## 6.27 Tower Karst and Cone Karst

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Glossary

Allogenic water  Comes from nonlimestone areas and is generally more aggressive in terms of its ability to dissolve limestone.

Blind valley or steeplehead valley  A deep, narrow, flat-bottomed valley with an abrupt ending in limestone or karst landscapes, where a layer of permeable rock lies above an impermeable substrate that is created by a stream flowing in a cave until the rock above collapses, opening up the valley which is then further eroded by the stream running across the valley floor.

Doline  Sink or sinkhole depression caused by solution and collapse of soluble rocks that allows drainage underground in karst regions.

Fengcong karst or peak cluster  In Chinese it is characterized by clustered limestone hills resembling egg carton-shaped topography that form by solution where well-developed vadose water zones exist above a deep water table. Also known as cockpit or kegel karst.

Fenglin karst or peak forest  In Chinese it is characterized by isolated residual limestone hills that stand up as unusual tall towers where the water table is close to the surface. Also known as tower karst or mogote karst.

Karren  Minor jagged ridges caused by solution of soluble rock exposed on the surface.

Karst window  A place where a length of cave roof has collapsed to expose the floor of the cave below the surface.

Polje  Large, flat-floored valleys with thin overlying sediment layers in limestone karst regions where drainage is by swallow holes or may have through-flowing rivers (open polje).

Swallet  Sink or sinkhole depression into which water flows.

Abstract

Cone karst and tower karst are spectacular types of tropical/subtropical karst formed under conditions of intense karstification, and occurring primarily in China, Vietnam, Cuba, Jamaica, Puerto Rico, and Java. The cone-tower karst system is classified into two basic types: fengcong-fenglin karst developed in hard, fissure-porosity rocks, and cockpit-mogotes karst in soft, high primary porosity carbonates. Key factors in the development of cone-tower karst include tropical or subtropical climate with abundant precipitation, tectonic uplift and base-level lowering, relatively pure and thick carbonate lithology, gentle anticline/syncline structures, allogenic input and through rivers. Differentiation into the cone (fengcong/cockpit) or tower (fenglin/mogote) subtypes is strongly influenced by surface flow and the thickness of the vadose zone.

Basic features of cone-tower karst, formation, and global distribution are discussed, with special emphasis on fengcong-fenglin karst and the role of point infiltration, linear infiltration, and surface flow. The simultaneous (as opposed to sequential) evolution of fengcong karst and fenglin karst is explained by systematically analyzing the karst development, as well as the formation rate and age of fengcong-fenglin karst.

6.27.1 Introduction

Tower karst and cone karst are the result of intense karstification forming spectacular landscapes both above and below ground. They have clear climate conditions, unique terrain features and include a diverse array of karst formations. They are characterized by complicated and well-developed hydrogeological conditions, a mature development system, and high vulnerability (Zhu, 2009).

Tower karst and cone karst can be considered as two subsystems of the same karst system. Their development is closely related; the conditions under which they form are similar, but have specific differences. Tower karst and cone karst generally develop in the same area; however, their morphological and hydrogeological features are very different.

Different terms are used for tower karst and cone karst in different areas in the world. For example, tower karst is called fenglin in China, mogotes in Spain, tourelles or pitons in France, turm in Germany, pepions in Puerto Rico and haystacks in English; cone karst is called fengcong in China, kegel in Germany, gunung in Indonesia, cockpit in Jamaica and polygonal karst in English. Most of these roughly parallel terms generally mean remnant limestone hills or solution mounds, so ‘tower karst’ and ‘cone karst’ are not accurate names for all these kinds of karst.

There is an unfortunate practice to define these two karst types by the shape of the karst pinnacles or remnant hills. Firstly, the peaks/hills are not just tower or cone-shaped, but exhibit a range of different morphologies. Moreover, there are very few tower-shaped peaks in the soft Cenozoic carbonates of Java, Jamaica, and Puerto Rico. Secondly, isolated peaks may be misinterpreted as tower karst by virtue of their tower shape. The terms ‘fenglin karst’ and ‘fengcong karst’ are recommended as more accurate terms to describe these two karst landforms.

Since ancient time tower karst and cone karst have been noted for their unusual landscape. During China’s Ming Dynasty, the great traveler and geographer Xu Xiake (1587–1641) investigated the widespread tower karst and cone karst of Guangxi, Guizhou, and Yunnan from 1636 to 1638. When he inspected the karst around Guilin in detail, he vividly described the karst phenomenon including landforms, karst types, caves, hydrogeology, and hydrology in ‘The Travel Diaries of Xu Xiake’, and was the first to use the terms ‘fenglin’ and ‘fengcong’ (Figure 1).

Since the 1930s and 1940s, Chinese scholars have had renewed interest in fengcong karst and fenglin karst. The famous geographer, Tseng Chiu-suen (1982), officially defined these terms as did ‘Introduction to Karst’ by Ren Mei-e and Liu Zhengzhong (1983), after which the terms ‘fenglin karst’ and
‘fengcong karst’ came into widespread use in China. The concepts of ‘tower karst’ and ‘cone karst’ were first proposed by a French team, which explored the South China karst in the 1920s, and in China these terms are popularly used together with fenglin karst and fengcong karst.

### 6.27.2 Basic Types of Tower Karst and Cone Karst

Tower karst and cone karst are classified here into two basic categories based on the type of carbonates in which they form. Fenglin karst and fengcong karst are formed on hard carbonates. Cockpit karst and mogotes karst are formed on soft carbonates.

#### 6.27.2.1 Fengcong-Fenglin Karst

Fengcong-fenglin karst is formed in hard carbonates mainly of late Paleozoic (Devonian, Carboniferous, and Permian) and Mesozoic age. These karst landforms are grand, massive, and steep due to their strong, complete, and mature karstification. This kind of karst is primarily found in south China and north Vietnam, where it occupies a total area of almost 160,000 km². In addition, there are some smaller areas of fengcong-fenglin karst in SE Asia and Cuba.

