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Karst in China

Karst in mainland China is unique in the world for several reasons. Formed principally of hard pre-Triassic compact carbonate rocks, it underwent strong Cenozoic uplift, has never been scoured by continental ice sheets and has been weathered under a monsoon climate with wet summers and dry winters. The relationship between karst processes (dissolution or precipitation) and the global carbon and water cycles has been determined through monitoring at stations located in different climatic and geological environments of China. Evolution sequences for vertebrate and anthropological fossils from caves have been determined. High-resolution (100-year) continuous records of climatic variations in south China from the last glaciation through the Holocene have been obtained from karst sediments by using AMS ^{14}C and other approaches. Most of the energy resources in China, i.e. coal measures, oil and gas reservoirs, and hydropower, are influenced by the geology of karst. About a quarter of China's groundwater resources are from karstic aquifers. Thin soil and development of underground drainage systems have made the karst area in China a fragile environment. Rock desertification is a major cause for poverty in the karstland. Karst collapse with serious damages has been reported at 738 sites.

Characteristics of karst in China

Karst in mainland China totals 3 443 000 km², including bare karst, covered karst and buried karst. Bare karst covers 907 000 km² (Figure 1). Globally, it is unique having suffered strong Cenozoic uplift but escaping continental ice sheet scouring during the last glaciation. The East Asia Monsoon climate also sets Chinese karst apart from that in other regions of the world (Yuan, 1991a).

Carbonate rocks in China are mainly pre-Triassic, except in Tibet where there are more Jurassic and Cretaceous carbonate rocks (Li Datong, 1983). The porosities of carbonate rocks of different geological periods are generally less than 2% for limestone and 4% for dolomite, while compressive strengths are above 1000 kg/cm². In some other major karst regions of the world, such as southern Australia, the London Basin, the Paris Basin and Central America, the carbonate rocks are Cenozoic or Mesozoic, with poor diagenesis and higher porosity (Downing, 1993). For example, the porosities of Tertiary limestone and dolomite in the Caribbean region are generally about 16% and 31–44% respectively. The physical and mechanical properties of carbonate rocks in mainland China strongly influence karst formation and karst features. On the surface, they result in the tower landforms of south China rising abruptly from the plains. Underground, they provide supporting skeletons for thousands of streams and great halls. In South-east Asia and the Caribbean region, tower karst features in Tertiary porous carbonate rocks are lower and more rounded (Troester, 1992), even though they are developed under climates similar to that in south China. The hard lithologies in China have also provided favourable conditions for the development and preservation of numerous microkarst features, such as deep sharp karren, kamenitza, notches and scallops.

The strong Cenozoic uplift in mainland China, especially in the western part, has not only resulted in spectacular karst landform, but has also elevated karst features, formed at different geological times, to different levels. This tectonic background, along with the hardness of the carbonate rocks, has endowed China with the longest and most continuous karst record. In other karst areas, such as the South China Sea Archipelago and the Yucatan Peninsula of Mexico (Back, 1992), Quaternary uplift has been so weak that no more than sea level fluctuation occurred during glaciation and interglaciation. Accordingly, karst records are mostly post-Late Pleistocene, with the earliest one extending back to the Early Pleistocene.

The basic tectonic pattern in the eastern part of mainland China, characterised by alternating, north-east-trending belts of uplift and subsidence in the Neocathaysian System (Lee, 1939), is also important to the formation of the karst of China. It results in alternating bare karst, buried karst (karst underlying insoluble cover rocks), and covered karst (karst covered by loose sediments), and is important to the formation of oil and gas in carbonate rock reservoirs. In the bare karst of the northern Guizhou

Figure 1 The distribution of karst types in China. I subtropical karst; II arid and semi-arid karst; III high mountain karst; IV temperate semi-humid karst.

Figure 2 Karst types in south-west China.

plateau and the south-east Sichuan Basin, because of the north-east-trending close folds and insoluble intercalations in carbonate rocks, karst features including tower karst, dolinen, sinkholes, underground streams, and caves are aligned in a north-east direction, to form a unique karst region (Figure 2).

