping off of some, or all loose, superficial deposits, as well as younger, thinly bedded, rock types, which may cover the edge of the inner limestone plateau. All streams sinks will be covered and blocked by ice. Some surface drainage associated with spring melts will flow on the surface of the ice, or in marginal channels; little, if any, of this melt water is likely to enter those cave systems covered by any appreciable thickness of ice. Such cave systems therefore drain to the nearest valley, and the whole system changes from being totally phreatic to being totally abandoned. Erosion by ice of valley floors and sides, and stripping of incompetent strata on plateaux, may result in the removal or truncation of parts of existing cave systems.

The weight of ice, over shallow subsurface caves, may result in places, of partial collapse of cave roofs into the underlying passages.

This state of affairs last throughout the full peak period of glaciation. Some ground water may be expected to enter the cave, carrying some carbonate, in solution, and some small scale development of stalactites and stalagmites may be expected on the roofs, walls and floors of the passages in the system, particularly in the upper portions, although such deposition may well be severely restricted, since all entrances to the system would be sealed by ice and virtually no air circulation can take place. Dependent on the size of whatever outlets may be left unsealed, the system may or may not fill up with water which will remain, in effect, stagnant, with little or no flow through the system.

Around the edges of the main ice mass, at any time during its advance and peak phases, and possibly also occurring in certain localities within the main glaciated area during temporary retreat phases or during inter-stadials (several of which are known to have occurred during the last major glacial period) is an area which undergoes erosion under peri-glacial conditions. This is characterised by a cold, dry climate, with the landscape being covered by a predominantly non-arboreal, tundra vegetation. The types of land form resulting from such a peri-glacial environment are well documented (Sparks & West, 1972, Chapter 4) and are of two types, both erosional and depositional. Hill tops and steep slopes suffer erosion and solifluction as a result of the intense, daily and annual, freeze/thaw regime

Frost wedging and shattering of rock surfaces commonly results in the development of extensive steep scree slopes around the foot of rock outcrops. These may develop to such an extent so as to almost completely bury the original cliff face; cryoturbation, stone heaving etc., are all characteristic, diagnostic, features of peri-glacial environment. On the lower slopes and in areas covered by sediments and soils the same process results in their mass transport downhill to form irregular blankets and heaps of these materials, often referred to by the term ‘head’. In the valley floors themselves, extensive outwash deposits form fans and planes of considerable thickness, composed of stratified clays, sands, gravels, pebbles etc., which originate from the areas of maximum ice erosion and which are transported into the peri-glacial zone by the enormous volumes of meltwater flowing from the ends of glacier and edges of ice sheets.

Lake deposits are common, particularly where melt water rivers are dammed by terminal moraines originating from former ice advances An unusual deposit, also diagnostic of peri-glacial conditions, may be considerable thickness of loess, which originates as wind-born dust particles, often transported considerable distances, as a result of the steady, high velocity flow of cool, dense, dry air outwards from centres of glaciation, (i.e. glaciers). The characteristic feature of peri-glacial tundra areas is that of perma-frost, where all but the topmost metre or so remains frozen throughout the year, often to a considerable depth. This effectively prevents all movement of ground water in the area, except in the topmost beds or deposits, and only then for one or two months of the year around mid-summer Thus even in a limestone area already possessing well developed cave systems, by far the greater part of the drainage is confined to the surface. Any open cave systems rapidly become sealed with fluvio-glacial deposits, and/or loess, and/or ice, and development of the cave system ceases.

One consequence of the confinement of the bulk of the drainage to the surface of the ground, even in cavernous limestone regions, is the development of extensive *systems of deep, narrow valleys, often with vertical walls or cliffs of considerable height.*

These are, of course, the characteristic limestone gorges, often now dry, which may be found in all massively bedded limestone regions where periglacial conditions formerly prevailed. The preservation of the apparent sharpness and freshness of their features is often mistakenly described to them having originated as caves, whose roof has subsequently collapsed. The total absence, in most cases, on the floor of such gorges of any massive blocks which might be expected to result from roof collapse, and the presence of fossil scree at the foot of each wall of such a gorge is conclusive proof of their origin as periglacial melt water channels, incised into massively bedded limestones, followed by the disappearance of all surface drainage into caves etc., at the end of the peri-glacial period and the return to normal temperate climate conditions. The resulting absence of normal surface drainage in limestone areas, by comparison with its continued existence on non-caverniferous rocks, and which results in the slow, steady retreat of valley sides, even under temperate conditions, is a totally convincing explanation for the preservation of such limestone gorges. They are in effect fossil features, preserved almost exactly as they were when water last flowed over the surface in the area.

