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Collapse processes at the tiankengs of Xingwen

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Abstract: The karst of Xingwen, China, contains the Xiaoyanwan tiankeng, alongside the degraded tiankeng of Dayanwan and also the potential collapse chambers in the Zhucaojing cave system. These three sites appear to represent an evolutionary sequence, whereby a tiankeng develops from multiple cave collapses, and subsequently degrades to the profile of a large doline.

Key words: collapse, geomorphology, evolution, tiankeng, doline, China

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The karst of Xingwen is cut into an escarpment of limestone in southern Sichuan, China. One segment of the escarpment is drained by long and active caves that lie beneath an extensive system of large, older, abandoned passages, in a sequence of limestone 350 m thick dipping at about 5° to the south. The surface topography is essentially a splendid karst of dolines and low cone hills that is broken by areas of stone forest.

THE XINGWEN KARST

The spectacular tiankeng of Xiaoyanwan lies at the heart of the Xingwen karst. Adjacent to it, a secnd tiankeng and a large cave system are genetically related to it.

Xiaoyanwan tiankeng

This fine example of a mature tiankeng is a huge collapse doline ringed almost completely by vertical limestone cliffs over 100 m high (Fig. 1). It is almost circular in plan, 625 m long and 475 m across, and its rim cuts through twelve conical hills and the intervening solution dolines within the karst. The highest point on the rim cliffs stands 248 m above the lowest point in the tiankeng, while the lowest col on the rim is still 178 m above the tiankeng floor. Its volume is therefore about 36M m^3.

Though the upper half of the tiankeng profile has vertical cliffs, the lower half tapers to a small, dry, grass-floored apex. Most of the lower slopes are ramps of scree that are covered by thin soil and vegetation, though there are some active runs of bare rock debris. Significantly, these lower slopes across the northern side of the tiankeng are broken by two bedrock cliffs (Fig. 2); the lower cliff is natural, but the upper scar has been enhanced by a vehicle track cut into it; small banks of scree stand between successive cliffs.

The perimeter of Xiaoyanwan is breached by four large cave entrances, each opening at the foot of the vertical cliffs. Each cave passage is about 60 m wide and at least 40 m high (Fig. 3), though the entrances into the tiankeng are modified by flaring of the roof due to weathering and spalling and are also partly obscured by large banks of breakdown debris below the overlying cliffs. All four caves are very old, abandoned, phreatic passages (Waltham & Willis, 1993; Waltham et al, 1993; Zhu et al, 1995). The three passages on the west side appear to be successive or contemporary routes of the trunk drainage out of the Zhucaojing cave system, though only the Xiang Shui passage can now be followed back into the main cave. The main passage of Tiencuan Dong opens in the east side of Xiaoyanwan, but a lower level passage through Spider Cavern is choked by breakdown under the edge of the tiankeng. The relationships, convergences and intersections of these three inlet passages from the west and the two outlet passages to the east have been lost by the tiankeng collapse; there may well be other passages obscured beneath the breakdown at the level of Spider Cavern.

The surface of Xiaoyanwan is now dry, and swallows all direct rainfall as percolation. However, its rock floor lies unseen beneath its fill of breakdown debris. A segment of Xingwen's main underground river (from the Xia Dong sink to the Donghe Dong resurgence) is accessible by a small shaft beneath Spider Cavern, and has been mapped as far as a sump beneath Xiaoyanwan (Fig. 6). This lies 70 m below the daylight floor of the tiankeng, and it is unknown if there is any connection between the active river cave and the Xiaoyanwan tiankeng.

It is not known if any significant flow of allogenic water ever sank into either an open tiankeng at Xiaoyanwan or through shafts into the underlying caves at the site where the tiankeng subsequently developed. The edge of the sandstone cover is now only 500 m from

Figure 1. *A distant view of Xiaoyanwan, seen from high on a mountain in the sandstone cover, with the crest of the Xingwen escarpment forming the nearer skyline profile (Photo: Dick Willis).*