Most karst areas in northern Europe and northern America were scoured by continental ice sheets during the last glaciation. For instance, in Yorkshire, northern England, Carboniferous limestones are widespread, but there are only minor karst features such as grikes, karren, kamenitza and shallow dish-shaped dolinen on the surface. They have developed after the last glaciation and all preglacial karst forms have been entirely scoured away (Paterson and Sweeting, 1986). A Pleistocene ice sheet on the Tibet plateau remains in question, but it is generally accepted that there were no ice sheets in the eastern part of mainland China. Because of this Quaternary history, along with the strong Cenozoic uplift and the presence of hard carbonate rocks, the karst of China can be regarded as a paleoenvironmental archive of immense information capacity.

The Mediterranean region is another important karst area of the world, but it has a climate under which precipitation and temperature are ill matched for optimum karst formation, i.e. the summers are dry and the winters wet. Although the snowmelt water in the summer is favourable for the development of big cave systems, mechanical weathering has caused serious deterioration to the surface karst (Yuan and Back, 1991b). In contrast, the East Asian monsoon climate in mainland China provides a good match between precipitation and temperature with its wet summers and dry winters. Meteoric water in the summer associated with active biogenic processes can bring about intense chemical dissolution not only on the surface, but also underground. Thus in mainland China, especially in the south, the marvellous subtropical karst has tower karst on the surface and underground stream systems below.

The basic topographical and climatic framework of mainland China defined by the Qinghai-Tibet plateau and Qinglin-Dabieshan Mountain Range prompts a tripartite division of major karst types, namely, the humid subtropical karst of south China; the arid and semiarid karst of north China; and the high mountain karst of the south-west (Figure 1). Each one has its particular karst feature complex. The complex is defined as a set of well-matched macro- and micro-karst forms, surface and subsurface karst forms, and dissolutional and depositional karst forms which have developed under similar environmental backgrounds.

Tropical and subtropical karst in south China is characterised by a karst feature complex composed of tower karst, numerous dolinen, especially deeply dissected polygonal types, sharp deep kar-

ren, red soils, surface tufa, big cave systems, underground stream systems, plus many minor corrosional features and major speleothems in caves.

The arid and semiarid karst in north China has a combination of normal-shaped mountains (with dendritic drainage systems), dry valleys, tiny karren, limestone screes, loess cover, big karst springs and a few caves with fewer minor dissolutional features and speleothems.

The basic morphologic features of high mountain karst in south-west China are various frost denudation products, such as small limestone peaks, natural bridges, stone walls, limestone screes, and some karst springs. At the outlets of karst springs, along modern active faults, there may be abundant calcareous tufa along with major emissions of CO_2 .

Mechanisms of karst formation

In modern karstology, the karst process is viewed as part of the global carbon cycle and the related cycles of water and calcium (magnesium) at the interfaces between the earth's lithosphere, hydrosphere, atmosphere and biosphere. The $\text{CO}_2\text{-H}_2\text{O-CO}_3^{2-}$ triphase disequilibrium open system is called the karst dynamic system. The entry of more CO_2 into the system will form more carbonic acid and thus intensify dissolution. On the contrary, the escape of CO_2 from the system will deviate the karst process in the direction of precipitation. Consequently, the system is quite sensitive to environmental change. For example, variation in the concentration of CO_2 in the atmosphere, various biogenic processes including photosynthesis, and the status of water flow including its depth, temperature, flow rate and turbulence will all change the intensity, manner, and even the direction of the karst process. Accordingly, the only way to reveal the mechanism of karst formation is to know the characteristics of different types of karst dynamic systems under different natural conditions through field monitoring.

Since 1981, the rate of limestone denudation under different natural conditions has been observed in 13 karst areas, covering a region from Yichun, Heilongjiang province in the north to

Figure 3 The results of limestone denudation observation in a north-south transect from Yichun to Guangzhou, east China.

