Chapter 1 Introduction

Karst and caves

Karst may be defined as a distinctive terrain created by erosion of a soluble rock where the topography and landforms are a consequence of efficient underground drainage. Its characteristic features therefore include disrupted surface drainage, closed depressions, dry valleys and caves. The essential underground drainage means that caves are an integral component of a karst landscape; however, caves are commonly defined as natural cavities large enough to be entered by humans, and some karst landscapes on the softer rocks are drained by fissures too narrow to be described as true caves. Limestone is the only common rock that is highly soluble in natural surface waters, so nearly all karst is formed on limestone. Dolomite may have karstic landforms, generally less well developed than those on limestone. Some karst features are formed by solution of gypsum or salt, but pseudokarsts on basalt or ice are not due to rock solution.

Most cavernous limestones have an unconfined compressive strength of around 100 MPa. They are strong rocks, capable of spanning large underground voids and forming stable cliffs; they are also massive, with widely spaced fractures, some of which are enlarged by solution to form discrete conduits. Chalk is the best known of the weaker, porous limestones, which form a type of karst with few caves large enough to be entered by humans. Because limestone contains little insoluble residue, soil generation is limited, but many karst areas have some cover of mineral soil derived from adjacent non-carbonate outcrops, organic debris, or residual soil accumulated over a very long time; bare rock outcrops are common features of karst.

Karst lands tend to provide some of the more spectacular natural landscapes, with hills and mountains of white crags and bare rock pavements, pitted by sinkholes and caves. Though limestones are soft (in that they are easily abraded), many are mechanically strong due to their microstructure of interlocking crystals, and all are topographically resistant because much of their erosion is underground; even the weakest limestones, such as chalk, survive as the high ground 'because they devour their own agents of erosion'. For the same reason, limestone karst contains many deep and spectacular gorges; formed in climatic environments of the past, they are preserved because their walls are not eroded by water which has sunk underground.

The preservation of landforms within a karst landscape is most significant beneath the ground surface. A complex cave system is the only erosional environment where each phase of erosion does not remove the features of earlier phases. Capture and diversion of drainage, rejuvenations and steady downcutting create new cave conduits at lower levels, and preserve the products of earlier erosion and deposition that have been abandoned in high-level cave passages — on a scale which can never be achieved in an evolving, eroding and lowering surface topography. Caves are therefore especially significant to geomorphological studies, as their erosional features and accumulated sediments are unique records of past environments in upland regions.

The karst of Great Britain is formed on a number of limestones spaced through the stratigraphical column, and also on some units of gypsum and salt (Figure 1.1). The outcrops of these rocks therefore define the areas of karst landscape, which are widely distributed across England and Wales, but are rather sparse in Scotland (Figure 1.2). They include all the well known karst sites much visited by students and researchers of geomorphology: the cliffs at Malham, the gorge at Cheddar, the caves of Dan-yr-Ogof, the pavements and potholes of Ingleborough, and the dry valleys of the Peak District and Chalk Downs. Most of these sites are on or in the massive limestone of Lower Carboniferous; this is by far the most important karstic rock in Britain, though the largest area of karst is on the Cretaceous Chalk, which has very limited cave development. The sites included in this volume of the Geological Conservation Review cover a wide sample of the surface and underground landforms in these areas of Britain's karst.

Solutional processes

Limestone consists largely of the mineral calcite, which is composed of calcium carbonate, which is only slightly soluble in pure water. Limestones are however much more soluble in acids, and the most important process in the overall development of surface karst landforms and caves is solution by carbonic acid, that is produced by the introduction of carbon dioxide. The process of dissolving the rock, to create the liquid solution of calcium and bicarbonate ions in water, may be referred to as either solution or dissolution; the term 'solution' is in common use, and is retained in this text. The many factors that influence the complex chemistry of limestone solution are reviewed by Ford and Williams (1989) and White (1988).

The solutional capability of water with respect to limestone is related directly to its carbon dioxide content. All rainwater absorbs small amounts of carbon dioxide from the atmosphere, but soil water contains biogenic carbon dioxide at far higher concentrations due to its production by plant roots. Biological activity increases greatly with temperature, and the development of karst landforms is therefore maximized in hot, wet, tropical environments where there is a dense cover of plants and organic soils. Although carbon dioxide is slightly more soluble in cold water than in hot water, karstic processes in cold climates are severely restricted by the reduced biogenic production of the gas.

Rates of limestone reaction and removal are a function of molecular diffusion that is determined by the kinetics of the calcite solution process (Dreybrodt, 1981a, 1988). Solutional erosion is distributed through a karst partly in relation to the source of biogenic carbon dioxide in the soil cover. The maximum increase in solutional load occurs at the soil/limestone interface within the zone of epikarst (Williams, 1983, 1985), and thus contributes directly to surface lowering. Caves receive flows of saturated percolation water, and of allogenic, sinking (or swallet) stream water which are also low in carbon dioxide and solutional capabil ity. The passages are enlarged by waters of minimal aggressiveness, because the flows are concentrated in fissures and conduits with wall areas far smaller than the area of soil-covered rockhead which receives only diffuse flows. Water in the phreatic, or flooded, zone is normally saturated, in equilibrium with the limestone walls of the conduits; it is capable of further solution due to the process of mixing corrosion. Two waters, each saturated to different levels of carbon dioxide and calcite, form an unsaturated, aggressive water when they combine, due to the non-linear equilibrium of carbon dioxide and calcite in solution (Bögli, 1964, 1971, 1980; Dreybrodt, 1981b).

Percolation water descending through a limestone is normally saturated with calcium carbonate in equilibrium with its high content of soil carbon dioxide; subsequent diffusion of the gas into a cave air causes precipitation of some of its calcium carbonate load, to form stalactites and other cave speleothems. Comparable loss of carbon dioxide from a surface stream, normally associated with algal growth, causes the precipitation of calcite as tufa or travertine (Ford, 1989b).

Limestone solution can also occur in the presence of acids other than the carbonic acid generated by carbon dioxide. Sulphuric acid occurs naturally, by oxidation of pyrite, and is extremely corrosive. Its effects in karst are subordinate to those of carbonic acid, except in the earliest stages of cave inception (Lowe, 1992b; Worthington and Ford, 1995); sulphuric acid generated by oxidation of sulphide minerals in the rock is probably important in opening the initial voids in a limestone mass, so allowing the input of increased flows of surface water charged with carbon dioxide. Organic acids from soils play a solutional role far subordinate to that of the carbonic acid. Solution of gypsum and salt is not dependent on acids, as both rocks are highly soluble in pure water.

Karst geomorphology

The geomorphology of karst is widely described and reviewed, and three of the major texts in the English language are by authors who originated from, and worked extensively in, Britain (Sweeting, 1972; Jennings, 1985; Ford and Williams, 1989). These volumes are the best guides to the very substantial literature through which karst geomorphology and cave science have evolved to their present levels of understanding.

Both the broadest structure and the topographic texture of a karst terrain are determined by the lithology, strength, porosity and structure of the exposed carbonate succession. In contrast, the main landforms, the karst types and many of the smaller solutional features are all functions of process, and can be identified in karst regions on all types of limestone, as well as on many other types of soluble rock.

Karst landforms

Dolines

A closed depression in the land surface, with no drainage outlet except underground, may be regarded as the diagnostic landform of karst topography. They are generally known as dolines, after the Slovene term for a surface depression in the classical karst landscape where there are no continuous valleys; they are also known as sinkholes, especially in the engineering and American literature. Dolines may form by a variety of mechanisms, and most are the product of multiple processes. There are no size constraints on dolines; most of those in Britain are 1–50 m in diameter, with width:depth ratios varying from 2:1 to 4:1.

Solution dolines are formed by localized surface lowering through chemical erosion of the limestone (or other karstic rock). Solution is dominantly at the subsoil rock surface, but may be subaerial, by rainwater converging on a bedrock fissure, which acts as a drainage outlet. The doline therefore slowly deepens over time, and the evolution of its cross profile is analogous to that of a non-karstic valley; it contrasts with the normal valley only in its closed long profile. The internal slope gradients are largely a function of the rock strength and fracture patterns, and of any degradation which has taken place after solutional processes have diminished. There is a spectrum of doline profiles, from the broadest of saucer-shaped depressions, through to the potholes and shafts which are the entrances to many underground drainage conduits.

Collapse dolines form by failure of the limestone into underlying caves; they are commonly identified by their internal rock walls and scars, which are the remnants of the failed rock spans. Dolines formed purely by collapse are extremely rare, but nearly all large dolines contain some elements of collapse processes. On a small scale, subsoil solution within a solution doline inevitably involves some bedrock fissure opening; this leaves residual blocks of unsupported rock, which ultimately fail and fall within the soil profile. On a larger scale, rock walls may collapse into an expanding doline; progressive failure of limestone ribs left between wide fissures may create the large quarry-like dolines, such as Hull Pot in the Yorkshire Dales.

Subsidence dolines form by the failure, sagging or collapse of an insoluble soil or cover rock into solutional voids in a buried limestone. The most common are those formed in unconsolidated soil, as infiltrating rainwater washes the soil into fissures within the limestone. Fines within the soil are washed away first, from beneath, followed by removal of the coarser particles, and then subsidence of the upper soil and surface. This process is known as suffosion, which is a type of piping failure of the soil, and the surface depressions may therefore be known as suffosion dolines. Many thousands of this type of doline have formed in the glacial till on the limestone of the northern Pennines, where they are known locally as shakeholes (Figure 1.3). Most are 1–15 m across, and are no deeper than the till cover; many have slumped so that the limestone is not exposed, but others contain open fissures and cave entrances. The formation of subsidence dolines by the failure of a strong cover rock into limestone voids is a feature of interstratal karst. The hundreds of large dolines in the Namurian sandstone outcrops of South Wales are of this type, and the mechanism of formation is similar to that of collapse dolines, wholly in limestone, except that there is no solutional weakening of the rock span over the void before collapse.

Poljes are larger forms of karstic closed depressions, with sharply defined rock slopes around the perimeter of wide flat floors, which are commonly alluviated (Gams, 1978). They form by lateral planation on the sediment floor or at the water table, and both their inflows and outflows are underground. There are no true poljes in Britain, though the karstic depressions at Hale Moss and the turlough of Pant-y-llyn have many features similar to those of a polje.

Continued enlargement of closely spaced dolines produces a landscape of increasingly disordered relief, where the residual hills ultimately become the dominant landforms. These positive features of a karst landscape include the cones, towers and similar hills in the mature tropical karst terrains, but none of these landforms occurs in Britain's limestone, due to the climatic constraints on the karstic evolution through the Quaternary. The conical hills in the Peak District, once thought to be remnants of Tertiary tropical karst, are exhumed reef knolls.

Karst valleys

The loss of surface drainage into sinkholes precludes the development of most surface valleys in a fully mature karst where dolines become the dominant landform. There are, however, many situations where valleys are or have been formed on limestone.

Blind valleys carry a surface stream but terminate where the water sinks underground. Most form where valleys extend from a non-karstic outcrop and end where the streams find fissure routes into caves beneath their limestone floors. Ingleborough's Fell Beck flows in a blind valley cut into the shale and drift as far as the sink into Gaping Gill.

Headless or pocket valleys form in complementary style where a substantial stream or river emerges from a limestone aquifer and cuts a valley downstream of its resurgence, as at Wookey Hole.

Allogenic or through valleys form where a surface river enters a karst with a flow too large to sink underground in the available fissures. They develop into larger features, and commonly into karst gorges, where the rate of entrenchment exceeds the local rate of fissure enlargement in the maturing karst; this precludes subsequent underground capture, especially where the hydraulic gradient in the limestone is low beneath a gently graded valley. The River Wye flows in an allogenic valley through the Peak District, where the opportunity for underground capture is also reduced by impermeable units within the limestone sequence. The Rivers Tawe and Wharfe are two of those which cross their limestone outcrops in inherited glacial valleys with very low gradients. Valleys with ephemeral streams, active only in flood conditions, are common both on cavernous limestones and on the weakly cavernous chalk.

Dry valleys are features of many karst terrains. They are fluvial landforms, cut by subaerial streams and rivers, and then abandoned and left dry when their flows were lost to underground captures (Smith, 1975b). Some were formed by surface flows on limestone when it was first exposed and was only minimally permeable, before secondary permeability was increased by solutional fissure enlargement. Many dry valleys in Britain were excavated or enlarged under periglacial conditions when ground ice of the permafrost sealed the limestone fissures during cold stages of the Pleistocene. Also in the cold conditions, surface valleys were deepened by annual snowmelt floods which exceeded the capacity of unfrozen sinks and choked them with sediment.

Karst gorges were formed by subaerial, fluvial entrenchment in limestones strong enough to stand in stable steep faces. Most were formed where river incision was accelerated in descents off upland blocks. Gordale Scar is one of many that was cut rapidly by powerful flows of proglacial or subglacial meltwater; Cheddar Gorge is one of those cut by seasonal flows of snow melt during the cold stages of the Pleistocene. The gorge at Matlock Bath is one of those cut by a large allogenic river; it is essentially superimposed and was never the site of a major river descent. Common to them all is their preservation in the limestone, even after the first two types were abandoned by the streams and rivers which cut them. At Gordale and Cheddar, surface erosion and degradation of the gorge walls were almost eliminated by underground capture of the surface drainage; this occurred when the permafrost melted as the climates ameliorated at the end of the Pleistocene cold stages. Surface water flows on the sides of the Matlock gorge have always been insignificant in comparison to the flow of the through river. Gorge formation by cavern collapse is extremely rare; in Britain it is limited to short sections of gorge immediately outside large cave entrances or exits whose roof arches are retreating, as at Wookey Hole and Porth-yr-Ogof. Small-scale collapse and unroofing of small cave passages are normal features which contribute to valley deepening in a limestone.

