8

KARST LANDSCAPES

Acid attacking rocks that dissolve easily, and some rocks that do not dissolve so easily, creates very distinctive and imposing landforms at the ground surface and underground. This chapter covers:

- the nature of soluble-rock terrain
- the dissolution of limestone
- landforms formed on limestone
- landforms formed within limestone
- humans and karst

Underground karst: Poole's Cavern, Derbyshire

Poole's Cavern is a limestone cave lying under Grin Wood, almost 2 km from the centre of Buxton, a spa town in Derbyshire, England (Figure 8.1). The waters of the River Wye formed it. In about 1440, the highwayman and outlaw Poole reputedly used the cave as a lair and a base from which to waylay and rob travellers. He gave his name to the cave. Inside the cave entrance, which was cleared and levelled in 1854, is glacial sediment containing the bones of sheep, goats, deer, boars, oxen, and humans. Artefacts from the Neolithic, Bronze Age, Iron Age, and Roman periods are all present. Further into the cave is the 'Dome', a 12-m-high chamber that was probably hollowed out by meltwater coursing through the cavern at the end of the last ice age and forming a great whirlpool. Flowstone is seen on the chamber walls, stained blue-grey by manganese oxide or shale. A little further in lies the River Wye, which now flows only in winter as the river enters the cave from a reservoir overflow. The river sinks into the stream bed and reappears about 400 m away at Wye Head, although thousands of years ago it would have flowed out through the cave entrance. The river bed contains the 'Petrifying Well', a pool that will encrust such articles as bird's nests

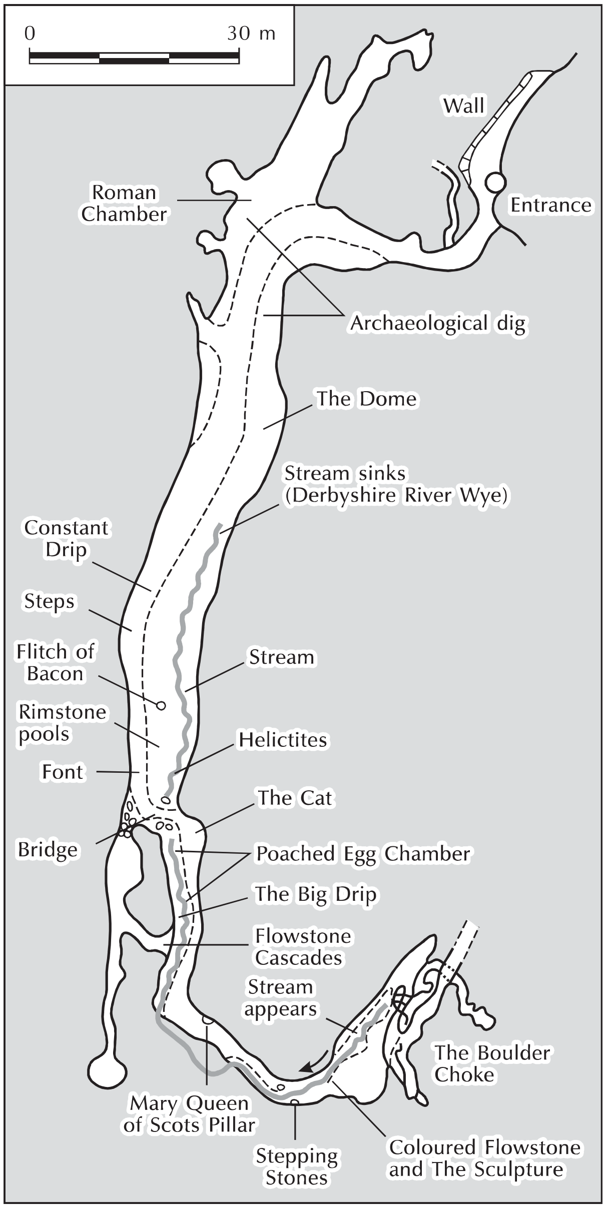


Figure 8.1 Plan of Poole's Cavern, Buxton.
Source: After Allsop (1992)

placed in it with calcite and 'turn them to stone'. The 'Constant Drip' is a stalagmite that has grown over thousands of years, but, perhaps owing to an increased drip rate over recent years, it now has a hole drilled in it. Nearby is a new white flowstone formation that is made by water passing through old lime-tips on the hillside above. Further along hangs the largest stalactite in the cave – the 'Flitch of Bacon', so called owing to its resemblance to a half-side of that meat. It is almost 2 m long, but was longer before some vandalous visitor broke off the bottom section around 1840. Nearby, on the cave floor, are rimstone pools. The next chamber is the 'Poached Egg Chamber', which contains stalactites, straws, flowstones, columns, and curtains, all coloured in white, orange (from iron oxide), and blue-grey (from manganese oxide). These formations are created from lime waste from an old quarry tip above the cave. The iron has coated the tips of stalagmites to give them the appearance of poached eggs. At the far end of the Poached Egg Chamber are thousands of straws and stalactites, with a cascade of new flowstone on top of an old one known as the 'Frozen Waterfall'. Above this formation is the 'Big Drip', a 0.45-m-high stalagmite that is very active, splashing drips around its sides, so making itself thicker. At this point, bedding planes in the limestone show signs of cavern collapse. Turning to the left, the 'Mary Queen of Scots Pillar', a 2-m-high stalactite boss, presents itself. This feature is said to have been named by Mary Queen of Scots when she visited the cavern in 1582. In the last chamber, the River Wye can be seen emerging from the 15-m-high boulder choke that blocks the rest of the cavern system. A beautiful flowstone structure in this chamber was named the 'Sculpture' by a party of local schoolchildren in 1977, and above it is the 'Grand Cascade', another impressive flowstone formation stained with oxides of iron and manganese.

KARST ENVIRONMENTS

What is karst?

Karst is the German form of the Indo-European word *kar*, which means rock. The Italian term is *carso*, and the Slovenian *kras*. In Slovenia, *kras* or *krš* means 'bare stony ground' and is also a rugged region in the west of the country. In geomorphology, **karst** is terrain in which soluble rocks are altered above and below ground by the dissolving action of water and that bears distinctive characteristics of relief and drainage (Jennings 1971, 1). It usually refers to limestone terrain characteristically lacking surface drainage, possessing a patchy and thin soil cover, containing many enclosed depressions, and supporting a network of subterranean features, including caves and grottoes. However, all rocks are soluble to some extent in water, and karst is not confined to the most soluble rock types. Karst may form in evaporites such as gypsum and halite, in silicates such as sandstone and quartzite, and in some basalts and granites under favourable conditions (Table 8.1). Karst features may also form by other means – weathering, hydraulic action, tectonic movements, meltwater, and the evacuation of molten rock (lava). These features are called **pseudokarst** as solution is not the dominant process in their development (Table 8.1).

Extensive areas of karst evolve in carbonate rocks (limestones and dolomites), and sometimes in evaporites, which include halite (rock salt), anhydrite, and gypsum. Figure 8.2 shows the global distribution of exposed carbonate rocks. Limestones and dolomites are a complex and diverse group of rocks (Figure 8.3). **Limestone** is a rock containing at least 50 per cent calcium carbonate ($CaCO_3$), which occurs largely as the mineral calcite and rarely as aragonite. Pure limestones contain at least 90 per cent calcite. **Dolomite** is a rock containing at least 50 per cent calcium–magnesium carbonate ($CaMg(CO_3)_2$), a mineral called dolomite. Pure dolomites (also called **dolostones**) contain at least 90 per cent dolomite. Carbonate rocks of intermediate composition between pure limestones and pure dolomites are given various names, including magnesian limestone, dolomitic limestone, and calcareous dolomite.

Karst features achieve their fullest evolution in beds of fairly pure limestone, with more than 80 per cent calcium carbonate, that are very thick, mechanically strong, and contain massive joints. These conditions are fulfilled in the classic karst area of countries bordering the eastern side of the Adriatic Sea. Chalk, although being a very pure limestone, is mechanically weak and does not favour the formation of underground drainage, which is a precondition for the evolution of medium-scale and large-scale surface-karst landforms.

KARST AND PSEUDOKARST PROCESSES

Few geomorphic processes are confined to karst landscapes, but in areas underlain by soluble rocks some processes operate in unique ways and produce characteristic features. Solution is often the dominant process

Table 8.1 Karst and pseudokarst

Formed in	*Formative processes*	*Examples*
Karst		
Limestone, dolomite, and other carbonate rocks	Bicarbonate solution	Poole's Cavern, Buxton, England; Mammoth Cave, USA
Evaporites (gypsum, halite, anhydrite)	Dissolution	Mearat Malham, Mt Sedom, Israel
Silicate rocks (e.g. sandstone, quartzites, basalt, granite, laterite)	Silicate solution	Kukenan Tepui, Venezuela; Phu Hin Rong Kla National Park, Thailand; Mawenge Mwena, Zimbabwe
Pseudokarst		
Basalts	Evacuation of molten rock	Kazumura Cave, Hawaii
Ice	Evacuation of meltwater	Glacier caves, e.g. Paradise Ice Caves, USA
Soil, especially duplex profiles	Dissolution and granular disintegration	Soil pipes, e.g. Yulirenji Cave, Arnhemland, Australia
Most rocks, especially bedded and foliated ones	Hydraulic plucking, some exsudation (weathering by expansion on gypsum and halite crystallization)	Sea caves, e.g. Fingal's Cave, Isle of Staffa, Scotland
Most rocks	Tectonic movements	Fault fissures, e.g. Dan y Ogof, Wales; Onesquethaw Cave, USA
Sandstones	Granular disintegration and wind transport	Rock shelters, e.g. Ubiri Rock, Kakadu, Australia
Many rocks, especially with granular lithologies	Granular disintegration aided by seepage moisture	Tafoni, rock shelters, and boulder caves, e.g. Greenhorn Caves, USA

Source: Partly after Gillieson (1996, 2)

in karst landscapes, but it may be subordinate to other geomorphic processes. Various terms are added to karst to signify the chief formative processes in particular areas. **True karst** denotes karst in which solutional processes dominate. The term holokarst is sometimes used to signify areas, such as parts of southern China and Indonesia, where karst processes create almost all landforms. **Fluviokarst** is karst in which solution and stream action operate together on at least equal terms, and is common in Western and Central Europe and in the mid-western United States, where the dissection of limestone blocks by rivers favours the formation of caves and true karst in interfluves. **Glaciokarst** is karst in which glacial and karst processes work in tandem, and is common in ice-scoured surfaces in Canada, and in the calcareous High Alps and Pyrenees of Europe. Finally, **thermokarst** is irregular terrain produced by the thawing of ground ice in periglacial environments and is not strictly karst or pseudokarst at all, but its topography is superficially similar to karst topography (see p. 284).

Karst drainage systems are a key to understanding many karst features (Figure 8.4). From a hydrological standpoint, karst is divided into the surface and near-surface zones, or epikarst, and the subsurface zones, or endokarst. **Epikarst** comprises the surface and soil (cutaneous zone), and the regolith and enlarged fissures (subcutaneous zone). **Endokarst** is similarly divided into two parts: the vadose zone of unsaturated water flow and the phreatic zone of saturated water flow. In the upper portion of the vadose zone, threads of water in the subcutaneous zone combine to form percolation streams, and this region is often called the percolation zone.