Figure 4 Time and space variation of pH and HCO_3^- karst dynamic system showing examples of dissolution in the Yudong underground stream, and deposition in the Sunjiawo calcreous cascade, Zhen'an County, Shaanxi, China.

Guangzhou in the south, and from Akiyoshidai, Japan (in cooperation with Dr Yoshimura Kazuhisa) in the east to Golmud, Qinghai in the west. Moreover, since 1989, seven typical karst sites have been used to study the relationship between karst processes and the behaviour of the carbon cycle, water cycle and calcium cycle in a karst dynamic system on the basis of a combined monitoring of the variation of pH, HCO_3^- and CO_2 in soil.

The results reveal the mechanism of karst formation in China from different angles (Yuan and Cai, 1988). For instance, observations of the limestone denudation rate show that the intensity of dissolution has a close relation with precipitation (Figure 3). In addition, because of the involvement of biogenic CO_2 , subsoil dissolution is generally much higher than the subaerial rate. However, in some regions like Guangzhou, the subsoil denudation is weaker than the subaerial as a result of the poor permeability of the stiff soil. In arid or semiarid regions like Beijing, because the annual mean evaporation is much higher than precipitation, the soil water readily becomes carbonate-saturated. There, the subsoil dissolution rate is lower than the subaerial and there is frequent deposition of calcite.

Monitoring the behaviour of the karst dynamic system has given a better understanding of the mechanism of karst formation in China. For example, in the Yudong underground stream, Zhen'an County, Shaanxi Province, the pH falls in summer, with a corresponding rise in HCO_3^- . This shows that, following the intensification of biogenic processes in summer, more CO_2 enters the system, thus intensifying the dissolution process. Observation of the Sunjiawo calcreous tufa cascade has shown not only similar seasonal variation, but also the spatial variation downstream from the outlet of the karst spring. It reveals clearly the processes of water flow and disturbance, the outgassing of CO_2 from the system, the rapid rise of pH, and the deposition of great amounts of calcreous tufa (Figure 4).

Observations in the Huanglong ravine, Sichuan Province, reveal that around some geothermal karst springs distributed along modern active faults, a great amount of CO_2 has been emitted into the atmosphere at concentrations as high as 23–78%. The $\delta^{13}\text{C}$ value of the gas

(-6.7‰) shows that it originated from great depth. This finding has raised a new issue for the study on the source-sink budget of greenhouse gas in the atmosphere. Rising pH values, and falling HCO_3^- downstream on the tufa cascades in the Huanglong ravine can also help determine the relationship between CO_2 degassing from karst systems and the precipitation of calcreous tufa (Liu et al., 1992).

Karst and Quaternary climatic change

Much work has been done in China to reconstruct Quaternary environmental change using data from karst sediments. Cave palaeontology, especially cave vertebrate palaeontology and palaeoanthropology, has been explored and studied for many years with success. The most important discoveries in north China are *Homo erectus pekinensis* (Black), (1929) from the Yuanrendong cave, and *Homo sapiens sapiens* from the Shandingdong cave (1933). Both caves are located on the Dragon Bone Hill at Zhoukoudian, 48 km south-west of Beijing. In recent years, multidisciplinary research in Zhoukoudian, using many new techniques, has enabled reconstruction of the Quaternary environment. In south China, detailed work has been conducted on the *Ailuropoda*–*Stegodon* fauna and the *Gigantopithecus* fauna unearthed from many caves. It is noteworthy that the now extinct *Gigantopithecus* fossils are all found in high-level caves located some 80 m above the local plain, whereas the general *Ailuropoda*–*Stegodon* fauna are found in low-level caves. A correlated evolution sequence has been established (Ji, 1977, Table 1).