Limestone pavements and karren

Subaerial and subsoil limestone surfaces are etched by solution into a variety of small features. Dominant are the solution runnels, which are better known by the German term, karren. These are most conspicuous on the bare limestone pavements which were scraped clean by the Pleistocene glaciers in the northern Pennines (Parry, 1960; Sweeting, 1966) (see Chapters 2 and 3). Postglacial solution by rainwater enlarging the bedrock fissures has left a pavement of *in situ* limestone blocks, each locally known as a Clint and separated from its neighbours by grikes. The clints are fretted by solution runnels, and some of the grikes are partly relicts of pre-Devensian erosion. Some of the modern pavement features may be inherited from Carboniferous palaeokarsts developed on intraformational calcretes (Vincent, 1995). The largest clints and the most extensive pavements lie where bedding planes have been scoured on top of strong beds of limestone. Where the surface steps across a sequence of beds and bedding planes, the terrain is known as staircase karst (from the German *Schichttreppenkarst*).

An exhaustive classification of karren forms uses German terms (Bögli, 1960; Sweeting, 1972); there are no equivalent terms in the English language. Only some of the types are widespread in Britain's karst, and rillenkarren and rundkarren are the most significant.

Rillenkarren have sharp crests between channels which are normally 10–20 mm wide and deep, and are aligned down gentle or steep rock faces, usually with some degree of channel convergence. They are the normal solutional features on bare limestone which is exposed to direct rainfall or snowfall, but good examples are rare in Britain.

Rundkarren have rounded crests and troughs and are generally 100–400 mm wide and deep, cut into almost level or sloping limestone surfaces. They are normally formed under a cover of dense vegetation or organic soil which retains rainwater over the ridges between the solution runnels, so that surface solution creates a rounded profile. Rundkarren are dominant on the bare pavement surfaces of the northern Pennines, suggesting that much of their development took place beneath a permeable, organic soil cover. Most of the original plant cover has been lost due to artificial clearance of the protecting trees, and sheep grazing has precluded regrowth of anything except grass. There has been almost no subsequent development of rillenkarren; this appears to be due to the very complete coverage of the limestone surfaces by lichen, which provides the cover beneath which rounded rundkarren evolve.

Rinnenkarren have rounded channels similar in size to rundkarren, but form with sharp rims cut into bare, sloping surfaces. They deepen downstream, and Britain's classic examples are those on the Rakes of Hutton Roof.

Kamenitzas are solution basins, or pans, generally 50–800 mm across, cut into level rock surfaces; they are rounded or elongate and commonly have an overflow channel from them. Once established in random hollows, they are self-deepening due to solution by the regularly recharged rainwater, commonly aided by organic acids produced by plants and peat trapped in the basins.

Trittkarren have stepped profiles on bare surfaces with slopes too gentle to support rillenkarren. Each step is typically 10–50 mm high, between wider flat treads; they are rare in Britain.

Kluftkarren are the deep, open fissures formed by solutional enlargement of primary tectonic fractures within the limestone; in northern England they are commonly known as grikes, and they separate the clints of remaining limestone. Grikes are typically 50–500 mm wide and can reach depths of many metres. Clint sizes and shapes, and grike spacing, are features of the limestone structure.

Spitzkarren are pinnacles or blades of limestone, with sharp or rounded crests. They are residuals of limestone left by deep subsoil or subaerial solution down closely spaced kluftkarren, and include some of the narrow or knife-edge clints in the more densely jointed Pennine pavements.

Karst types

Different assemblages of limestone landforms create identifiable karst types which are largely related to the present and past climatic environments in which they have evolved. Within each type, the geological structure of the host soluble rock determines the patterns of underground drainage and also influences the surface topography. The contrasting karst types in the different regions of Britain are functions of both Pleistocene history and local geology.

Glaciokarst is characterized by the inheritance of glacial landforms, and is distinguished by the bare rock surfaces scoured by Pleistocene (or more recent) glaciers. Limestone pavements and scars form on the tops and edges of the outcrops of stronger beds; they are fretted by postglacial karren, and there is minimal development of postglacial soil cover. Deep karst gorges were formed by temporary meltwater rivers, but generally there are few dry valleys. The Yorkshire Dales contain Britain's finest glaciokarst (Figure 1.4).

Fluviokarst is characterized by dendritic systems of dry valleys. The finest area in Britain is the Peak District (Figure 1.5), where the valleys were largely excavated under periglacial conditions during the Pleistocene. Karst gorges are developed where the valleys entrenched into steeper slopes, but there are few rock scars; most outcrops of the limestone are covered by soils of solutional residue and aeolian loessic silt.

Polygonal karst is a more mature karstic terrain where dolines have replaced valleys as the main form, and a polygonal network of topographical divides has replaced the dendritic systems of interfluves. This type of karst is poorly represented in Britain, where the Pleistocene climatic fluctuations and glaciations repeatedly interrupted solutional erosion; it is better developed in Mediterranean climatic regimes (Gams, 1969, 1974).

Tropical karsts are the climatic extreme, where the negative landforms of valleys and dolines are replaced by the positive, residual landforms of cones and towers. There is no trace of these karst types in Britain's modern landscape; the classic areas of cone karst include those in Java (Lehmann, 1936) and Jamaica (Sweeting, 1958), and tower karst is largely restricted to the limestones of southern China (Zhang, 1980; Smart *et al.,* 1986).

Fossil karst or palaeokarst has its solutional landforms buried by later sediments of either clastic or carbonate composition. It includes features as old as the intra-depositional structures within the Carboniferous limestone sequence (Ford, 1984), and the many fissures filled with Triassic sediments (Simms, 1990). It also includes the many buried and filled dolines containing Tertiary and Quaternary sediments in the Carboniferous limestones of the Peak District and in the Chalk of south-east England; the latter include the many buried and steep-sided features commonly known as pipes.

Chalk karst is a very distinctive style of topography, developed on the mechanically weak, porous, very permeable and only mildly cavernous chalk; it extends across large outcrops in south-east England (see Chapter 7). It has extensive dry valley systems, which were enlarged under periglacial conditions, and numerous subsidence dolines formed in weak cover rocks. Soil cover is complete, and there are no scars or crags in the weak rock. Underground drainage is efficient, but there are few caves large enough to be accessible (Lowe, 1992a).

Salt karst and gypsum karst are formed on the respective evaporite rocks, both of which are extremely soluble in water. Surface landforms are dominated by solution dolines and broad depressions too shallow to be described as true dolines; these occur on both rock types in Britain (see Chapter 7). Gypsum karst may also have large cave systems, but there are only a few small caves in Britain's gypsum.

Evolution of caves

Cave passages form through a limestone karst where there is an available flow of water, with chemical potential to dissolve the limestone, with an adequate hydraulic gradient between a sink and a rising, in a favourable geological structure. Extensive cave development therefore depends on a combination of geological and topographical factors, and on a climate which provides meteoric water charged with biogenic carbon dioxide.

Any single cave passage evolves through three distinct stages. Initiation creates the openings through the rock, which permit the flow of groundwater and allow the accelerated erosion of the next stage. Enlargement is the main stage of cave development, when the small, initial fissures are enlarged to reach and pass the size limit of accessibility by humans, that defines a cave. Degradation is the terminal phase of destruction, where the cave either collapses, is filled with sediment or is removed by surface lowering. In a complex cave system, all three processes take place simultaneously in passages at different depths and positions in the limestone; solutional enlargement and sediment infilling can take place at the same time in a single passage.

The time-scales of cave evolution are long. The enlargement and degradation stages can be observed and monitored. An order of magnitude for their combined completion in Britain's karst is about a million years. A cave passage can develop to a diameter of a metre inside 10 000 years (Mylroie and Carew, 1987). Caves can evolve over many millions of years in karsts of greater depth, thicker limestone and slower surface lowering (without interruption by glaciations) than are found in Britain. In all situations, the initial stage of cave evolution may take vastly longer; it is nearly impossible to observe and assess, but it should be viewed on a time-scale of tens of millions of years.

Cave passage dimensions vary greatly. The smallest are those which can just be entered by a human, but there is a continuity from these down to the solutionally enlarged fissures and proto-caves which are abundant in karst aquifers. The largest caves are about 100 m in diameter, but these are restricted to warmer climatic zones with longer records of rapid limestone solution. In Britain, a cave passage 5 m high and wide is described as large, and there are few which exceed 15 m in diameter. Cave systems may have complex passage networks which reach great lengths. Any figures quoted are for the mapped lengths only, and most caves extend beyond the flooded, choked or constricted passage sections which are the contemporary limits of exploration. Currently there are in the world 28 cave systems which have been explored for longer than 50 km, and two of these are in Britain (Ease Gill Cave System and Ogof Ffynnon Ddu). Cave depths are limited by the heights of the limestone mountains which contain them, and Britain cannot have very deep caves. Throughout the world, there are 50 caves known with depths exceeding 1000 m, but Ogof Ffynnon Ddu is the deepest in Britain and reaches only 308 m.

Cave initiation

The longest stage in cave evolution involves the creation of the initial opening through a solid rock mass. Only after completion of a route through the limestone can groundwater flow and solutional erosion progress. Some initial openings are provided by the primary porosity of the rock; highly porous limestones such as chalk have more diffuse groundwater flow, and hence less tendency to direct solutional effort into conduit, or cave, enlargement. Tectonic fractures and bedding planes constitute the main initial openings in the less porous limestones. These are present to some extent in all limestones in older terrains and structural blocks, including those of Britain. They may be opened by unloading in response to erosional reduction of the cover; alternatively, they may be tight in zones of high tectonic compression, plastic deformation and metamorphism, accounting for minimal cave development in some limestones of the younger mountain chains outside Britain.

At depth in a limestone mass, solutional enlargement of the initial openings is independent of meteoric water which has no access to them. Available connate waters and mineral acids are probably dominated by sulphuric acid that is generated by oxidation of sulphides (Ball and Jones, 1990; Hill, 1987). The limestone solution process is influenced and directed by the smallest of chemical contrasts within the rock sequence. An inception horizon is a locus of cave initiation (Lowe, 1992b); it may be a shale parting within the limestone, perhaps containing pyrite as a source of sulphuric acid, or it may be no more than a bedding plane between limestones of slightly contrasting lithologies. Faults and joints may provide links between inception horizons and are themselves enlarged by solution, but most cave passages are initiated on the bedding or at bed-ding/fracture intersections.

The geological control of cave inception is absolute, but hydraulic factors start to influence the cave evolution after the initial openings are established. Flow is laminar until the fissure is wide enough to permit turbulent flow; the breakthrough dimension is about 5 mm (White and Longyear, 1962; Atkinson, 1968a; White, 1988). Turbulent flow in wider fissures permits far higher rates of solution and erosion, which are enhanced by throughflows of meteoric water, charged with biogenic carbonic acid (Thrailkill, 1968). The cave then enters its second stage of evolution.

Cave enlargement

As the limestone fissures are enlarged, the permeability of the rock mass increases, and the hydraulic gradients decrease. The upper zone of the aquifer drains and some form of water table is established. Above it, the fissures and caves are drained so that they contain free air surfaces within the vadose zone. Below it, all openings remain full of water within the phreatic zone, also known as the saturated zone or phreas. The water table does not have a uniform slope, as in a diffuse aquifer, but is a complex stepped surface partly related to, and changing with, the pattern of cave conduits (Drew, 1966). The onset of turbulent flow permits increased erosion by mechanical abrasion in cave streams that carry surface sediment. Hydraulic advantages also become apparent, and many proto-caves are abandoned while fewer favoured routes continue to be enlarged. All caves are initiated under phreatic conditions, but are enlarged in styles which contrast above and below the water table.

Vadose cave passages, enlarged above the water table, are dominated by canyons or trenches. They are either cut downwards by freely flowing streams or headwards by waterfall retreat, and they maintain downstream gradients. They may meander due to erosional exaggeration of bends, or may be straight rift passages where guided by rock fractures; canyons at different levels are connected by waterfall shafts enlarged by spray corrosion. Undercutting of passage walls occurs along geological weaknesses or where the stream is deflected laterally by sediment accumulation that prevents downcutting.

Phreatic cave passages that are full of water are enlarged by solution of their floor, walls and roof, and can therefore have very complex shapes. The dominant form of a conduit is a rounded tube, but this may have an elliptical cross-section extended along a bedding plane, or may enlarge into a high rift on a fracture plane. Roof hollows and doss-rifts are common, and some are the product of mixing corrosion. Phreatic caves have looping or irregular long profiles with phreatic lifts and reverse gradients, as their flow is maintained by hydrostatic pressure. They are commonly formed in a shallow phreatic situation, following the shortest available routes just below the water table, as in the Kingsdale caves, but many are guided by inclined geological structures into deep phreatic loops, as in Wookey Hole.

Many phreatic cave passages are left in the vadose zone when the local or regional water table falls to a lower level. A passage may be abandoned and left completely dry. Alternatively, any stream still in it cuts a vadose trench in the floor of the old phreatic tube, and creates a passage with a keyhole profile (Figure 1.6). This very distinctive cross-section is always evidence of rejuvenation, or a slow lowering of base level, in response to surface lowering between two phases in the cave's evolution.