The end of a glacial peak is marked by a slow but steady rise in the mean annual temperature and possibly accompanied by an increase in the amount of relatively warm, moist air entering the hitherto stable high pressure, cool, dry air mass, which covered much of the ice sheet during the period of its maximum extent. Spring and summer melt phases become rapid and prolonged and the ice sheet thins and shrinks, releasing vast quantities of melt-water, heavily laden with sediments of many kinds, particularly many sharp fragments of rock eroded from valley floors, walls and upland plateaux. The size of the sediment ranges from the finest rock flour to enormous boulders weighing many hundreds of tons. As the ice retreat continues, ground temperatures rise above freezing point and melt water can re-enter such cave systems as may remain open, or which may have been exposed as a result of plateau and valley erosion. This process occurs in the first instance on the upper surfaces of the limestone. Here open caves may take annual melt water streams of considerable size, which carry into the caves huge quantities of clastic sediments.

Meanwhile former valley floor or low level outlet springs may still be totally or partially blocked by ice, still occupy the valleys. Many caves therefore undergo a massive phase of infill. At the same time former predominantly vadose cave systems may return to an almost totally phreatic phase of development, as a result of the same type of process and/or as a result of the formation of pro-glacial lakes, developing behind terminal moraines. This is particularly the case if the retreat of the valley glaciers occurs in distinct stages. Overflow channels may develop as these lakes establish easier, lateral, outflow routes, which may cut down through the uppermost blankets of boulder clay, lateral moraines, ice marginal channel deposits etc., and become incised into the limestone ridges between valleys. Meltwater overflow channels of this nature may often be distinguished from those formed under periglacial conditions by their steep-walled V-cross section, and the fact that they were essentially distributaries from existing valleys as opposed to being tributaries.

Accidents of topography result in the isolation of considerable masses of ice from their parent glaciers or ice sheets. These therefore become stagnant and melt in situ. The resulting deposits may take the form of erratic blocks of considerable size resting on otherwise clean-washed, bare limestone rock surfaces or proto-pavements, or may alternatively take the form of irregular hills, hummocks and hollows of ill-sorted elastic deposits of all types and origin.

The difference between these two extreme types of stagnant ice deposits and the continuous spectrum of types of deposit lying between, is largely due to the considerable variation in quantity, type, nature and location, within the body of the stagnant ice mass, of the original fragments of erosion. Surface melt, evaporation or ablation, may result in the build up of thickness' of clastic materials on the surface of the decaying ice mass, which insulate the ice beneath from the rising temperature, and which allow the persistence, deep within the body of such deposits, of lenses of ice for considerable periods. When these finally melt, inward collapse of the sediments surrounding them may give rise to circular, conical or elongated depressions, often known as kettle holes, and which may bear more than a superficial resemblance to dolines Frequently they collect surface run-off to form small boggy ponds or lakes. To summarise therefore, the end of a glacial period, and the resulting retreat of ice sheets and valley glaciers in a limestone area, implies a stage of massive infill of most cave systems.

No mention will be made here of the implications of sub-glacial melt-water streams, in ice caves, or at the base of valleys glaciers, which are now recognised to be of considerable importance in the development of many forms of subglacial and outwash deposits, particularly eskers, although it is possible that such features play an important part in the initial stages of infill of cave entrances lying below the ice.

As a full interglacial becomes established the overall climate warms, becomes dryer, and the barren wastes of glacial and fluvio-glacial deposits become colonised by vegetation which slowly invades the area. At the height of a full interglacial, the climate may be such that the tree line has risen to as high as 400 to 600m above sea level. Soil of considerable thickness may develop on the upper surface of the glacial deposits, and groundwater moving through the soil zone acquires very high concentrations of carbon dioxide. This may percolate directly through the glacial deposits if they are of a permeable nature, i.e. sands, gravels, etc. Upon encountering the top surface of the limestone this highly aggressive percolation water will rapidly dissolve all vertical lines of weakness, i.e. fault zones, joints etc., some of which may be in the process of active formation or development following unloading of the rock, as a result of the disappearance of great thickness', and therefore considerable weights, of ice. Percolation water originating in this way can and will rapidly widen all such vertical planes of weakness and will flow down them under gravity, particularly in the zones of shattered rock along major fault lines, to considerable depths.