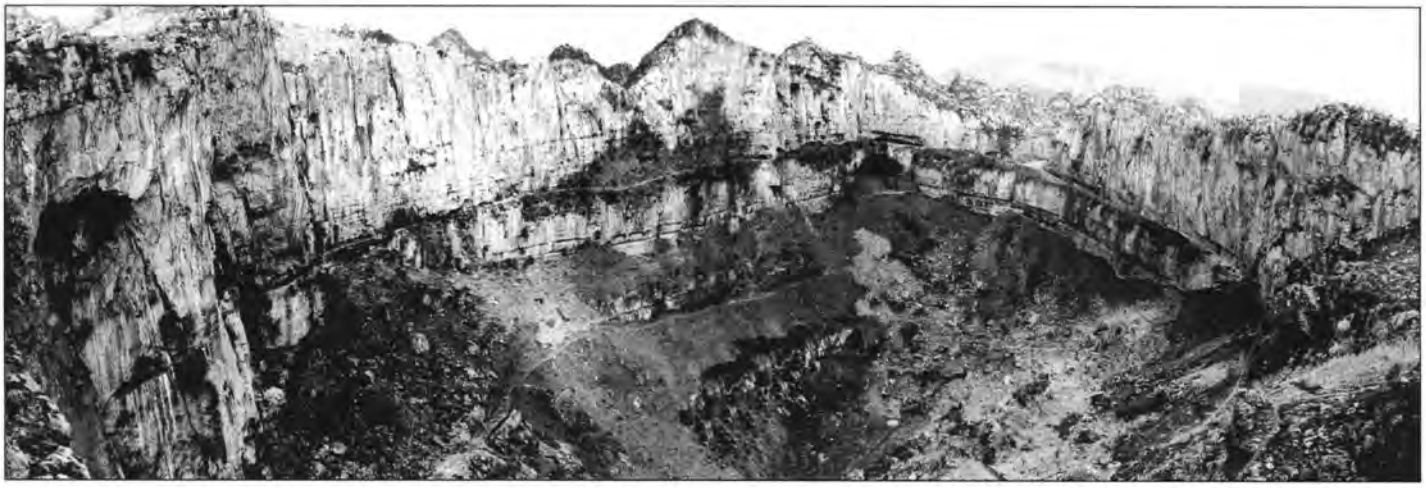

***Figure 2**. Looking east along the length of the Xiaoyanwan tiankeng; on the lower slopes, note the bedrock ribs on the north side (left) contrasting with the debris ramp on the south side (right) (Photo: Zue Xuewen).*

the tiankeng, and it has steadily retreated by dipslope erosion on the escarpment, at the same time as the caves have been developing in the underlying limestone. There must have been allogenic inflow to the tiankeng site when the sandstone cover reached further north, but there is no evidence that this was ever a major stream or river.

Dayanwan tiankeng

Less than a kilometre from Xiaoyanwan, Dayanwan is an older tiankeng that is greatly degraded. Its ragged outline reaches 680 m long, with a maximum width of 280 m. Vertical cliffs form the perimeter, except at the western end where they are lost under a steep bank of debris. Many parts of the cliffs are about 100 m high; their crest line varies as it cuts through a series of hills and solution dolines. Parts of the tiankeng floor have a thick soil cover that has been terraced into fields, but most consists of aprons and fans of scree and breakdown with discontinuous plant cover (Fig. 4). The bedrock floor lies at an unknown depth, except where a small section is exposed near the eastern end of the tiankeng, on the rim of the deepest of three dolines on the tiankeng floor. The base of the limestone sequence lies less than 100 m below daylight within Dayanwan.

There are no caves exposed in the walls of this tiankeng. Various sections of large old trunk passage are choked by breakdown not far outside the Dayanwan perimeter (Fig. 2), and it is reasonable to interpret some of these as remnants of caves that once continued through the tiankeng site. The modern underground river from Xia Dong passes close to the northern edge of Dayanwan, but has no connection or relation to the tiankeng in the section so far explored.

***Figure 3**. The truncated cave passage of Tiencuan Dong looking towards the debris pile in the eastern slope of Xiaoyanwan tiankeng; scale is given by the footpath with 30 steps up to the first switchback.*

Zhucaojing cave

The cave system of Zhucaojing is the largest fragment of the Xingwen caves so far explored, where nearly 9 km of passages were mapped in 1992. Most of the cave lies downdip beneath the sandstone cover, but one major tunnel extends to its truncation in the wall of the Xiaoyanwan tiankeng. A series of chambers lies under the cave entrances close to the sandstone boundary (Fig. 6), and this constitutes an active zone of dissolution, collapse, erosion and cave enlargement.

***Figure 4**. The degraded tiankeng of Dayanwan, seen from its eastern rim, with the edge of its deep internal doline visible in the foreground (Photo: Zhu Xuewen).*

Figure 5. The Entrance Chamber of the Zhucaojing cave system looking west (Photo: Tony Baker).