A special type of phreatic cave develops in a confined aquifer containing slowly moving water. All potential flow routes are enlarged equally, so that a maze cave is formed on the network of available fractures (Figure 3.23). There is no focusing of flow on input or outlet points, as where conduits develop at the expense of abandoned proto-caves (Palmer, 1975). A similar effect is produced where water enters the limestone at many points from an adjacent diffuse aquifer, and maze caves may also be formed by backflooding.

Active cave entrances at stream sinks are either at the heads of gently graded cave passages, or are vertical shafts or potholes. Active resurgences may be outlets of vadose cave passages. Far more resurgence passages rise from limestone which extends below the outlet level, and are therefore flooded; deep phreatic lifts of this type are known as vauclusian risings.

Cave systems evolve with increasing complexity as individual passages are abandoned in favour of new routes at lower levels. The progressive abandonment is partly due to the availability of new resurgences at lower sites in a topography subjected to surface lowering, but is also due to the karst system becoming more mature. Rejuvenation may affect the whole cave system or just an individual passage. Phreatic up-loops are eliminated by vadose entrenchment through their crests; down-loops are reduced by paragenesis, where the cave roof in the trough is preferentially eroded while solution of the floor is hindered by a protective cover of clastic sediment. New shorter routes are initiated in both the vadose and phreatic zones. The trunk drain through the cave system progressively approaches a graded profile, where the initial stepped water table is replaced by one which slopes gently and lies close to the level of the resurgence (Figure 1.7).

Cave degradation

Degradation and destruction of cave passages involve filling and choking by sediments, collapse, and total removal, in most cases after abandonment by their formative streams. Within a large cave system, individual passages are at all stages of initiation, enlargement and degradation at any one time. Abandoned passages are largely left in the vadose zone, and their degradation may commence while they are still being enlarged by an underfit stream cutting a floor trench.

Clastic stream sediments are carried into caves from allogenic surface sources (Ford, 1976; Ford and Williams, 1989). Some are washed through the system, but others accumulate underground. Massive influxes of sediment from glacier melt streams commonly choked cave passages at a time when solutional activity and cave enlargement were at a minimum, as happened widely in Britain's caves during the Pleistocene Ice Ages. Many cave entrances and exits are also blocked or buried by glacial till and other clastic sediments.

Calcite deposition is common in caves where saturated percolation water issues from fissures, loses carbon dioxide to the cave air and deposits calcium carbonate to regain equilibrium. The variety of calcite deposits, or speleothems, is immense (White, 1976; Ford and Williams, 1989). Stalactites hang from the cave roof, and many in Britain retain the thin hollow structure of the straw stalactite without external thickening; others are distorted by crystal growth patterns into the complex shapes of helictites (Figure 1.8), and others extend into curtains where dripwater flows laterally down a sloping roof. Deposition on the cave floor creates tall stalagmites or rounded bosses, whose profiles relate to saturation levels and drip rates. A flowstone floor is formed by seepage water, commonly over layers of clastic sediment, which subsequently may be removed to leave a false floor; gour dams, crystal pool linings and cave pearls are additional types of floor deposit.

Other secondary mineral deposits in caves are less abundant than calcite, and barely contribute to the blocking of a cave. Crystals, or anthodites, of aragonite grow by deposition from surface film water and condensate, and gypsum, or selenite, crystals can grow by sulphate generation within some clastic cave sediments; both these crystal forms are well developed in the Llangattwg caves.

Wall and roof collapse is a widespread feature in caves; it modifies passage profiles, and contributes to cave enlargement where fallen blocks expose new surfaces to solutional attack. Extensive collapse ultimately blocks cave passages, because the fallen material occupies larger volumes than the undisturbed rock. Cave roof failure occurs where the passage widths exceed the stable span, which is dictated by the local bed thickness and fracture density (White, 1988); the Time Machine in Daren Cilau, and other large cave passages are typified by extensive block collapse. Total failure is not common, and many cave boulder chokes are composed of inwashed debris.

A cave is totally destroyed when it is overtaken by surface lowering. More common is the fragmentation of a cave system where surface valleys cut down through it, leaving truncated passages in their walls. The extensive cave unroofing and collapse, characteristic of the final stage in karstic evolution, has not been reached in Britain, mainly because of interruptions and rejuvenations due to Pleistocene climatic changes.

Research in limestone geomorphology

Concepts and theories on the origin and development of karst landforms, above and below ground, have matured internationally, with parallel and frequently overlapping sequences of ideas evolving in different countries. The level of activity in scientific research in any one country has been dictated in part by the extent, and therefore the parochial relevance, of limestone karst within the national borders; China, the USA and the nations which once formed Yugoslavia have all been world leaders in their time. By comparisons with other countries, Britain has only small areas of cavernous karst (thereby excluding the distinctive chalk karst), but these include the internationally renowned glaciokarst of the Yorkshire Dales, and they contain some of the world's longest known cave systems. On international scales, the level of karst research in Britain has probably exceeded that which would be expected on the basis of the extent of its limestone outcrops, and has certainly included some contributions of international significance.

Development of karst research

An early, partial understanding of the landforms and processes within karst regions evolved progressively as part of wider geomorphological research, and the role of solution by carbonic acid was recognized before 1800. The benchmark studies originated from the Dinaric karst, led by Cviji■ (1893, 1918) and Grund (1903, 1914) who documented the critical roles of dolines, underground drainage, caves and collapse in the evolution of limestone landscapes. The disorganized relief, discontinuous valleys and large closed basins were seen as the products of solutional erosion, and the special case of poljes was further described by Rogli■ (1938). Limestone pavements are better developed in the Alpine karsts than in the Dinaric karst, and the classic description of their karren features originated from Switzerland (Bögli, 1960).

Parallel studies of karst landscapes in the warmer climatic zones within China had little influence on Western thought. Lehmann (1936) described the cone karst of Java, and the limestone landscapes of the wet Tropics were then recognized as extreme forms of solutional erosion; the tower karst of China largely remained an enigma to Western geomorphologists until the political barriers to access and communications were lowered in the 1970s.

Early karst research in Britain largely followed the lead from the far greater limestone lands of Europe, though Reid (1887) was ahead of his time when he recognized the formation of dry valleys in the chalk during bygone periods of periglacial conditions. Among numerous regional studies of Britain's karst, research reports of wider significance include those concerning the dry valleys in the Peak District (Warwick, 1964), the pavements of the Yorkshire Dales (Sweeting, 1966), the depressions and valleys of the Mendip Hills (Ford and Stanton, 1968) and the dolines of South Wales (Thomas, 1974).

Britain's contributions to limestone research were summarized by Sweeting (1972). Modern studies have diversified from pure geomorphology, and have emphasized research into processes (Smith and Atkinson, 1977; Trudgill, 1985a). They have also included applied aspects of the science, relevant to both engineering (Waltham, 1989) and groundwater resources (Atkinson and Smith, 1974), and have expanded into all aspects of karst research in the limestone terrains of foreign lands.

Development of cave research

The earliest theories on cave origins suffered from a shortage of geomorphological data on underground features, and are now of only historical interest (Halliwell, 1974; Shaw, 1992). Archaeological excavations of near-surface cave sediments dominated cave studies in Britain in the nineteenth century, when the origin of the caves was largely ignored.

Cviji■ (1893) recognized the role played by underground drainage in the evolution of karst topography, but it was Katzer (1909) and Martel (1921) who expounded the special case of karst drainage by discrete conduits and cave passages. Subsequently, a series of American papers established contemporary understanding of cave genesis in the English language. Davis (1930) favoured deep phreatic cave development when he tried to fit karst processes into his cyclic pattern of landscape evolution (Davis 1899), but his ideas lacked a foundation of underground observations. Swinnerton (1932) backed the concept of shallow phreatic cave development, at or just below the water table, and a dominance of vadose cave development was postulated by Gardner (1935) and Malott (1937). Bretz (1942) interpreted the features of cave morphology to identify early phreatic development and subsequent vadose development in most caves. Each of these authors was only partly correct in his understanding of the complex initiation of caves and the polygenetic nature of subsequent cave development (Lowe, 1992c).

A hydrological approach to the environment of cave development (Rhoades and Sinacori, 1941), combined with an early concept of the role of the water table, promoted papers on the levels of cave development (with respect to altitude), including studies of the Yorkshire caves by Sweeting (1950) and the Mendip caves by Ford (1965b). The concept of the water table in a complex karst aquifer was later questioned (Drew, 1966), and cave levels have been re-assessed in the light of modern knowledge by Palmer (1987).

Geological controls on the Yorkshire caves were identified by Simpson (1935), Myers (1948), Atkinson (1963) and Waltham (1970), and were then more widely recognized as the dominant influence on cave development (Rauch and White, 1970, 1977; Waltham, 1971a). The Mendip caves were the model for a wider theory on cave development established by Ford (1965b) and then modified to take increasing account of geology (Ford, 1971). Ultimately this matured into a general theory by Ford and Ewers (1978) which respected geological guidance within vadose, shallow phreatic and deep phreatic environments. The special case of the evolution of maze caves was described by Palmer (1975) and related to British examples by Ryder (1975).

The essential feature of the environments, processes and controls of cave development are now well established (Palmer, 1984, 1991; Ford, 1988; White, 1988; Ford and Williams, 1989), and general theories have been reviewed by Lowe (1992c). Modern cave studies are evolving on lines beyond pure geomorphology. The earliest stages of cave initiation are viewed with reference to the role of solution by sulphuric acid (Lowe, 1992b; Worthington and Ford, 1995). Research into the. increased secondary permeability due to circulation of saline groundwater is based on fieldwork in submarine karstic caves in the Bahamas, and has important implications with respect to hydrocarbon circulation and storage in oil reservoirs (Smart *et al.,* 1988a; Whitaker and Smart, 1993). Cave systems in subaerial karst regions are providing unique evidence of the times-scales of landscape evolution, because many of them contain the longest sequences of dated sediments — which can be related to surface events on geomorphological principles.

Dating of cave sediments

There is no means of directly measuring the age of a cave. As the early stages of initiation may take millions of years, the timing of a cave's origin is arbitrary, but the main phase of enlargement from a narrow fissure to a large cave passage is commonly a recognizable event within its erosional history. This event cannot be dated, but any sediments within the cave must post-date the erosional enlargement, and there are various methods available for dating the sediments (Ford and Williams, 1989; Smart and Frances, 1991).

Absolute or radiometric dating relies on measurement of some process which has taken place in the material at a known rate from a known starting level. Radiocarbon dating is based on the decay of the unstable carbon-14 isotope since it was trapped in a sediment at the time of deposition; the initial isotopic ratio is that which is constant in the atmosphere, and the half-life is known. Dates are only reliable back to 45 000 years (45 ka), so the application to cave sediments is limited.

Uranium-series dating is based on the decay of unstable uranium-234 to produce thorium-230 where uranium-234 is trapped in the calcite lattice on deposition but the daughter thorium isotope is absent. Thorium-230 is produced by decay of the uranium-234, and measurement of the isotope ratio indicates time from the initial deposition. If the calcite is subjected to re-solution, or is contaminated by detrital thorium, the technique does not yield reliable ages. The normal age limit for this technique is 350 ka, though a stalagmite may be positively identified as being older than the limit; mass spectrometric techniques, and the measurement of other uranium isotopes, can extend this limit to around 500 ka in some cases. Uranium-series analyses have provided the most numerous cave sediment dates (Gascoyne *et al.,* 1978; Ford and Williams, 1989).

Electron spin resonance (ESR) and thermoluminescence provide measures of the exposure of any calcite speleothem material to environmental radiation. The accumulated radiation dose received by a sample is determined by laboratory irradiation and deterioration of the thermoluminescence or ESR signal strength, while *in situ* measurement of the site-specific radiation dose rates allows calculation of the sample age. It is necessary to assume that the dose rate has been constant since deposition, but ages up to about 900 ka can be achieved with about 15% accuracy.

Comparative dating methods rely on correlation of a recognizable parameter with an externally calibrated chronology. Fossil and artefact records provide the conventional methods, but have limited application in most caves. Palaeomagnetic stratigraphy is based on identifying the polarity and orientation of the natural remanent magnetism recorded at the time of deposition by ferric minerals trapped in the sediments. It can be applied to sequences of clastic cave sediments, and also to calcite speleothems that carry weaker magnetic signals from their impurities but are not prone to post-depositional disturbance (Latham *et al.,* 1979). Sediment ages up to 2 million years (Ma) have been recorded from caves.

Determinations of cave sediment ages provide minimum ages for the cave passages in which they lie. Passage sequences may then be correlated, by their geomorphology, with surface palaeotopographies, and this constitutes a powerful tool in the elucidation of landscape evolution. Stalagmites are subaerial deposits formed in caves that are at least partially drained, and their positions therefore indicate the maximum elevations of the contemporary local resurgences and valley floors; dated stalagmites provide important evidence of the rates of valley excavation and surface lowering through much of the Pleistocene. Speleothem sequences may also yield valuable information on palaeoclimates, as the trace element contents and the ratios of stable isotopes, notably oxygen-18, may relate to the temperature at the time of deposition.