Fengcong-fenglin karst is typical tropical/subtropical karst with exposed rocks on a large scale, spectacular landforms, diverse formations, and regional distributions. This karst system consists of two subsystems: the fengcong karst system and the fenglin karst system.

#### 6.27.2.2 Fenglin Karst

The fenglin karst subsystem belongs to the surface flow karst type. It features isolated karst pinnacles separated by surface flows into lumpy, island-like, or strip-shaped peaks on a flat surface such as a valley, basin, polje, or plain. Depending on the lithology, stratigraphy, and structural geology of an area, the peaks can take the form of towers, cones, columns, or combinations of these shapes. They range from dozens of meters to more than 200 m in height and from dozens of meters to 200 m in diameter.

Pure, thick, and horizontally bedded limestone normally develops into towers or columns, such as those of the Guilin area; whereas thinly bedded limestone and dolomite forms cones or gentle mounds, such as those along the south bank of the Yangtze Gorges area. In areas of limestone overlying dolomite, peaks may develop with tower tops and conical bases, such as those in Liuozhou, Guangxi, which were described as ‘cones in a bag’ by Xu Xiake (1637).

One of the features of fenglin karst is the great number of caves in the bodies of the peaks, the most common of which are foot caves, which inject surface water into the aquifer. In mature fenglin karst areas the water table is near the surface, forming an epiphreatic aquifer. Normally the surface landscape includes deep pools, ponds and lakes, as well as a complete surface hydrological network (Figure 2). The vadose zone between the peaks is insignificant or entirely absent.

There are various fenglin karst morphologies, including valley fenglin, polje fenglin, plain fenglin and isolated stone peak plains. Valley fenglin karst occurs along the banks of major surface rivers. Flooding plays an important role in the development of this type of fenglin karst. Polje fenglin karst mainly occurs along the karst/nonkarst border, where it develops primarily due to the flow of allochthonous water and floods. However, polje fenglin karst may also occur in large depressions whose bottoms are near the water table. Surface rivers and isolated peaks are signatures of this kind of karst.

Plain fenglin karst consists of plains with epiphreatic features and isolated peaks – normally also with small-scale islands of fengcong (e.g., Guilin). The main driving forces for the formation of plain fenglin karst are the flow of allochthonous water from surrounding areas and rainy season floods. Where isolated peaks are quite far away from each other, the area is referred to as an isolated stone peak plain.

#### 6.27.2.3 Fengcong Karst

The fengcong karst subsystem is a type of infiltration karst. On the surface it consists of peak clusters with connected bases and many ‘sinking water’ features such as shafts, sinkholes,
dolines, depressions, valleys, gorges, and tiankengs (large collapse dolines). There are large-scale cave systems and subterranean river systems underground, as well as vertical shafts ranging from several tens to over a thousand meters deep.

The steep and imposing fengcong landscape is spectacular, with peaks that are mainly cone-shaped (Figure 3), although some may be towers or columns. Many saddles occur between the peaks due to the dolines, depressions, and valleys situated among the peaks. The height difference between the peaks and the saddles or depressions (including dolines) varies from dozens to several hundreds of meters. Those with a height difference more than 200 m are termed ‘deep depression fengcong.’ Fengcong karst areas generally have through rivers, but not a complete surface hydrological network. The water table is deep and the aquifer has vadose, epiphreatic, and phreatic zones.

Fengcong karst morphological types include doline fengcong, depression fengcong, and dry valley fengcong. In China these morphologies can occur together in large areas of fengcong karst or in fengcong karst catchment areas, where they are always arranged in the above sequence from the surface drainage divide to the margin of the fengcong karst area. This can be explained as a result of the progressive increase in the dynamics and energy of karstification. Examples occur in the fengcong areas of Qibailong, Dashuwei and Mulun in Guangxi, as well as Maolan and Longgong in Guizhou.

The differences between the fenglin and fengcong sub-systems are due to uneven energy distribution, uneven intensity of karstification and geologic self-organization.

Fengcong karst dominates the fengcong-fenglin karst system in China and Vietnam. This is due to several factors, which favor the formation of fengcong karst: the effects of allogetic input and a relatively stable base level, the relative dynamic stability of the fengcong karst system, and the large-scale Quaternary tectonic uplift in the fengcong-fenglin karst areas.

6.27.2.4 Remote Sensing of Fengcong-Fenglin Karst

Fenglin karst and fengcong karst can be clearly identified in satellite imagery. Fenglin karst appears as isolated peaks or hills on a plain, or separated islands, blocks or strips of peak clusters, or even as a surface river network. Fengcong karst appears in two patterns in satellite imagery. The first pattern is egg box-shaped, which generally indicates hemispherical fengcong karst with peak-depression height differences <100 m. Examples in China include the south bank of Yangtze Gorges area where there are Triassic carbonates with interbedded non-carbonates. The second pattern, which has the appearance of scales or side-lit waves, is indicative of typical dolines, depressions and cones as well as ridges. Most of the fengcong karst in China and northern Vietnam falls into this category. Good examples also occur in Java, Jamaica, and Puerto Rico.

6.27.2.5 Comparison of Fengcong Karst and Fenglin Karst

Fengcong karst is characterized by the following:
1. Morphologies include doline (dry valley) fengcong, depression fengcong, valley fengcong, and polje or marginal polje fengcong, which occur in sequence from the watershed outward.
2. Epikarst, vadose, epiphreatic, and phreatic zones.
3. A complete, well-developed subterranean hydrologic system, which usually includes large caves, and cave chambers.
4. Many surface and subsurface landforms, including tiankengs, karren, pinnacles, dolines, sinkholes, shafts, natural bridges, dry valleys, blind valleys, swallow streams, depressions, poljes and karst springs, as well as solution features and collapses.