The Entrance Chamber is 250 m long, 120 m across and about 30 m high; its roof is a dipping bedding plane modified by collapse, with a large opening to daylight on one side (Fig. 5). The floor of mud banks and scree slopes obscures breakdown of an unknown depth, and is crossed by small streams derived from inlet fissures and percolation. The adjacent Western Chamber is not as wide but is just as tall, with one small skylight in its roof that is domed over a floor of breakdown. The String of Pearls is a line of three skylight shafts in a major rift that lies across the outlet passage (which itself is about 50 m wide and 30 m high). The shafts reach down from the dissected floor of a large doline about 100 m above the cave; they carry showers of water after rainfall, as they have small allogenic catchments on the adjacent sandstone cover.

EVOLUTION OF THE TIANKENGS

It is suggested that the three adjacent sites at Xingwen represent three successive stages in the same process of tiankeng development (Fig. 6). If this is accepted, they may demonstrate the processes that are largely lost in large and mature tiankengs elsewhere.

Zhucaojing represents the initial stage of major cave enlargement prior to the roof collapse that then creates an open tiankeng. Progressive stream dissolution will undercut and extend outwards the cave walls, leaving intervening pillars and screens that are excessively narrow. Ultimately, these narrow pillars and the cave roofs will collapse in either a single or multiple events. When the two large cave chambers and the passages around the String of Pearls skylights all collapse, a tiankeng 500 m long and 200 m across will be created. The new perimeter cliffs will cut vertically through five hills and five dolines, and would reach 140-200 m above the new tiankeng floor (though the pile of breakdown blocks may reduce this depth until they were removed by erosion). This is comparable in size to Dayanwan, and would increase towards the size of Xiaoyanwan by a phase of cliff retreat that would also give it a more rounded shape.

The Zhujaoing situation appears to imply that tiankeng development in the Xingwen karst is by multiple collapses of a suite of cave passages and chambers. The large tiankengs, in China and elsewhere, are significantly larger than all known cave chambers (with the singular exception of Sarawak Chamber in the

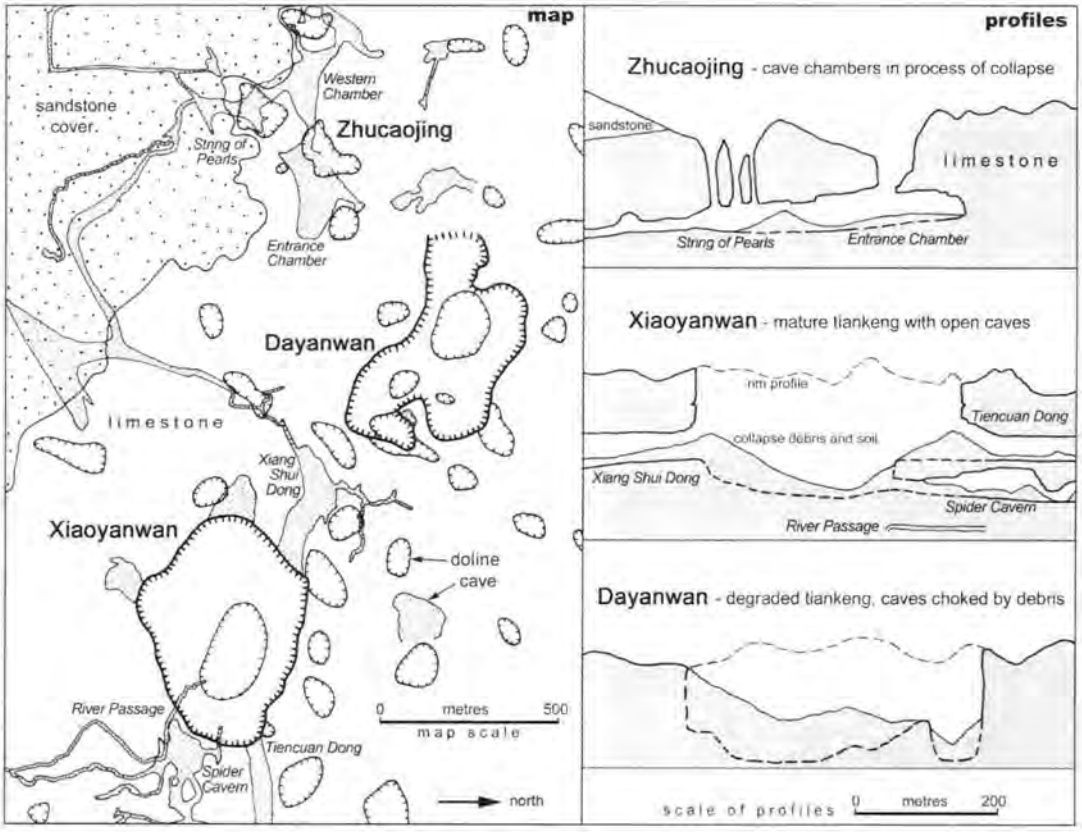

Figure 6. Map and profiles of the three collapse sites at Xingwen, including the Xiaoyanwan tiankeng; most of the bedrock profiles are postulated as they are largely obscured by the breakdown debris.