In the course of re-entering the mass of limestone, percolation water containing high concentrations of calcium carbonate in solution encounters an open void such as a passage or chamber forming part of a cave system developed before the glacial period, then immediate precipitation of some or all of the carbonate in solution can occur in the form of stalagmite and stalagmite deposits on the roof, walls and floor of all such passages and chambers. This process will be particularly enhanced if the cave passage thus encountered is of sufficient size and extent and/or still maintains open connections with the surface, allowing free movement of air between the cave and the external atmosphere. Extensive and massive development of stalagmite deposits can and will take place under these circumstances. Inwash deposits of glacial origin which may exist in the cave passages and chambers may be subsequently partially or totally covered by a thick layer of stalagmite, sealing them in place. If the climate during the interglacial improves sufficiently, it may resemble that presently occurring in the Mediterranean area. Under these circumstances stalagmite deposition of the kind characteristic of that area may be expected to occur, i.e. at a relatively great rate and in places may completely fill most open spaces. Thus one of the most important processes occurring in existing caves during a long, warm, interglacial period, is a stage of massive infill by calcite deposits.

In other caves and in other areas the glacial deposits may be predominantly impermeable in nature, i.e. thick blankets, heaps and mounds of boulder clay. Soil water therefore is forced to continue to flow at or close to the surface and a surface drainage pattern commences. Depending upon the frequency and amount of precipitation, this will readily excavate deep valleys in the soft, clastic, deposits of glacial origin, until limestone bed rock is reached. Thereafter active solution and erosion of all existing vertical lines of weakness in the limestone will commence. Sooner or later, water thus entering the body of the limestone, will encounter an existing cave passage or chamber, partially or wholly filled with inwash material. The underground stream will then proceed to remove such deposits, particularly at peak flood periods and provided they are not sealed with a covering layer of calcite previously deposited under the conditions described above. Valley floor deepening, resulting from former glacial erosion, and the eventual drainage of all proglacial lakes etc., will allow all such allogenic streams to find the easiest route through the limestone mass to a former or newly developed spring or resurgence. Drainage of the mass of the limestone will occur relatively rapidly down to valley floor, or impermeable layer, whichever has the greatest altitude, and vadose conditions will gradually become established throughout the bulk of the limestone.

However many such vadose streams

will encounter and excavate only portions of former cave passages, whether of vadose or phreatic type. The greater part of all cave sytems existing prior to the onset of the glacial period may well remain completely filled with inwash deposit, in places sealed with thick layers of calcite, and will remain innaccessible and often un-noticed. The process is therefore one of re-invasion, on an almost random basis, of small sections of former cave networks. Such sections may remain as fossil, relict features, only partly integrated with the present active cave systems, and whose full extent is seldom, if ever, ascertainable.

The development of the pattern of cave systems wiill continue throughout the greater part of the interglacial, until such time as a climatic swing towards cooler weather heralds the onset of the next glacial cycle. The overall pattern and type of cave development during an idealised interglacial/glacial/interglacial is therefore one of excavation and/or enlargement, followed by a gradual cessation of all types of development. In turn a major stage of infill follows, then a major phase of stalagmite deposition. The process gradually slows and re-excavation and re-development re-commences at the onset of the next glacial cycle.

As may be seen from the many alternative processes and results which may occur from place to place and from time to time, during such an ideal climatic cycle, this conceptual model is deliberately structured in the simplest possible outline. Among the many factors ommitted are the implications of the occurence of the relatively minor climatic fluctuations known to have been superimposed upon each part of the cycle. In particular, the effects of a temporary ameliorations which appear to occurred during during the onset and peaks of at least the last major glaciation, i.e. the inter-stadials, have been deliberately ommitted. However, it is hoped that examination of the detailed morphology and relative chronology of the various passages formed in any given cave system, together with the information provided by all inherent, independent, methods of dating cave sediments, will afford an overall outline chronology, both relative and absolute, for each cave system studied in detail. Until such time as evidence of this nature becomes available for a significant number of the major cave systems in a given area, it would be futile to attempt to elaborate the above model.