Fenglin karst is characterized by the following:
1. Morphologies include valley fenglin, polje fenglin, plain fenglin, and isolated stone peak plains.
2. An incomplete or absent vadose zone, but well-developed epiphreatic zone.
3. A network of surface rivers.
4. Surface planation and development of isolated peaks.
5. Well-developed caves, particularly foot caves, in peaks.

6.27.2.6 Cockpit-Mogotes Karst

Cockpit-mogotes karst occurs in relatively soft, porous Cenozoic carbonates – mainly Paleocene to Miocene thick bedded limestone, reef limestone, and limy dolomite. In Java, Jamaica, and Puerto Rico there are examples of cockpit-mogotes karst that cover wide areas and display obvious karst features. These landforms are normally shallow, rounded, and gentle. It is a typical ‘young’ karst.

Cockpit, kegel, and mogotes are all terms used in Java, Jamaica, and Puerto Rico to describe karst formed in Neogene carbonates. These ‘young’ karsts have major differences in morphology, formation, and hydrogeological features where compared to the typical cone-tower karst occurring in the ancient, hard carbonates of southern China and northern Vietnam (i.e., fengcong-fenglin karst). However, the fundamental
development conditions of carbonate strata and humid tropical or subtropical climate are basically the same. Therefore, the authors use the terms ‘cockpit karst’ and ‘mogotes karst’ as the soft-rock analogs of fengcong karst and fenglin karst, respectively.

### 6.27.2.7 Cockpit Karst

Cockpit karst consists of many terrain elements with various degrees of karstification, including negative landforms such as solution fissures, solution holes and dolines, closed valleys and depressions arranged one after the other; chain, polygonal and round ridges; and cone-shaped or hemispherical remnant hills. The height differences between positive landform and negative landform are mainly within several dozens of meters, and seldom over 100 m. Dry valleys in various sizes commonly occur, as in a few cases examples of poljes exist in Jamaica. Swallets exist in some parts of the area. Little surface water exists, and no surface streams, with the exception of a single through river, which flows through the karst area. The depth of the water table ranges from dozens of meters to over a hundred meters below the surface. Most cockpit karst areas have porous aquifers that are advantageous for water extraction; however, they are highly vulnerable to groundwater pollution or salt water intrusions. Similar to the domination of cone karst or fengcong karst in China and Vietnam, cockpit karst dominates the karst of Java, Jamaica, and Puerto Rico, comprising more than 95%.

### 6.27.2.8 Mogotes Karst

Although ‘mogotes’ means ‘tower’, mogotes karst mainly features rounded or semispherical remnant hills with gentle slopes, with a network of valleys or plains (Day and Tang, 2004). The remnant hills are generally dozens of meters in height and diameter, and a few of them have steep cliffs. They primarily occur along the edge of karst blocks in the lower reaches of the drainage area, and/or along areas of isolated hills at the edge of poljes. Some tongues of mogotes karst also extend in into cockpit areas. Mogotes karst areas may have surface streams, and the water table is shallow. This is beneficial for local agriculture and development, thus mogotes areas are often more densely populated than other karst areas. This type of karst is well formed in Jamaica and Puerto Rico.

### 6.27.3 Tower Karst and Cone Karst around the World

In current academic circles, ‘tower karst’ and ‘cone karst’ are widely used as generic terms for tropical karst and subtropical karst. This kind of karst may be classified into two basic types. The first is hard rock karst, which is in hard, well-lithified pre-Cenozoic carbonates, which occurs on a large scale in southern China and northern Vietnam, with lesser exposures in Thailand, Philippines, Burma, Laos, Cambodia, Malaysia, Indonesia, Cuba, and Mexico. The second type is soft-rock karst, which occurs in soft Cenozoic carbonate found in regions of Java, Jamaica, and Puerto Rico, with smaller distributions in Papua New Guinea, Belize, Guatemala, and some other places with less obvious karst features.

### 6.27.3.1 South China

The fengcong-fenglin karst developed in hard carbonates is primarily located in China and northern Vietnam (Figure 4). China has approximately 140 000 km² of fengcong-fenglin karst (98% of the fengcong-fenglin karst worldwide), of which 92% is fengcong karst. The typical fengcong-fenglin karst area in southern China extends north up to the southern bank of the Yangtze Gorges area, at about 30° N. Here the landforms are shallow depressions and valley fengcong karst. South of 27° N there are areas of fengcong karst spanning thousands to tens of thousands of square kilometers in south-east Yunnan, south Guizhou, and north-eastern, and south-western Guangxi. Of these areas, Guangxi has the lion’s share of the fengcong-fenglin karst, with 85% of the fengcong karst and 95% of the fenglin karst.

The average altitude of the fengcong-fenglin karst in southern China decreases from 2445 m in the north-west to 240 m in the south-east. Regional distributions of fengcong karst with massive peaks and peak-depression height differences greater than 200 m are mainly located along tributaries of the Hongshui River. Fengcong karst is located near watershed boundaries and on the banks of through rivers, whereas fenglin karst is mainly found in areas with allogenic inflow, which forms diffuse surface flow, as well as zones under strong lateral effects of surface rivers (Figure 5).

### 6.27.3.2 Northern Vietnam

In Vietnam fengcong-fenglin karst mainly occurs in the north. In Cao Bang and northern Ha Giang fengcong-fenglin karst is contiguous with that of Guangxi, China. Fengcong-fenglin karst is also located in western Lang Son and eastern Thai Nguyen; along the right-hand bank of Tuo River from Lai Chau through north-west and south-east San La to the Cuc Phuong National Park in Ninh Binh; and in north-east Thanh Hao and Binh Minh, where it is consistent with a linear fold zone. Low-relief fengcong-fenglin occurs on the edge of the alluvial plain extending north and south from Ha Nam to Mieu Mon in northern Ninh Binh. Perhaps the most famous fengcong-fenglin karst in Vietnam is the fenglin in Ha Long Bay and Cam Pha, and fengcong on Cat Ba island (Waltham, 2005).