In recent years, higher resolution records of palaeoenvironmental change have been obtained from detailed studies on loess in north China, and ice cores and lacustrine deposits on plateaus and high mountains of south-west China. Some of them have already provided information for reconstructing the course of Quaternary climatic change at a resolution of 100 years. However, for the broad expanse of south China, karst sediments are the only possible source of information on environmental change over long time periods. Because of the sensitivity of karst processes to environmental change, it has much potential. AMS ^{14}C dating was made of microlaminar in a 1.22 m long stalagmite from the Panlongdong cave, 37 km south of Guilin. A complete reconstruction of climatic change in south China since the last glaciation has been made on the basis of variation in the growth rate of the stalagmite, isotopic data, and trace

Figure 5 A comprehensive profile showing the results of AMS ^{14}C dating and stable isotopic data.

element concentrations (Figure 5). The time resolution is about 100 years. Several events of rapid change are revealed (Yuan, 1994).

Resources and environmental problems in karst areas

Karst in China is rich in energy resources, minerals and groundwater, and is a significant tourist attraction. The Shanxi plateau is endowed with key coal fields but it overlies a karst aquifer. In addition, with a buried karst hill oil reservoir to the east, the Ordos palaeo-karst gas reservoir on its west flank, and the waterpower resources on the middle reaches of the Yellow River, it has become the most important energy base of China. The karst plateau in south China is another important energy base because of its favourable hydropower construction sites on the Wujiang and Hongshuihe rivers. Over 20 types of mineral deposit are associated with karst processes including lead, zinc, antimony, mercury, iron, aluminium, tin, manganese, gold, uranium, copper, realgarite, kaolin, fireclay, phosphate, quartz, barite, fluorite, Iceland spar, and talc. Karst groundwater resources in China totals $2039.67 \times 10^8 \text{ m}^3/\text{a}$, more than a quarter of the total groundwater resources of the country. Importantly, the 2836 underground streams in south China, with a total length of 13 919 km and a total flow of $1482 \text{ m}^3/\text{s}$, and the more than 50 big karst springs in north China, each having a discharge around $1 \text{ m}^3/\text{s}$, are usually major sources of local water supply.

The calcium-rich lithosphere in karst regions, with its unique surface and subsurface double-layer structure of its atmosphere, hydrosphere and biosphere, has brought about a series of particular environmental problems, such as leakage of water resources, drought and flood, poverty of soil, rock desertification, surface collapse, and flooding of mine workings, so that environment scientists regard karst areas as environmentally fragile just like the desert margins. Pure carbonate rocks contain a small percentages of non-soluble substances making their soil-forming capability very low. The small amount of residual soil surviving intense karstification is usually washed down and accumulates at the bottom of karst depressions such as dolines. However, such places are very unfavourable for vegetation, because of annual flooding by underground stream water. Most of the trees grow on the upper parts of doline slopes on very thin soil or even bare rock. Consequently, they usually have very long root systems. If such karst forest is cleared, it is very difficult to recover, and soil erosion and rock desertification will occur. For example, in Guizhou Province, the area of rock desertification increased by 3212 km^2 during the five years from 1974 to 1979. Moreover, the process has been accelerating in recent years, resulting in spring exhaustion, and even shortage of drinking water for humans and domestic animals. These areas are now the major remaining centres of poverty in the country.

There are 738 registered surface collapse sites in the karst areas of China, including more than 30 000 collapse points. Karst collapse usually follows repeated and rapid fluctuation of the water table induced by natural or artificial factors. It is one of the major geological hazards in China, and can bring about serious disasters, such as building subsidence, train derailments, farmland collapse, inundation of mines, and groundwater pollution.

Karst problems stem from the basic scenario of land at the top (plateau surfaces at different elevations) and water resources at depth (deeply dissected gorges of surface rivers, or deeply buried underground streams). In the Shanxi karst plateau of north China for example, problems arise from the superposition of coal resources (the Permo-Carboniferous coal measures) on water resources (the Cambrian-Ordovician karst aquifers). The environmental geological problems related to such basic land-water resource distribution patterns in the karst plateau of south-west China will continue to be an important subjects for study in the next century.

Acknowledgements

This research is based on the results of IGCP 299, *Geology, Climate, Hydrology and Karst Formation*, and supported jointly by the Ministry of Geology and Mineral Resources (Project 8502218) and the National Natural Science Foundation of China (Project 49070155).

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