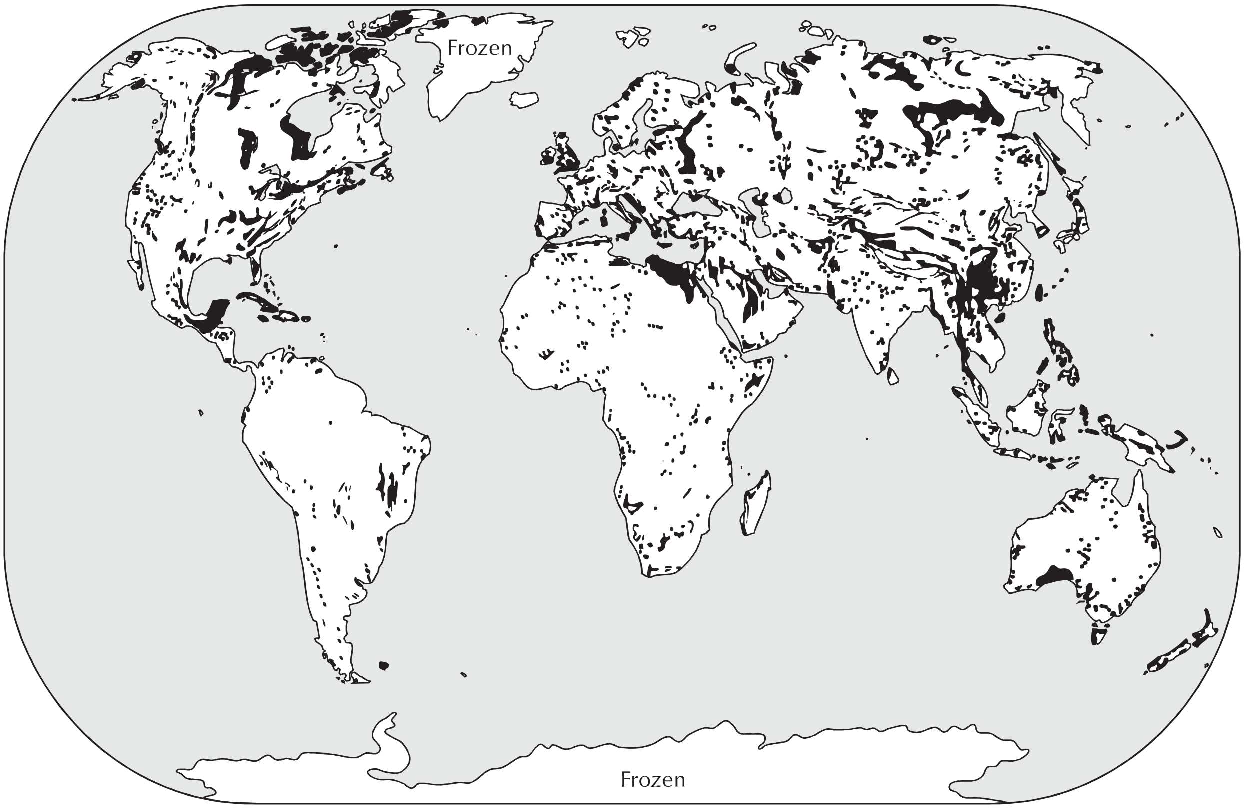


Figure 8.2 World distribution of carbonate rocks.
Source: Adapted from Ford and Williams (1989, 4)

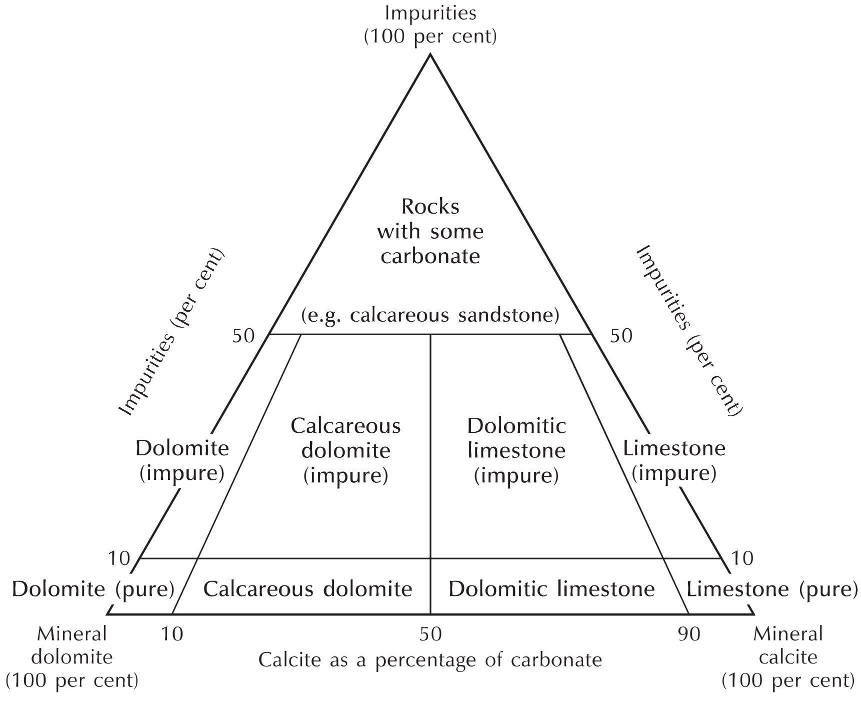


Figure 8.3 Classification of carbonate rocks.
Source: Adapted from Leighton and Pendexter (1962)

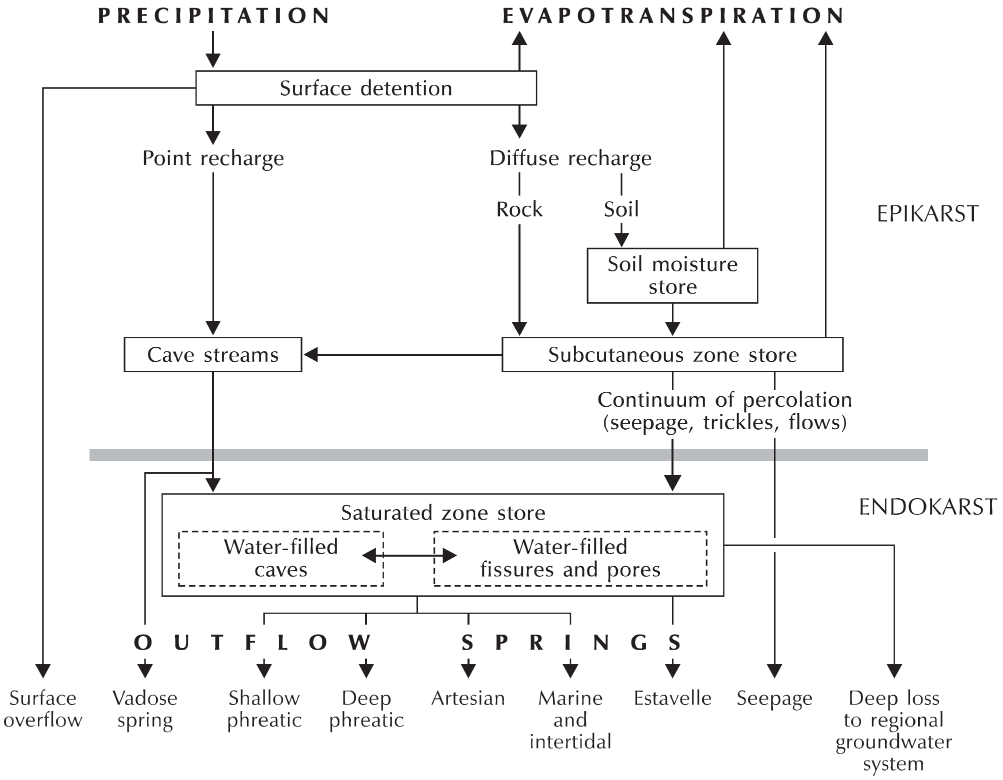


Figure 8.4 The karst drainage system: storages and flows.
Source: Adapted from Ford and Williams (1989, 169)

Each zone has particular hydraulic, chemical, and hydrological properties, but the zones expand and contract with time and cannot be rigidly circumscribed.

The chief geomorphic processes characteristic of karst landscapes are solution and precipitation, subsidence, and collapse. Fluvial processes may be significant in the formation of some surface and subterranean landforms. Hydrothermal processes are locally important in caves. A distinction is often drawn between **tropical karst** and karst in other areas. The process of karstification is intense under tropical climates and produces such features as towers and cones (p. 201), which are not produced, at least not to the same degree, under temperate and cold climates. Discoveries in northwest Canada have shown that towers may form under cold climates (pp. 201–2), but the widespread distribution of tropical karst testifies to the extremity of limestone solution under humid tropical climatic regimes.

SOLUTION AND PRECIPITATION

Limestone, dolomite, and evaporites

As limestone is the most widespread karst rock, its solution and deposition are important karst processes. With a saturation concentration of about 13 mg/l at 16°C and about 15 mg/l at 25°C, calcite has a modest solubility in pure water. However, it is far more soluble in waters charged with carbonic acid. It also appears to be more soluble in waters holding organic acids released by rotting vegetation, and is very soluble in waters containing sulphuric acid produced by the weathering of sulphide minerals such as pyrite and marcasite. Carbonic acid is the main solvent in karst landscapes, limestones readily succumbing to carbonation (p. 56). Dolomite rock behaves similarly to limestones in natural waters, although it appears to be slightly less soluble than limestone under normal conditions. Complexities are added by the presence of magnesium in dolomites. Evaporites, including gypsum, are much more soluble than limestone or dolomite but carbon dioxide is not involved in their solution. Gypsum becomes increasingly soluble up to a maximum of 37°C. It is deposited as warm water cools sufficiently and when evaporation leads to supersaturation.

Silicate rocks

Active sinkholes, dolines, and cave systems in quartzite must be produced by the excavation and underground transport of rock. As quartzite has a very low solubility, it is difficult to see how such processes could proceed. One possibility is that, rather than dissolving the entire rock, it is necessary only to dissolve the cementing material around individual quartz grains. Quartz grains have a solubility of less than 10 mg/l, while amorphous silica, which is the chief cement, has a solubility of 150 mg/l. With the cement dissolved, the quartzite would become mechanically incoherent, and loose grains could be removed by piping, so eroding underground passages. Alternatively, corrosion of the quartzite itself might produce the underground karst features. Corrosion of quartz is a slow process but, given sufficient time, this process could open underground passages. To be sure, some karst-like forms excavated in quartzites of the Cueva Kukenan, a Venezuelan cave system, consist of rounded columns some 2–3 m high. If these had been formed by cement removal, they should have a tapered cross-section aligned in the direction of flow. All the columns are circular, suggesting that corrosion has attacked the rock equally on all sides (see Doerr 1999). Also, thin sections of rocks from the cave system show that the individual grains are strongly interlocked by silicate overgrowths and, were any silica cement to be removed, they would still resist disintegration. Only after the crystalline grains themselves were partly dissolved could disintegration proceed.

Slow mass movements and collapse

It is expedient to distinguish between collapse, which is the sudden mass movement of the karst bedrock, and the slow mass movement of soil and weathered mantles (Jennings 1971, 32). The distinction would be artificial in most rocks, but in karst rocks solution ordinarily assures a clear division between the bedrock and the regolith.

Slow mass movements

Soil and regolith on calcareous rocks tend to be drier than they would be on impervious rocks. This fact means that lubricated mass movements (rotational slumps, debris slides, debris avalanches, and debris flows) are less active in karst landscapes. In addition, there is little insoluble material in karst rocks, and soils tend to be shallow, which reduces mass movement. Calcium carbonate deposition may also bond soil particles, further limiting the possibility of mass movement. Conversely, the widespread action of solution in karst landscapes removes support in all types of unconsolidated material, so encouraging creep, block slumps, debris slides, and especially soilfall and earthflow. As a rider, it should be noted that piping occurs in karst soil and regolith, and indeed may be stimulated by solutional processes beneath soils and regolith covers. Piping or tunnelling is caused by percolating waters transporting clay and silt internally to leave underground conduits that may promote mass movements.