The fengcong-fenglin karst of Vietnam shares many features with that of China. In Vietnam, as in China, a close relationship exists between the fenglin karst and the fengcong karst in spatial distribution, and the fengcong karst subtype covers a greater area than the fenglin karst subtype (although it comprises a smaller percentage of the total fengcong-fenglin karst than in China). The fengcong-fenglin karst also decreases in elevation from north to south and from north-west to south-east.

However, the fengcong-fenglin karst of Vietnam has several unique features. In Vietnam there is low-relief fengcong karst with very complete landforms and structures. Vietnam also has fengcong-fenglin karst submerged in seas, lakes, or alluvium (most notably the fengcong-fenglin karst system in the sea at Ha Long Bay and Cam Pha, which is the result of fault
Figure 4  The distribution of fengcong-fenglin karst in south China and in north Vietnam.
subside during the latest tectonic movement and the accompanying marine transgression). The fengcong-fenglin karst features tidal sea caves as well as caves above the water level, sea-level dissolution notches, and dolines and depressions immersed in sea water, which are called 'hongs' locally (Waltham, 2007).

**6.27.3.3 Other SE Asian Countries and Cuba**

In south-east Asia, outside of Vietnam, wide areas of hard carbonates occur in Thailand, Laos, and Burma. However, in these countries regional distributions of typical tower or cone karst rarely occur inland. Solitary tower-shaped peaks and sea-erosion caves occur in some coastal area and bays, but no other typical cone-tower karst features (Waltham, 2008). This may be due to an insufficient area or continuous thickness of pure carbonates, resulting from a change in lithofacies as compared to Vietnam.

In Cuba, Cretaceous and Jurassic hard (and moderately hard Eocene) carbonates outcrop over 70 000 km² (Day, 2009). In Sierra de Los Organos in south-west Havana, there is a limestone area, which is 75 km-long north-east to south-west and 6 km wide, with a total area of 400–500 km². In the south, widespread allogetic input has shaped a red soil plain with a few isolated stone towers (called mogotes locally) protruding from it, each dozens to a hundred meters high. In the north, a limestone highland extends in the east–west direction (Zhu, 1990). Maybe because of its limited width, the peaks and depressions are not as dense as those in the fengcong karst of China, although the landscape is still quite spectacular and the isolated peak plain in the Vinales valley has been developed into a tourist attraction.

**6.27.3.4 Jamaica**

The karsts of Puerto Rico, Java, and Jamaica are the world’s three great examples of young tropical soft-rock karst. Jamaica is a major area of humid tropical soft-rock karst, with spectacular examples of mogotes-cockpit karst. The term 'cockpit karst' originates from this area. The karst of Jamaica covers 7500 km² (Day, 2009) and is located on the mid-island highlands where altitudes vary from 300 to 700 m. It is comprised of 100–300 m of coarse-grained, light white to brownish-yellow Eocene carbonates comprising pure or dolomitized calcite. The former’s mechanical strength is higher than the latter’s. Joints and faults are well developed, and joints trending north-east to south-west control the cave and landfill development.

Various karst erosion planes and thus different karst formations and landforms are presented in the karst of Jamaica:

- **Linear cockpit karst**: in this landscape the negative landforms are aligned in a single direction and parallel elongated ridges occur that have not yet formed into regular haystack hills. Examples occur around St. Bran’s Burg.
- **Labyrinth cockpit karst**: in this landscape the negative landforms are aligned along two axes – the ridges have been divided into hillocks whereas linear depressions have become dolines. This kind of landform occurs throughout the karst of Jamaica, and the area around Mandeville is a good example.
- **Polygonal cockpit karst**: in these areas the karstification is significantly deepened. The area of the positive features (cone-shape remnant hills) is almost equal to that of the surrounding negative features (valleys) and the cone karst is nearly mature (i.e., it has a complete set of formations, a perfect structure, typical function, and is relatively stable). Examples occur in Alexandria, Inverness, and Phoenix Park.

Other mogotes-cockpit karst forms in Jamaica include plains and valleys with isolated hills, as seen in Chudleigh and Walderston. Data and satellite images also indicate that there are poljes in excess of 1 km-long at the east and west ends of the Jamaican karst. Additionally, Jamaican karst features many collapsed dolines and shafts deeper than 200 m (Day and Chenoweth, 2004).

**6.49.3.5 Puerto Rico**

The karst of Puerto Rico is located at the northern end of the island, continuously extending from Aguadilla on the west coast to Sabana Seca, covering about 1500 km² (Day, 2009). The karst inliers of Puerto Rico’s few carbonate outcrops are comparable to those of Jamaica. They include linear cockpit karst and labyrinth cockpit karst, as well as flat areas in the initial stages of karstification and plains with remnant hills. Cockpit karst dominates the landscape, although mogotes karst also commonly occurs.

The most significant features of Puerto Rican karst are the four through rivers that run south to north through the karst area. The two rivers in the east have wide, box-shaped valleys, wide terraces that developed in more than two stages, and steep cliffs tens to a hundred meters high. The two valleys are parallel and very similar in terms of length and scale. In contrast, the two through rivers to the west are both having narrow streams in serpentine valleys, running from south to north into the sea. It is interesting that the hillocks extend northwards with the valleys. This may be because karstification along both banks of the valley is intensified by the valley’s drainage. The four through rivers must be developmentally of the same age as the local karst.
In Puerto Rico the karst is mostly covered by non-carbonates, with few carbonate outcrops presenting microlandforms such as karren and grikes.