Radiometric cave sediment ages are conventionally expressed in ka, which represents thousands of years before the date of analysis. Only radiocarbon dates are expressed in years BP, measured before an arbitrary 'present' at 1950 AD. All ages are defined with error bars, which are commonly around ± 5–10%, increasing slightly for the older material; these are all published in the primary records of the data, but are not included in this review. Cave sediment dates are particularly valuable sources of geomorphological data. Published data of major significance in Britain include those referring to the Mendip caves (Atkinson *et al.,* 1984; *Smart et al.,* 1988b; Farrant, 1995), the Yorkshire caves (Gascoyne *et al.,* 1981, 1983a, b; Gascoyne and Ford, 1984; Baker *et al.,* 1995b, 1996), the Peak District caves (Ford *et al.,* 1983;

Rowe *et al.,* 1989b), caves in Devon (Proctor and Smart, 1991), caves throughout Britain (Atkinson *et al.,* 1978, 1986; Gordon *et al.,* 1989) and caves over a wider area (Hennig *et al.,* 1983; Baker *et al.,* 1993).

British karst regions

Most of Britain's caves and karst landforms occur on the thick and strong limestones of the Lower Carboniferous succession. The submarine palaeogeography of the Dinantian seas varied considerably across the area now occupied by Britain. Consequently, there is substantial lateral variation within the Carboniferous succession; the main limestone units in the main karst regions are correlated in outline in (Figure 1.9). Most of the karst and caves are formed in the more massively bedded facies of the carbonates, which were deposited on slowly subsiding shelf, lagoonal and ramp areas. Contemporaneous clastic sediments accumulated in adjacent troughs, and interrupted the carbonate deposition when they extended over the shelf areas.

The major regions of cavernous karst are therefore defined by the major outcrops of the massive facies of the Carboniferous limestones — in the two parts of the Yorkshire Pennines, the Peak District, the Mendip Hills and South Wales (Figure 1.2). The finest limestone landscapes and the greatest extent of cave development lie in the glaciokarst of the Yorkshire Dales, formed on the thick Great Scar Limestone in the area around Ingleborough and Malham. The peripheral zone of the northern Pennines includes all the karst on the thin Yoredale limestones, and also on outcrops of the thinner and faulted equivalents of the Great Scar fringing the adjacent Lake District and Morecambe Bay. Both the White Peak limestone area of the Derbyshire Peak District and the Mendip Hills are upland karsts which are clearly defined by geology and topography. The South Wales karst is spread along the limestone outcrop which fringes the coalfield syncline; it is not a conspicuous feature of the regional topography but it does contain many long, deep and important cave systems.

Each of the five main karst regions has suites of landforms and cave systems with their own distinctive characteristics (Table 1.1). The regional individualities are largely imposed by the geological structure, the relationships between geology and topography, and the local Pleistocene history of fluvial, periglacial and glacial stages. The geomorphology of the caves in the four main cavernous karsts have been comprehensively reviewed in the British Cave Research Association series of books on the limestones and caves of Britain (Northwest England — Waltham, 1974a; Mendip — Smith, 1975a; Peak District — Ford, 1977a; Wales — Ford, 1989a).

Outside the main areas of Carboniferous limestone, Britain's karst is dominated by the large area of chalk outcrop (Figure 1.2); this has a distinctive landscape of rolling downland and dry valleys, but contains very few caves. There are more caves in the smaller outcrops of older limestones, notably in North Wales, the Forest of Dean, Devon and Scotland. Individually, these lesser karst regions are often overlooked, but they form important components of Britain's landscape; for statistical purposes they are grouped together in (Table 1.1). The Jurassic limestones, and other less extensive carbonates, have limited development of karst landforms and very few caves; they are briefly reviewed in Chapter 7.

Karst in the Quaternary

Most of Britain's landforms are the products of erosion and deposition during the Quaternary. The broad pattern of highlands and lowlands is a function of geological structure, with origins that reach back to Tertiary and earlier times. There are also remnants of uplifted, deformed and dissected erosion surfaces which pre-date the Pleistocene. But most individual landforms, and all the details of the landscapes, evolved within the Pleistocene and Holocene — when the cyclic climatic Variations exercised great influence over the karst processes. Solutional activity was at a maximum during each warm phase. Conversely, it was greatly reduced in most cold phases; it ceased completely in most areas during periods of total ice cover, though glacial meltwater poured through the caves in some limestone blocks.

The main features of the later half of the Quaternary are outlined in (Figure 1.10). The most conspicuous single event was the Anglian glaciation in the Middle Pleistocene, during which ice sheets extended across the whole of Britain north of a line roughly through London and the Bristol Channel (Figure 1.2); glaciers covered all the main karst regions, except for the Mendip Hills and the southern half of the chalk karst. Earlier and subsequent glacial advances covered lesser areas of Britain.

Little is known of the pre-Anglian cold phases, but there is evidence for at least five stages of glaciation in the northern parts of Britain (Bowen *et al.,* 1986). The chronology of these is uncertain, but sediments in the Mendip caves (Figure 5.7) identify multiple cold phases both before and after the Matuyama/Brunhes magnetic reversal, which is dated to 780 ka (Baksi *et al.,* 1992). The end of the Early Pleistocene is not defined within Britain, and is variously ascribed to the 780 ka magnetic event or the base of the Beestonian (Bowen *et al.,* 1986).

Following the Anglian glaciation, the warm interglacials of the Hoxnian and Ipswichian were important periods of renewed karstic activity. Glacial tills were deposited by a limited ice advance in north-eastern England during the intervening cold stage of Oxygen Isotope Stage 6 (Bowen *et al.,* 1986). This stage is widely referred to as the Wolstonian glaciation, but the age of the sediments at the Wolston section are open to question (Rose, 1987). The Wolstonian label may therefore be regarded as inappropriate, but it is still in use until a substitute name is accepted for this glacial event. There is similar uncertainty over events in the Early Devensian, where the Upton Warren and Chelford interstadials cannot be reliably correlated with the warm phases of 5a and 5c in the oxygen isotope record. Although these climatic oscillations can be recognized and dated in cave sediment sequences, the critical sediment profiles on the surface cannot yet be correlated to those underground.

The major ice expansion of the Late Devensian extended across Scotland, north and north-east England and most of Wales (Figure 1.2). It is referred to as the Dimlington glaciation, and is distinguished from the lesser Loch Lomond re-advance which post-dates it. Both the ice cover and the climatic change had massive impacts on many of the karst landscapes. The limestone outcrops of the Yorkshire Dales were scoured to form the basis of Britain's finest glaciokarst. Periglacial conditions were imposed on the Peak District, Mendip Hills and most of the chalk karst, during which time most of the modern dry valleys were deepened by subaerial fluvial activity. The Devensian ice cover retreated when the late glacial Windermere interstadial opened at about 13 ka; evidence of the warmer climate from fossil beetles in subaerial sediments (Coope, 1977; Gordon and Sutherland, 1993) correlates closely with the renewed cave stalagmite growth (Gascoyne *et al.,* 1983b; Atkinson *et al.,* 1986). A subsequent, short, cold stage was marked by the Loch Lomond Stadial glaciation in the Scottish Highlands, and stalagmite growth recommenced in many caves only at the beginning of the Flandrian (Gascoyne *et al.,* 1983b). From then until the present day, solutional processes have been dominant in the continued evolution of Britain's karst.

(Table 1.1) A comparison of the major features which give the individual character to each main karst region of Britain

Region	**Yorkshire Dales**[1]	**Northern Pennines**[2]	**Peak District**	**Mendip Hills**	**South Wales**	**Rest of Britain**[3]
Geology						
Karst area[4]	320 km^2	220	420 km^2	110 km^2	220 km^2	9000 km^2 (mostly chalk)
Karst reliefs	270 m	70 m	260 m	260 m	330 m	200 m (chalk)
Limestone thickness[6]	200 m	40 m	400 m	700 m	150 m	200 m (chalk)
Typical dip	1°	1°	5°	30°	10°	Varies between areas
Last glaciation	Devensian	Devensian	Anglian[7]	None	Devensian	Varies between areas
Karst[8]						
Glaciokarst	* * *	* *				* (Scotland)[9]
Fluviokarst			* *	* *		* * (chalk)
Interstratal karst			*		* *	
Pavement areal[10]	677 ha	613 ha	0	0	8 ha	28 ha (Scotland, North Wales)
Dry valleys	*		* *	*	*	* * (chalk)
Karst gorges	* *	*	*	* *		
Collapse features	*		*			

Doline fields	* *				* *	* * (covered chalk)
Ephemeral lakes					*	* (chalk)
Polygonal karst	*			*		

1 The main southern Dales area on the Askrigg Block, including Dentdale, and excluding Nidderdale.

2 Including Nidderdale, the karst east of Morecambe Bay, and the eastern fringe of the Lake District.

3 Mostly the weakly cavernous karst of the chalk and oolitic limestones; including the cavernous karst of Devon, Forest of Dean, North Wales and Scotland.

4 Approximate area of karstic landscapes; does not include all the limestone outcrops.

5 Approximate values for the local relief within the limestone, which dictates the maximum descent from sink to rising, added to any depth of karstification beneath the resurgence level.

6 Geological data are generalized for purposes of comparison.

7 Or possibly Wolstonian — see text.

8 Most karst features are found to some extent in all the main karst regions, but their importance is assessed in relative terms:

* = significant, but minor;

* * = important and widespread;

* * * = internationally important.

9 Location of the major features noted in parentheses.

10 From Ward and Evans (1976).

[Part 2]

Region	**Yorkshire Dales**[1]	**Northern Pennines**[2]	**Peak District**	**Mendip Hills**	**South Wales**	**Rest of Britain[5]**
Famous sites	Malham Cove Gaping Gill	Hutton Roof Crags	Dove Dale Peak Cavern	Cheddar Gorge Wookey Hole	Dan-yr-Ogof Porth-yr-Ogof	
Caves						
Major passage types	Vadose joint shafts, phreatic on bedding	Joint mazes	Phreatic on veins and bedding	Downdip phreatic loops	Downdip vadose, strike phreatic	Vary between areas
Number of caves[11]	1420	620	210	220	270	410
Total cave length[11]	325 km	65 km	50 km	55 km	195 km	45 km

Caves over 1 km long	50		9		9		10		12		6		
Longest caves[12] (km)	Ease Gill System	71	Goyden Pot	6	Peak-Speedwell System	14	Swildon's Hole	9	Ogof Ffynnon Ddu	50	Slaughter Cave	11	(Forest of Dean)
	Kingsdale System	24	Knock Fell Caverns	5	Giants Hole	5	St Cuthbert's Swallet	7	Ogof Draenen	48	Ogof Llyn Parc	4	(North Wales)
	Gaping Gill System	18	Fairy Hole	4	Bagshaw Cavern	4	Wookey Hole	4	Ogof Agen Allwedd	34	Uamh an Claonaite	3	(Scotland)
	Ireby-Notts System	12	Devis Hole	2	Carlswark Cavern	2	Gough's Cave	2	Ogof Daren Cilau	30	Ogof Llyn Du	2	(North Wales)
Deepest caves[12] (m)	Ease Gill System	211	Goyden Pot	61	Giants Hole	214	Eastwater Cavern	180	Ogof Ffynnon Ddu	308	Ogof Llyn Parc	115	(North Wales)
	Meregill Hole	206	Scrafton Pot	44	Masson Cavern 1	90	Longwood Swallet	175	Ogof Daren Cilau	217	Slaughter Cave	99	(Forest of Dean)
	Pen y ghent Pot	196	Pate Hole	33	Peak-Speedwell System	184	Swildon's Hole	167	Ogof Agen Allwedd	177	Cnoc nan Uamh	90	(Scotland)
	Gaping Gill System	195	Ayleburn Mine Cave	30	Nettle Pot	180	Manor Farm	151	Dan-yr-Ogof	140	Ogof Hesp Alyn	90	(North Wales)

11 Recorded caves longer or deeper than 5 m; figures rounded to nearest 10 caves and 5 km of passage; from unpublished database of Limestone Research Group, University of Huddersfield.

12 Subject to continuous revision, as lengths (and less frequently depths) are increased by newly discovered passages or by links found between known caves.

Selection of GCR sites

The karstlands of Britain contain a great range of surface and underground landforms, many of which are worthy of conservation in order to maintain the integrity of the nation's geological heritage. They include famous landmarks such as Cheddar Gorge and Malham Cove, some of which already receive a measure of protection within the National Parks. They also include remote cave passages, only ever visited by a handful of cave explorers. Their scientific values do not correspond to their fame or their accessibility, but they have been assessed on a national basis for the purpose of the Geological Conservation Review (GCR).

The aim of the GCR has been to compile a list of karstic landforms suitable for designation as Sites of Special Scientific Interest (SSSI). These represent all the important aspects of Britain's karst, and include the sites which have scientific significance for both the present and the future. The criteria for selection have therefore been any one of four factors:

1. The finest example of any particular landform or cave type, such as Cheddar Gorge, the Kingsdale cave system and the pavements of Asby Scar.
2. Unique sites, such as Malham Cove, Langcliffe Pot, the Pant-y-llyn turlough and Beachy Head Cave.
3. Sites important for teaching and research, such as the glaciokarst of Malham and Ingleborough and the Dove Dale fluviokarst.
4. Important assemblages of landforms, such as the Ingleborough karst and some of the more extensive cave systems.

By these criteria in their simplest form, 22 of the sites are included as the best examples of the features listed in (Table 1.2). The values of the sites in the secondary listings of (Table 1.2) are not diminished, as many are the best examples of important subtypes; the dolines of Wurt Pit, Sandpit and High Mark have structures and origins that are totally different from each other and from those of Ingleborough. There are also many local features of the geology which define important contrasts between the karst landforms of the different regions; geological controls are particularly conspicuous in the morphology of caves, and sites are included in the GCR to establish the regional characteristics.