Collapse

Rockfalls, block slides, and rock slides are very common in karst landscapes. This is because there are many bare rock slopes and cliffs, and because solution acts as effectively sideways as downwards, leading to the undercutting of stream banks.

Fluvial and hydrothermal processes

Solution is the chief player in cave formation, but corrasion by floodwaters and hydrothermal action can have significant roles. **Maze caves**, for instance, often form where horizontal, well-bedded limestones are invaded by floodwaters to produce a complicated series of criss-crossing passages. They may also form by hydrothermal action, either when waters rich in carbon dioxide or when waters loaded with corrosive sulphuric acid derived from pyrites invade well-jointed limestone.

SURFACE KARST FORMS

Early studies of karst landscapes centred on Vienna, with work carried out on the Dinaric karst, a mountain system running some 640 km along the eastern Adriatic Sea from the Isonzo River in north-eastern Italy, through Slovenia, Croatia, Bosnia and Herzegovina, Montenegro and Serbia, to the Drin River, northern Albania. The Dinaric karst is still regarded as the 'type' area, and the Serbo-Croat names applied to karst features in this region have stuck, although most have English equivalents. However, the reader should be made aware that karst terms are very troublesome and the subject of much confusion. It may also be helpful to be mindful of a contrast often made between **bare karst**, in which bedrock is largely exposed to the atmosphere, and **covered karst**, in which bedrock is hardly exposed to the atmosphere at all. All degrees of cover, from total to none, are possible. Another basic distinction is drawn between **free karst**, which drains unimpeded to the sea, and **impounded karst**, which is surrounded by impervious rocks and has to drain through different hydrogeological systems to reach the sea.

Figure 8.5 illustrates diagrammatically some of the main karst landforms that are discussed in the following sections.

Karren

Karren is an umbrella term, which comes from Germany, to cover an elaborately diverse group of small-scale solutional features and sculpturing found on limestone and dolomite surfaces exposed at the ground surface or in caves. The French word *lapiés* and the Spanish word *lapiaz* mean the same thing. Widespread, exposed tracts of karren on pavements and other extensive surfaces of calcareous rocks are termed ***Karrenfeld*** (**karren fields**). The terminology dealing with types of karren is bafflingly elaborate.

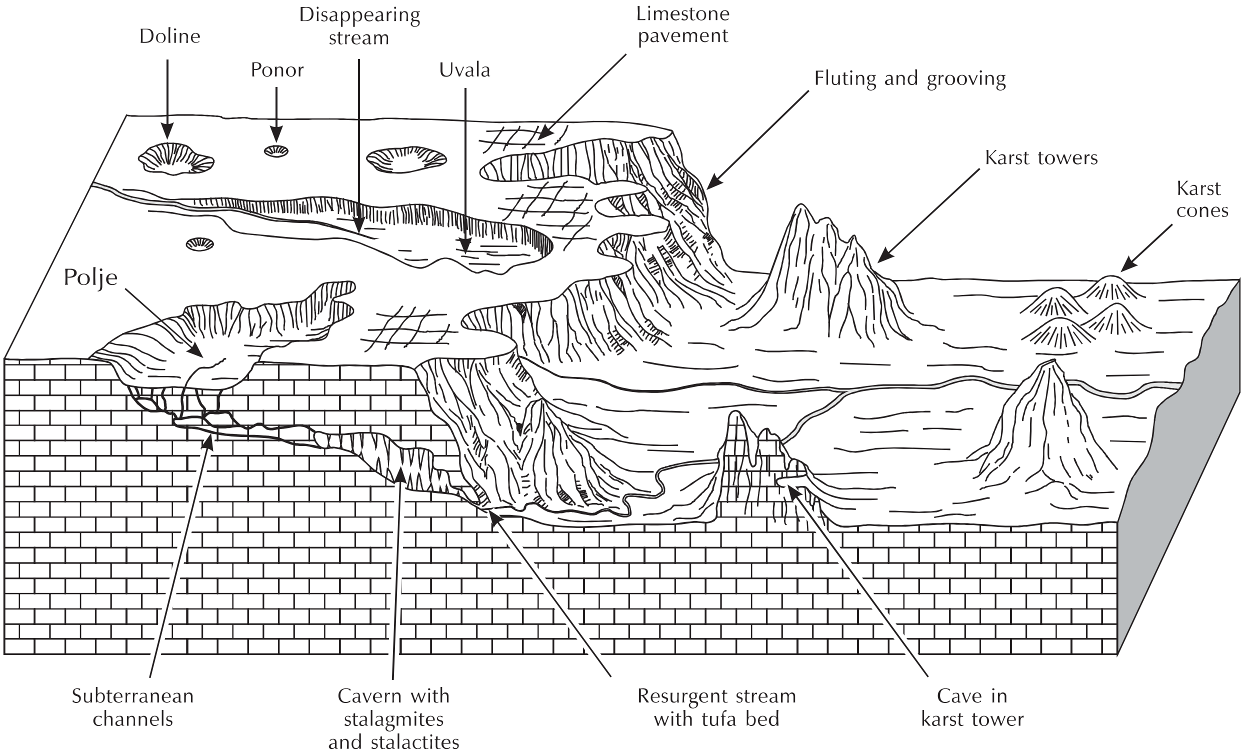


Figure 8.5 Schematic diagram of some karst features.

The nomenclature devised by Joe Jennings (1971, 1985) brings some sense of order to a multilingual lexicon of confused and inconsistent usage. The basic forms are divided according to the degree of cover by soil and vegetation – bare ('free karren'), partly covered ('half-free karren'), and covered ('covered karren') (Bögli 1960). The bare forms are divided into those produced by surface wetting and those produced by concentrated surface runoff. Derek Ford and Paul Williams (1989, 376–7) offered a purely morphological classification of karren types because current understanding of karren-forming processes is too immature to build useful genetic classifications. However, their scheme, although using morphology as the basis for the major divisions, uses genetic factors for subdivisions. Jennings's classification underpins the following discussion, but a few types mentioned by Ford and Williams, and their 'polygenetic' class, are included (Table 8.2).

Bare forms

Bare forms produced by surface wetting comprise **pits**, **ripples**, **flutes**, **bevels**, and **runnels**, all of which are etched into bare limestone by rain hitting and flowing over the naked rock surface or dripping or seeping on to it. They are small landforms, the smallest, **micropits** and **microrills**, being at most 1 cm wide and deep, and the largest, **solution flutes** (***Rillenkarren***), averaging about 1.0–2.5 m wide and 15 m long. The smallest features are called **microkarren**. Solutional features of a few micrometers can be discerned under an electron microscope. Exposed karst rocks may develop relief

Table 8.2 Small limestone landforms produced by solution

Form	*Comment*
Bare limestone forms (surface wetting)	
Micropits and etched surfaces	Small pits produced by rain falling on gently sloping or flat bare rocks
Microrills	Rills no deeper or wider than about 1.0 mm and not longer than a few centimetres. Called *Rillenstein* when formed on stones and blocks
Solution ripples or fluted scallops	Shallow, ripple-like flutes formed on steep to vertical surfaces by flowing water normal to the direction of water flow. Prominent as a component of cockling patterns (a mixture of scallops, fluted scallops, or ripples) on steep and bare slopes
Solution flutes (*Rillenkarren*)	Longitudinal hollows that start at the slope crest and run down the maximum slope of fairly steep to vertical rock surfaces. They are of uniform fingertip width and depth, with sharp ribs between neighbouring flutes. May occur with rippling to give the rock a netted appearance
Solution bevels (*Ausgleichsflächen*)	Very smooth, flat or nearly so, forming tiny treads backed by steeper, fluted rises. A rare variant is the solution funnel step or heelprint (*Trittkarren* or *Trichterkarren*)
Solution runnels (*Rinnenkarren*)	Solution hollows, which result from Hortonian overland flow, running down the maximum slope of the rock, larger than solution flutes and increasing in depth and width down their length owing to increased water flow. Thick ribs between neighbouring runnels may be sharp and carry solution flutes
Decantation runnels	Forms related to solution runnels and including meandering runnels (*Mäanderkarren*) and wall solution runnels (*Wandkarren*). Produced by the dripping of acidulated water from an upslope point source. Channels reduce in size downslope
Decantation flutings	Packed channels, which often reduce in width downslope, produced by acidulated water released from a diffuse upslope source

Continued

Table 8.2—Cont'd

Form	*Comment*
Bare limestone forms (concentrated surface runoff)	
Microfissures	Small fissures, up to several centimetres long but no more than 1 cm deep, that follow small joints
Splitkarren	Solution fissures, centimetres to a few metres long and centimetres deep, that follow joints, stylolites, or veins. Taper with depth unless occupied by channel flow. May be transitional to pits, karren shafts, or grikes
Grikes (*Kluftkarren*)	Major solution fissures following joints or fault lines. The largest forms include *bogaz*, corridors, and streets
Clints (*Flackkarren*)	Tabular blocks between grikes
Solution spikes (*Spitzkarren*)	Sharp projections between grikes
Partly covered forms	
Solution pits	Round-bottomed or tapered forms. Occur under soil and on bare rock
Solution pans	Dish-shaped depressions formed on flat or nearly flat limestone, with sides that may overhang and carry solution flutes. The bottom of the pans may have a cover of organic remains, silt, clay, or rock debris
Undercut solution runnels (*Hohlkarren*)	Similar to runnels but become larger with depth resulting from damp conditions near the base associated with humus or soil accumulations
Solution notches (*Korrosionkehlen*)	Inward-curved recesses etched by soil abutting rock
Covered forms	
Rounded solution runnels (*Rundkarren*)	Runnels formed under an 'acidulated' soil or sediment cover that smooths out the features
Cutters	An American term for soil-covered grikes that are widened at the top and taper with depth. Intervening clints are called subsoil pinnacles
Solution pipes, shafts, or wells	Cylindrical or conical holes developed along joint planes that connect to proto-caves or small caves. Shaft-like forms weathered below a deep and periodically saturated soil cover contain small caverns and are known as 'bone yard' forms. These are popularly used in ornamental rockeries
Polygenetic forms – assemblages of karren	
Karren fields (*Karrenfeld*)	Exposed tracts of karren that may cover up to several square kilometres
Limestone pavement	A type of karren field characterized by regular clints and grikes. They are called stepped pavements (*Schichttreppenkarst*) when benched
Pinnacle karst and stone forest	Topography with pinnacles, sometimes exposed by soil erosion, formed on karst rocks. Pinnacles may stand up to 45 m tall and 20 m wide at the base
Ruiniform karst	Karst with wide grikes and degrading clints exposed by soil erosion. Transitional to tors
Corridor karst or labyrinth karst or giant grikeland	Large-scale clint-and-grike terrains with grikes several metres or more wide and up to 1 km long
Coastal karren	A distinctive solutional topography on limestone or dolomite found around coasts and lakes

Source: After discussion in Jennings (1971, 1985) and Ford and Williams (1989, 376–7) of 1 mm or more within a few decades. The main bare forms resulting from surface wetting are **solution ripples**, **solution flutes** (***Rillenkarren***), **solution bevels** (***Ausgleichsflächen***), **solution runnels** (***Rinnenkarren***), and **decantation runnels** and **flutings** (Table 8.2; Figure 8.6; Plates 8.1 and 8.2).