### 6.27.3.6 Java, Indonesia

The karst of Java, Indonesia is located in the middle of the island in Miocene reef limestone. It extends in an east–west direction along the south coast, from around Kretek in the west to Pringkuku in the east, mainly within the Special Region of Yogyakarta, with a total area of more than 1300 km² (Haryono and Day, 2004).

The local name for Java’s karst is ‘gunung sewu’, meaning ‘a thousand peaks’. Other names include ‘kegel karst’ (Lehmann, 1936) and ‘sewu cone karst’ (Waltham, 2004). In satellite photos the topography has the appearance of small ripples or blotches. These ripples are smaller than those which can be seen in satellite imagery of Jamaica and Puerto Rico, perhaps due to the relative induration of the strata. The karst highlands are 250 to ~ 600 m above sea level. The low, hemispherical limestone hills are tens to 200 m in diameter and dozens of meters tall. Normally the peaks are not sharp in profile. There are also landforms in the shape of discontinuous ridges (labyrinth cockpit karst), which indicate immature karst development. The karst highlands do not have surface water systems, but rarely karst windows occur. Many short dry valleys occur as well. For example, in the karst near Giritontro there is a dry valley that once contained a through river. It is important for research into the local karst development.

Java’s karst is primarily cockpit karst, with very little mogotes karst. A possible major reason for this morphology is the lack of allogenic input.

### 6.27.4 Controls on the Development of Fengcong-Fenglin Karst

Compared to other types of carbonate landform, the development threshold for fengcong-fenglin karst is rather high, requiring specific conditions for the system’s formation.

**6.27.4.1 Lithology, Stratigraphy and Regional Geology**

The most basic requirement for the formation of fengcong-fenglin karst is pure and hard carbonate strata, of which pure limestone is best, followed by dolomite. Differences in lithology and sedimentary characteristics have a direct effect on the morphology of fengcong-fenglin karst. For example, pure, thick limestone may develop into fengcong karst consisting of huge, steep-sided peaks with great peak-depression height differences, and fenglin karst consisting of tower or column-shaped peaks. In contrast dolomite and thin-bedded limestone will only develop into hills with smooth profiles, such as conical peaks with rounded summits, smooth hills or gently undulating terrain (Figure 6).

Secondly, there must be sufficient continuous thickness of carbonates without major impermeable layers. In the major fengcong-fenglin karst areas of China the carbonates are 2000–4000 m thick, and even 11 000 m thick in extreme cases. A complete fengcong-fenglin karst system cannot form and be preserved if there is insufficient continuous thickness of carbonate rocks, or if there are impermeable layers.

Finally, the carbonates must be widespread, ideally outcropping over a relatively independent drainage area, or at least the main part of it. This is why large areas of fengcong-fenglin karst commonly have gently dipping strata.

### 6.27.4.2 Tropical or Subtropical Climate with Abundant Precipitation

It is well-known that climate is of great importance in karstification, since it directly relates to the sources of karst dynamics and energy, including precipitation, rainfall intensity, temperature, and biological factors. Fengcong-fenglin karst is a high efficiency karst type – the karstification takes place under conditions of high energy exchange and strong dynamic activity. Thus, high precipitation is a must. Based on the observations around the world, the minimum precipitation required for fengcong-fenglin karst formation is 800–1000 mm a⁻¹. Precipitation of 2000–3000 mm a⁻¹ is optimal and, given that all other conditions are favorable, it will lead to the formation of perfect fengcong-fenglin karst. Precipitation rates much higher or lower than this optimum level are likely to result in gently sloping landscapes with smaller peak-depression height differences. Highly intensive precipitation may result in big streams (in fengcong karst) and floods (in fenglin karst). The former may cause huge dynamic damage in the epiphreatic zone, for example, collapses along subterranean river passages. Tiankengs, which are formed where huge collapse chambers break though to the surface, are an extreme case, among which Dashiwei tiankeng in the fengcong karst area of Leye, Guangxi is an outstanding example of this dynamic behavior. Likewise, surface floods play an important role in the development of plain fenglin karst and valley fenglin karst.

Temperature is another key factor. High temperature in combination with high humidity results in denser biota and thus greater sources of CO₂ and increased dissolution. The fengcong-fenglin karst of China and Vietnam is mainly located in areas where the average annual temperature is 16–22 °C, and the average annual precipitation is 1500–2200 mm with distinctive dry and rainy seasons.
6.27.4.3 Tectonic Uplift and Local Base Level Lowering

Tectonic uplift and base level lowering are driving forces behind the development of fenglin-fengcong karst (particularly fengcong karst). Uplift results in river incision, base level lowering, vadose zone development and increased hydrologic dynamics, thus providing continuous dynamics for karstification. When uplift is much faster than the local total denudation rate, it is advantageous for fengcong karst development. Examples occur in southern Guizhou, western Guangxi and the Yangtze Gorges, where large-scale fengcong karst occupies a dominant position in the landscape. However, slow uplift, especially an uplift rate similar to the local denudation rate, is advantageous for fenglin karst development. Examples can be seen occurring in central and south-eastern Guangxi.

6.27.4.4 Geological Structures

The influence of geologic structures on the development of fengcong-fenglin karst can be observed as follows:

1. Fengcong-fenglin karst develops on tectonic platforms because they facilitated the thick and continuous deposition of pure and stable carbonate rocks.

2. Folds and fractures directly control the exposure and spatial distribution of the carbonate strata. Gentle anticlines are most favorable for the development of fengcong karst, thus fengcong-fenglin karst mainly occurs along anticlinal/synclinal axes, respectively.

3. Excluding bedding plane partings and surface weathering fractures, the permeability of hard carbonates depends mainly on the degree of fracturing in the rock. However, highly compact joints, highly fragmented rocks and highly intensive folds are not favorable for the formation of fengcong-fenglin karst. Gentle folds and subhorizontal bedding not only favor the formations of conjugate joint sets that are vertical and deep but also result in the widespread exposure of the same carbonate rock layer, thus these conditions are the most advantageous for the development of fengcong-fenglin karst. They also favor the formation of collapse chambers and even tiankengs above subterranean rivers.