Among the karst landforms, the cave systems and the limestone pavements constitute special cases with regard to their needs of conservation (Glasser and Barber, 1995; Webb, 1995; Bennet *et al.,* 1995).

Beside their values to karst geomorphology, many caves have great importance and value in the stratigraphy of the sediments that they contain. In erosional upland environments, caves constitute unique preservation sites where sediments can accumulate in stable conditions and remain safe from destruction by continued surface denudation. The value of these sediments is enhanced by the climatic sensitivity of solution processes and karst hydrology, and also by the chronological record that is deduced from their radiometric dating. The cave sediments provide a record of events with implications for research into the evolution of landscapes far beyond the confines of the karst. Many of the known cave sediment sequences have not yet been studied in detail, but as a data source for Pleistocene research, caves have unparalleled value. Remnants of sediments can survive in so many obscure corners of cave systems that a large proportion of caves could be considered as scientific resources worthy of conservation. Not every site can be sensibly protected, but this factor has been taken into account in the selection of GCR sites, which therefore include the most important known cave sediment sequences.

Limestone pavements form a special case for conservation because of their sensitivity to rapid and total destruction under the guise of small-scale stone extraction. The solutionally fretted clints forming the surface layer of many pavements have been in demand as a weird form of decorative stone, and many areas of very fine natural rock outcrop have been destroyed in the past. The pavements of the Yorkshire Dales and northern Pennines are of international repute, and are also of very special botanical value (Ward and Evans, 1976). The more important sites are designated as SSSIs, and separate protection measures have been created for many other valuable sites which cannot be included in the GCR (Webb, 1995).

The list of sites in the GCR can never be taken as a complete citation of Britain's karst geomorphology. New discoveries underground, and new research results from above and below ground, continually add to the geomorphological record. Three potential GCR sites have been identified during the documentation phase. The importance of Slaughter Stream Cave and Ogof Draenen were recognized when cavers removed sediment chokes from the entrances, and in each case discovered many kilometres of cave passage that have considerable geomorphological importance. Helbeck Scars is also a potential GCR site, reflecting the improving perception of the values of the limestone pavements in the wilder areas of the Pennines. These three sites are proposed for SSSI status, but have not been designated at the time of writing.

(Table 1.2) The finest examples of individual karst and cave features within the GCR sites of Britain. The listing of features is in the order of their description in Chapter 1. The tabulated data are recognized as being subjective, especially among the important secondary examples, which are not presented in any sequence of merit and are referred to by short versions of their full site titles.

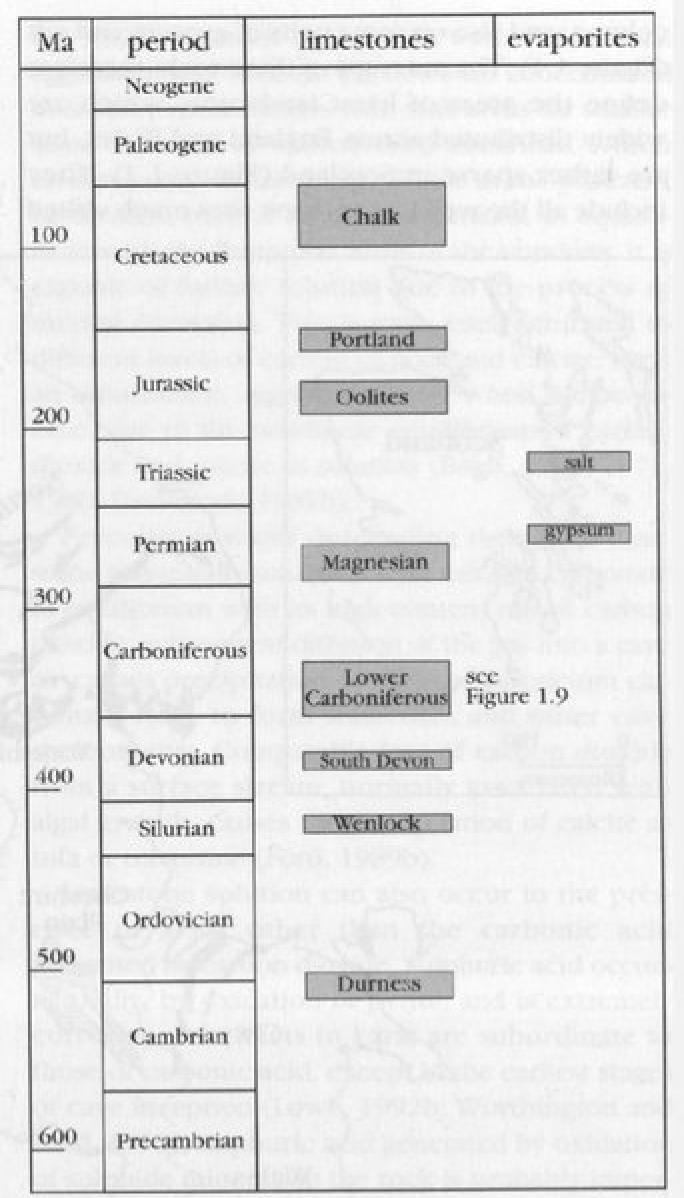
Feature	**Prime example**	**Important examples**
Limestone karst		
Dolines	Ingleborough karst	Wurt Pit, Sandpit, High Mark
Dry valley	Lathkill Dale	Cave Dale, Coniston, Malham & Gordale
Karst gorge	Cheddar Gorge	Malham and Gordale, Hell Gill, Winnats
Collapsed cave	Penyghent Gill	God's Bridge, Porth-yr-Ogof
Limestone pavement	Great Asby Scar	Scales Moor, Ingleborough, Gait Barrows

Glaciokarst	Malham & Gordale	Ingleborough, Traligill
Fluviokarst	Manifold Valley	Lathkill Dale, Dove Dale
Polygonal karst	High Mark	Brimble & Cross
Interstratal karst	Mynydd Llangynidr	Draenen, Nidderdale, Llangattwg
Fossil karst	Green Lane Pits	Masson Hill, Pikedaw
Limestone caves		
Deep phreatic	Wookey Hole	Ease Gill, Cheddar
Shallow phreatic	Kingsdale caves	Ingleborough
Abandoned phreatic	Dan-yr-Ogof	Alyn Gorge, Ingleborough, Castleton, Llangattwg, Minera, Priddy, Sleets Gill
Maze cave	Knock Fell Caverns	Mossdale and Langcliffe, Hale Moss
Vadose canyons	Ease Gill Caves	Ogof Ffynnon Ddu, Castleton
Vadose shafts	Ingleborough caves	Ease Gill, Brants Gill, Buttertubs
Calcite deposits	Otter Hole	St Dunstan's, Boreham, Dan-yr-Ogof
Dated sediments	Charterhouse caves	Cheddar, Traligill, Ease Gill
Chalk karst		
Dolines	Cull-pepper's Dish	Devil's Punchbowl, Castle Lime Quarry
Dry valleys	Millington Pastures	Manger, Devil's Dyke
Cave	Beachy Head Cave	Water End
Salt karst		
Subsidence	Moston Long Flash	Rostherne

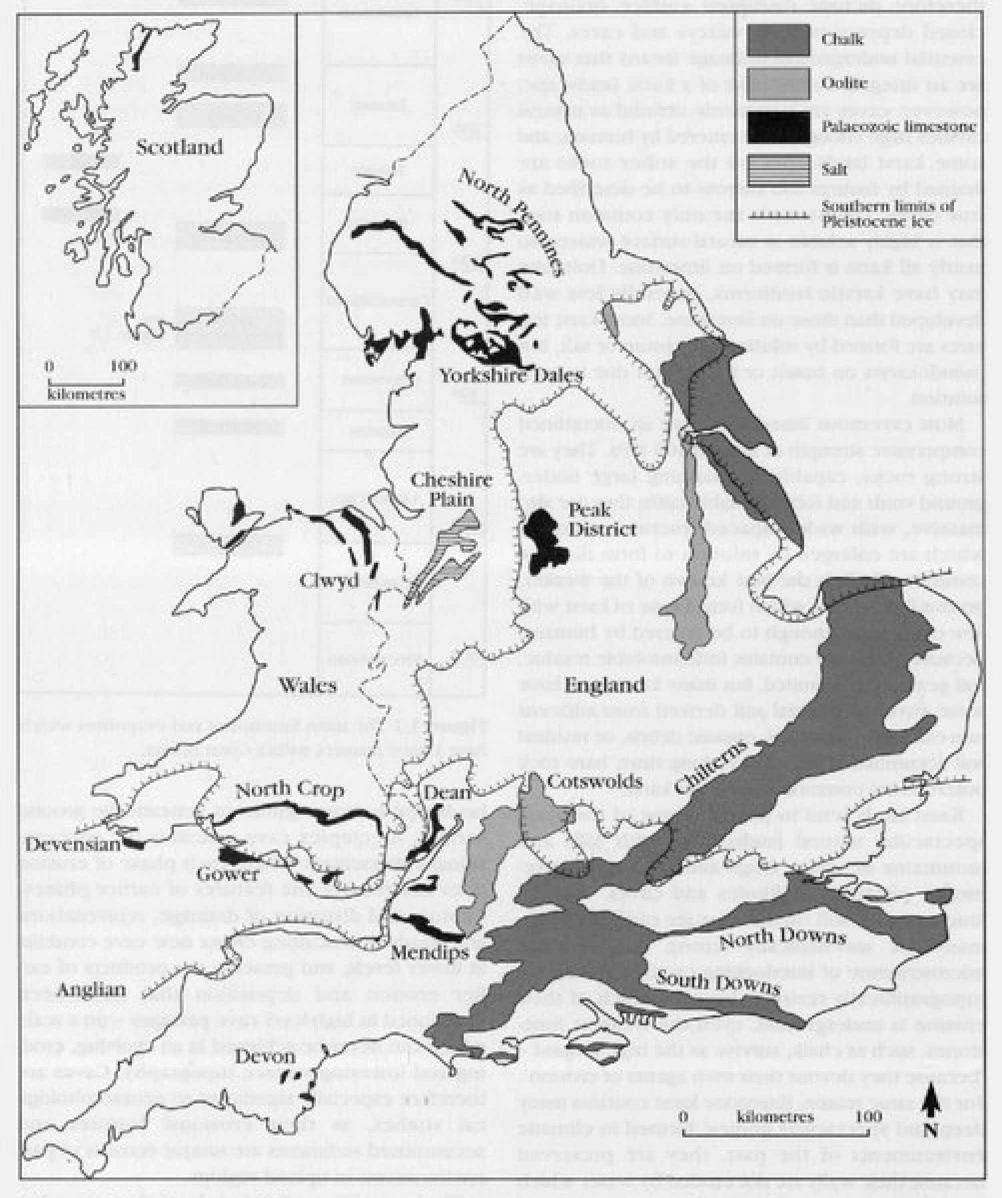
This volume of the GCR embraces the various aspects of karst geomorphology, but there are some notable omissions. Many cave entrances or passages with immediate access from the surface have been used as animal lairs or have become natural pitfall traps. These bone caves have therefore accumulated valuable records of past faunas (Stuart, 1983; Andrews, 1990; Simms, 1994), but their importance is to Pleistocene palaeontology rather than karst geomorphology. Some famous British cave sites, including Victoria Cave, Kirkdale Cave, Creswell Crags, Minchin Hole and Kent's Cavern, are therefore excluded from this volume, but are described in other parts of the GCR. Similarly, the major tufa deposits of Caerwys are of karstic significance, but are included with the Pleistocene sites of Wales. Many small caves are protected because they are important bat roosts, but they are not included in this review of the geomorphologically valuable sites. Britain does have some areas of gypsum karst, worthy of geomorphological study, but the subsiding dolines of the Ripon area are currently of more significance to the construction industry, and are not included in the GCR.

The GCR karst and cave sites are distributed across most of the country (Figure 1.11). The struc. ture adopted in this volume is to document the karst and caves of each main limestone region within their own chapter, covered by Chapters 2 to 6. The lesser karst regions are reviewed, and their more important sites are described in Chapter 7, except for the Scottish karst (reviewed in Chapter 8) and the North Wales karst (included in Chapter 6).