Bare forms resulting from concentrated runoff are microfissures, splitkarren, grikes, clints, and solution spikes. **Microfissures** are solutional features following small joints. **Splitkarren** are larger solution channels that run along larger lines of weakness – joints, stylolites, and veins. **Grikes** (***Kluftkarren***), which are called solution slots in America, follow joints and cleavage planes, so may be straight, deep, and long, often occurring in networks (Plate 8.3). Grikes are the leading karren feature in most karren assemblages. Large openings may develop at joint intersections, some several metres deep and called karst wells, which are related to solution pipes and potholes. The intervening tabular blocks between grikes are called **clints** (***Flackkarren***) (Plate 8.3). Grikes in upright bedding planes are enlarged in the same ways as joints in flat bedding planes and are called **bedding grikes** (***Schichtfugenkarren***). However, residual blocks left between them commonly break into **pinnacles** or **solution spikes** (***Spitzkarren***) and beehives decorated by solution flutes. In horizontal strata, the near-surface bedding planes are likely to be opened up by seepage. This process may free the intervening clints and lead to their breaking up to form **shillow** (a term from northern England), which is roughly equivalent to the German *Trümmerkarren* and *Scherbenkarst*. All these forms are small. Grikes average about 5 cm across and up to several metres deep, clints may be up to several metres across, and solution spikes up to several metres long. Large-scale grikes, variously termed *bogaz*, corridors, and streets, are found in some areas and follow major joints and faults. ***Bogaz*** are up to 4 m wide, 5 m deep, and tens of metres long. **Karst corridors** and **streets** are even larger and take the form of gorges.

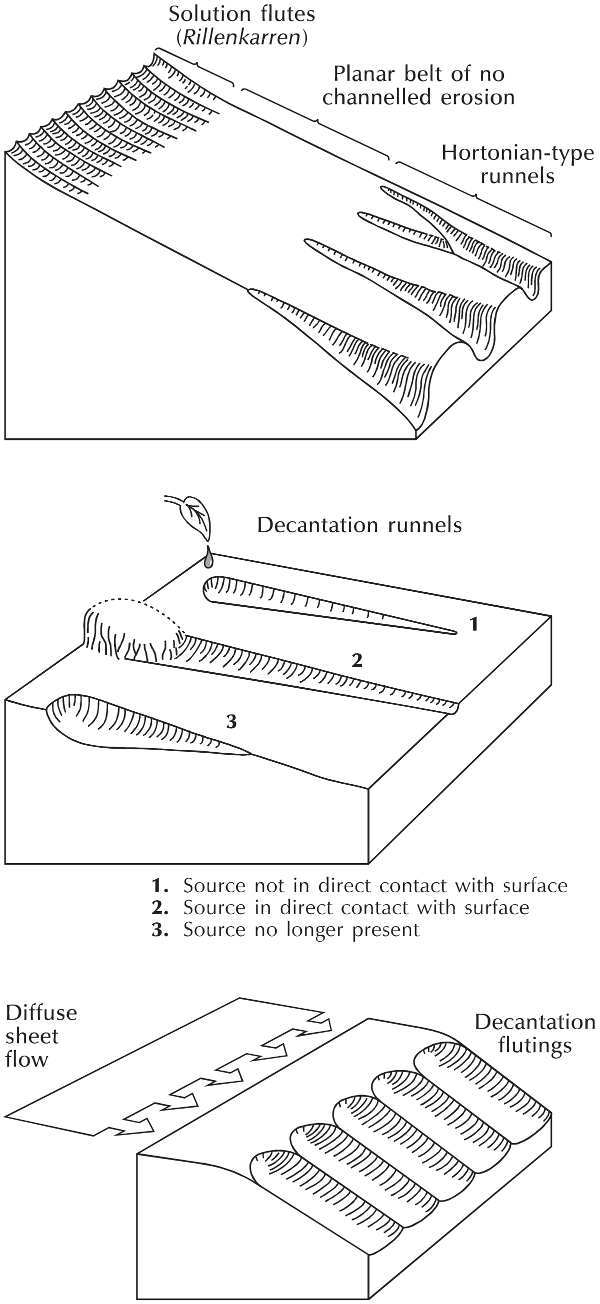


Figure 8.6 Solution flutes (*Rillenkarren*), decantation runnels, and decantation flutings.
Source: After Ford and Williams (1989, 383)

Covered and partly covered forms

Partly covered forms develop in areas with a patchy soil, sediment, litter, or moss cover. **Solution pits** are round-bottomed or tapered forms, usually less than 1 m

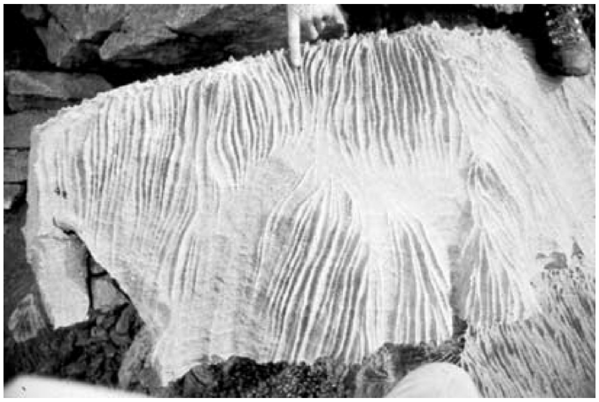


Plate 8.1 Rillenkarren formed on a limestone block in a Holocene landslide pile, Surprise Valley, near Jasper, Jasper National Park, Alberta, Canada. The blocks are chaotically orientated in the pile, but are rilled down the modern drainage lines.
(*Photograph by Derek C. Ford*)

in diameter. Larger ones merge into **solution pans**. They occur under soil and on bare limestone. Along with shafts, they are the most widespread karren form. Many are transitional to shafts. Solution pans or solution basins are small depressions shaped like basins or dishes, usually with a thin cover of soil or algal or vegetal remains. They are no more than 3 m wide and 0.5 m deep, but many are much smaller. Some of the carbon dioxide released by the decaying organic matter dissolves in the water collected in the pans and boosts their dissolution. The Slav term for them is *kamenice* (singular *kamenica*), and the American term is tinajitas. **Undercut solution runnels** (***Hohlkarren***) are like runnels in form and size, except that they become wider with increasing depth, probably owing to accumulated organic matter or soil keeping the sides and base near the bottom damp. **Solution notches** (***Korrosionkehlen***) are about 1 m high and wide and 10 m long. They are formed where soil lies against projecting rock, giving rise to inward-curved recesses.

Covered forms develop under a blanket of soil or sediment, which acts like 'an acidulated sponge' (Jennings 1971, 48). Where it contacts the underlying limestone, the 'sponge' etches out its own array of landforms, the chief among which are rounded solution runnels and solution pipes. **Rounded solution runnels** (***Rundkarren***) are the same size as ordinary runnels but they are worn smooth by the active corrosion identified with acid soil waters. They are visible only when the soil or sediment blanket has been stripped off (Plate 8.3, foreground). Cutters are soil-covered clints that are widened at the top and taper with depth (Colour Plate 2, inserted between pages 208 and 209). **Solution pipes** (or **shafts** or **wells**) are up to 1 m across and 2–5 m deep, usually becoming narrower with depth, but many are smaller. They are cylindrical or conical holes, occurring on such soft limestones as chalk, as well as on the mechanically stronger and less permeable limestones. Solution pipes usually form along joint planes, but in the chalk of north-west Europe they can develop in an isolated fashion.

Plate 8.2 Decantation runnels (*Rinnenkarren*) on marble near Pikhauga Ridge, Svartisen, Norway.
(*Photograph by Derek C. Ford*)

Plate 8.3 Clints and grikes on 'textbook' limestone pavement on the lip of Malham Cove, Yorkshire. Towards the cliff edge, the soils have always been thin; the grikes are simple linear features and the clints show little dissection. In the fore- and middle-ground, grike edges are rounded and clints dissected by subsoil *Rundkarren*. The figure is a young Paul Williams.
(*Photograph by Derek C. Ford*)

Polygenetic karst

Limestone pavements

Limestone pavements are karren fields developed in flat or gently dipping strata. They occur as extensive benches or plains of bare rock in horizontally bedded limestones and dolomites (Plate 8.3). Solution dissolves clefts in limestone and dolomite pavements that are between 0.5 and 25 m deep. The clefts, or grikes, separate surfaces (clints) that bear several solution features (karren). A survey in the early 1970s listed 573 pavements in the British Isles, most of them occurring on the Carboniferous limestone of the northern Pennines in the counties of North Yorkshire, Lancashire, and Cumbria (Ward and Evans 1976).

Debate surrounds the origin of pavements, some geomorphologists arguing that a cover of soil that is from time to time scoured by erosion encourages their formation. To be sure, the British pavements appear to have been produced by the weathering of the limestone while it was covered by glacial till. Later scouring by ice would remove any soil cover and accumulated debris. It may be no coincidence that limestone pavements are very common in Canada, where ice-scouring has occurred regularly (Lundberg and Ford 1994). Lesser pavements occur where waves, rivers in flood, or even sheet wash on pediments do the scouring instead of ice.

Pinnacle karst

Pinnacle karst is dominated by large *Spitzkarren*. In China, a famous example of pinnacle karst is the Yunnan Stone Forest (Plate 8.4; Colour Plate 3, inserted between pages 208 and 209). This is an area of grey limestone pillars covering about 350 km^2. The pillars stand 1–35 m tall with diameters of 1–20 m. **Arête-and-pinnacle karst**, which is found on Mount Kaijende in

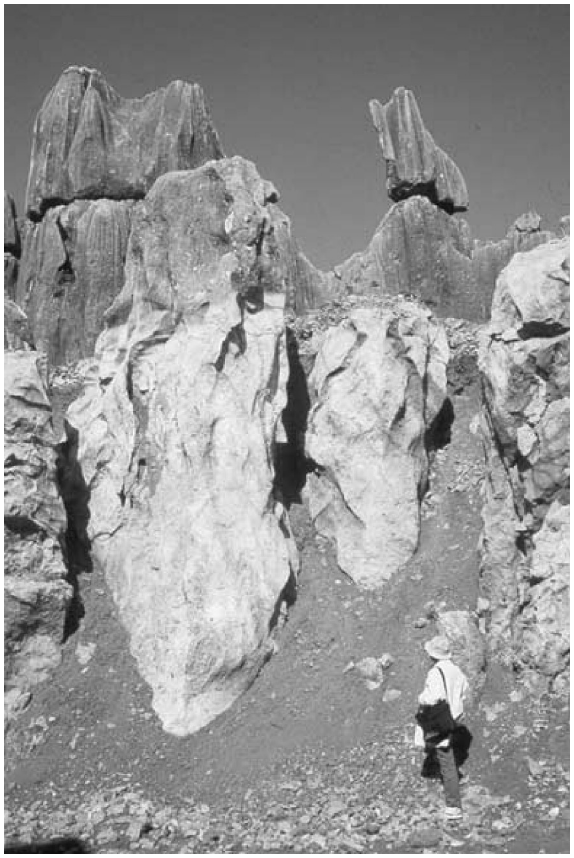


Plate 8.4 Pinnacle karst or shilin (shilin means 'stone forest' in Mandarin) exposed in a road-cut in Shilin National Park, Yunnan, China. The subsoil origin of the pinnacles is plainly seen. Their emergence is due to the general erosion of regional cover sediment.
(*Photograph by Derek C. Ford*)

Papua New Guinea and Mount Api in Sarawak, consists of bare, net-like, saw-topped ridges with almost vertical sides that stand up to 120 m high. The spectacular ridges rise above forest-covered corridors and depressions. They seem to have formed by limestone solution without having previously been buried.

Ruiniform karst

This is an assemblage of exceptionally wide grikes and degrading clints that have been exposed by soil erosion (Plate 8.5). The clints stick out like 'miniature city blocks in a ruined townscape' (Ford and Williams 1989, 391). Ruiniform karst is found in the French Causses, where deforestation and soil erosion have occurred. On high crests, ruiniform karst is transitional to limestone tors.