4. Some geologic structures, for example, large faults, may expose previously deeply buried carbonates.

5. Quaternary tectonic movement has greatly contributed to the formation of vast fengcong-fenglin karst areas in China and Vietnam.

6.27.4.5 Water Table Control

The depth of the water table plays a decisive role during the genesis, development, and evolution of fengcong-fenglin karst. Fengcong karst can only form well in environments with a deep water table and a well-developed vadose zone. In contrast, fenglin karst can only develop where there is no vadose zone and the water table is close to the surface. Fengcong karst can transform into fenglin karst only if the water table rises to the surface, that is, if it changes from deep phreatic to epiphreatic and the vadose zone entirely disappears. As Tseng Chiu-suen wrote:

> Groundwater in the Guizhou plateau generally flows vertically, resulting in negative landforms. When the groundwater forms a system, the landforms develop into fengcong karst. When the groundwater circulates horizontally, there are rivers on the surface, and fenglin landforms are shaped. (Tseng, 1960)

6.27.4.6 Allogenic Input

Fengcong-fenglin karst regions always border non-karst regions. Karst drainage areas normally include some non-karst areas. For example, the Li River drainage area in the Guilin basin is 7423 km², of which 5080 km² (65.5%) is non-karst (Zhu et al., 1988). In these areas, extrinsic water from the non-karst sectors flows into the karst sectors, and is more corrosive than the intrinsic water. According to Liu Zhaihua:

> The dissolution rates of limestone and dolomite in extrinsic water are quite high, some even reach 13.6 mm a⁻¹, which are dozens or hundreds of times of those of the carbonate rocks samples in normal soil. This indicates that extrinsic water plays a vital role in shaping fenglin karst. (Liu, 2007)

The author has pointed out many times that cave inlets may commonly be larger than the corresponding outlets. This is because the water flowing into a cave entrance may be totally or partially extrinsic, which is more corrosive than pure intrinsic flow. It may also have great physical dynamic and working energy from floods, commonly with suspended sediments, resulting in overall corrosive rates that are rather high.

6.27.4.7 Through Rivers

In fengcong-fenglin karst, fenglin karst has comprehensive surface hydrological networks, whereas fengcong karst instead has subsurface hydrological networks. However, longitudinal or transverse (primarily the latter) through rivers commonly pass through fengcong karst areas (Figure 7).

> Figure 7 A through river (Lijiang River) in a fengcong karst area in Guilin, Guangxi, China. Photo by Zhu, X.W.
A through river is firstly an antecedent river, and in most cases it has incised a gorge. It also constitutes the lowest base level of the fengcong karst area through which it passes, providing a basis for evaluating the thickness of the vadose zone and of the scope and speed of local tectonic uplift. It is a key factor in the development of local caves and subterranean rivers, and the adaptability of the aquifer hydrodynamics. Thus, it is important for research into the age and phases of fengcong karst. The development and formation of through rivers in Puerto Rican karst are most noticeable, and seem to be synchronous with the local karstification. It also seems clear that through rivers enhance the formation and development of fengcong karst and cockpit karst.

6.27.5 Processes in Fengcong-Fenglin Karst Development

Although fenglin karst and fengcong karst both belong to the same large-scale regional system, there are significant differences in the morphology, hydrological characteristics, and development processes of the two subsystems. At present the formation and evolution of fengcong-fenglin karst is not well understood, and there is a great divergence of views, especially in China.

6.27.5.1 Development by Collapse

The importance of collapse processes in the development of fengcong-fenglin karst should be stressed. The cliffs of fenglin karst towers, the cones of fengcong karst, the sides of poljes and some underground river resurgences are all formed in part by collapse, commonly involving foot-cave erosion in fenglin areas. Collapse also plays a key role in tiankeng (collapse doline) development in fengcong karst areas.

6.27.5.2 Development by Dissolution

The different effects of point infiltration, linear infiltration and surface-flow form a basis for the contemporaneous formation of fenglin and fengcong.

6.27.5.3 Surface Flow in Fenglin Karst

Regardless of the original morphology of a fenglin karst area, the development of fenglin karst requires surface flow, thus it is called surface-flow karst. Stochastic flow, storm water, surface floods, and allogenic water course migration are the basic dynamics for the formation of fenglin karst. Unlike fengcong karst development that does not involve surface river action, fenglin karst development is closely related to surface flow.

6.27.5.4 Vertical Infiltration in Fengcong Karst

Meteoric infiltration gives rise to fengcong karst topography. The karst features include karren, stone teeth, stone forest, sinkholes, shafts, dolines, blind valleys, depressions, and dry valleys, all of which are characteristic of dissolution by sinking water. Thus the authors term fengcong ‘infiltration’ karst, which can be further classified into point infiltration and linear infiltration karst.

In hard, gently dipping strata, cross joints are the main dissolution pathway (little water flows along bedding plane partings) in the early stages of karst development. Point infiltration forms dolines and typical cone karst, whereas linear infiltration forms dry valleys and ridges in linear cockpit karst. A mixture of point infiltration and linear infiltration results in irregular fengcong terrain. In pure, thick carbonate rock areas, most short dry or blind valleys with similar relative heights at the valley bottoms are the result of linear infiltration. Only few of the short valleys are the result of allogenic water input (and they are generally deeper than those due to linear infiltration). Deeper, longer, and meandering valleys with residual alluvial sediment may be remnants of old surface rivers.