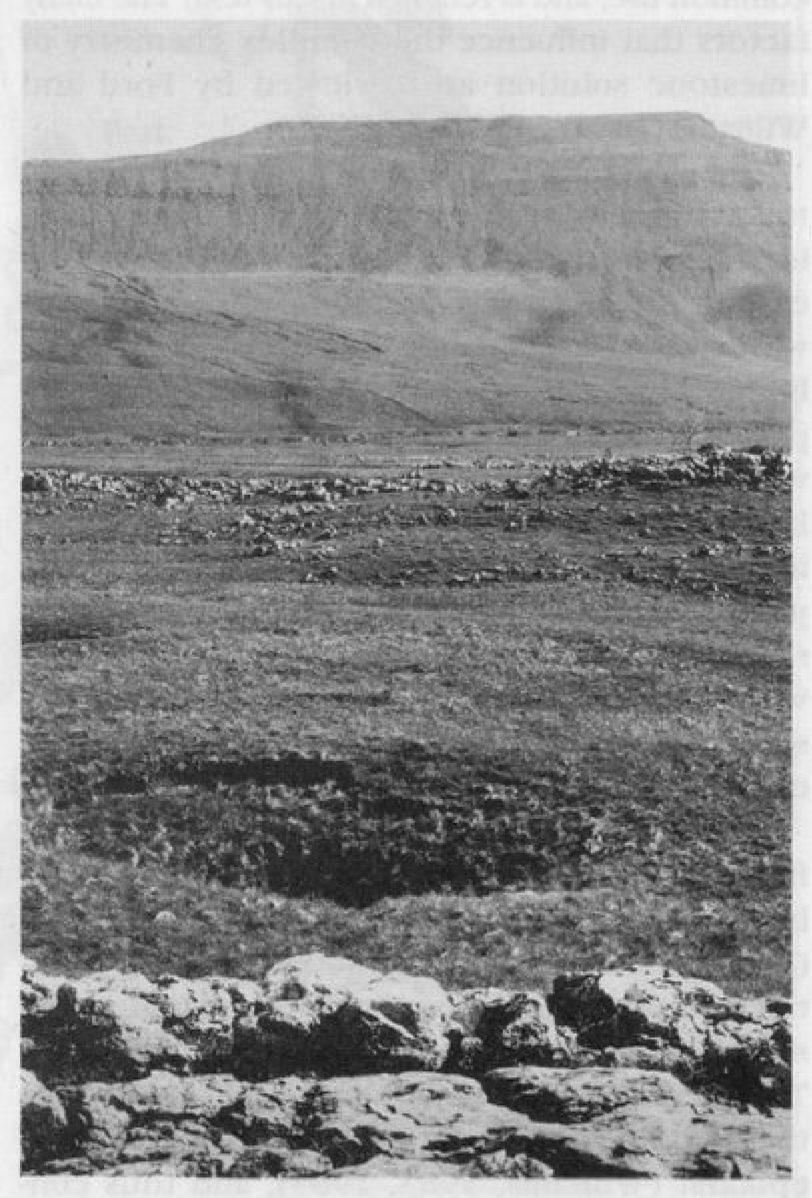
References



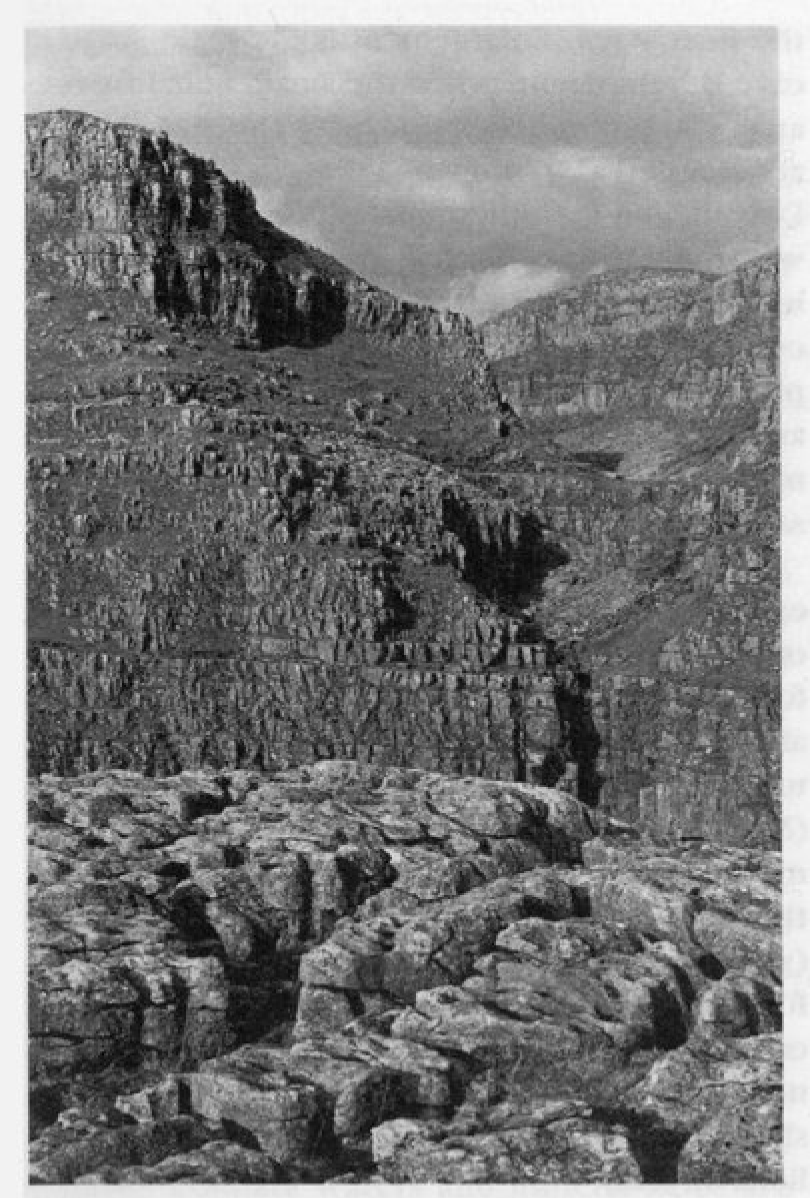
(Figure 1.1) The main limestones and evaporites which have karstic features within Great Britain.



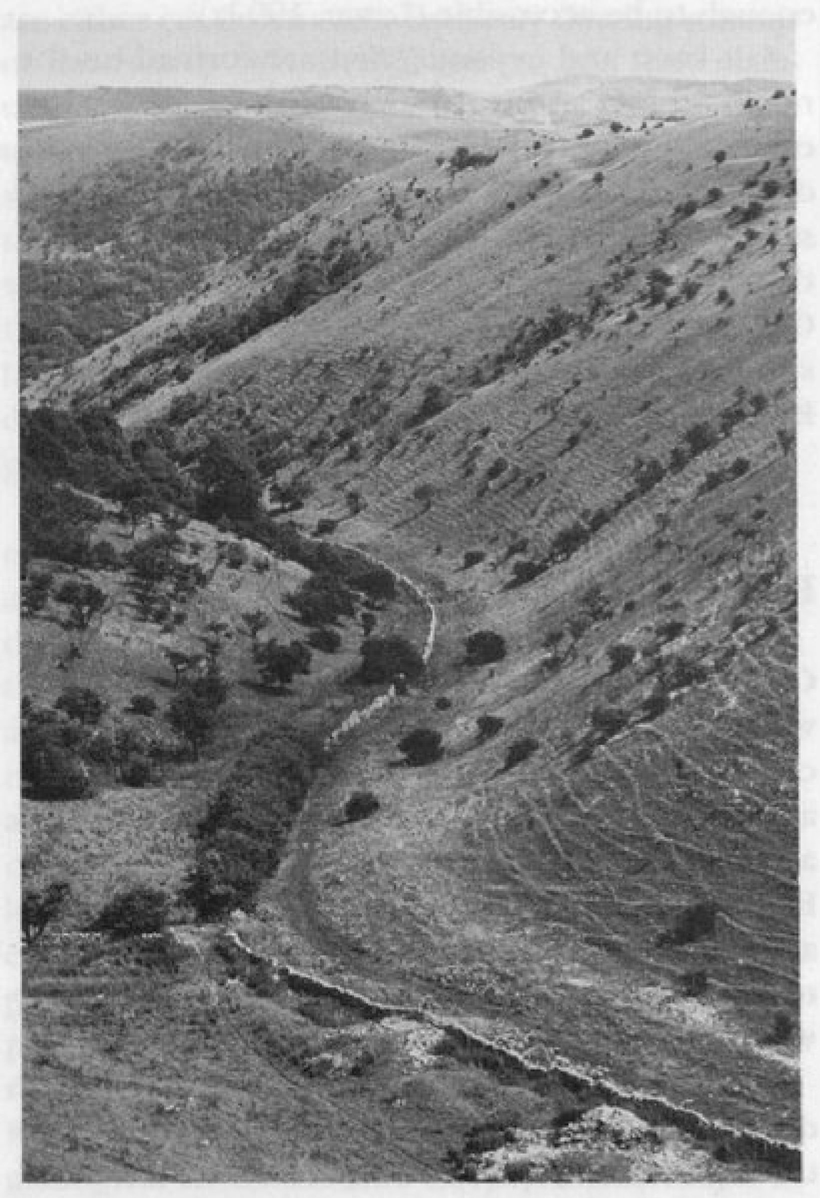
(Figure 1.2) Outline map of the main areas of karst in Great Britain. The Palaeozoic limestones are of Lower Carboniferous age, except for the Devonian limestone in Devon, and the Cambrian–Ordovician limestone in Scotland.



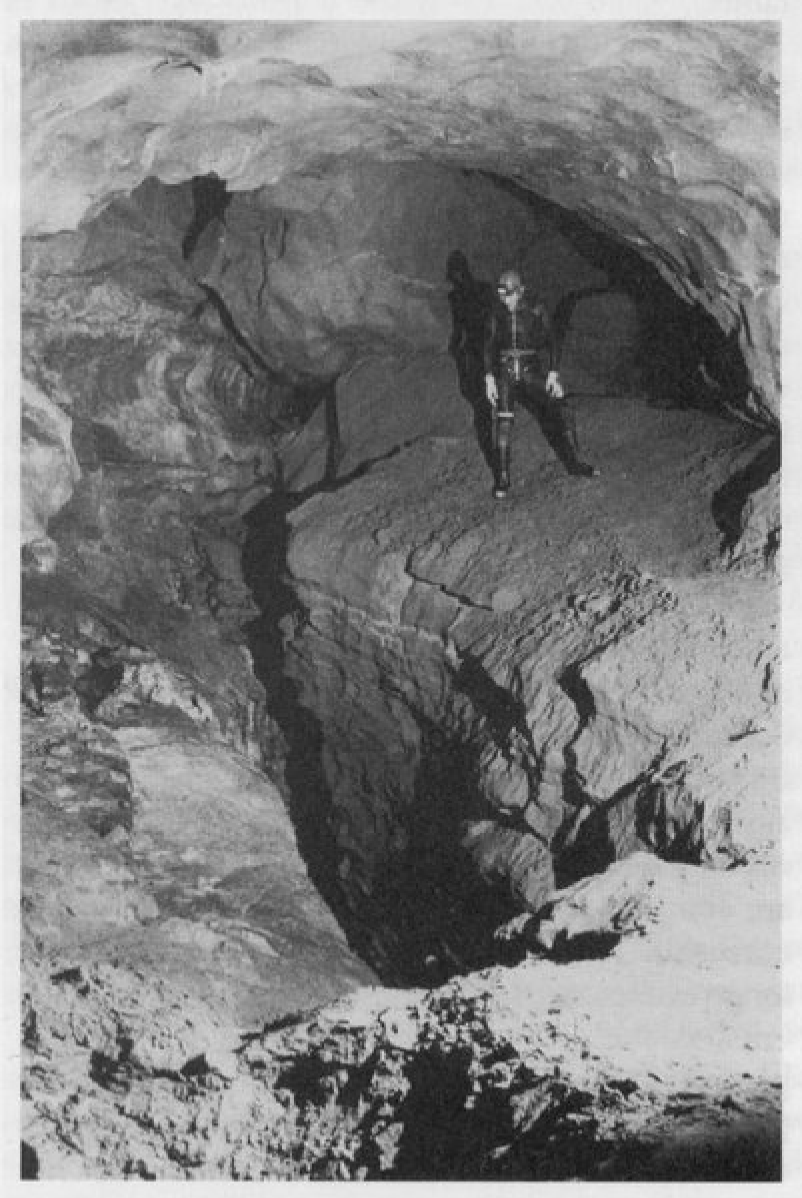
(Figure 1.3) A small subsidence doline, or shakehole, recently formed where the glacial till and soil cover have been washed into a fissure in the underlying limestone; on Ingleborough, in the Yorkshire Dales karst. (Photo: A.C.Waltham.)



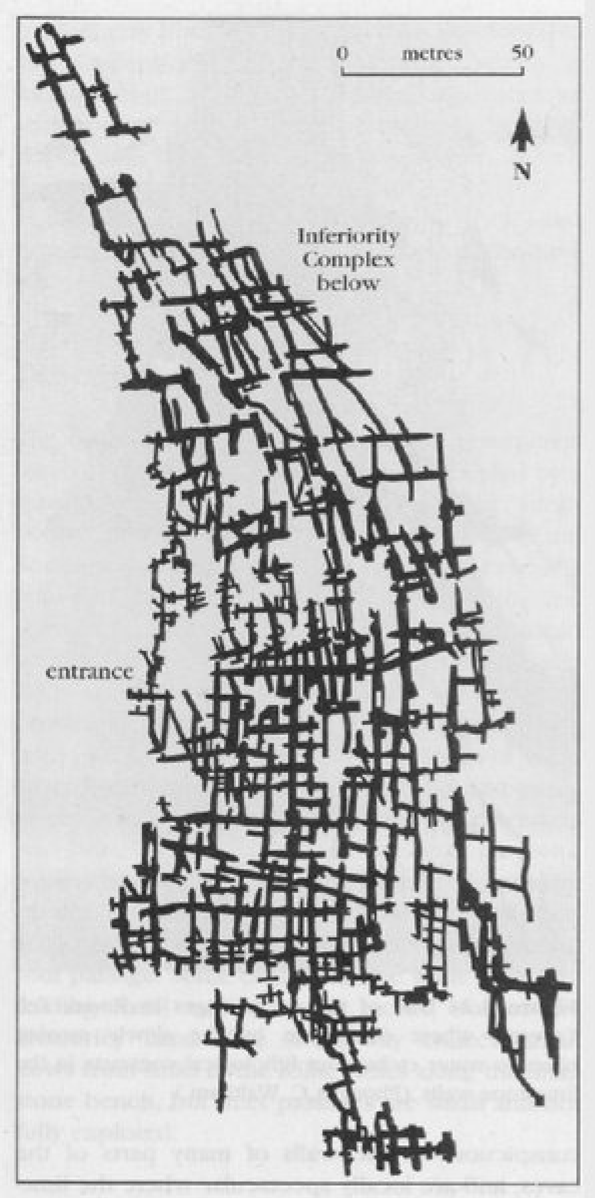
(Figure 1.4) The Yorkshire Dales glaciokarst, with bare cliffs and scars, limestone pavement and a fossil meltwater channel at Comb Scar, above Malham. (Photo: A.C. Waltham.)