extraordinary Mulu karst), and it may be that many of them have also developed by multiple collapses instead of by the roof failure of a single, very large, cave chamber. It is also notable that the Zhucaojing site is developing beneath surface dolines that focus rainfall infiltration and also modest allogenic input. Though the cave chambers extend under adjacent hills, which would therefore be cut into by any future collapse, the dolines do appear to play an important role by focussing dissolutional effort within the limestone. Zhucaojing's evolution into a tiankeng is destined to take place more slowly, or possibly even fail, since the trunk drainage through the site has been diverted to lower levels, and the dissolutional and mechanical removal of collapse debris is therefore greatly retarded.

Xiaoyanwan represents the mature stage of the tiankeng. However, it may have evolved slightly beyond its stage of maximum activity, as it appears that there is no longer an active cave river removing material from it; the tiankeng is therefore in the initial stages of old age and decline. It is likely that Xiaoyanwan developed at the convergence of at least five major cave passages; enlarged chambers probably developed at this convergence, and there was scope for progressive failure of intervening units of rock. The evidence from Zhucaojing suggests that the tiankeng developed by a series of failures of cave walls and chamber roofs. The role of allogenic water and overlying dolines is unknown.

Dayanwan is a degraded tiankeng that represents the final stage in tiankeng evolution. No cave entrances survive in the tiankeng, but remnants are likely to lie beneath the aprons of breakdown. The underground river (that removed the rock mass to form the tiankeng) has been captured by younger and lower caves that lie away from the site. Some sections of the perimeter cliffs still stand tall and vertical, but other sections are becoming buried by talus. Further degradation will convert the overall morphology into that of many large old dolines that have been formed by both dissolution and collapse. This conversion has started at the western end, where a debris slope now reaches from the rim level to the depression floor. Over time Dayanwan will evolve into a shallower and slightly wider mega-doline that will not warrant description as a tiankeng.

Comparisons with other tiankengs

Some elements of the Xingwen landforms do conform to those of tiankengs elsewhere, but others do not. Xiaoyanwan conforms in that it is a collapse doline well over 100 m in each of its three dimensions and has a perimeter of vertical cliffs. It has no cave river across its floor (though one may pass unseen through the breakdown pile that is of unknown depth), but otherwise it has the morphology of a mature, large tiankeng. Zhucaojing is not yet a tiankeng, but it should evolve into one in the future, unless its collapse debris cannot be cleared away since it lost its underground river. Dayanwan is a much degraded tiankeng that will in the foreseeable future degrade to a point where it should no longer be described as a tiankeng.

However, Xiaoyanwan does not conform to the original concept of a tiankeng (Zhu, 2001) in that it appears to have evolved by the collapse of a suite of large phreatic caves, rather than by failure of a single cave chamber. It may never have lain over a large river cave within the vadose zone.

The three Xingwen sites are clustered in the limestone beneath a high spur formed of the sandstone cover rock, and there is no evidence that any large allogenic stream ever entered the limestone at any of the sites. However, their proximity to the impermeable cover boundary suggests that small allogenic flows have contributed to their development. This is clearly the case at Zhucaojing, where the String of Pearls is currently being enlarged by inlet vadose water. This is diagnostic of an erosional tiankeng (Zhu and Chen, this volume), but collapse is already a significant process at Zhucaojing. It is difficult to distinguish between the collapse and erosional types of tiankeng, as both collapse and dissolution processes contribute to both types.

The age of the Xingwen tiankengs cannot yet be determined. However, it is significant that all three sites relate to large old phreatic trunk caves, whose development pre-dates a water-table decline of around 200 m. Non-quantitative comparisons with other dated caves suggest that the major enlargement of the caves under the Xingwen tiankengs (and in the Zhucaojing proto-tiankeng) took place some hundreds of thousands of years ago, though the final collapses that breached the surface probably occurred within the last 100,000 years. A younger date for the collapses is commensurate with the freshness of the perimeter cliffs around the Xiaoyanwan tiankeng.

The two Xingwen tiankengs both cut through dolines and limestone hills alike, but it is not clear if they developed independently of the surface topography. Active doline development and sinking streams do appear to contribute to the evolution of the Zhucaojing site, though when this develops into a tiankeng, the large-scale collapse will also cut through a suite of karst hills. The topographic and geomorphic relationships at Xingwen appear to be instructive with regard to the wider study of tiankeng development.

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