Corridor karst

In places, grikes grow large to form a topography of aligned or criss-crossing corridors. The large grikes are called *bogaz*, corridors, *zanjones*, and streets. Grike-wall recession produces square-shaped or box valleys and large closed depressions called **platea**. Corridor karst landscapes are called **labyrinth karst**, **corridor karst**, or **giant grikeland**. It is large-scale clint-and-grike terrain but may have a complex history of development. Grikelands form under tropical and temperate rainforest and in arid and semi-arid areas. Smaller-scale versions are known from the Nahanni limestone karst region of the Mackenzie Mountains, Canada (Brook and Ford 1978). Here, the labyrinth karst is stunning, with individual streets longer than 1 km and deeper than 50 m (Plate 8.6).

Plate 8.5 A ruiniform assemblage (residual clint blocks) in flat-lying limestones near Padua, Italy.
(*Photograph by Derek C. Ford*)

Coastal karren

Around coasts and lakes, limestone or dolomite outcrops often display a distinctive solutional topography, with features including intertidal and subtidal notches (also called nips; Plate 8.7) and a dense formation of pits, pans, micropits, and spikes (Plate 8.8). Boring and grazing organisms may help to form coastal karren, as may

Plate 8.6 View of Nahanni labyrinth karst, showing intersecting networks of karst streets interspersed with karst platea.
(*Photograph by George A. Brook*)

Plate 8.7 A limestone solution notch on a modern shore platform on the east coast of Okinawa, Japan.
(*Photograph by Derek C. Ford*)

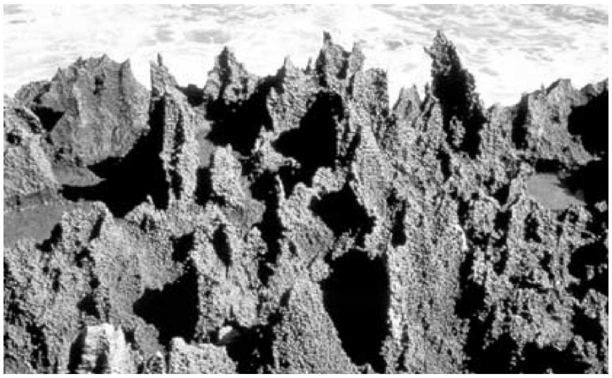


Plate 8.8 Limestone coastal karren pitting (sometimes called phytokarst or biokarst) on the west coast of Puerto Rico.
(*Photograph by Derek C. Ford*)

wave action, wetting and drying, salt weathering, and hydration.

Coral island karst

Carbonate sediments are the building material of the world's coral islands, all of which bear at least some karst features. For instance, Navassa Island, a 5-km^2 island in the Caribbean Sea between Haiti and Jamaica, may have started life as a small coral atoll. Some 5 million years ago, these coral reefs began to emerge, leading the conversion of calcium carbonate sediments (aragonite) to calcium–magnesium carbonate rock (dolomite), the formation of a terrace around the island, and the onset of chemical weathering and the evolution of karst landforms, particularly caves and karst holes. Similarly, Yoron-Jima, a 21-km^2 carbonate island located in the central Ryukyu Island Arc of southern Japan, was raised above sea level in the Quaternary period. Subsequent karst processes have produced many closed depressions (Terry 2005).

Closed depressions

Dolines

The word **doline** is derived from the Slovene word *dolina*, meaning a depression in the landscape. It is applied to the simpler forms of closed depressions in karst landscapes. **Sinkhole**, **swallet**, and **swallow hole** are English terms with rather loose connotations. Dolines resemble various shapes – dishes, bowls, cones, and cylinders. They range in size from less than a metre wide and deep to over hundreds of metres deep and several hundred metres or even a kilometre wide. The large forms tend to be complex and grade into other classes of closed depressions.

Dolines are formed by several processes: surface solution, cave collapse, piping, subsidence, and stream removal of superficial covers. Although these processes frequently occur in combination and most dolines are polygenetic, they serve as a basis for a five-fold classification of dolines (Jennings 1985, 107; Ford and Williams 1989, 398) (Figure 8.7):

1 **Solution dolines** start where solution is concentrated around a favourable point such as joint intersections. The solution lowers the bedrock surface, so eating out a small depression (Figure 8.7a; Plate 8.9). The depression traps water, encouraging more solution and depression enlargement. Once begun, doline formation is thus self-perpetuating. However, insoluble residues and other debris may clog the doline floor, sometimes forming swampy areas or pools to form **pond dolines**. Dolines are one of the few karst landforms that develop in soft limestones such as chalk (e.g. Matthews *et al.* 2000).

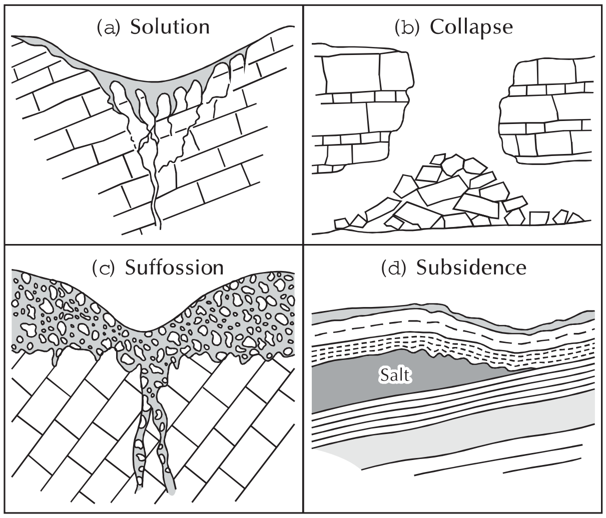


Figure 8.7 The main genetic classes of doline. (a) Solution doline. (b) Collapse doline. (c) Suffossion doline. (d) Subsidence doline.
Source: After Ford and Williams (1989, 398)

Plate 8.9 Small doline in steeply dipping limestone in the Rocky Mountain Front Ranges. The doline is formed on a cirque floor in the valley of Ptolemy Creek, Crownest Pass, Alberta, Canada.
(*Photograph by Derek C. Ford*)

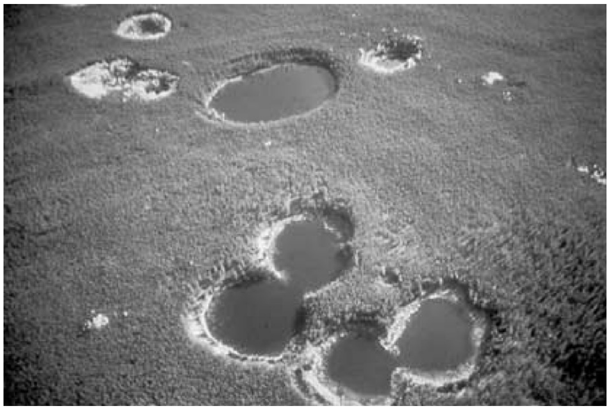


Plate 8.10 Collapse dolines at the watertable, Wood Buffalo National Park, Alberta, Canada. The dolines are created by collapses through dolostone into underlying gypsum. The diameters are 40–100 m.
(*Photograph from Parks Canada archives*)

2 **Collapse dolines** are produced suddenly when the roof of a cave formed by underground solution gives way and fractures or ruptures rock and soil (Figure 8.7b; Plate 8.10). Initially, they have steep walls, but, without further collapse, they become cone-shaped or bowl-shaped as the sides are worn down and the bottom is filled with debris. Eventually, they may be indistinguishable from other dolines except by excavation. The largest open collapse doline is Crveno Jezero ('Red Lake') in Croatia, which is 421 m deep at its lowest rim and 518 m deep at its highest rim. If the collapse occurs into a water-filled cave, or if the water table has risen after the collapse occurred, the collapse doline may contain a lake, often deep, covering its floor. Such lakes are called **cenotes** on the Yucatán Peninsula, Mexico, and '***obruk***' lakes on the Turkish plateau. Some of the cenotes near the Mayan ruins of the northern Yucatán are very large. Dzitnup, at the Mayan ruins of Chichén Itzá, is a vertical-walled sinkhole some 60 m wide and 39 m deep, half-filled with water. **Subjacent karst-collapse dolines** form even more dramatically than collapse dolines when beds of an overlying non-calcareous rock unit fall into a cave in the underlying limestone. An example is the Big Hole, near Braidwood, New South Wales, Australia. Here, a 115-m-deep hole in Devonian quartz sandstone is assumed to have collapsed into underlying Silurian limestone (Jennings 1967). As with collapse dolines, subjacent karst-collapse dolines start life as steep-walled and deep features but progressively come to resemble other dolines.

3 **Suffossion dolines** form in an analogous manner to subjacent karst-collapse dolines, with a blanket of superficial deposits or thick soil being washed or falling into widened joints and solution pipes in the limestone beneath (Figure 8.7c). In England, the 'shakeholes' of Craven, near Ingleborough, northern England, are conical suffossion dolines in glacial moraine laid upon the limestone during the ultimate Pleistocene glaciation (Sweeting 1950).

4 **Subsidence dolines** form gradually by the sagging or settling of the ground surface without any manifest breakage of soil or rock (Figure 8.7d). Natural dolines of subsidence origin are rare and are found where the dissolution of underground evaporite beds occurs, as in Cheshire, England, where salt extraction from Triassic rocks has produced depressions on the surface, locally known as **flashes**.

5 **Alluvial stream-sink dolines** form in alluvium where streams descend into underlying calcareous rocks. The stream-sink is the point at which a stream disappears underground. Several examples are found in the White Peak District of Derbyshire, England (Figure 8.8).

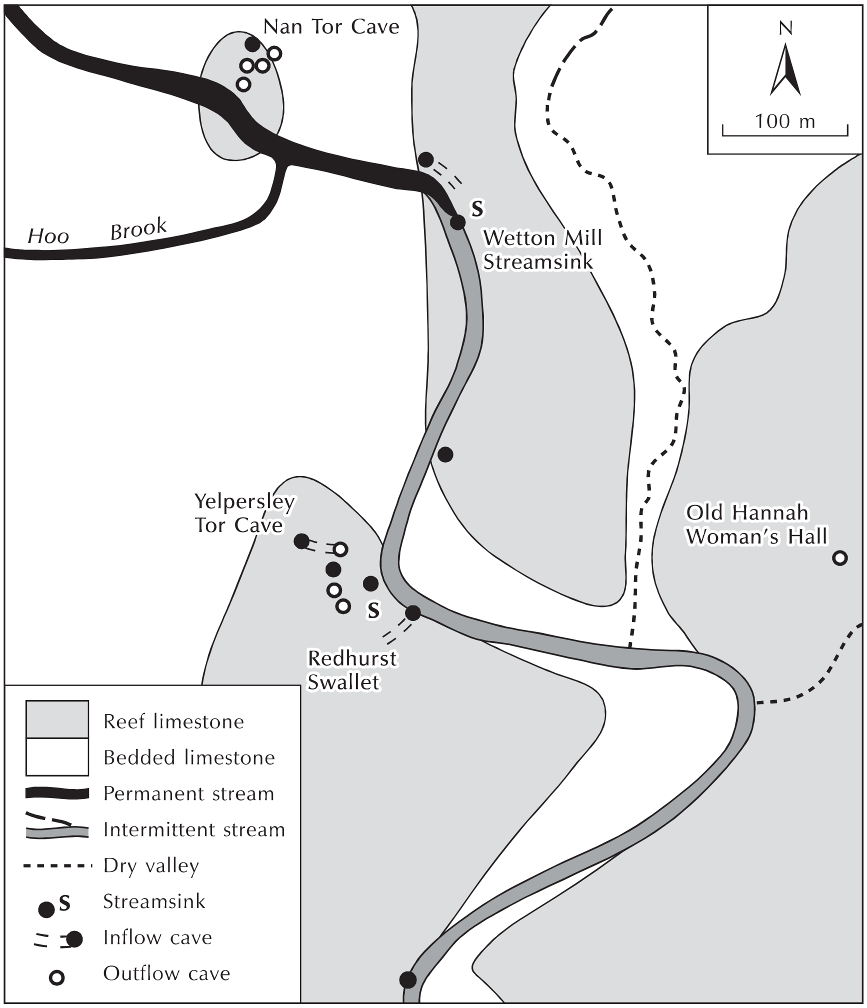


Figure 8.8 Stream-sinks on the River Manifold in the English Peak District.
Source: Adapted from Warwick (1953)

Karst windows

These are unroofed portions of underground caverns in which streams flow out of the cavern at one end, across the floor, and into a cavern at the other end. The openings may be mere peepholes or much larger.