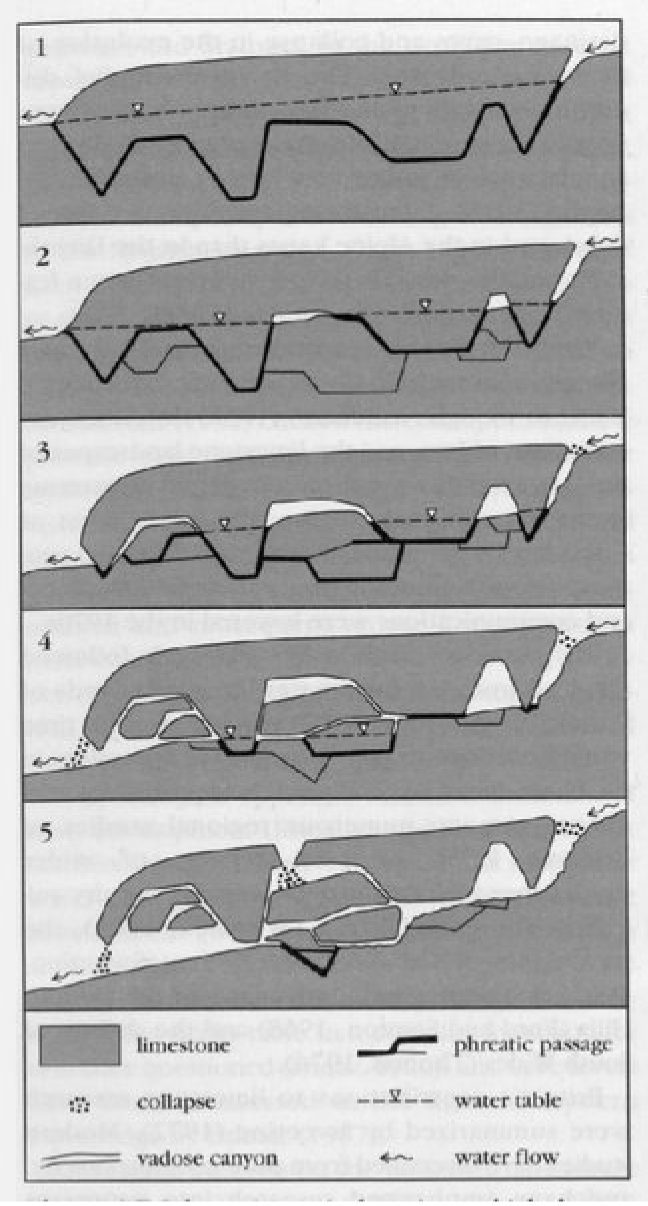
(Figure 1.5) The dry valley of Deep Dale, in the Peak District fluviokarst. (Photo: A.C. Waltham.)



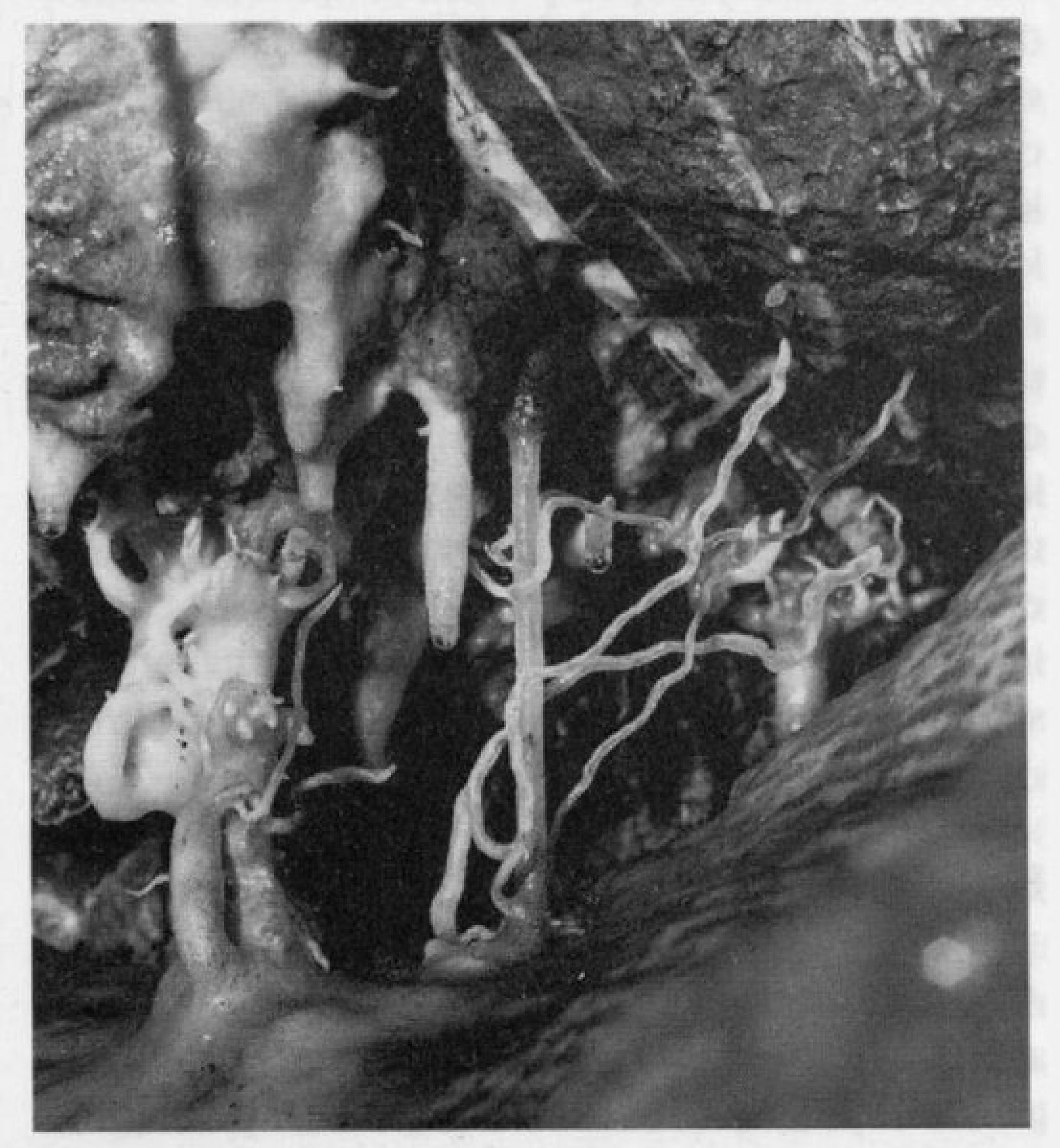
(Figure 1.6) The classic keyhole profile of a cave, where a drained phreatic tube has a vadose canyon cut in its floor; above the Far Streamway of White Scar Cave in the Yorkshire Dales karst. (Photo: A.C. Waltham.)



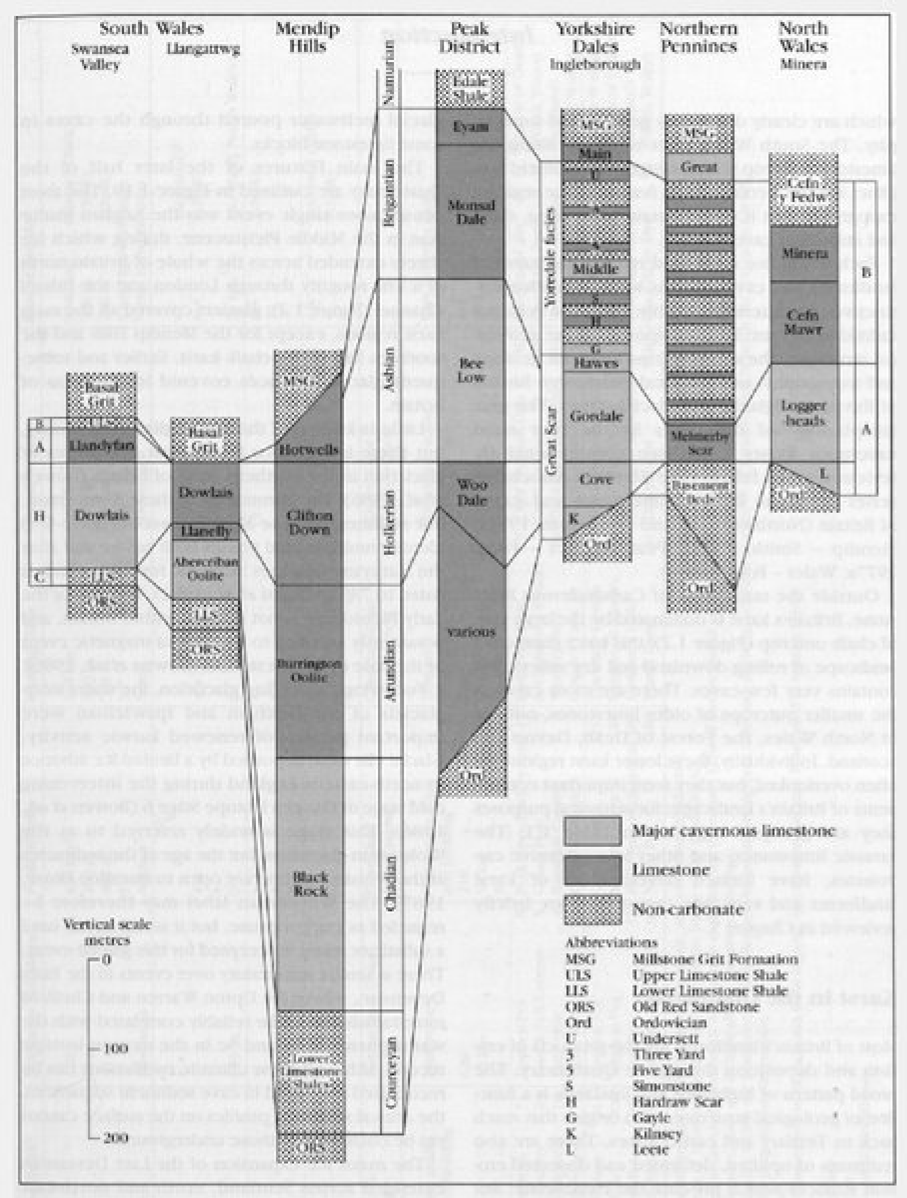
(Figure 3.23) Outline map of Knock Fell Caverns, without the much shorter lower series which are omitted for clarity (from survey by Gritstone Club).



(Figure 1.7) Schematic vertical sections which demonstrate five stages in the evolution of a cave system in response to time and a falling base level. The early stages are mainly of phreatic re-routing and captures; the middle stages are dominated by the entrenchment of vadose canyons through the crests of the phreatic loops; the later stages continue the deepening of the vadose canyons. The model is based on Ogof Ffynnon Ddu, which is developed close to the strike direction in dipping limestones. The principles could apply to many other cave systems if the geometry of the passages was adapted to the local geological structure. (After Smart and Christopher, 1989.)



(Figure 1.8) Secondary deposition of calcite in a cave passage, forming straw stalactites, small stalagmites, a sloping flowstone floor and delicate helictites; in Withyhill Cave in the Mendip Hills karst. (Photo: J.R.Wooldridge.)



(Figure 1.9) The main limestone units of the Lower Carboniferous within the major karst region of Britain. Thicknesses are generalized as there are considerable lateral variations. All the limestones are Dinantian, except for the Namurian Main and Great Limestones of the Pennines. In the Yorkshire Dales karst, the Great Scar Limestone is the massive carbonate facies developed on the Askrigg Block, and the Yoredale facies belongs to the Brigantian Wensleydale Group. In South Wales the Abercriban Oolite Group includes the Blaen Onneu Oolite. The main cover and basement rocks are identified; the Cefn y Fedw Sandstone extends across thp Brigantian/Namurian boundary. All the named limestones are karstified to some extent, but the major cavernous units are distinguished. (Largely after George et al., 1976; Arthurton et al., 1988; Lowe, 1989a.)