Many infiltration forms have been studied in detail, and here dry valleys in fengcong karst are discussed in particular. Like dolines and depressions, dry valleys commonly occur in fengcong areas. Generally two types of dry valleys occur in typical fengcong karst. The first type is the ‘structural solution dry valley’ which develops along one or two conjugate joints, commonly hundreds or even thousands of meters long. This is the most common type of dry valley, and can be seen clearly in satellite imagery. These valleys are straight, and arranged parallel or crossing depending on local jointing.

Like dolines and depressions, dry valleys originally formed by meteoric infiltration. If shafts are a type of point infiltration karst, then structural solution dry valleys are linear infiltration karst. Infiltration along tensional fractures is the basis for the formation of structural solution dry valleys, as each fracture will collect equal amounts of rain in a linear direction. If the infiltration is not collected uniformly, then the result is shafts and depressions or a nonuniform or discontinuous series of dry valleys. From this the authors can conclude that in the development of fengcong karst there is coordination not only between peaks and negative point features (e.g., shafts and depressions), but also between ridges and negative linear features. This can be seen clearly in both hard and soft-rock karst.

The second type of dry valley is a ‘surface flow dry valley’ which was initially formed by surface water. Surface flow dry valleys are large in scale, but relatively few in number, and do not occur throughout the whole fengcong area – they occur at low elevations. A surface flow dry valley often has an obvious meandering river course and alluvial deposits. Generally there will be a new underground river course indicated by springs or karst windows. So it is very easy to identify this type of dry valley. Examples include the 6 km-long Shantiziya-Qiutianlong dry valley in the Liuchong River drainage, Guizhou (Yang, 2003a), Changyangcao–Heidong dry valley in Qingjiang River drainage, Lichuan, China (Qian, 2001), and Giritontro dry valley in western Java. Additionally, in quasifengcong karst areas there are also dry valleys that were ancient hydrogeological networks.

6.27.6 Stability and Age of Fengcong-Fenglin Karst

6.27.6.1 Fengcong-Fenglin Karst System Stability

6.27.6.1.1 Fengcong karst subsystem stability

The fengcong karst system is stable under moderate changes in development conditions and environment. Fengcong
development will continue until there is no longer sufficient thickness of carbonates to sustain a vadose zone, and the evolution of fengcong karst into fenglin karst will not occur if the saturated zone does not rise to the surface.

6.27.6.1.2 Fenglin karst subsystem stability
Fenglin karst consists of surface flow and remnant peaks (mostly towers). Allogenic water is the main source of energy. Fenglin karst is typical surface flow karst, and can be found in areas with relatively low elevation, relatively more river networks or allogenic input, as well as the lower reaches or headwaters of rivers. Fenglin karst is formed when the vadose zone thins and is eliminated, and will continue under small relative changes of the base level. When allogenic input weakens or disappears and the base level descends quickly, the development of fenglin karst will cease or change into doline and fengcong karst. This is the rejuvenating evolution or 'double-circulation' of fenglin karst (Yang et al., 1998). Thus, the stability of the fenglin karst subsystem is weaker than that of the fengcong karst subsystem.

6.27.6.2 Fengcong-Fenglin Karst Development Age
Differing opinions exist as to the age of fenglin karst and fengcong karst in China, in part due to its complicated topography, geological structure, and lithological age, as well as the great geological environment changes that the area has undergone.

In the 1940s the geological geographer Yang proposed that south China’s landforms could be divided into three physiographic stages: Daloushan stage (late Cretaceous to Paleogene), Shanyuan stage (Neogene), and Wujiang stage (Quaternary). Based on this theory, fengcong development is believed to have occurred during the late Daloushan, whereas fenglin development occurred during the Shanyuan stage. Thus, in China it is widely believed that fengcong karst is 65 Ma old.

In the last 20 years, scientists in China have established a series of monitoring sites in karst regions to record corrosion rates in the air, ground, and soil. They have determined corrosive–erosive base levels, being similar to erosional landform development, which includes particular evolution order from karst highland development firstly, then through young stage, mature stage and aged stage, accomplishing a karst cycle.

Specifically, the fengcong-fenglin evolutionary cycle proceeds from youth (fengcong) to maturity (fenglin), and finally old age (isolated peak plain). Rejuvenation by tectonic uplift will then cause the cycle to repeat. This theory was introduced in 'Introduction to Karst' by Ren and Liu (1983), which had an enormous influence on geological research in China.

The geomorphological cycle theory proposed by M.W. Davis and others is mainly concerned with non-karst landform or karst topography under 'normal conditions.' However, we must consider that under identical tropical and subtropical climate conditions, the formation, development, and evolution of landforms will be different for soluble strata and non-soluble strata. The main external processes influencing the development of non-karst landforms are denudation, weathering (excluding glaciation and volcanoes) and erosion by surface water (Tseng, 1964). They occur in regional distribution patterns and development is controlled by surface river systems. However, in fengcong-fenglin karst the main development dynamics are dissolution and collapse, as well as the processes of point infiltration, linear infiltration, and groundwater flow as discussed above.

According to field corrosion experiments, the dissolution of carbonate rocks is astonishingly rapid under humid tropical and subtropical climate conditions (Liu, 2007). Fengcong-fenglin karst is much less than 10 Ma old, although it may occur in areas where the history of karstification is much older and has undergone multiple stages. In geological terms, the development of fengcong-fenglin karst occurs in a very short time, and it is not comparable to non-karst development.

Thus, the geomorphological cycle theory does not include fengcong-fenglin karst as we know it today, and for historical reasons, it has become a barrier to fully understanding the development and evolution of fengcong-fenglin karst.

6.27.7 Genetic Relationship of Fenglin Karst and Fengcong Karst

In China there are several viewpoints concerning the genetic relationship and evolution of fenglin karst and fengcong karst.