Uvalas and egg-box topography

Uvalas, a word from Slovenia, are compound sinkholes or complex depressions composed of more than one hollow. They are larger than small dolines. Elongated forms follow strike lines or fault lines, while lobate forms occur on horizontal beds. Solution may play a big role in their formation, but, without further study, other processes cannot be discounted.

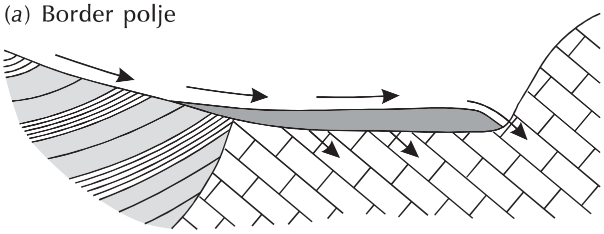
On thick limestone, where the water table is deep, solutional sinkholes may be punched downwards to form **egg-box topography**, known as ***fengcong*** in China, with sharp residual peaks along the doline rim and a local relief of hundreds of metres.

Polja

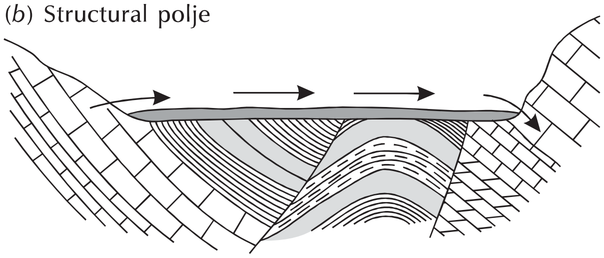
A **polje** (plural *polja*) is a large, usually elongated, closed depression with a flat floor (Plate 8.6). Polja have many regional names, including *plans* in Provence, France; *wangs* in Malaysia; and *hojos* in Cuba. Intermittent or perennial streams, which may be liable to flood and become lakes, may flow across their floors and drain underground through stream-sinks called **ponors** or through gorges cutting through one of the polje walls. The floods occur because the ponors cannot carry the water away fast enough. Many of the lakes are seasonal, but some are permanent features of polje floors, as in Cerkniča Polje, Slovenia.

Polja come in three basic kinds: border polja, structural polja, and baselevel polja (Figure 8.9) (Ford and Williams 1989, 431–2). **Border polja** are fed by rivers from outside the karst region (allogenic rivers) that, owing to the position of the water table in the feed area and floodplain deposits over the limestone, tend to stay on the ground surface to cause lateral planation and alluviation. **Structural polja** are largely controlled by geology, often being associated with down-faulted inliers of impervious rocks in limestone terrain. They include the largest karst depressions in the world and are the dominant type of polje in the Dinaric karst. **Baselevel polja** occur in limestone where a regional water table intersects the ground surface.

(*a*) Border polje



(*b*) Structural polje



(*c*) Baselevel polje

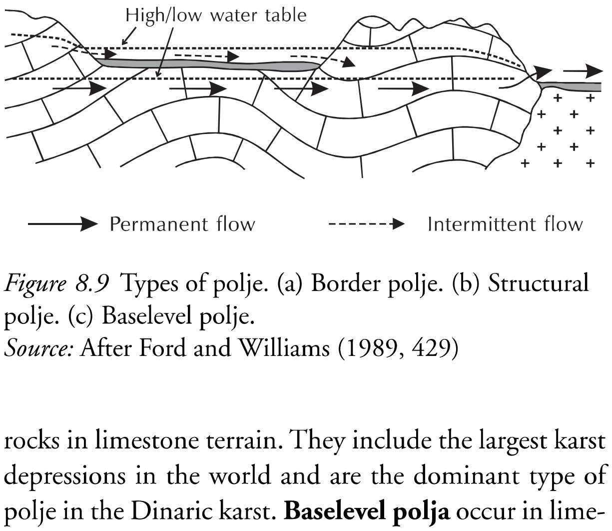


Figure 8.9 Types of polje. (a) Border polje. (b) Structural polje. (c) Baselevel polje.
Source: After Ford and Williams (1989, 429)

Cone karst

Tropical karst is one of the landform wonders of the world. Extensive areas of it occur in southern Mexico, Central America, the Caribbean, South-East Asia, southern China, South America, Madagascar, the Middle East, New Guinea, and northern Australia. Under humid tropical climates, karst landscapes take on a rather different aspect from 'classic' karst. In many places, owing to rapid and vigorous solution, dolines have grown large

Plate 8.11 Limestone cone karst near Anxhun, Guizhou Province, China.
(*Photograph by Derek C. Ford*)

enough to interfere with each other and have destroyed the original land surface. Such landscapes are called **cone karst** (***Kegelkarst*** in German) and are dominated by projecting residual relief rather than by closed depressions (Plate 8.11). The outcome is a polygonal pattern of ridges surrounding individual dolines. The intensity of the karstification process in the humid tropics is partly a result of high runoff rates and partly a result of thick soil and vegetation cover promoting high amounts of soil carbon dioxide.

Two types of cone karst are recognized – cockpit karst and tower karst – although they grade into one another and there are other forms that conform to neither. Cockpits are tropical dolines (Figure 8.10). In **cockpit karst**, the residual hills are half-spheres, called *Kugelkarst* in German, and the closed depressions, shaped like starfish, are called cockpits, the name given to them in Jamaica owing to their resembling cock-fighting arenas. In **tower karst** (***Turmkarst*** in German), the residual hills are towers or **mogotes** (also called **haystack hills**), standing 100 m or more tall, with extremely steep to overhanging lower slopes (Plate 8.12). They sit in broad alluvial plains that contain flat-floored, swampy depressions. The residual hills may have extraordinarily sharp edges and form **pinnacle karst** (p. 195).

Studies in the Mackenzie Mountains, north-west Canada, have shattered the notion that cone karst, and especially tower karst, is a tropical landform (Brook and

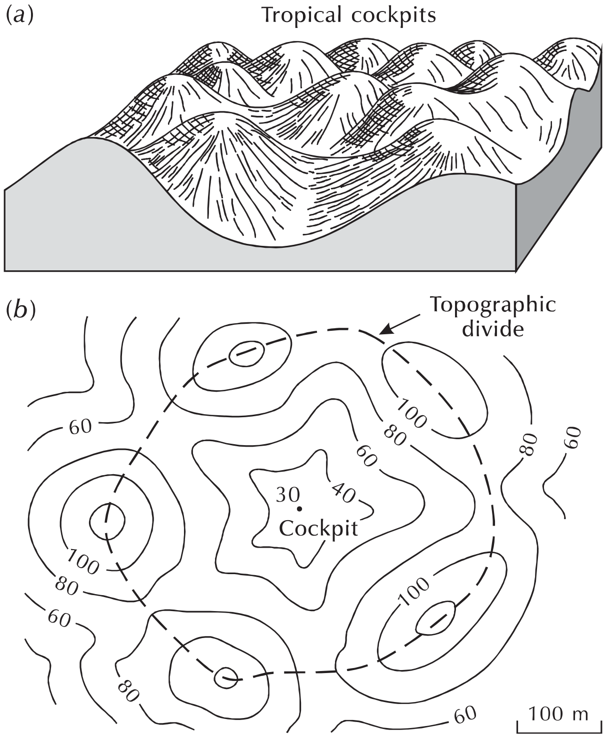


Figure 8.10 Tropical dolines (cockpits). (a) Block diagram. (b) Plan view.
Source: Adapted from Williams (1969)

Plate 8.12 Tower karst on the south bank of the Li River near Guilin, Guangxi Province, China.
(*Photograph by Derek C. Ford*)

Ford 1978). Limestone in the Mackenzie Mountains is massive and very thick with widely spaced joints. Karst evolution in the area appears to have begun with the opening of deep dolines at 'weak' points along joints. Later, long and narrow gorges called karst streets formed, to be followed by a rectilinear network of deep gorges with other cross-cutting lines of erosion – **labyrinth karst**. In the final stage, the rock wall of the gorges suffered lateral planation, so fashioning towers.

Fluvial karst

Although a lack of surface drainage is a characteristic feature of karst landscapes, several surface landforms owe their existence to fluvial action. Rivers do traverse and rise within karst areas, eroding various types of valley and building peculiar carbonate deposits.

Gorges

In karst terrain, rivers tend to erode **gorges** more frequently than they do in other rock types. In France, the Grands Causses of the Massif Centrale is divided into four separate plateaux by the 300–500-m-deep Lot, Tarn, Jonte, and Dourbie gorges. The gorges are commonplace in karst landscape because river incision acts more effectively than slope processes, which fail to flare back the valley-sides to a V-shaped cross-section. Some gorges form by cavern collapse, but others are 'through valleys' eroded by rivers that manage to cross karst terrain without disappearing underground.

Blind and half-blind valleys

Rivers flowing through karst terrain may, in places, sink through the channel bed. The process lowers the bedrock and traps some of the sediment load. The sinking of the channel bed saps the power of the stream below the point of leakage. An upward step or threshold develops in the long profile of the stream, and the underground course becomes larger, diverting increasingly more flow. When large enough, the underground conduit takes all the flow at normal stages but cannot accommodate flood discharge, which ponds behind the step and eventually overspills it. The resulting landform is a **half-blind valley**. A half-blind valley is found on the Cooleman Plain, New South Wales, Australia (Figure 8.11a). A small creek flowing off a granodiorite hill flows for 150 m over Silurian limestone before sinking through an earth hole. Beyond the hole is a 3-m-high grassy threshold separating the depression from a gravel stream bed that only rarely holds overflow. If a stream cuts down its bed far enough and enlarges its underground course so that even flood discharges sink through it, a **blind valley** is created that is closed abruptly at its lower end by a cliff or slope facing up the valley. Blind valleys carry perennial or intermittent streams, with sinks at their lower ends, or they may be dry valleys. Many blind valleys occur at Yarrangobilly, New South Wales, Australia. The stream here sinks into the Bath House Cave, underneath crags in a steep, 15-m-high counter-slope (Figure 8.11b).

Steepheads

Steepheads or **pocket valleys** are steep-sided valleys in karst, generally short and ending abruptly upstream where a stream issues forth in a spring, or did so in the past. These cul-de-sac valleys are particularly common around plateau margins or mountain flanks. In Provence, France, the Fountain of Vaucluse emerges beneath a 200-m-high cliff at the head of a steephead. Similarly, if less spectacularly, the Punch Bowl at Burton Salmon, formed on Upper Magnesian Limestone, Yorkshire, England, is a steephead with a permanent spring issuing from the base of its headwall (Murphy 2000). Malham Cove, England, is also a steephead (Colour Plate 4, inserted between pages 208 and 209). Steepheads may form by headward recession, as spring sapping eats back into the rock mass, or by cave-roof collapse.