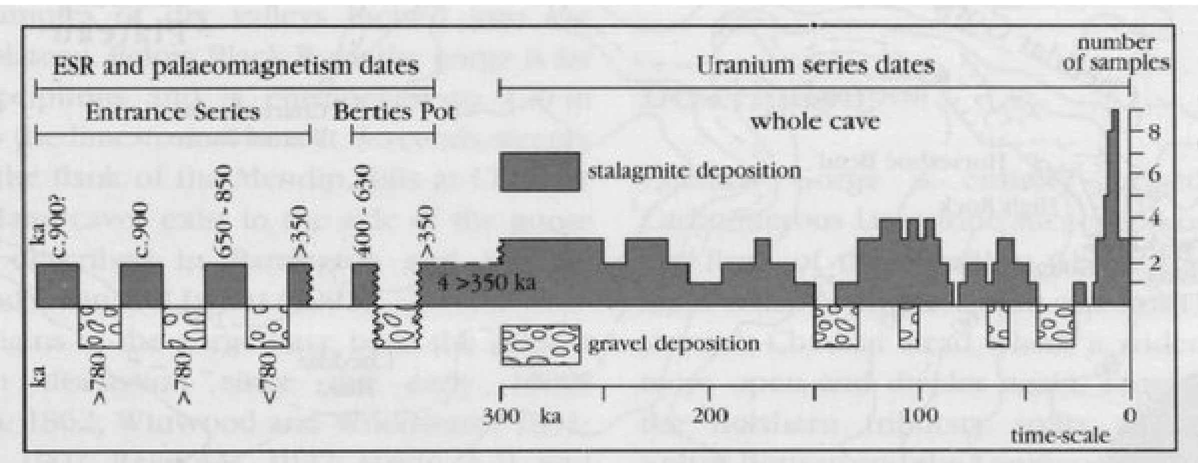
Region	Yorkshire Dales[1]	Northern Pennines[2]	Peak District	Mendip Hills	South Wales	Rest of Britain[3]
Geology						
Karst area[4]	320 km^2	220	420 km^2	110 km^2	220 km^2	9000 km^2 (mostly chalk)
Karst relief[5]	270 m	70 m	260 m	260 m	330 m	200 m (chalk)
Limestone thickness[6]	200 m	40 m	400 m	700 m	150 m	200 m (chalk)
Typical dip	1°	1°	5°	30°	10°	Varies between areas
Last glaciation	Devensian	Devensian	Anglian[7]	None	Devensian	Varies between areas
Karst[8]						
Glaciokarst	• • •	• •				• (Scotland)[9]
Fluviokarst			• •	• •		• • (chalk)
Interstratal karst			•		• •	
Pavement area[10]	677 ha	613 ha	0	0	8 ha	28 ha (Scotland, North Wales)
Dry valleys	•		• •	•	•	• • (chalk)
Karst gorges	• •	•	•	• •		
Collapse features	•		•			
Doline fields	• •				• •	• • (covered chalk)
Ephemeral lakes					•	• (chalk)
Polygonal karst	•			•		
Famous sites	Malham Cove Gaping Gill	Hutton Roof Crags	Dove Dale Peak Cavern	Cheddar Gorge Wookey Hole	Dan-yr-Ogof Porth-yr-Ogof	
Caves						
Major passage types	Vadose joint shafts, phreatic on bedding	Joint mazes	Phreatic on veins and bedding	Downdip phreatic loops	Downdip vadose, strike phreatic	Vary between areas
Number of caves[11]	1420	620	210	220	270	410
Total cave length[11]	325 km	65 km	50 km	55 km	195 km	45 km
Caves over 1 km long	50	9	9	10	12	6
Longest caves[12] (km)	Ease Gill System 71	Goyden Pot 6	Peak-Speedwell System 14	Swildon's Hole 9	Ogof Ffynnon Ddu 50	Slaughter Cave 11 (Forest of Dean)
	Kingsdale System 24	Knock Fell Caverns 5	Giants Hole 5	St Cuthbert's Swallet 7	Ogof Draenen 48	Ogof Llyn Parc 4 (North Wales)
	Gaping Gill System 18	Fairy Hole 4	Bagshaw Cavern 4	Wookey Hole 4	Ogof Agen Allwedd 34	Uamh an Claonaite 3 (Scotland)
	Ireby-Notts System 12	Devis Hole 2	Carlswark Cavern 2	Gough's Cave 2	Ogof Daren Cilau 30	Ogof Llyn Du 2 (North Wales)
Deepest caves[12] (m)	Ease Gill System 211	Goyden Pot 61	Giants Hole 214	Eastwater Cavern 180	Ogof Ffynnon Ddu 308	Ogof Llyn Parc 115 (North Wales)
	Meregill Hole 206	Scrafton Pot 44	Masson Cavern 1 90	Longwood Swallet 175	Ogof Daren Cilau 217	Slaughter Cave 99 (Forest of Dean)
	Pen y ghent Pot 196	Pate Hole 33	Peak-Speedwell System 184	Swildon's Hole 167	Ogof Agen Allwedd 177	Cnoc nan Uamh 90 (Scotland)
	Gaping Gill System 195	Aylebum Mine Cave 30	Nettle Pot 180	Manor Farm 151	Dan-yr-Ogof 140	Ogof Hesp Alyn 90 (North Wales)

1 The main southern Dales area on the Askrigg Block; including Dentdale, and excluding Nidderdale.
2 Including Nidderdale, the karst east of Morecambe Bay, and the eastern fringe of the Lake District.
3 Mostly the weakly cavernous karst of the chalk and oolitic limestones; including the cavernous karst of Devon, Forest of Dean, North Wales and Scotland.
4 Approximate area of karstic landscapes; does not include all the limestone outcrops.
5 Approximate values for the local relief within the limestone, which dictates the maximum descent from sink to rising, added to any depth of karstification beneath the resurgence level.
6 Geological data are generalized for purposes of comparison.
7 Or possibly Wolstonian – see text.
8 Most karst features are found to some extent in all the main karst regions, but their importance is assessed in relative terms:
• = significant, but minor;
• • = important and widespread;
• • • = internationally important.
9 Location of the major features noted in parentheses.
10 From Ward and Evans (1976).
11 Recorded caves longer or deeper than 5 m; figures rounded to nearest 10 caves and 5 km of passage; from unpublished database of Limestone Research Group, University of Huddersfield.
12 Subject to continuous revision, as lengths (and less frequently depths) are increased by newly discovered passages or by links found between known caves.

(Table 1.1) A comparison of the major features which give the individual character to each main karst region of Britain

climate	stage		oxygen isotope stage	ka	period	culture
warm	Flandrian		1	3.8	Holocene	Neolithic
wet				5		
warm				10		Mesolithic
cold	Late Devensian	Loch Lomond	2	11	Late Pleistocene	Palaeolithic
warm		Windermere		13		
cold		Dimlington		24		
warm	Middle Devensian		3	59		
cold	Early Devensian			116		
warm	Ipswichian		5e	128		
cold	'Wolstonian'		6		Middle Pleistocene	
warm	Hoxnian			423		
cold	Anglian		12	478		
warm	Cromerian		13	524		
cold	Beestonian					
warm	Pastonian				? Early Pleistocene	
4 earlier cold phases						

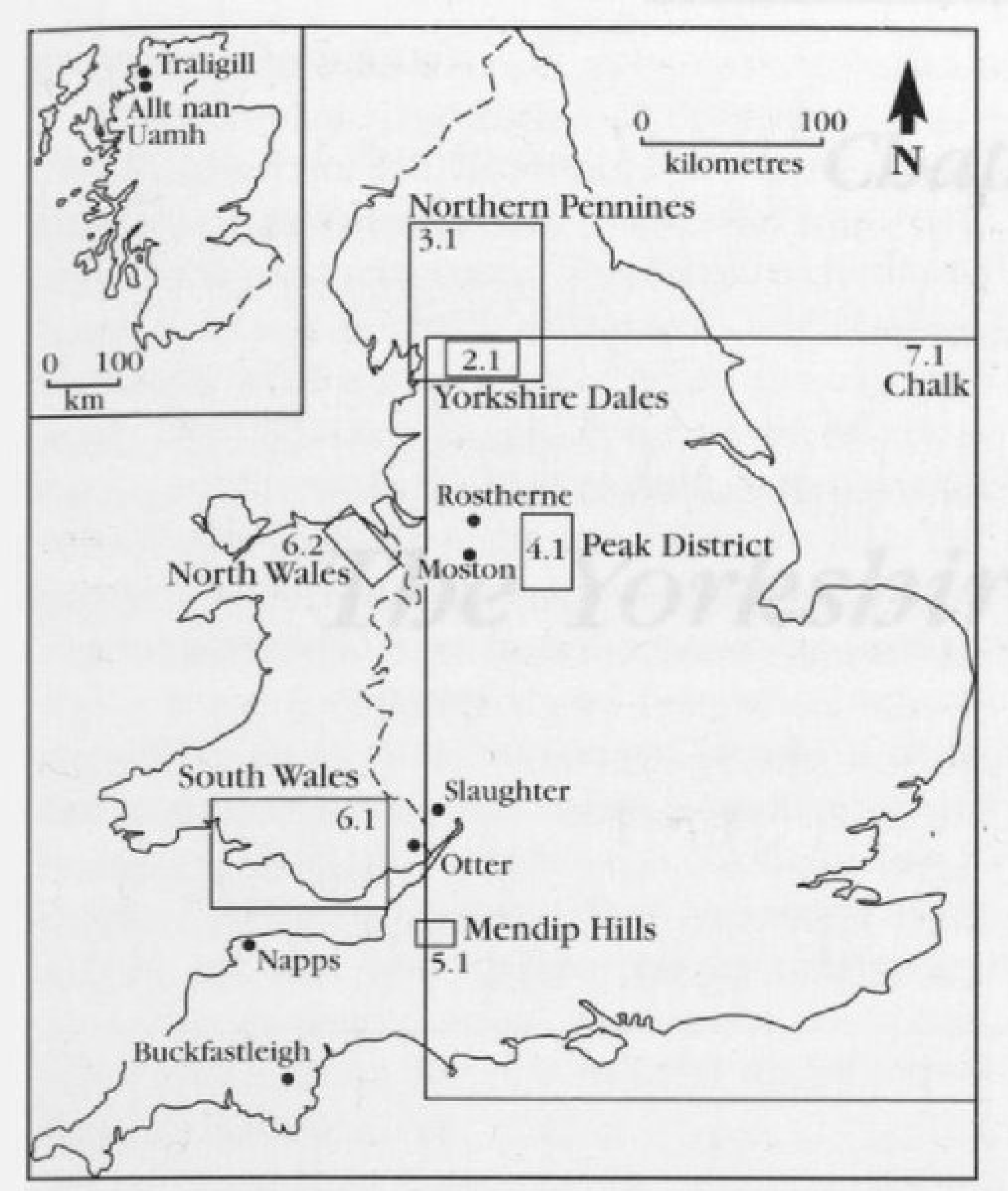
(Figure 1.10) The major glaciations and climatic variations, stages and subdivisions, and cultural phases, of the later parts of the Quaternary. The chronology is based on terrestrial material since about 120 ka, and on correlation with the earlier oxygen isotope stages in the marine sediment record. A more complex pattern of climatic variations is known to exist; both they and other debatable correlations are omitted. The problems of the Early Devensian subdivisions, the 'Wolstonian' glaciation and the Early/Middle Pleistocene boundary are referred to in the text. (After Imbrie et al., 1984; Bowen et al., 1986; Martinson et al., 1987; Campbell & Bowen, 1989; Shackleton et al., 1990.)



(Figure 5.7) Phases of stalagmite and gravel deposition in GB Cave, with a chronology based on stalagmite dates obtained from uranium-series, ESR and palaeomagnetic techniques (after Farrant, 1995). Stalagmite ages are *represented covering the error bars on the dated samples; actual time spans of the deposition phases may be smaller, but data from stalagmites as yet undated may increase the lengths of the deposition phases.*

Feature	Prime example	Important examples
Limestone karst		
Dolines	Ingleborough karst	Wurt Pit, Sandpit, High Mark
Dry valley	Lathkill Dale	Cave Dale, Conistone, Malham & Gordale
Karst gorge	Cheddar Gorge	Malham and Gordale, Hell Gill, Winnats
Collapsed cave	Penyghent Gill	God's Bridge, Porth-yr-Ogof
Limestone pavement	Great Asby Scar	Scales Moor, Ingleborough, Gait Barrows
Glaciokarst	Malham & Gordale	Ingleborough, Traligill
Fluviokarst	Manifold Valley	Lathkill Dale, Dove Dale
Polygonal karst	High Mark	Brimble & Cross
Interstratal karst	Mynydd Llangynidr	Draenen, Nidderdale, Llangattwg
Fossil karst	Green Lane Pits	Masson Hill, Pikedaw
Limestone caves		
Deep phreatic	Wookey Hole	Ease Gill, Cheddar
Shallow phreatic	Kingsdale caves	Ingleborough
Abandoned phreatic	Dan-yr-Ogof	Alyn Gorge, Ingleborough, Castleton, Llangattwg, Minera, Priddy, Sleets Gill
Maze cave	Knock Fell Caverns	Mossdale and Langcliffe, Hale Moss
Vadose canyons	Ease Gill Caves	Ogof Ffynnon Ddu, Castleton
Vadose shafts	Ingleborough caves	Ease Gill, Brants Gill, Buttertubs
Calcite deposits	Otter Hole	St Dunstan's, Boreham, Dan-yr-Ogof
Dated sediments	Charterhouse caves	Cheddar, Traligill, Ease Gill
Chalk karst		
Dolines	Cull-pepper's Dish	Devil's Punchbowl, Castle Lime Quarry
Dry valleys	Millington Pastures	Manger, Devil's Dyke
Cave	Beachy Head Cave	Water End
Salt karst		
Subsidence	Moston Long Flash	Rostherne

(Table 1.2) The finest examples of individual karst and cave features within the GCR sites of Britain. The listing of features is in the order of their description in Chapter 1. The tabulated data are recognized as being subjective, especially among the important secondary examples, which are not presented in any sequence of merit and are referred to by short versions of their full site titles.



(Figure 1.11) Key map showing the coverage of location maps in each chapter, identified by their figure numbers, and also the location of sites which are documented in the text but fall outside the chapter location maps.