6.27.7.1 Karst Cycle Theory
The most common theory is that of the karst cycle, which is based on W.M. Davis’ theory of geomorphic formation. According to this theory, karst development was controlled by corrosive–erosive base level, being similar to erosional landform development, which includes particular evolution order from karst highland development firstly, then through young stage, mature stage and aged stage, accomplishing a karst cycle. Specifically, the fengcong-fenglin evolutionary cycle proceeds from youth (fengcong) to maturity (fenglin), and finally old age (isolated peak plain). Rejuvenation by tectonic uplift will then cause the cycle to repeat. This theory was introduced in 'Introduction to Karst' by Ren and Liu (1983), which had an enormous influence on geological research in China.

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6.27.7.2 Karst Hydrogeomorphology Theory
The second viewpoint is that the development of fenglin karst and fengcong karst is the result of flowing karst water. Fengcong karst can evolve into fenglin karst through erosional parallel recession, erosional base extension; fenglin karst can evolve into fengcong karst by fenglin karst plate erosion and doline development (Tan, 1993; Yang et al., 1998).
6.27.7.3 Uplift Rate Theory

The third theory is that the development of fenglin karst and fengcong karst may be explained by comparing the rate of tectonic uplift to the rate of local erosion, denudation, and kastification, that is, fengcong karst forms when the rate of uplift is greater than the erosion rate; fenglin karst forms when both are nearly equal (Zhang, 2006).

6.27.7.4 Simultaneous Evolution Theory

The final theory is that of ‘simultaneous system evolution of fenglin karst and fengcong karst’:

1. Fenglin karst and fengcong karst belong to a synergetic coexistence system. Fenglin is surface flow karst, fengcong is infiltration karst, and there are great differences in the formation and morphology of the two subsystems.

2. The same basic conditions are required to form both fenglin karst and fengcong karst: thick hard carbonate rocks, high levels of precipitation, and a tropical or subtropical climate. However, there are great differences in the development conditions for the two subsystems. For example, the development of fengcong karst requires meteoric infiltration (main source of energy); tectonic uplift/lowering of the local base level in excess of the local erosion rate; and a deep water table and corresponding vadose zone. In contrast, the formation of fenglin karst requires allogenic water flowing in surface streams; the water table must be close to the surface; and there should be a well-developed network of surface flow.

3. The generation and development of fenglin karst and fengcong karst in southern China and Vietnam was simultaneous and synchronous. That is to say, fenglin karst did not evolve from fengcong karst. Fengcong karst may in fact be older than fenglin karst, although it looks younger. The fact that they occur together in a single region or drainage area indicates that they developed contemporaneously.

4. In a given open system (e.g., region or drainage area) differentiation into fenglin karst and fengcong karst is the result of spatial anisotropy in intensity and dynamics as well as uneven distribution of material and energy inputs and kastification outputs. Fenglin karst and fengcong karst evolved, respectively, from the beginning (Figure 8). The picture indicates that where the rocks are exposed to the surface and subject to folding and faulting there will be differences in karst dynamics (vertical infiltration and surface flow) and efficiency (strong and weak) due to differences of topography (high and low), geological structure (anticline and syncline) and relationship to non-carbonate rocks layers. The more advantageous the surface flow, the more intensive the surface karstification, which will result in fenglin karst. In contrast, in areas of higher relief the precipitation will undergo vertical infiltration instead of horizontal surface flow, resulting in weaker surface karstification and doline-like landforms leading to fengcong karst. As a result of these differing intensities of surface karstification, fengcong karst looks younger than fenglin karst of the same age (Figure 8).

5. The fengcong karst subsystem is more stable than the fenglin karst subsystem. This is due to its larger vadose zone, complete system structure (especially aquifer) and better adaptability to changes in environment and generating conditions. This is one of the reasons that fengcong karst occupies a much larger area than fenglin karst.

Figure 8 The simultaneous evolution of fenglin karst and fengcong karst. Reproduced from Zhu, X.W., 1988. Guilin Karst. Shanghai Scientific and Technical Publishers, Shanghai.
6. Given sufficient thickness of carbonate rocks, fengcong karst can change into fenglin karst if other essential conditions are met: the vadose zone must disappear, the water table must be close to the surface and a network of surface flow must develop. For doline fenglin karst, the major cause of its evolution into fengcong karst is a steep increase in the depth of the water table relative to the surface and the original network of surface flow degrading into dry valleys.

This theory was first proposed by Zhu et al. (1980) and discussed in depth in subsequent publications (Zhu et al., 1988; Zhu, 1991).

In contrast with the karst cycle theory, the simultaneous evolution theory proposes that fenglin and fengcong developed simultaneously by the same generating system and are spatially distributed together. The fengcong/fenglin differences are due to their different development directions, development conditions, adaptability to environmental variation, and system stability. The key factors in the formation of fenglin and fengcong karst are the internal and external conditions and dynamic changes in the environment, not the age of the landscape.

References


Biographical Sketch

Prof. Zhu Xuewen is a Researcher at the Institute of Karst Geology, Chinese Academy of Geological Sciences, focusing on hydrogeology, engineering geology, speleology, and karstology. Since the 1980s he has devoted himself to the investigation and study of karst and caves around China, resulting in many discoveries. Zhu Xuewen proposed the theories of 'simultaneous evolution of fenglin-fengcong karst' in 1991, 'underground river system evolution mode' in 1993 and 'tiankeng' in 2003. He has published more than 100 papers and three books.

In 1990 Zhu Xuewen was a visiting scholar at McMaster University. Over the past 20 years he has visited the UK, Ireland, Canada, the US, Hungary, Austria, Cuba, Australia, Korea, France, and Switzerland as a researcher.

Zhu Xuewen was born in Shucheng, Anhui province, China and graduated from Nanjing University in 1954. He has published more than 100 papers and three books.

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In 1990 Zhu Xuewen was a visiting scholar at McMaster University. Over the past 20 years he has visited the UK, Ireland, Canada, the US, Hungary, Austria, Cuba, Australia, Korea, France, and Switzerland as a researcher.
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