Dry valleys

Dry valleys are much like regular river valleys save that they lack surface stream channels on their floors. They occur on many types of rock but are noticeably common in karst landscapes. Eye-catching dry valleys occur where rivers flowing over impermeable rock sink on entering karst terrain, but their former courses are traceable above ground. In the Craven district, England, the Watlowes is

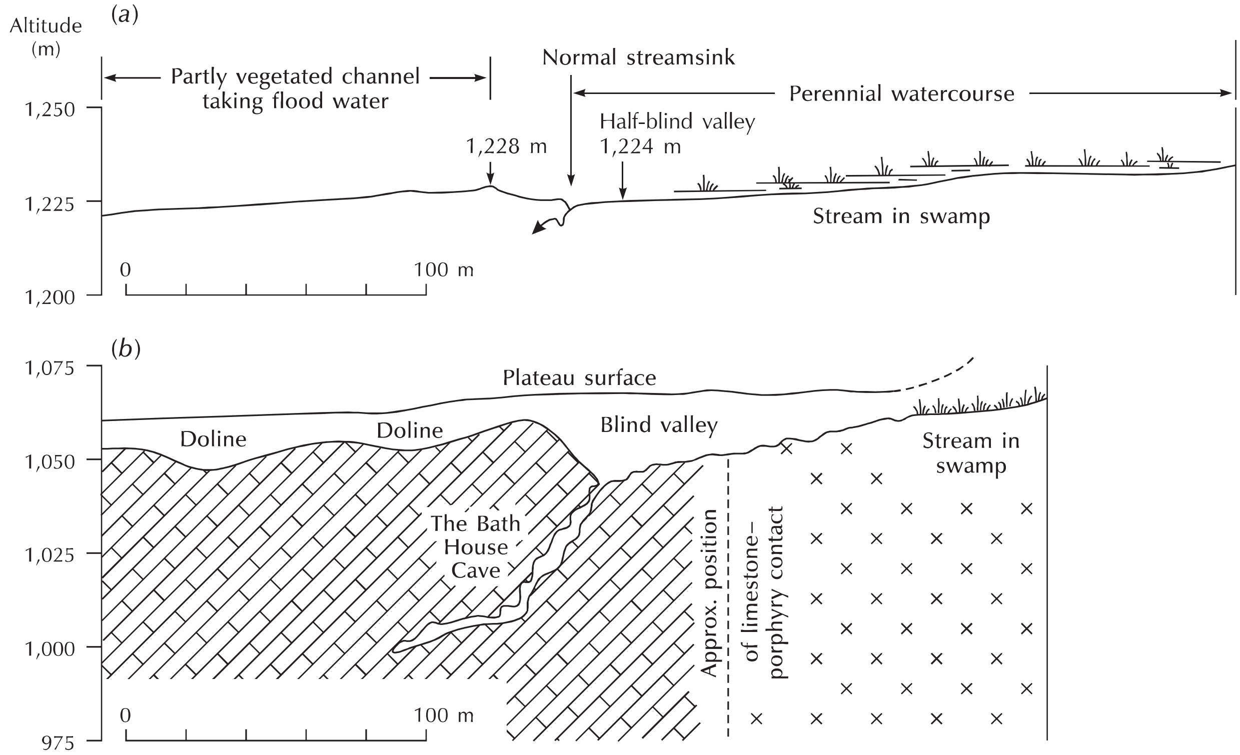


Figure 8.11 Blind and half-blind valleys in New South Wales, Australia. (a) A half-blind valley on Cooleman Plain. (b) A blind valley at Yarrangobilly.
Source: Adapted from Jennings (1971, 110, 111)

a craggy dry valley in which the stream fed by Malham Tarn formerly flowed over the limestone to cascade over the 75-m cliff of Malham Cove (Figure 8.12; Colour Plate 4).

Extensive dry valley networks occur in some areas of karst. An impressive set is found in the White Peak, England. Here, a few major streams – the Rivers Manifold, Dove, and Wye – flow across the region, but most other valleys are dry (Figure 8.13). Many of the dry valleys start as shallow, bowl-like basins that develop into rock-walled valleys and gorges. Other, smaller dry valleys hang above the major dry valleys and the permanent river valleys. The origin of such networks is puzzling but appears to be the legacy of a former cover of impervious shales (Warwick 1964). Once the impervious cover was removed by erosion, the rivers cut into the limestone beneath until solution exploited planes of weakness and diverted the drainage underground. The 'hanging valleys', which are reported in many karst areas, resulted from the main valleys' continuing to incise after their tributaries ceased to have surface flow.

Meander caves

Meander caves are formed where the outer bend of a meander undercuts a valley-side. Now, stream debris does not hamper rivers from lateral erosion in karst landscapes as it does rivers on other rocks, because rivers carrying a large clastic load cannot move laterally by corrasion as easily as rivers bearing a small clastic load can by corrosion. For this reason, meander caves are better developed in karst terrain than elsewhere. A prime example is Verandah Cave, Borenore, New South Wales, Australia (Figure 8.14).

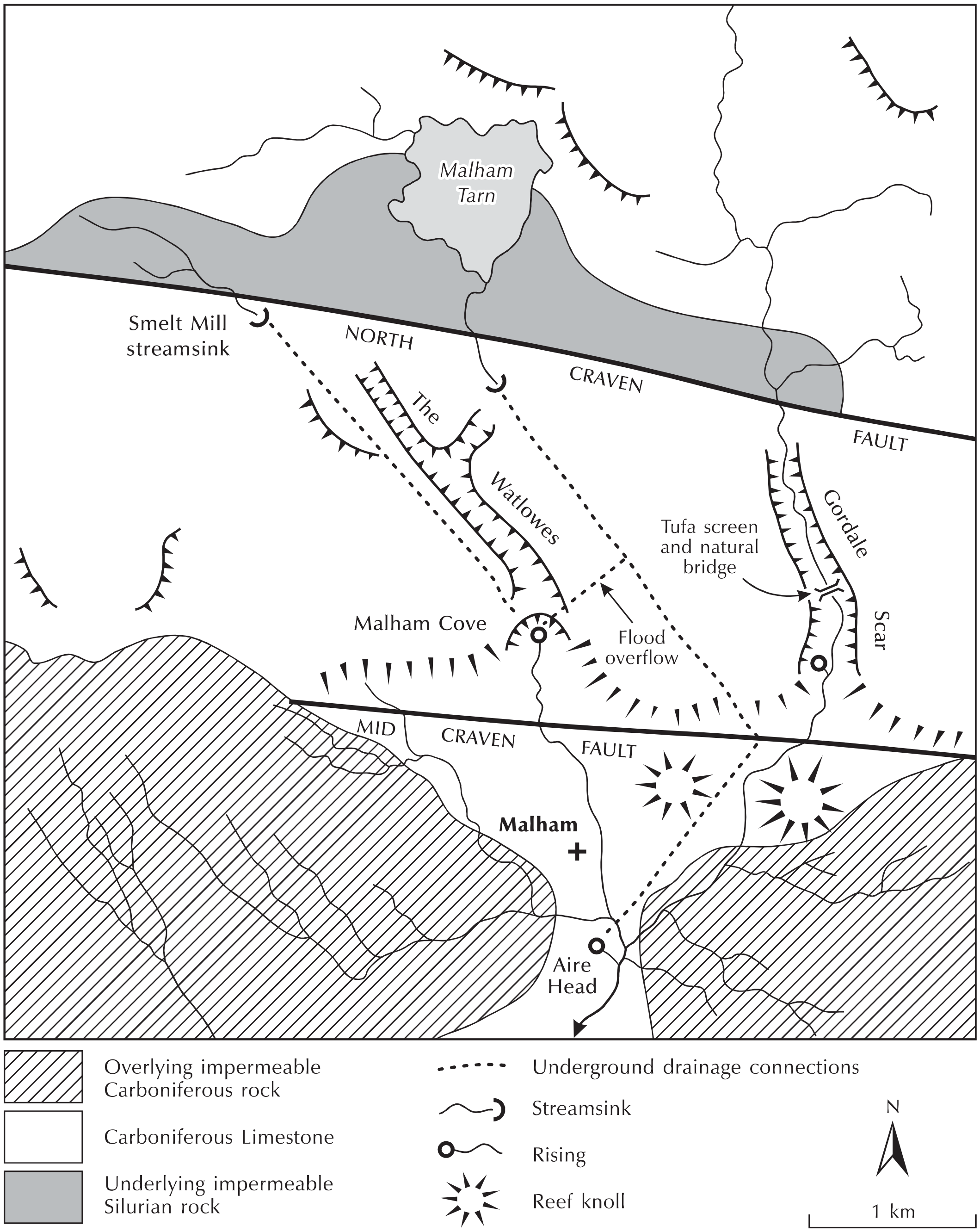


Figure 8.12 Limestone features around Malham Cove, Craven, England. Compare with Colour Plate 4.
Source: Adapted from Jennings (1971, 91)

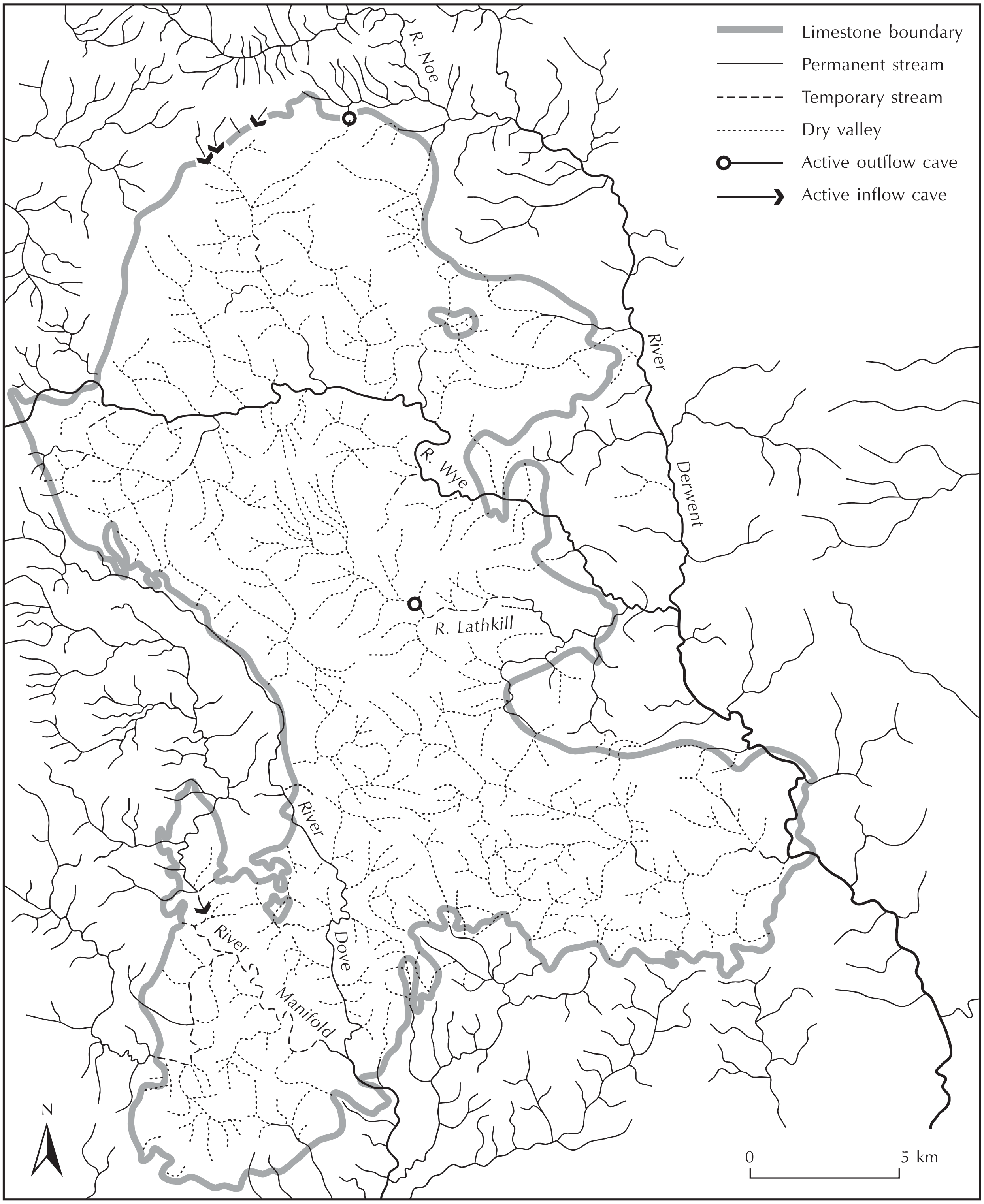


Figure 8.13 Dry valley systems in the White Peak, England.
Source: Adapted from Warwick (1964)

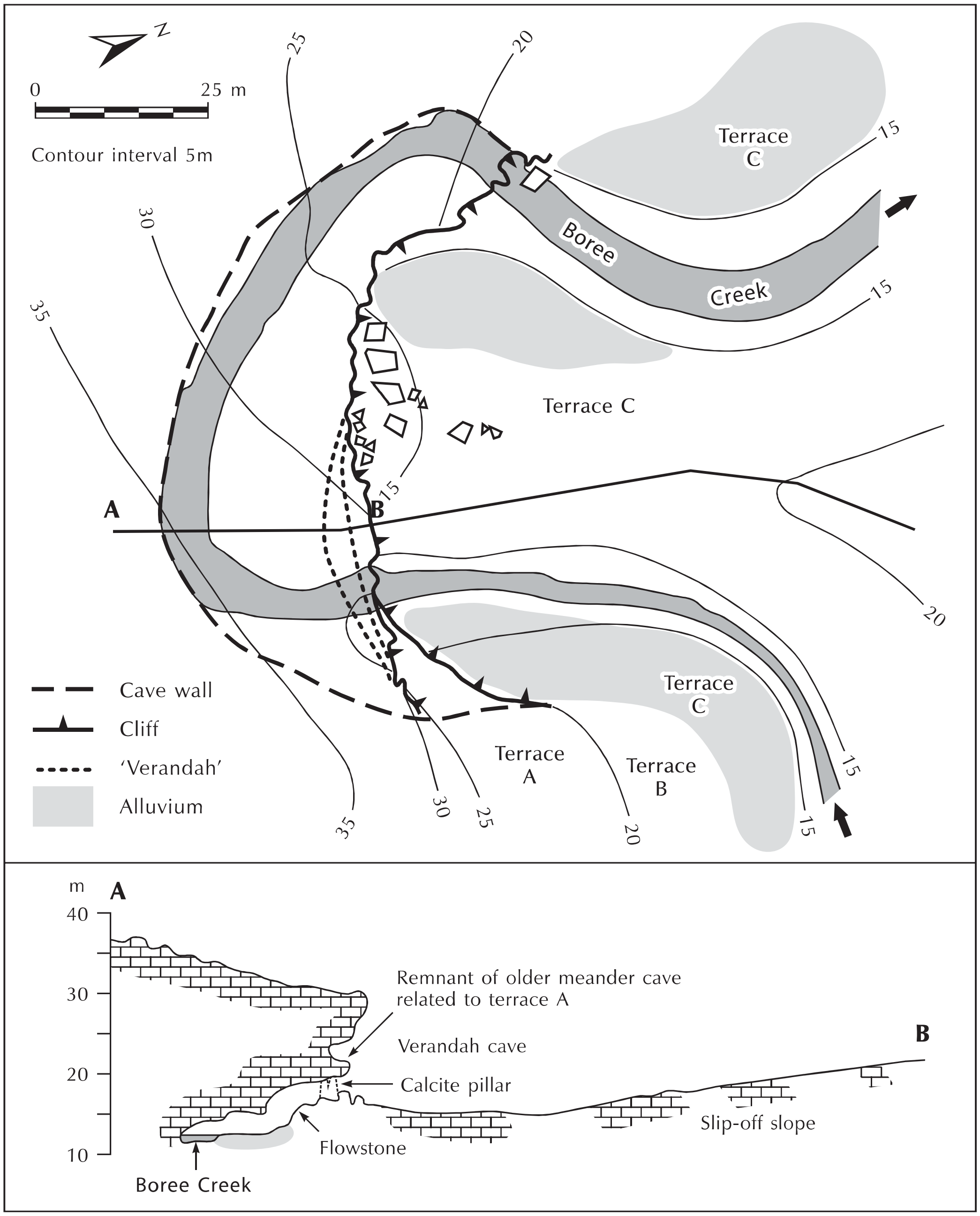


Figure 8.14 A meander cave on Boree Creek, Borenore, New South Wales, Australia.
Source: Adapted from Jennings (1971, 101)

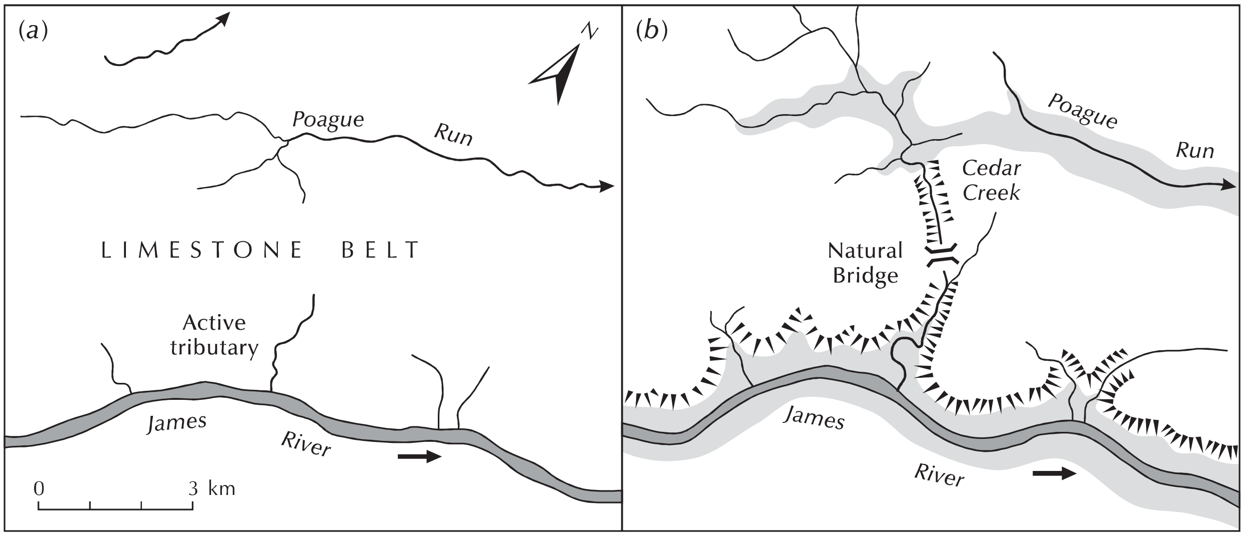


Figure 8.15 Natural Bridge, Cedar Creek, Virginia, USA. (a) Landscape before river piracy. (b) Landscape after river piracy.
Source: Adapted from Woodward (1936)

Natural bridges

Natural bridges are formed of rock and span ravines or valleys. They are productions of erosion and are commoner in karst terrain than elsewhere. Three mechanisms seem able to build natural bridges in karst areas. First, a river may cut through a very narrow band of limestone that crosses its path. Second, cave roofs may collapse leaving sections still standing. Third, rivers may capture each other by **piracy** (Figure 8.15). This happens where meander caves on one or both sides of a meander spur breach the wall of limestone between them (Figure 8.15).

Tufa and travertine deposits

Karst rivers may carry supersaturated concentrations of carbonates. When deposited, the carbonates may build landforms. Carbonate deposition occurs when (1) water is exposed to the atmosphere, and so to carbon dioxide, on emerging from underground; (2) when evaporation supersaturates the water; and (3) when plants secrete calcareous skeletons or carbonate is deposited around their external tissues. Porous accumulations of calcium carbonate deposited from spring, river, or lake waters in association with plants are called **tufa** (Colour Plate 5, inserted between pages 208 and 209). Compact, crystalline, often banded calcium carbonate deposits precipitated from spring, river, or lake water are called **travertine**, or sometimes **calc-sinter** (Plate 8.13). However, some geomorphologists use the terms tufa and travertine interchangeably. Tufa and travertine deposition is favoured in well-aerated places, which promote plant growth, evaporation, and carbon dioxide diffusion from the air. Any irregularity

Plate 8.13 Hot spring travertine terraces at Pummukale, Turkey.
(*Photograph by Derek C. Ford*)

in a stream profile is a prime site. A barrier slowly builds up, on the front side of which frothing and bubbling encourage further deposition. The end result is that a dam and waterfall form across a karst river. The waterfall may move down the valley leaving a fill of travertine in its wake. Travertine may cover large areas. In Antalya, south-west Turkey, a travertine complex, constructed by the supersaturated calcareous waters of the Kirkgöz spring group, occupies 600 km^2 and has a maximum thickness of 270 m (Burger 1990). A sequence of tufa dams in the Korana Valley, Croatia, impounds the impressive Plitvice Lakes.

Karst forms on quartzite

It was once thought that quartzites were far too insoluble to be susceptible to chemical weathering. Starting in the mid-1960s with the discovery of quartzite karst in Venezuela (White *et al.* 1966; see also Wirthmann 2000, 104–9), karst-like landforms have been found on quartzose rock in several parts of the tropics. The quartzitic sandstone plateau of the Phu Hin Rong Kla National Park, north-central Thailand, bears features found in limestone terrain – rock pavements, karren fields, crevasses, and caves – as well as weathered polygonal crack patterns on exposed rock surfaces and **bollard-shaped rocks** (Doerr 2000). The crevasses, which resemble grikes, occur near the edge of the plateau and are 0.5–2 m wide, up to 30 m deep, and between 1 and 10 m apart. Smaller features are reminiscent of solution runnels and solution flutes. Caves up to 30 m long have been found in the National Park and were used for shelter during air raids while the area was a stronghold for the communists during the 1970s. Some of the caves are really crevasses that have been widened some metres below the surface, but others are underground passages that are not associated with enlarged vertical joints. In one of them, the passage is 0.5–1 m high and 16 m long. The bollard-shaped rock features are found near the plateau edge (Plate 8.14). They are 30–50 cm high with diameters of 20–100 cm. Their formation appears to start with the development of a **case-hardened surface** and its sudden cracking under tensile stresses to form a polygonal cracking pattern (cf. Williams and Robinson 1989; Robinson and Williams 1992). The cracks are then exploited by weathering. Further weathering deepens the cracks, rounding off the tops of the polygonal blocks, and eventually eradicates the polygonal blocks' edges and deepens and widens the cracks to form bollard-shaped rocks (Figure 8.16).

Plate 8.14 Bollard rocks formed in quartzitic sandstone, north-central Thailand.
(*Photograph by Stefan Doerr*)

Karst-like landforms also exist on the surfaces of quartzite table mountains (Tepuis) in south-eastern Venezuela (Doerr 1999). At 2,700 m, the Kukenan Tepui is one of the highest table mountains in South America (Plate 8.15). The topography includes caves, crevasse-like fissures, sinkholes, isolated towers 3–10 m high, and shallow karren-like features. Evidence points to corrosion, rather than to erosive processes, as the formative agent of these landforms (see pp. 189).